fib CEB-FIP

PCI Precast/Prestressed Concrete Institute

Bulletin 99




Conceptual Design of Precast Concrete Bridge Superstructures

Technical report

Bulletin 99

fib CEB-FIP

PCI Precast/Prestressed Concrete Institute

Conceptual Design of Precast Concrete Bridge Superstructures

Technical Report

Task Group 6.5

August 2021

Approval for this bulletin

Subject to priorities defined by the Technical Council and the Presidium, the results of the *fib*'s work in commissions and task groups are published in a continuously numbered series of technical publications called *bulletins*. The following categories are used:

Category:	**Approval by**:
Technical report	Task group and chairpersons of the commission
State-of-the-art report	Commission
Manual / Guide to good practice / Recommendation	Technical Council
Model code	General Assembly

Any publication not having met the above requirements will be clearly identified as a preliminary draft.

fib Bulletin 99 was approved as a Technical Report by Commission 6 in 2021.

The *fib* Task Group 6.5 includes the following members:

Conveners: Hugo Corres Peiretti (FHECOR, Spain) until October 2018 and Marcelo Waimberg (EGT Engenharia, Brazil) since October 2018, co-convener: Kenichi Kata (Sumitomo Mitsui Construction Co, Ltd., Japan).

Musa Alawneh (e.construct LLC, UAE), Freddy Ariñez Fernandez (Universidad Politécnica de Madrid, Spain), Chen Baochun (Fuzhou University, China), Yin-Wen Chan (National Taiwan University, Taiwan), André de Chefdebien (Rector Lesage, France), Albert De la Fuente (Universitat Politècnica de Catalunya, Spain), Sameh El-Ashri (e.Construct, UAE), David Fernández-Ordóñez (*fib*, Switzerland), Helder Figueiredo (IDEAM SA, Spain), Mario Garcia Gonzalez (Grupo Pacadar, Spain), Pankaj Garg (Atkins, India), Manyop Han (KCI, South Korea), V. N. Heggade (STUP Consultants Pvt. Ltd, India), Milan Kalny (Pontex s.r.o. Prague, Czech Republic), Byungsuk Kim (Hanyang University, South Korea), Lars Lundrof Nielsen (COWI, Denmark), Luis Matute Rubio (IDEAM SA, Spain), William Nickas (PCI, USA), Steven Nolan (Florida Department of Transportation, USA), Chong Yong Ong (Experiva Solutions, Malaysia), Alessandro Palermo (University of Canterbury New Zealand), Sung-Yong Park (KICT, South Korea), Mario Petrangeli (Mario Petrangeli & Associati, Italy), José Rui Pinto (Mota-Engil Pré-fabricados, Portugal), Ruslan Pogrbniak (Slavutich, Russia), Jong Sung Sim (Hanyang University, South Korea), Fernando Rebouças Stucchi (ABECE/EGT, Brazil), Maher Tadros (University of Nebraska-Lincoln, USA), Jasson Tan (Dura Technology, Malaysia), Pieter van der Zee (Ergon, Belgium), Yen Lei Voo (Dura Technology, Malaysia), and Robert Wheatly (Atkins, UK).

Cover images: Figures 5-9, 5-110, 5-197b, and 5-261.

ISSN 1562-3610
ISBN 978-2-88394-150-2
https://doi.org/10.35789/fib.BULL.0099
Layout by Marie Reymond (*fib*).
Printed by DCC Document Competence Center Siegmar Kästl e.K., Germany

Acknowledgements

This report was drafted by Task Group 6.5 "Precast concrete bridges" within the *fib* Commission 6.

Authors:

Hugo Corres Peiretti (Convener/Editor)
FHECOR, Spain

Freddy Arinez
FHECOR, Spain

Baochun Chen
Fuzhou University, China

Andre de Chefdebien
LB7, France

David Fernández-Ordoñez
International Federation for Structural Concrete, Switzerland

Albert de la Fuente
Technical University of Catalonia, Spain

Helder Figueiredo
IDEAM, Spain

Mario Garcia
Pacadar, Spain

Pankaj Garg
Atkins, India

Man Yop Han
Ajou University, South Korea

Milan Kalný
Pontex, Czech Republic

Kenichi Kata
Sumitomo Mitsui, Japan

Byung Suk Kim
KICT, South Korea

Luis Matute
IDEAM, Spain

William Nickas
PCI, USA

Lars Lundorf Nielsen
COWI, Denmark

Alessandro Palermo
University of Canterbury, New Zealand

Sung Yong Park
KICT, South Korea

Mario Petrangeli
Mario Petrangeli & Associati, Italy

Jongsung Sim
Hanyang University, South Korea

Fernando Stucchi
EGT, Brazil

Maher Tadros
e.Construct, USA

Pieter van der Zee
Ergon, Belgium

Yen Lei Voo
Dura Technology, Malaysia

Marcelo Waimberg
EGT, Brazil

Robert Wheatley
Atkins, UK

Contact details of Task Group members can be found in the members only section of the *fib* website, www.fib-international.org.

DOI by chapter

Chapters	DOI
1	https://doi.org/10.35789/fib.BULL.0099.Ch01
2	https://doi.org/10.35789/fib.BULL.0099.Ch02
3	https://doi.org/10.35789/fib.BULL.0099.Ch03
4	https://doi.org/10.35789/fib.BULL.0099.Ch04
5	https://doi.org/10.35789/fib.BULL.0099.Ch05
6	https://doi.org/10.35789/fib.BULL.0099.Ch06

Foreword

Concrete bridges are an important part of today's road infrastructure. An important part of those concrete bridges is to a large extent prefabricated. Precast concrete enables all the advantages of an industrialized process to be fully utilized. Contemporary concrete mixtures are used to realize high-strength bridge girders and piers that exactly meet the requirements set, both structurally and aesthetically, with a small ecological footprint. Sustainable and durable! On the construction site, there is no need for complex formwork, the execution time is drastically reduced and where road, water and rail traffic on or under the bridge has to be temporarily interrupted, it is only minimally inconvenienced during the execution of the project.

Bridges capture the imagination. In addition to their pure functionality, overcoming a height difference, they offer designers unprecedented opportunities to shape their creativity, including when using precast concrete.

This bulletin, prepared by the experts of Task Group 6.5 'Precast concrete bridges', takes a closer look at the conceptual (preliminary) design of prefabricated concrete bridges. The bulletin does not have the ambition to define the umbrella term 'conceptual design' but shows in a pragmatic way, using 24 examples spread all over the world, how leading designers use this methodology to select from the many possibilities to arrive at an ideal solution taking into account all design conditions.

One often reads that experience is a necessary condition for good conceptual design. The pooled knowledge and experience in this bulletin already provide the reader with a good head start.

Commission 6 thanks the former convener of the Task Group Hugo Corres, editor of this document, and the current co-conveners Marcello Waimberg and Ken-ichi Kata as well as all active members of the Task Group for sharing their knowledge and experience and for the successful realization of this bulletin.

Stef Maas

Chair of Commission 6 *Prefabrication*

Harry Gleich

Chair of PCI Technical Activities Council

Contents

1. Scope

The purpose of this document is to present preliminary design procedures for bridge superstructures that are made partially or completely of precast concrete. This document deals with continuous and simply supported superstructures, used in integral or nonintegral bridges.

The document is intended for engineers with limited experience who will find it an instructive detailed guide to carry out conceptual design of superstructures of these types.

Additionally, it is intended for experienced engineers who are interested in learning how different countries solve similar conceptual design problems.

Finally, it is intended to enrich the knowledge of precasters everywhere, to be able to enhance their own designs with ideas and methods from many different countries.

https://doi.org/10.35789/fib.BULL.0099.Ch01

2. Introduction

Preliminary or conceptual design of precast concrete superstructures is a process that is similar to that used for design of other types of structures.

The *fib* Model Code for Concrete Structures 2010[2-1] defines, in general terms, this process, which is summarized in the flowchart in Fig. 2-1. More detailed information on this subject was published in *fib* Bulletin 51[2-2].

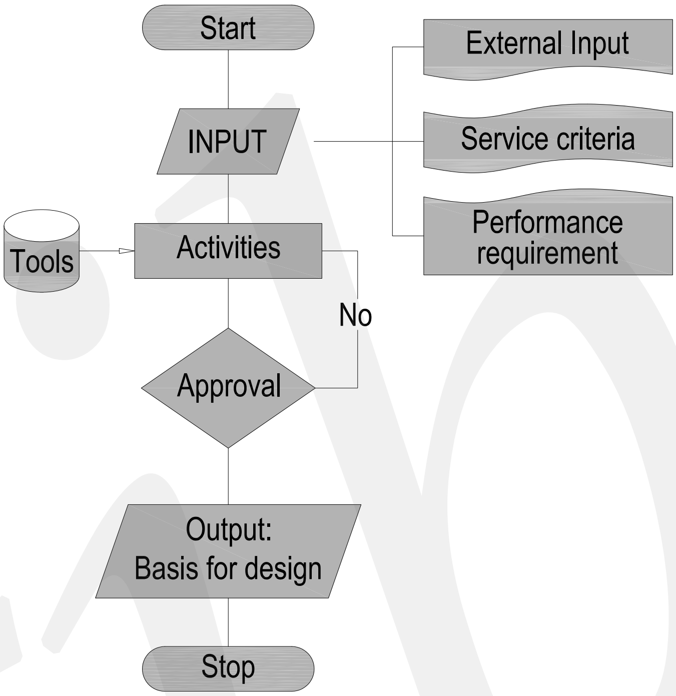


Fig. 2-1 Flowchart that summarizes the conceptual design process[2-1; 2-3].

The conceptual design process begins with the definition of the problem to be solved, followed by the collection of all pertinent information for the details of the design to be executed. During this process, the bridge engineer must interact with other professionals such as geotechnical, hydraulic engineers, etc. and thoroughly evaluate all existing conditions. Unfortunately, this process is not always carried out with adequate thoroughness, which often strongly impacts the final solution due to incomplete definition of the problem.

When searching for a solution, the bridge engineer often uses available tools, general geometrical proportions, criteria for estimation of the different solutions, as well as experience with similar projects[2-4; 2-5].

Preliminary design is an iterative process. It begins with the definition and detailed evaluation of all possible solutions. Possible solutions include details about the longitudinal and transverse definition of the superstructure, and proposed primary details of support conditions, including longitudinal continuity or simply supported systems, and precast bridge elements and/or systems.

https://doi.org/10.35789/fib.BULL.0099.Ch02

Possible solutions are strongly influenced by local conditions, such as cost and availability of materials, labor, equipment, and available technology and skills.

Each possible solution must be compared with others according to established criteria—such as some measure of performance, economy, aesthetics, and durability—in order to choose the optimum solution.

Once the conceptual design has been selected, it is then developed in greater detail.

Bridges with precast concrete superstructures are very popular and known practically the world over. Nevertheless, it is interesting to observe how different countries often use different precast concrete superstructure solutions. In some cases, the differences are radical.

This document presents examples of precast concrete superstructures developed in different countries that correspond to real bridges or ideal bridges that have been specifically studied for this report.

3. Input—General design considerations

As described in the previous chapter, when the preliminary design of a structure is not approached carefully and responsibly, it can lead to inadequate data and inefficient solutions that may need to be reevaluated more than once.

This chapter describes the typical, relevant considerations for preliminary design and their effects on the final design.

Superstructures that are usually constructed of precast concrete are underpasses, overpasses, interchange bridges, water crossings, and viaducts. In general, these bridges are a part of a larger project and interact with and affect other structures or elements of the project. Therefore, bridges are never isolated elements that can be designed with complete freedom, but instead a series of related project considerations must be evaluated. Some of these considerations include:

- layout
- geological and geotechnical
- code limits or design criteria for structural materials
- legal
- construction
- aesthetics
- environmental
- sustainability
- maintenance
- functional

From these considerations, the designer generally can choose:

- cross-section type
- preferred materials
- construction methods
- details of the primary elements

For precast concrete solutions, options are often impacted by construction or other specific limitations, which are explained in the following sections. Precast concrete superstructures are also affected by code limits, including the components that are able to be fabricated, erected, and transported in the country where the structure is to be built, and the equipment available.

For example, precasters in some countries have absolute freedom to define the shape of the prefabricated elements. In other countries, there are predefined standard cross-section shapes of the elements (Fig. 3-1). In many countries, both possibilities exist.

In some countries, the prefabrication industry is well developed and able to offer a variety of solutions. In some countries, the prefabrication industry regularly develops innovative precast concrete solutions that are atypical, to create extraordinary solutions such as the ones shown in *fib* bulletin 29[3-1]. This may be the future of prefabrication, where precasters adopt new industry developments to produce groundbreaking solution[3-2;3-3].

https://doi.org/10.35789/fib.BULL.0099.Ch03

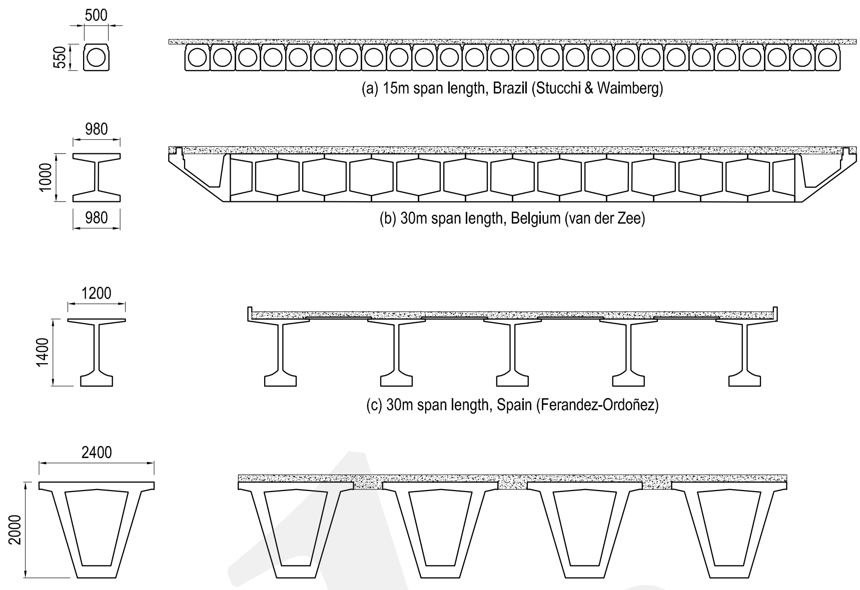


Fig. 3-1 Various girder cross sections used in different countries. Note: Dimensions in single cross sections on left are in millimeters. 1 mm = 0.0394 in.; 1 m = 3.281 ft.

3.1 Layout

Layout considerations are those that affect the structure and are typically caused by the geometry of the road to be connected and the obstacles to be bridged, including highways, railways, or bodies of water. Additionally, the following should be considered:

- Plan and elevation geometry
  For precast concrete superstructures, this consideration is relevant because there are some limitations for these structures. For example, for sharply curved bridges, if the girders are straight, they must be arranged in the form of a polygon that approaches the desired layout.
- Unusually large longitudinal or transverse slopes
- Transverse cross-section geometry
  This includes superstructure width, road width, requirements for pedestrian or some other types of lanes, requirements for large variations in width due to merging or exiting lanes.
- Vertical and horizontal clearances
- Need for longitudinal or transverse drainage
- Skewed layouts

In the design of a highway bridge, it is common practice to first define the plan and elevation, and later define the structures. However, from the very beginning, there should be a coordinated analysis between the highway engineers and the structural engineers to reach a common preliminary layout for the structure while aiming for the optimization of the solution.

3.2 Geological and geotechnical factors

Geology and terrain not only dictate the layout of the structure, but also can affect the position of the piers, and therefore the span lengths.

Geotechnical conditions can heavily influence some solutions, for example limiting the span length to reduce the loads transferred to the foundations or increasing the number of spans and the length of the bridge to reduce the height of abutments.

3.3 Codes

Every country has its codes that define the loads to be supported and the combinations to be taken into account, both at ultimate limit state (ULS) and serviceability limit state (SLS). The codes often define the expected behavior of the structure during its service life in terms of functionality, durability, sustainability, and robustness. There are also constraints reflecting each country's tradition and experience.

Many codes have been developed to define the forces to be considered in both highway and railway bridges, and codes that control structural concrete construction[3-4;3-5;3-6; 3-7; 3-8]. The general principles are often similar.

3.4 Construction factors

Construction issues are important in the preliminary design of a precast concrete superstructure. Fabrication conditions at the precast concrete manufacturing facilities, and transportation conditions of the elements and their installation at the jobsite should be considered.

The fabrication conditions at the precast concrete manufacturing facilities must consider local practice. Sometimes, fabrication at the jobsite offers a different set of possibilities, as well as constraints.

Some countries use post-tensioned or pretensioned draped (also known as deflected or harped) strands, while other countries only consider straight pretensioned strands. In some countries, the strands may be debonded, while other countries do not allow it.

Different countries have different weight limits that can be transported on their highway networks. This aspect is very important because these limits are often very different and control the size of the precast concrete elements that may be used. Precasters often solve these limitations by transporting segments of the precast concrete longitudinal elements and later joining them with post-tensioning at the project site.

In many cases the dimensions of the precast concrete elements, particularly their length and weight, require evaluation of highway conditions and transportation with specialized hauling equipment.

The transportation of precast concrete pieces is also strongly influenced by the accessibility to the jobsite. In many cases it is not possible to access the jobsite because there is no highway network that allows adequate road transportation. In other cases, it is necessary to construct access for the hauling vehicles to the location of the bridge. All these challenges must be adequately considered and solved.

Finally, the installation of the precast concrete elements should be studied in detail. It is necessary to account for the following:

- height of the structure
- accessibility and topography
- feasibility of creating detours when traffic is affected
- layout geometry and compatibility with the potential installation measures
- deadline and work schedules to consider solutions compatible with these needs
- equipment availability

In many locations, the use of high-capacity cranes allows the installation of large and heavy elements. With these possibilities, it is necessary to carry out a detailed study to ensure access conditions for the cranes for the installation of the precast concrete elements.

In some cases, the cranes can be moved directly on the bridge under construction, especially for the installation of elements such as deck panels or slabs. Naturally, this aspect must be considered at this level of study.

3.5 Aesthetics

Structures must be integrated with their surroundings and, as much as possible, they should be pleasing to neighbors and the traveling public. However, aesthetics is subjective, and constraints are often linked to cultural issues that vary with time. It is necessary to consider this aspect in the conceptual design process.

Precast concrete structures can be designed to meet aesthetic requirements for their environment.

An aesthetically pleasing structure is not necessarily more expensive.

Proportions are crucial in bridge aesthetics. Adopting proportions compatible with structural behavior usually results in pleasing forms.

In precast concrete girder superstructures, the selection of the shape of the piers to be compatible with the superstructure is important to provide an aesthetic solution.

Details are paramount in the appearance of the bridge.

Using slabs with overhangs can create a pattern of shadows, which can considerably improve the appearance of the structure. In addition, this solution allows defining the pier, which can also improve the overall appearance of the project.

The use of safety barriers at the edges of the superstructure should be avoided, if possible, to enhace the appearance of the bridge. In urban bridges, with pedestrian lanes at the edges of the superstructure, the safety barrier is automatically placed in a more interior area of the bridge, which reduces its impact on the appearance of the structure. Furthermore, when the railings are incorporated into the design, the aesthetic quality is also improved.

The definition of an aesthetically pleasing solution should be a goal of every designer and can be accomplished every time that this aspect is seriously considered in the design process.

3.6 Environmental factors

A structure should be designed to respect specific environmental conditions, which are usually defined in the applicable environmental impact studies (earthquake, wind, temperature, freezing and thawing, deicing chemicals, and the like). Environmental factors should be considered not only for the finished bridge, also during construction, when the environmental requirements are often very important.

Another aspect that should be considered in detail in the design is the environment that determines durability conditions. Different elements of a bridge can have different requirements. For example, the substructure of bridges over seawater will very likely need to meet harsher durability requirements than the superstructure.

3.7 Sustainability

In nearly every new project, sustainability must be considered in the selection of the structure type, the materials, and the construction processes used.

Producing sustainable structures should be an important goal of designers to minimize environmental, economic, and social impacts.

A sustainable solution requires a global concept that integrates the different structural, environmental, economic, and social aspects. In this context, it is important to minimize the consumption of natural resources compatible with the required service life and behavior of the structure.

In some ways, the adoption of sustainability as a design criterion has led to a design paradigm shift. Whereas the previous philosophy saw that the challenge was to obtain greater benefits (more resistance, less cost, etc.), sustainable design moves the target towards finding equilibrium between the potential benefits and necessary resources, such as discussed by Voo and Foster[3-9].

This entails a challenge that can only be met with an experienced structural and technological knowledge and with a new sensitivity towards these other aspects that define the service life of the structure.

In many scenarios, structures form part of a much larger project (for example, a highway, and a railway line). In this sense, a sustainable approach should also link the sustainability of the structure with the sustainability of the balance of the project.

A good conceptual design process is the best guarantee of sustainable solutions.

3.8 Maintenance

It is important to consider the maintenance requirements of the structure during its design.

Ideally, the proposed solution should require minimum maintenance. However, the structure also has certain service life demands, usually established in the relevant codes, that are greater than those that correspond to nonstructural elements, such as bearings and joints. The use of elements with a shorter service life than the structure results in maintenance needs, and thus should also be considered.

Finally, from the beginning, the proposed solution should consider which measures are necessary for the structure to accommodate inspection and ordinary maintenance tasks, such as control and cleaning of transverse and longitudinal drainage, and inspection and replacement of bearings and joints.

3.9 Economy

The project budget must always be considered. Minimizing costs often results in the optimal solution and is an important task when funds are scarce.

Costs should be evaluated for the life of the bridge not merely based on initial cost, considering the construction costs, material costs, and maintenance costs.

3.10 Safety in construction, operation, and maintenance

It is important for the bridge engineer to consider how the design will be safely constructed, operated, and maintained when developing the design concept. Producing designs that are safer to build or maintain helps accomplish the objective of every worker going home uninjured at the end of every day. This is different from structural reliability, which is adequately covered by design standards. A safe design gives attention to the choice of materials, details, and construction methods, well in advance of the start of construction. Good design practice in this way can often also produce cost and program benefits.

Safe design needs to be determined in accordance with local customs and practices, but at the same time strive to minimize the risk of accidents during construction and maintenance. Examples of this could be the reduction of exposure to working at heights using precast concrete deck panels, eliminating the use of hand-held texturing equipment by roughening a joint during initial curing, or cutting off piles using passive or active integrated pile-breaking methods. Increasing off-site manufacturing is seen as one of the ways of improving safety, as fabrication can be done in controlled factory conditions compared to exposed and less-well-controlled field conditions. Safe maintenance should also be considered during the design. Some examples could be the provision of secure access to components for regular inspections, or the design of designated lifting points for jacks when replacing bearings.

3.11 Other considerations

Because every bridge is unique, there is no exhaustive checklist that can cover all cases. In many cases it will be necessary to identify additional constraints.

The result of this stage is the design solution that optimally satisfies all of the issues identified for the particular challenge.

4. Activities—Preliminary Design Guidelines

4.1 Scope

This chapter presents guidelines for the preliminary design of bridge superstructures made of precast, prestressed concrete girders, with or without composite deck slabs. Both simple and continuous spans are considered.

Design aids are provided to help establish cost-effective arrangements for superstructure framing.

The different criteria presented in this section correspond to recommendations applied in some of the member countries of *fib* Task Group 6.5 ″Precast Concrete Bridges″ that have prepared this document.

These are general guidelines and initial guiding steps in the design process but should not be taken as requirements.

4.2 General Design Considerations for Selecting Precast Concrete Girder Systems

4.2.1 Girder length and depth

If clearance and other constraints allow (usually related to higher bridges such as more earthwork, more fuel consumption, etc.), it is generally more economical to use a deeper section of a given girder type, if it meets local handling and shipping limitations. A 2'000 mm (79 in.) deep section costs only slightly more than a 1'000 mm (39 in.) deep section in the same family of girders because the cost of additional concrete is more than offset by the reduction in cost due to less prestressing steel and possibly lower concrete strength. Also, manufacturing steps are essentially the same, which works in favor of deeper sections in high-labor-cost regions. For example, in the United States most highways have vertical clearance limits of 4.3 to 5.5 m (14.1 to 18 ft) overall. Weight limits vary from country to country, even in different regions of the same country, and often depend on the equipment available from the precast manufacturer. In the United States, girder weights of up to 100 tonnes (110 tons) are typically allowed on most roads, with weights of up to 150 tonnes (165 tons) allowed with special permits in selected areas. A plant equipped with two 50 tonne (55 ton) cranes would require a girder weight limit of 90 tonnes (99 tons) to allow for the spreader beam weight. Gantry cranes of 75 to 100 tonne (83 to 110 ton) capacity are used in precast concrete manufacturing facilities with increasing frequency.

Another consideration is the length of the precast concrete girders. Normally, girder length should not exceed approximately 50 times the widest flange width for stability during shipping, handling, and erection[4-1;4-2].For girders near or exceeding this ratio, analysis for lateral stability should be conducted[4-3;4-4;4-5]. Bracing the top flange with a horizontal steel truss, or other means, can be used to overcome lateral stability concerns[4-2].

https://doi.org/10.35789/fib.BULL.0099.Ch04

Girders as long as 65 m (213 ft) have successfully been transported on the roads in the United States and Canada. Transporting such long girders must be planned carefully and analyzed for stability especially if sharp road curvatures and sloped roadways and terrain are anticipated.

For I-girders with composite deck slabs, it is recommended to limit the overhang length, from centerline of exterior web to edge of deck, to 50% of the girder spacing. The length should in no case be less than half of the top or bottom flange width, whichever is greater, to avoid reducing the width of the top flange. Doing so might impact stability and cause stormwater to drip directly on the bottom flange. An overhang width of between 0.75 and 1.50 m (2.46 to 4.92 ft) is reasonable in most applications.

The following sections discuss common situations for typical length bridges.

4.2.1.1 Water stream crossing

For water stream crossings of relatively short length, the most efficient arrangement is a single span to avoid placing piers in the water. Piers constructed within the water channel are more expensive than those on dry land. Also, they result in hydraulic inefficiencies and there is higher risk that piers might become unstable. However, because the superstructure depth is often restricted to avoid bridge flooding, it is often necessary to construct the bridge with more than one span. A common arrangement is three spans, because two-spans would place the pier in the deep-water zone.

For example, given a 58 m (190 ft) long water crossing and a maximum allowed superstructure depth of 1'200 mm (4 ft), a single span precast concrete girder system would not be economically feasible, as it would result in a span-to-depth ratio of 48.3 (58 × 1'000/1'200).

Reasonable span arrangements for this bridge are to use three spans with the largest center span allowed for the 1'200 mm (47 in.) depth. Three options are shown in Table 4-1. The maximum recommended span-to-depth ratio depends on the girder type and spacing, as shown later in this section. For a superstructure 1'200 mm deep and a girder separation of 1500 mm (59 in.), it is assumed to be 22, 25, or 30, depending on the degree of continuity. As will be shown later, it is possible to build the superstructure as a series of simple spans, or to make the girders continuous for live loads only, or for all superimposed loads applied to the girder after the girder is set on the supports (CSDL). A large central span appears to be inefficient if only the amount of concrete and steel in the girders is considered. However, a large central span may offer great benefits in terms of construction and hydraulics.

Table 4-1 Possible span arrangements for a three-span bridge based on different continuity conditions, 58 m (190 ft) long bridge with 1'200 mm (47 in.) depth limits

	Assumed maximum span-to-depth ratio	Center span length, m	End span length, m
Simple span system	22	26	16
Simple for dead loads, continuous for live loads system	25	30	14
Simple for self-weight, continuous for superimposed loads system	30	36	11

Note: 1 m = 3.281 ft.

Nevertheless, these options should be carefully studied by the bridge engineer, in particular the third option in Table 4-1, where it is likely that uplift of extreme bearings will occur due to superimposed and live loads.

4.2.1.2 Roadway overpass crossing

For a roadway overpass crossing, in most cases, the arrangement of a two-span bridge is the most favorable option due to the central pier location being in the median of the roadway under the bridge, although often a four-span bridge is used for visibility. For example, for an 85 m (279 ft) long roadway crossing with a 1500 mm (59 in.) superstructure depth limit, and using the same assumed span-to-depth ratios as in the preceding example, the only economically feasible option is the simple span for self-weight, continuous for superimposed loads system, available span-to-depth ratio = 42.5/1.5 = 28 < 30 allowed for the CSDL system. More detailed discussion is given in Section 4.3. Due to roadway constraints, a two-span overpass bridge often has unequal spans. The longer span would control the minimum depth criteria for preliminary design purposes. As will be shown in the following sections, some cross-section shapes, such as adjacent box beams and slabs, allow for shallower depths than others, such as I-girders.

4.2.1.3 Long bridges

For relatively long bridges, whether crossing major bodies of water or bridging over an extended surface obstacle, a decision must be made relative to division of the bridge into reasonable span lengths. Pier locations depend on the conditions of the area being bridged. Locating piers in deep water or too close to railroad tracks, for example, should be avoided. Pier locations that negatively impact sight distance or other safety issues should be avoided.

Other than natural site limitations, the bridge is divided into “frames” of multiple girder spans, separated by expansion joints. The frames for a concrete girder bridge are generally limited to 230 to 350 m (755 to 1'148 ft) in length, although longer frames have been successfully built.

When the superstructure is continuous, the ratio of end span to interior span should be balanced to give the same size and approximately the same reinforcement for all spans. The ratio is typically 0.80 to 1.00 depending on the level of continuity achieved.

4.2.1.4 Skewed, curved, and variable-width bridges

Modern roadway design requires that a bridge generally follow the roadway geometry on which it is located. As such, it is possible that the bridge must accommodate skews, curvatures, and variation in deck width. Stringer type bridge superstructures can be designed to accept these conditions. One such bridge is shown in Fig. 4-1.

Skew angle between the bridge and its supports can, in some cases, be as large as 70 degrees. For bridges with skews less than 30 degrees, there is no need for special considerations during the preliminary design stage. For larger skews, more care should be given to assess the system being chosen and more detailed analysis may be warranted, even at the preliminary stages.

Horizontally curved bridges are treated differently for different degrees of curvature. It is generally accepted to use straight concrete girders between the supports and to curve the deck slab edge to match the roadway, but only if the curve is 3 degrees or smaller, for example, for a 30.480 m (100 ft) span length,

Note that to convert from degree of curvature to radius of curvature, divide 30.480 m (100 ft) by the degree in radians. Thus a 3-degree curve corresponds to a 582 m (1909.45 ft) radius. The radius depends on the span and vice-versa. For curvatures larger than 3 degrees, until recently, curved steel I-girders were generally thought of as the obvious solution. However, several U-shaped girders of relatively sharp curvatures, with radii as short as 200 m (656 ft) have recently been successfully built in the United States, often as much as 30% below the cost of steel U girders. Box girders or U girders with integral lid slabs to create torsionally stiffer members are suitable for curved bridges.

In recent years, rising structural steel costs and improved precasting technologies have resulted in several innovative precast concrete girder solutions that have mostly been implemented as a result of value engineering on individual projects. The designer is advised to consider these solutions in the preliminary stages and to provide them as alternatives to steel in the initial bidding package to maximize owner value.

In the United States, these innovative solutions have one common aspect. The precast concrete girders are made as a chorded (rather than true) curve, with each chord length being about 6 to 12 m (20 to 39 ft) long to be modular with standard straight girder form lengths[4-6]. Kinks between the straight chords are seldom noticed by the traveling public or even the trained engineer's eyes. These girders are currently precast and post-tensioned in the precast concrete plant[4-6].

Fig. 4-1 Precast concrete superstructure with chord length concrete girders[4-7] Source: *fib* Bulletin 29, *Precast concrete bridges* (Lausanne, Switzerland: International Federation for Structural Concrete, 2004).

Pretensioning of curved girders is common practice in the European countries. An example of a curved girder bridge is shown in Fig. 4-2.

Fig. 4-2 Precast concrete superstructure with curved concrete girders[4-7] Source: *fib* Bulletin 29, *Precast concrete bridges* (Lausanne, Switzerland: International Federation for Structural Concrete, 2004).

4.2.2 Girder spacing arrangement

The following are some of the considerations that influence the selection of the number of I-girders with composite decks, and similar beam sections in a bridge cross section.

- The number of girder lines should not be less than four, to allow deck replacement on one-half the bridge at a time.
- The overhang length should be about 40% of the girder spacing for all girder lines of the bridge to have approximately the same design. However, this depends on truck load, which varies significantly in different codes.

Some codes, including the American Association of State Highway and Transportation Officials' AASHTO LRFD Bridge Design Specifications[4-8], stipulate a maximum overhang length before the exterior girder is required to have a live load distribution factor other than the one used for the interior girder design.

Many U.S. states enforce an overhang length that makes the exterior girder design match that of the interior girder. This simplifies the design, especially because some bridges might be required to be widened in the future, in which case the exterior girder becomes an interior one. However, for some applications with relatively heavy truck loads, the exterior girder may carry a significantly heavier load than the interior ones[4-9]. In all situations, it would be simpler to balance the overhang length and girder spacing to achieve uniform girder loading, for the sake of simplified initial construction and future widening.

4.3 Preliminary design

In nearly every country, in accordance with applicable design codes, many different types of precast concrete elements are available. These elements result in different solutions depending on such issues as span lengths, superstructure width, number of precast concrete girders used, and type of continuity.

The Appendices provide useful information to consider for preliminary design.

Appendix A Preliminary design charts for different precast concrete sections used in the United States.

Appendix B Preliminary design criteria used in Spain.

Appendix C Comparison of vertical live loads. The general provisions of the load models specified in three design codes: Eurocode EC1, AASHTO LRFD HL-93, and NBR 7178, followed by graphs comparing the moments, shear forces, and torsion moments that result in girders in a typical bridge superstructure.

Appendix D Summary table of preliminary design examples. The table gives the following information for the 28 design examples.

- author
- country of origin
- number of spans
- span length
- girder depth
- deck slab depth
- span/depth ratios
- web widths
- girder spacing
- girder weight
- straight or draped prestressing strands or tendons
- design concrete strength for the girder and deck slab
- ultimate strength of prestress and mild steel
- type of girder continuity
- diaphragms used at supports and intermediate

4.4 Continuity methods

The simple span system can be structurally optimized by increasing the degree of continuity, leading to longer spans or wider spacing for the same girder depth. Increasing the girder span or spacing for the same depth greatly reduces the bridge cost. In addition, continuous precast, prestressed concrete girders can be used in long bridges.

Bridge design loads can be categorized into three major components: girder weight, deck slab weight, and superimposed dead and live loads. Each of these components comprises about one-third of the total loads, for spans in the short-to-medium range encountered in girder-type bridge superstructures (see Appendix C of this document).

Continuity for girder weight can be achieved through post-tensioning using a precast concrete pier segment.

Continuity for deck weight and live loads can be achieved with threaded rod continuity methods or post-tensioning.

Continuity for live loads only, can be achieved using reinforcement in the deck slab over the pier. Table 4-2 shows different methods of continuity and their efficiency effects. For example, threaded rod continuity for deck weight, superimposed dead load and live load, allows for the maximum span length to increase by 20 percent, compared to the conventional system of providing continuity only for superimposed dead load and live load[4-10].

Table 4-2 Efficiency improvement due to degree of continuity

<table>
<tr><th colspan="2">Continuity method</th><th>Loads on simple span system</th><th>Loads on continuous span system</th><th>Span efficiency improvement (multipliers)</th><th>Spacing efficiency improvement (multipliers)</th></tr>
<tr><td colspan="2">Reinforcement in the deck slab</td><td>GW, DW</td><td>SIDL, LL</td><td>10%</td><td>4%</td></tr>
<tr><td colspan="2">Threaded rod</td><td>GW</td><td>DW, SIDL, LL</td><td>20%</td><td>8%</td></tr>
<tr><td rowspan="2">Post-tensioning system</td><td>One precast concrete beam per span</td><td>GW</td><td>DW, SIDL, LL</td><td>20%</td><td>8%</td></tr>
<tr><td>Pier + span segments</td><td></td><td>GW, DW SIDL, LL</td><td>25%</td><td>10%</td></tr>
</table>

Note: DW = deck weight; GW = girder weight; LL = live load; SIDL = superimposed dead load.

4.4.1 Conventional deck reinforcement

For multispan bridges, prestressed concrete girders are generally designed as simple spans for self-weight and deck weight, and continuous for superimposed dead loads and live loads.

Cast-in-place (CIP) pier diaphragms and longitudinal reinforcement in the deck over the piers serve as means of resisting the negative continuity moment (Fig. 4-3). With this continuity method, the prestressed girders are made continuous for only about one-third of the total load. Additionally, because virtually all dead load is applied before continuity is put into effect, some bridges have experienced bottom fiber cracking near the piers due to high positive time-dependent restraint moments caused by creep camber, especially with large prestressing forces.

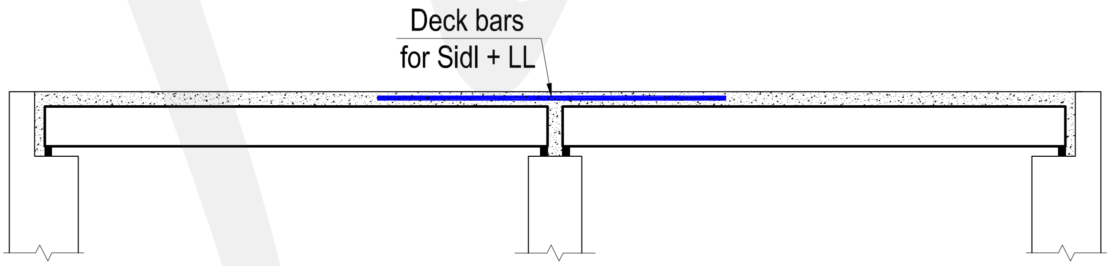


Fig. 4-3 Conventional deck reinforcement continuity method. Note: LL = live load; SIDL = superimposed dead load.

This method is the simplest and least costly compared to other continuity methods. Additional reinforcement does not require extra equipment or specialized labor. In this method, the precast concrete girders are installed on the abutments and the piers, the diaphragm is formed and reinforced, and then two-thirds of the diaphragm height is cast. The deck slab is then formed. The reinforcement is installed and then cast with the haunch (space between the top of girder and bottom of slab) and the balance of the diaphragm. The barriers are installed, and the railing and wearing surface are cast after that. The bridge is then ready to be opened to traffic.

Additional continuity for the deck weight can be achieved by casting slab concrete in two steps. Detailed description of this system is given in a 2016 study[4-10]. In the first step, once reinforcement over piers is provided, only a small volume of concrete sufficient to ensure overlap between that reinforcement and bars on top of the girder should be placed. With this approach, reinforcement for deck continuity is available when the deck is placed. For the remaining second step concrete, continuity is already provided. Obviously, the convenience of having two steps should be evaluated in consideration of the next solution.

4.4.2 Continuous bridge using threaded rods

A continuity system was introduced in Nebraska and received attention in the United States. The "threaded rod continuity system" allows the girders to be continuous for deck weight as well as live loads.

Hence, the bridge is continuous for about two-thirds of the total load. In this system, the precast concrete I-girders are fabricated with high-strength threaded rods located at the top flange and projecting from the girder ends.

This solution has several significant advantages over the continuous-for-live-load system:

- Because the girders are continuous for most of the load, the maximum positive moment is significantly reduced, resulting in reduced prestress demand and reduced demand for high-strength concrete at release.
- The same girder size will span about 15% more than the conventional continuous-for-live-loads system only.
- The increased dead load negative moment with this system guarantees no net positive moment at piers and no possibility of cracking due to creep restraint.
- The continuity of negative moment reinforcement in the girders at time of deck placement ensures adequate resistance to girder end rotation and no diaphragm distress or cracking, which has occasionally occurred with the continuous-for-live-load method.

In this method, I-girders are fabricated with 1034 MPa (150 ksi) high-strength threaded rods embedded in the top flange. The threaded rods are mechanically spliced in the field at the diaphragms over the piers (Fig. 4-4). This study[4-10] gives full details of this system including photographs of actual bridges. The diaphragm concrete is then placed, and the deck slab is cast after the diaphragm concrete gains the required strength. This continuity reinforcement is designed to resist the negative moment due to the weight of the deck slab. Conventional longitudinal reinforcement is placed in the deck in the negative moment regions to resist the additional negative moments due to superimposed dead and live loads.

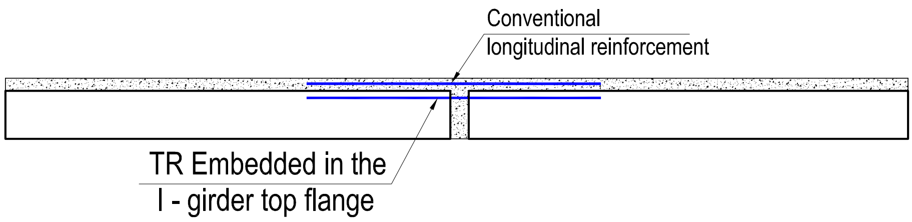


Fig. 4-4 Threaded rod continuity schematic.

In places with extreme environmental conditions, the continuity reinforcement is specified to be of corrosion-resistant steel.

4.5 Spliced girders

An established system for creating continuity of the girder before the deck is placed is to introduce full-bridge-length post-tensioning. This method is particularly cost-effective when girder splicing is not over the piers, due to length or weight limits (Fig. 4-5). Post-tensioning has been used economically even when the splice joints are over the piers.

This does, however, require widening of the usually thin webs of I-girders and other stemmed members, to accommodate post-tensioning ducts and to offset the shear capacity reduction due to using the ducts inside the precast concrete girder webs. A post-tensioning anchorage block is added cost and weight to the precast concrete members. Also, post-tensioning is a specialty skill generally not provided by most local contractors.

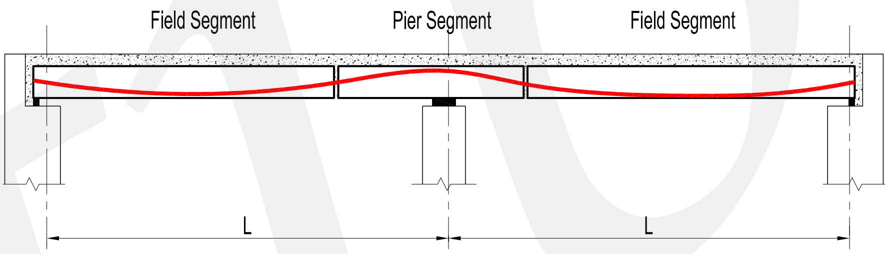


Fig. 4-5 Splicing away from piers using post-tensioning.

Adequate pretensioning is required only to support the self-weight of the girder during shipping, handling, and erection. This relatively small prestress results in small cambers and minimizes the need for high-strength concrete at transfer of pretensioning. The girder segments are erected first, and then the diaphragms are formed, cast, and cured.

Some or all the post-tensioning tendons may then be installed and tensioned. If the proper level of post-tensioning is introduced at this stage, the girders are continuous for the deck weight and construction loads. Such post-tensioning must be large enough to produce concrete stresses of acceptable levels in the continuous member for the loads that are applied before the next post-tensioning stage, if one is included in design. This second post-tensioning stage is generally introduced after the deck has cured and before the application of live loading.

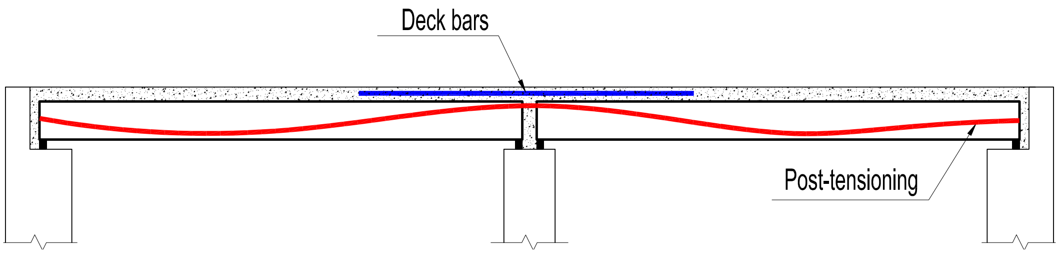


Fig. 4-6 Post-tensioning continuity method over piers.

Refer to NCHRP Report 517[4-11] for more information about spliced-girder systems.

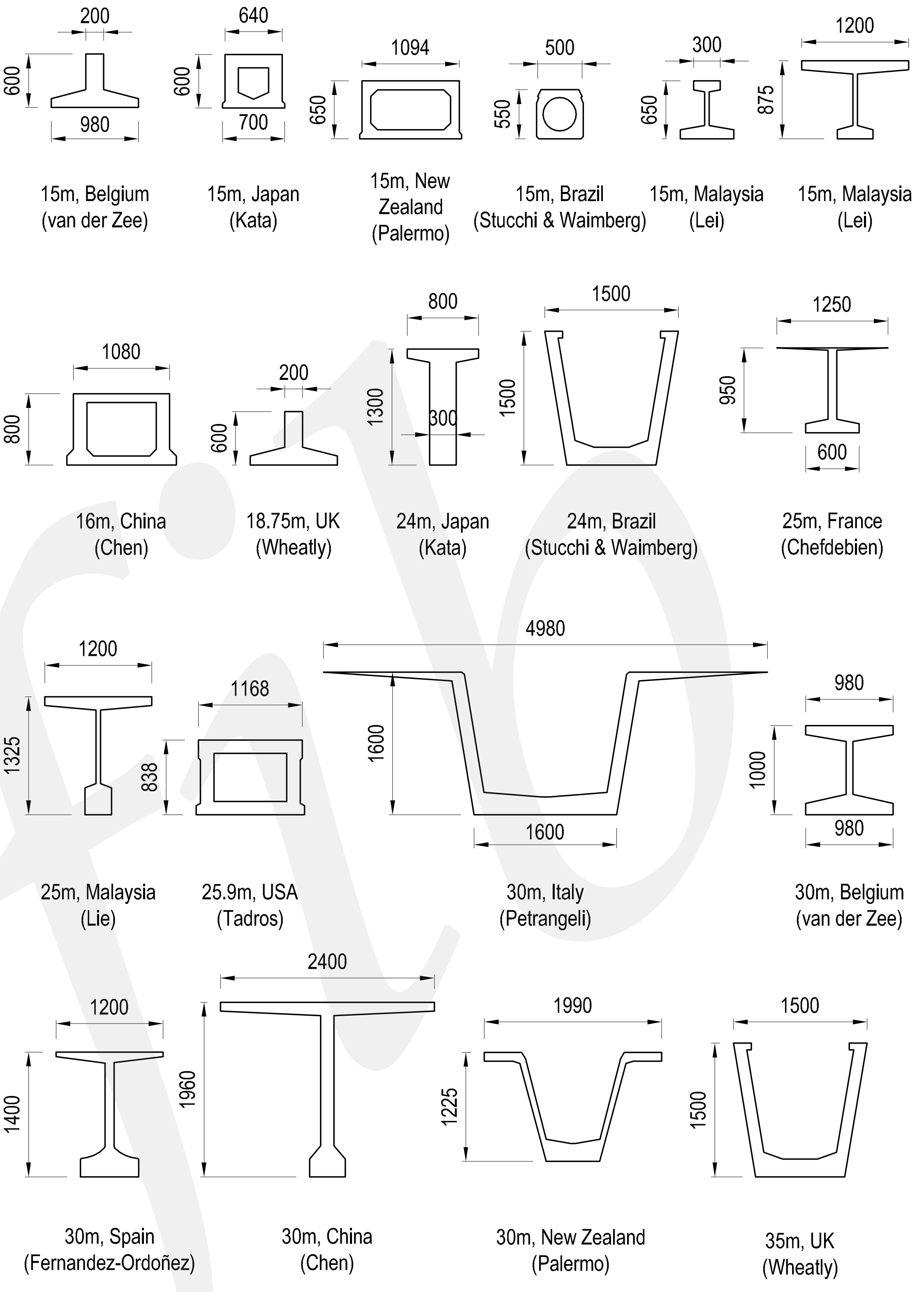
5. Output—Examples From Several Countries

fib Task Group 6.5 has been fortunate to encompass colleagues from numerous countries and almost all continents in the world. Moreover, task group members from 11 countries have provided conceptual design examples of precast concrete bridges. These contributions by various designers from very different places give a special value to this document.

Fig. 5-1 Countries of origin of authors of included conceptual design examples.

Figure 5-2 summarizes the different girder types used in examples presented in the following subsections of Section 5. The girders are organized by span length to identify similarities and differences. All girders are shown to the same scale.

https://doi.org/10.35789/fib.BULL.0096.Ch05


200
600
980
15m, Belgium (van der Zee)
640
600
700
15m, Japan (Kata)
1094
650
15m, New Zealand (Palermo)
500
550
15m, Brazil (Stucchi & Waimberg)
300
650
15m, Malaysia (Lei)
1200
875
15m, Malaysia (Lei)
1080
800
16m, China (Chen)
200
600
18.75m, UK (Wheatly)
800
1300
300
24m, Japan (Kata)
1500
1500
24m, Brazil (Stucchi & Waimberg)
1250
950
600
25m, France (Chefdebien)
1200
1325
25m, Malaysia (Lie)
1168
838
25.9m, USA (Tadros)
4980
1600
1600
30m, Italy (Petrangeli)
980
1000
980
30m, Belgium (van der Zee)
1200
1400
30m, Spain (Fernandez-Ordoñez)
2400
1960
30m, China (Chen)
1990
1225
30m, New Zealand (Palermo)
1500
1500
35m, UK (Wheatly)

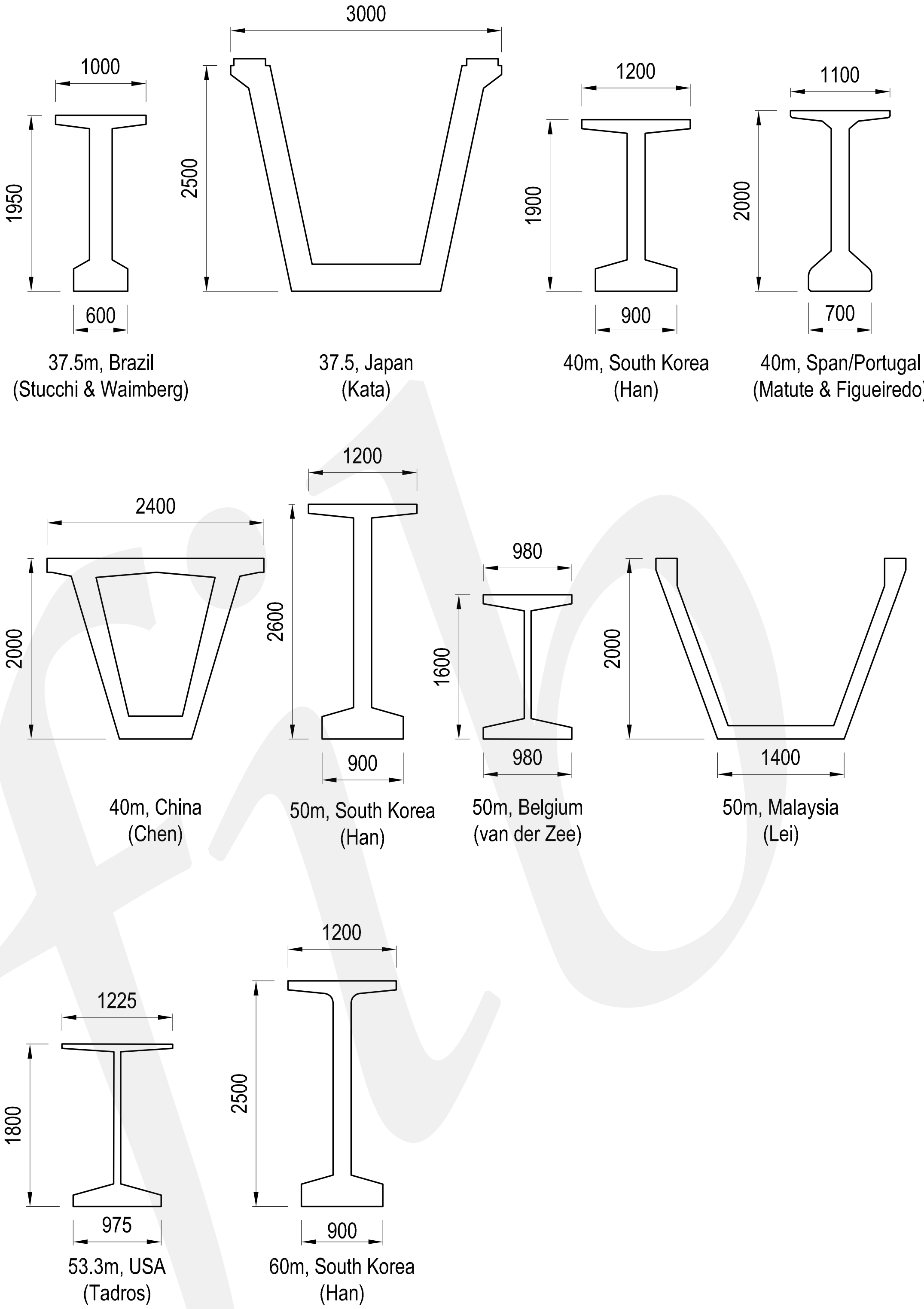


Fig. 5-2 Different girder sections used in the examples included in Section 5. Note: Girder dimensions in the cross sections are in millimeters. 1 mm = 0.0394 in. 1 m = 3.281 ft.

In addition, Table 5-1 shows the various span lengths of the designs and the corresponding number of the example.

Table 5-1 Span lengths and example numbers

Span lengths, m	Number of example
15	2, 4, 12, 15, 16, 19
16	7
18.75	22B
25	5, 10, 13, 17
25.9	23
30	1, 8, 11, 20, 21
35	22A, 28
37.5	6
40	9, 14, 25
50	3, 18, 26
53.34	24
60	27

Note: 1 m = 3.281 ft.

The superstructures of the examples are framed by adjacent girders in Examples 1, 4, and 12; I-girders in Examples 1, 6, and 21; and U girders in Examples 9, 14, and 18.

Most of the examples use pretensioned strands and, in some cases, post-tensioned tendons, such as Examples 7, 8, and 9, or transverse post-tensioning to join different segments of girders, such as in Examples 13 and 14.

In all the cases, the examples assume prestressing strands with a strength of 1860 MPa (270 ksi). In addition, the reinforcing steel in the girders and the top slab is assumed to have yield strengths of 345, 414, 450, and 500 MPa (50, 60, 65, and 73 ksi).

The examples have been developed considering different local design codes. Many of them have used the AASHTO LRFD specifications[5-1] or Eurocode 1-2[5-2; 5-3] for vertical live loads. Appendix C of this document presents a comparison of these live loads.

All of the information available related to the different examples is summarized in Appendix D, which is a table that shows geometry, material characteristcs, continuity method adopted, etc. Furthermore, Figures 5-3, 5-4, 5-5, 5-6, 5-7, and 5-8 show some of the main characteristics of the precast concrete structures studied in the examples to have a broader view of their parameters. The numbers shown in the figures correspond to the example number.

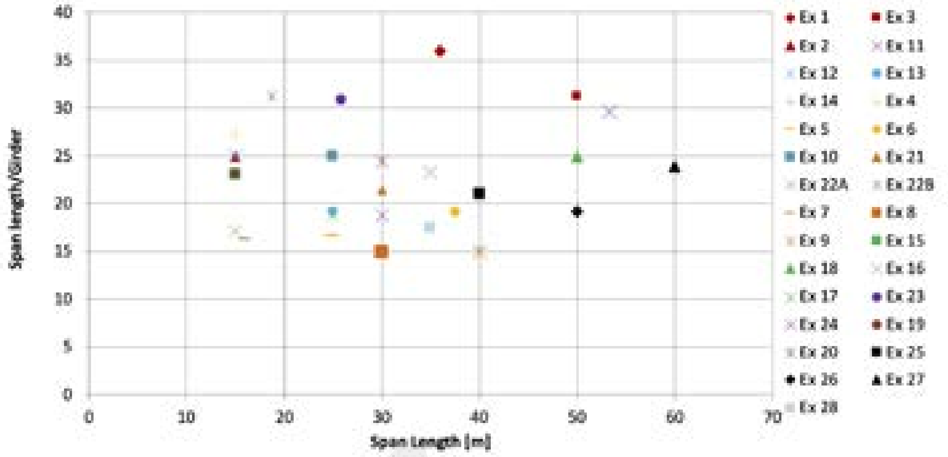


Fig. 5-3 Span length/girder depth ratio by span lengths of the design examples.Note: 1 m = 3.281 ft.

There is a wide range in girder slenderness. I-girders, in general, show span length/depth ratios on the order of 16 to 25. U girders, in general, show span length/depth ratios of 14 to 21, which is generally smaller than I-girders.

Figure 5-4 shows the ratio between the span length and the total height of the superstructure (precast concrete girder plus haunch and top slab). In the cases that do not consider the use of a top slab, the values are identical to ones shown in the previous figure.

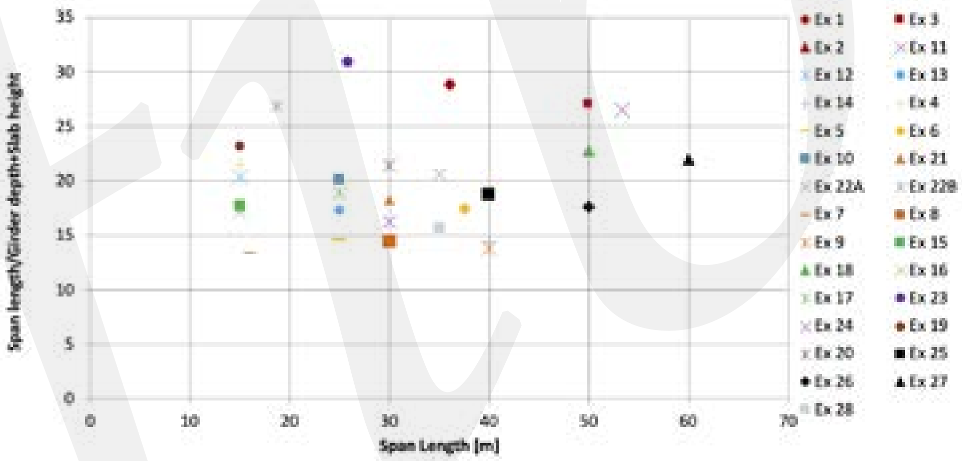


Fig. 5-4 Span length/girder + slab height ratio by span lengths of the design examples. Note: 1 m = 3.281 ft.

Figure 5-4 shows the same trends discussed for Fig. 5-3.

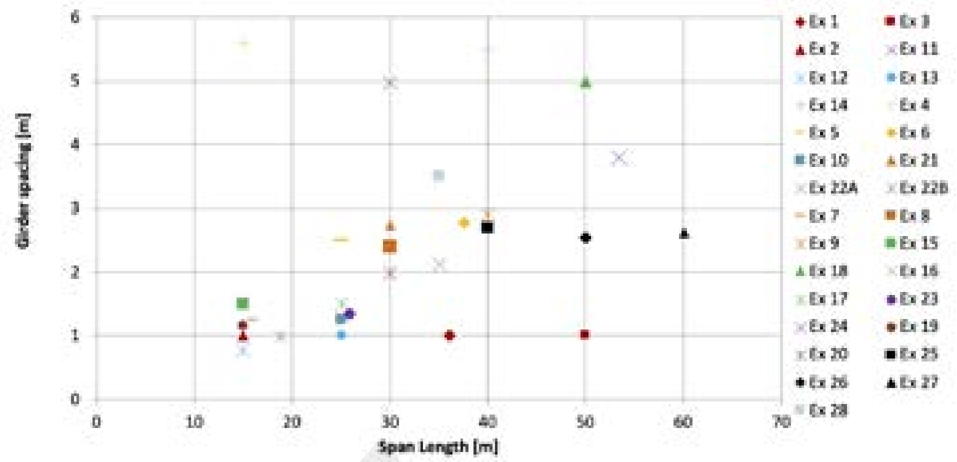


Fig. 5-5 Lateral girder spacing by span lengths of the design examples. Note: 1 m = 3.281 ft.

The examples with small distances between longitudinal elements correspond to precast concrete elements placed side by side (adjacent girders) and often represent solutions for short span lengths, where the superstructure behaves like a slab.

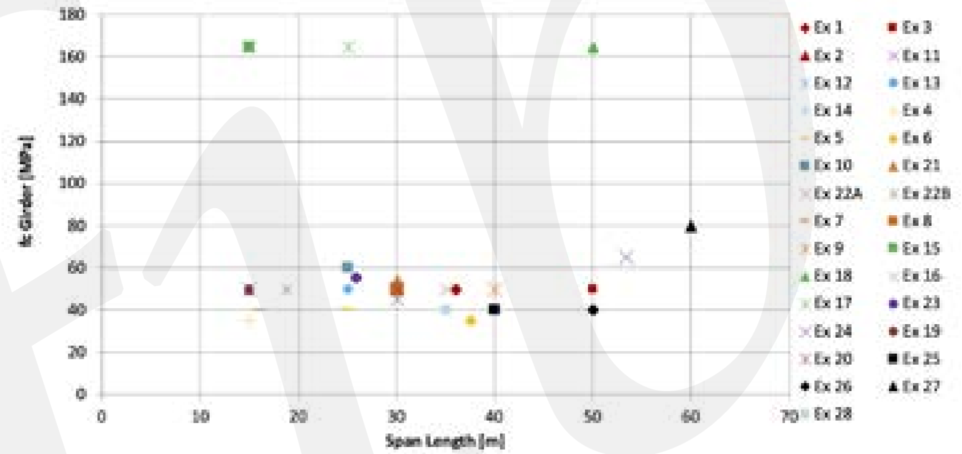


Fig. 5-6 Concrete strength of the girder by span lengths of the design examples. Note: f_c = Unfactored compressive strength of concrete. 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

Figure 5-6 shows that, in general, the precast concrete elements are fabricated with concrete with a compressive strength between 35 to 80 MPa (5 to 12 ksi), except for the ultra-high-performance concrete structures with a compressive strength of 165 MPa (24 ksi).

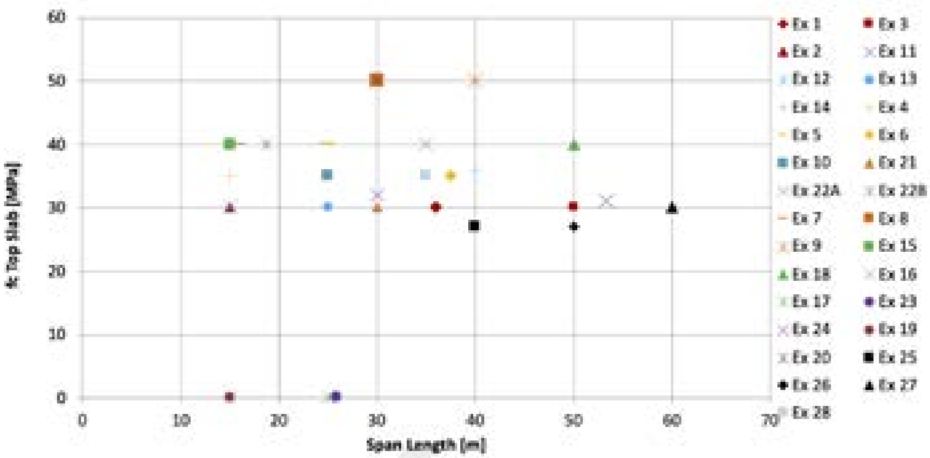


Fig. 5-7 Design concrete strength of the top slab by span lengths of the design examples.

Figure 5-7 shows that, in general, the deck slabs are fabricated with concrete with compressive strength between 30 to 40 MPa (4 to 6 ksi).

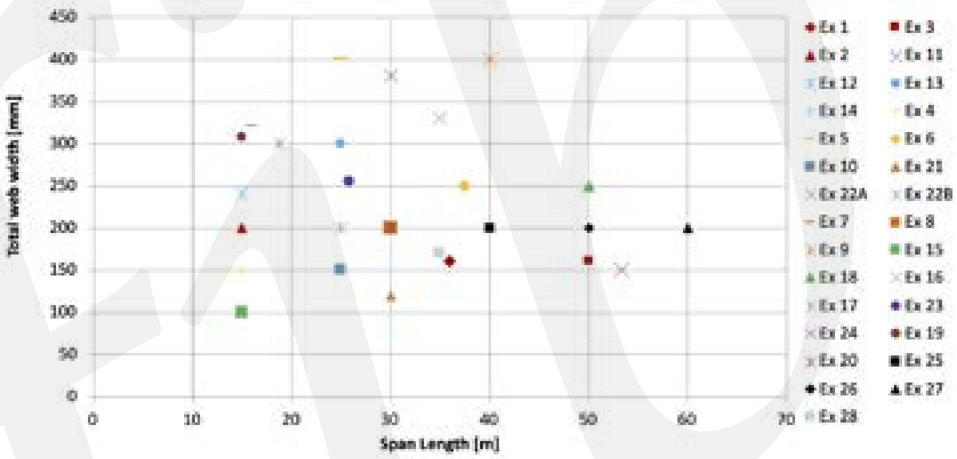


Fig. 5-8 Total web width by span lengths of the design examples.

Figure 5-8 compares the total web width by span lengths, this dimension is often conditioned by practical production aspects of the cross section of the girder, because a minimum web width is necessary to ensure ease of concrete placement.

On the other hand, ultra-high-performance concrete girders usually have narrow webs because these elements do not have vertical stirrups and the concrete has a compressive strength of 140 to 165 MPa (20 to 24 ksi) and a tensile strength of 15 to 20 MPa (2 to 10 ksi), enough to resist shear forces acting on the structure without reinforcement.

5.1 Example 1: bridge with five 30 m (98 ft) long spans in Belgium

This example was furnished by Pieter van der Zee.

The bridge is in the city of Grobbendonk in Belgium and spans the “Kleine Nete” river.

Fig. 5-9 Photo of the bridge in Example 1.

5.1.1 Considerations identified

- Bridge layout: The structure has a total length of 210 m (689 ft) and a total width of 13.2 m (43.3 ft).
- Geological and geotechnical factors: Over a small river which made the average 30 m (98 ft) span length necessary.
- Codes: Loads according to EN 1990[5-4] and EN 1991-2[5-2];design according to EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Construction factors: The bridge was required to look like the CIP bridge proposed by the architect, which was a massive continuous slab deck bridge. Furthermore, the general contractor was not allowed to place temporary construction in the river. Because the contractor could not find a method to cast the bridge in place, he sought a precast concrete solution.
- Aesthetics: This solution uses two U girders to improve the appearance of the elevation of the bridge.
- Environmental factors: The general contractor could not place any temporary construction in the river because it is a protected area. For durability the bridge is considered to be XC4, XD3, and XF4 following the specifications in EN 1992-1-1[5-5].

5.1.2 Proposed solution

This bridge consists of seven spans with variable span length, from 21.5 to 36.0 m (70.5 to 118 ft). The cross section of the superstructure consists of 12 precast concrete girders with a depth of 1000 mm (3.3 ft), comprising 10 I-girders and two U girders placed at the edges of the superstructure to modify its appearance. To obtain a closed soffit and eliminate the need for deck slabs or deck forming, the precast concrete girders are adjacent to each other (placed side by side) and the concrete placement of the top slab takes place directly on top of the precast concrete girders, except for the side U girders, which needed reinforced concrete deck slabs.

(a) Closed soffit

(b) Top of the slab form

Fig. 5-10 Photos showing the closed soffit and top of the slab form provided by the adjacent (edge-to-edge) girder placement in Example 1.

5.1.2.1 Plan

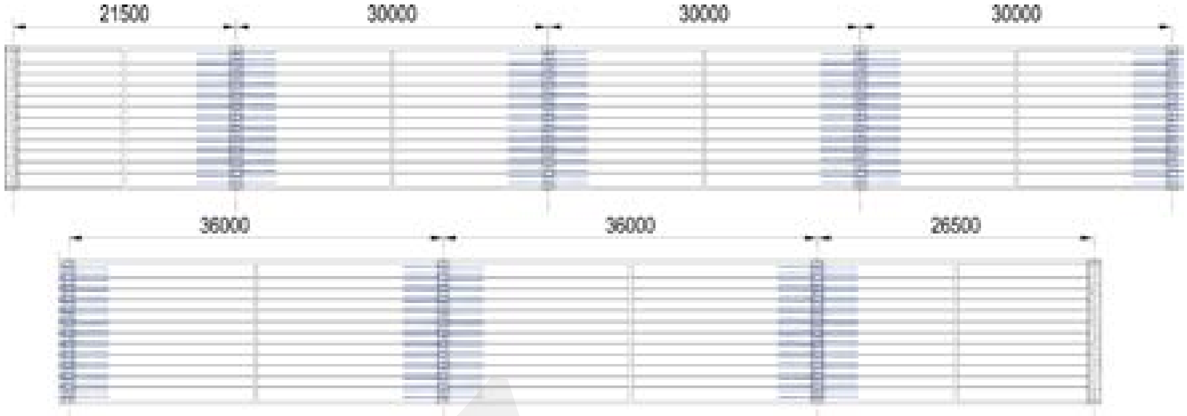


Fig. 5-11 Plan of the bridge in Example 1. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.1.2.2 Elevation

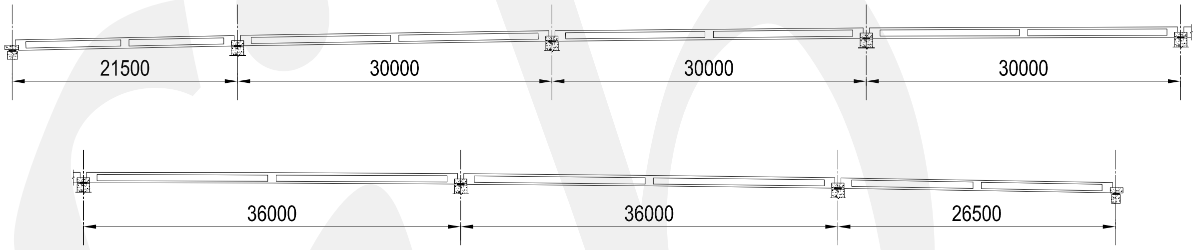


Fig. 5-12 Elevation of the bridge in Example 1. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.1.2.3 Superstructure cross section

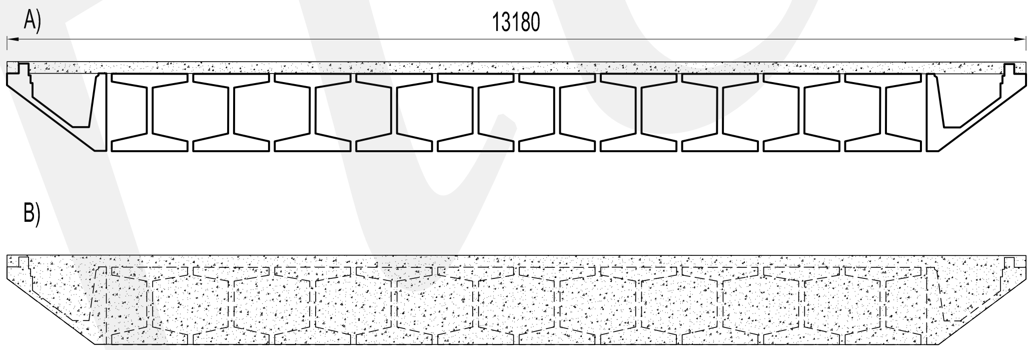


Fig. 5-13 Cross-section view of the bridge in Example 1: (a) without diaphragm between piers and (b) with diaphragm over the piers. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.1.3 Superstructure

5.1.3.1 Precast concrete girders

5.1.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1860 MPa (270 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.1.3.1.2 Description of the cross section

Ten I-girders, 1'000 mm (39 in.) deep, placed side by side, and two U girders, one at each edge of the bridge. The I-girders are symmetric, and when placed adjacent to each other, form a closed superstructure that eliminates the need of deck panels and facilitates the concrete placement of the deck slab. The U girders are asymmetric and modify the appearance of the structure as well as reduce the required length of the crossbeam over the piers.

Close to the supports, the cross section of the precast concrete girders transitions to form a solid rectangular block and becomes part of the end diaphragms. At midspan, the cross section of the girders also transitions to a solid block and forms an intermediate diaphragm.

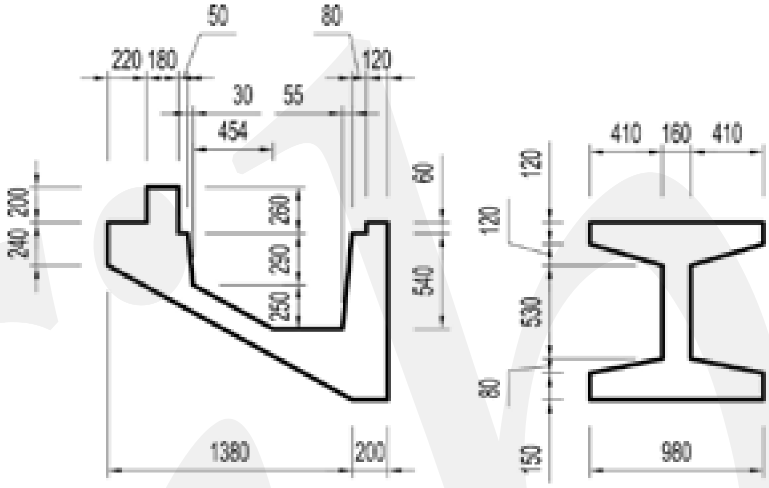


Fig. 5-14 Cross-section dimensions of precast concrete girders.Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

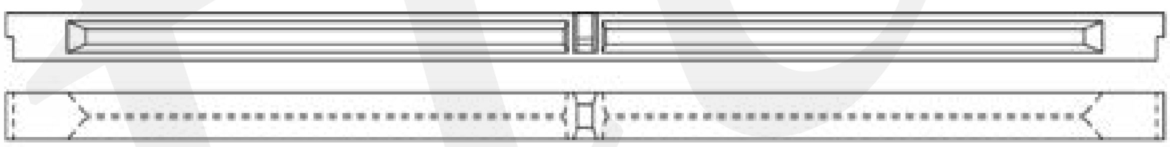


Fig. 5-15 Elevation and plan of precast concrete I-girder.

Fig. 5-16 Photo of the bridge that shows the overhang formed by the edge U girder.

5.1.3.1.3 Prestressing

The precast concrete girders are pretensioned. There is a total of 26 straight strands: 24 strands in the bottom flange and two strands in the top flange of the I-girders.

5.1.3.2 Deck slab

5.1.3.2.1 Materials

Concrete: 30 MPa (4 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.1.3.2.2 Deck slab description

The deck is a CIP slab with a thickness of 25 cm (10 in.), cast on top of the I-girders without the need of deck panels or formwork. To place the concrete over the U girders, precast reinforced concrete deck panels were used.

5.1.3.3 Details

5.1.3.3.1 Vertical alignment

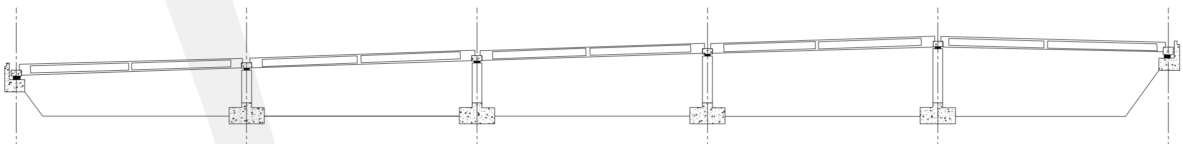


Fig. 5-17 Detail of the varying bearing elevations of the girders.

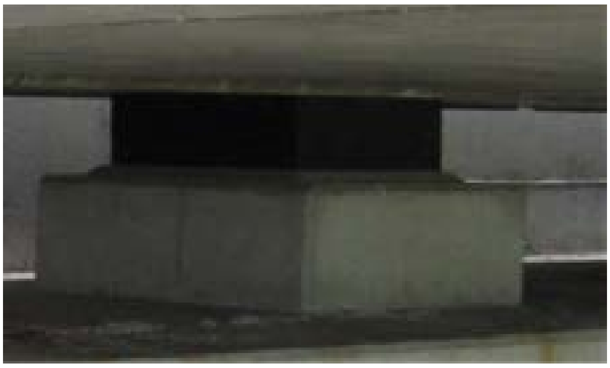


Fig. 5-18 View of a mortar bed and neoprene bearings on a precast pier beam accommodating the slope of the girders.

The vertical alignment of the bridge requires the use of piers with varying heights and differing elevations for the bearings of the girders across a precast concrete pier beam. The longitudinal slope across a precast concrete pier beam is accomplished with neoprene bearings placed on mortar pads of varying thickness and dapped ends on the girders.

5.1.3.3.2 Typical continuity detail over a pier

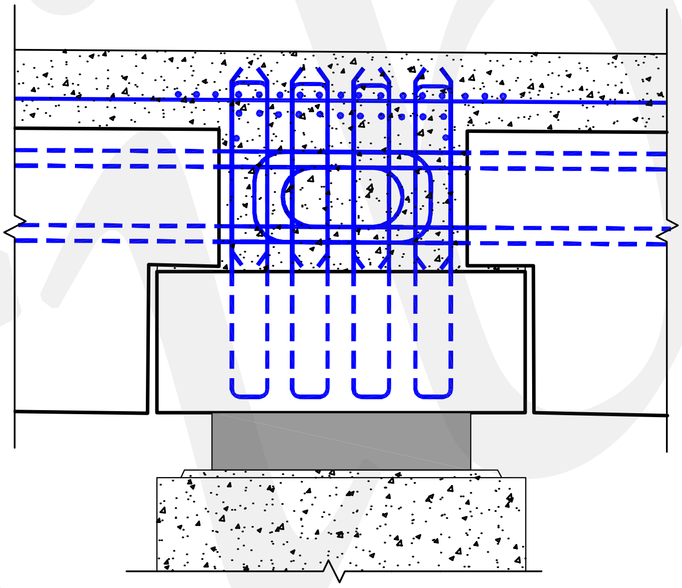


Fig. 5-19 Continuity detail over a pier showing the mortar bed, neoprene bearing, precast concrete pier cap beam, dapped girder ends, and reinforcement.

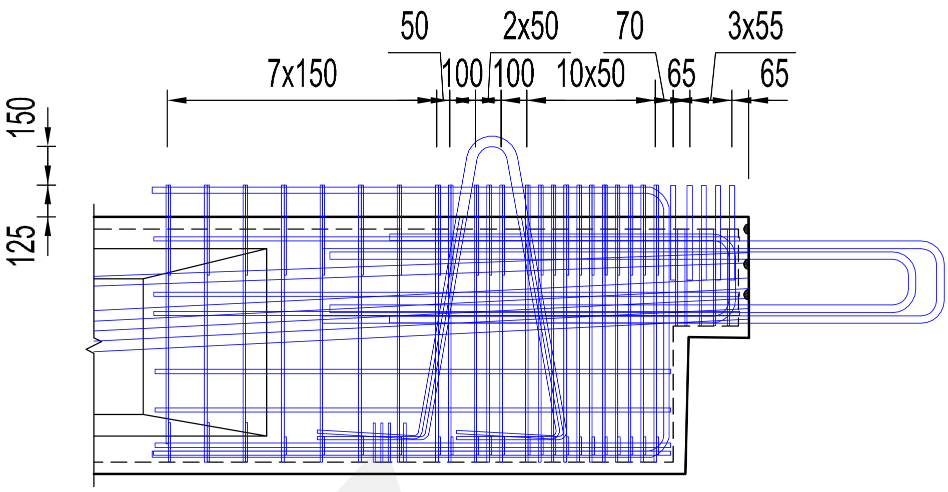


Fig. 5-20 Reinforcement detail of the girder at a dapped end. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Fig. 5-21 Photo of the precast concrete pier beam at the edge of the bridge.

Fig. 5-22 Typical reinforcement extending vertically from the precast concrete pier beam.

Fig. 5-23 Another view of the continuity reinforcement extending from the pier cap and dapped ends of the U girders.

Full structural continuity. On top of the support bearings there are 700 × 1200 mm (276 × 472 in.) precast concrete pier beams that eliminate the need for formwork for the CIP concrete at the piers.

The pier beams have evenly spaced vertical reinforcement that matches the horizontal bars extended from the beams. CIP concrete is used in the diaphragm over the piers.

5.1.3.3.3 Transverse slopes

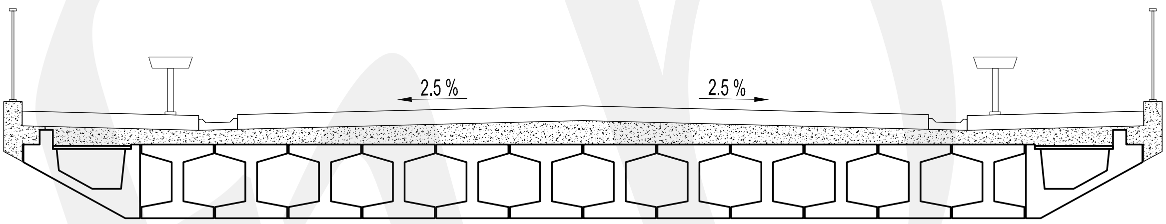


Fig. 5-24 Bridge superstructure with 2.5% transverse slopes.

The bridge deck has 2.5% transverse slopes formed by the concrete deck slab.

5.1.3.3.4 Transverse diaphragms

This solution uses diaphragms over the supports as well as intermediate transverse diaphragms at two locations between supports. The diaphragms are reinforced concrete without transverse post-tensioning.

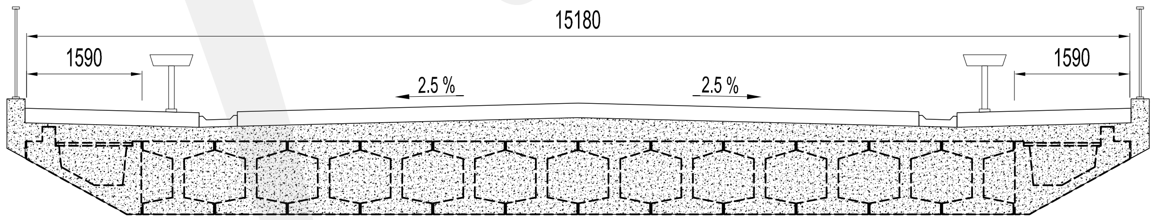


Fig. 5-25 Intermediate diaphragm detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Fig. 5-26 Typical diaphragm reinforcement at a pier.

5.1.3.4 Summary of the preliminary design

Number of spans	7
Continuity	Full structural continuity
Average span length *L*, m	36
Girder depth *G*, mm	1'000
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	1'250
Web width *W*, mm	160
Girder spacing *S*, m	1
Precast concrete girder weight, tonnes	38.2
L/D	28.8
L/G	36
Average depth, mm/m²	750
Prestressing steel, kg/m²	28.34
Reinforcing steel – girder, kg/m³	34
Reinforcing steel – top slab, kg/m³	251
Reinforcing steel in a diaphragm, kg	678

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 mm/m^2 = 0.0037 in./ft^2; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 kg/m^3 = 0.0624 lb/ft^3; 1 tonne = 1.102 tons.

5.1.4 Construction sequence

- Piers were cast in place.
- Neoprene bearings were placed on top of the piers.
- Precast concrete pier beams were installed on top of the neoprene bearings.
- Precast concrete girders were installed on the precast concrete pier beams, eliminating the need for falsework and temporary structures.
- Reinforcement was installed for the deck slab and the slab concrete was placed.
- A few weeks later, to avoid creep problems, the concrete for the continuity connection between girders was placed.

Fig. 5-27 Top flanges of girders just before installation of slab reinforcement. Holes in flanges provide access to place intermediate diaphragm connection concrete.

Fig. 5-28 Elevation view of the bridge before casting deck slab.

5.1.5 Substructure

The substructure of this bridge was constructed of CIP concrete.

5.1.5.1 Piers

The piers consist of two inclined reinforced concrete columns that share the same foundation. In general, on top of each column there are two neoprene bearings.

The height of the piers varies from 2.8 to 5.6 m (9.2 to 18.4 ft).

Fig. 5-29 Typical bridge pier.

5.1.5.2 Foundations

The piers are supported by reinforced concrete shallow footings. Generally, they measure 1000 × 480 cm (394 × 189 in.) by 160 cm (63 in.) deep.

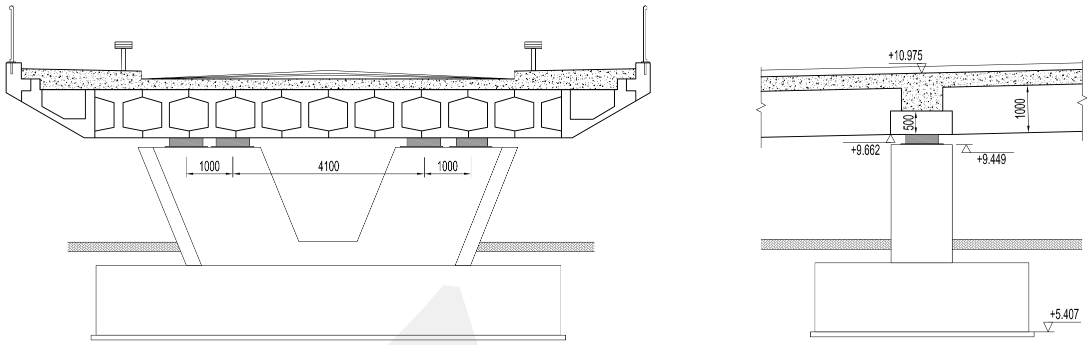


Fig. 5-30 Cross-section and elevation views of piers and shallow foundations. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.)

5.1.5.3 Abutments

The abutments are CIP reinforced concrete structures. On top of the abutments, the structure is supported by three neoprene bearings, and the back wall of the abutment supports the approach slab.

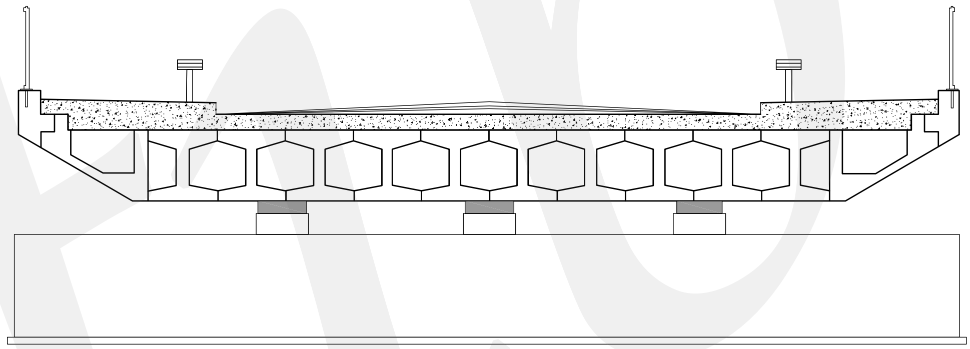


Fig. 5-31 Bridge cross section and abutment cross-section views.

5.2 Example 2: bridge with ten 15 m (49 ft) long spans in Belgium

This example was furnished by Pieter van der Zee.

5.2.1 Considerations identified

- Bridge layout: This structure has a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Geological and geotechnical factors: Spans a small river, which made the span of 15 m necessary.
- Codes: Loads according to EN 1990[5-4] and EN 1991-2[5-2] and design codes EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Construction factors: The bridge needed to replicate the appearance of the CIP bridge proposed by the architect, which was a massive continuous plate deck.

Furthermore, the general contractor was not permitted to place falsework in the river, and he could not find a method for the CIP solution. Therefore, he sought a precast concrete solution.

- Aesthetics: At the edges of the superstructure, this solution uses two U girders to achieve the required appearance.
- Environmental factors: The general contractor could not place any temporary construction in the river because it is a protected area. For durability, the bridge is considered to be XC4, XD3, and XF4 following the specifications in EN 1992-1-1[5-5].

5.2.2 Proposed solution

This bridge has 10 spans, each with a length of 15 m (49 ft). The cross section of the superstructure uses 14 precast concrete girders with a depth of 600 mm (24 in.), twelve inverted T girders and two U girders placed at the edges of the superstructure to modify its final appearance. To obtain a closed soffit, the precast concrete girders are placed adjacent to each other (side by side) and the concrete placement of the deck slab takes place directly on top of the precast concrete girders.

The CIP deck slab is 25 cm (10 in.) thick and provides 2.5% transverse slopes.

The superstructure includes reinforced concrete diaphragms over piers and abutments.

The precast concrete girders are pretensioned and the layout of the prestressing reinforcement consists of straight strands in the bottom flanges and top of the web of the inverted T girders.

This solution provides full continuity over the piers. There is an end-block in the T section where the slab can be connected with the beam, so a linked-slab system is used

5.2.2.1 Plan

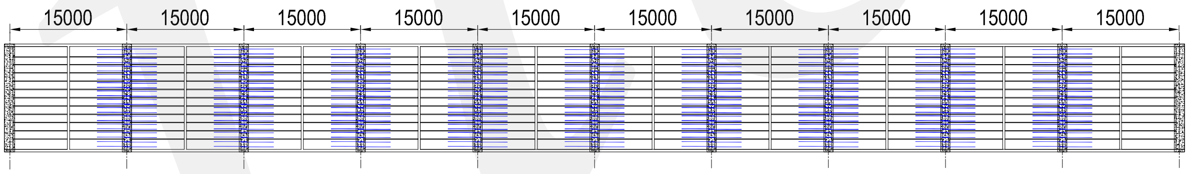


Fig. 5-32 Plan of the bridge in Example 2. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.2.2.2 Elevation

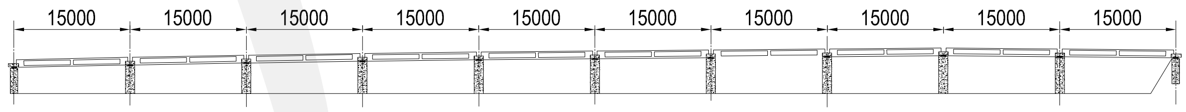


Fig. 5-33 Elevation of the bridge in Example 2. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.2.2.3 Superstructure cross section

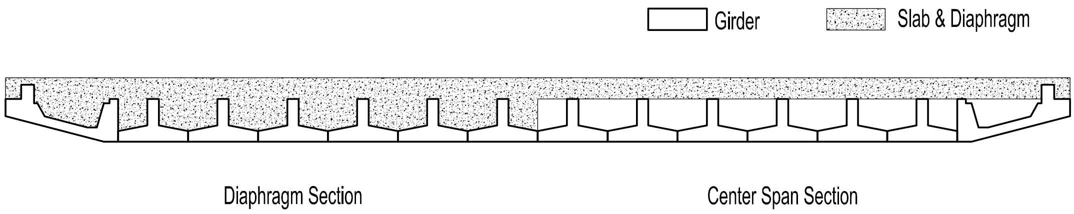


Fig. 5-34 Cross-section view of the bridge illustrating both with and without diaphragm.

5.2.3 Superstructure

5.2.3.1 Precast concrete girders

5.2.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1860 MPa (270 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.2.3.1.2 Description of the cross section

Twelve inverted T girders, 600 mm (24 in.) deep, placed adjacent to each other (side by side), and two U girders at the edges of the bridge.

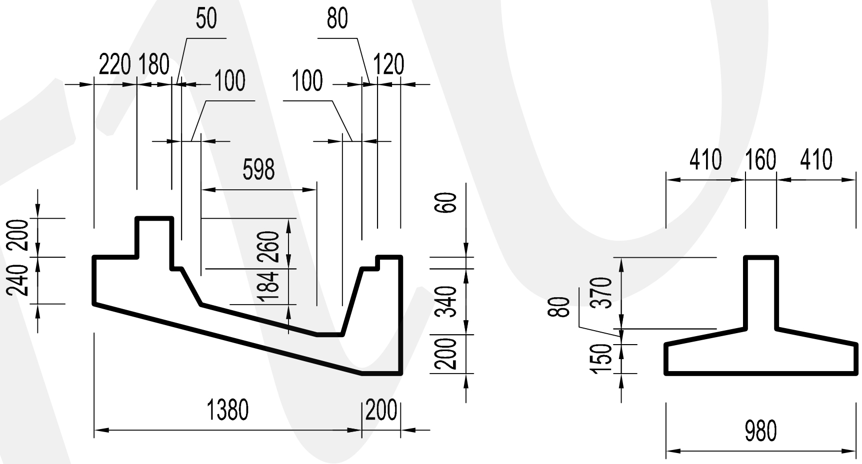


Fig. 5-35 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.2.3.1.3 Prestressing

The precast concrete girders are pretensioned. For this structure, there is a total of 16 straight strands in the bottom flange and the web of the precast concrete girders.

5.2.3.2 Deck slab

5.2.3.2.1 Materials

Concrete:	30 MPa (4 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.2.3.2.2 Description of the deck slab

The CIP deck slab has a thickness of 250 mm (10 in.) and is cast on top of the girders, including 80 mm (3 in.) thick precast concrete deck panels.

5.2.3.3 Details

5.2.3.3.1 Vertical alignment

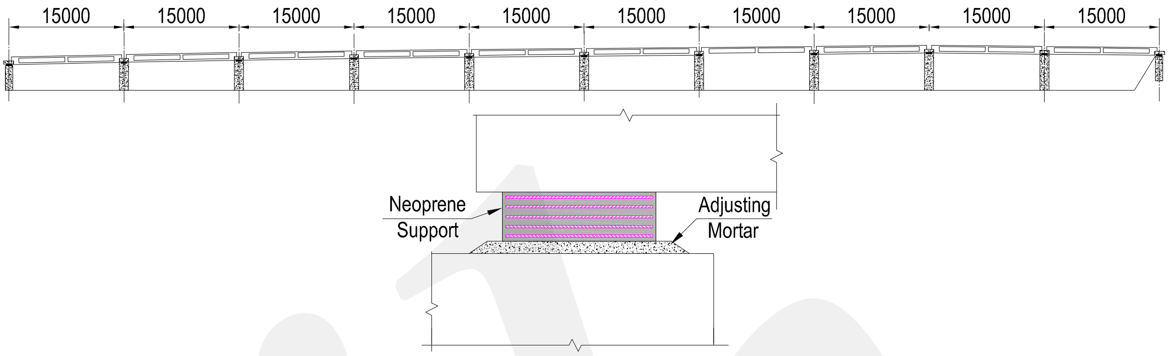


Fig. 5-36 Detail of the bearings. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The precast concrete pier caps are placed on neoprene bearings. The longitudinal slope of the bridge is adjusted by a variable thickness mortar bed under the bearings and dapped ends on the girders.

5.2.3.3.2 Continuity detail over the pier

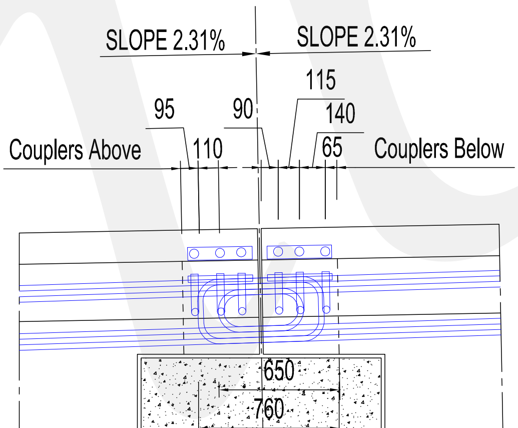


Fig. 5-37 Continuity detail over the pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Full structural continuity. The bearings on the piers, support precast concrete pier beams and on these, the continuity is achieved by a linked-slab method.

5.2.3.3.3 Transverse diaphragms

This solution incorporates diaphragms over the supports. There are no diaphragms at midspan. The diaphragms are reinforced concrete elements without transverse post-tensioning.

5.2.3.4 Summary of the preliminary design

Number of spans	10
Continuity	Full structural continuity
Span length *L*, m	15
Girder depth *G*, mm	600
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	850
Web width *W*, mm	200
Girder spacing *S*, m	1
Precast concrete girder weight, tonnes	11
L/D	17.65
L/G	25
Average depth, mm	509
Prestressing steel, kg/m^2	11. 68
Reinforcing steel – girder, kg/m^3	65
Reinforcing steel – top slab, kg/m^3	251

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 kg/m^3 = 0.0624 lb/ft^3; 1 tonne = 1.102 tons.

5.3 Example 3: bridge with three 50 m (164 ft) long spans in Belgium

This example was furnished by Pieter van der Zee.

5.3.1 Considerations identified

- Bridge layout: The structure has a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Geological and geotechnical factors: Spans a small river that requires the 50 m (164 ft) span.
- Codes: Loads according to EN 1990[5-4] and EN 1991-2[5-2] and design codes EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Construction factors: The bridge was required to appear like the CIP bridge proposed by the architect, which was a massive continuous slab deck bridge. Furthermore, the general contractor was not permitted to place temporary construction in the river. Because the contractor could not find a method to cast the bridge in place, he sought a precast concrete solution.
- Aesthetics: At the edges of the superstructure this solution uses two U girders to modify the appearance of the elevation of the bridge.
- Environmental factors: The general contractor could not place any temporary construction in the river because it is a protected area. For durability, the bridge is considered to be XC4, XD3, and XF4 following the specifications in EN 1992-1-1[5-5].

5.3.2 Proposed solution

This bridge has three spans, each with a length of 50 m (164 ft). The cross section of the superstructure consists of 14 precast concrete girders with a depth of 1600 mm (63 in.). There are twelve I-girders and two U girders placed at the edges of the superstructure to modify its final appearance. To obtain a closed soffit and eliminate the need for precast concrete deck slabs, the precast concrete girders are placed adjacent to each other (side by side) and the concrete placement of the deck slab takes place directly on the top flanges of the precast concrete I-girders.

The CIP deck slab is 25 cm (10 in.) thick and has 2.5% transverse slopes.

CIP reinforced concrete diaphragms are used over piers, abutments, and at midspan.

The precast concrete girders are pretensioned and the layout of the prestressed reinforcement consists of both straight and draped strands placed in the top and bottom flanges of the I-girders.

This solution incorporates full continuity over the piers, which is accomplished by a linked-slab system.

5.3.2.1 Plan

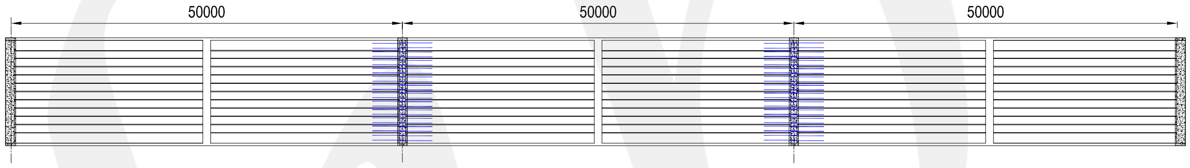


Fig. 5-38 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.3.2.2 Elevation

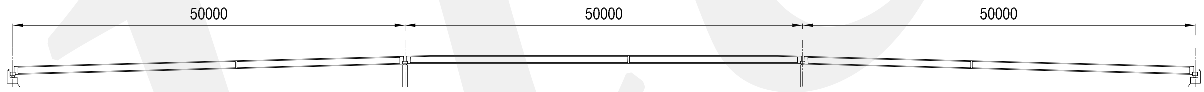


Fig. 5-39 Elevation of the bridge.

5.3.2.3 Superstructure cross section

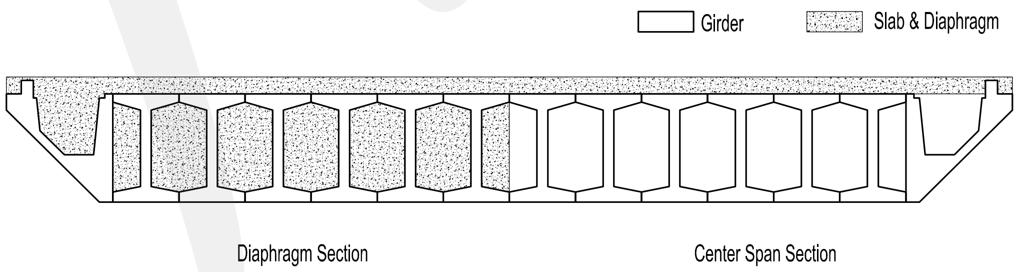


Fig. 5-40 Cross-section view of the bridge illustrating both with and without diaphragms.

5.3.3 Superstructure

5.3.3.1 Precast concrete girders

5.3.3.1.1 Materials

Concrete: 50 MPa (7 ksi)

Prestressing steel: 1860 MPa (270 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.3.3.1.2 Description of the cross section

There are twelve I-girders, 1600 mm (63 in.) deep, placed side by side, and two U girders at the edges of the bridge.

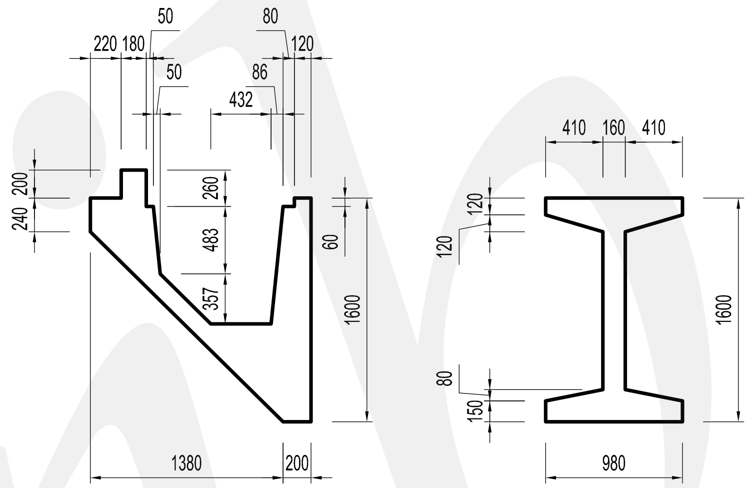


Fig. 5-41 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.3.3.1.3 Prestressing

The precast concrete girders are pretensioned. There are 28 straight strands: 26 strands in the bottom flange and 2 strands in the top flange of the I-girders. There are 20 draped strands. No post-tensioning is used.

5.3.3.2 Deck slab

5.3.3.2.1 Materials

Concrete: 30 MPa (4 ksi)

Reinforcing steel: 500 MPa (73 ksi)

5.3.3.2.2 Deck slab description

The CIP deck slab has a thickness of 25 cm (10 in.) and cast directly on the I-girders.

5.3.3.3 Details

5.3.3.3.1 Vertical alignment

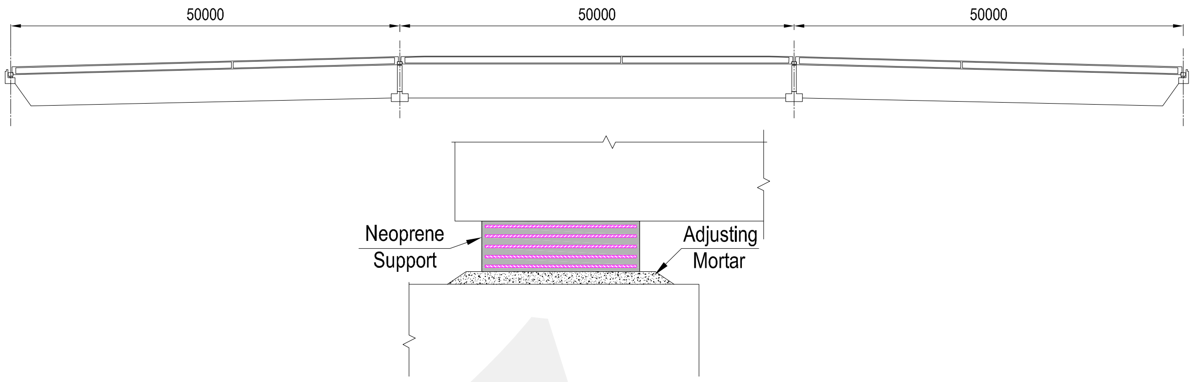


Fig. 5-42 Bearing detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Precast concrete pier beams are placed on neoprene bearings on the piers. To fine-tune the longitudinal slope of the bridge, a variable-depth mortar bed was used under the bearings.

5.3.3.3.2 Typical continuity detail over a pier

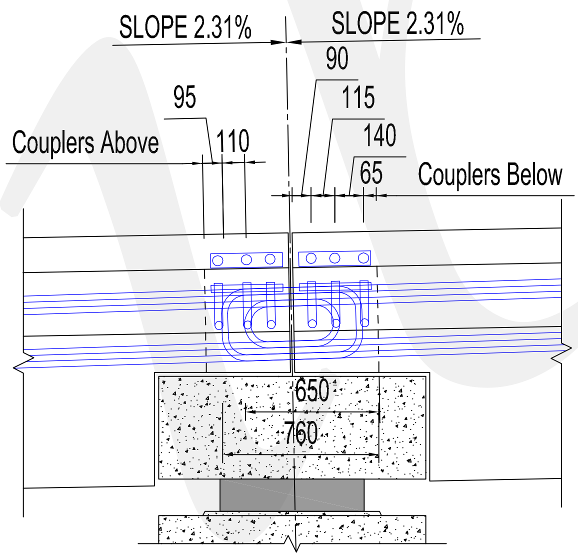


Fig. 5-43 Continuity detail over the pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Full structural continuity. On top of the bearings on the piers, precast concrete pier beams were placed. Superstructure continuity over the piers is engaged by extending the prestressing strands from the girders and bending them as seen in the detail in Figure 5-43.

5.3.3.3.3 Diaphragms

This solution uses diaphragms over the supports as well as intermediate diaphragms at midspan. The diaphragms are reinforced concrete elements without post-tensioning.

5.3.3.4 Summary of the preliminary design

Number of spans	3
Continuity	Full structural continuity
Span length *L*, m	50
Girder depth *G*, mm	1600
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	1850
Web width *W*, mm	160
Girder spacing *S*, m	1
Precast concrete girder weight, tonnes	76.8
L/D	27
L/G	31.25
Average depth, mm/m²	812
Prestressing steel, kg/m²	52.32
Reinforcing steel – girder, kg/m³	76
Reinforcing steel – top slab, kg/m³	251
Reinforcing steel in a diaphragm, kg	678

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 mm/m² = 0.0037 in./ft²; 1 kg = 2.205 lb; 1 kg/m² = 0.2048 lb/ft²; 1 kg/m³ = 0.0624 lb/ft³; 1 tonne = 1.102 tons.

5.4 Example 4: Bridge with ten 15 m (49 Ft) long spans in Brazil

This example was furnished by Fernando Stucchi and Marcelo Waimberg.

This is a theoretical example created for comparison with different practices, but a possible solution for a precast concrete bridge in Brazil.

5.4.1 Considerations identified

- Bridge layout: This example is a bridge with a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: Loads according to NBR 7188[5-6]; design according to NBR 6118[5-7] and NBR 8681[5-8].
- Construction factors: Typical precast concrete girders weighing up to 120 tonnes (132 tons) and 45 m (148 ft) long are achievable because of available launching or erecting equipment. By installing girders side by side, no additional formwork is required for the deck slab.
- Maintenance: Simple neoprene profiles are installed at expansion joints. Thus, a large number of these joints should be avoided, because this is a critical point in terms of maintenance.
- Functional factors: Reducing expansion joints also improves driver comfort.

- Economy: In Brazil, most precast concrete bridges are built in a precasting yard near the jobsite. Nevertheless, there are some commercially manufactured products that would fit this range of spans.

5.4.2 Proposed solution

This bridge has ten spans, each 15 m (49 ft) long. The superstructure comprises 550 mm (22 in.) wide precast concrete hollow-core girders that are assembled side by side, transversely prestressed and covered by a 10 cm (4 in.) thick CIP concrete deck slab. These girders are produced by a centrifugal casting process.

At midspan and over each pier, transverse diaphragms are used, providing adequate lateral stiffness and strength to the deck, working as an orthotropic slab. Because the girders are installed side by side, these diaphragms are constructed by grouting the joints between girders, casting the top slab and post-tensioning them.

The deck has a transverse slope of 2%, obtained by staggering the girders' bearings at appropriate heights.

Expansion joints are installed every five spans.

This solution uses partial continuity over the piers with link slabs.

5.4.2.1 Plan

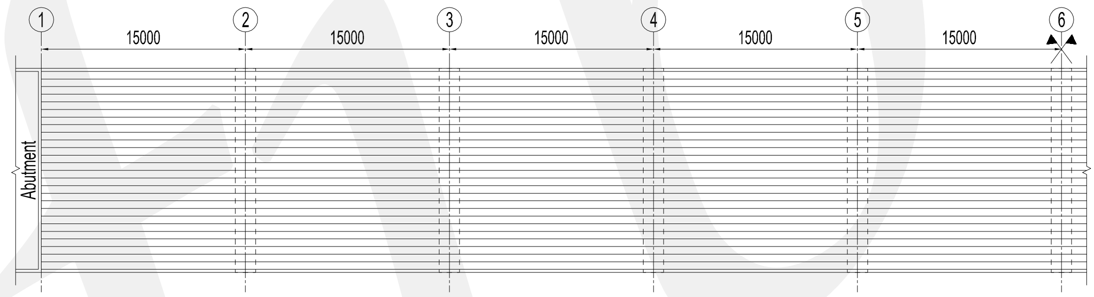


Fig. 5-44 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.4.2.2 Elevation

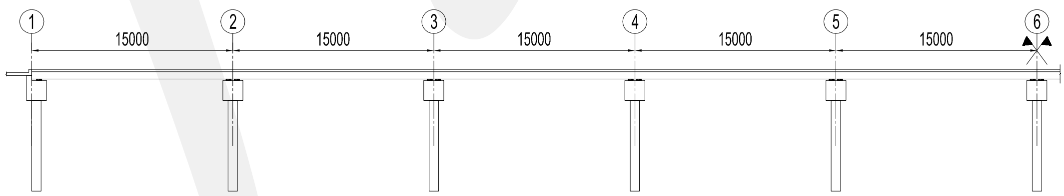


Fig. 5-45 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.4.2.3 Superstructure cross section

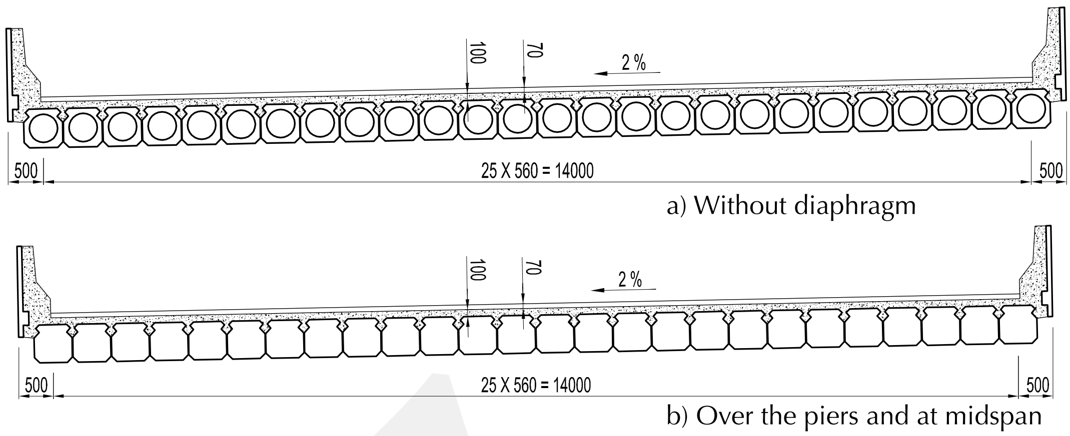


Fig. 5-46 Cross-section view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.4.3 Superstructure

5.4.3.1 Precast concrete girders

5.4.3.1.1 Materials

Concrete:	35 MPa (5 ksi)
Prestressing steel:	1'900 MPa (276 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.4.3.1.2 Description of the cross section

There are 26 hollow-core girders, 550 mm (217 in.) deep, 550 mm wide, placed adjacent to each other (side by side).

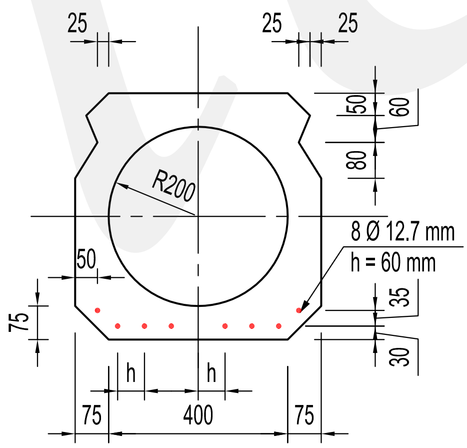


Fig. 5-47 Cross-section dimensions of precast concrete girder. Note: *h* = strand spacing. Dimensions are in centimeters unless otherwise indicated. 1 cm = 0.3937 in.; 1 mm = 0.0394 in.

5.4.3.1.3 Prestressing

The precast concrete girders are pretensioned. There is a total of eight 12.7 mm (0.5 in.) diameter straight strands per girder. Two straight post-tensioned tendons are used in each diaphragm.

5.4.3.2 Deck slab

5.4.3.2.1 Materials

Concrete: 35 MPa (5 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

Deck slab description: The deck slab is a 100 mm (4 in.) thick, CIP concrete slab that also fills the joints between adjacent girders. The deck has a transverse slope of 2%, achieved by varying the bearing elevation of each girder.

5.4.3.3 Details

5.4.3.3.1 Bearings

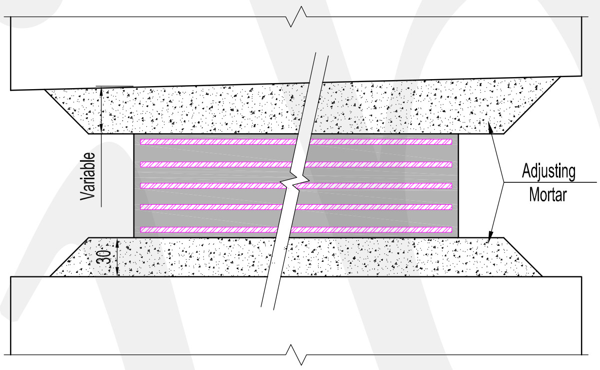


Fig. 5-48 Bearing detail.

The vertical alignment of the bridge varies along its length. Longitudinal slopes can be achieved with variable height piers. Neoprene bearing pads are placed on top of adjusting mortar. Over these devices a CIP mortar layer is provided to ensure compatibility with the bottom of the girder.

5.4.3.3.2 Continuity

Partial structural continuity is provided by link slabs over piers. At midlength and at both abutments, expansion joints are used every five spans, 75 m (246 ft) apart.

To allow flexibility in the deck slab, a polystyrene plate is placed on top of the girders under the slab, and between the two adjacent diaphragms at a pier for the full width of the bridge. See Figures 5-49 and 5-51 for details.

Additional reinforcement is placed at this point to resist bending moments and tension arising from direct truck load and rotation compatibility of the girders.

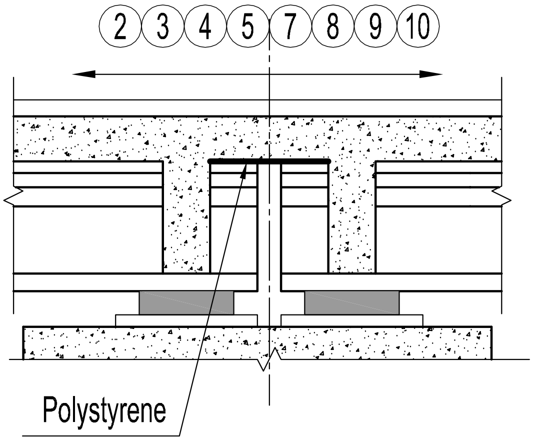


Fig. 5-49 Continuity detail over the pier.

5.4.3.3.3 *Transverse slope*

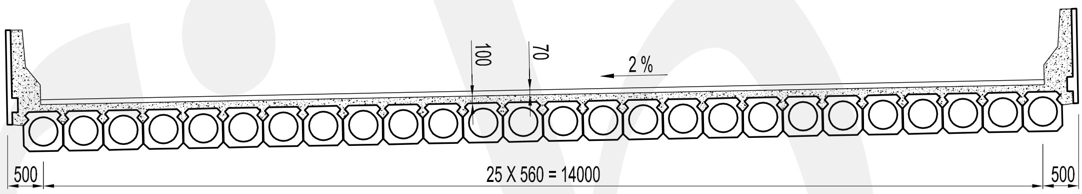


Fig. 5-50 Bridge superstructure with 2% transverse slope. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The bridge has a 2% transverse slope formed by installing each girder at a different elevation.

5.4.3.3.4 *Transverse diaphragms*

This solution includes diaphragms at every midspan and over the piers, providing transverse strength and stiffness to the deck. These elements are partially precast together with the girders. After grouting the interface between girders and casting the deck slab, these diaphragms are post-tensioned with two straight tendons.

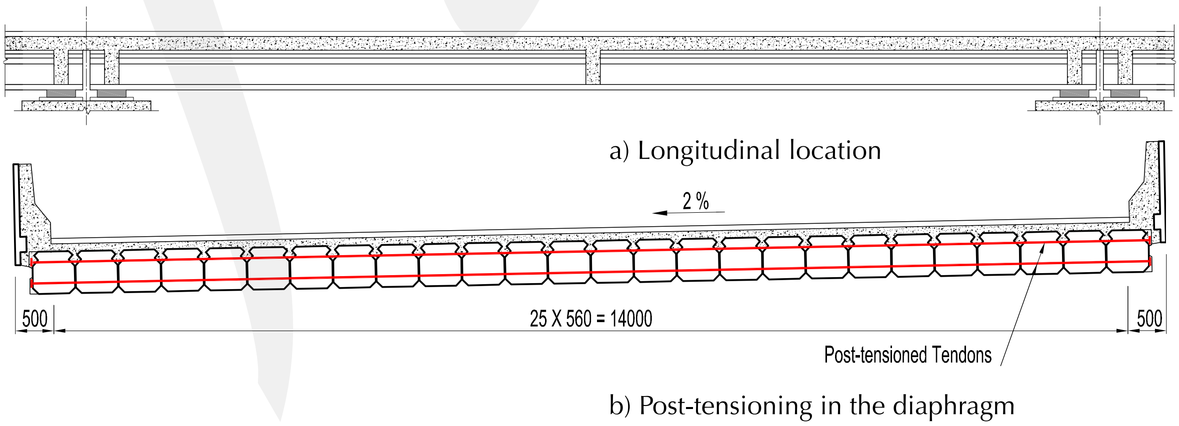


Fig. 5-51 Diaphragms. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.4.3.4 Summary of the preliminary design

Number of spans	10
Continuity	Partial with link slab
Span length *L*, m	15
Girder depth *G*, mm	550
Slab depth *H*, mm	100
Total depth $D = G + H$, mm	650
Web width *W*, mm	2 @ 75
Girder spacing *S*, m	0.560
Precast concrete girder weight, tonnes	6
L/D	23.08
L/G	27.27
Average depth, mm	410
Prestressing steel, kg/m^2	12.5
Reinforcing steel – girder, kg/m^2	43
Reinforcing steel – top slab, kg/m^2	10
Reinforcing steel in a diaphragm, kg	130

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.4.4 Superstructure construction sequence

- Following construction of the piers, neoprene bearing pads are installed on mortar beds.
- Typically, girders are transported by truck and installed with cranes.
- Girders are placed on temporary supports on the piers, allowing the placement of mortar on the neoprene pads. Temporary supports are removed.
- Reinforcement is installed for the deck slab and CIP concrete is placed, completing the deck.
- When the deck concrete has reached a predetermined strength, post-tensioning tendons are installed and tensioned in each diaphragm.

5.5 Example 5: bridge with six 25 m (82 ft) long spans in Brazil

This example was furnished by Fernando Stucchi and Marcelo Waimberg.

This is a theoretical example created for comparison with different practices, but a very typical solution for precast concrete bridges in Brazil. Some of the following pictures show an example of a similar solution used in Trensurb, a suburban railway system in Porto Alegre, Brazil.

5.5.1 Considerations identified

- Bridge layout: This example considers a bridge with total length of 150 m (492 ft) and total width of 15 m (49 ft).
- Codes: Loads according to NBR 7188[5-6],and design according to NBR 6118[5-7] and NBR 8681[5-8].
- Construction factors: Typical precast concrete girders weighing up to 120 tonnes (132 tons) and 45 m (148 ft) long are achievable because of available launching or erecting equipment. To avoid additional formwork and reduce activities at the jobsite, the deck slab is almost entirely precast.
- Aesthetics: Considering construction in a populated area, U girders are more aesthetically appealing than I-girders.
- Construction factors: In a densely populated area, girders would be launched with steel truss travelers, rather than cranes, reducing traffic interference.
- Maintenance: Simple rubber devices are installed at expansion joints. Therefore, an excessive number of these joints should be avoided, because this is critical in terms of maintenance.
- Functional: Reducing expansion joints also improves driver comfort.

5.5.2 Proposed solution

This solution has six spans, each 25 m (82 ft) long. The superstructure consists of five precast concrete U girders with a depth of 1500 mm (59 in.) with a spacing of 2.7 m (8.9 ft) on center. In the Brazilian experience, the spacing of girders can be up to 4 m (13 ft) or sometimes more, but some authorities limit this distance to a lower value.

The deck slab is precast concrete. The panels are 20 cm (8 in.) thick, bearing on the top flange of the girders and a CIP concrete layer is placed connecting the panels and girders. The deck has a 2% transverse slope, accomplished by varying girder bearing elevations.

By using a 1.35 m (4.43 ft) deck cantilever, five girders are used in the 15 m (49 ft) wide deck.

Expansion joints are used every three spans.

Over each pier, transverse diaphragms are provided adding torsional strength and stiffness for the girders and the entire deck when subjected to lateral forces. The diaphragms are cast in place, together with the 10 cm (4 in.) thick panel topping. Intermediate diaphragms are not used, simplifying deck construction.

This solution employs partial continuity over the piers using link slabs.

5.5.2.1 Plan

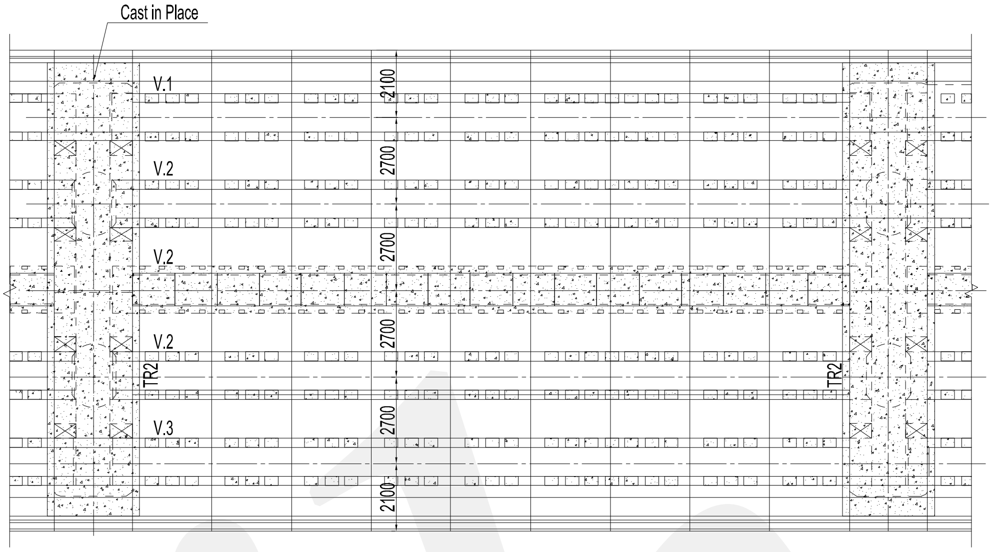


Fig. 5-52 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.5.2.2 Elevation

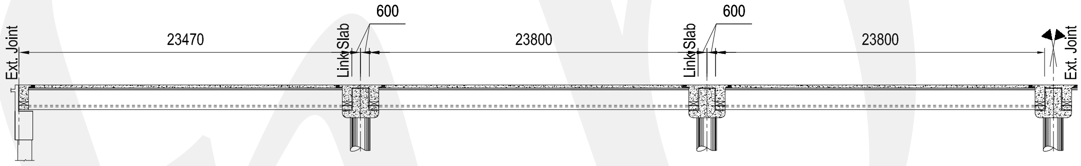
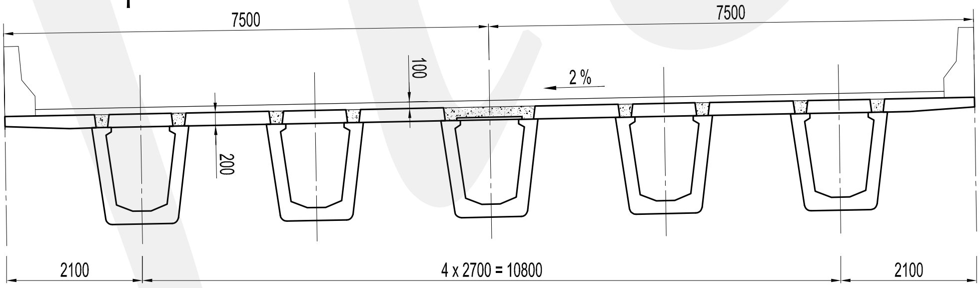
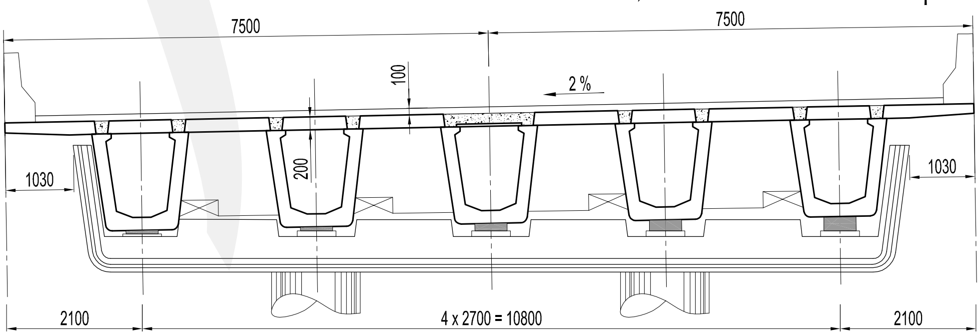


Fig. 5-53 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.5.2.3 Superstructure cross section



a) Cross section near midspan



(b) Cross section at a pier

Fig. 5-54 Cross section of the bridge. Note: All dimensions are in millimeters . 1 mm = 0.0394 in.

5.5.3 Superstructure

5.5.3.1 Precast concrete girders

5.5.3.3.1 Materials

Concrete: 40 MPa (6 ksi)

Prestressing steel: 1'900 MPa (276 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.5.3.3.2 Description of the cross section

Five U girders, 1500 mm (59 in.) deep, placed 2.7 m (8.9 ft) on center, with constant cross-section properties.

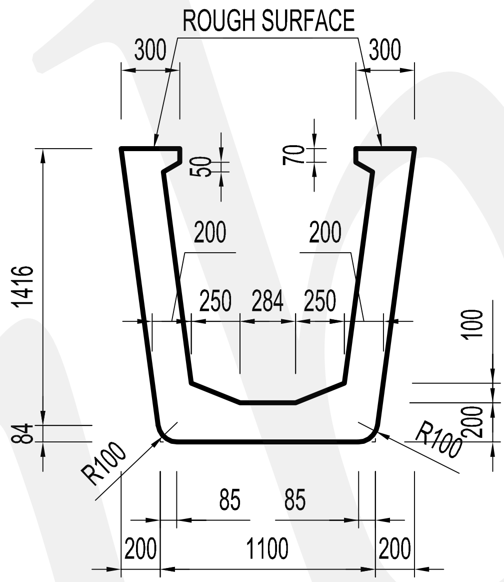


Fig. 5-55 Cross-section dimensions of the precast concrete U girder. Note: All dimensions are in centimeters. 1 cm = 0.3937 in.

5.5.3.1.3 Prestressing

Each precast concrete girder is pretensioned with 34 12.7 mm (0.5 in.) diameter straight strands. No additional post-tensioning in girders or diaphragms is provided.

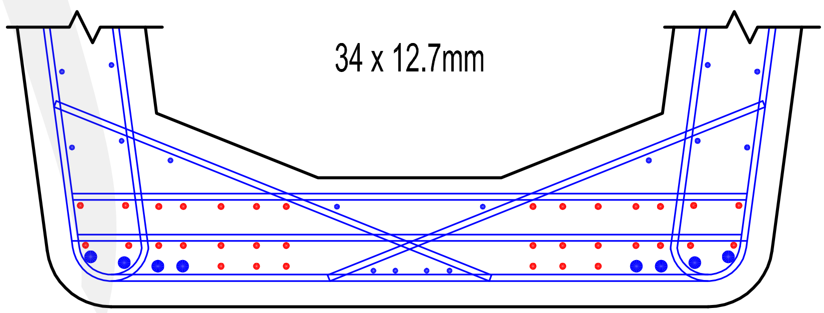


Fig. 5-56 Prestressing in the precast concrete girders. Note: 1 mm = 0.0394 in.

5.5.3.2 Deck slab

5.5.3.2.1 Materials

Concrete: 40 MPa (6 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.5.3.2.2 Deck slab description

The deck slab is precast using 20 cm (8 in.) thick panels bearing on the top flanges of the girders. CIP concrete is placed between the panels on the girders. To reduce the risk of misalignment of bearings, two panels are used to cover the deck width. This permits lighter panels to be installed.

The deck has a 2% transverse slope, achieved with varying bearing elevations.

Fig. 5-57 Example precast concrete erection photos of a similar bridge.

5.5.3.3 Details

5.5.3.3.1 Bearings

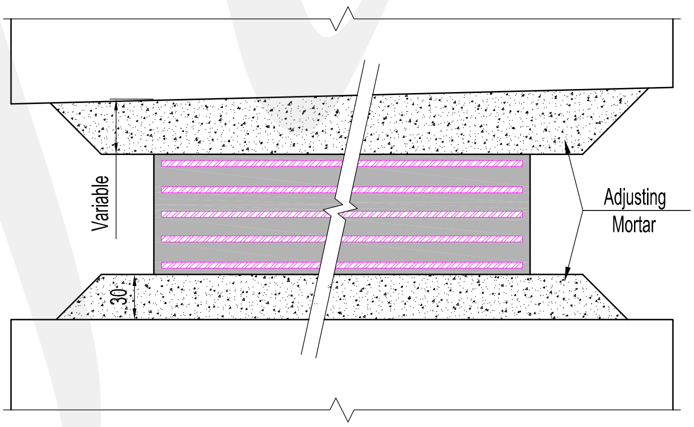


Fig. 5-58 Bearing detail

The elevation of the bridge varies along its length and is achieved with piers of different heights. Neoprene bearing pads are placed on mortar pads on the piers. A CIP mortar is provided to ensure full contact with the bottom of the girder.

5.5.3.3.2 Continuity

Partial structural continuity is accomplished with link slabs over the piers. Expansion joints are installed at midlength of the bridge and at both abutments every three spans or 75 m (246 ft) apart.

At every other pier, the slab is continuous over the transverse inverted T pier cap beam. This geometry ensures that the slab allows the girders to rotate.

Additional reinforcement is placed at this point to resist bending moments and tension arising from direct truck load and rotation of the girders.

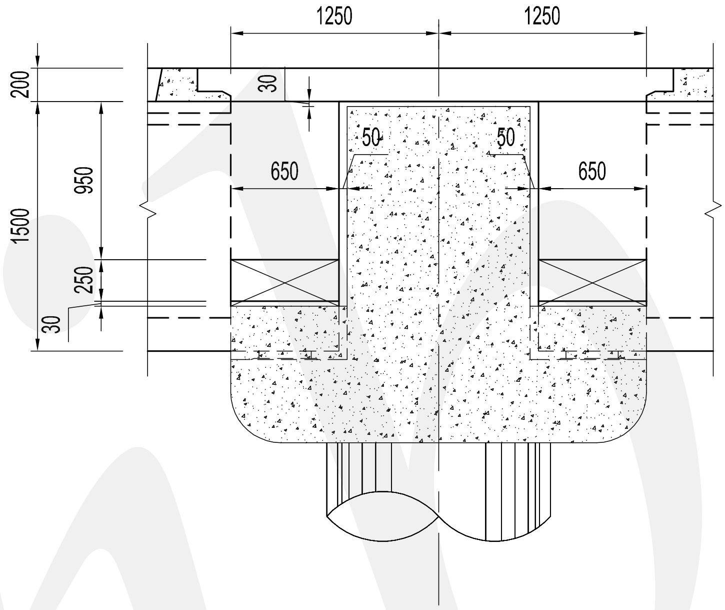


Fig. 5-59 Continuity detail over a pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.5.3.3.3 Transverse slope

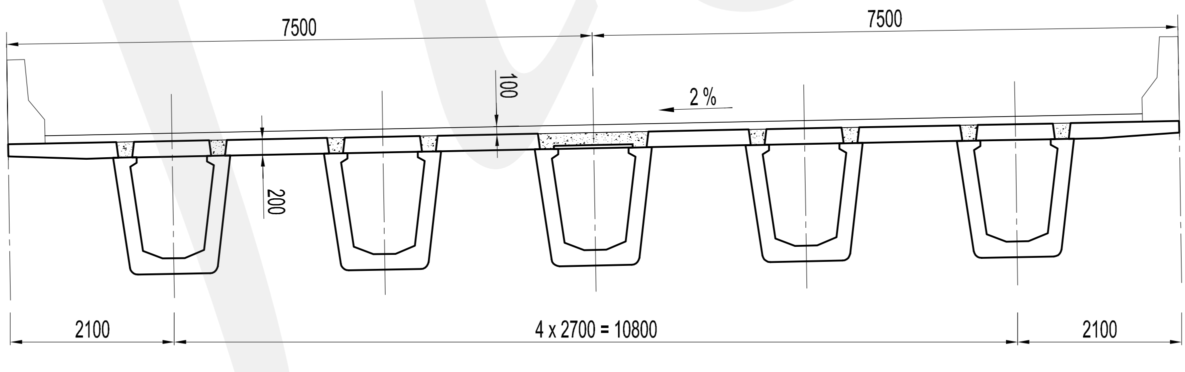


Fig. 5-60 Bridge superstructure with 2% transverse slope. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The bridge has a 2% transverse slope formed by installing each girder at a different elevation.

For larger slopes, closed box girders can be installed rotated around their longitudinal axes. This would simplify installation of the precast concrete panels.

5.5.3.3.4 *Transverse diaphragms*

This solution uses reinforced concrete diaphragms over the piers that are cast in place just before installing precast concrete deck panels. Diaphragm concrete is placed both inside and outside the girders.

These diaphragms provide torsional strength and stiffness to the girders.

No intermediate diaphragm is used.

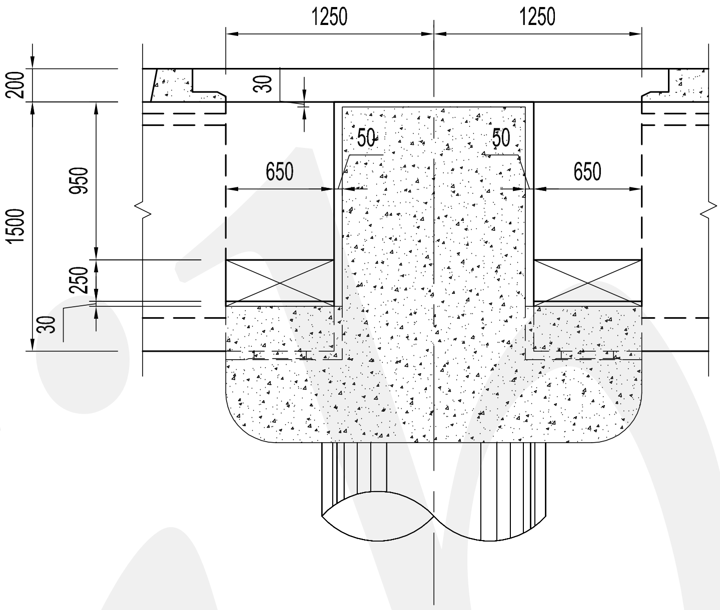


Fig. 5-61 Diaphragm detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.5.3.4 Summary of the preliminary design

Number of spans	6
Continuity	Partial with link slab
Span length *L*, m	25
Girder depth *G*, mm	1'500
Panel depth *H*, mm	200
Total depth $D = G + H$, mm	1'700
Web width *W*, mm	2 @ 200
Girder spacing *S*, m	2.70
Precast concrete girder weight, tonnes	49
L/D	14.70
L/G	16.67
Average depth, mm	460
Prestressing steel, kg/m^2	9
Reinforcing steel – girder, kg/m^2	45
Reinforcing steel – top slab, kg/m^2	35
Reinforcing steel in a diaphragm, kg	740

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.5.4 Construction sequence

- After completing CIP construction of the piers, neoprene bearing pads are installed on mortar beds.
- Typically, girders are transported by truck and launched with truss travelers.
- Girders are placed on temporary devices on top of the piers, allowing placement of adjusting mortar on the neoprene pads.
- Precast concrete panels are erected on tops of the girders.
- Additional reinforcement is installed both for diaphragms and continuity between adjacent deck panels. Concrete is placed in diaphragms.
- The connection is made between the girders' flanges and deck panels with concrete placed through panel blockouts.

Fig. 5-62 Examples of transporting and installing girders.

5.6 Example 6: bridge with four 37.5 m (123 ft) long spans in Brazil

This example was furnished by Fernando Stucchi and Marcelo Waimberg.

This is a theoretical example created for comparison with different practices, but a very typical solution for precast concrete bridges in Brazil.

5.6.1 Considerations identified

- Bridge layout: This example considers a bridge with a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: Loads according to NBR 7188[5-6], and design according to NBR 6118[5-7] and NBR 8681[5-8].
- Construction factors: Typical precast concrete girders weighing up to 120 tonnes (132 tons) and 45 m (148 ft) long were considered because of available launching or erecting equipment. To avoid additional formwork, no lateral overhangs were considered.
- Maintenance: Simple neoprene profiles are installed at expansion joints. Therefore, a large number of these joints should be avoided, because this is a critical point in terms of maintenance.
- Functional: Reducing expansion joints also improves driver comfort.

5.6.2 Proposed solution

This example bridge has four spans, each 37.5 m (124 ft) long. The cross section comprises six precast concrete I-girders with a depth of 1'950 mm (77 in.), 2.77 m (9 ft) on center. In the Brazilian experience, the transverse spacing can be up to 3.2 m (10.5 ft) sometimes higher, but some authorities would limit the spacing to 3.0 m (9.8 ft).

The deck slab is partially precast with 70 mm (3 in.) thick panels placed on the top flanges of the girders. Concrete topping, 130 mm (5 in.) thick, is added. The deck has a 2% transverse slope, obtained by varying the girders' bearing elevations.

In this example, there is no deck overhang, avoiding the use of formwork for that section of the deck. Transverse bottom reinforcement in the slab is provided in the precast concrete panels.

Over each pier, transverse diaphragms are assumed, providing adequate torsional strength and stiffness for the girders and the whole deck when subjected to lateral forces. The diaphragms are cast in place together with the deck topping. Intermediate diaphragms are not used, which simplifies deck construction.

This solution assumes partial continuity over the piers using link slabs.

5.6.2.1 Plan

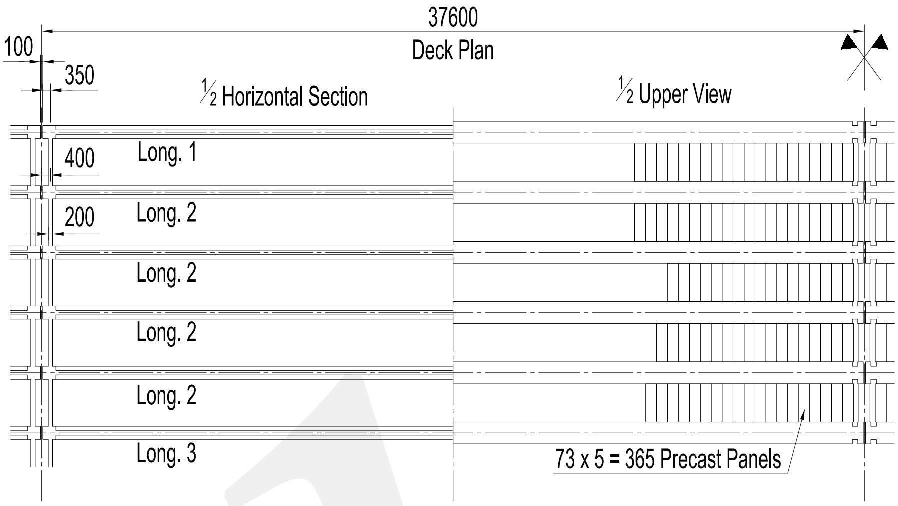


Fig. 5-63 Plan of two spans of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.6.2.2 Elevation

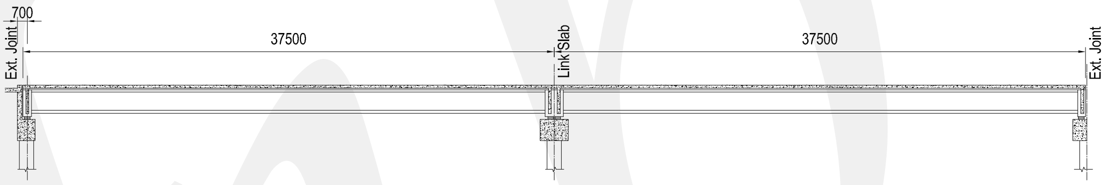


Fig. 5-64 Elevation of two spans. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.6.2.3 Superstructure cross section

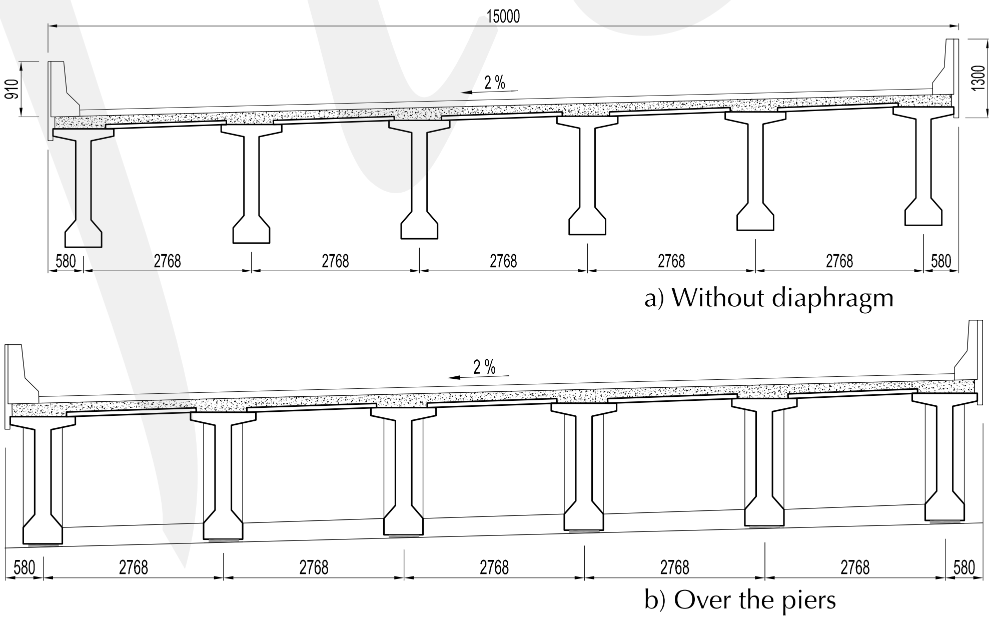


Fig. 5-65 Cross-section view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.6.3 Superstructure

5.6.3.1 Precast concrete girders

5.6.3.1.1 Materials

Concrete:	40 MPa (6 ksi)
Prestressing steel:	1'900 MPa (276 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.6.3.1.2 Description of the cross section

Six I-girders, 1'950 mm (77 in.) deep, placed 2.77 m (9.09 ft) on center, with a constant cross section over the full length, except at supports, where the flared-end section widens to 600 mm (24 in.).

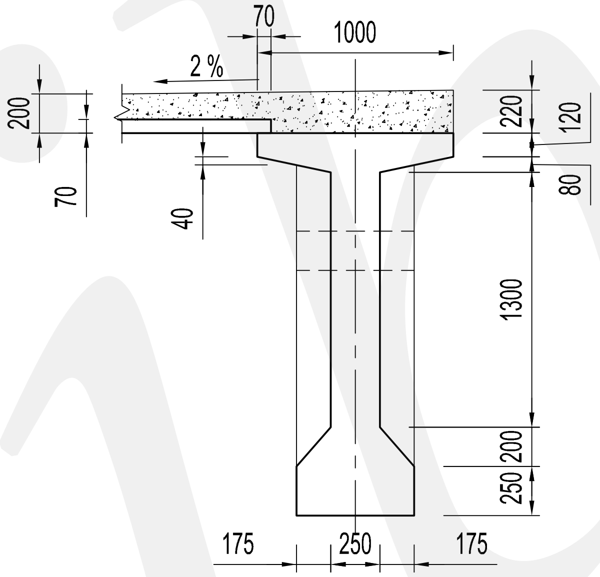


Fig. 5-66 Cross-section dimensions of precast concrete girder. Note: All dimensions are in centimeters. 1 cm = 0.3937 in.

5.6.3.1.3 Prestressing

Each precast concrete girder is pretensioned with a total of 32 15.2 mm (0.6 in.) diameter straight strands. No additional post-tensioning for girders or diaphragms is provided.

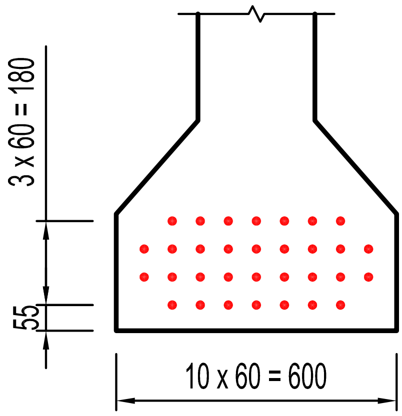


Fig. 5-67 Prestressing strand layout in precast concrete girders. Note: All dimensions are in centimeters. 1 cm = 0.3937 in.

5.6.3.2 Deck slab

5.6.3.2.1 Materials

Concrete: 35 MPa (5 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.6.3.2.2 Deck slab description

The deck slab is partially precast using 70 mm (3 in.) thick panels placed on the edges of the top flanges of the girders. Concrete topping, 130 mm (5 in.) thick, is placed afterwards. The deck has a 2% transverse slope, achieved by varying the bearing elevations.

Transverse bottom reinforcement for the deck is provided in the precast concrete panels. No transverse reinforcement is used, but the top surface of the panels is left intentionally rough to ensure composite action with the CIP concrete.

Fig. 5-68 Typical precast concrete panel installation.

5.6.3.3 Details

5.6.3.3.1 Bearings

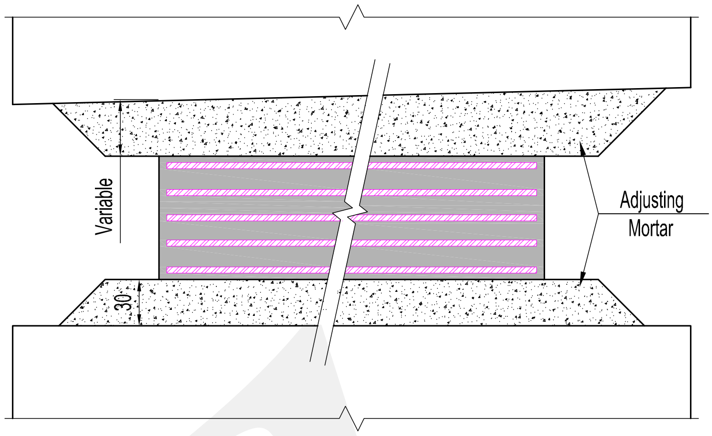


Fig. 5-69 Bearing detail

The elevation of the bridge varies along its length. This is achieved with piers of different heights. Neoprene bearing pads are placed on top of mortar pads. A CIP mortar layer is provided to ensure full contact with the bottom of the girder.

5.6.3.3.2 Continuity

Partial structural continuity is provided by link slabs over piers. At midlength and at both abutments, expansion joints are installed 75 m (246 ft) apart.

To provide flexibility in the slab, bearings are not allowed between adjacent diaphragms. This is achieved with of a polystyrene plate placed before casting the deck topping.

Additional reinforcement is placed at this point to resist bending moments and tension from direct truck load and rotation of the girders.

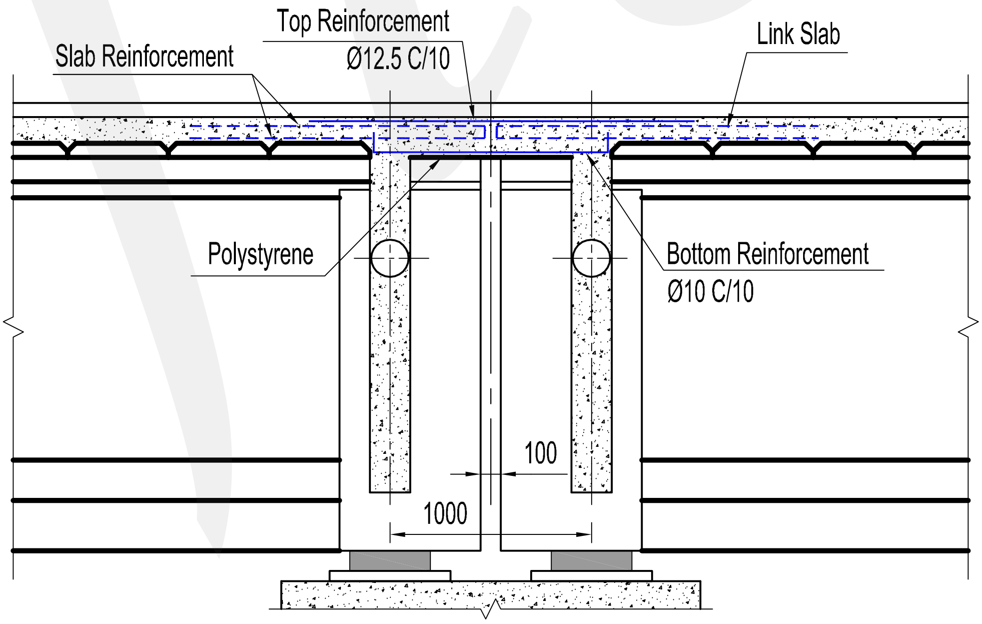


Fig. 5-70 Continuity detail over a pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.6.3.3.3 Transverse slope

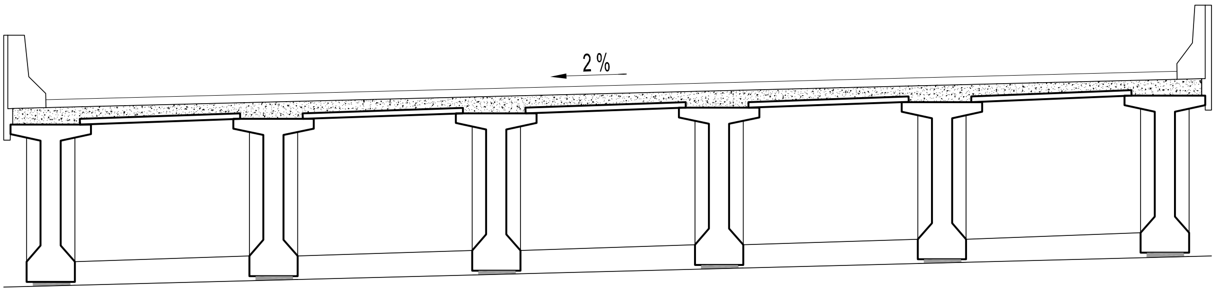


Fig. 5-71 Bridge superstructure with 2% transverse slope.

The bridge has a 2% transverse slope formed by installing each girder at a different elevation.

5.6.3.3.4 Transverse diaphragms

This solution uses reinforced concrete diaphragms over the piers that are cast in place at the same time as the topping slab.

These diaphragms provide torsional strength and stiffness to the girders.

No intermediate diaphragm is used.

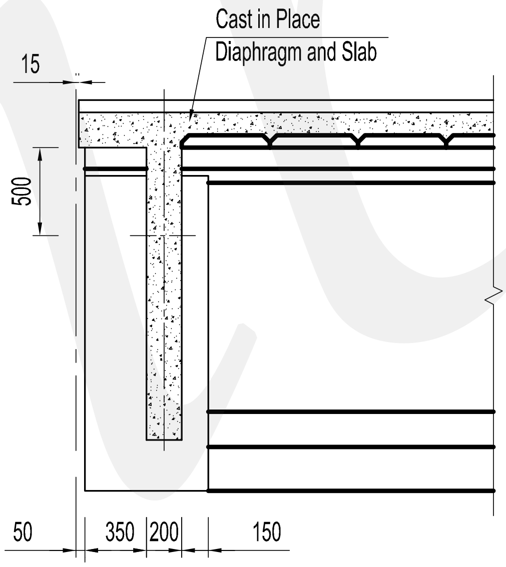


Fig. 5-72 Diaphragm detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.6.3.4 Summary of the preliminary design

Number of spans	4
Continuity	Partial with link slab
Span length *L*, m	37.5
Girder depth *G*, mm	1'950
Deck slab depth *H*, mm	200
Total depth *D* = *G* + *H*, mm	2'150
Web width *W*, mm	250
Girder spacing *S*, m	2.77
Precast concrete girder weight, tonnes	68
L/D	17.44
L/G	19.23
Average depth, mm	500
Prestressing steel, kg/m^2	16
Reinforcing steel – girder, kg/m^2	74
Reinforcing steel – deck slab, kg/m^2	35
Reinforcing steel in a diaphragm, kg	260

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.6.4 Construction sequence

- After completing CIP construction of the piers, neoprene bearing pads are installed on mortar beds.
- Typically, girders are transported by truck and installed with cranes.
- Girders are placed on temporary devices on top of the piers, allowing placement of adjusting mortar on neoprene pads.
- Precast concrete panels are installed on top of girders and additional reinforcement is installed, both for panels and diaphragms.
- Topping concrete is placed completing the deck.

Fig. 5-73 Transporting and installing girders.

5.6.5 Substructure

5.6.5.1 Piers

The previous three examples disregard the substructure.

Usually, in Brazilian bridges these are CIP structures. However, precast concrete elements are sometimes considered for pile caps, columns, or pier caps.

Fig. 5-74 shows an example of precast concrete columns.

Fig. 5-74 Example of precast concrete columns.

5.7 Example 7: bridge with ten 16 m (52 ft) long spans in China

This example was furnished by Bao-Chun Chen.

This is a theoretical example developed with solutions commonly adopted in China.

5.7.1 Considerations identified

- Bridge layout: This example considers a bridge with total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: This example uses the following codes: JTG B01-2003[5-9], JTG D60-2004[5-10], JTG D62-2004[5-11], JTJ041-2000[5-12], JTG D81-2006[5-13].
- Aesthetics: The two precast concrete edge girders have asymmetric overhangs to improve the appearance of the bridge as well as reduce the formwork needed.

5.7.2 Proposed solution

This solution has 10 spans, each with a length of 16 m (52 ft). The cross section of the superstructure consists of nine precast concrete hollow-core girders with a depth of 800 mm (31 in.) and variable length. The nine girders form a slab bridge joined with infill concrete, deck panels, and a CIP topping slab.

The CIP topping slab is 18 cm (7 in.) thick and the bridge has a 2% transverse slope.

Reinforced concrete diaphragms are used over piers and abutments but there are none at midspan.

The precast concrete girders are post-tensioned. The tendons are single strands with a parabolic profile along the length of the girder.

5.7.2.1 Superstructure cross section

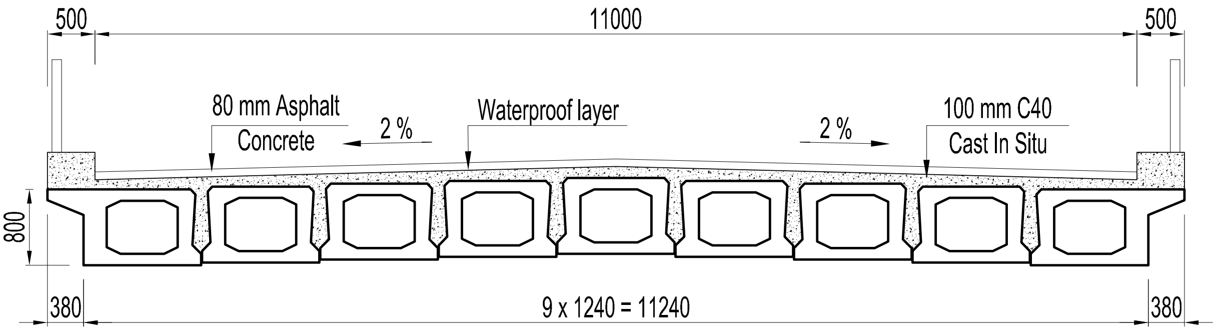


Fig. 5-75 Cross section of the bridge between diaphragms. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.7.3 Superstructure

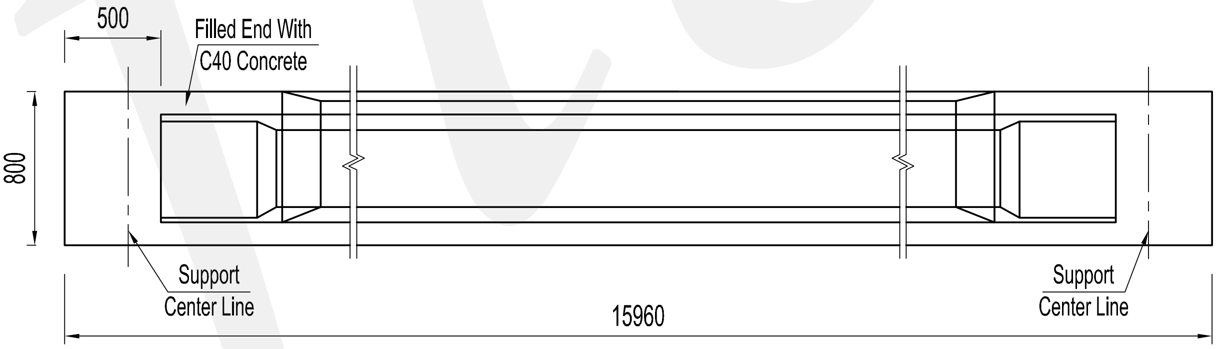
5.7.3.1 Precast concrete girders

5.7.3.1.1 Materials

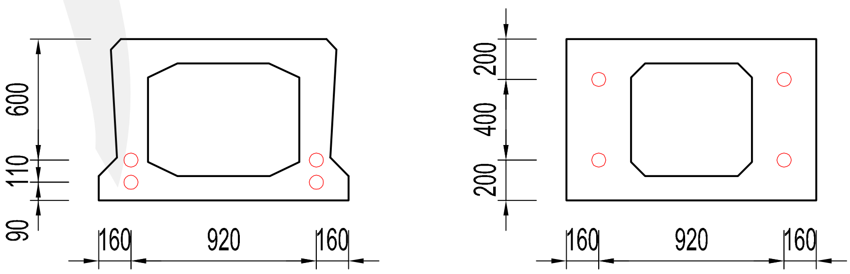
Concrete:	40 MPa (6 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	335 MPa (49 ksi)

5.7.3.1.2 Description of the cross section

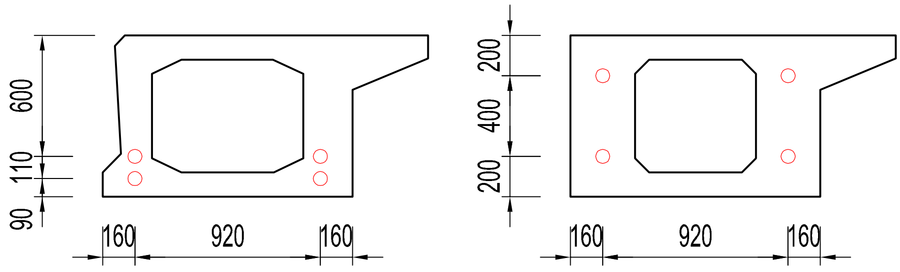
Nine hollow-core girders form a slab bridge superstructure with varying cross-section dimensions (Fig. 5-76). The two edge girders have overhangs that improve the appearance of the bridge and reduce the need for formwork for the deck slab.



a) Longitudinal and vertical dimensions



b) Interior girders

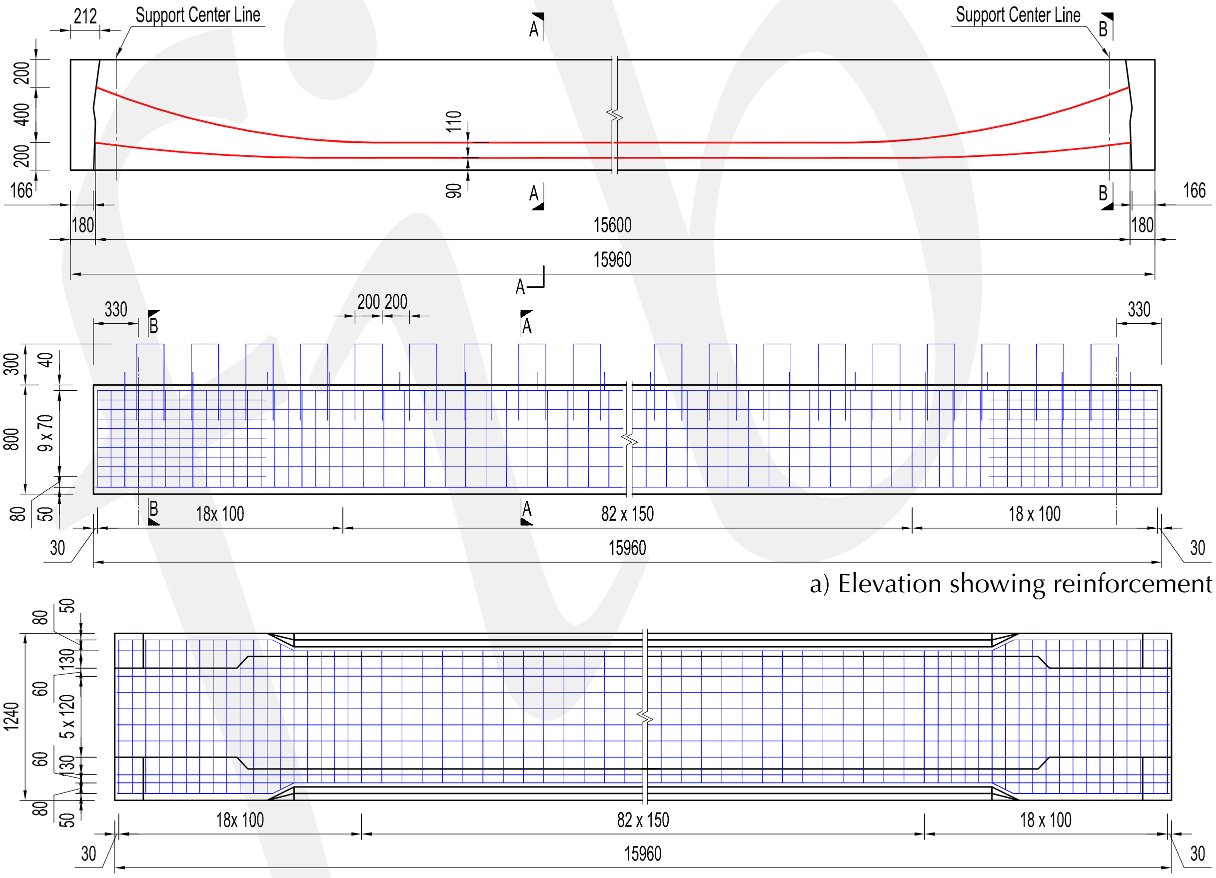


c) Exterior girders

Fig. 5-76 Dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.7.3.1.3 Prestressing

The precast concrete girders are post-tensioned. The post-tensioning tendons consist of four strands, 15.2 mm (0.6 in.) diameter in each precast concrete girder (Fig. 5-77 and 5-78). These figures also show the mild reinforcement in the precast concrete girder.



a) Elevation showing reinforcement

b) Plan of reinforcement

Fig. 5-77 Reinforcement layout of the interior girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

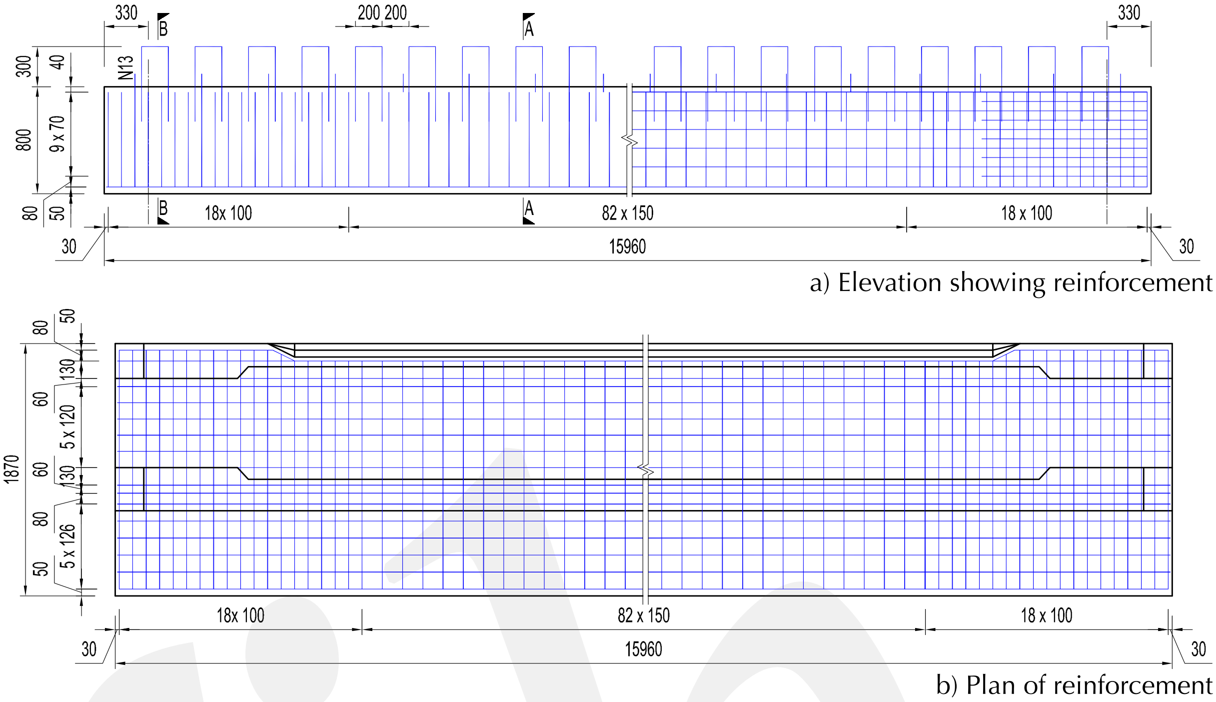


Fig. 5-78 Reinforcement layout of exterior girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.7.3.2 Deck slab

5.7.3.2.1 Materials

Concrete: 40 MPa (6 ksi)

Mild reinforcing steel: 335 MPa (49 ksi)

5.7.3.3.2 Deck slab description

CIP slab with a thickness of 18 cm (7 in.) and cast on top of deck panels placed on the girders with the reinforcement (Fig. 5-79 and 5-80).

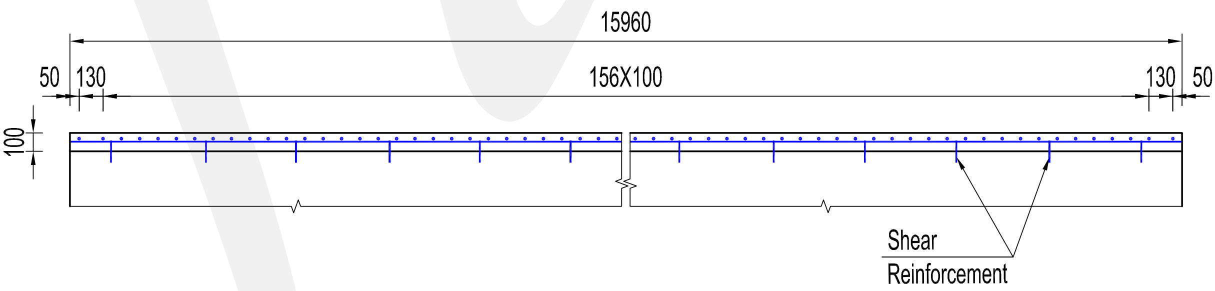


Fig. 5-79 The connection detail between the deck panels and the cast-in-place slab. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

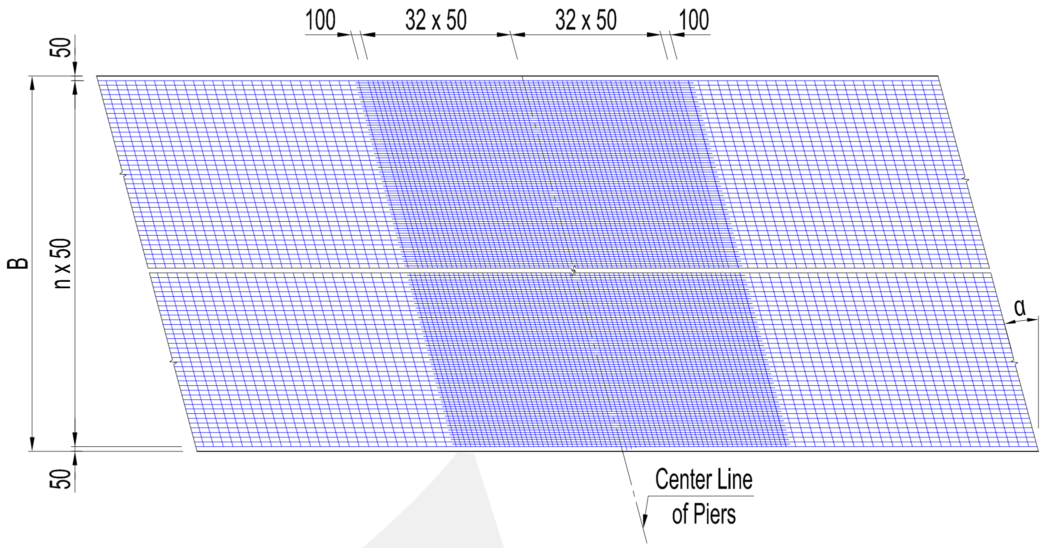


Fig. 5-80 Plan view of the reinforcement of the top slab.Note: *B* = Slab width ; *n* = number of rebars; *α* = skew angle. ll dimensions are in millimeters. 1 mm = 0.0394 in.

5.7.3.3 Details

Continuity

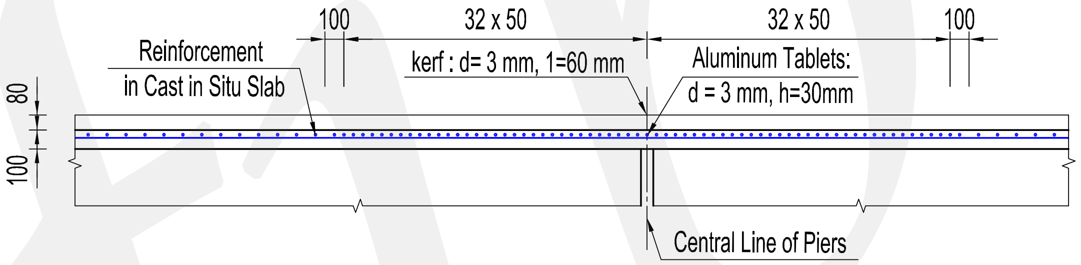


Fig. 5-81 Continuity detail over the pier. Note: *d* = tablet thickness; *h* = distance between tablets. All dimensions are in millimeters. 1 mm = 0.0394 in.

Full structural continuity was used in this example.

5.7.3.4 Summary of the main information

Number of spans	10
Continuity	Structural continuity
Span length *L*, m	16
Girder depth *G*, mm	800
Slab depth *H*, mm	180
Total depth *D* = *G* + *H*, mm	980
Web width *W*, mm	270
Girder spacing *S*, m	1.25
Precast concrete girder weight, tonnes	28.9
L/D	13.33
L/G	16.32
Prestressing steel, kg/m²	9.32

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m² = 0.2048 lb/ft²; 1 tonne = 1.102 tons.

5.8 Example 8: bridge with five 30 m (98 ft) long spans in China

This example was furnished by Bao-Chun Chen. This is a theoretical example developed with solutions commonly adopted in China.

5.8.1 Considerations identified

- Bridge layout: This example is a bridge with total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: This example uses the following codes: JTG B01-2003[5-9], JTG D60-2004[5-10], JTG D62-2004[5-11], JTJ041-2000[5-12], JTG D81-2006[5-13].

5.8.2 Proposed solution

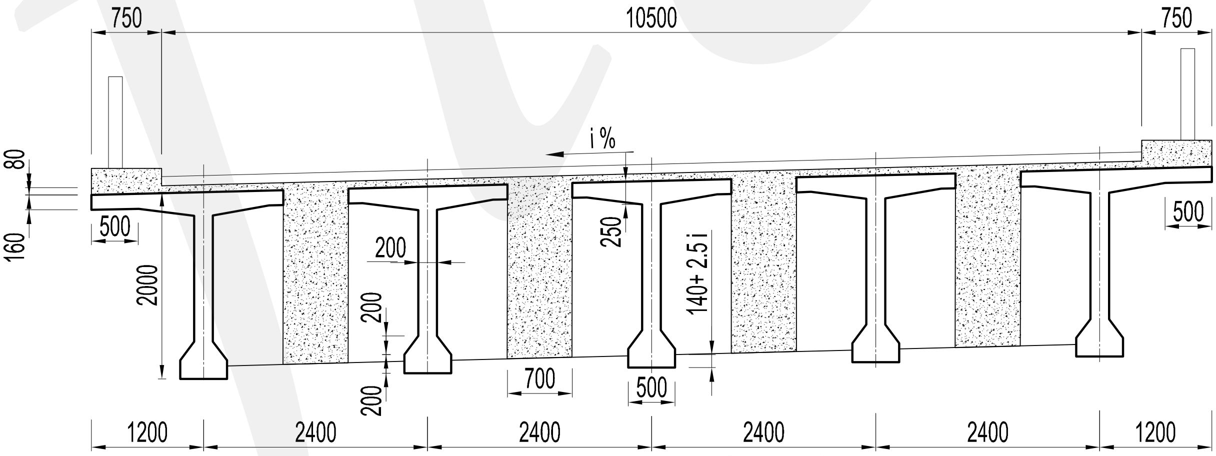
This example has five spans, each 30 m (98 ft) long. The cross section of the superstructure consists of five precast concrete T-girders with a depth of 2000 mm (79 in.). There are two types of precast concrete girders, interior and exterior "edge" girders. Precast reinforced concrete deck panels are placed on top of the girders and a topping slab is cast on the deck panels.

The CIP topping slab is 8 cm (3 in.) thick. A bituminous wearing course is used over the concrete. The deck has a 2% transverse slope.

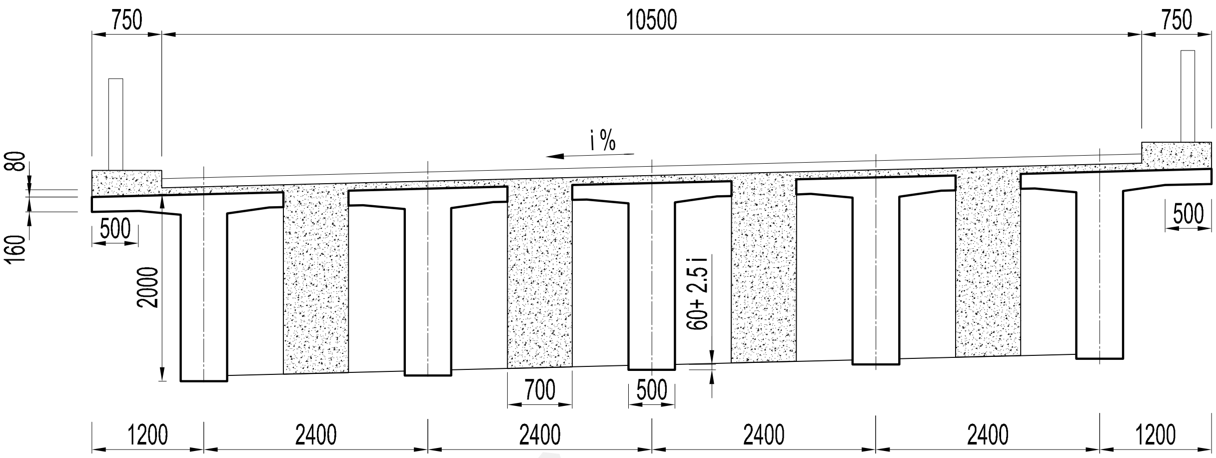
Mildly reinforced concrete diaphragms are used over the piers and abutments as well as at three intermediate locations at midspan and quarter points of the girders.

The precast concrete girders are post-tensioned. The layout of the tendons is a parabolic profile.

5.8.2.1 Superstructure cross section



a) Cross section at midspan diaphragm showing cast-in-place and precast concrete portions of diaphragm



b) Cross section at supports

Fig. 5-82 Cross section at diaphragms.Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.8.3 Superstructure

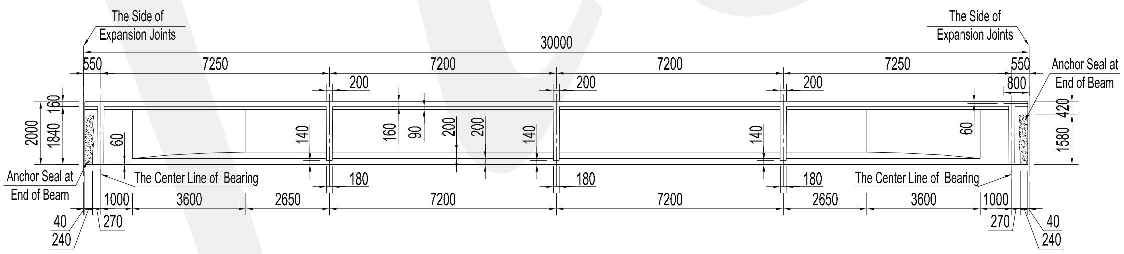
5.8.3.1 Precast concrete girders

5.8.3.1.1 Materials

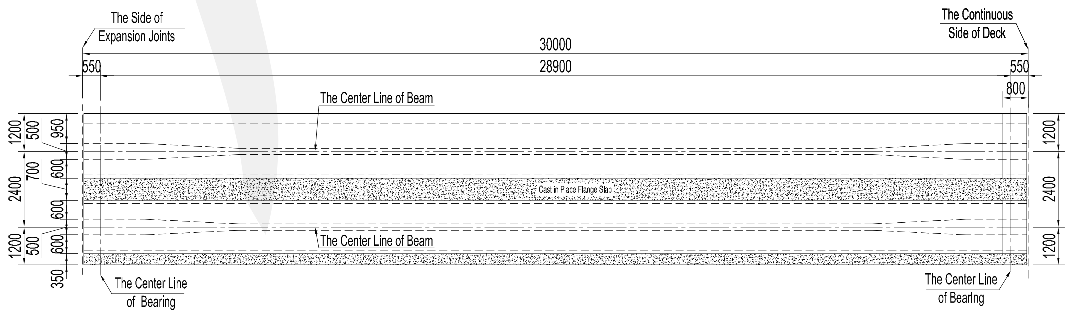
Concrete:	50 MPa (7 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	335 MPa (49 ksi)

5.8.3.1.2 Description of the cross section

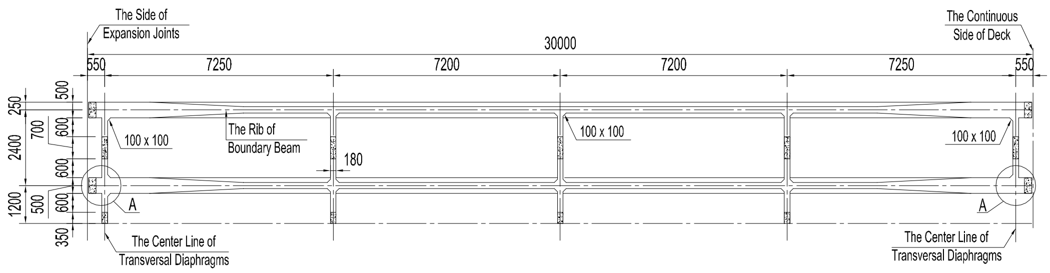
Five T girders, three interior and two exterior girders spaced at 2.4 m (7.9 ft) on center. As can be seen in Fig. 5-83, the cross section of the precast concrete girders varies along the length of the bridge, with flared end sections the same width of the bottom flange at supports.



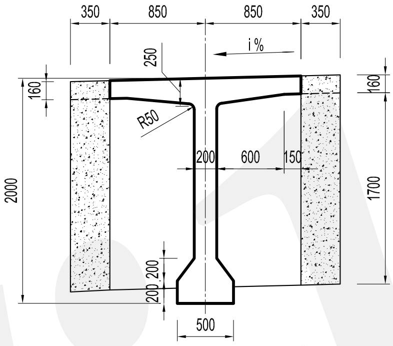
a) Elevation



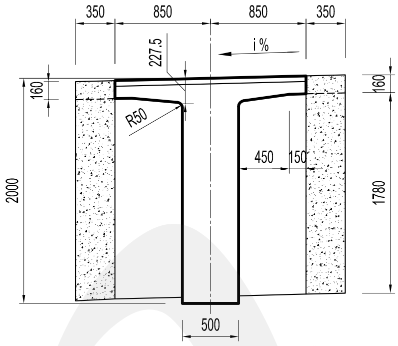
b) Plan of an exterior and one interior girder



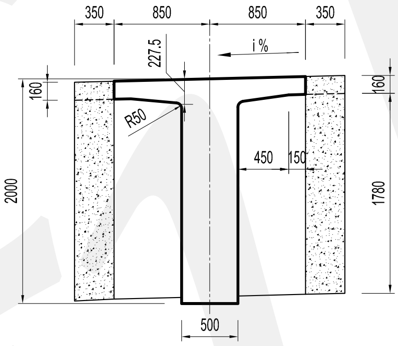
c) Bottom view of an exterior and one interior girder showing diaphragms with cast-in-place portions dimensioned



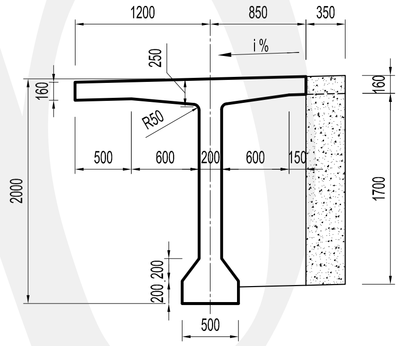
d) Section A-A (interior girder)



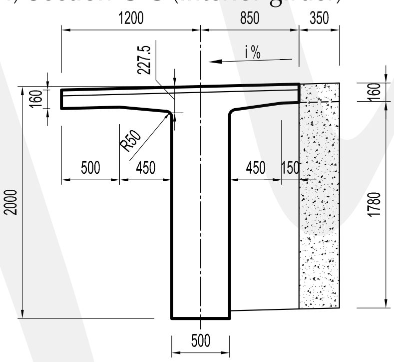
e) Section B-B (interior girder)



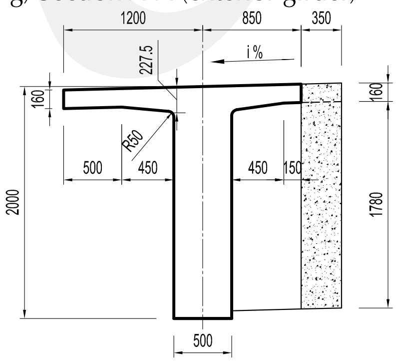
f) Section C-C (interior girder)



g) Section A-A (exterior girder)



h) Section B-B (exterior girder)



i) Section C-C (exterior girder)

Fig. 5-83 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.8.3.1.3 Prestressing

The precast concrete girders are post-tensioned. The longitudinal prestressing consists of three parabolic tendons with 15.2 mm (0.6 in.) diameter strands. Figure 5-84 shows the location of the longitudinal post-tensioning and the location in the cross section at midspan and supports.

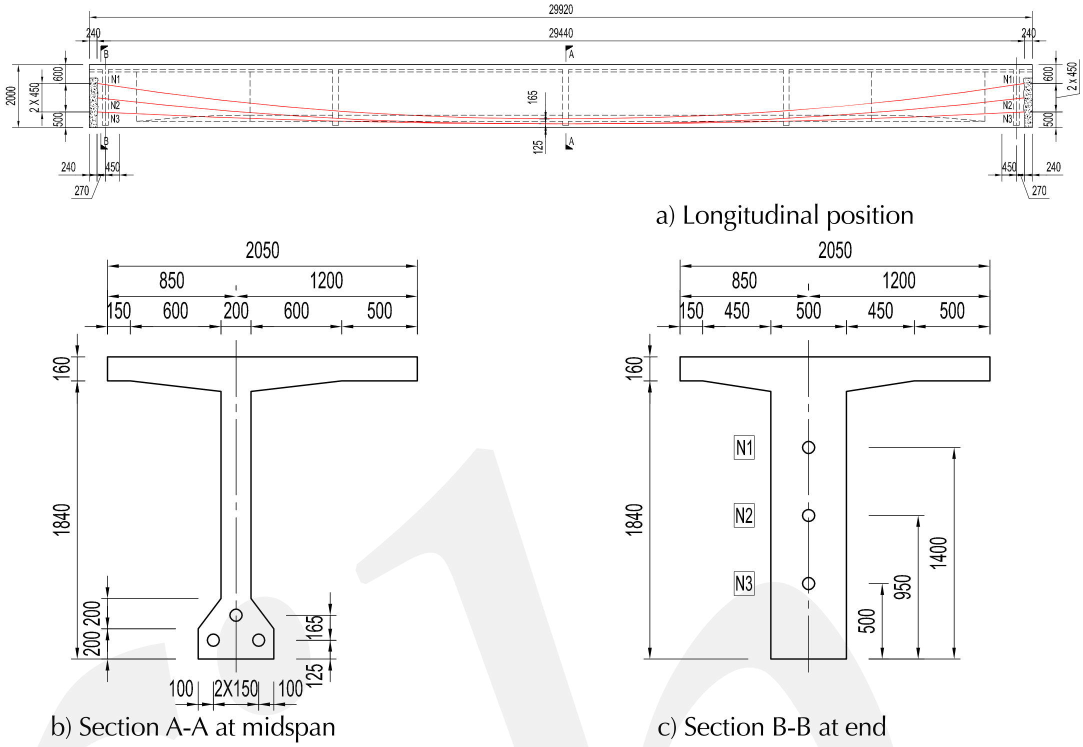


Fig. 5-84 Post-tensioning layout of precast concrete beams. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.8.3.2 Deck slab

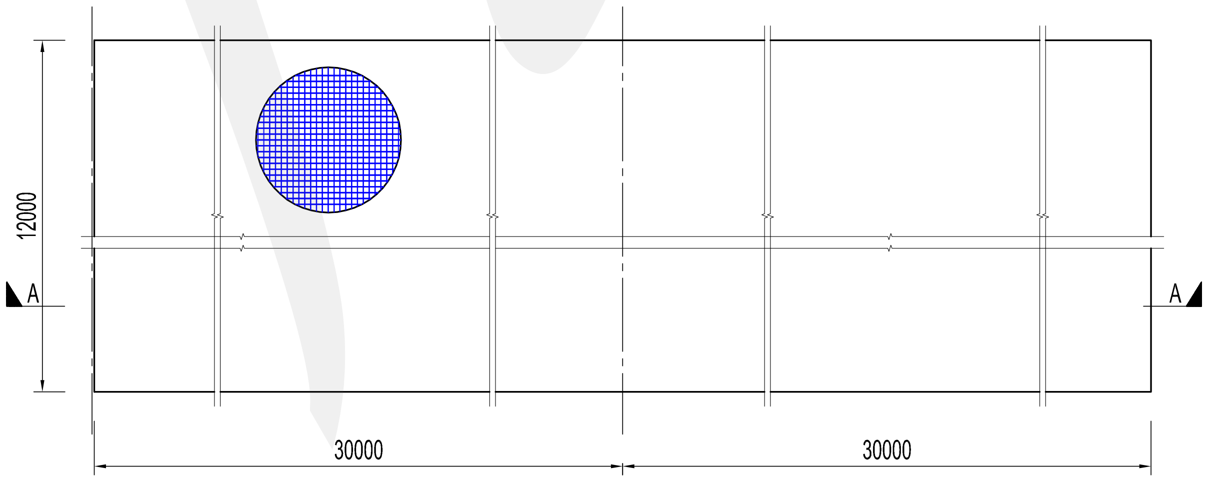
5.8.3.2.1 Materials

Concrete: 50 MPa (7 ksi)

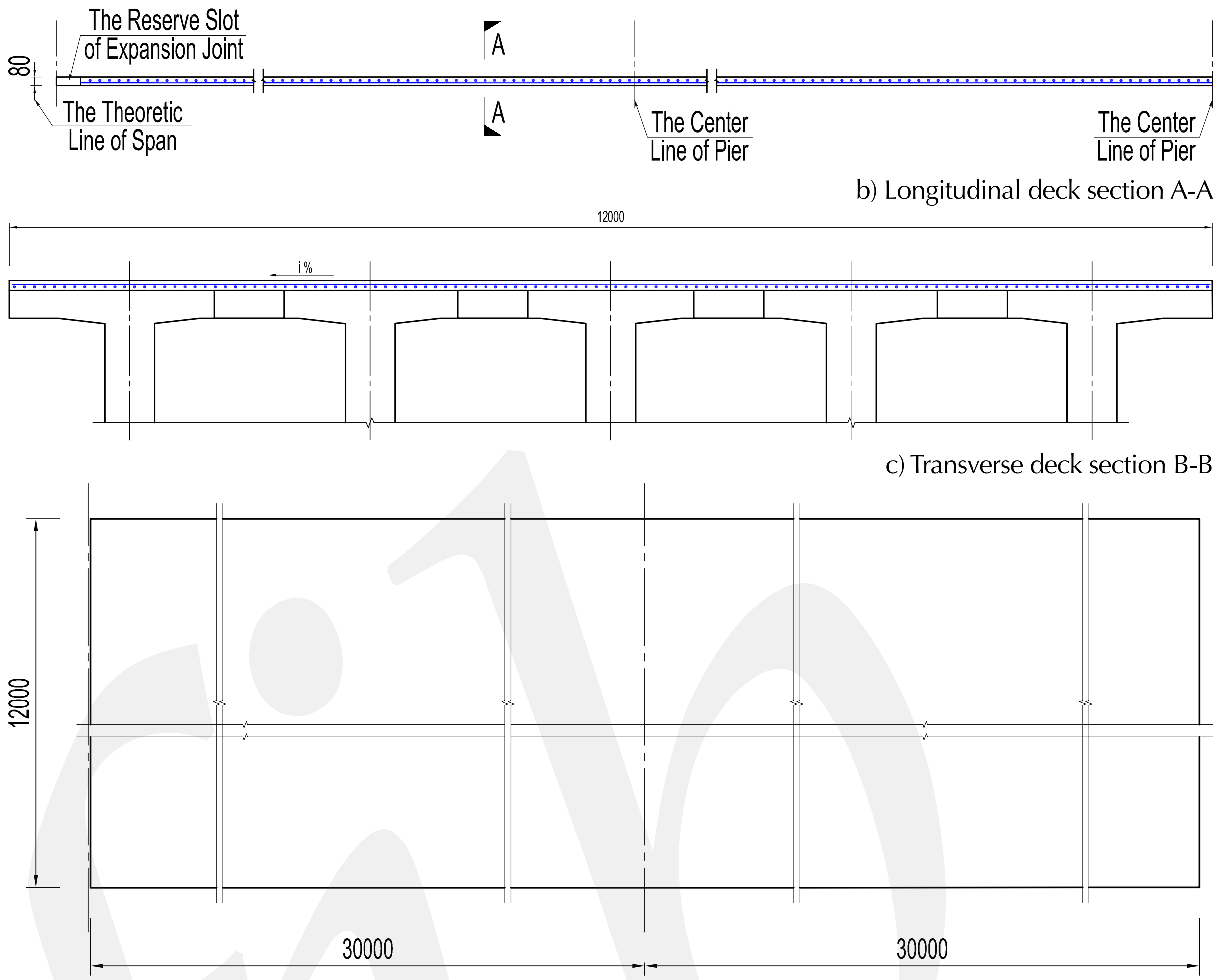
Mild reinforcing steel: 335 MPa (49 ksi)

5.8.3.2.2 Deck slab description

An 8 cm (3 in.) thick slab is cast on top of deck panels on the girders with the reinforcement shown in Fig. 5-85.



a) Plan view



b) Longitudinal deck section A-A

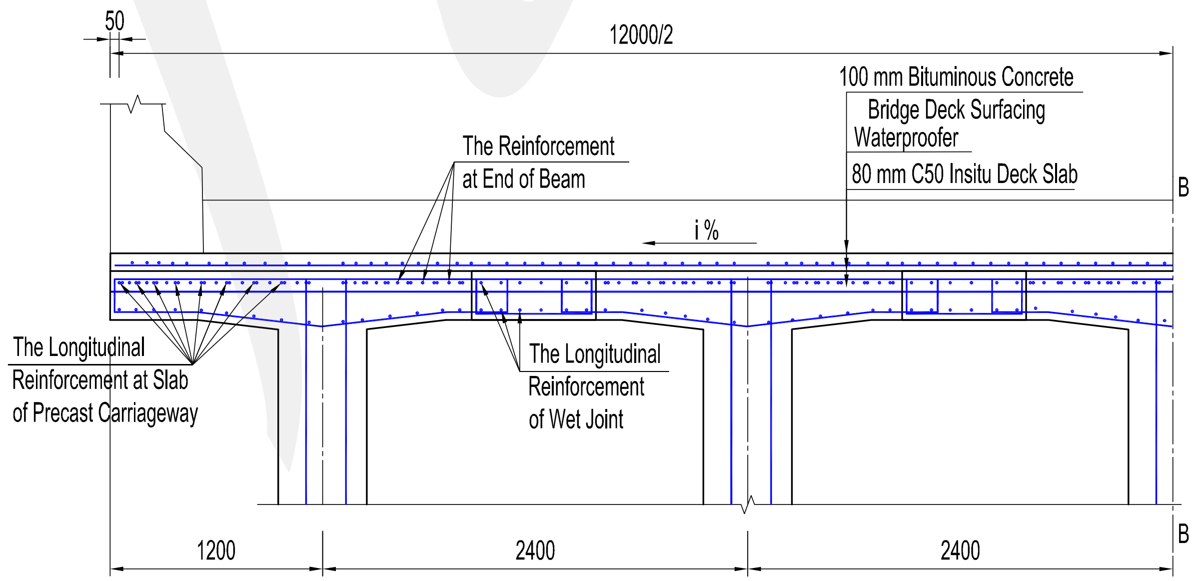
c) Transverse deck section B-B

d) Plan view of cast-in-place deck slab

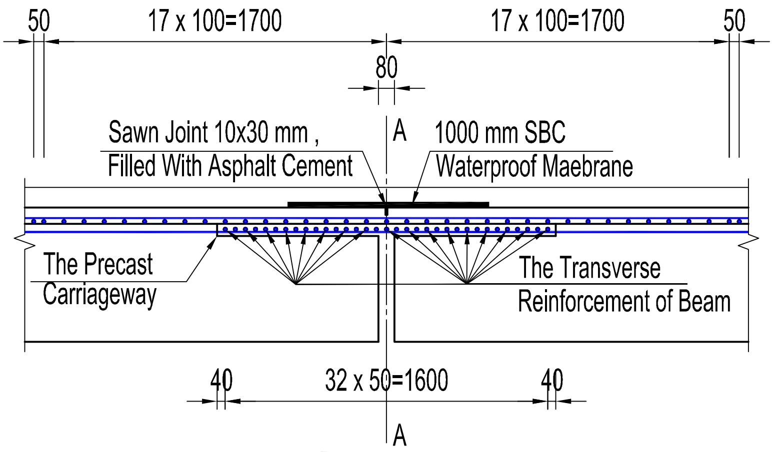
Fig. 5-85 Deck panels and topping slab. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.8.3.3 Details

5.8.3.3.1 Continuity



a) One-half transverse section



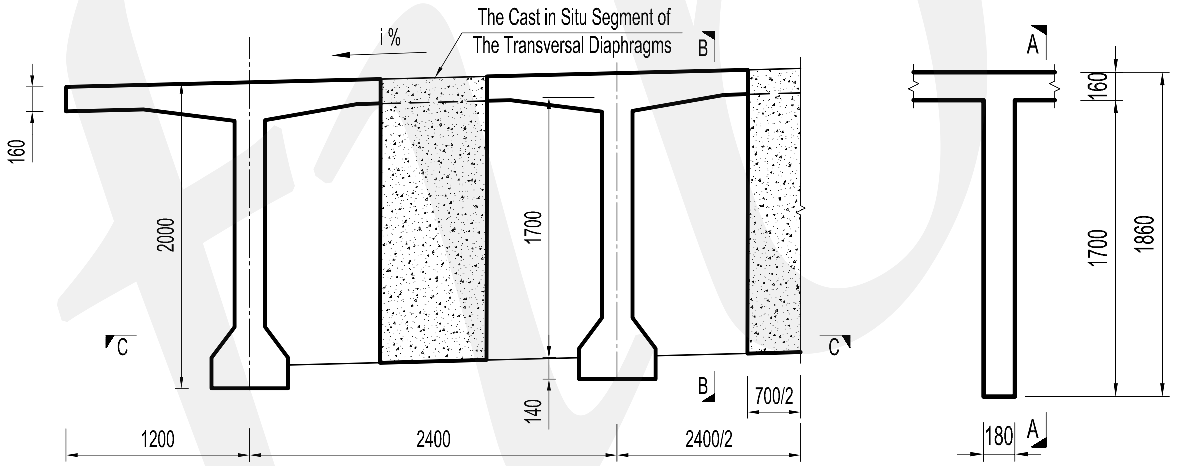
b) Partial longitudinal section at the pier showing link slab

Fig. 5-86 Continuity detail over the pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

This solution develops partial continuity with a link slab.

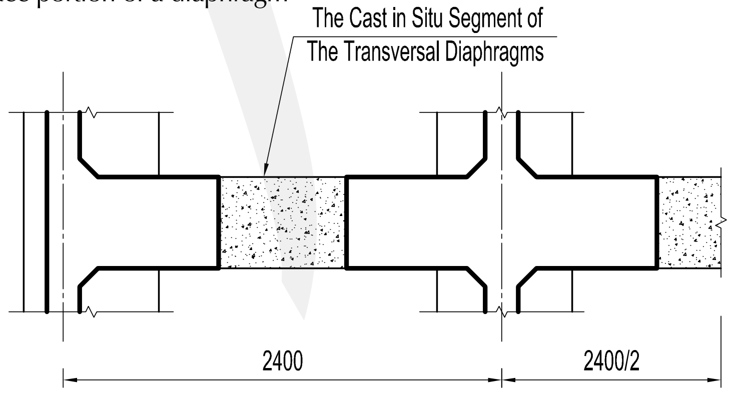
5.8.3.3.2 Transverse diaphragms.

This solution uses CIP reinforced concrete diaphragms over all supports as well as intermediate diaphragms at midspan and quarter points of the T girders.



a) One-quarter section A-A through a diaphragm, showing an exterior and one interior girder, the partial precast concrete diaphragms and cast-in-place portion of a diaphragm

b) Vertical section B-B through a precast concrete diaphragm



c) Section C-C looking down near the bottom of a diaphragm

Fig. 5-87 Diaphragm details. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.8.3.4 Summary of the preliminary design

Number of spans	5
Continuity	Partial with link slabs
Span length L, m	30
Girder depth G, mm	2'000
Slab depth H, mm	80
Total depth $D = G + H$, mm	2'080
Web width W, mm	240
Girder spacing S, m	2.4
Precast concrete girder weight, tonnes	76.5
L/D	14.42
L/G	15
Prestressing steel, kg/m^2	9.32

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.9 Example 9: bridge with four 40 m (131 ft) long spans in China

This example was furnished by Bao-Chun Chen.

This is a theoretical example developed with solutions commonly adopted in China.

5.9.1 Considerations

- Bridge layout: This example is a bridge with a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: This example uses the following codes: JTG B01-2003[5-9], JTG D60-2004[5-10], JTG D62-2004[5-11], JTJ041-2000[5-12], JTG D81-2006[5-13].

5.9.2 Proposed solution

This example has four spans, each with a length of 40 m (131 ft). The cross section of the superstructure consists of four precast concrete trapezoidal box girders with a depth of 2'000 mm (79 in.). There are two types of precast concrete girders, two interior and two exterior (edge) girders.

Reinforced concrete deck panels are placed on top of the girders and a topping slab is cast on the deck panels. The topping slab is 18 cm (7 in.) thick and the deck of the bridge has a 2% transverse slope.

The superstructure has reinforced concrete diaphragms over piers and abutments as well as an intermediate diaphragm at midspan.

The precast concrete girders are post-tensioned. The tendons have a parabolic profile.

5.9.2.1 Superstructure cross section

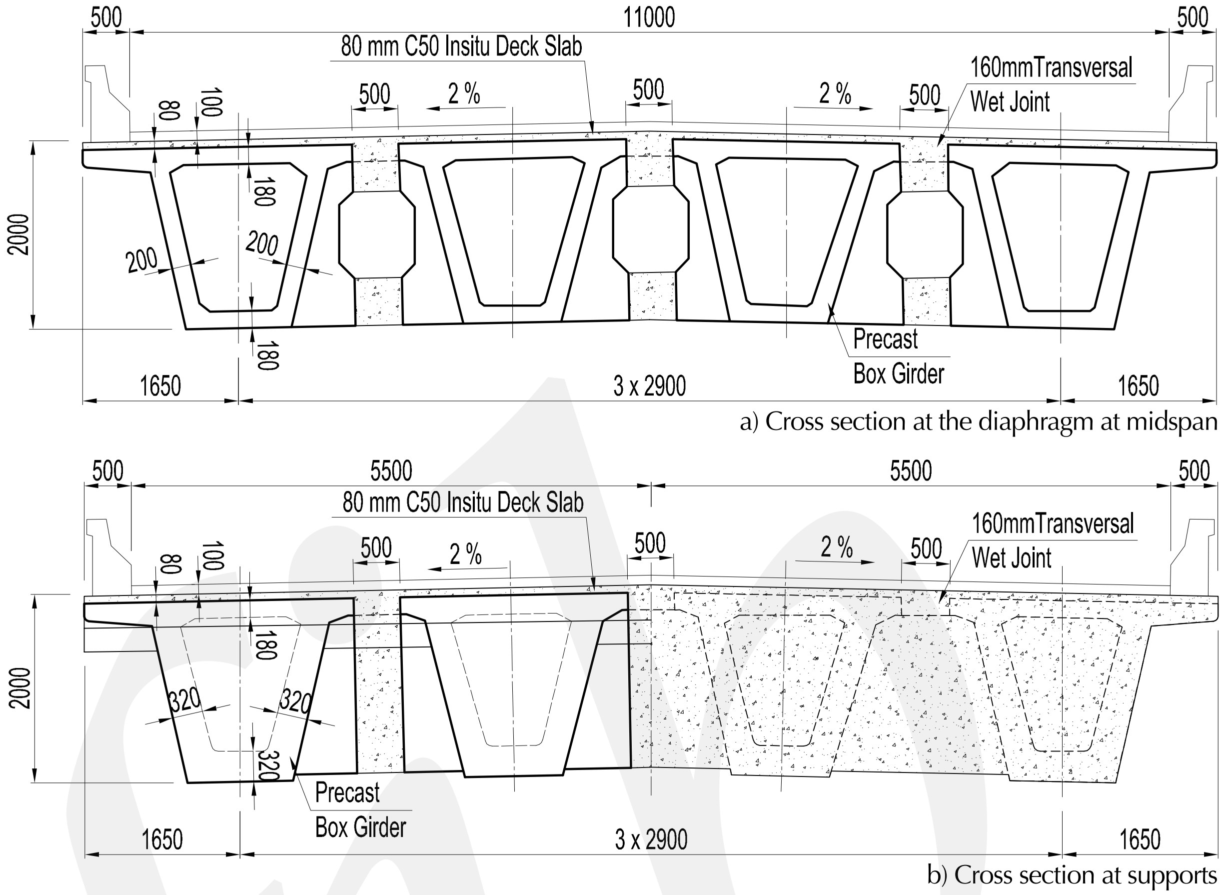


Fig. 5-88 Cross section of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.9.3 Superstructure

5.9.3.1 Precast concrete girders

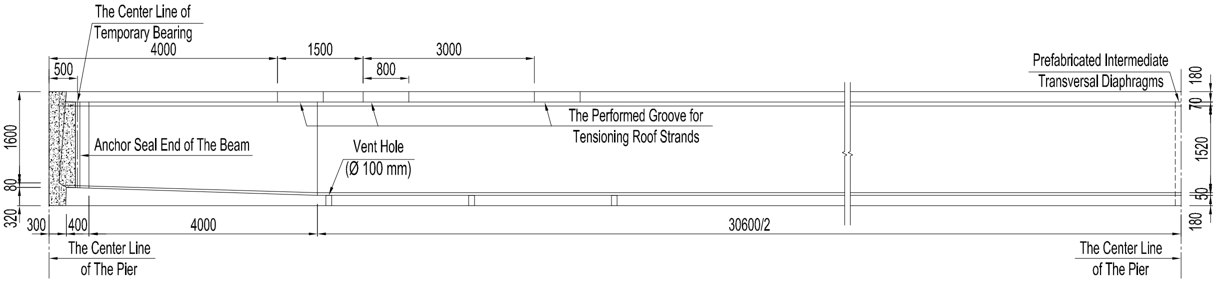
5.9.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	335 MPa (49 ksi)

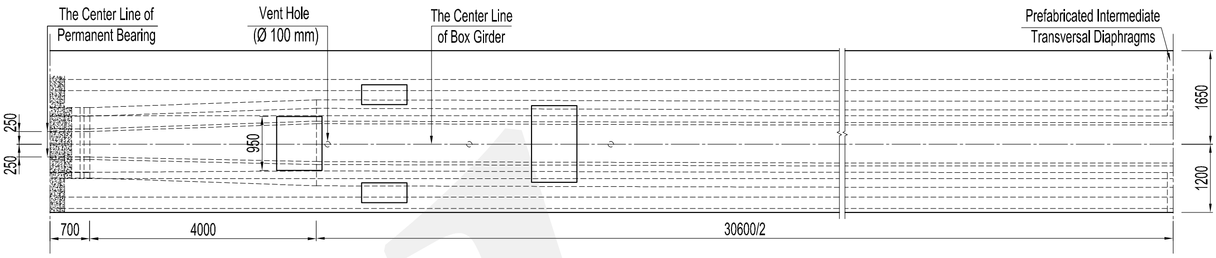
5.9.3.1.2 Description of the cross section

There are four trapezoidal box-girders, two interior girders and two exterior girders spaced at 2.9 m (9.5 ft) on center. The interior girders have symmetric top flanges, and the exterior girders have asymmetric top flanges to provide support for the deck overhangs.

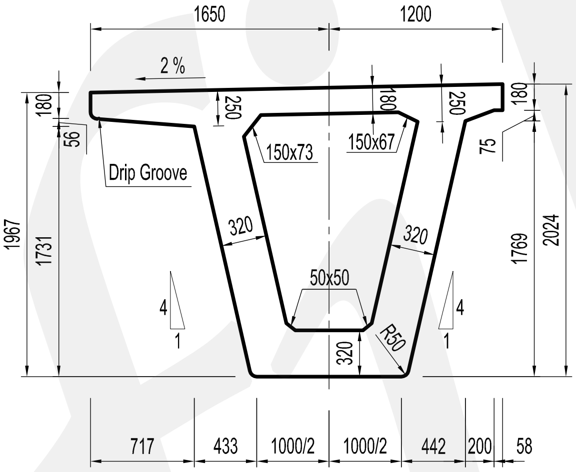
The cross section of the precast concrete girders varies along the length of the bridge, with thicker webs at the supports.



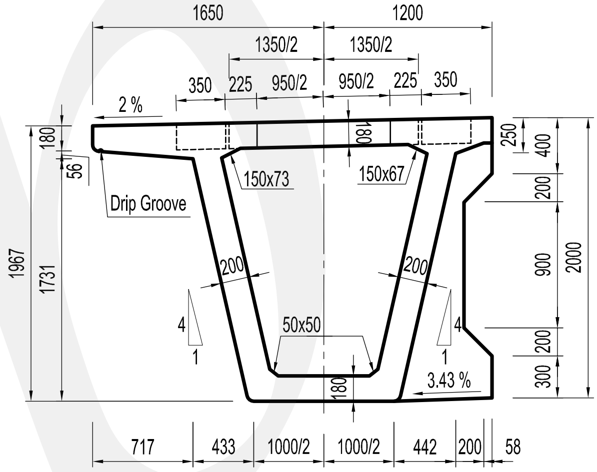
a) Elevation of an interior girder



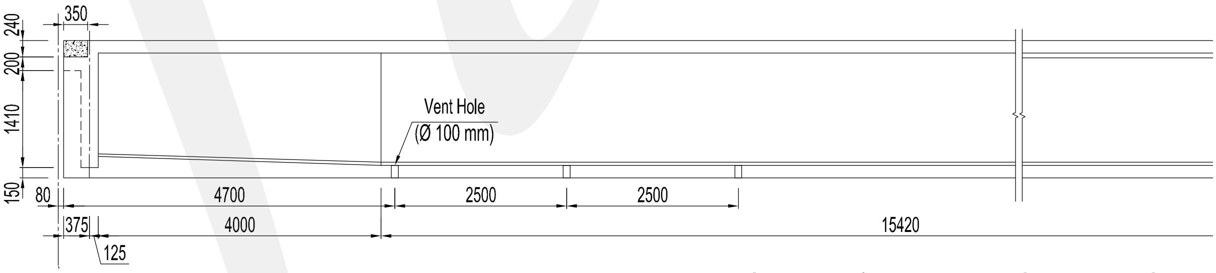
b) Plan of an interior girder in an interior span



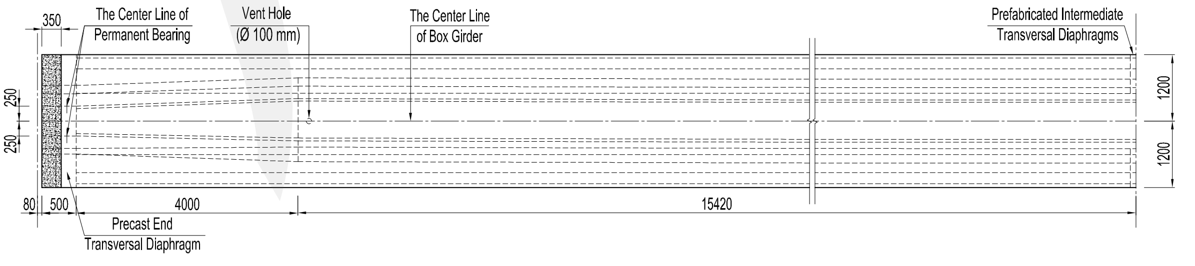
c) Section B-B of an exterior girder from an interior span



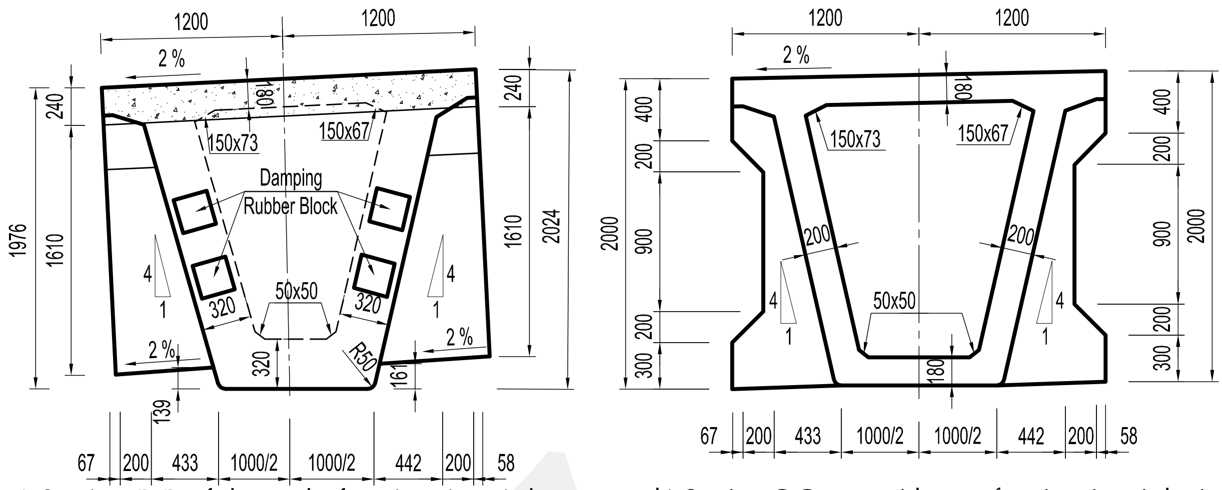
d) Section C-C of an exterior girder from an interior span



e) Elevation of an interior girder in an end span



f) Plan of an interior girder in an end span



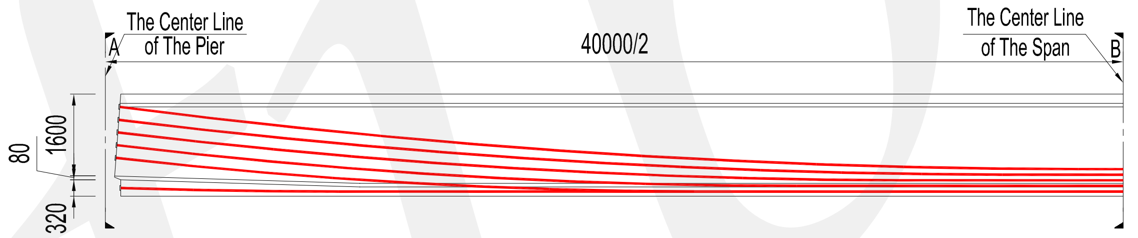
g) Section B-B of the end of an interior girder in an end span

h) Section C-C near midspan of an interior girder in an end span

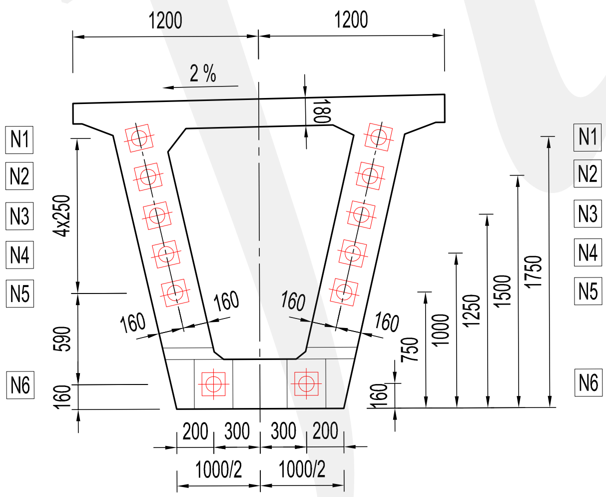
Fig. 5-89 Details and dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.9.3.1.3 *Prestressing*

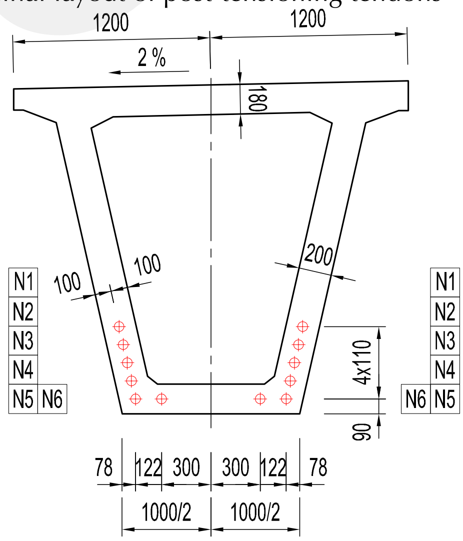
The precast concrete girders are post-tensioned. The longitudinal prestressing consists of 12 draped parabolic tendons in each precast concrete element as seen in Fig. 5-90 and 5-91. These figures also show the reinforcement in the precast concrete girder.



a) Longitudinal layout of post-tensioning tendons



b) Section A-A showing tendon anchorage locations



c) Section B-B showing tendon locations at midspan

Fig. 5-90 Post-tensioning locations in precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

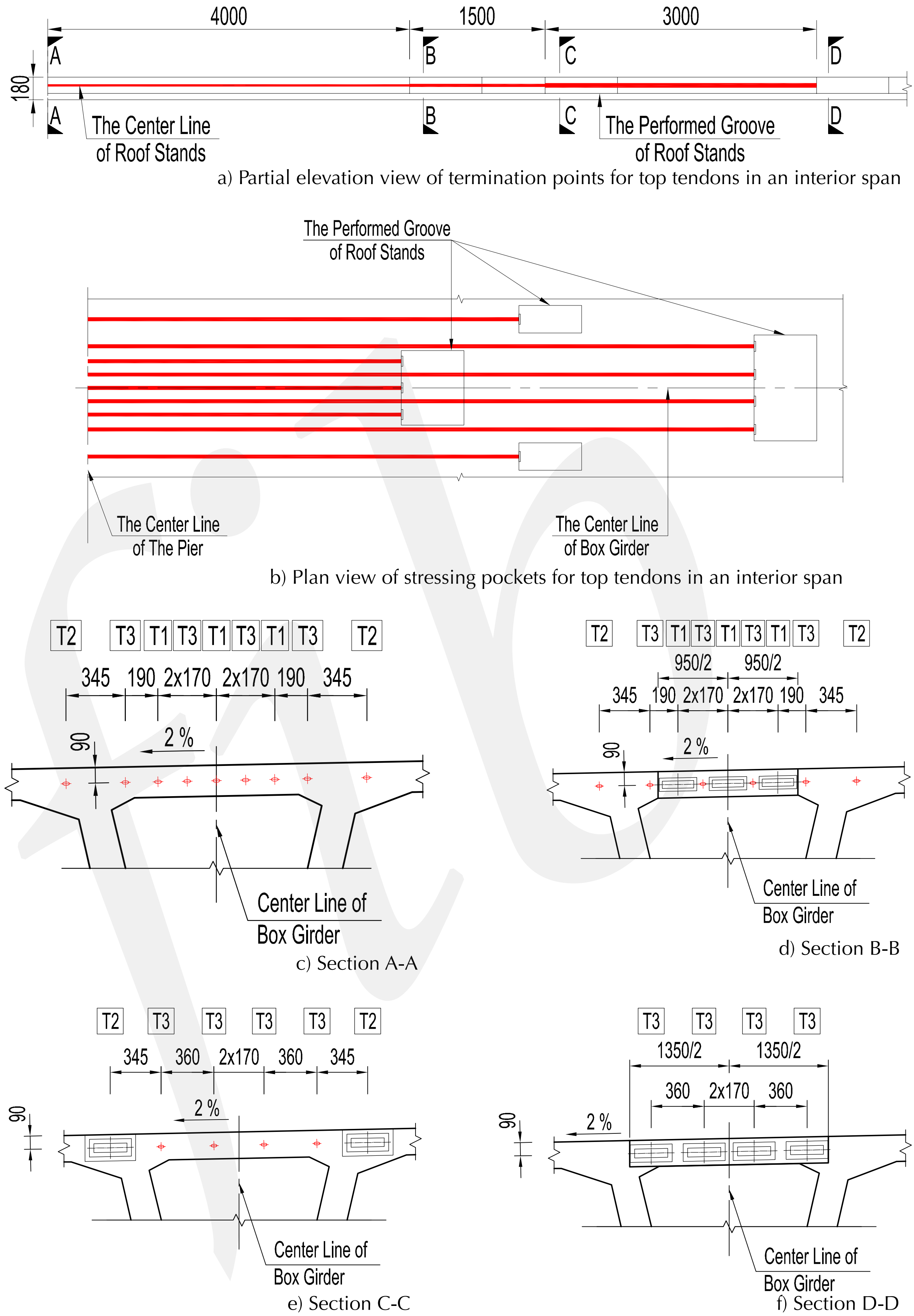


Fig. 5-91 Top tendon locations in the flange of an interior girder. Note: All dimensions are in millimeters.
1 mm = 0.0394 in

5.9.3.2 Deck slab

5.9.3.2.1 Materials

Concrete: 50 MPa (7 ksi)

Mild reinforcing steel: 335 MPa (49 ksi)

5.9.3.2.2 Deck slab description

Slab with a thickness of 18 cm (7 in.) and cast on top of deck panels placed on the girders with the reinforcement shown in Fig. 5-92 and 5-93.

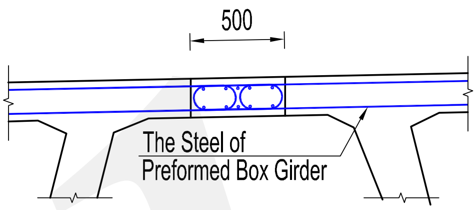


Fig. 5-92 Reinforcement in the area formed between girder flanges. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

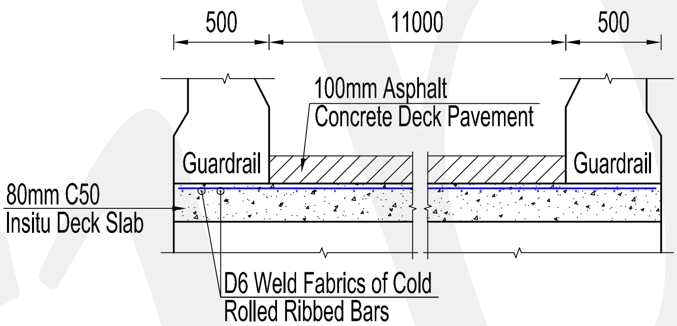
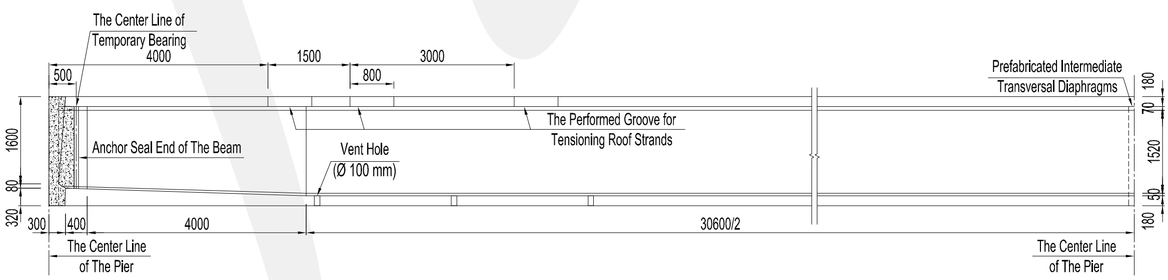


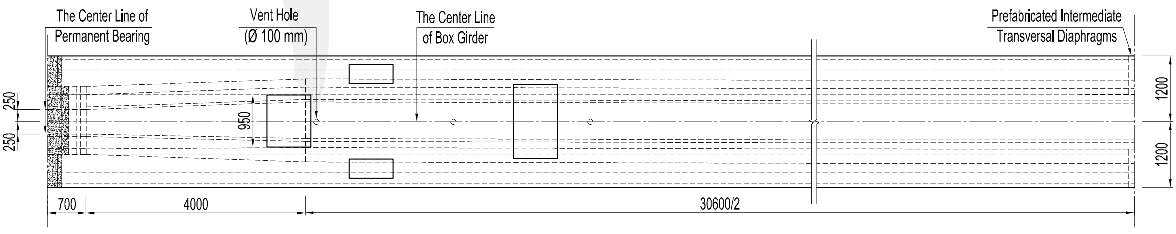
Fig. 5-93 Elevation of cast-in-place slab. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.9.3.3 Details

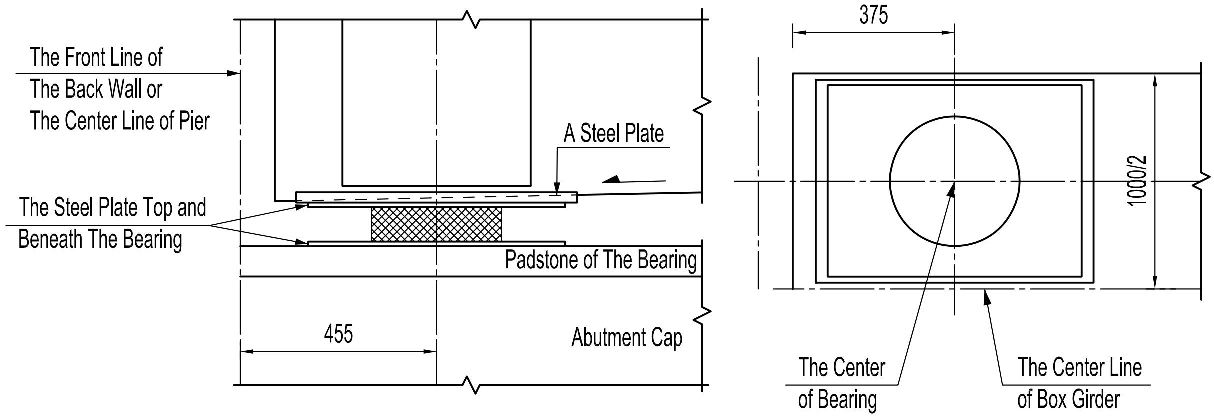
5.9.3.3.1 Bearings



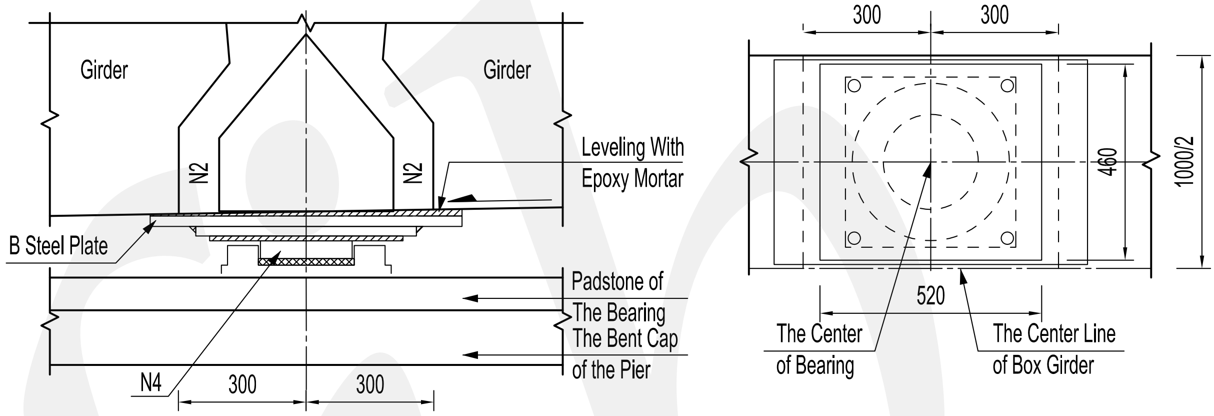
a) Bearing locations for an interior girder of an interior span



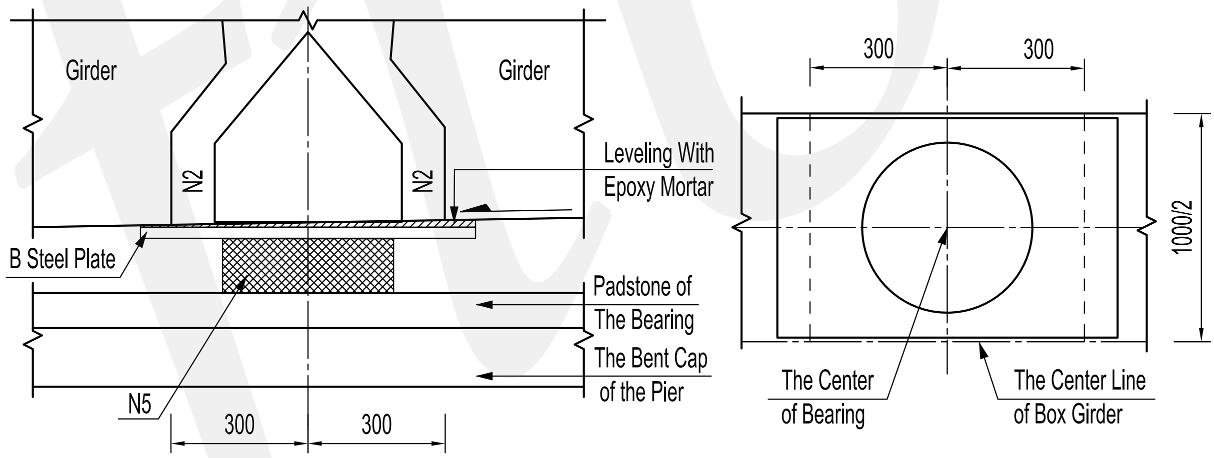
b) Plan details for an interior girder of an interior span



c) Sliding bearing at the end support



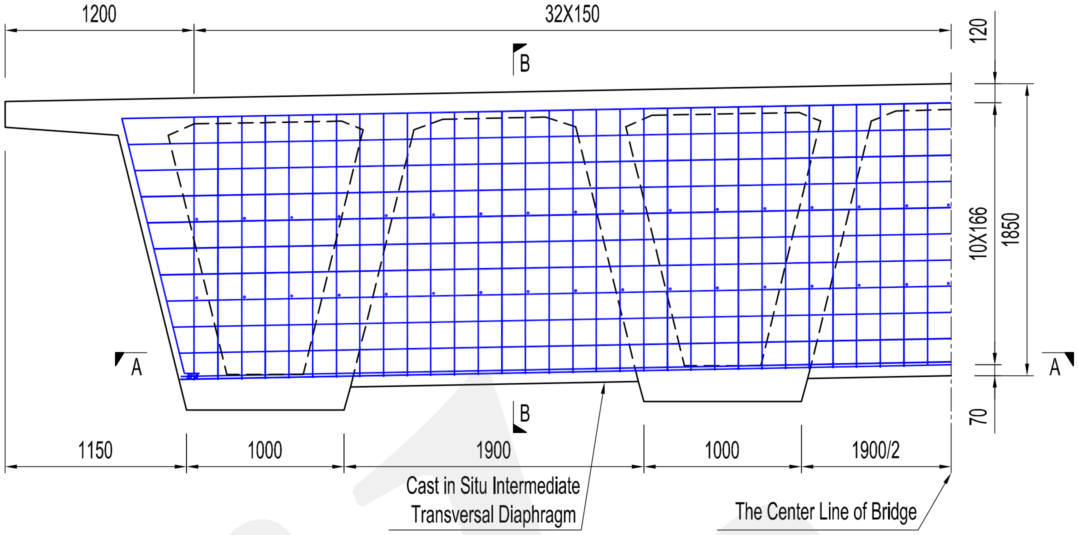
d) Sliding bearing at an interior support



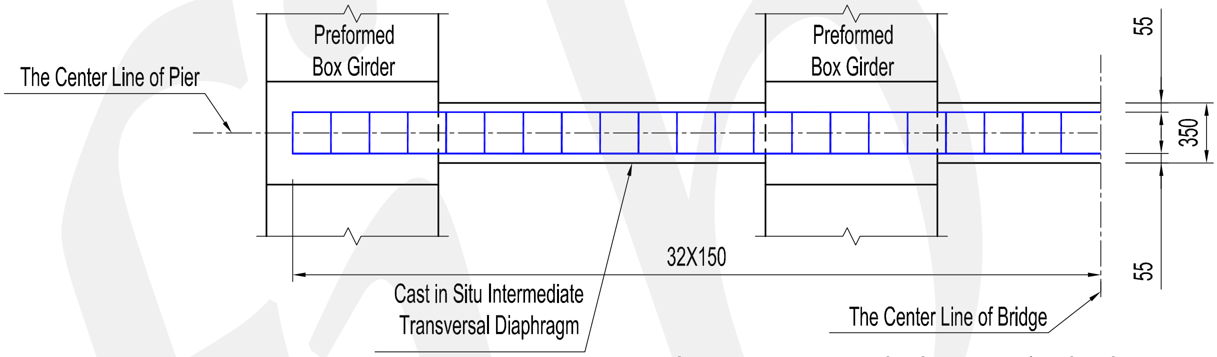
e) Fixed bearing at the interior fulcrum

Fig. 5-94 Details of the bearings of the bridge.Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

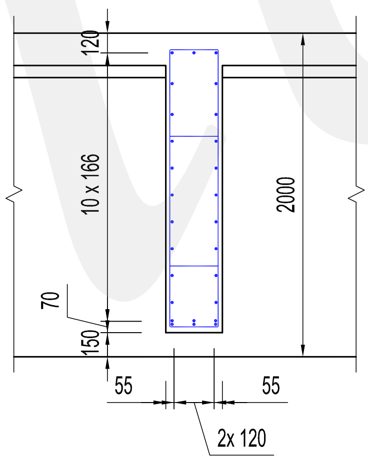
5.9.3.3.2 *Continuity detail over piers*



a) Elevation of a diaphragm at a pier



b) Section A-A at the bottom of a diaphragm



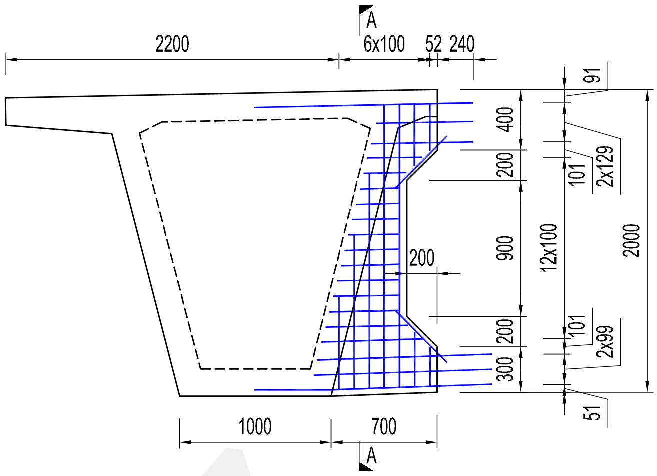
c) Section B-B through a diaphragm between girders

Fig. 5-95 Continuity details over the pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

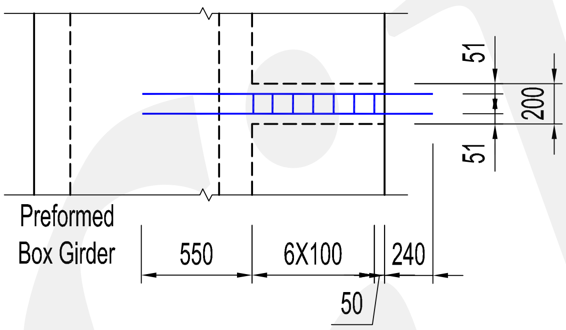
This solution provides full structural continuity.

5.9.3.3.3 *Transverse diaphragms*

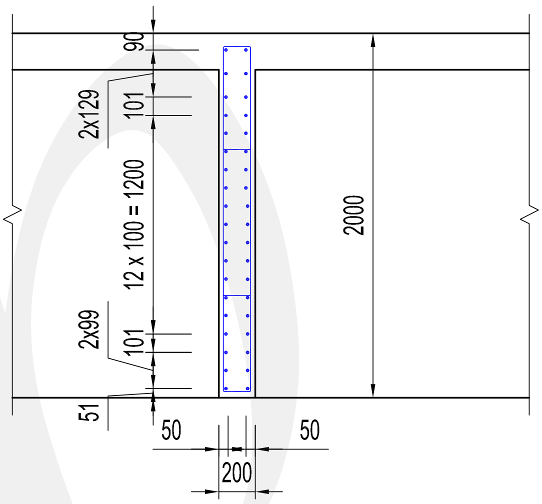
This solution uses reinforced concrete diaphragms over the supports as well as an intermediate diaphragm at midspan.



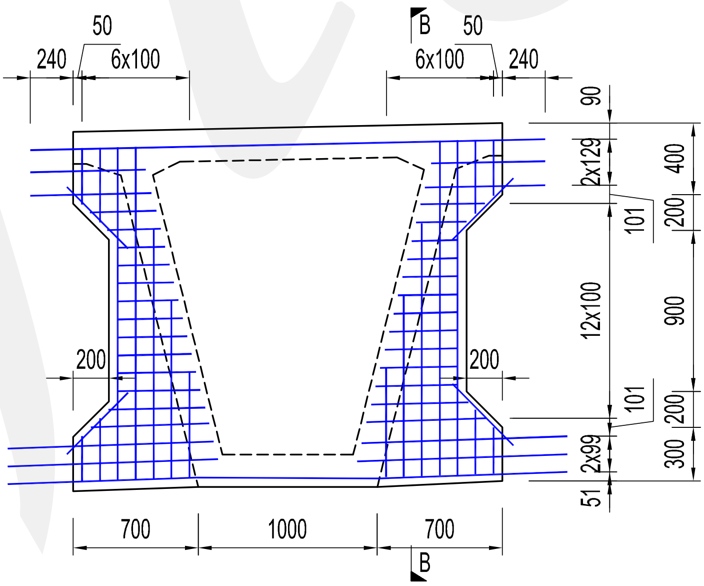
a) Section of a midspan intermediate precast concrete diaphragm of an exterior girder



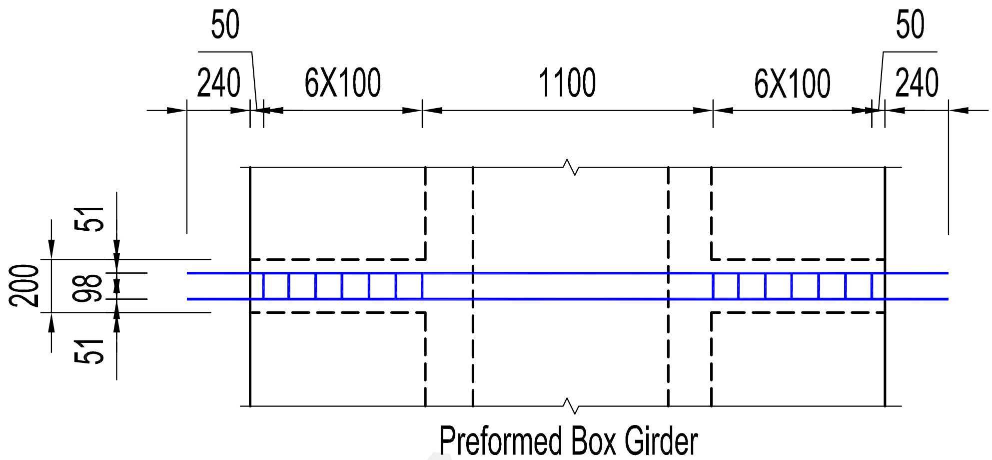
b) Plan of a midspan precast concrete diaphragm of an exterior girder



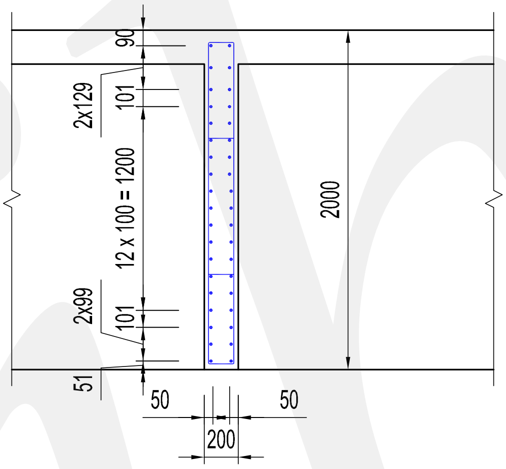
c) Section A-A of the midspan diaphragm of an exterior girder



d) Elevation of the reinforcement in the precast concrete portion of a midspan diaphragm of an interior girder

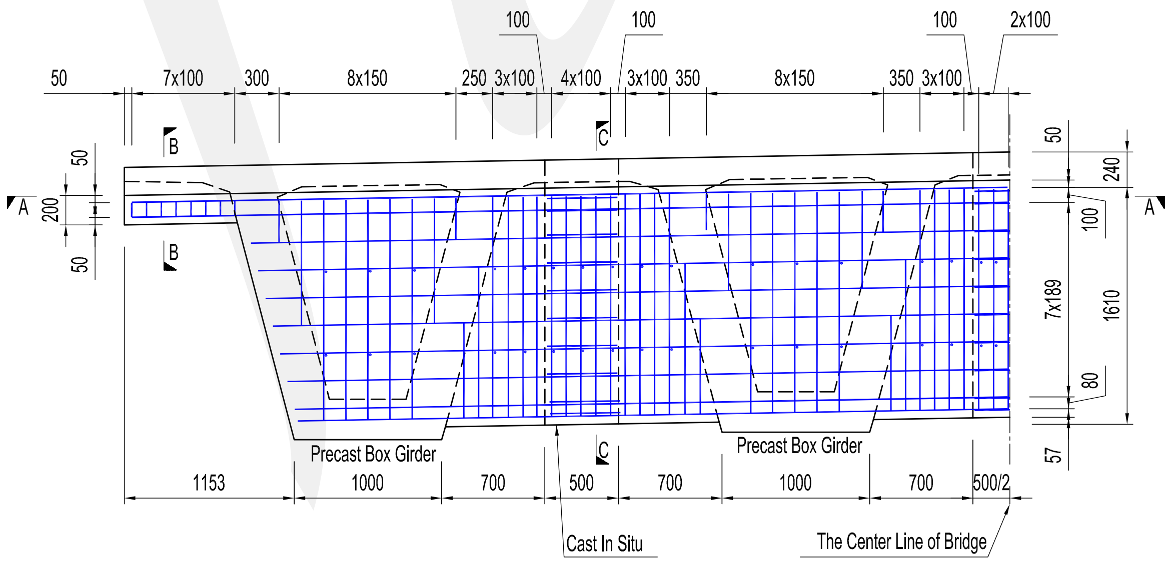


e) Plan of reinforcement in a midspan precast concrete diaphragm in an interior girder

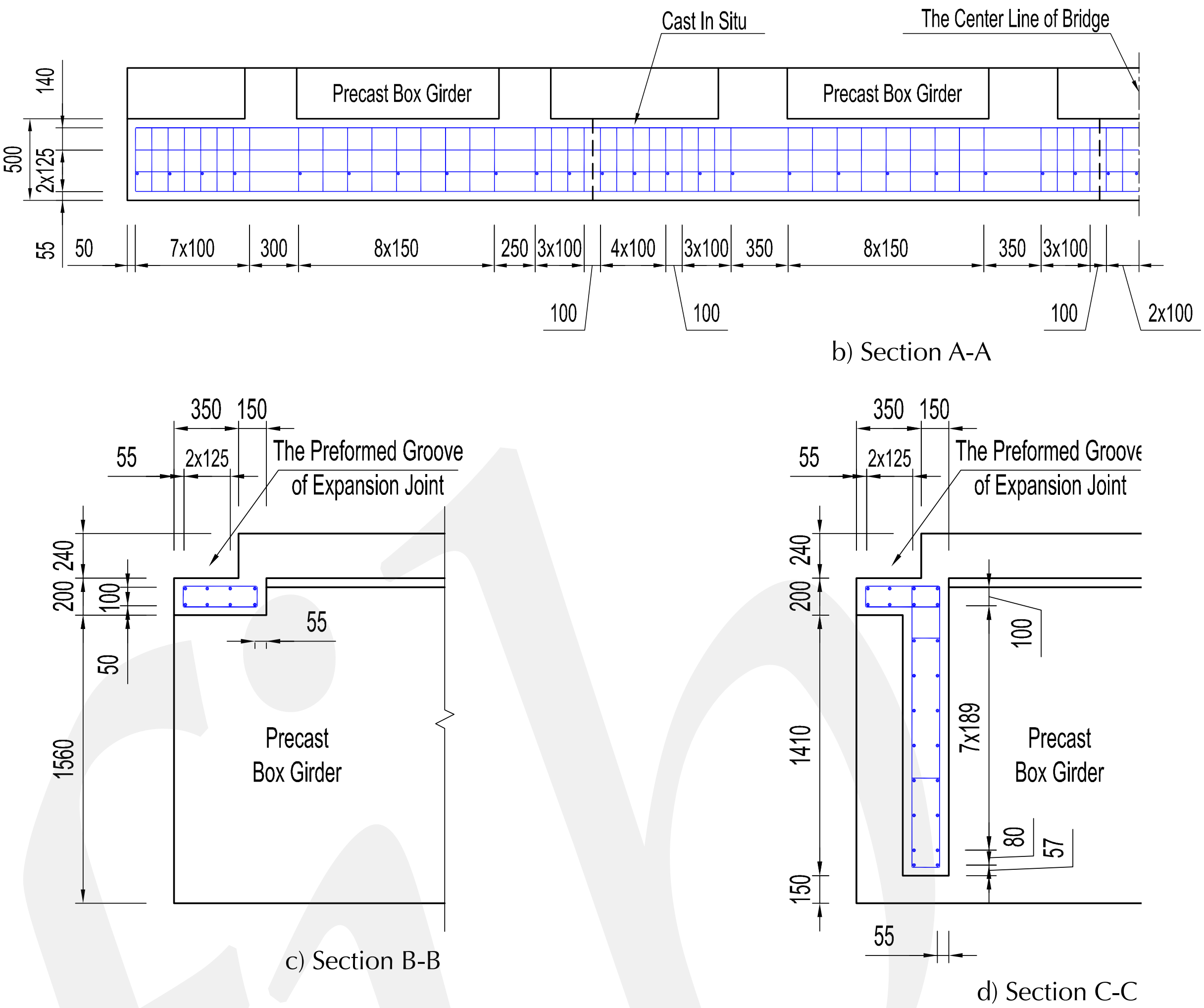


f) Section A-A showing reinforcement in the precast concrete portion of a midspan diaphragm in an interior girder

Fig. 5-96 Details of intermediate diaphragms. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.



a) Elevation of an end diaphragm



b) Section A-A

c) Section B-B

d) Section C-C

Fig. 5-97 End diaphragm details. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.9.3.4 Summary of the preliminary design

Number of spans	4
Continuity	Full structural continuity
Span length *L*, m	40
Girder depth *G*, mm	2'000
Slab depth *H*, mm	180
Total depth $D = G + H$, mm	2'180
Web width *W*, mm	200
Girder spacing *S*, m	2.9
Precast concrete girder weight, tonnes	153.1
L/D	13.76
L/G	15
Prestressing steel, kg/m^2	9.32

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.10 Example 10: Bridge with Six 25 m (82 ft) long spans in France

This example was furnished by André de Chefdebien.

This example is inspired by an actual bridge with similar considerations that resulted in 2 × 3 spans of 22 m (72 ft).

5.10.1 Considerations identified

- Bridge layout: This example is a bridge with a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: Loads according to EN 1990[5-4] and EN 1991-2[5-2] and design according to EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Aesthetics: A combination of a shallow superstructure with slender piers is required to minimize the visual impact of the bridge.
- Environmental factors: Piers are not permitted in the water of a 22 m (72 ft) wide river.
- Sustainability factors: Corrosion induced by carbonation and relative humidity of 70%.
- Maintenance: To reduce maintenance costs, the number of bearings must be minimized.
- Safety: The bridge is an overpass on a regional road with heavy traffic.

5.10.2 Proposed solution

The aesthetic and environmental considerations droved the choice for equal spans with 1/20 slenderness ratio.

To reduce the visual mass at the top of the pier, girders are supported by a recessed pier cap between the ends of the girders. The girders are made continuous for superimposed dead load and live load by mean of this CIP connection. The continuity also allows a wider beam spacing.

Soft soil conditions do not permit shoring, so temporary supports are fixed to the piers.

The concrete diaphragms cast over the piers and abutments are mildly reinforced. No intermediate diaphragms are used at midspan.

Fig. 5-98 Example of temporary support fastened to the pier.

The top flanges of the girders are placed adjacent to each other (side by side). Once the beams are erected on the temporary support and stabilized by struts or temporary transverse rods, the safety of workers is greatly improved. This is important especially when the deck is over a heavily used road during construction.

The transverse pier beam atop the temporary supports is precast, providing for more rapid construction. When joined compositely with the diaphragm concrete, fewer bearing pads than the total number of beams are required, which reduces maintenance costs.

The choice of six 25 m (82 ft) spans limits the transportation and erection costs. The deck cross section consists of 12 precast concrete bulb-tee girders with a depth of 1000 mm (39 in.), a top flange width of 1'230 mm (48 in.), and a CIP deck slab thickness of 250 mm (10 in.).

A 2% transverse slope is necessary to deal with runoff. It is achieved by positioning the bearings of the girders with the slope (using a precast concrete supporting beam with the slope included or with a stepped top surface).

Fig. 5-99 Example of a precast concrete soffit beam with transverse slope.

To minimize the work required on-site, there is no intermediate diaphragm at midspan. Intermediate diaphragms are very unusual for these kinds of decks despite the advantages provided.

The precast concrete girders are pretensioned. Prestressing uses straight strands in the bottom flanges of the bulb-tee girders. Partial debonding is achieved with plastic tubes on some strands near the beam ends.

This solution provides full continuity over the piers.

5.10.2.1 Plan

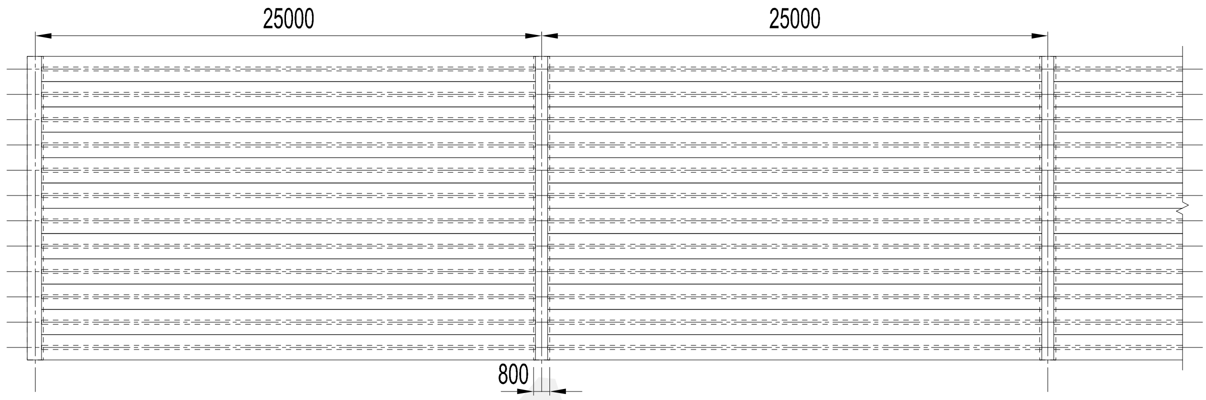


Fig. 5-100 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.10.2.2 Elevation

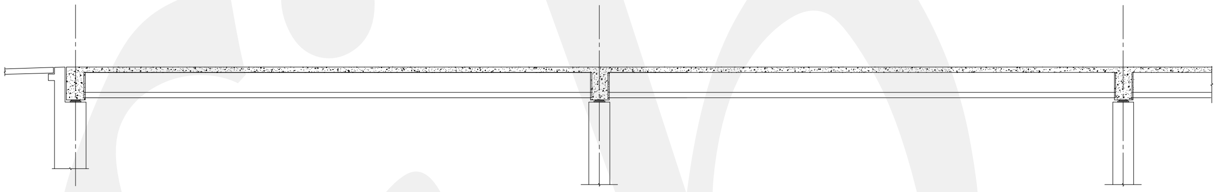


Fig. 5-101 Elevation of the bridge.

5.10.2.3 Superstructure cross section

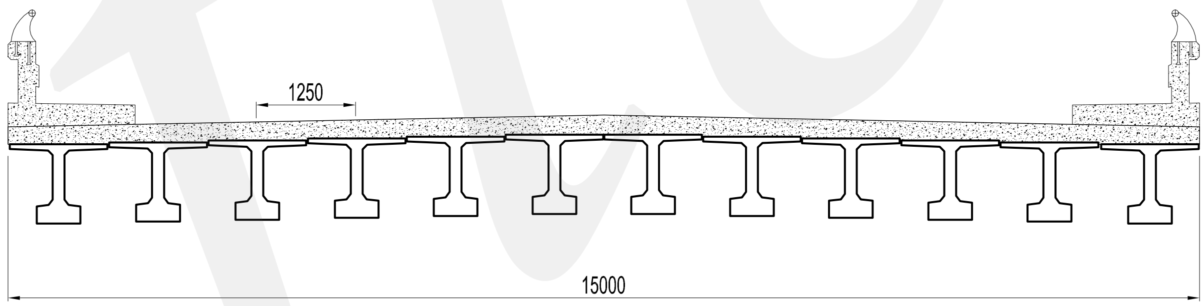


Fig. 5-102 Cross section near midspan.Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

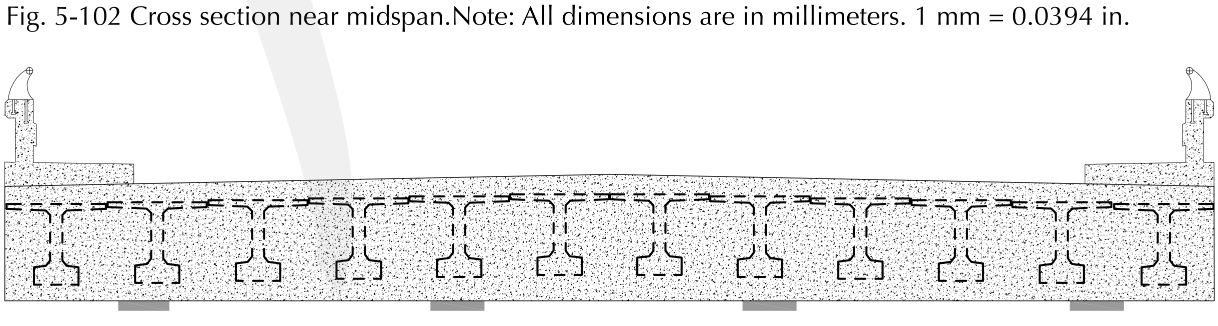


Fig. 5-103 Cross section through a pier cap diaphragm.

5.10.3 Superstructure

5.10.3.1 Precast concrete girders

5.10.3.1.1 Materials

Concrete:	60 MPa (9 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.10.3.1.2 Description of the cross section

Twelve deck bulb-tee girders, 1000 mm (39.37 in.) deep, placed adjacent to each other (side by side).

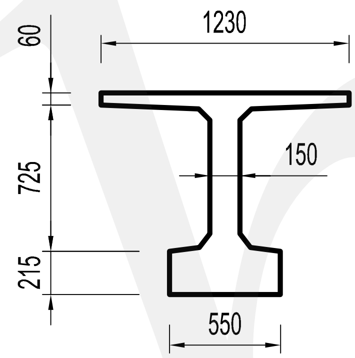


Fig. 5-104 Cross-section dimensions of deck bulb-tee girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.10.3.1.3 Prestressing

Each precast concrete girder is pretensioned with a total of 18 straight strands with 15.7 mm (0.6 in.) diameter – 150 mm2 (0.2 in.2). Fifty percent of the strands are debonded at the ends of the girders to reduce the top tensile stresses at release and to reduce long-term redistribution sagging moment due to creep under the prestress forces. Asymmetric debonding is used for the first and end span to fit with prestress demand.

5.10.3.2 Deck slab

5.10.3.2.1 Materials

Concrete:	35 MPa (5 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.10.3.2.2 Deck slab description

A 25 cm (10 in.) thick slab is cast directly on top of the girder flanges.

The CIP slab is considered composite with the precast concrete girder in the longitudinal direction. In the transverse direction, the top flange of the girder does not resist the transverse bending moment.

5.10.3.3 Details

5.10.3.3.1 Bearings

The precast concrete pier soffit beam is supported on four steel-reinforced neoprene pads. The elevation of the pad is adjusted by reinforced concrete blocks glued on the piers and abutments. The longitudinal alignment (for example, 3%) is maintained by sloping the precast concrete girders. The bearing pads and the soffit of the crossbeam remain horizontal.

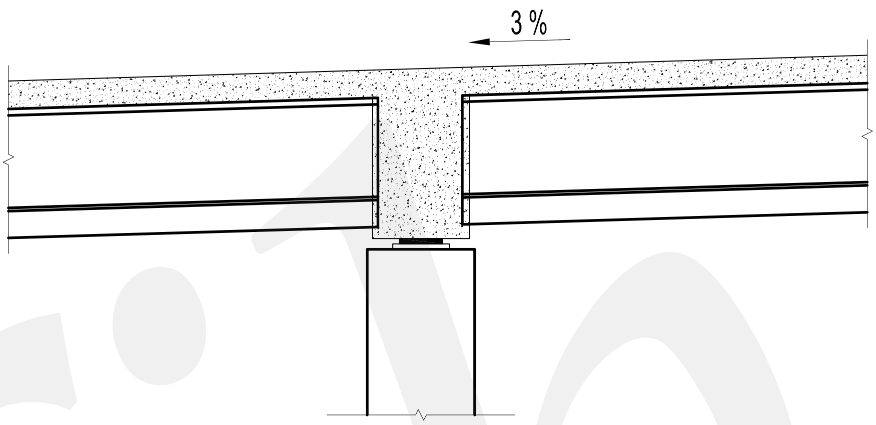


Fig. 5-105 Detail of the vertical alignment of the bridge.

5.10.3.3.2 Continuity

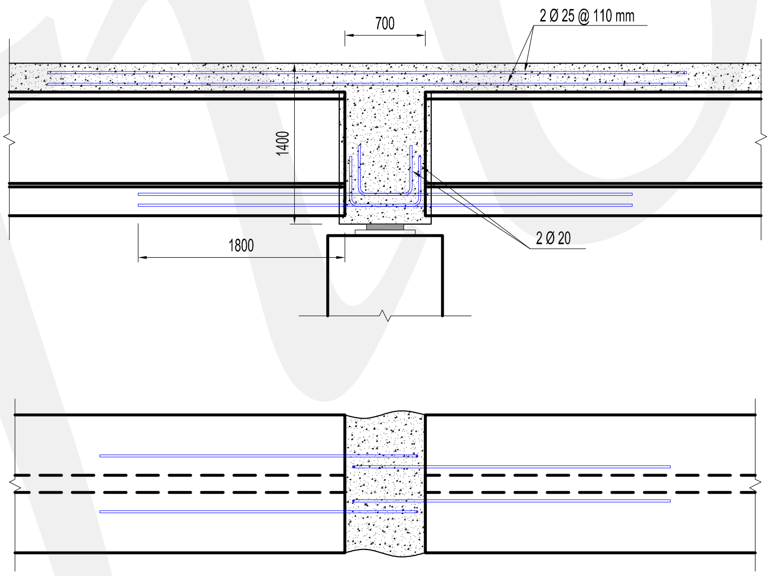


Fig. 5-106 Continuity top and bottom reinforcement in a cast-in-place pier cap and diaphragm. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The deck is considered fully continuous after casting the top slab and pier beams. The precast concrete girders are shorter than the span length to allow casting the 0.7 m (2.3 ft) wide recessed pier beam. Reinforcement extending from the bottom of the girders is required to resist sagging moments at supports and approximates end struts, while negative moments are resisted by longitudinal reinforcing bars embedded in the CIP slab.

Fig. 5-107 Example of bottom positive moment continuity reinforcement in a bridge girder.

5.10.3.3.3 Transverse slopes

Transverse slopes can be achieved by positioning the precast concrete girders on a transverse pier beam with stepped bearings.

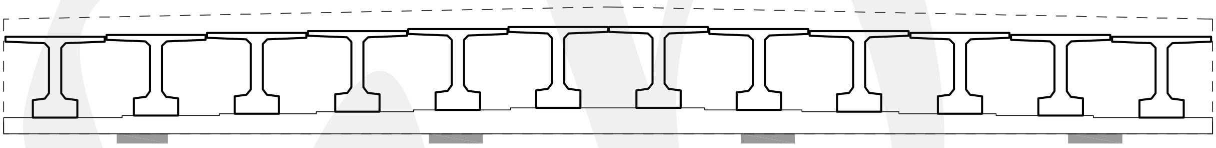


Fig. 5-108 Bridge superstructure with 2% transverse slopes.

5.10.3.3.4 Transverse diaphragms

This example assumes diaphragms over the supports. The diaphragms are reinforced concrete elements without post-tensioning. They have a width of 700 mm (28 in.) and a total height of 1'400 mm (55 in.) after becoming composite with the precast concrete soffit beams.

5.10.3.4 Summary of the main information

Number of spans	6
Continuity	Full structural continuity
Span length *L*, m	25
Girder depth *G*, mm	1'000
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	1'250
Web width *W*, mm	150
Girder spacing *S*, m	1.25
Precast concrete girder weight, tonnes	19.3
L/D	20
L/G	25
Average depth, mm	518
Prestressing steel, kg/m²	16.8
Reinforcing steel – girder, kg/m²	36.2
Reinforcing steel – top slab, kg/m²	220
Reinforcing steel in a diaphragm, kg	3'000

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m² = 0.2048 lb/ft²; 1 tonne = 1.102 tons.

5.10.4 Construction sequence

- The girders, weighing 20.5 tonnes (22.5 tons), can be transported by truck, two at a time.
- The precast concrete transverse soffit beam is placed atop the pier and stabilized by mechanical devices.
- The girders are positioned on the precast concrete soffit beam and braced at the top.
- Longitudinal and transverse slab reinforcement, as well as diaphragm reinforcement, is placed.
- The deck slab and pier beam/diaphragm are cast.
- After the CIP concrete has reached its design strength, mechanical devices under the pier beams allow transfer to the final bearings.

Fig. 5-109 Transverse precast concrete soffit beam and mechanical supports.

5.11 Example 11: bridge with five 30 m (98 ft) long spans in Italy

This example was furnished by Mario Petrangeli.

This proposed cross section has been recently adopted for the construction of the following Italian viaducts:

- Rome, Italy: five new viaducts, most of which are 268 m (879 ft) long, along the new carriageways of the A24 urban highway, between the Lunghezza and Palmiro-Togliatti junctions.
- Teramo, Italy: St. Antonio Viaduct (2'400 m [7'874 ft] long) and Vomano Viaduct, along the A24 Highway between L'Aquila and Teramo.

Fig. 5-110 St. Antonio Viaduct in Teramo.

Fig. 5-111 Vomamo Viaduct in Teramo.

5.11.1 Considerations identified

- Bridge layout: This example considers a bridge with a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: Loads according to EN 1990[5-4] and EN 1991-2[5-2] and design according to EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Construction and functional factors: It is desired to establish continuity of the deck for the entire length of the viaduct.
- Maintenance: Low maintenance costs for expansion joints.
- Economy: Low construction costs for the deck.

5.11.2 Proposed solution

This solution has five spans, each 30 m (98 ft) long. The superstructure comprises two or three precast concrete U girders (depending on width), 1600 mm (63 in.) deep, with wide flanges. The girders are placed side by side to eliminate the need for deck forms. Precast concrete deck panels are placed to close the tops of the girders.

The CIP deck slab is 25 cm (10 in.) thick with a 2.5% transverse slope. The transverse slope is obtained by placing the girders at different elevations and inclined at the slope. Therefore, the single inclined surface of the deck slab has a constant thickness.

Due to the torsional stiffness of the box girders no intermediate diaphragms are required.

This solution provides partial continuity over the piers with link slabs and the superstructure can accommodate unexpected vertical settlements of the foundations.

The design can also be efficiently adapted for span lengths up to 38 m (125 ft), using girders 2'000 mm (79 in.) deep.

Full continuity may be achieved by introducing CIP segments at piers and "external" two-stage post-tensioning tendons. This solution has been used for the new "Quattro Querce" Viaduct along highway A3 Salerno-Reggio Calabria (see Fig. 5-112 below and for five viaducts along the SS675 Highway Rieti-Orte-Viterbo–Civitavecchia.

Fig. 5-112 Example of full continuity in the "Quattro Querce" Viaduct .

5.11.2.1 Plan

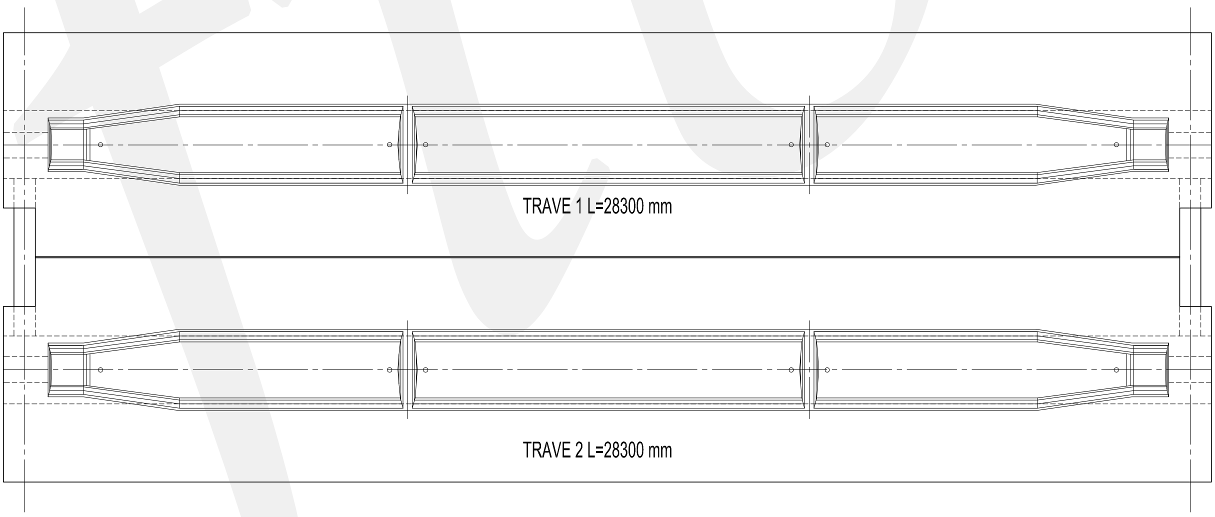


Fig. 5-113 Plan of an 11.25 m (37 ft) wide bridge with two girders. Note: 1 mm = 0.0394 in.

5.11.2.2 Elevation

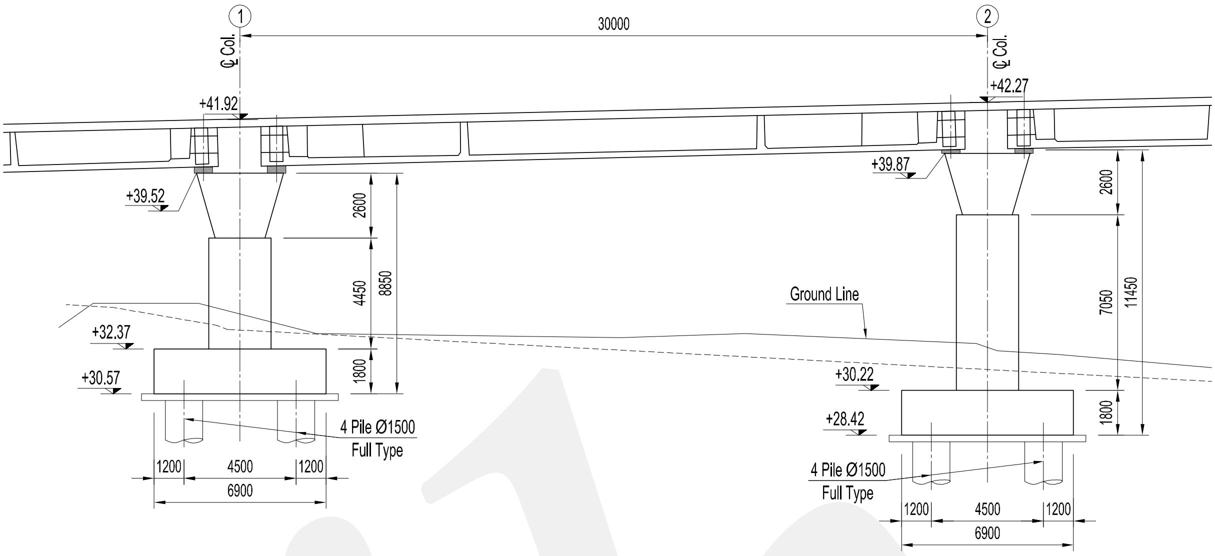
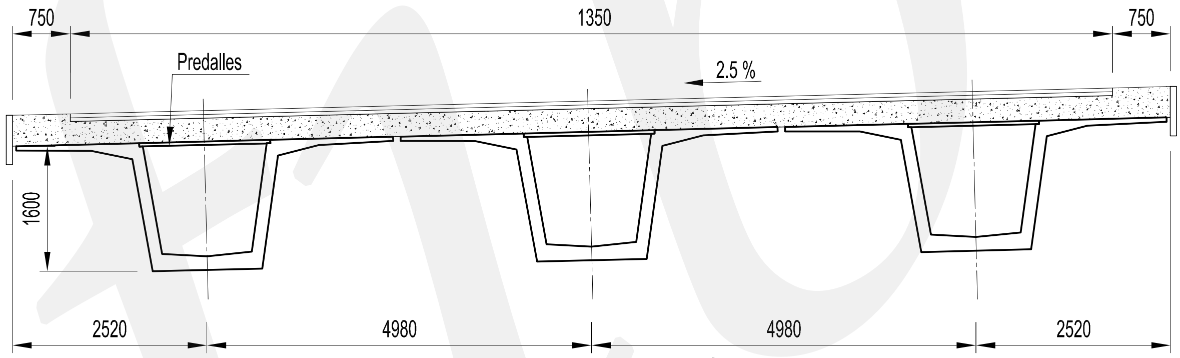
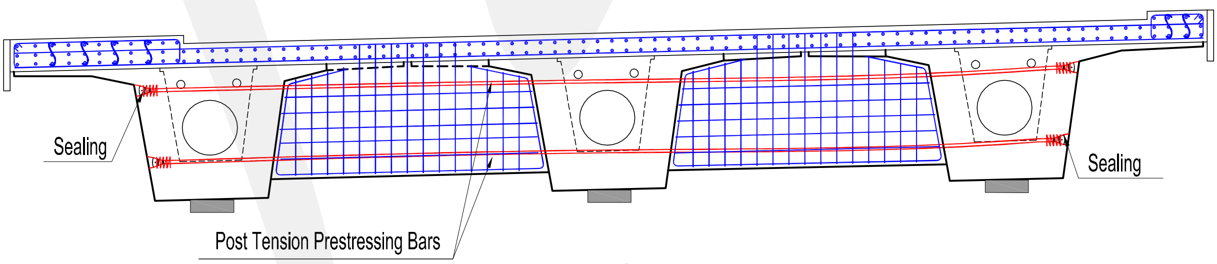


Fig. 5-114 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.11.2.3 Superstructure cross section



a) Typical cross section



b) Cross section over piers

Fig. 5-115 Cross section of a bridge 15.00 m wide with three girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.11.3 Superstructure

5.11.3.1 Precast concrete girders

5.11.3.1.1 Materials

Precast concrete girders:	45 MPa (7 ksi)
CIP diaphragms:	32 MPa (5 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Post-tensioning bars:	1'030 MPa (149 ksi)

5.11.3.1.2 Description of the cross section

The cross section consists of two or more U girders, depending on the width, with wide top flanges, placed side by side. The width of the girder can be varied from a minimum of 2.7 m (8.9 ft) up to a maximum of 5.61 m (18.41 ft) to accommodate several deck configurations.

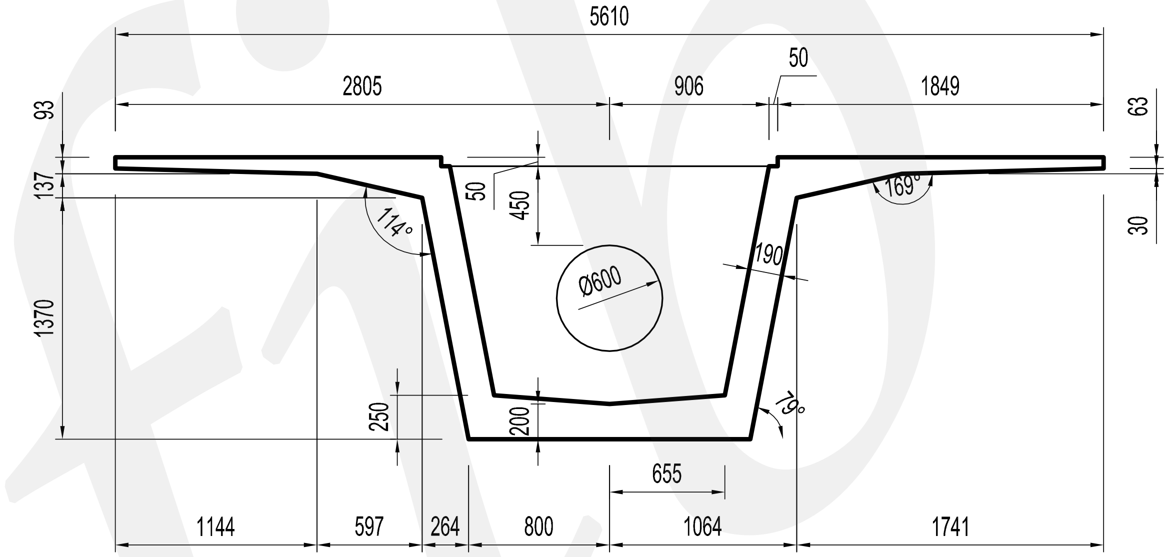


Fig. 5-116 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.11.3.1.3 Prestressing

The precast concrete girders are pretensioned. In this structure there is a total of 82 straight strands.

At the ends of the girder, for a length of 1.6 to 2.6 m (5.2 to 8.5 ft), some of the strands are unbonded using sheaths. This allows bending moment reduction at support sections.

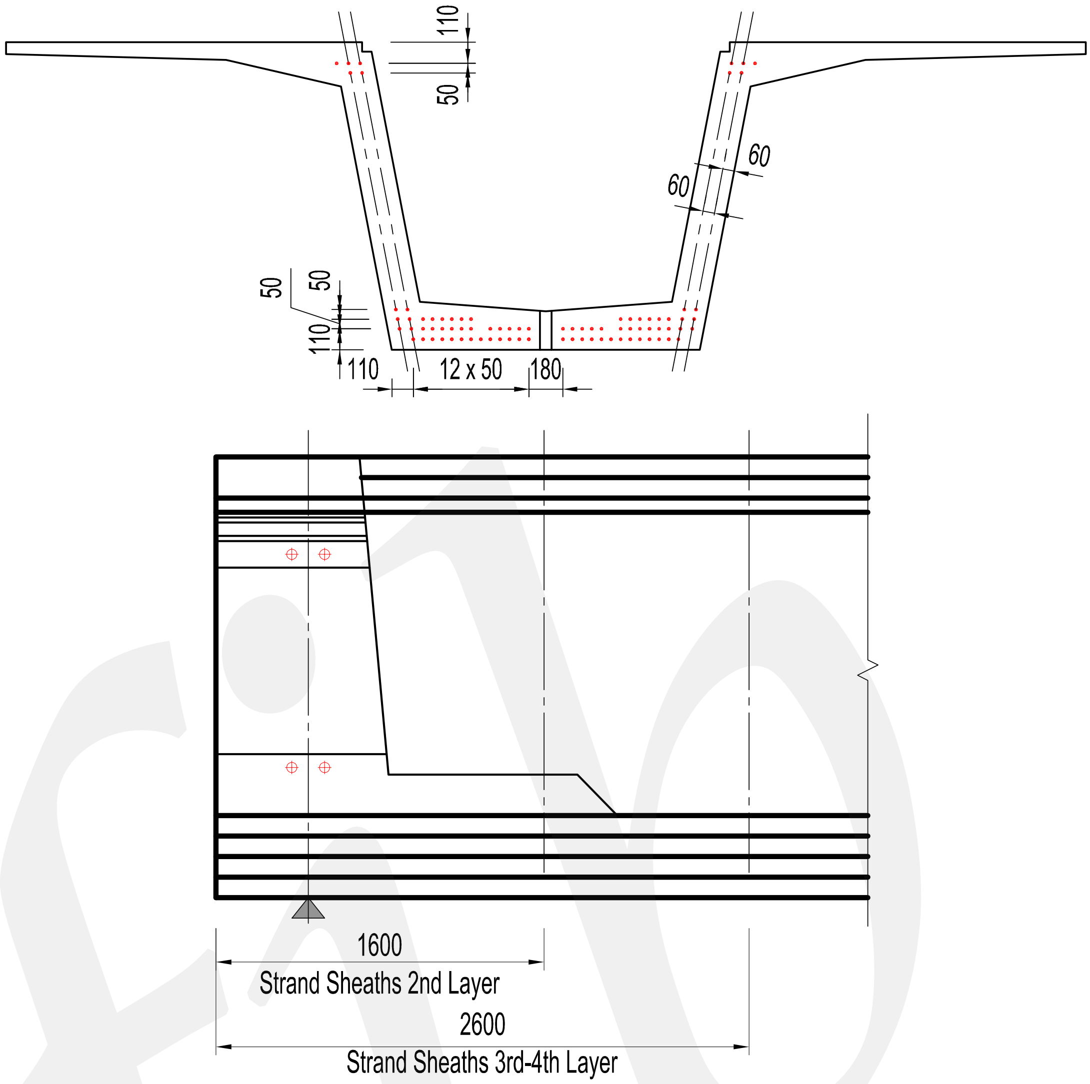


Fig. 5-117 Prestressing strand layout. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.11.3.2 Deck slab

5.11.3.2.1 Materials

Slab:	32 MPa (5 ksi)
Mild reinforcing steel:	450 MPa (65 ksi)

5.11.3.2.2 Deck slab description

The bridge deck is a CIP slab, 25 cm thick. Formwork is not needed because of the adjacent girder flanges and precast concrete deck panels that close the top of the U girder (Fig. 5-115).

The slab is continuous throughout the bridge. To increase its free length and reduce the stiffness of the continuous slab segment, it is debonded from the girder with a 1 cm (0.4 in.) thick polystyrene layer.

The necessary free length of the slab obtained in this way (2.00 m [6.56 ft] in this example) depends on the rotation of the ends of the girders. This rotation is in fact what induces bending moment and stresses in the slab, proportional to its stiffness.

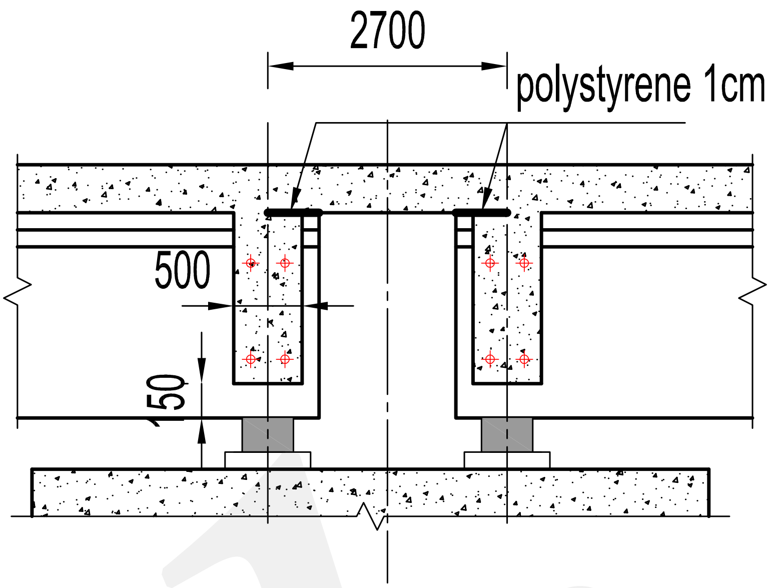


Fig. 5-118 Continuous slab details. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

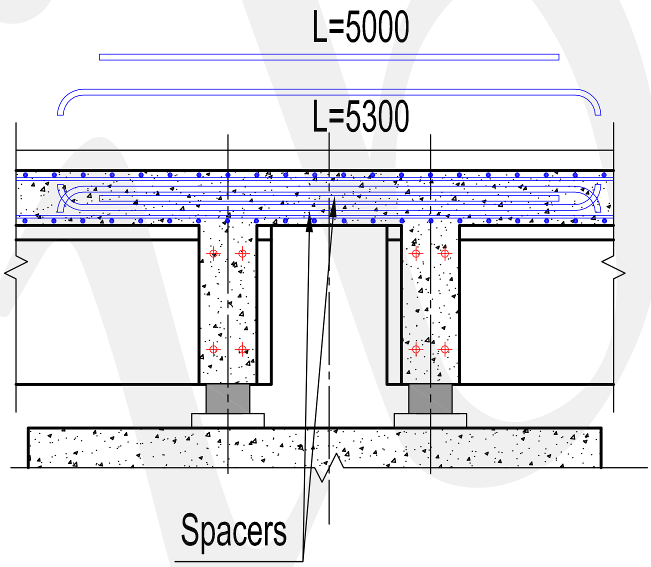


Fig. 5-119 Continuous slab reinforcement. All dimensions are in millimeters. 1 mm = 0.0394 in.

The superstructure continuity over the piers with a continuous slab maintains many of the advantages of continuous girders in terms of rideability, lower maintenance costs for the deck joints, longitudinal and transverse continuity of the viaduct, but it is easier to build. On the other hand, the structural behavior for vertical loads is less favorable compared to continuous girders, even if, in the case of precast concrete girders made continuous on-site, a percentage of the advantage is lost due to long-term effects.

5.11.3.3 Bearings

Guided or free-sliding pot bearings are used. The longitudinal and transverse slope of the girder is adjusted by means of temporary steel wedge plates placed between the bearing and the bottom of the girder.

5.11.3.3.1 Diaphragms

This solution uses diaphragms between girders over the supports only. These are reinforced concrete elements with post-tensioning applied with two tendons of two 36 mm (1.4 in.) diameter threaded bars. Due to the torsional stiffness of the box girders, an efficient transverse distribution of live load is ensured, and no intermediate diaphragms are needed. To increase precast concrete girder stability during construction, two intermediate diaphragms inside the girders are present.

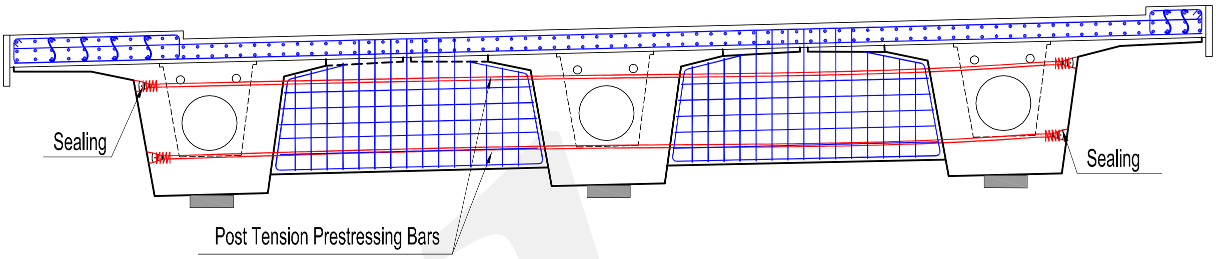


Fig. 5-120 End diaphragms detail.

5.11.3.4 Summary of the preliminary design

Number of spans	5
Continuity	Partial with link slab
Span length *L*, m	30
Girder depth *G*, mm	1'600
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	1'850
Web width *W*, mm	190
Girder spacing *S*, m	4.98
Precast concrete girder weight, tonnes	110
L/D	16.22
L/G	18.75
Average depth, mm	500
Prestressing steel in girders, kg/m²	15
Reinforcing steel – girders, kg/m²	50
Reinforcing steel – top slab, kg/m²	60
Reinforcing steel – diaphragms, kg	5

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m² = 0.2048 lb/ft²; 1 tonne = 1.102 tons.

5.11.4 Construction sequence

- In this solution, the roughly 28 m (92 ft) long U girders must be manufactured in a CE (European Community)- certified factory.
- The girders are shipped to the construction site by trucks and installed by means of specialized launching equipment (Fig. 5-122).

- Temporary bearings and restraints are needed to ensure the stability of the girders until the completion of the diaphragms.
- After installation of the precast concrete deck panels over the open girders followed by reinforcement, the deck slab is placed, finished, and cured.

Fig. 5-121 Moving the girder from the precasting area of the factory to the storage lot.

Fig. 5-122 Launching the U girder under a trussed steel launching beam.

5.11.5 Substructure

Due to the large variability of the seismic hazard along the Italian peninsula, it is not possible to define a typical solution.

To provide some guidance for the present example, due to the designed deck continuity, the following are general structural concepts:

- To minimize the reactions on piers it is possible to connect the deck to one of the abutments with seismic isolators and connect the deck to the abutments only to resist transverse seismic loads. This leaves the piers free of horizontal forces with the only exception of friction at bearings and seismic reactions due to the pier self-weight.
- If the purpose is, instead, to distribute the seismic loads to the substructures, shock transmission unit (STU) devices can be adopted to connect the deck to the piers for longitudinal seismic restraint and transversally, by calibrating the stiffness of seismic isolators, it is possible to optimize the design loads on the substructures.

It is also possible to combine the two suggested solutions to obtain several others that might fit the specific site conditions.

In the present example, there was a specific necessity to minimize loads on piers because of the presence of adjacent substructures of an existing highway and railway. Therefore, structural scheme No. 1 was adopted.

5.12 Example 12: bridge with ten 15 m (49 ft) long spans in Japan

This example was furnished by Kenichi Kata.

For 15 m (49 ft) long spans, slab bridge structure is typically used in Japan. This solution is one of the typical structures for short-span bridges in Japan. This structure type is authorized by the Japan Industrial Standards (JIS) for single-girder bridges[5-14].

5.12.1 Considerations identified

- Bridge layout: This example bridge has a total length of 150 m (492 ft) and a total width of 14.3 m (47 ft).
- Codes: This example uses the following standard codes: Specifications for Highway Bridges in Japan[5-14]. The precast concrete section was approved by the Japanese Industrial Standards[5-14].

5.12.2 Proposed solution

This solution has 10 spans, each with a length of 15 m (49 ft). The cross section of the superstructure consists of 19 precast, prestressed concrete hollow-core girders with a depth of 600 mm (24 in.). Concrete diaphragms are constructed over the piers and every span has three intermediate diaphragms. The 19 precast concrete girders are installed adjacent to each other and form a slab bridge. The joints are filled with concrete and transverse prestressing is applied at the diaphragms.

The precast concrete girders are prefabricated at the factory and transported by trucks. Usually, transportation companies have license to transport payloads under 30 tonnes (33 tons) when using public roads. Therefore, it is one of the criteria for planning and designing precast concrete bridges in Japan.

The precast concrete girders are pretensioned with straight strands. Four strands are partially debonded to control the compressive stresses in the girder.

This solution applies full structural continuity over the piers, which is accomplished with mild steel reinforcement and CIP concrete.

5.12.2.1 Plan

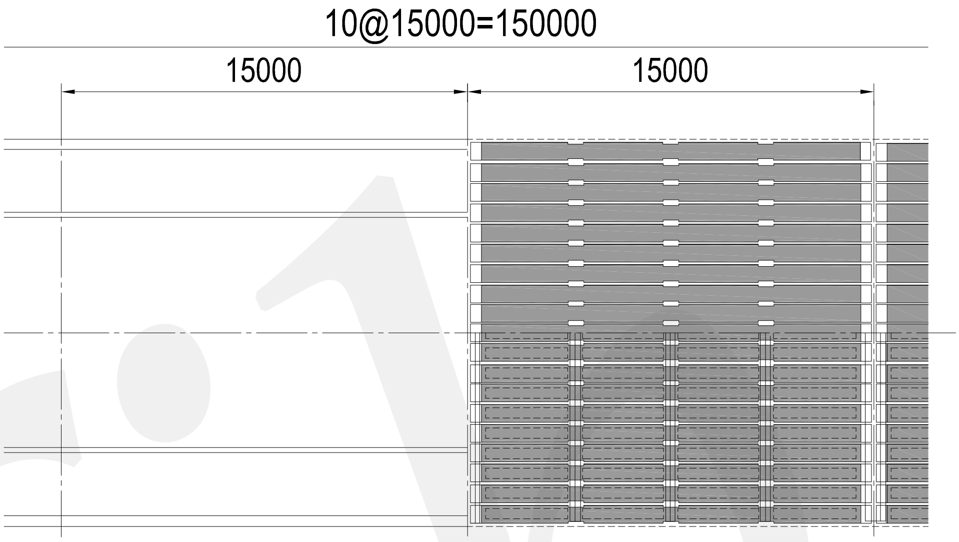


Fig. 5-123 Plan of one span of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.12.2.2 Elevation

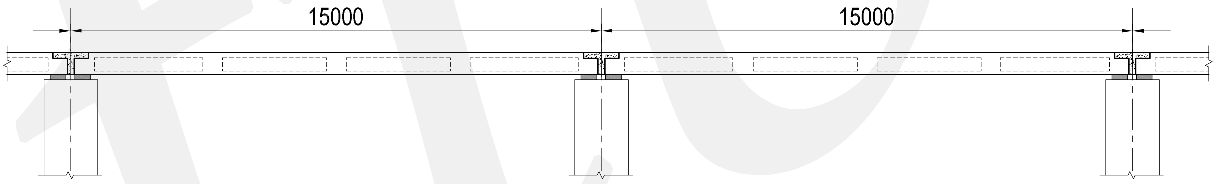


Fig. 5-124 Partial longitudinal section of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.12.2.3 Transverse cross section

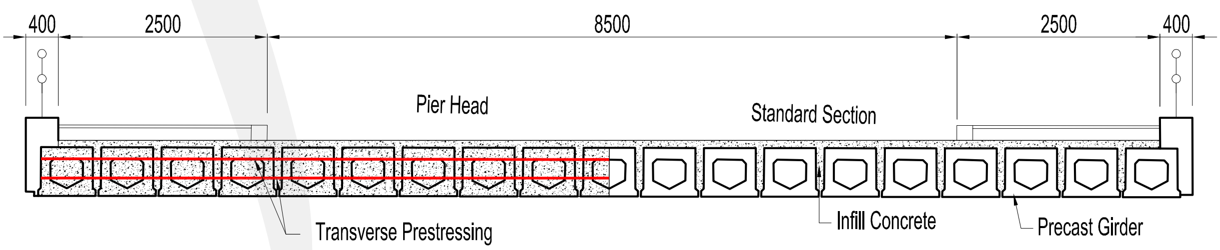


Fig. 5-125 Cross section of the bridge (left: diaphragm at a pier; right: between diaphragms). Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.12.3 Superstructure

5.12.3.1 Precast concrete girders

5.12.3.1.1 Materials and allowable stresses

Concrete:	Compressive strength	50 MPa (7 ksi)
	Allowable compressive stress	16 MPa (2 ksi) (under service load)
	Allowable tensile stress	1.8 MPa (0.3 ksi) (under service load)
Prestressing steels:	Yield strength	1'860 MPa (270 ksi)
	Allowable tensile stress	1'100 MPa (160 ksi) (under service load)
Mild reinforcing steel:	Yield strength	295 MPa (43 ksi)
	Allowable tensile stress	180 MPa (26 ksi) (under service load)

5.12.3.1.2 Description of the cross section

There are 19 hollow-core girders that form a slab bridge superstructure.

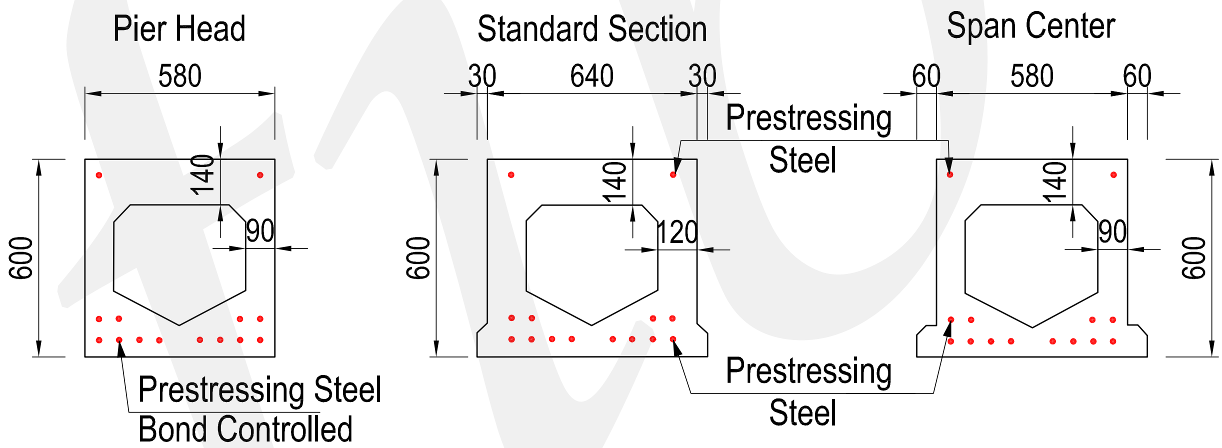


Fig. 5-126 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.12.3.1.3 Prestressing

The precast concrete girders are pretensioned with 14 straight strands, 15.2 mm (0.6 in.) in diameter. Transverse post-tensioning is applied at the diaphragms to connect each precast concrete girder.

5.12.3.2 Deck slab

This solution does not have a CIP slab over the precast concrete girder. The pavement on the precast concrete girder is 75 mm (3 in.) thick. CIP concrete properties (joint infill concrete, diaphragm concrete) are as follows:

Concrete:	Compressive strength	30 MPa (4 ksi)
	Allowable compressive stress	12 MPa (2 ksi) (under service load)
	Allowable tensile stress	0 MPa (under service load)

5.12.3.3 Details

5.12.3.3.1 Bearings

Neoprene bearings are typically used for the shoe. It is set level on a mortar seat and the longitudinal slope is adjusted by the concrete layer between the bearing and the underside of the girder.

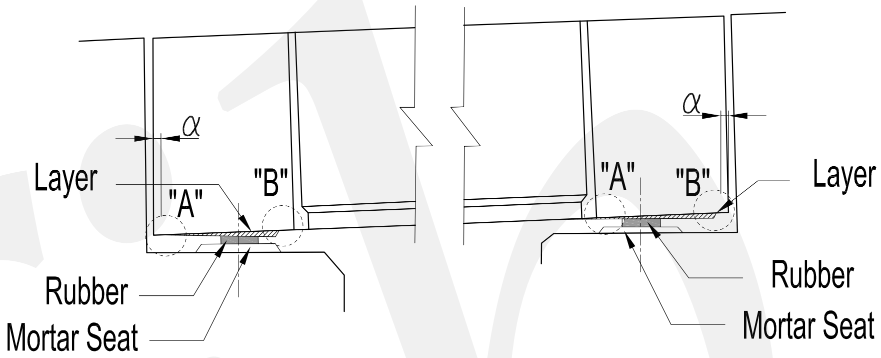


Fig. 5-127 Detail of the bearings. Note: α = Distance between abutment and girder end.

5.12.3.3.2 Continuity

This solution requires neoprene bearings for the precast concrete girders. Fig. 5-127 shows the position of the neoprene pads. Mild steel reinforcement is used in the diaphragms over the piers to attain the superstructure continuity.

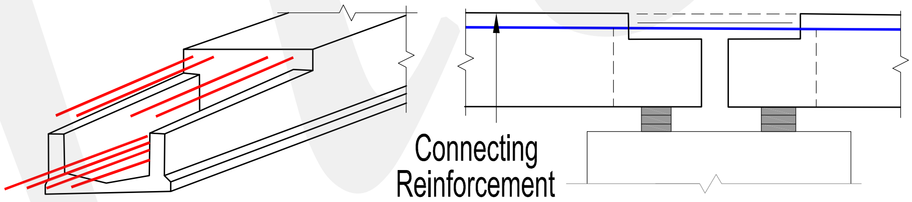


Fig. 5-128 Continuity reinforcement in the diaphragm over the pier.

5.12.3.3.3 Transverse slope

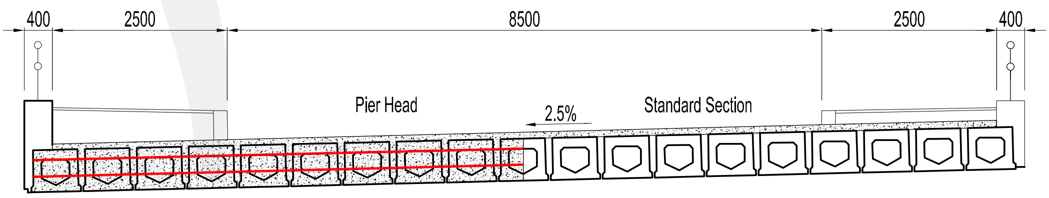


Fig. 5-129 Cross section showing 2.5% transverse slope. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

If the transverse slope of the deck is 4.0% or less, the precast concrete girders are rotated about their longitudinal axes and set on the pier cap. Therefore, the thickness of the pavement is usually constant.

With a slope over 4.0%, precast concrete girders are rotated as previously described and set on the pier head with 4.0% slope and additional adjustment is applied by the surface concrete or pavement thickness.

5.12.3.3.4 Transverse diaphragms

This solution has diaphragms over the supports and three intermediate transverse diaphragms. The diaphragms are CIP concrete that includes transverse post-tensioning.

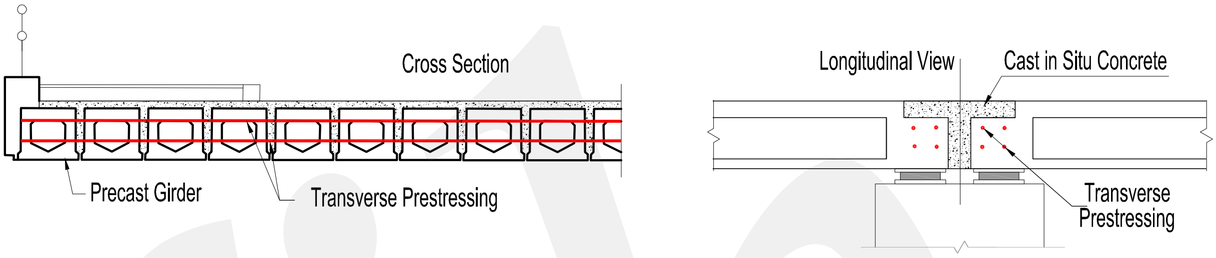


Fig. 5-130 Diaphragm details.

15.12.3.4 Summary of the preliminary design

Number of spans	10
Continuity	Full structural continuity
Span length *L*, m	15.0
Girder depth *G*, mm	600
Slab depth *H*, mm	No slab
Total depth $D = G + H$, mm	600
Web width *W*, mm	240
Girder spacing *S*, m	0.77
Precast concrete girder weight, tonnes	11
L/D	25
L/G	25
Average depth, mm	477
Prestressing steel, kg/m^2	25.1
Reinforcing steel – girder, kg/m^2	22.1
Reinforcing steel – top slab, kg/m^2	n/a
Prestressing steel in a diaphragm, kg	23.9

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

Prestressing steel: Weight of longitudinal prestressing steel/area of precast concrete girder.

5.12.4 Construction sequence

- This type of precast concrete girder is usually erected by truck crane.
- Concrete is placed between girders, and the end and intermediate diaphragms are constructed.
- Then transverse prestressing steels are tensioned.
- CIP concrete pavement is installed.

Fig. 5-131 Transporting the precast concrete girder by truck.

Fig. 5-132 Erection by a single crane.

Fig. 5-133 Concrete is being placed between precast concrete girders and will be followed by casting concrete in the diaphragms.

5.13 Example 13: bridge with six 25 m (82 ft) long spans in Japan

This example was furnished by Kenichi Kata.

The T-girder bridge structure in this example is one commonly found in Japan. T girders are generally used in bridges with span lengths from 20 to 40 m (66 to 131 ft). This structure type is approved for use by the Japan Industrial Standards (JIS)[5-14].

5.13.1 Considerations identified

- Bridge layout: This example is for a bridge with a total length of 150 m (492 ft) and a total width of 14.3 m (47 ft).
- Codes: This example considers the following standard codes: Specifications for Highway Bridges in Japan[5-14]. The precast concrete section was approved by the Japanese Industrial Standards[5-14].
- In addition, in Japan the maximum weight for transportation on the highway is generally limited to 30 tonnes (33 tons).

5.13.2 Proposed solution

This solution has six spans, each 25 m (82 ft) long. The superstructure comprises 14 precast concrete T girders, 800 mm (31 in.) wide with a depth of 1'300 mm (51 in.). They are installed spaced at 1.015 m (3.33 ft) on center. The concrete diaphragm is constructed over the pier and an intermediate concrete diaphragm is cast in place at midspan. The 14 precast concrete girders form a bridge with 215 mm (8 in.) wide joints between flanges that are joined with CIP concrete and transverse post-tensioning through the flanges and diaphragms.

The precast concrete girders are pretensioned and the layout consists of a combination of straight and draped strands.

This solution considers full structural continuity over the piers, which is accomplished with mild steel reinforcement and CIP concrete.

5.13.2.1 Plan

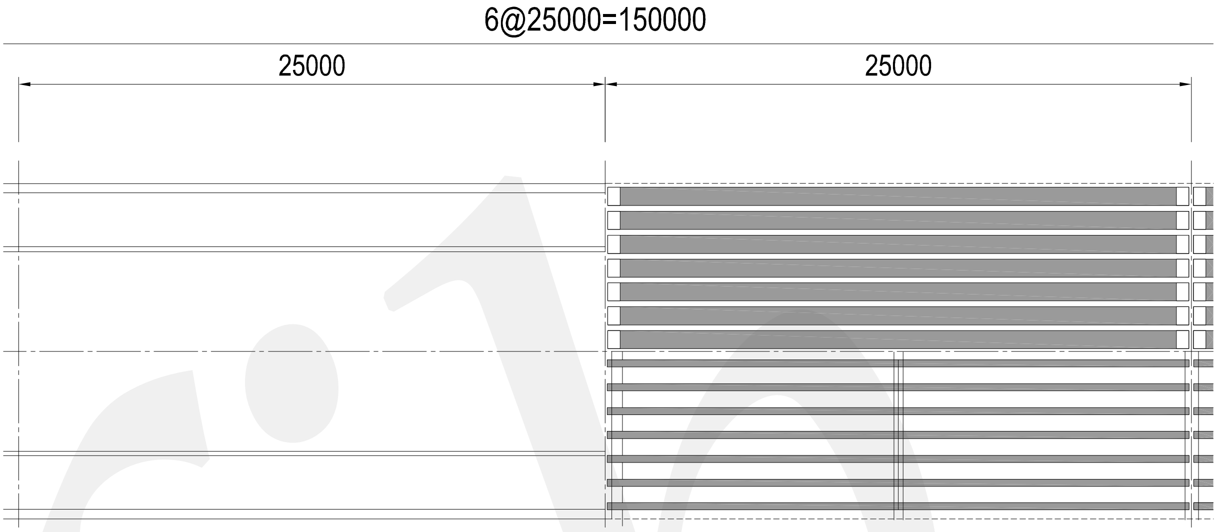


Fig. 5-134 Plan of two spans of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.13.2.2 Elevation

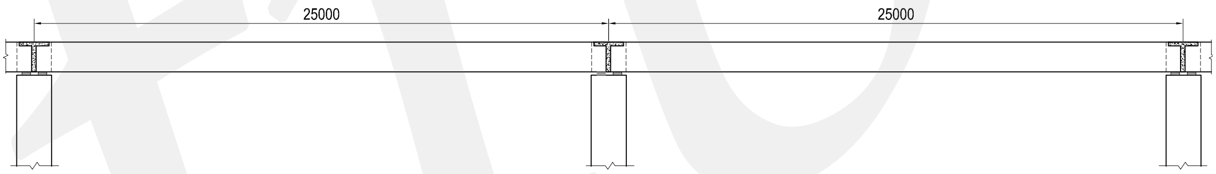


Fig. 5-135 Elevation of two spans of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.13.2.3 Cross section

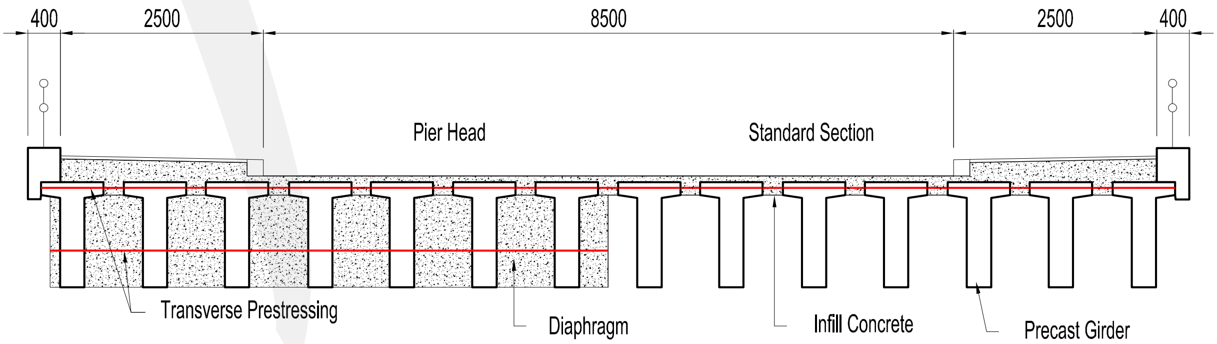


Fig. 5-136 Cross-section view of the bridge (left: through the diaphragm over a pier; right: between diaphragms). Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.13.3 Superstructure

5.13.3.1 Precast concrete girders

5.13.3.1.1 Materials and allowable stresses

Concrete:	Compressive strength	50 MPa (7 ksi)
	Allowable compressive stress	17 MPa (2 ksi) (under service load)
	Allowable tensile stress	1.8 MPa (0.3 ksi) (under service load)
Prestressing steels:	Yield strength	1'860 MPa (270 ksi)
	Allowable tensile stress	1'100 MPa (160 ksi) (under service load)
Mild reinforcing steel:	Yield strength	345 MPa (50 ksi)
	Allowable tensile stress	180 MPa (26 ksi) (under service load)

5.13.3.1.2 Description of the cross section

There are 14 T girders set at 1.015 m (3.33 ft) on center leaving a 215 mm (8 in.) wide space between flanges. The flanges are connected with CIP concrete and transverse post-tensioning in the top flanges and diaphragms.

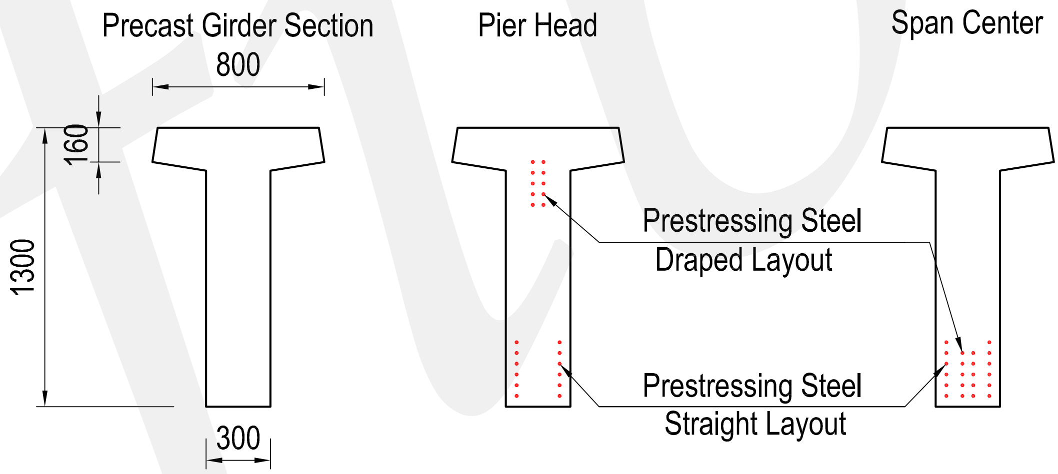


Fig. 5-137 Cross sections of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.13.3.1.3 Prestressing

The precast concrete girders are pretensioned. The longitudinal prestressing consists of 22 straight and draped strands, 15.2 mm (0.6 in.) in diameter. At the diaphragms, this solution also uses transverse post-tensioning.

Due to the weight restrictions established by Japanese highway authorities, if the weight of the precast concrete girder is more than 30 tonnes (33 tons), then the girder must be divided into segments during manufacture and assembled on-site using post-tensioning techniques.

5.13.3.2 Deck slab

This solution does not use a CIP slab over the precast concrete girder. The pavement wearing course on the precast concrete girder is 75 mm (3 in.) thick. CIP concrete properties (infill concrete, diaphragm concrete) are as follows:

Concrete:	Compressive strength	30 MPa (4 ksi)
	Allowable compressive stress	12 MPa (2 ksi) (under service load)
	Allowable tensile stress	0 MPa (under service load)

5.13.3.3 Details

5.13.3.3.1 Bearings

Neoprene pads are used for the shoe. They are set level on a mortar seat and the longitudinal slope is adjusted by the CIP concrete layer on the underside of the girder.

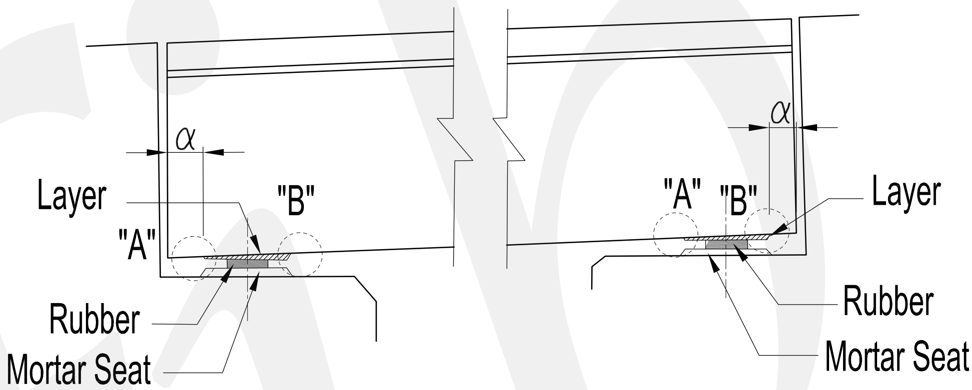


Fig. 5-138 Bearing detail. Note: α = ?.

5.13.3.3.2 Continuity

This solution requires neoprene bearings for each girder. Fig. 5-138 shows the arrangement of the neoprene pads. Longitudinal reinforcement extends from the girders. Additional mild steel reinforcement is added, and CIP concrete is used to attain the superstructure continuity through the diaphragms over the piers

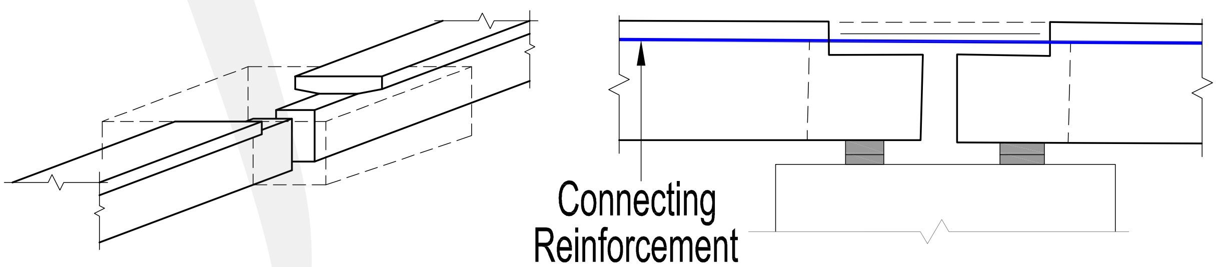


Fig. 5-139 Continuity detail over the pier.

5.13.3.3.3 Transverse slope

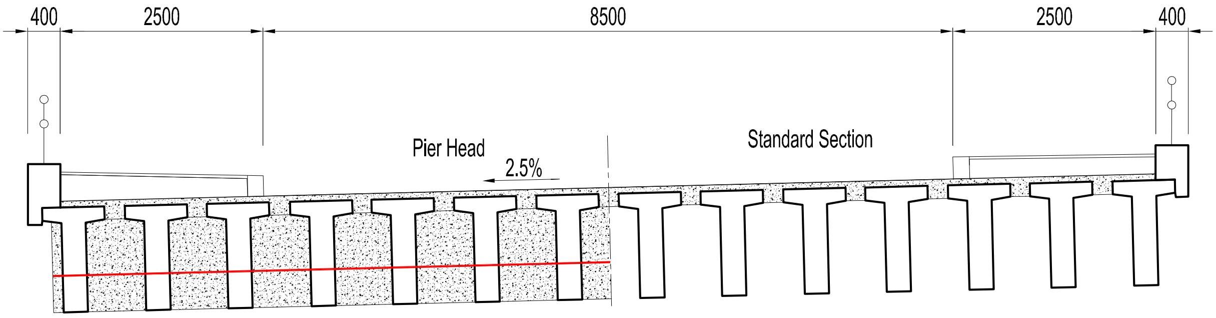


Fig. 5-140 Bridge superstructure with 2.5% transverse slope. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The T girders are set on the piers. If the transverse slope of the deck is under 4.0 %, the slope is formed by the concrete thickness in the flange of the precast concrete girders. Therefore, the thickness of the pavement is usually constant.

In the case of a slope over 4.0%, additional adjustment is made by CIP topping or the pavement thickness.

5.13.3.3.4 Transverse diaphragms

This solution uses diaphragms over the supports and one intermediate transverse diaphragm at midspan. The diaphragms are CIP concrete and include transverse post-tensioning, primarily in the top flange of the T girders and through their webs (Fig. 5-141).

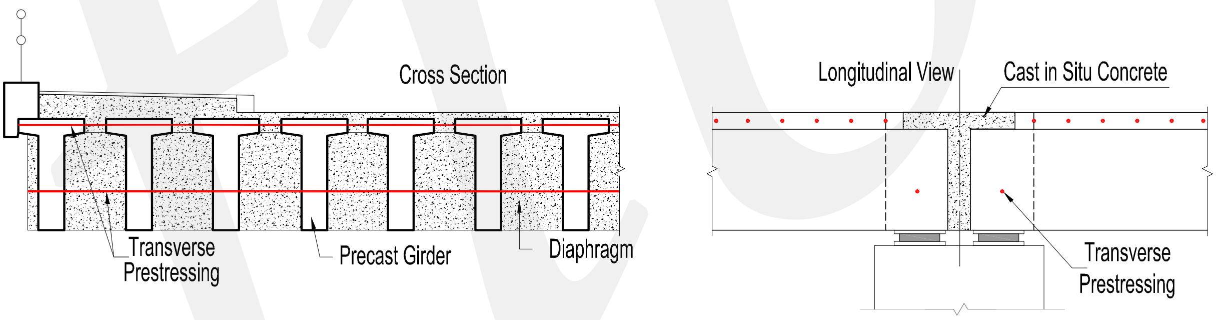


Fig. 5-141 Diaphragms detail.

5.13.3.4 Summary of the preliminary design

Number of spans	6
Continuity	Full structural continuity
Span length *L*, m	25.0
Girder depth *G*, mm	1'300
Wearing course depth *H*, mm	(160)
Total depth *D* = *G* + *H*, mm	1'300
Web width *W*, mm	300
Girder spacing *S*, m	1.015
Precast concrete girder weight, tonnes	29.4
L/D	19.23
L/G	19.23
Average depth, mm	503
Prestressing steel, kg/m^2	30.0
Reinforcing steel – girder, kg/m^2	35.1
Reinforcing steel – top slab, kg/m^2	n/a
Prestressing steel in a diaphragm, kg	132.5

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.13.4 Construction sequence

- Usually this type of precast concrete girder is erected by crane or erection girder.
- Next, CIP concrete is used to fill the space between and connect the flanges of the girders.
- Pier diaphragms and intermediate diaphragms are constructed.
- Then transverse post-tensioning is applied.
- The wearing course pavement is constructed.
- When transportation limitations are encountered, precast concrete girder segments are assembled at the construction site using conventional post-tensioning techniques.

Fig. 5-142 Erection using two-point picks with two cranes.

Fig. 5-143 Erection using an erection girder.

Fig. 5-144 Transportation of a precast concrete girder segment by truck.

5.14 Example 14: bridge with four 40 m (131 ft) long spans in Japan

This example was furnished by Kenichi Kata.

For 40 m (131 ft) long spans, the U girder bridge structure is common in Japan. This structure comprises open-topped U girders plus a precast concrete lid panel, or "plate," over and between girders, finished with a CIP concrete deck slab. As stated in Example 12, Japan has severe weight restrictions for transportation using public highways. This solution has the advantage of lower precast concrete girder weight. Therefore, this method can reduce the required capacity of the erection equipment, such as the launching girder. This solution was applied to the "Atsugi Second Viaduct" in Kanagawa prefecture in Japan.

5.14.1 Considerations identified

- Bridge layout: This example considers a bridge with a total length of 160 m (525 ft) and a total width of 14.3 m (47 ft).
- Codes: This example is governed by the following standard codes: Specifications for Highway Bridges in Japan[5-14]. The precast concrete profile was approved by the Japanese Industrial Standards[5-14].
- In Japan, the maximum weight for transporting using the highway is generally limited to 30 tonnes (33 tons).

5.14.2 Proposed solution

This solution has four spans, each with a length of 40.0 m (131.2 ft) . The cross section comprises three precast concrete, open-topped U girders with a depth of 2600 mm (102 in.) and a 200 mm (8 in.) thick CIP deck slab. Precast, prestressed concrete deck panels are placed in ledges cast into the edges of the girder flanges to close the top of the girders and the space between girders. A CIP deck is constructed on the panels. Due to the weight restrictions established by Japanese highway authorities, the girders are transported in segments, 5.0 m (16.4 ft) long. The precast concrete girders are then assembled using post-tensioning techniques at the project site.

CIP diaphragms are built over piers and abutments, and two intermediate diaphragms are constructed at splice points of segments between piers. The pier beam is designed to establish full structural continuity over the piers and also serves as anchorage for the post-tensioning tendons.

5.14.2.1 Plan

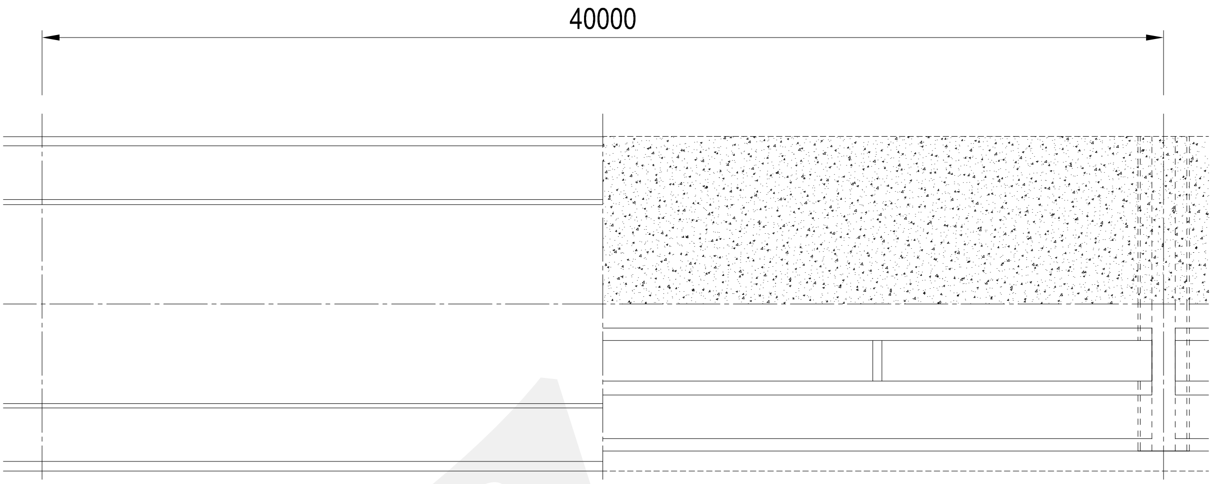


Fig. 5-145 Plan of one span of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.14.2.2 Elevation

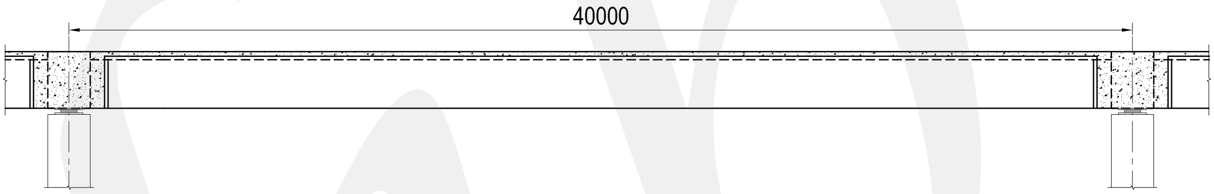


Fig. 5-146 Elevation of one span of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.14.2.3 Cross section

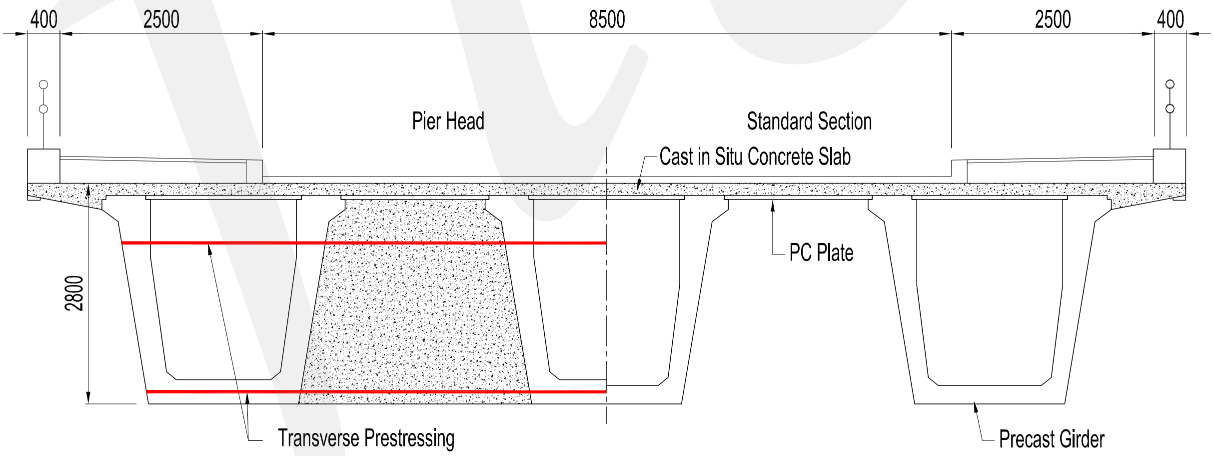


Fig. 5-147 Cross-section view of the bridge (left: through the pier beam; right: typical section between diaphragms). Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.14.3 Superstructure

5.14.3.1 Precast concrete girders

5.14.3.1.1 Materials and allowable stresses

Concrete:	Compressive strength	40 MPa (6 ksi)
	Allowable compressive stress	14 MPa (2 ksi) (under service load)
	Allowable tensile stress	1.5 MPa (0.2 ksi) (under service load)
		0.0 MPa (segment joint; under service load)
Prestressing steels:	Yield strength	1'860 MPa (270 ksi)
	Allowable tensile stress	1'100 MPa (160 ksi) (under service load)
Mild reinforcing steel:	Yield strength	345 MPa (50 ksi)
	Allowable tensile stress	180 MPa (26 ksi) (under service load)

5.14.3.1.2 Description of the cross section

The cross section consists of three open-topped U girders installed with a girder spacing of 4.65 m (15.26 ft) with internal and external post-tensioning tendons. The precast concrete girder has ledges at the upper edges of its top flanges to receive the precast concrete deck panel or "plate."

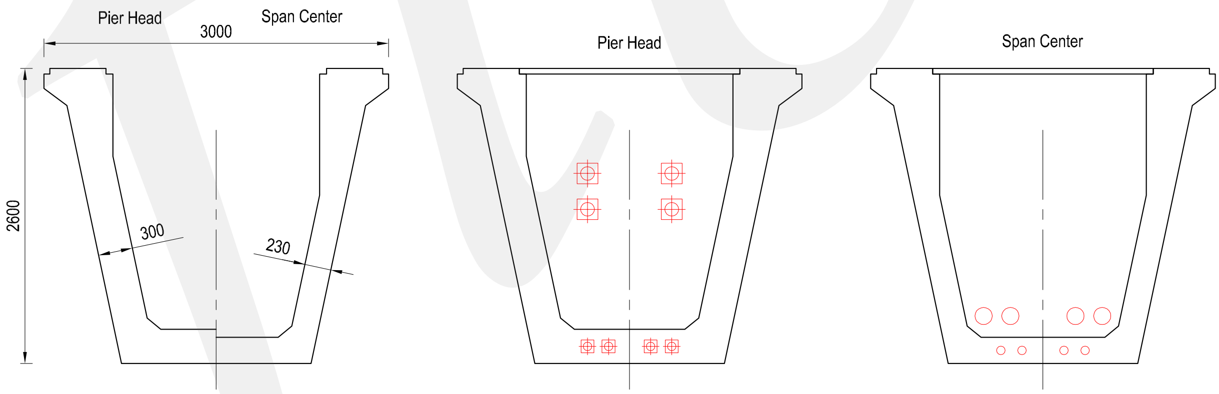


Fig. 5-148 Cross sections of the precast concrete girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.14.3.1.3 Prestressing

The precast concrete U girders are post-tensioned. The longitudinal prestressing consists of four straight internal tendons in the bottom flange and four draped external tendons located inside the U girder. Transverse post-tensioning is used in the pier beam.

The internal tendons in the bottom flange are used to connect the individual segments together to permit the single-span girder to be erected. This is necessary when shorter segments are required to maintain weights under the 30 tonne (33 ton) limit established by the Japanese highway authorities.

5.14.3.2 Deck slab

5.14.3.2.1 Materials and allowable stresses

Concrete:	Compressive strength	36 MPa (5 ksi)
	Allowable compressive stress	12.8 MPa (1.9 ksi) (under service load)
	Allowable tensile stress	1.38 MPa (0.2 ksi) (under service load)
		0.0 MPa (segment joint: under service load)
Mild reinforcing steel:	Yield strength	345 MPa (50 ksi)
	Allowable tensile stress	180 MPa (26 ksi) (under service load)

5.14.3.2.2 Deck slab description

The CIP deck slab has mild steel reinforcement and is 200 mm (8 in.) thick.

5.14.3.3 Details

5.14.3.3.1 Bearings

A seismic base isolation rubber bearing is typically used for the shoe. It is set level on a mortar seat and the longitudinal slope is accommodated with a tapered concrete layer on the underside of the pier beam.

5.14.3.3.2 Continuity

The pier beam is cast in place. The CIP diaphragms and U shaped girders are connected using mild steel reinforcement in the CIP deck slab and the external post-tensioning tendons are anchored at the pier beam. Fiber-reinforced CIP concrete fills the joint between the precast concrete girder and CIP diaphragm.

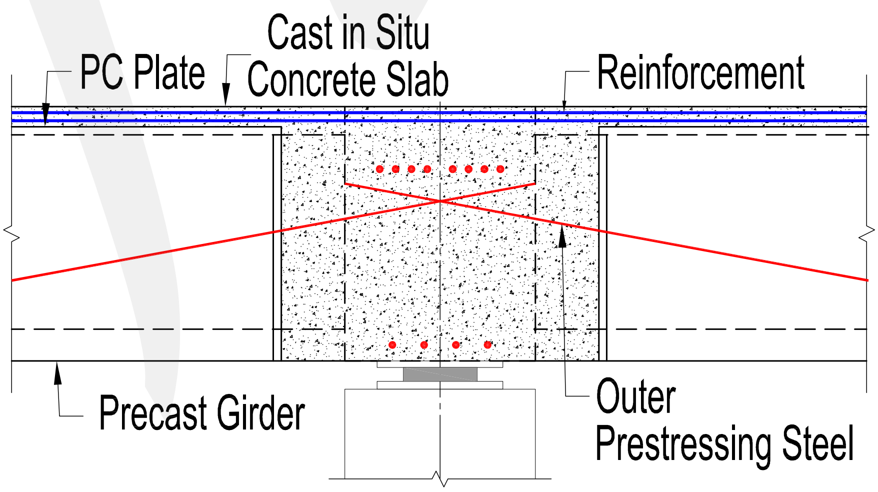


Fig. 5-149 Pier beam, tendon anchorage and diaphragm detail over the pier.

Full structural continuity was used.

5.14.3.3.3 Transverse slope

Precast concrete girders are rotated along their longitudinal axes and set on and parallel to the pier head. Therefore, the thickness of the pavement is usually constant without regard to the transverse slope.

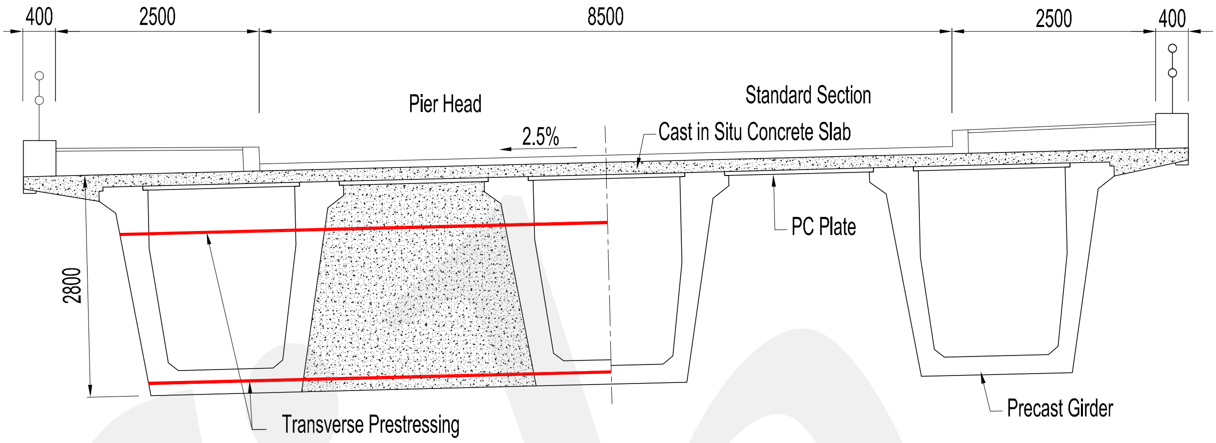


Fig. 5-150 Bridge superstructure with 2.5% transverse slope. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.14.3.3.4 Transverse diaphragms

This solution uses diaphragms over the supports and two intermediate transverse diaphragms within the span. The diaphragms are reinforced concrete elements that include transverse post-tensioning.

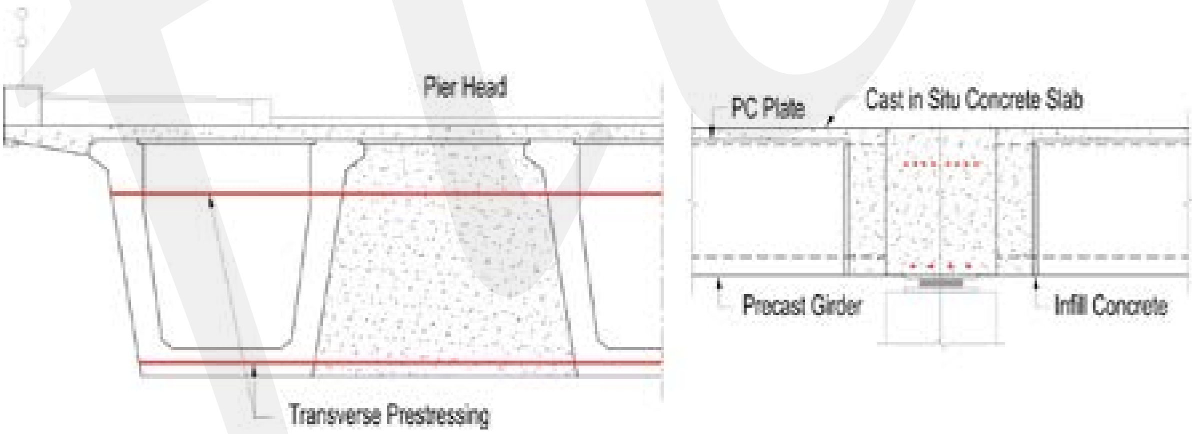


Fig. 5-151 Diaphragms detail.

5.14.3.4 Summary of the preliminary design

Number of spans	4
Continuity	Full structural continuity
Span length *L*, m	40.0
Girder depth *G*, mm	2'600
Slab depth *H*, mm	200
Total depth *D* = *G* + *H*, mm	2'800
Web width *W*, mm	300
Girder spacing *S*, m	4.65
Precast concrete girder weight, tonnes	24
L/D	14.28
L/G	15.38
Average depth, mm	616
Prestressing steel, kg/m^2	19.7
Reinforcing steel – girder, kg/m^2	67.7
Reinforcing steel – top slab, kg/m^2	35.5
Prestressing steel in a diaphragm, kg	213

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

Prestressing steel: Weight of longitudinal prestressing strands/concrete deck area of a precast concrete girder .

5.14.4 Construction sequence

- Usually, precast concrete U girder segments are fabricated at the factory and transported to the site by truck.
- Each segment is arranged and internal post-tensioning tendons in the bottom flange are tensioned.
- The U girder is erected by an erection truss or girder and connected to the pier beam diaphragm by tensioning the external post-tensioning tendons.
- Following erection of the U girder, the precast concrete deck panel or "plate" is set, and deck slab reinforcement is arranged.
- Finally, deck concrete is cast.

This structure can be constructed not only by using an erection girder, but also by crane and temporarily support of the segments.

If there is enough space to fabricate the precast concrete girder at the construction site, it may be fabricated full length. This eliminates the issue of weight restrictions on the highways.

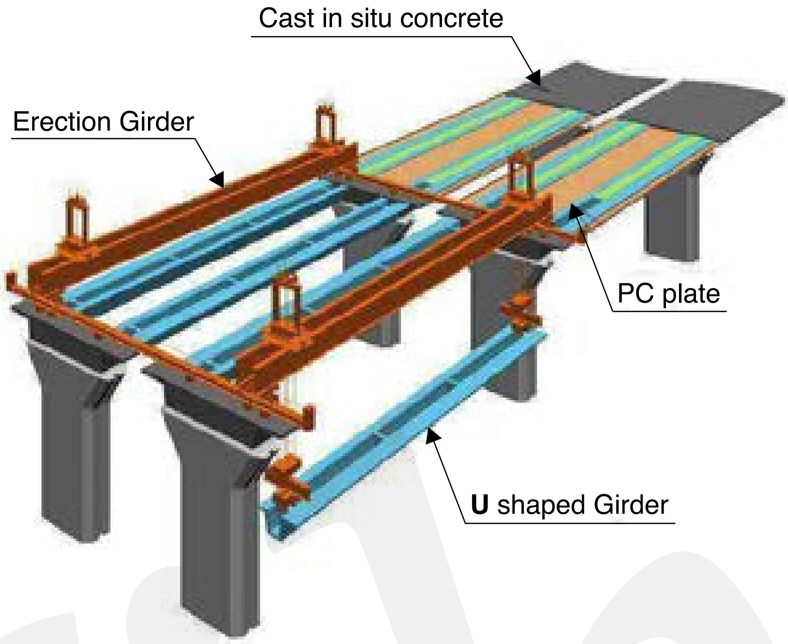


Fig. 5-152 Depiction of the construction process by erection girder.

Fig. 5-153 Transporting the U girder segments.

Fig. 5-154 Erection of the U girder. The post-tensioning ducts and anchorages are seen at the end.

Fig. 5-155 Transporting a precast concrete girder fabricated at the jobsite.

5.15 Example 15: bridge with ten 15 m (49 ft) long spans in Malaysia using UHPFRC

This example was furnished by Voo Yen Lei.

This theoretical example was based on a real project designed by the author to replace the road bridge crossing the Bukit Merah spillway at Perak.

The following figure shows a picture of the finished structure that inspired this example.

Fig. 5-156 View of the Bukit Merah Dam Bridge.

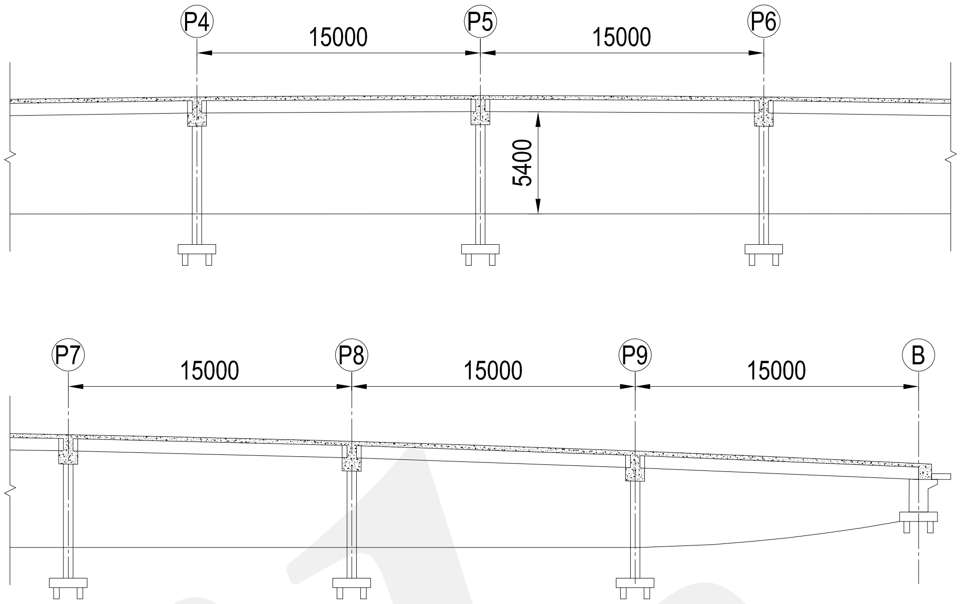
The original structure was built about 15 years ago, however, the local authority decided to demolish the superstructure due to severe corrosion issues detected in the soffit of the precast girders.

5.15.1 Considerations identified

- Bridge layout and headroom: This bridge has a total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: This example is governed by the following codes: BS 5400 Parts 1 to 10[5-15] and live load requirements of MoT, UK BD37/01[5-16].
- Maintenance: UHPFRC girders are nearly impermeable, which leads to reduced maintenance requirements.

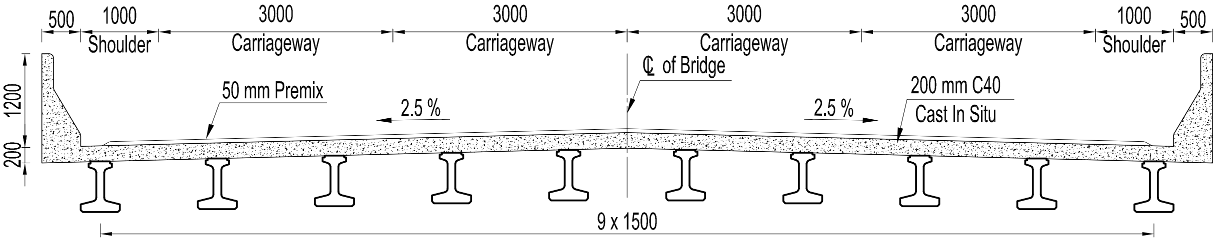
5.15.2 Proposed solution

The proposed example has 10 spans, each with a length of 15 m (49 ft). The cross section consists of 10 precast UHPFRC I-girders, 650 mm (26 in.) deep. The 10 girders are spaced at 1.5 m (4.9 ft) on center. Twenty-five millimeter (1 in.) thick, UHPFRC stay-in-place deck form panels are placed between the I-girders and a 200 mm (8 in.) thick, CIP concrete deck is added.



a) Elevation of the bridge

b) Plan of the bridge



c) Cross-section view

Fig. 5-157 Typical elevation, plan, and cross-section view of the superstructure. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The precast concrete girders are fabricated with UHPFRC 150 with a 28-day characteristic compressive strength of 150 MPa (22 ksi). The CIP deck slab is a 40 MPa (6 ksi) normal strength concrete 200 mm (8 in.) thick and the deck of the bridge has 2.5% transverse slopes each way from centerline. The superstructure uses reinforced concrete diaphragms over piers and abutments but no intermediate diaphragms at midspan. All the precast UHPFRC I-girders are pretensioned with straight strands without debonding of the strand at the anchorage zones.

This solution provides full structural continuity over the abutments and piers by making the deck continuous, and the diaphragms are integral with the substructure.

5.15.3 Superstructure

5.15.3.1 Precast concrete girders

5.15.3.1.1 Materials

Table 5-2 Material properties of precast concrete girder

	UHPFRC150
Characteristic cylinder compressive strength f_{ck}, MPa	150
Characteristic cube compressive strength $f_{ck,cube}$, MPa	165
Characteristic tensile limit of elasticity $f_{ctk,el}$, MPa	7.0
Characteristic post-cracking tensile f_{ctfk}, MPa	8.0
Characteristic modulus of rupture $f_{ctk,fl}$, MPa	20
Mean value of Modulus of elasticity E_{cm}, GPa	50
Poisson's ratio of UHPFRC ν	0.2
Basic creep coefficient $\varphi_{b,28d}$	0.2
After curing shrinkage ε_{sh}	0

Note: UHPFRC = ultra-high-performance fiber-reinforced concrete. 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

Table 5-3 Material properties of steel reinforcement used

Grade 270 strands (ASTM A416-85*)			**Grade 460 steel reinforcement (BS 4449†)**						
Type	**S15**		**Type**	**T10**	**T12**	**T16**	**T20**	**T25**	**T32**
Diameter, mm	15.2		Diameter, mm	10	12	16	20	25	32
A_p, mm^2	140		A_s, mm^2	79	113	201	314	491	804
E_p, GPa	195		E_s, GPa	200	200	200	200	200	200
σ_{py}, MPa	1750		σ_{sy}, MPa	460	460	460	460	460	460
ε_{py}	0.01		ε_{sy}	0.002	0.002	0.002	0.002	0.002	0.002
F_{py}, kN	250		F_{sy}, kN	36	52	92	115	226	370
σ_{pu}, MPa	1888		σ_{su}, MPa	550	550	550	550	550	550
ε_{pu}	0.06		ε_{su}	0.1	0.1	0.1	0.1	0.1	0.1
F_{pu}, kN	270		F_{su}, kN	43	62	110	172	270	442

Note: A_p = area of prestressing tendons; A_s = cross sectional area of reinforcing steel; E_p = modulus of elasticity of prestressing steel; E_s = modulus of elastiticy of reinforcing steel; F_{pu} = ultimate tensile force of prestresssing steel; F_{py} = 1% proof-force of prestressing steel ; F_{su} = ultimate tensile force of reinforcing steel; F_{sy} = yield force of reinforcing steel; ε_{pu} = ultimate tensile strain of prestressing steel; ε_{py} = 1% strain of prestressing steel; ε_{su} = ultimate tensile strain of reinforcing steel; ε_{sy} = yield strain of reinforcing steel; σ_{pu} = ultimate tensile strength of prestresssing steel; σ_{py} = 1% proof-stress of prestressing steel; σ_{su} = ultimate tensile strength of reinforcement; σ_{sy} = yield strength of reinforcement. 1 mm = 0.0394 in.; 1 mm^2 = 0.00155 in.2; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

* ASTM A416/A416M-18. Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete.

† BS 4449:2005, Steel for the reinforcement of concrete. Weldable reinforcing steel. Bar, coil and decoiled product.

5.15.3.1.2 Description of the cross section

Ten I-girders, 650 mm (26 in.) deep with a bottom flange larger than its top flange. The bottom flange is 500 mm (20 in.) wide and the top flange is 300 mm (12 in.) wide. The web is 100 mm (4 in.) thick.

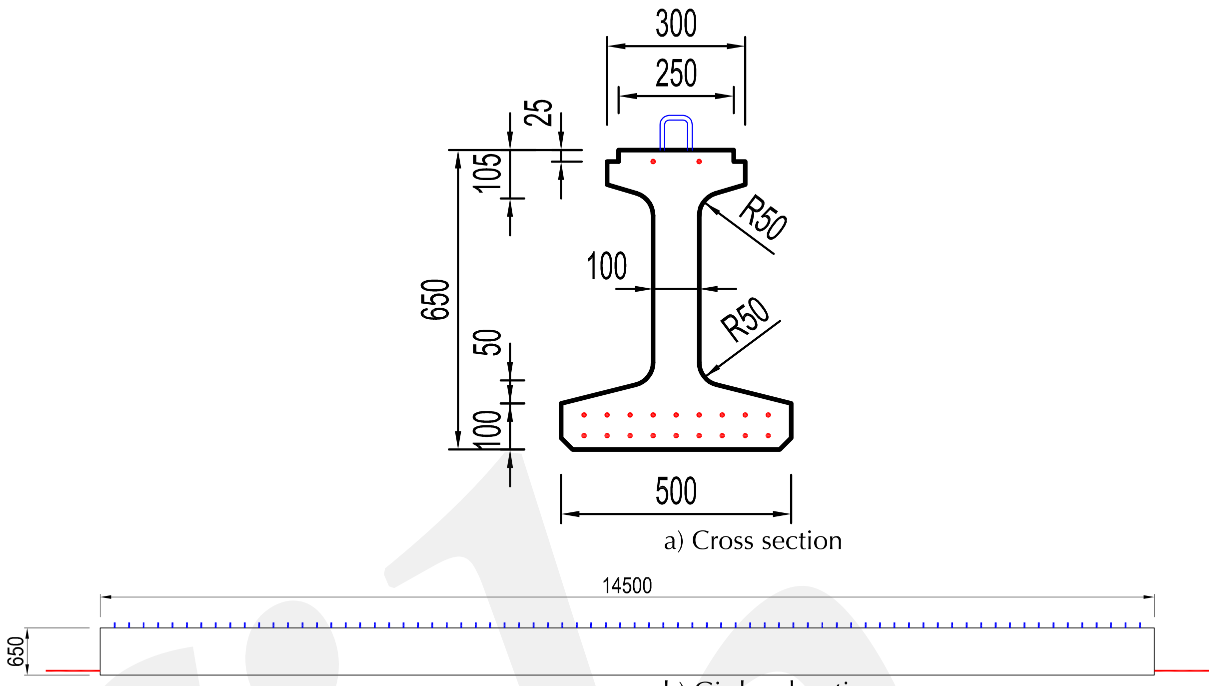


Fig. 5-158 Cross section of I-girder and girder elevation. Note: All dimensions are in millimeters. 1 mm = 0.0394 in

5.15.3.1.3 Prestressing

The precast concrete I-girders are pretensioned with 18 straight strands, 15.2 mm (0.6 in.) in diameter. There are two strands in the top flange and 16 strands in the bottom flange. As a direct benefit of the use of UHPFRC, the precast concrete girders do not have any additional longitudinal reinforcement or any shear reinforcement in any part of the beam, except for the extended bars at the top flange (designed for composite action with the CIP deck). There are extended reinforcing bars at the ends of the girders (Fig. 5-158b).

5.15.3.2 Deck slab

5.15.3.2.1 Materials

Concrete:	40 MPa (6 ksi)
Mild reinforcing steel:	460 MPa (67 ksi)

5.15.3.2.2 Deck slab description

The deck is a CIP slab with a thickness of 200 mm (8 in.). It is cast on the precast concrete deck panels that were placed between the girders. The deck is designed to have allowable crack width of 0.2 mm (0.08 in.) under SLS condition according to Eurocode 2[5-3].

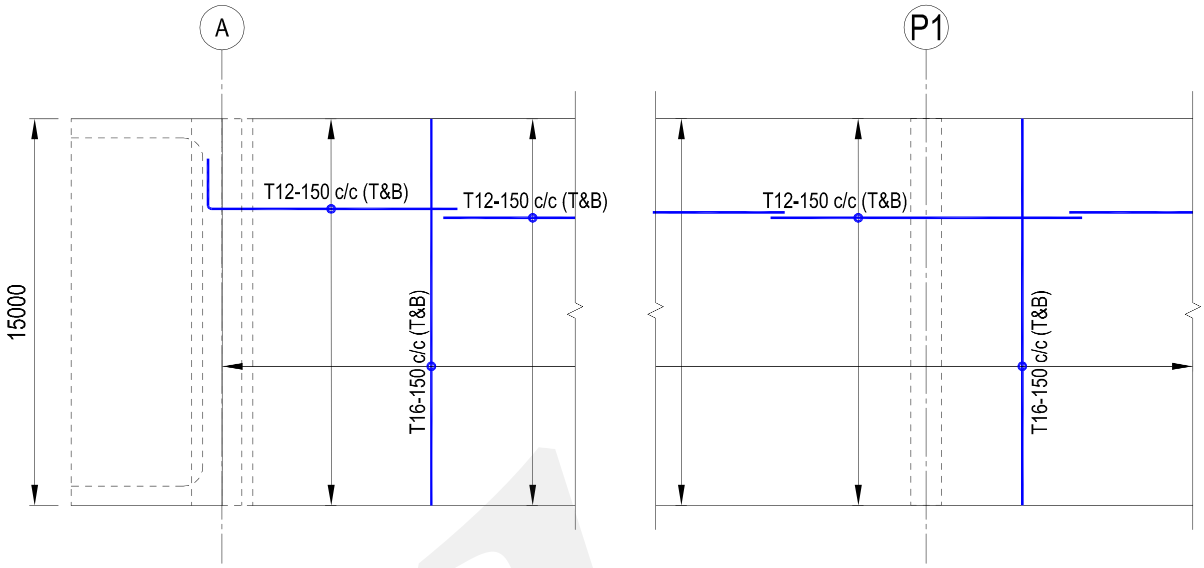
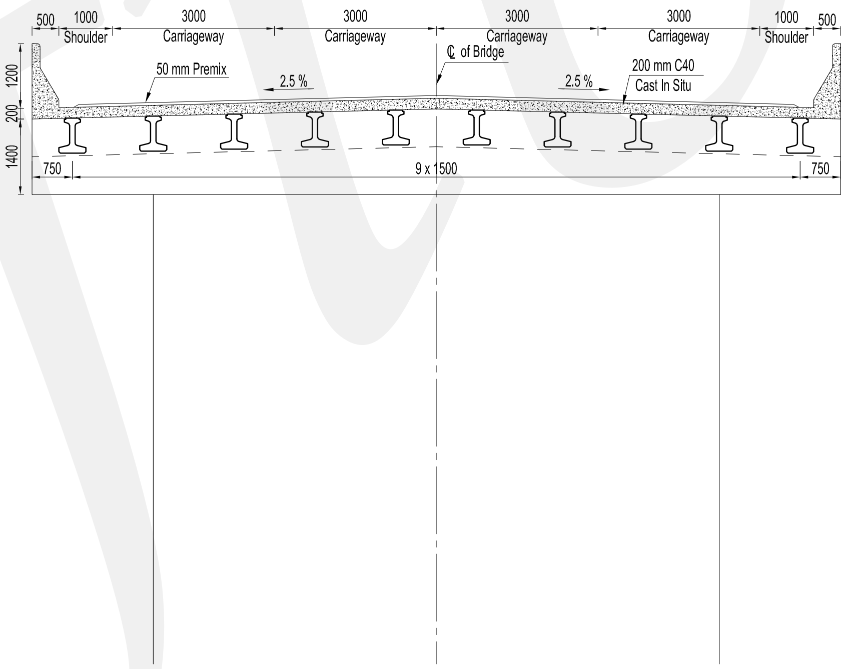


Fig. 5-159 Reinforcement detail of the cast-in-place deck slab. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

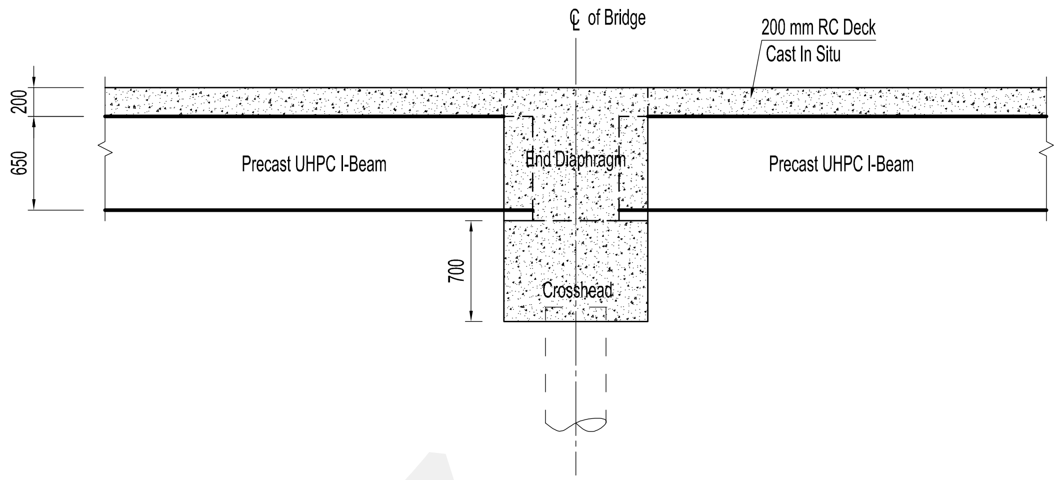
5.15.4 Substructure

5.15.4.1 Piers

Fig.5-160 shows the piers of the structure are one large reinforced concrete column that is cast on the pile cap. In general, on top of each column there is a pier cap. The height of the piers varies and is determined by the vertical alignment.



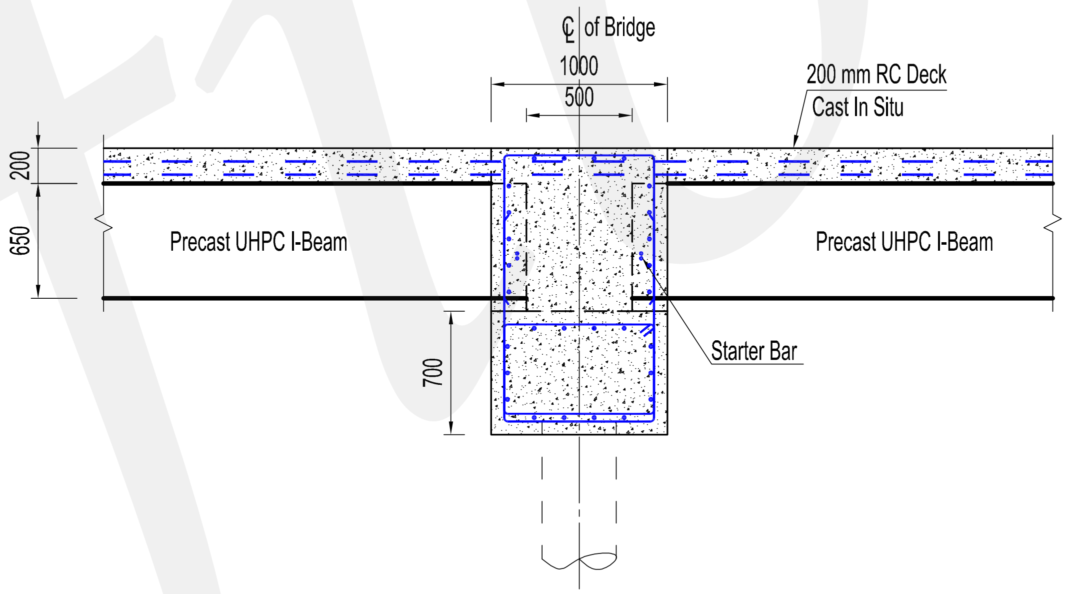
a) Typical transverse elevation of pier



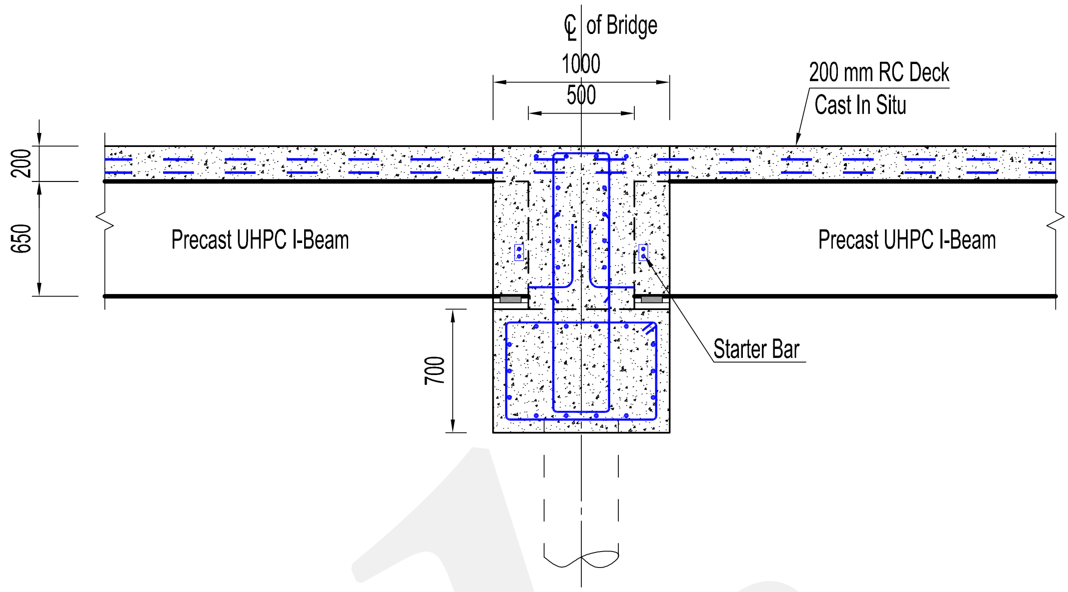
b) Cross section of pier with pier cap and diaphragm

Fig. 5-160 Typical transverse elevation of pier and cross section of pier with pier cap and diaphragm. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in

The following shows a schematic diagram of the continuity of the UHPFRC girders over the pier and pier cap. The superstructure is made continuous at both piers and abutments by casting 40 MPa (6 ksi)concrete end diaphragms. Mild steel reinforcement is provided between and alongside the girders to provide negatvie moment reinforcement to make the connection continuous at the pier or abutment sections (Fig. 5-161). All girders are set on a thin plinth and rubber strips (not elastomeric) placed on the abutments and piers.



a) Continuity detail over the pier between the precast concrete beams



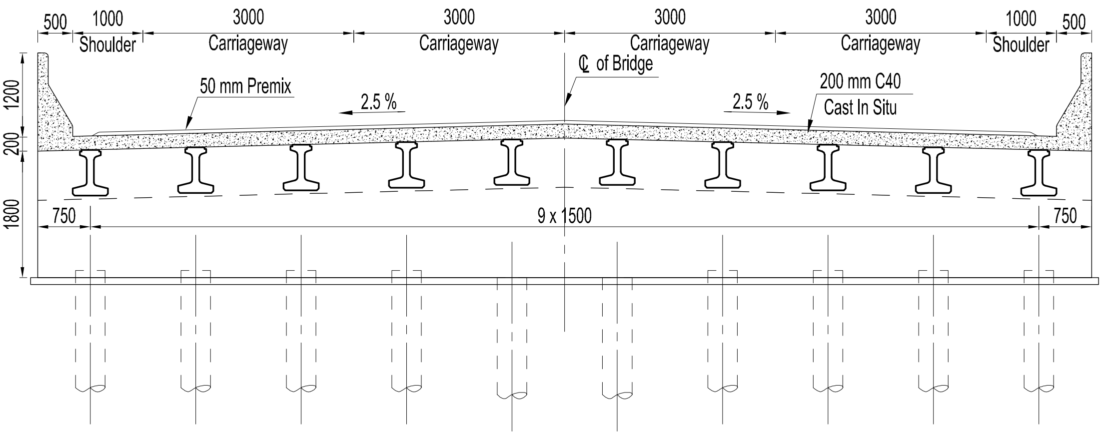
b) Continuity detail over the pier inside the beam

Fig. 5-161 Continuity detail over the pier between the precast concrete beams and inside the beam. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

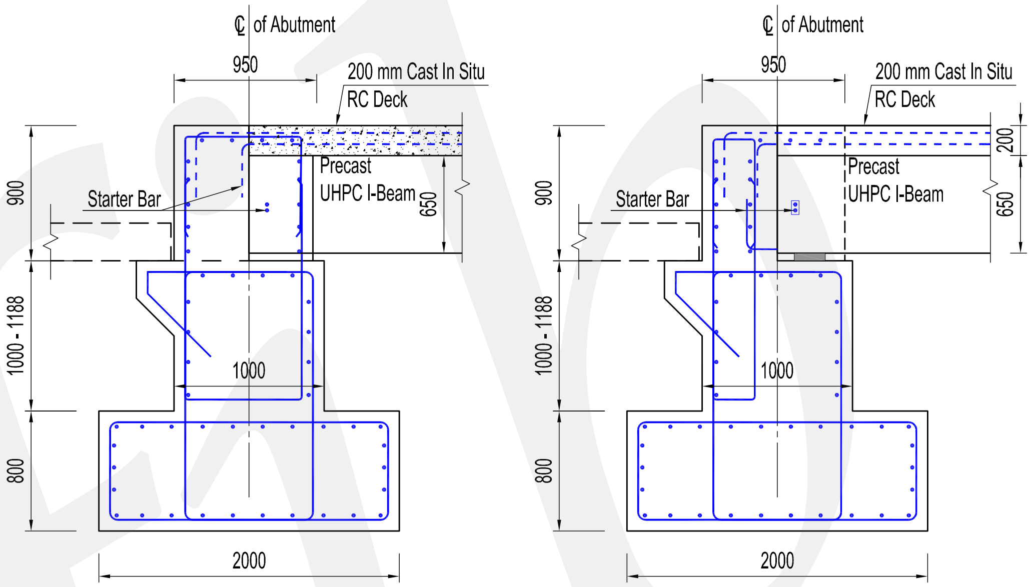
Fig. 5-162 Connection over piers.

5.15.4.2 Abutments

The abutments are reinforced concrete structures. On top of the abutments, the girders are supported by a plinth and rubber strip. The opposite side of the abutment supports an approach slab to the bridge (Fig. 5-162).



a) Elevation view of abutment



b) Cross-section views of abutment

c) Example of Installation of girders on abutment

Fig. 5-163 Views of abutment. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.15.5 Transverse slopes

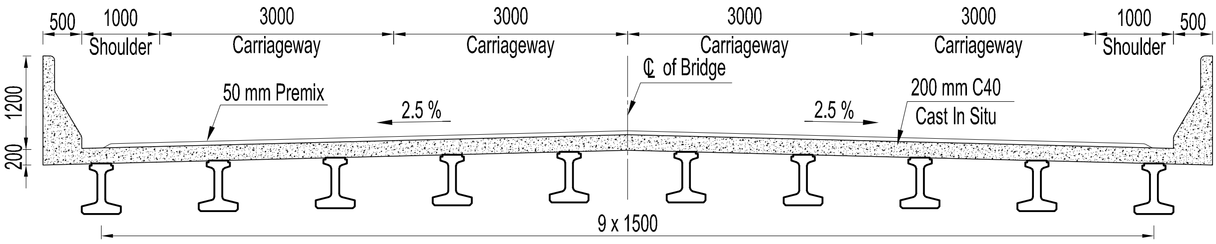
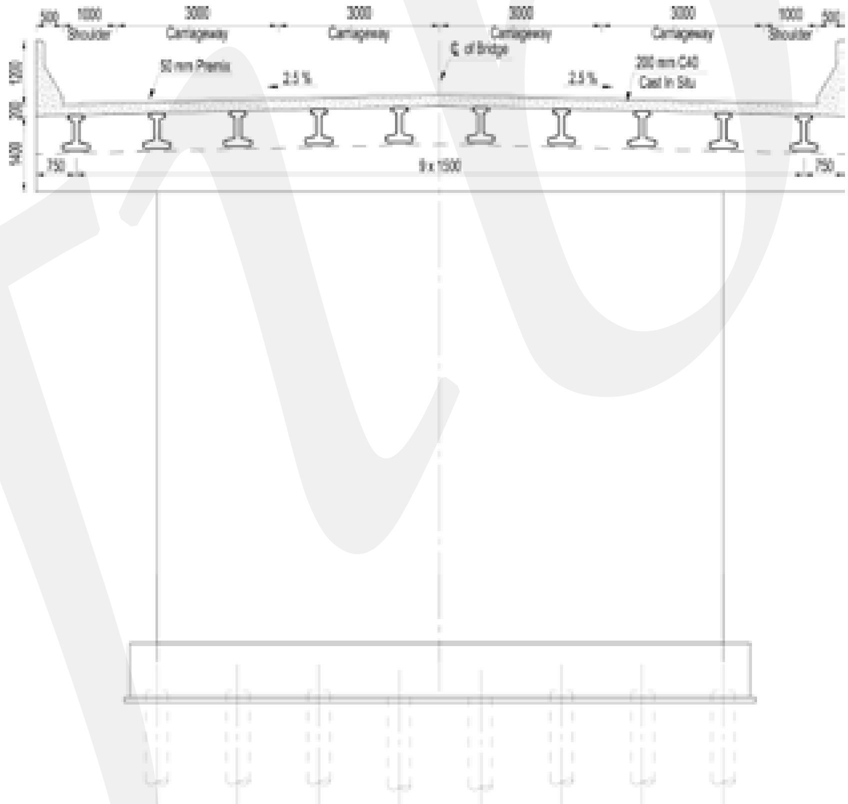


Fig. 5-164 Bridge cross section showing 2.5% transverse slopes. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

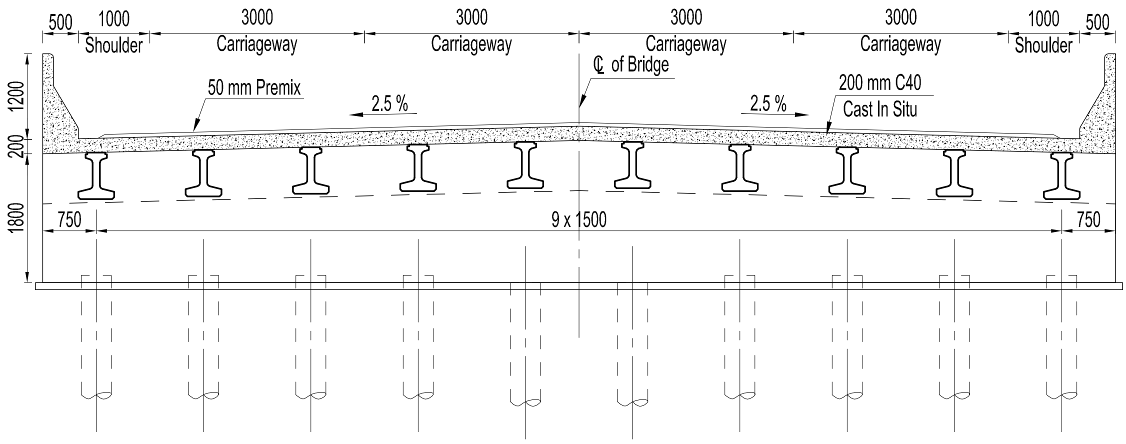
The deck of the bridge has 2.5% transverse slopes formed by varying the thickness of plinths beneath the beams.

5.15.6 Transverse diaphragms

This solution uses diaphragms over the supports but no intermediate transverse diaphragms at midspan. No post-tensioning is used.



a) End diaphragm integrated with piers



b) End diaphragm integrated with abutments

Fig. 5-165 End diaphragm integrated with piers and abutments. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.15.7 Summary of the preliminary design

Number of spans	10
Continuity	Fully integral
Span length *L*, m	15
Girder depth *G*, mm	650
Slab depth *H*, mm	200
Total depth *D* = *G* + *H*, mm	850
Web width *W*, mm	100
Girder spacing *S*, m	1.5
Precast concrete girder weight, tonnes	340 kg/m × 14.5 = 4.93 tonnes per girder
L/D	17.65
L/G	23.1
Average depth, mm	(0.2 m × 15 m wide + 0.14 m^2 × 10 girders) / (15 m wide) = 293 mm
Prestressing steel, kg/m^2	18 strands /girder × 1.12 kg/m × 14.5 m × 10 girders/(15 m × 15 m) = 13 kg/m^2
Reinforcing steel – girder, kg/m^2	(horz. Reo.) 120 kg × 10 girders/ (15 m × 15 m) = 5.33 kg/m^2
Reinforcing steel – top slab, kg/m^2	200 kg/m^3 × 0.2 m thick = 40 kg/m^2
Reinforcing steel in a diaphragm, kg/m^2	120 kg/m^3 × 0.7 m × 1 m × 15 m/(area 15 m × 15 m) = 5.6 kg/m^2

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.15.8 Construction sequence

This type of bridge is built with the following typical construction procedure.

- The construction starts with the installation of piles.
- Construction of pile caps, abutments, and piers follows.

- Columns and pier caps or pier beams are cast in place using conventional concrete at piers and abutments. Reinforcement from pier caps is extended for embedment in the diaphragm. The girders are fabricated in a factory. They are transported to the site and erected by crane on the piers and abutments.
- After erecting girders, UHPFRC stay-in-place deck panels are placed between beams.
- Temporary timber formwork is installed at both edges of the bridge, after which reinforcement is installed for the deck and diaphragms.
- The concrete deck and diaphragms are then cast together with conventional concrete to provide continuity at connections.

Fig. 5-166 Example of precast girder installation

Fig. 5-167 Example of execution of superstructure

5.16 Example 16: bridge with ten 15 m (49 ft) long spans in Malaysia using UHPFRC

This example was furnished by Voo Yen Lei.

This theoretical example was based on a real project designed by the author in Kampung Banir, Daerah Batang Padang, Perak D.R.

The following figure shows a picture of the finished structure that inspired this example.

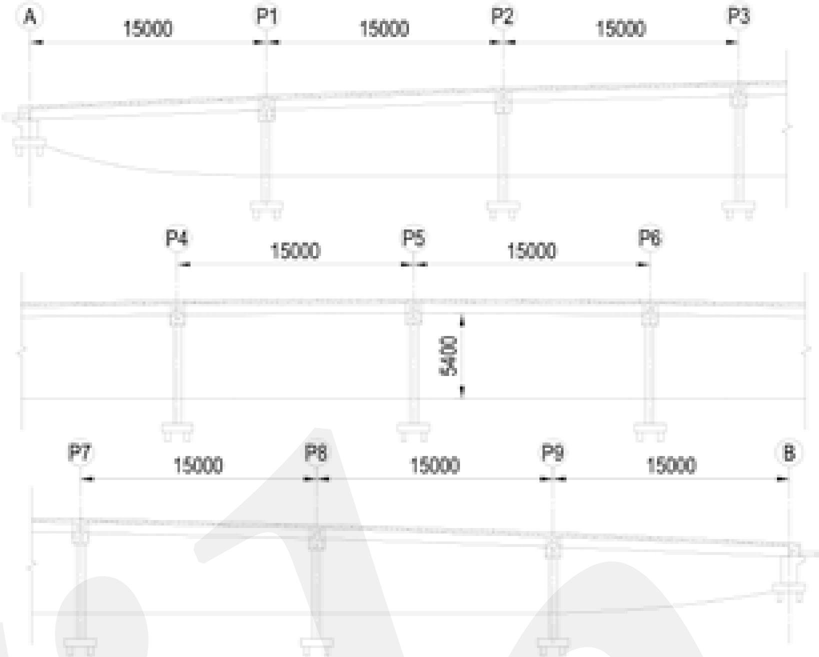
Fig. 5-168 View of Kampung Banjar Bridge.

5.16.1 Considerations identified

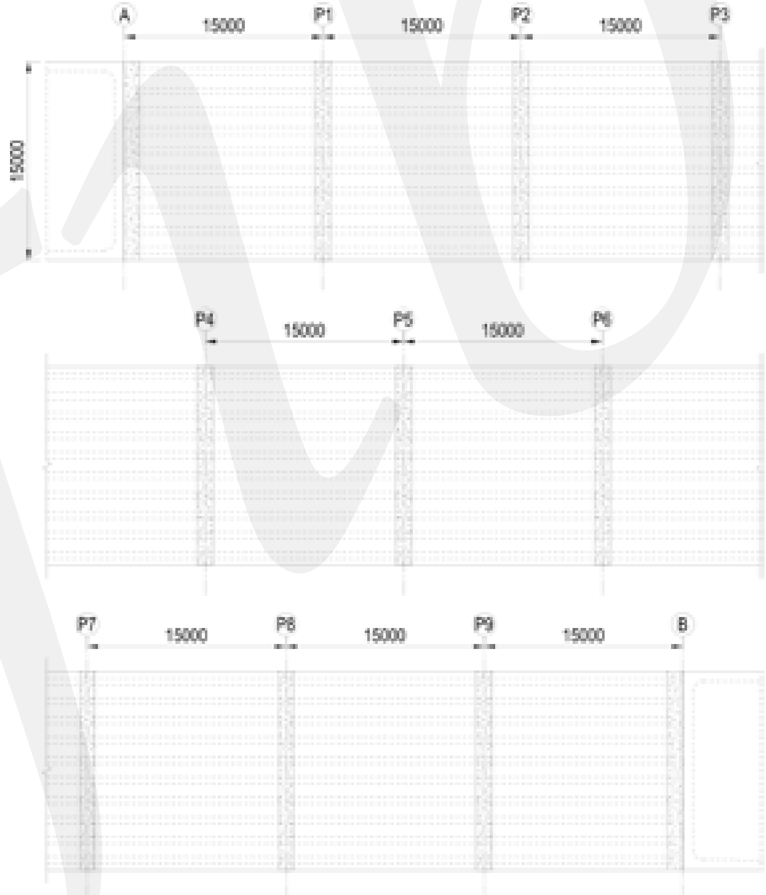
- This example considers a bridge with total length of 150 m (492 ft) and a total width of 15 m (49 ft).
- Codes: This example is governed by the following codes: BS 5400 Parts 1 to 10[5-6] and live load requirements of Ministry of Transport UK BD37/01[5-7].
- Maintenance: UHPFRC girders are nearly impermeable, which leads to reduced maintenance requirements.

5.16.2 Proposed solution

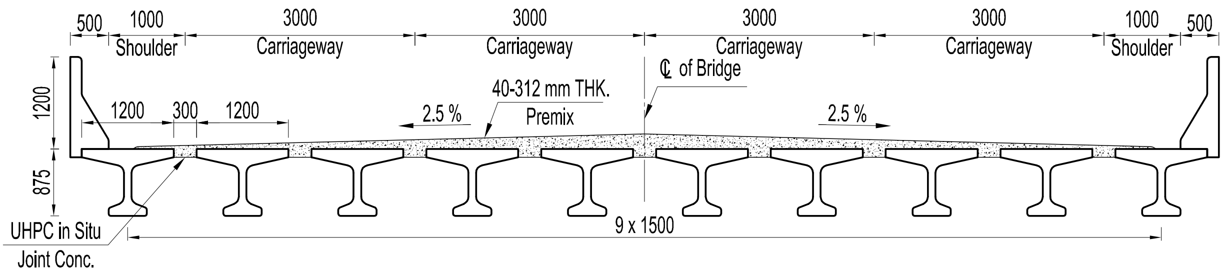
This solution uses 10 spans, each with a length of 15 m (49 ft). The cross section consists of 10 precast UHPFR concrete T girders with a depth of 875 mm (34 in.). The T girders are 1'200 mm (47 in.) wide and spaced 1.5 m (4.9 ft) on center. They have a wide top flange and are erected leaving a 250 mm (10 in.) wide space between flanges. These joints are joined together with UHPFRC. The wearing course layer is placed directly on top of these top flanges. There is no structural top slab.



a) Elevation of the bridge



b) Plan of the bridge



c) Cross-section view

Fig. 5-169 Typical elevation, plan, and cross-section view of the bridge. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

The precast concrete elements are fabricated with UHPFRC150 with a 28-day characteristic compressive strength 150 MPa (22 ksi). The deck has 2.5% transverse slopes in both directions from centerline formed by tapering the wearing surface. The superstructure uses CIP reinforced concrete diaphragms over piers and abutments. The precast UHPFRC T girders are pretensioned with straight strands without the need for debonding. This solution provides full structural continuity over the abutments and piers by making the deck continuous and casting the end diaphragm at the pier integral with the substructure.

5.16.3 Superstructure

5.16.3.1 Precast concrete girders

5.16.3.1.1 Materials

Table 5-4 Material properties of precast concrete beam

	UHPFRC150
Characteristic cylinder compressive strength f_{ck}, MPa	150
Characteristic cube compressive strength $f_{ck,cube}$, MPa	165
Characteristic tensile limit of elasticity $f_{ctk,el}$, MPa	7.0
Characteristic post-cracking tensile f_{ctfk}, MPa	8.0
Characteristic modulus of rupture $f_{ctk,fl}$, MPa	20
Mean value of Modulus of elasticity E_{cm}, GPa	50
Poisson's ratio of UHPFRC υ	0.2
Basic creep coefficient $\varphi_{b,28d}$	0.2
After curing shrinkage ε_{sh}	0

Note: UHPFRC = ultra-high-performance fiber-reinforced concrete. 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

Table 5-5 Material properties of the steel reinforcement used.

Grade 270 strands (ASTM A416-85*)			Grade 460 steel reinforcement (BS 4449†)						
Type	S15		Type	T10	T12	T16	T20	T25	T32
Diameter, mm	15.2		Diameter, mm	10	12	16	20	25	32
A_p, mm^2	140		A_s, mm^2	79	113	201	314	491	804
E_p, GPa	195		E_s, GPa	200	200	200	200	200	200
σ_{py}, MPa	1750		σ_{sy}, MPa	460	460	460	460	460	460
ε_{py}	0.01		ε_{sy}	0.002	0.002	0.002	0.002	0.002	0.002
F_{py}, kN	250		F_{sy}, kN	36	52	92	115	226	370
σ_{pu}, MPa	1888		σ_{su}, MPa	550	550	550	550	550	550
ε_{pu}	0.06		ε_{su}	0.1	0.1	0.1	0.1	0.1	0.1
F_{pu}, kN	270		F_{su}, kN	43	62	110	172	270	442

Note: A_p = area of prestressing tendons; A_s = cross sectional area of reinforcing steel; E_p = modulus of elasticity of prestressing steel; E_s = modulus of elastiticy of reinforcing steel; F_{pu} = ultimate tensile force of prestresssing steel; F_{py} = 1% proof-force of prestressing steel; F_{su} = ultimate tensile force of reinforcing steel; F_{sy} = yield force of reinforcing steel; ε_{pu} = ultimate tensile strain of prestressing steel; ε_{py} = 1% strain of prestressing steel; ε_{su} = ultimate tensile strain of reinforcing steel; ε_{sy} = yield strain of reinforcing steel; σ_{pu} = ultimate tensile strength of prestresssing steel; σ_{py} = 1% proof-stress of prestressing steel; σ_{su} = ultimate tensile strength of reinforcement; σ_{sy} = yield strength of reinforcement. 1 mm = 0.0394 in.; 1 mm^2 = 0.00155 in.^{2}; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

* ASTM A416/A416M-18. Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete.

† BS 4449:2005, Steel for the reinforcement of concrete. Weldable reinforcing steel. Bar, coil and decoiled product.

5.16.3.1.2 Description of the cross section

Ten T girders , 875 mm (34 in.) deep, spaced 1.5 m (4.9 ft) on center, with a single thin web 100 mm wide. The top flanges of the precast concrete girders are typically 1.2 m (3.9 ft) wide and therefore provide for 300 mm (12 in.) wide, CIP UHPFRC130/145 stitches (except the edge beam, where the top flange is 1350 mm [53 in.] wide). The wearing surface is placed directly on the top flanges of the girders and no CIP concrete structural deck slab is needed.

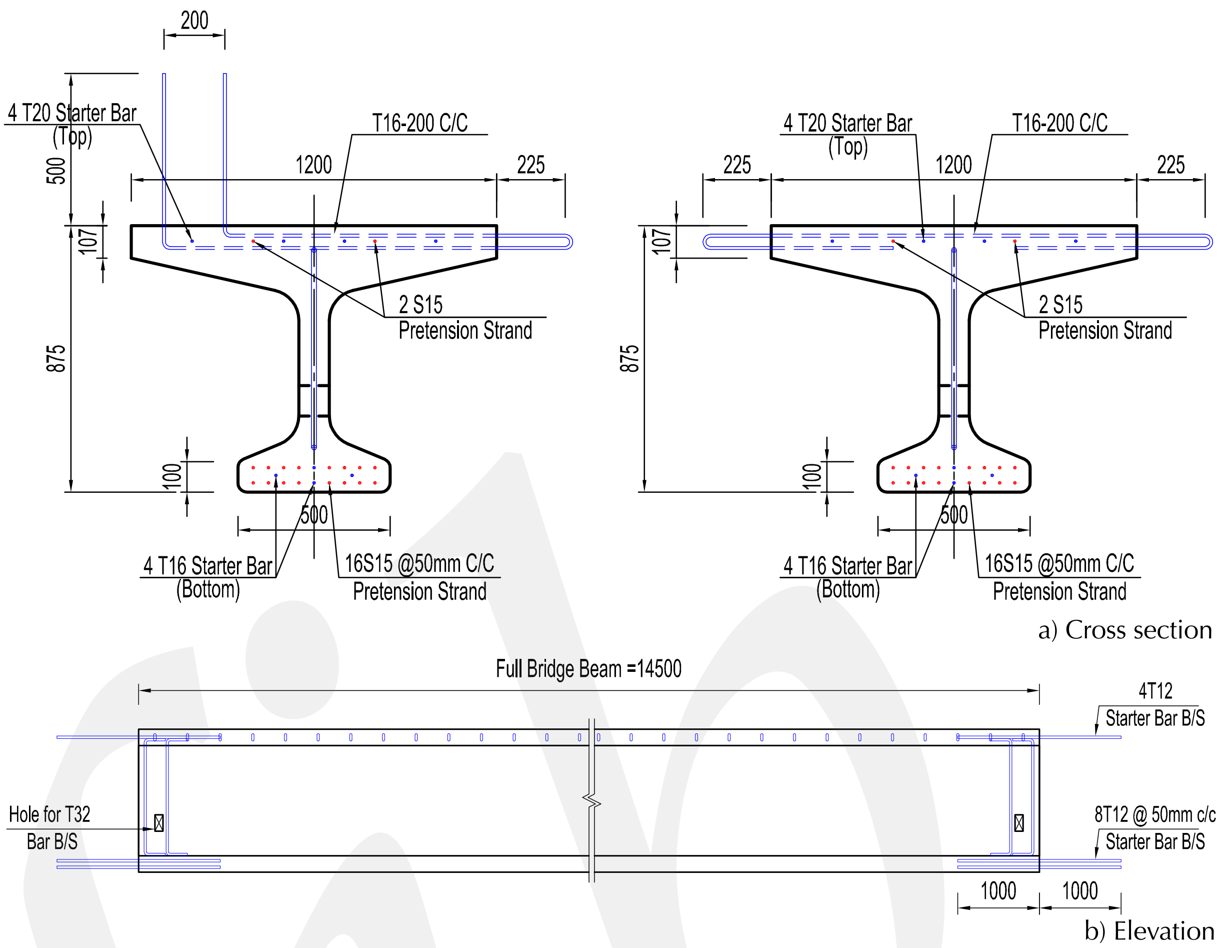


Fig. 5-170 Cross section and elevation of the T girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.16.3.1.3 Prestressing

The precast concrete girders are pretensioned with two strands in the top flange and 16 straight strands in the bottom flange. All strands are 15.2 mm (0.6 in.) in diameter. The precast UHPFRC girders do not have major longitudinal or shear mild reinforcing steel at any part of the girders, with the exception of continuity bars at the top flanges, minimal bursting reinforcement, and continuity bars at the anchorage zone (Fig. 5-170b).

5.16.3.2 Slab

5.16.3.2.1 Materials

Concrete: 150 MPa (22 ksi)

Reinforcing steel: 460 MPa (67 ksi)

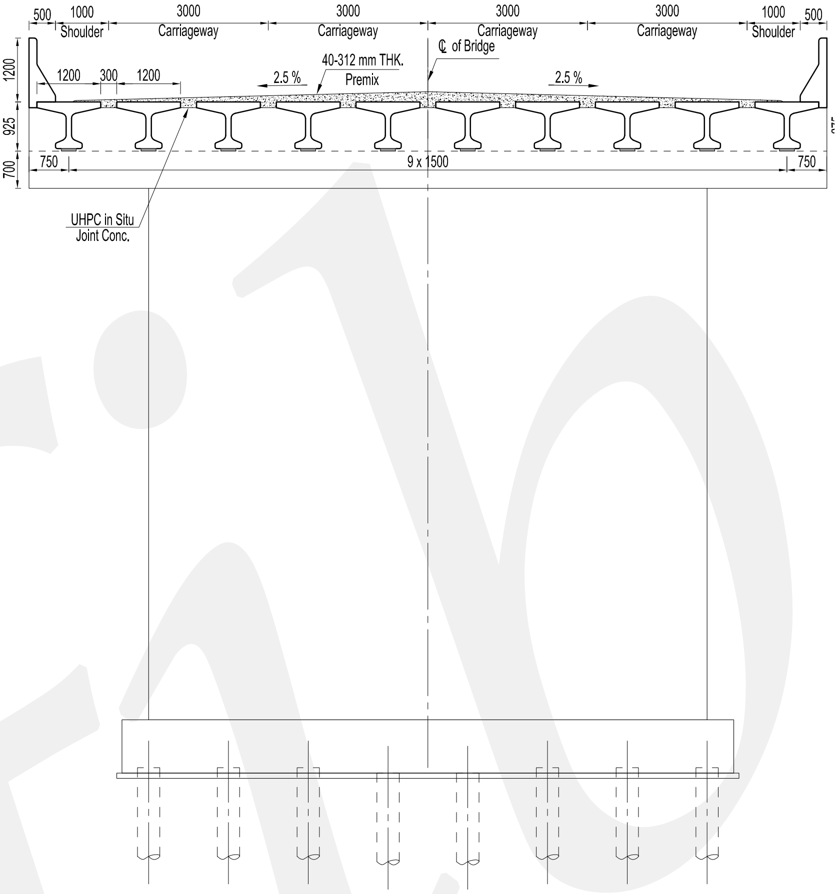
5.16.3.2.2 Deck slab description

The slab is integrated as the top flange of the precast girder—sometimes referred to as a "decked" T girder. During design, for simplicity, the section properties contributed by the 300 mm (12 in.) wide UHPFRC joint (that is composite with the top flanges) is neglected because it does not offer a significant contribution to the moment capacity of the section.

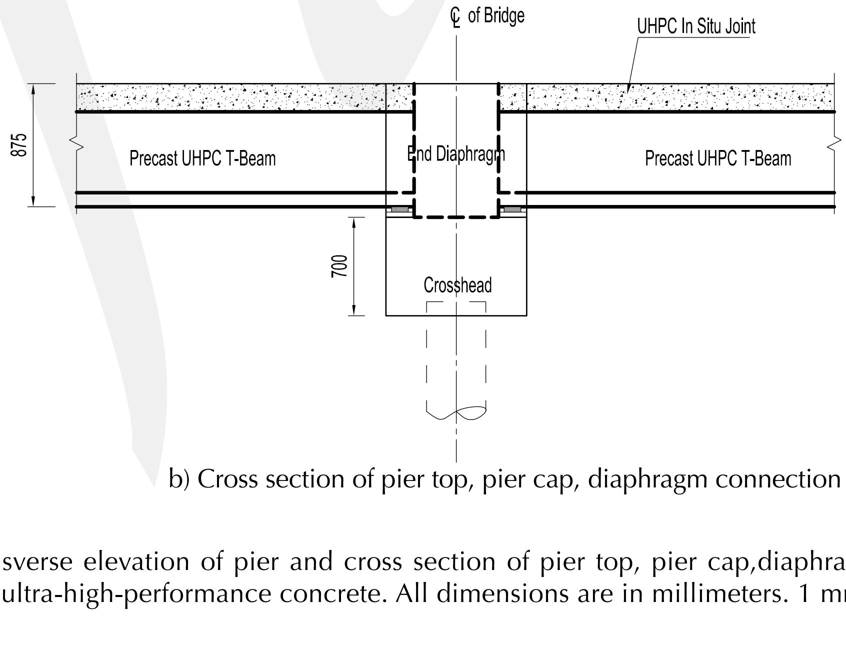
5.16.4 Substructure

5.16.4.1 Piers

The piers of the structure consist of one solid reinforced column that is founded on a pile cap (Fig. 5-171a). In general, on top of the pier, there is a pier cap. The height of the piers varies as required by the vertical alignment.



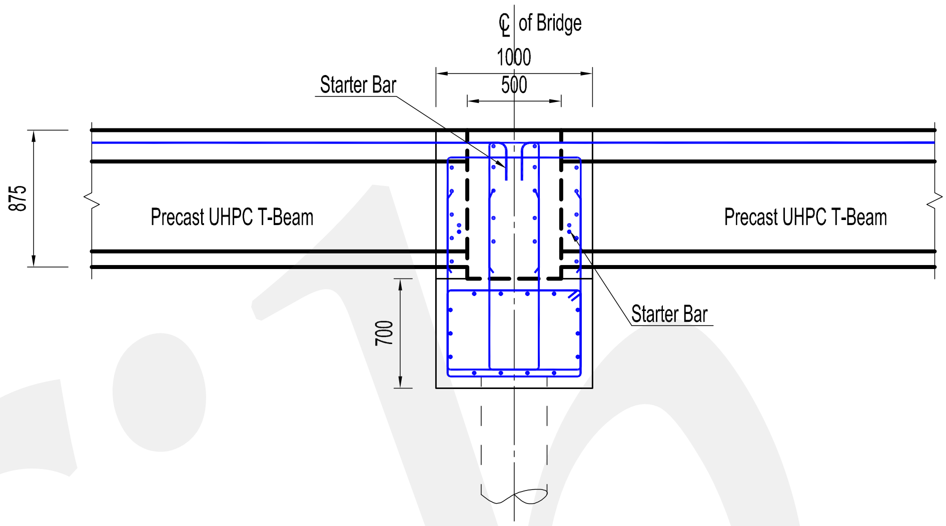
a) Transverse elevation of pier



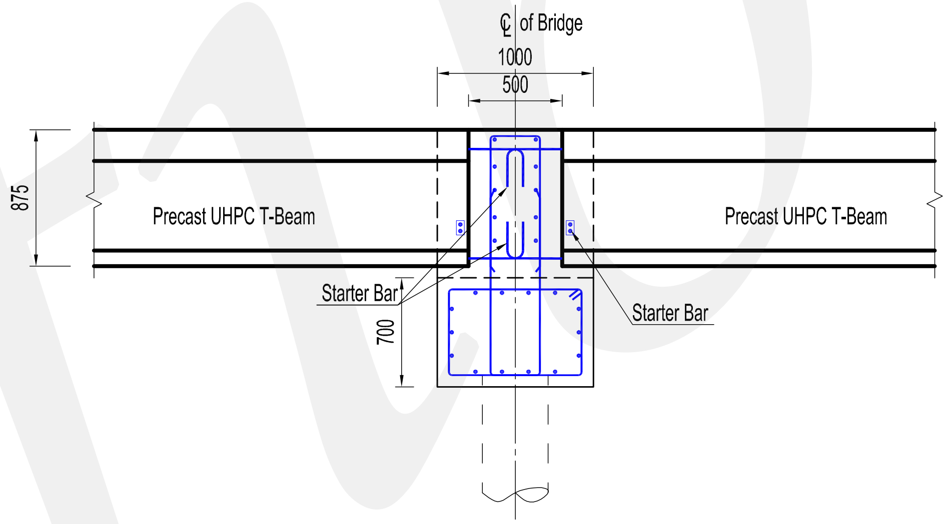
b) Cross section of pier top, pier cap, diaphragm connection

Fig. 5-171 Transverse elevation of pier and cross section of pier top, pier cap,diaphragm connection. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

The following shows a schematic diagram of the continuity connection of the UHPFRC girders over the pier and pier cap. The superstructure is made continuous at both piers and abutments by casting 40 MPa (6 ksi) concrete end diaphragms. Mild steel reinforcement is provided between and alongside the girders to provide negative moment reinforcement to make the connection continuous at the pier or abutment sections . All girders are set on a thin plinth and rubber strips (not elastomeric) placed on the abutments and piers.



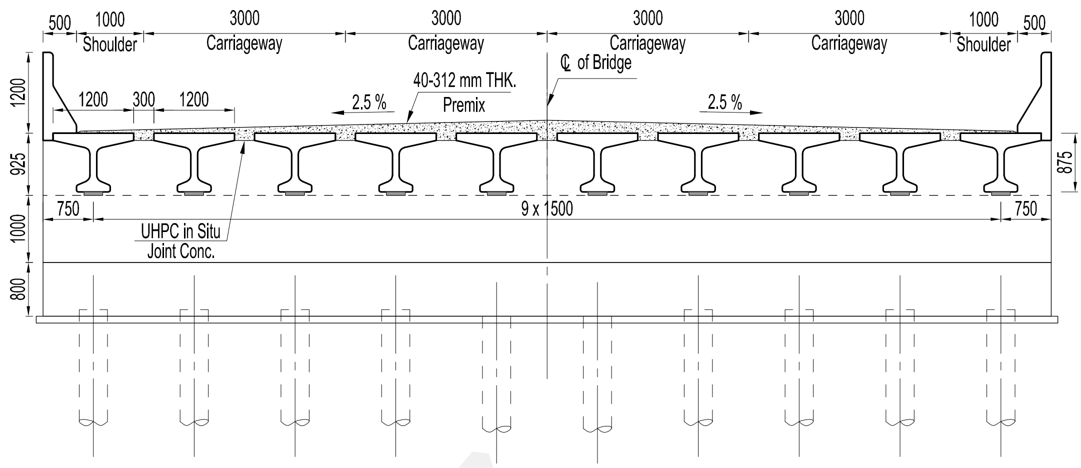
a) Between precast concrete girders



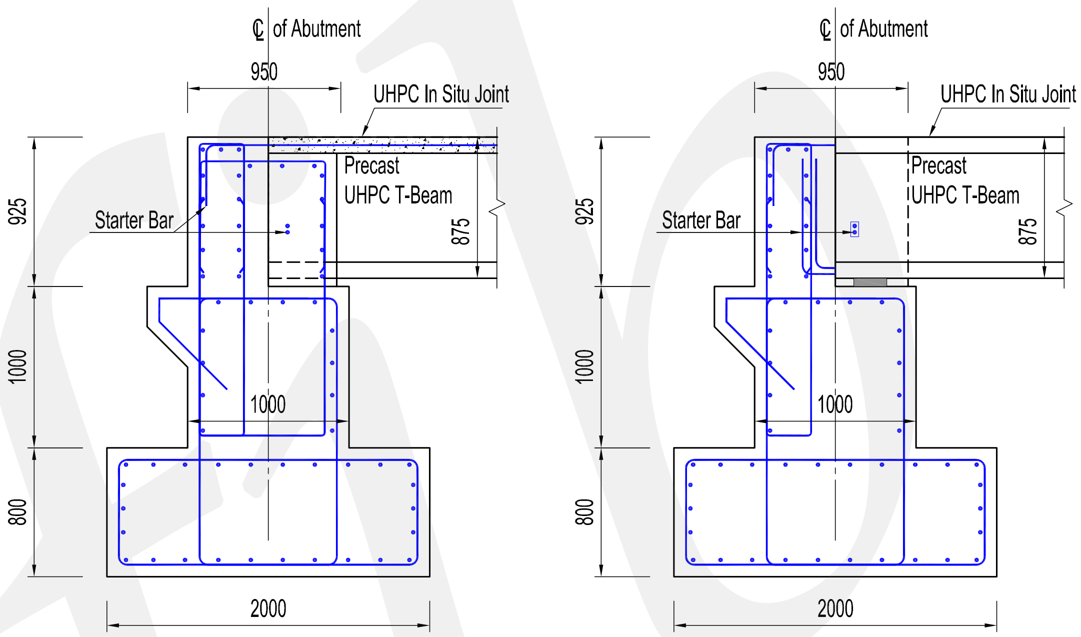
b) Through the girder

Fig. 5-172 Cross section of the continuity connection over the pier between precast concrete girders and through the girder. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

The abutments are CIP reinforced concrete structures. On top of the abutments, the girders are supported by a plinth and rubber strip. The opposite side of the abutment supports an approach slab to the bridge (Fig. 5-173).



a) Transverse elevation view of abutment



b) Cross-section views of abutment

c) Photo of example of abutment

Fig. 5-173 Views of abutment. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.16.5 Transverse slopes

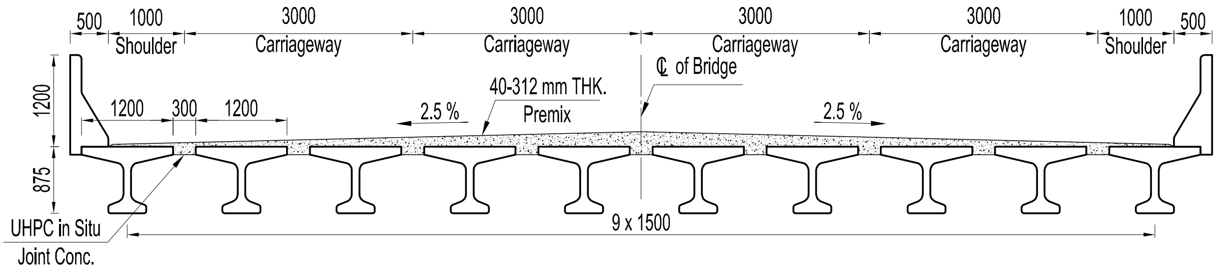
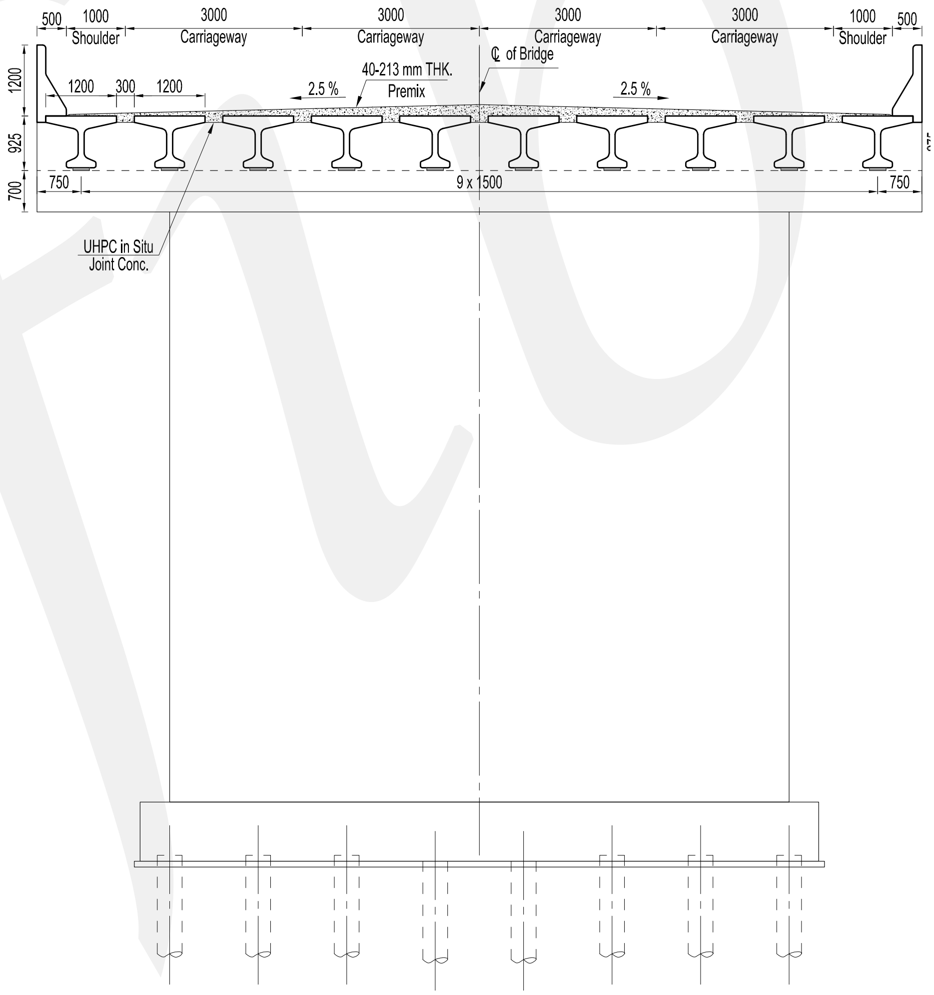


Fig. 5-174 Bridge cross section showing 2.5% transverse slopes. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

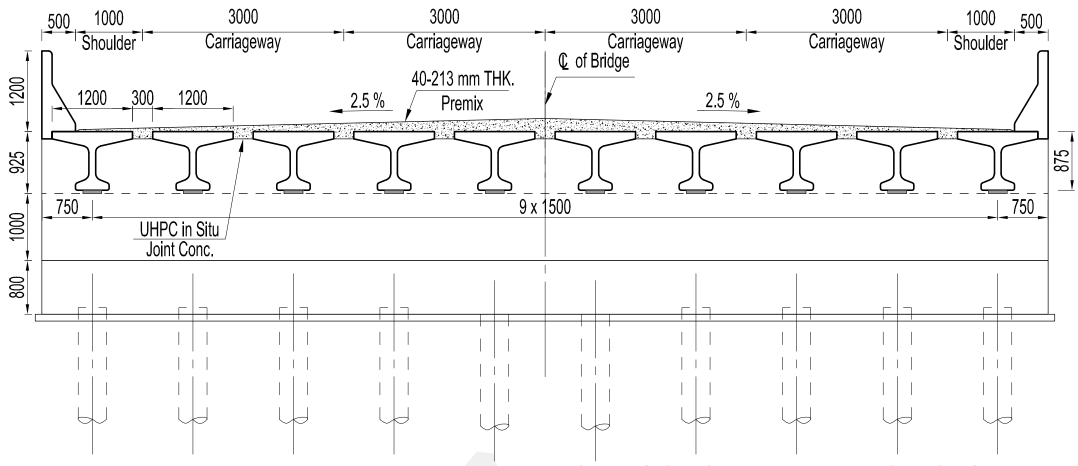
The deck of the bridge has 2.5% transverse slopes formed by varying the thickness of plinths beneath the girders.

5.16.6 Transverse diaphragms

This solution uses diaphragms over the piers and abutments. No post-tensioning is used.



a) End diaphragm integrated with piers



b) End diaphragm integrated with abutments

Fig. 5-175 End diaphragm integrated with piers and abutments. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.16.7 Summary of the preliminary design

Number of spans	10
Continuity	Fully integral
Span length *L*, m	15
Girder depth *G*, mm	875
Slab depth *H*, mm	No slab
Total depth *D* = *G* + *H*, mm	875
Web width *W*, mm	100
Girder spacing *S*, m	1.5
Precast concrete girder weight, tonnes	850 kg/m × 14.5 m = 12.33 tonnes (include stitching)
L/*D*	17.14
L/*G*	17.14
Average depth, mm	(0.348 m^2 × 10 beams)/15 m width = 232 mm
Prestressing steel, kg/m^2	(2+16) strands/beam × 1.12 kg/m × 14.5 m × 10 beams/(per span area 15 m × 15 m) = 13 kg/m^2
Reinforcing steel – girder, kg/m^2	450 kg × 10 beams/(per span area 15 m × 15 m) = 20 kg/m^2
Reinforcing steel – top slab, kg/m^2	n/a
Reinforcing steel in a diaphragm, kg/m^2	120 kg/m^3 × 0.925 × 1 × 15 m/(per span area 15 m × 15 m) = 7.4 kg/m^2

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.16.8 Construction sequence

- This type of bridge is built with the following construction procedures:
- The construction starts with the installation of piles.
- The pile cap is constructed on the piles.

- Columns and pier caps or pier beams are cast in place using 40 MPa (6 ksi) normal concrete at piers and abutments where the reinforcement from pier caps is extended for the composite connection with the diaphragm.
- The T girders are fabricated in a factory and transported to the site and erected on the piers and abutments.
- Following erection of the girders, joints between the T girders will be stitched using CIP UHPFRC150(22 ksi).
- The diaphragm is then CIP with normal 40 MPa (6 ksi) concrete to provide continuity using laps of reinforcement extended from the faces of girders and from the joints.

5.17 Example 17: bridge with ten 25 m (82 ft) long spans in Malaysia using UHPFRC

This example was furnished by Voo Yen Lei.

This theoretical example was based on a real project designed by the author in Sungai Nerok, Kota Tampan Air (Muaran), Jalan Lenggong, Gerik, Hulu Perak District, Perak D.R.

The following figure shows a picture of the finished structure that inspired this example.

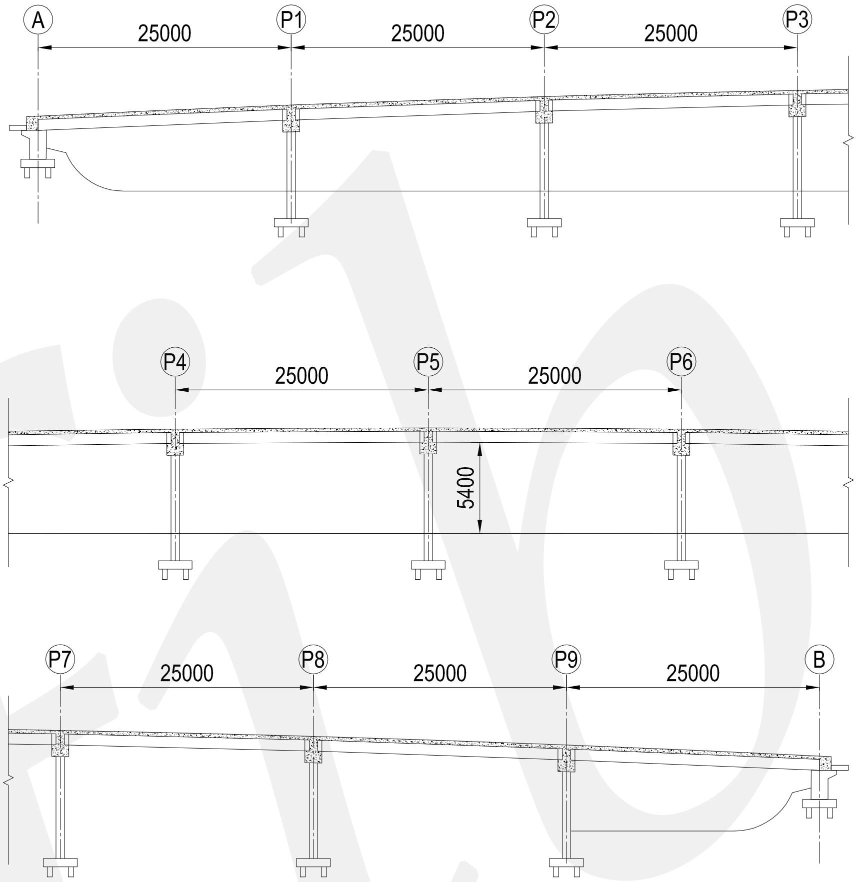
Fig. 5-176 View of Sungai Nerok Bridge.

5.17.1 Considerations identified

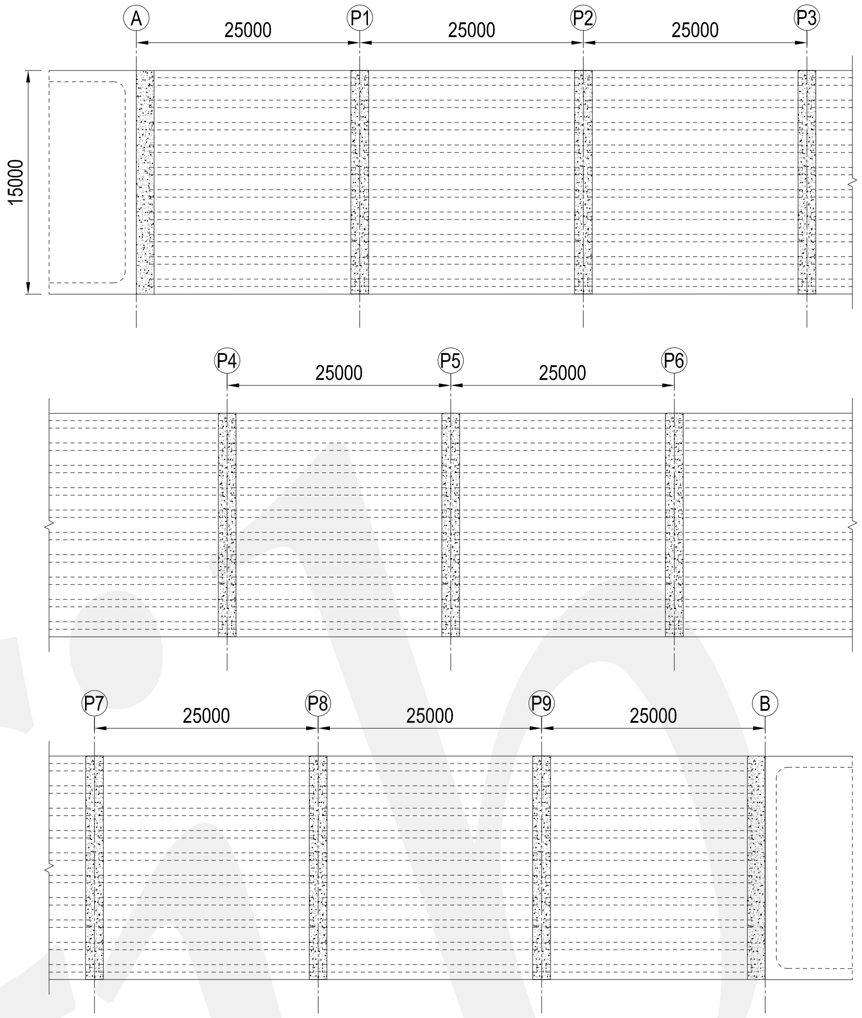
- Bridge layout: This example bridge has a total length of 250 m (492 ft) and a total width of 15 m (49 ft). The actual completed Sungai Nerok bridge that this example is based on is three spans of 30 or total 90 m (98 or 295 ft) long and 15 m (49 ft) wide.
- Codes: This example is governed by the following codes: BS 5400 Parts 1 to 10[5-6] and live load requirements of MoT, UK BD37/01[5-7].
- Maintenance: UHPFRC girders are nearly impermeable, which leads to reduced maintenance requirements.

5.17.2 Proposed solution

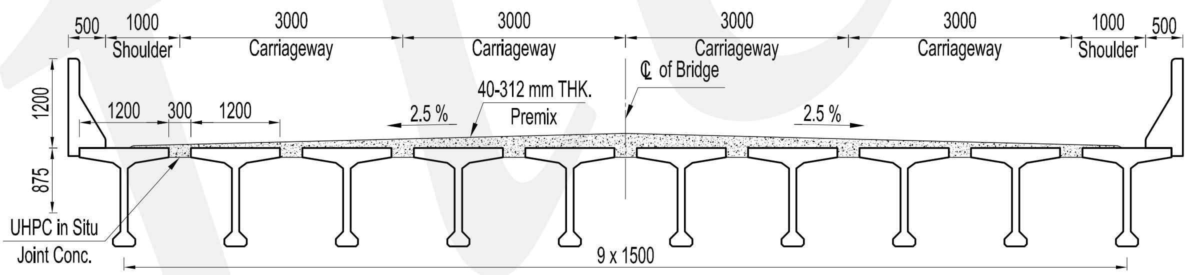
This example has ten spans, each with a length of 25 m (82 ft). The cross section consists of ten precast UHPFRC decked T girders 1'325 mm (52 in.) deep. The 1.2 m (3.9 ft) wide girders are spaced at 1.5 m (4.9 ft) on center leaving 300 mm (12 in.) wide joints. These spaces are later filled with UHPFRC stitching concrete. The wearing course is placed directly on top of the top flanges.



a) Elevation of the bridge



b) Plan of the bridge



c) Cross-section view

Fig. 5-177 Typical elevation, plan, and cross-section views of the bridge. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

The girders are fabricated with UHPFRC 150 having a 28-day characteristic compressive strength of 150 MPa (22 ksi). The deck of the bridge has a 2.5% transverse slope on both sides of center formed by the wearing surface on top of the flanges. The superstructure uses CIP reinforced concrete diaphragms over piers and abutments and CIP UHPFRC intermediate diaphragms at midspan. The UHPFRC T girders are post-tensioned with straight tendons. This solution provides structural continuity over the abutments and piers, accomplished by making the deck continuous and the end diaphragms at piers together with the extended reinforcement from the girders.

5.17.3 Superstructure

5.17.3.1 Precast concrete girders

5.17.3.1.1 Materials

Table 5-6 Material properties of precast concrete girders.

	UHPFRC150
Characteristic cylinder compressive strength f_{ck}, MPa	150
Characteristic cube compressive strength $f_{ck,cube}$, MPa	165
Characteristic tensile limit of elasticity $f_{ctk,el}$, MPa	7.0
Characteristic post-cracking tensile f_{ctfk}, MPa	8.0
Characteristic modulus of rupture $f_{ctk,fl}$, MPa	20
Mean value of Modulus of elasticity E_{cm}, GPa	50
Poisson's ratio of UHPFRC υ	0.2
Basic creep coefficient $\varphi_{b,28d}$	0.2
After curing shrinkage ε_{sh}	0

Note: UHPFRC = ultra-high-performance fiber-reinforced concrete. 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

Table 5-7 Material properties of the steel reinforcement used

Grade270 strands (ASTM A416-85*)			Grade 460 steel reinforcement (BS 4449†)						
Type	S15		Type	T10	T12	T16	T20	T25	T32
Diameter, mm	15.2		Diameter, mm	10	12	16	20	25	32
A_p, mm^2	140		A_s, mm^2	79	113	201	314	491	804
E_p, GPa	195		E_s, GPa	200	200	200	200	200	200
σ_{py}, MPa	1750		σ_{sy}, MPa	460	460	460	460	460	460
ε_{py}	0.01		ε_{sy}	0.002	0.002	0.002	0.002	0.002	0.002
F_{py}, kN	250		F_{sy}, kN	36	52	92	115	226	370
σ_{pu}, MPa	1888		σ_{su}, MPa	550	550	550	550	550	550
ε_{pu}	0.06		ε_{su}	0.1	0.1	0.1	0.1	0.1	0.1
F_{pu}, kN	270		F_{su}, kN	43	62	110	172	270	442

Note: A_p = area of prestressing tendons; A_s = cross sectional area of reinforcing steel; E_p = modulus of elasticity of prestressing steel; E_s = modulus of elastiticy of reinforcing steel; F_{pu} = ultimate tensile force of prestresssing steel; F_{py} = 1% proof-force of prestressing steel ; F_{su} = ultimate tensile force of reinforcing steel; F_{sy} = yield force of reinforcing steel; ε_{pu} = ultimate tensile strain of prestressing steel; ε_{py} = 1% strain of prestressing steel; ε_{su} = ultimate tensile strain of reinforcing steel; ε_{sy} = yield strain of reinforcing steel; σ_{pu} = ultimate tensile strength of prestresssing steel; σ_{py} = 1% proof-stress of prestressing steel; σ_{su} = ultimate tensile strength of reinforcement; σ_{sy} = yield strength of reinforcement1 mm = 0.0394 in.; 1 mm^2 = 0.00155 in.^{2}; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

* ASTM A416/A416M-18. Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete.

† BS 4449:2005, Steel for the reinforcement of concrete. Weldable reinforcing steel. Bar, coil and decoiled product.

5.17.3.1.2 Description of the cross section

Ten decked T girders, 1325 mm (52 in.) deep spaced at 1.5 m (4.9 ft) on center and with a single thin web 100 mm (4 in.) wide. The top flanges of the precast concrete girders are typically 1.2 m (3.9 ft) wide and provide for 300 mm (12 in.) wide CIP UHFRPC stitches (except the edge beam where the top flange is 1350 mm [53 in.] wide). The wearing surface is placed directly on the top flanges of the girders and no forms or CIP structural deck is needed.

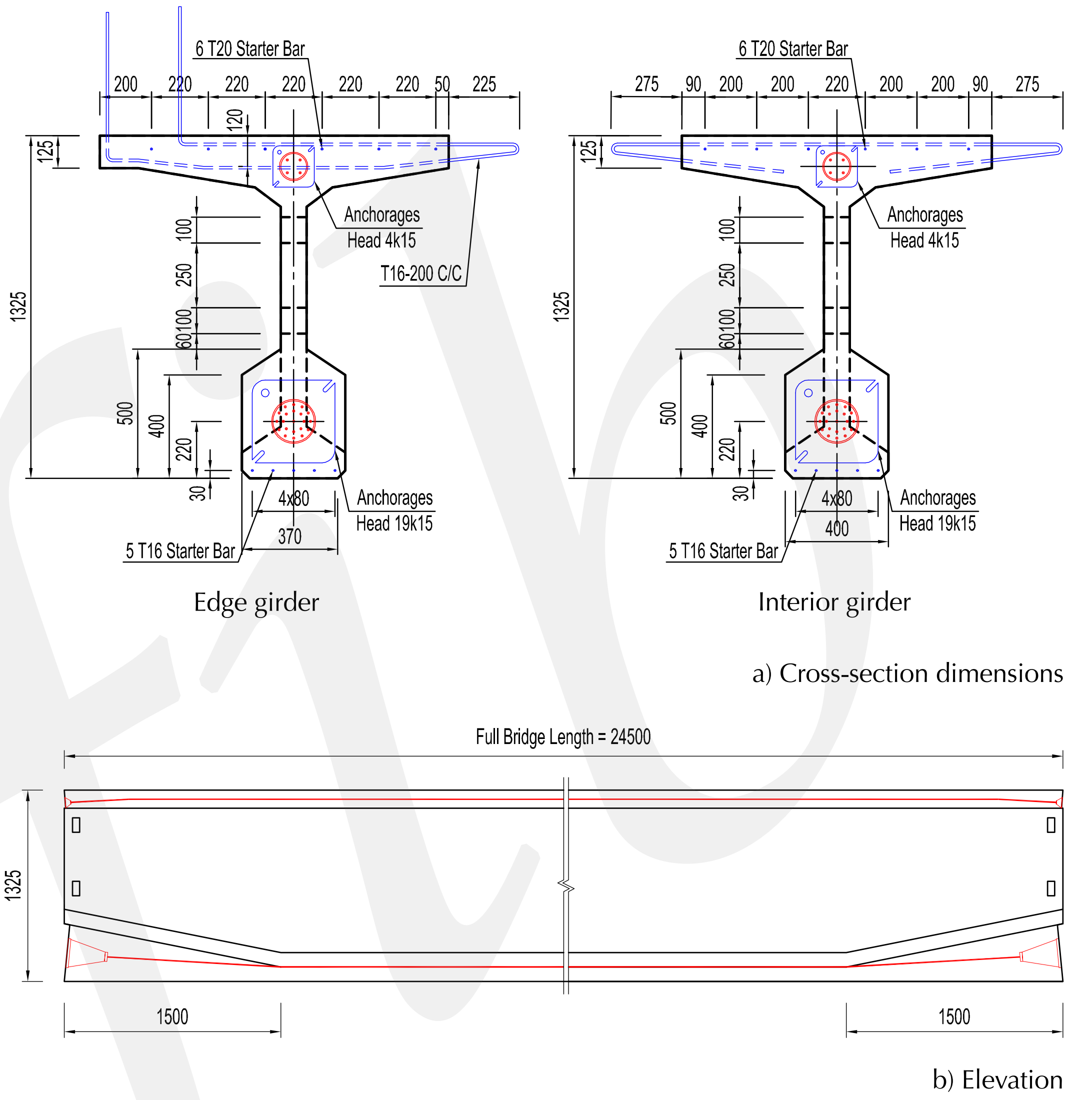


Fig. 5-178 Cross-section dimensions of T girder and elevation. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.17.3.1.3 Prestressing

The decked T girders are post-tensioned. The two straight tendons use 15.2 mm (0.6 in.) diameter strands: four strands in the tendon in the top flange and 19 strands in the tendon in the bottom flange. The precast UHPFRC girders do not have any major longitudinal or shear reinforcing steel at any part of the beams, with the exception of extended bars at the top flanges for composite connection purposes for the deck and minimal bursting reinforcement and extended bars at the anchorage zone of the beams

5.17.3.2 Slab

5.17.3.2.1 Materials

Concrete: 150 MPa (22 ksi)

Mild reinforcing steel: 460 MPa (67 ksi)

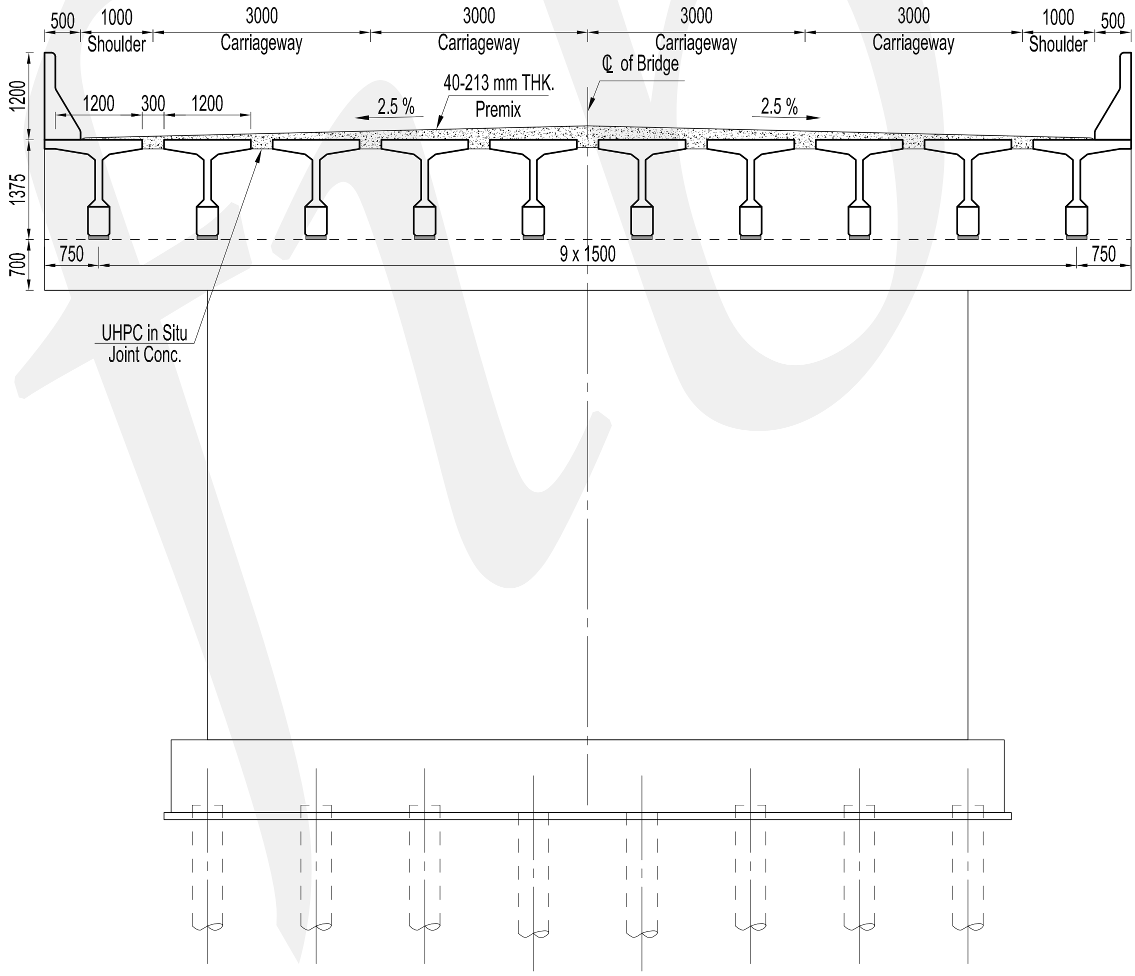
5.17.3.2.2 Deck slab description

The slab is integrated with the decked girder during manufacturing in the factory. During structural design, for simplicity, the engineer has neglected the 300 mm wide UHPFRC stitching concrete that is composite with the top flange as it does not add significant moment capacity to the section.

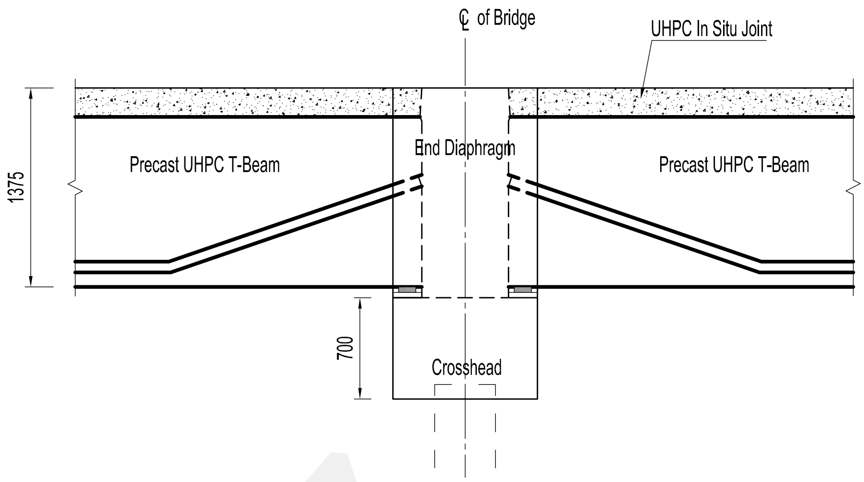
5.17.4 Substructure

5.17.4.1 Piers

The piers consist of one solid reinforced column that is CIP on the pile cap. In general, on top of each column there is a pier beam or pier cap. The height of the piers varies according to the vertical alignment.



a) Typical transverse elevation of a pier

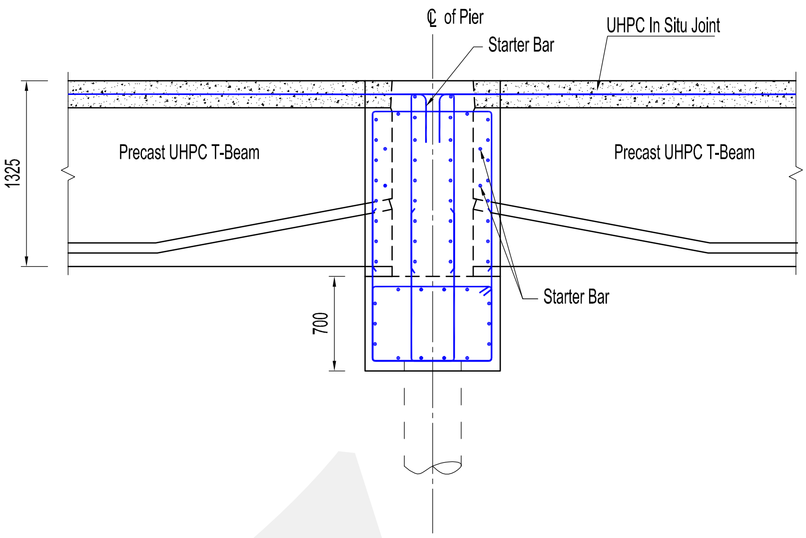


b) Cross section of pier cap and diaphragm

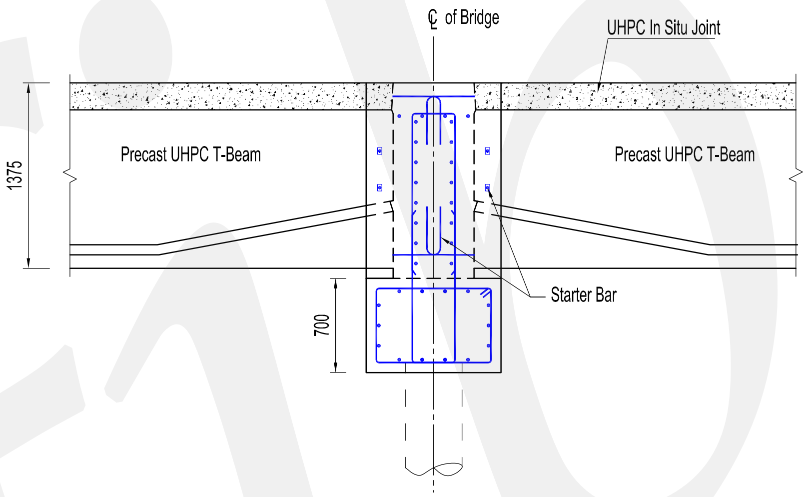
c) Example of typical diaphragm pier connection

Fig. 5-179 Typical transverse elevation of a pier, cross section of pier cap and diaphragm, and picture of a typical diaphragm pier connection. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

Figure 5-180 shows the schematic diagram on the continuity connection over the pier and pier cap. The superstructure is made continuous and integral at both piers and abutments by casting 40 MPa (6 ksi) concrete end diaphragms where reinforcement is provided between and alongside girders to provide negative moment reinforcement. The girders are seated on a thin plinth and rubber strips (not elastomeric) that are added on the abutments and pier caps.



a) Section between precast concrete girders

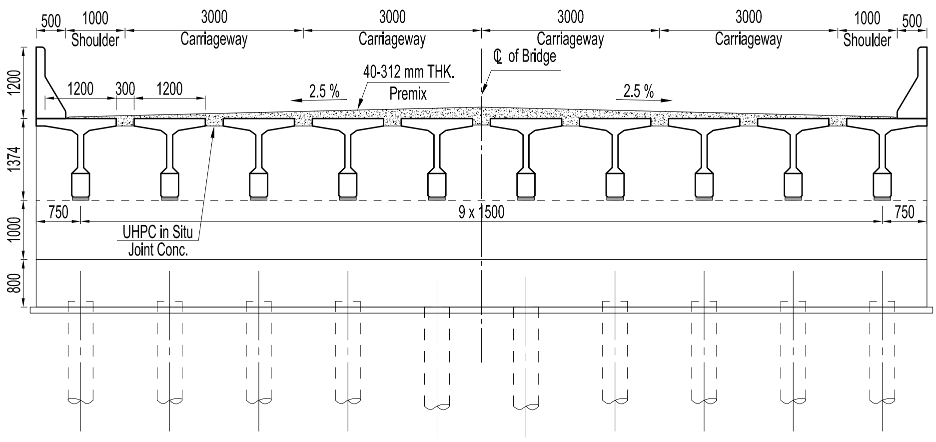


b) Section through the beam

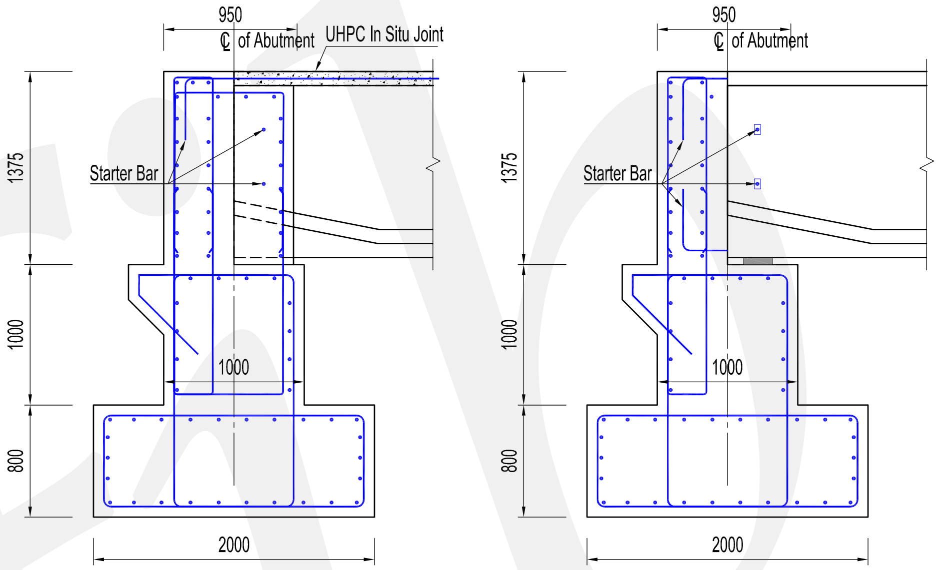
Fig. 5-180 Continuity detail over the pier: section between precast concrete girders and section through the beam. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.17.4.2 Abutments

The abutments are CIP reinforced concrete structures. On top of the abutments, the superstructure is supported by a plinth and rubber strip. The opposite side of the abutment supports the approach slab. See Fig. 5-180 for details.



a) Transverse elevation view of abutment



b) Section through abutment

Fig. 5-181 Transverse elevation view of abutment and section through abutment. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.17.5 Transverse slopes

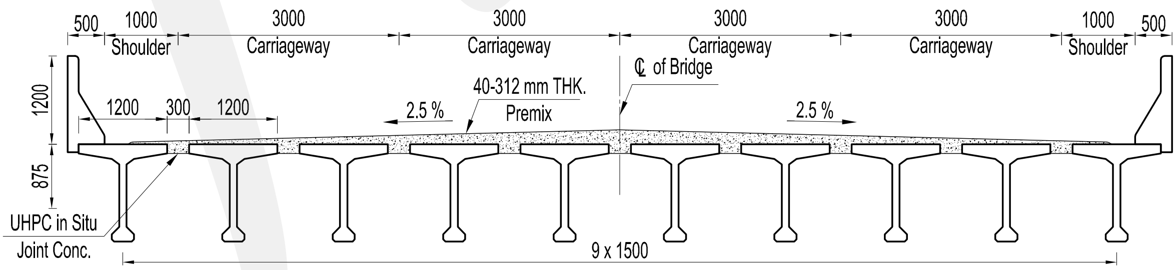
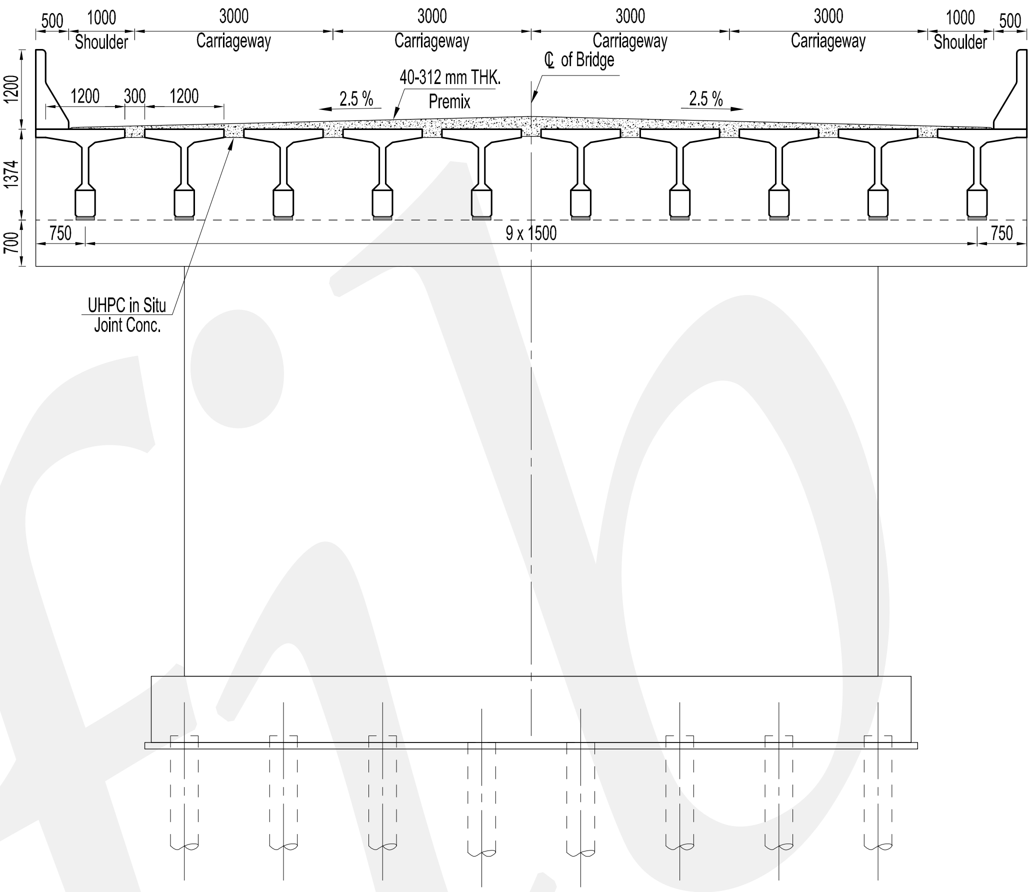


Fig. 5-182 Transverse elevation view of abutment and section through abutment. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

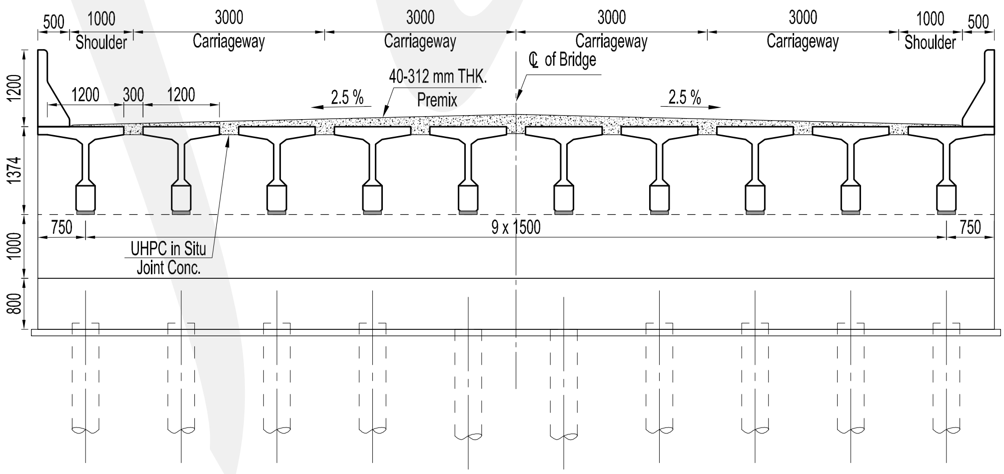
Figure 5-182 shows the bridge with 2.5% transverse slopes on both sides of centerline formed by varying the thickness of the wearing surface.

5.17.6 Transverse diaphragms

This solution uses diaphragms over the piers and abutment and intermediate transverse diaphragms at midspan. No post-tensioning is used.



a) End diaphragm integrated with piers



b) End diaphragm integrated with abutments

Fig. 5-183 End diaphragm integrated with piers and abutments. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

5.17.7 Summary of the preliminary design

Number of spans	10
Continuity	Fully integral
Span length *L*, m	25
Girder depth *G*, mm	1'325
Slab depth *H*, mm	No slab
Total depth *D* = *G* + *H*, mm	1325
Web width *W*, mm	100
Girder spacing *S*, m	1.5
Precast concrete girder weight, tonnes	1'000 kg/m × 24.5 m = 24.5 tonnes (include stitching)
L/*D*	18.86
L/*G*	18.86
Average depth, mm	(0.418 m^2 × 10 girders)/15 m width = 278 mm
Prestressing steel, kg/m^2	23 strands/girder × 1.12 kg/m × 24.5 m × 10 girders/(per span area 25 m × 15 m) = 16.83 kg/m^2
Reinforcing steel – girder, kg/m^2	760 kg × 10 girders/ (per span area 25 m × 15 m) = 20.3 kg/m^2
Reinforcing steel – top slab, kg/m^2	n/a
Reinforcing steel in a diaphragm, kg/m^2	120 kg/m^3 × 1.375 × 1 × 15 m/ (per span area 25 m × 15 m) = 6.6 kg/m^2

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.17.8 Construction sequence

This type of bridge is built with the following typical construction procedure.

- The construction work starts with the installation of piles.
- The pile cap is constructed on the piles.
- Abutments, columns, and pier caps or pier beams are cast in place using conventional concrete. Reinforcement from pier caps and abutments is extended for embedment in the diaphragm.
- The girders are fabricated in a factory and are transported directly to the site, where they are erected on the piers and abutments.
- After erecting girders on the piers and abutments, joints between the girders will be stitched using CIP UHPFRC.
- After erecting girders, they will be connected with CIP UHPFRC in the joints.
- The joint will be filled with UHPFRC and the diaphragm is constructed with conventional CIP concrete. The UHPFRC provides complete transverse continuity across the deck. The connection at the diaphragm provides continuity using extended reinforcement from the faces of beams.

Fig. 5-184 Example of construction of an abutment shown from the approach side.

Fig. 5-185 An example of typical pier and pier cap ready for installation of girders.

Fig. 5-186 Example of Transporting a decked T girder by truck and trailer.

Fig. 5-187 Girder arriving at bridge construction site, where it will be placed in temporary storage until needed for installation.

Fig. 5-188 Girders in temporary storage. Shores under flanges ensure stability.

In Fig. 5-188, note the post-tensioning anchorages in top and bottom flanges and the thickened bottom flange for strength around the anchorage there.

Fig. 5-189 The decked T girders are light enough to permit lifting by a single crane.

Fig. 5-190 Final positioning of the last edge girder.

Fig. 5-191 The 300 mm (12 in.) wide spaces will be filled with ultra-high-performance fiber-reinforced concrete and will develop the bars in that distance.

Fig. 5-192 Edges of the flanges are shown here having been protected, bottom forms are suspended from the wooden strong backs, and reinforcement is at the ready to extend from the joints at the ends.

Fig. 5-193 Ultra-high-strength fiber-reinforced concrete being placed using a tremie, then leveled.

Fig. 5-194 Final hand-finishing of the joint.

Fig. 5-195 Application of curing compound.

Fig. 5-196 Applying curing cover.

5.18 Example 18: Bridge with three 50 m (164 ft) long spans in Malaysia using UHPFRC

This example was furnished by Voo Yen Lei.

This theoretical example was based on a real project designed by the author in Section 49, Freeway 4 (KM157 Gerik-Kota Bahru), Corridor Ecology of Central Forest Spine (CFS), Gerik, Perak D.R.

The following figure shows a picture of the finished structure that inspired this example.

a) Aerial view of the CFS Bridge on which this example was based

b) Under view of CFS Bridge

c) Elevation view of CFS Bridge

Fig. 5-197 Various views of the CFS Bridge on which Example 18 is based.

5.18.1 Considerations identified

Bridge layout: This example bridge has a total length of 150 m (492 ft) and a total width of 15 m (49 ft). The actual completed CFS bridge consists of five 40 m (131 ft) long spans and 17.6 m (57.7 ft) wide deck and it is fully integral with the abutments and piers without expansion joints.

Codes: This example is governed by the following codes: BS 5400 Parts 1 to 10[5-15] and live load requirements to MoT, UK BD37/01[5-16].

Maintenance: UHPFRC girders are nearly impermeable, which leads to reduced maintenance requirements.

5.18.2 Proposed solution

This solution has three spans, each with a length of 50 m (164 ft). The cross section consists of three precast, prestressed UHPFRC U girders with a depth of 2'000 mm (79 in.). The three precast concrete elements are spaced 5 m (16 ft) on center and a 200 mm (8 in.) thick CIP deck slab is used.

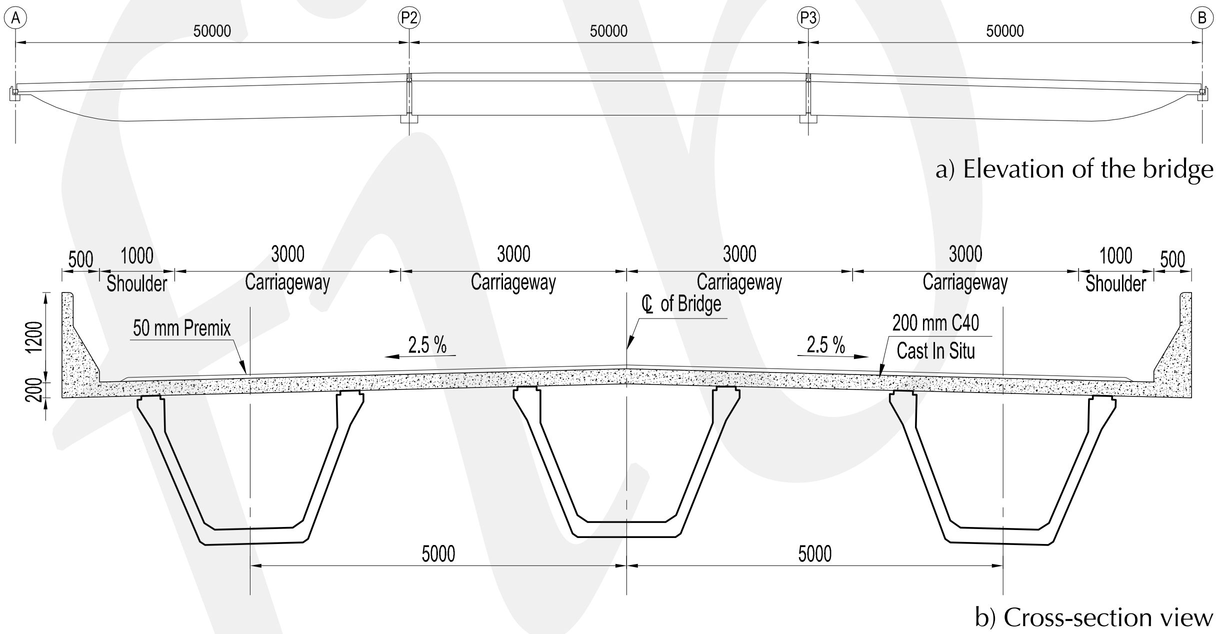


Fig. 5-198 Typical elevation and cross-section view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

The U girders are fabricated with UHPFRC 150 with a 28-day characteristic compressive strength above 150 MPa (22 ksi). The CIP conventional concrete deck slab is 200 mm (8 in.) thick. The bridge has 2.5% transverse slopes on both sides of centerline. CIP reinforced concrete diaphragms are used at piers and abutments, but no intermediate diaphragms are used at midspan. The precast UHPFRC U girders are post-tensioned. This solution provides structural continuity at the abutments and over piers. This is accomplished by making the deck continuous and by casting the end diaphragm at pier together with the deck.

5.18.3 Superstructure

5.18.3.1 Precast concrete girders

5.18.3.3.1 Materials

Table 5-8 Material properties of precast concrete beam.

	UHPFRC150
Characteristic cylinder compressive strength f_{ck}, MPa	150
Characteristic cube compressive strength $f_{ck,cube}$, MPa	165
Characteristic tensile limit of elasticity $f_{ctk,el}$, MPa	7.0
Characteristic post-cracking tensile f_{ctfk}, MPa	8.0
Characteristic modulus of rupture $f_{ctk,fl}$, MPa	20
Mean value of modulus of elasticity E_{cm}, GPa	50
Poisson's ratio of UHPFRC υ	0.2
Basic creep coefficient $\varphi_{b,28d}$	0.2
After curing shrinkage ε_{sh}	0

Note: UHPFRC = ultra-high-performance fiber-reinforced concrete. 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

Table 5-9 Material properties of the steel reinforcement used.

Grade 270 strands (ASTM A416-85*)		Grade 460 steel reinforcement (BS 4449†)						
Type	S15	Type	T10	T12	T16	T20	T25	T32
Diameter, mm	15.2	Diameter, mm	10	12	16	20	25	32
A_p, mm^2	140	A_s, mm^2	79	113	201	314	491	804
E_p, GPa	195	E_s, GPa	200	200	200	200	200	200
σ_{py}, MPa	1750	σ_{sy}, MPa	460	460	460	460	460	460
ε_{py}	0.01	ε_{sy}	0.002	0.002	0.002	0.002	0.002	0.002
F_{py}, kN	250	F_{sy}, kN	36	52	92	115	226	370
σ_{pu}, MPa	1888	σ_{su}, MPa	550	550	550	550	550	550
ε_{pu}	0.06	ε_{su}	0.1	0.1	0.1	0.1	0.1	0.1
F_{pu}, kN	270	F_{su}, kN	43	62	110	172	270	442

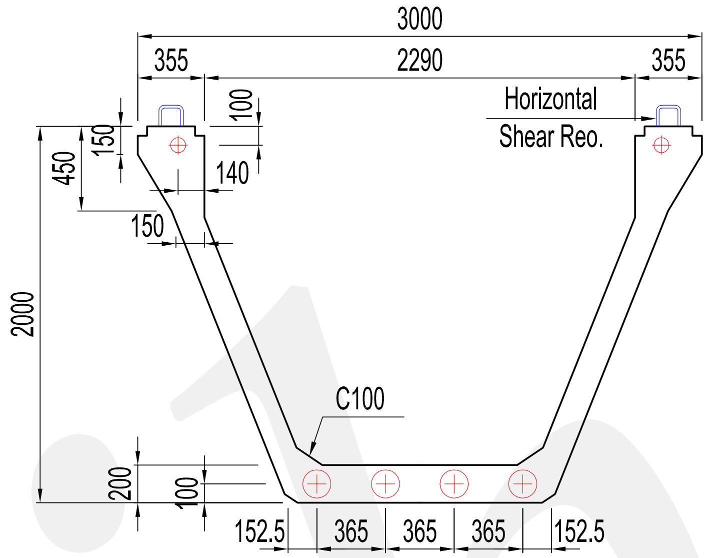
Note: A_p = area of prestressing tendons; A_s = cross sectional area of reinforcing steel; E_p = modulus of elasticity of prestressing steel; E_s = modulus of elastiticy of reinforcing steel; F_{pu} = ultimate tensile force of prestresssing steel; F_{py} = 1% proof-force of prestressing steel; F_{su} = ultimate tensile force of reinforcing steel; F_{sy} = yield force of reinforcing steel; ε_{pu} = ultimate tensile strain of prestressing steel; ε_{py} = 1% strain of prestressing steel; ε_{su} = ultimate tensile strain of reinforcing steel; ε_{sy} = yield strain of reinforcing steel; σ_{pu} = ultimate tensile strength of prestresssing steel; σ_{py} = 1% proof-stress of prestressing steel; σ_{su} = ultimate tensile strength of reinforcement; σ_{sy} = yield strength of reinforcement 1 mm = 0.0394 in.; 1 mm^2 = 0.00155 in.^{2}; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi.

* ASTM A416/A416M-18. Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete.

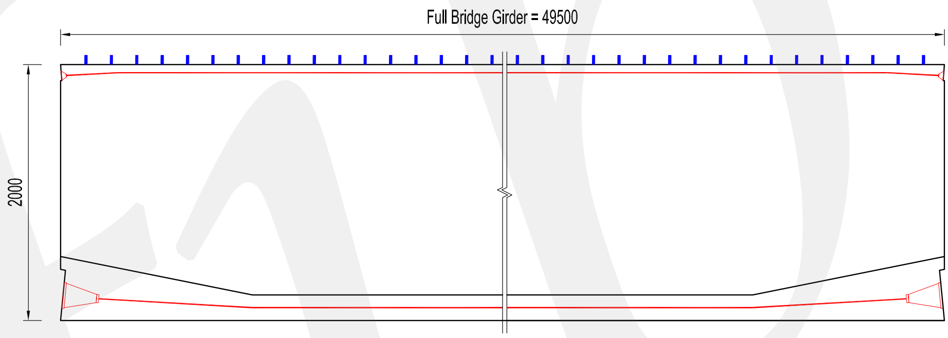
† BS 4449:2005, Steel for the reinforcement of concrete. Weldable reinforcing steel. Bar, coil and decoiled product.

5.18.3.1.2 Description of the cross section

Three U girders 2000 mm (79 in.) deep. The bottom flange is 1'400 mm (55 in.) wide and the top flanges are each 355 mm (14 in.) wide. The web is 150 mm (6 in.) thick.



a) Cross section



b) Elevation

Fig. 5-199 Cross section and elevation of U girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.18.3.1.3 Prestressing

The precast concrete U girders are post-tensioned with six straight tendons of 15.2 mm (0.6 in.) diameter strands. The tendon in each top flange has four strands and each of the four tendons in the bottom flange contains 27 strands. Otherwise, the precast concrete girders do not have any other longitudinal or shear reinforcement, except for extended vertical rebars at the top flange (to ensure composite action with the CIP concrete deck) and extended tie bars at the ends of the girders.

5.18.3.2 Deck slab

5.18.3.2.1 Materials

Concrete: 40 MPa (6 ksi)

Mild reinforcing steel: 460 MPa (67 ksi)

5.18.3.2.2 Deck slab description

A CIP concrete deck slab with a thickness of 200 mm (8 in.) is cast on top of precast concrete deck panels. These panels serve as stay-in-place forms. They are placed on ledges cast on both top edges of the top flanges of the girders, both over and between the girders. Conventional deck slab reinforcement is placed on top of the panels.

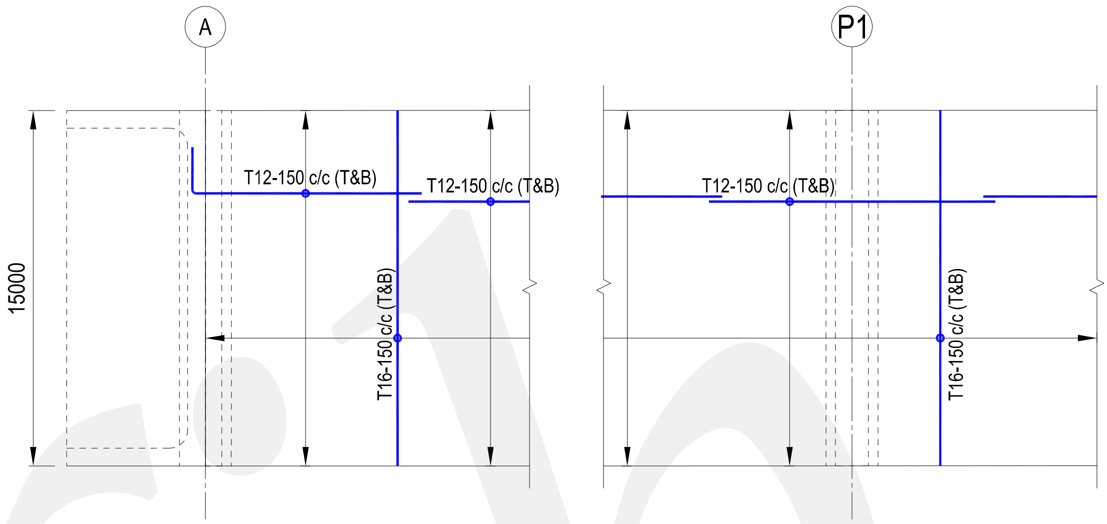
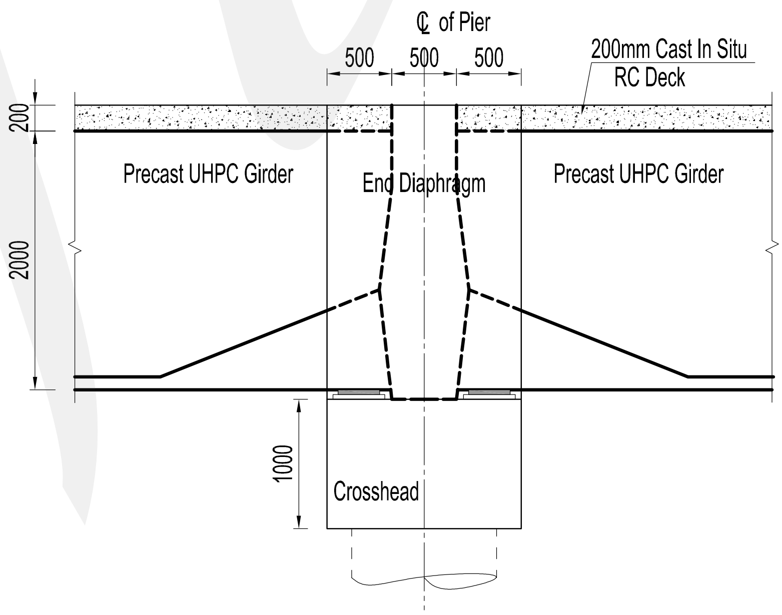


Fig. 5-200 Reinforcement details of the cast-in-place deck. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

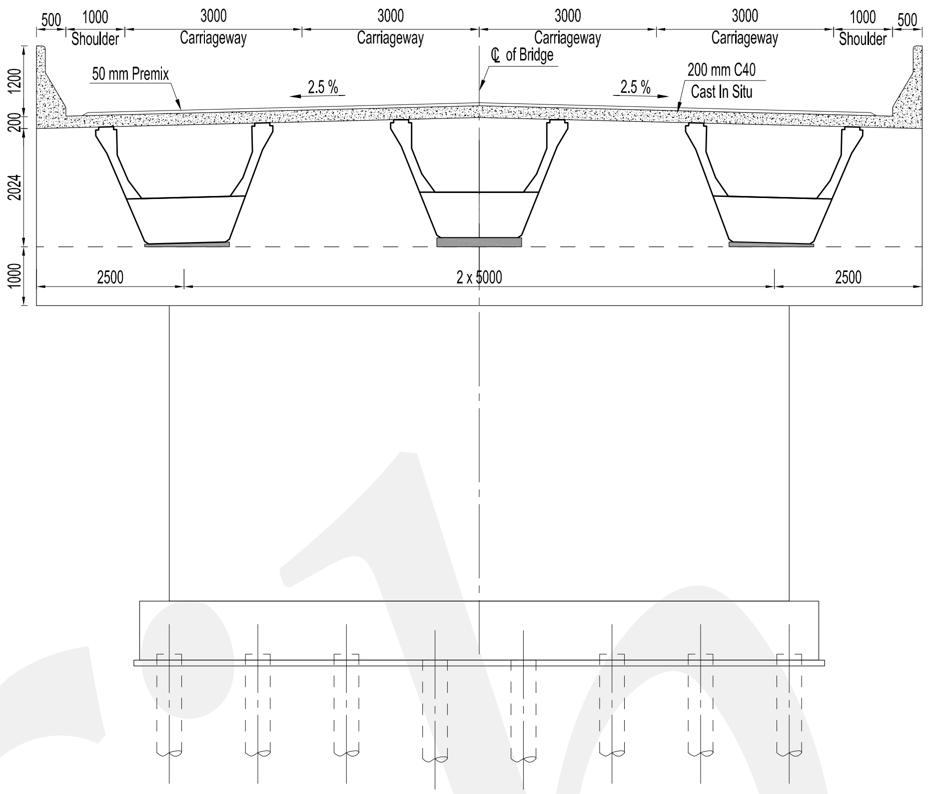
5.18.4 Substructure

5.18.4.1 Piers

Figure 5-201 shows an elevation of a pier and a section through a pier cap and diaphragm. The pier is one solid reinforced column cast on a pile cap. On top of each column there is a CIP pier cap. The height of the piers varies as determined by the vertical alignment.



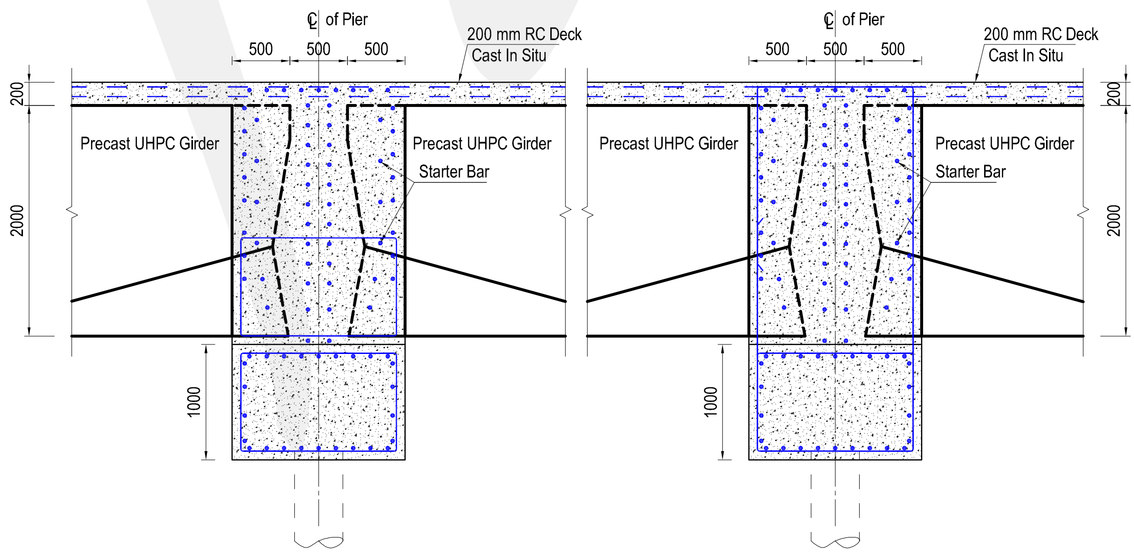
a) Typical cross section of pier cap and diaphragm



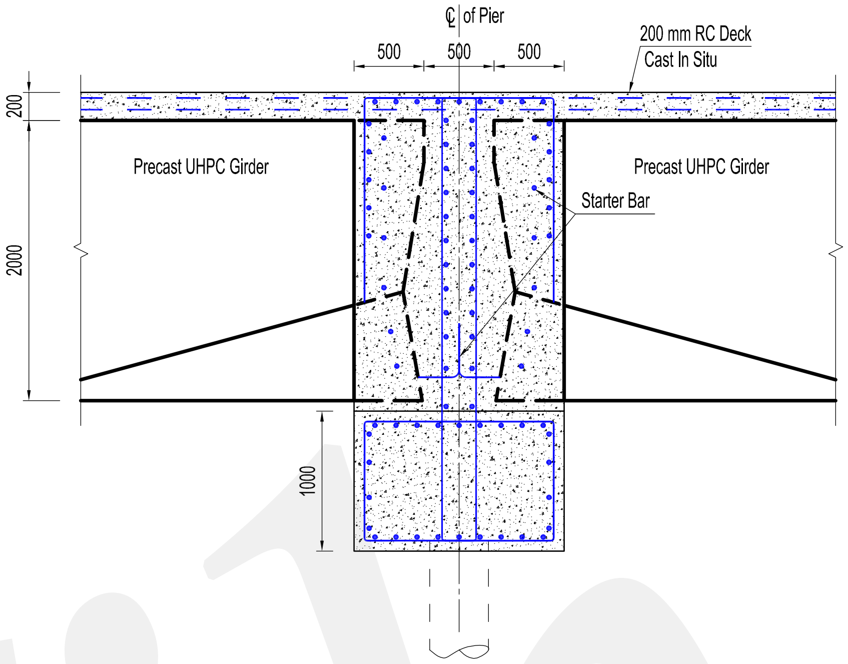
b) Transverse elevation of the structure at a pier

Fig. 5-201 Typical cross section of pier cap and diaphragm and transverse elevation of the structure at a pier. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.

Figure 5-202 shows the schematic diagram of the continuity connection of the UHPFRC beams over the pier and pier cap. The superstructure is continuous and integral at piers and abutments by casting 40 MPa (6 ksi)concrete end diaphragms where reinforcement is provided between and alongside girders to provide negative moment reinforcement. The girders sit on thin, variable depth plinths and rubber strips (not elastomeric), which placed on the abutments and pier caps.



a) Between precast concrete girders



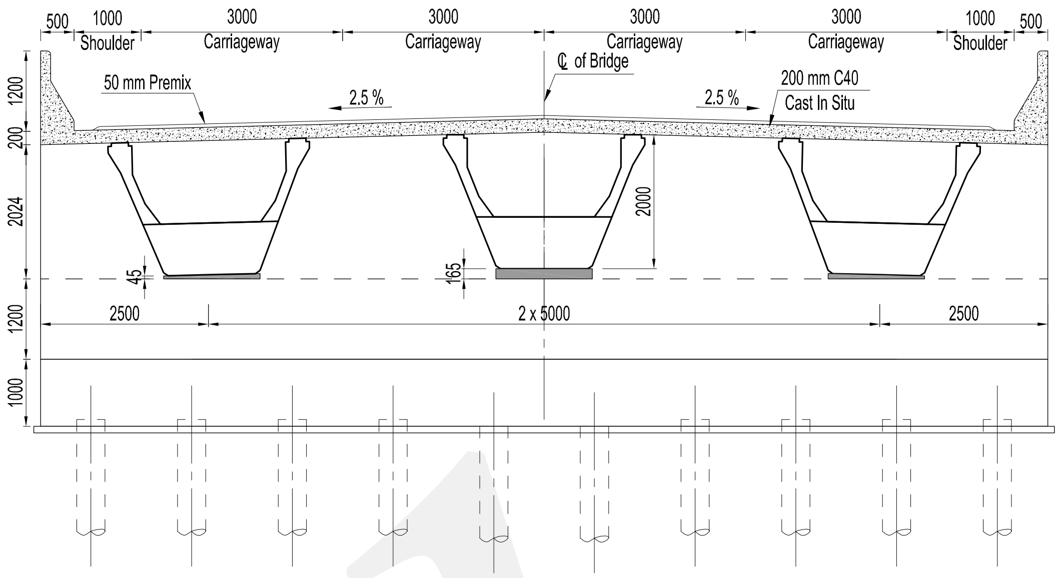
b) Through the girder

Fig. 5-202 Continuity detail shown in a section through the pier capbetween the precast concrete girders and through the girder. Note: UHPC = ultra-high-performance concrete. All dimensions are in millimeters. 1 mm = 0.0394 in

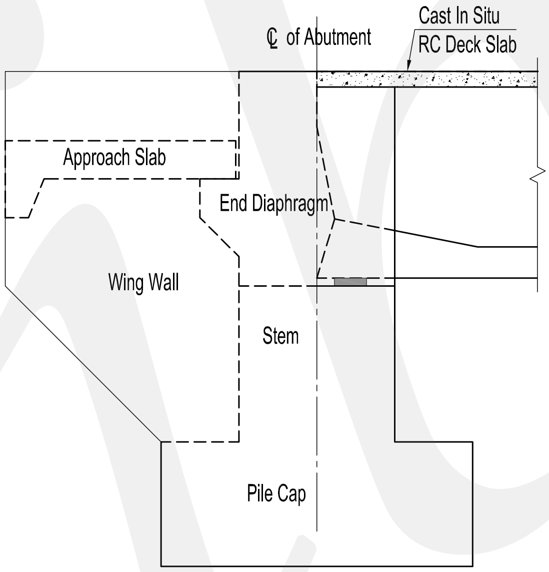
Fig. 5-203 Preparing to form a diaphragm on a pier beam on this bridge, similar to the example.

5.18.4.2 Abutments

The abutments are CIP reinforced concrete structures. On top of the abutments, the superstructure is supported by variable thickness plinths and rubber strips. The opposite side of the abutment supports the approach slab.



a) Transverse elevation view of abutment



b) Section through abutment

c) Construction of similar bridge nearly ready for forming the diaphragm

Fig. 5-204 Transverse elevation view of abutment, section through abutment, and construction of similar bridge nearly ready for forming the diaphragm. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.18.5 Transverse slopes

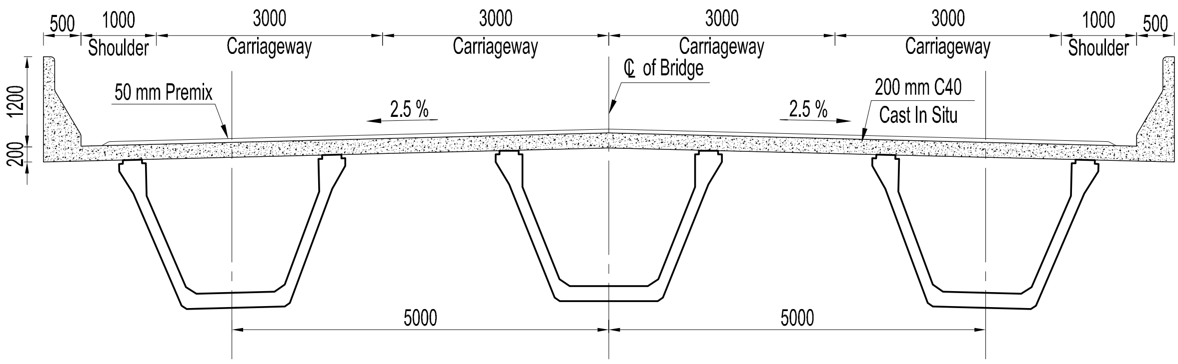
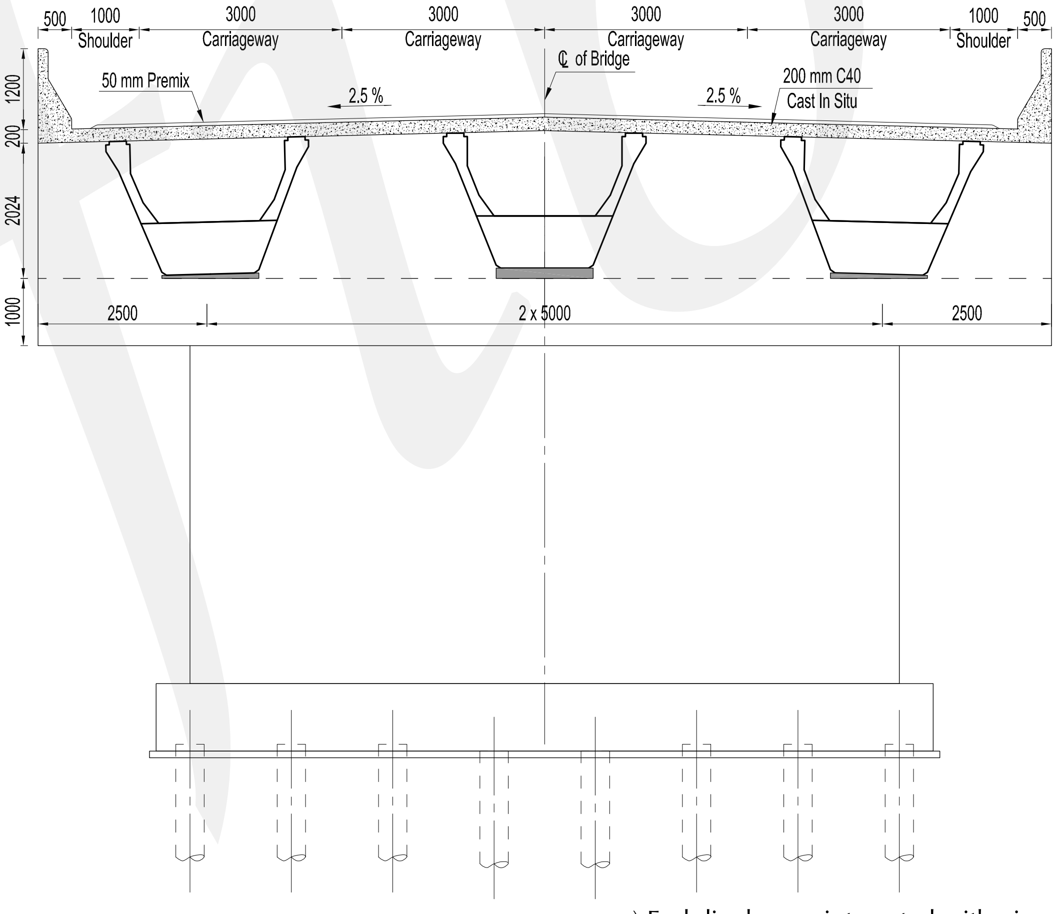


Fig. 5-205 Bridge superstructure showing 2.5% transverse slopes. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

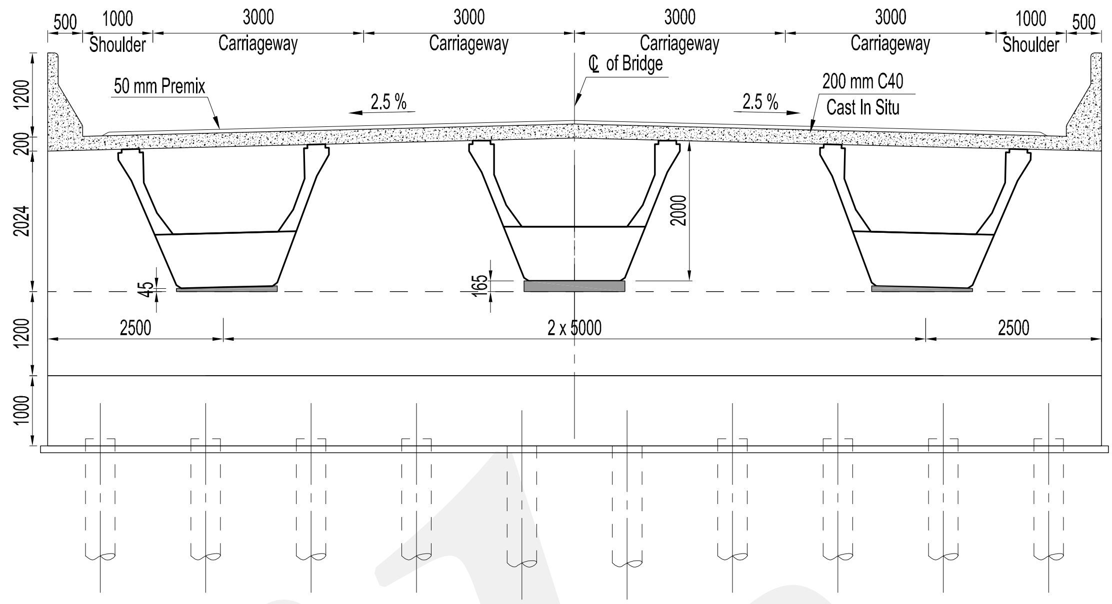
The bridge has transverse slopes created by varying the thickness of plinths beneath the girders. Girders are erected plumb.

5.18.6 Transverse diaphragms

This solution uses diaphragms over the supports but no intermediate diaphragms at midspan. No post tensioning is used.



a) End diaphragm integrated with piers



b) End diaphragm integrated with abutments

Fig. 5-206 End diaphragms integrated with piers and abutments. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.18.7 Summary of the preliminary design

Number of spans	3
Continuity	Fully integral
Span length *L*, m	50
Girder depth *G*, mm	2'000
Slab depth *H*, mm	200
Total depth *D* = *G* + *H*, mm	2'200
Web width *W*, mm	2 webs × 150 = 300
Girder spacing *S*, m	5
Precast concrete girder weight, tonnes	2300 kg/m × 49.5 m = 114 tonnes
L/D	22.73
L/G	25
Average depth, mm	(0.2 m × 15 m wide + 0.95 m^2 × 3 girders) / (15 m wide) = 390 mm
Prestressing steel, kg/m^2	(2 × 4 + 4 × 27) strands/girder × 1.12 kg/m × 49.5 m × 3 girders/(15 m × 50 m) = 25.72 kg/m^2
Reinforcing steel – girder, kg/m^2	3'500 kg × 3 girders/ (50 m × 15 m) = 14 kg/m^2
Reinforcing steel – top slab, kg/m^2	314 kg/m^3 × 0.2 m thick = 63 kg/m^2
Reinforcing steel in a diaphragm, kg/m^2	140 kg/m^3 × 2.25 × 1.5 × 15 m/ (area of each span 50 m × 15 m) = 9.45 kg/m^2

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.18.8 Construction sequence

This type of bridge is built with the following construction procedure.

- The construction work starts with the installation of piles.
- Pile caps are cast on the piles.
- Abutments, columns, and pier caps or pier beams are CIP conventional concrete. Reinforcement from the pier caps and abutments extends out for embedment in the diaphragm.
- The girders are fabricated in a factory and are transported directly to the site, where they are erected on the piers and abutments.
- After erecting girders, precast concrete stay-in-place forms are placed over and between the girders.
- Formwork is installed at the edges of the bridge and reinforcement is installed for the CIP concrete deck and diaphragms.
- The concrete deck and diaphragms are then cast at one time using conventional concrete to provide continuity.

Fig. 5-207 Forms for the construction of the pier beam have been removed. Girders are staged nearby ready to be put in place.

Fig. 5-208 Another view of piers with girders awaiting erection. Girders have begun to be set in the background.

Fig. 5-209 These U girders require two cranes for erection.

Fig. 5-210 This bridge, like the example bridge, has three girders in the cross section and vertical curvature.

Fig. 5-211 Edge forms for the deck and curb have been built and reinforcement placed awaiting casting of the deck concrete.

Fig. 5-212 The completed bridge in service.

Fig. 5-213 An aerial view of the completed bridge.

Fig. 5-214 Aerial view of completed bridge constructed in a very rural environment.

Fig. 5-215 Underside view of the finished bridge showing an integral pier connection.

5.19 Example 19: bridge with ten 15 m (49 ft) spans in New Zealand

This example was furnished by Alessandro Palermo.

5.19.1 Considerations identified

- Bridge layout: This example bridge has a total length of 150 m (492 ft) and a total width of 15 m (49 ft). The deck carries two lanes of traffic. There are sidewalks for pedestrians and cyclists on each side of the bridge. All spans are equal in length and all piers are the same height.
- Geological and geotechnical factors: The soil is Class D (soil) and the site is 20 km (93 mi) from any known fault.

- Codes: This example is governed by the action code NZS 1170.5 (2004)[5-17], the concrete design code NZS 3101 (2006)[5-18],and the New Zealand Transport Agency Bridge Manual[5-19].
- Environmental: The structure does not span flowing water.

5.19.2 Proposed solution

This solution has 10 spans, each with a length of 15 m (49 ft). The cross section chosen consists of 15 single hollow-core units which are commonly used for short-span bridges in New Zealand. The single hollow-core units are designed to carry HN-HO-72 loading in accordance with the New Zealand Transport Agency Bridge Manual[5-19]. Single hollow-core units have the following advantages:

- They are seated on rubber strip bearings, which are much less expensive than elastomeric bearings required for other designs.
- No CIP structural deck is required, reducing dead load demand and the depth of girders.

For this bridge, a set of 13 x 650 mm (26 in.) deep single hollow-core girders, 11 interior and 2 exterior girders, prestressed longitudinally with straight strands and designed as simply supported elements. No top slab is required, and the asphalt wearing surface is placed directly on the single hollow-core girders. The bridge has 3% transverse slopes, on both sides of centerline. An asphalt concrete course is needed.

The spans are seated on 15 mm (0.6 in.) thick rubber strip bearings built up with mortar as required.

Transversally bonded post-tensioned diaphragms are used.

5.19.2.1 Plan

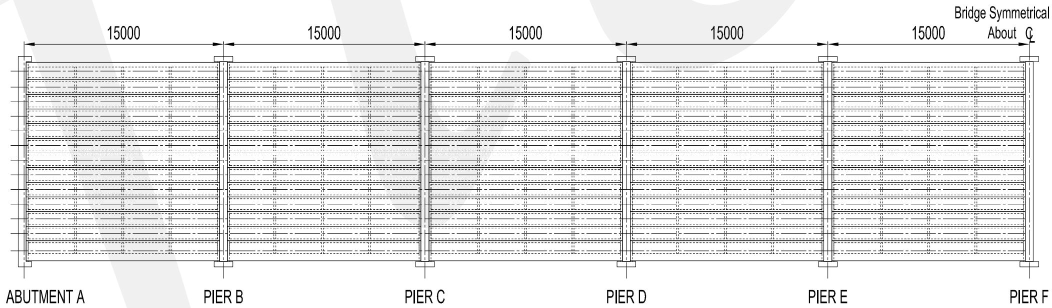


Fig. 5-216 Plan of one-half of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.2.2 Elevation

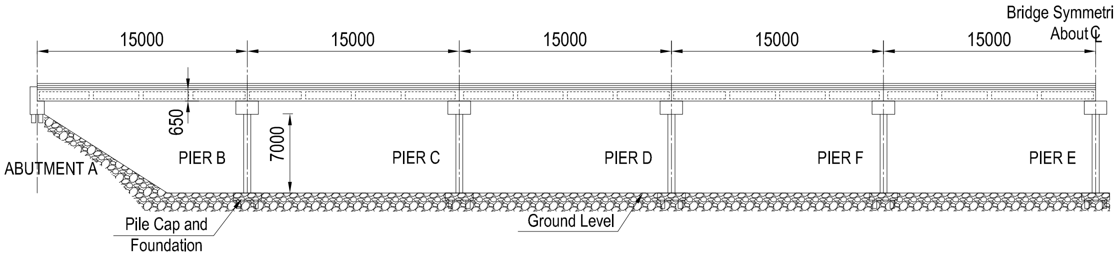


Fig. 5-217 Elevation of one-half of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.2.3 Cross section

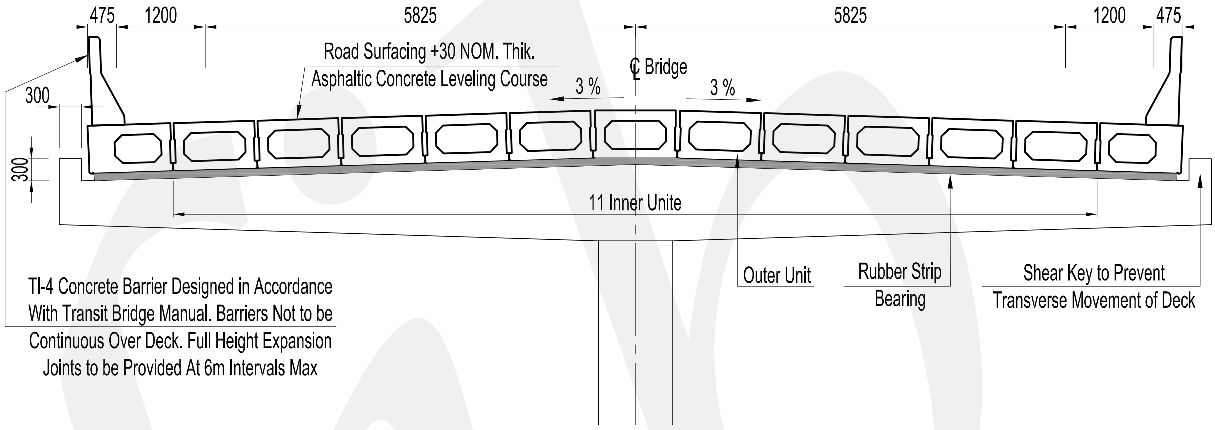


Fig. 5-218 Cross-section view of the bridge .Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.3 Superstructure

5.19.3.1 Precast concrete girders

5.19.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1'840 MPa (269 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.19.3.1.2 Description of the cross section

Thirteen single hollow-core girders, 650 mm (26 in.) deep, placed adjacent to each other (side by side). There are 11 interior and two exterior girders.

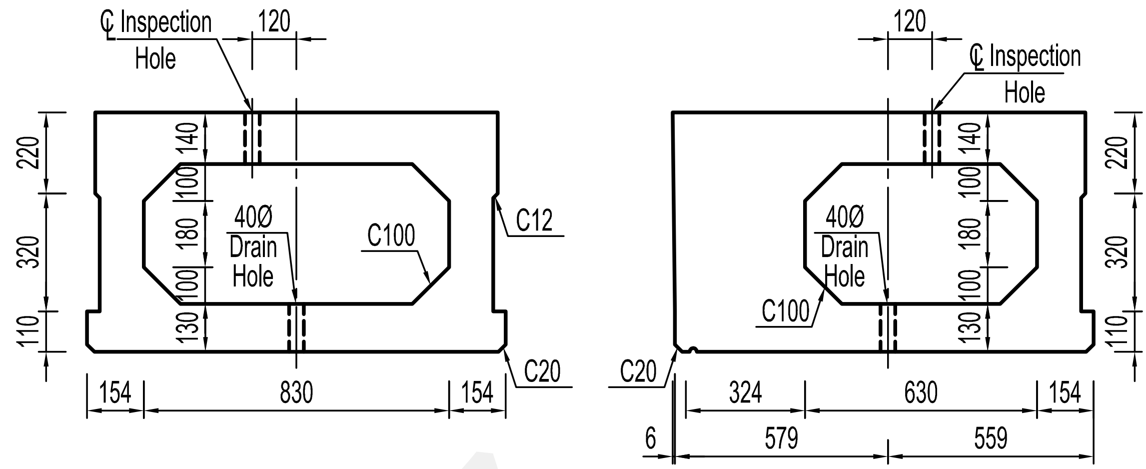


Fig. 5-219 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.3.1.3 *Prestressing*

The single hollow-core units are partially prestressed longitudinally with straight strands. For each girder there is a total of twenty 12.7 mm (0.5 in.) diameter, seven-wire, super special, prestressing strands, two in the top flange and 18 in the bottom flange.

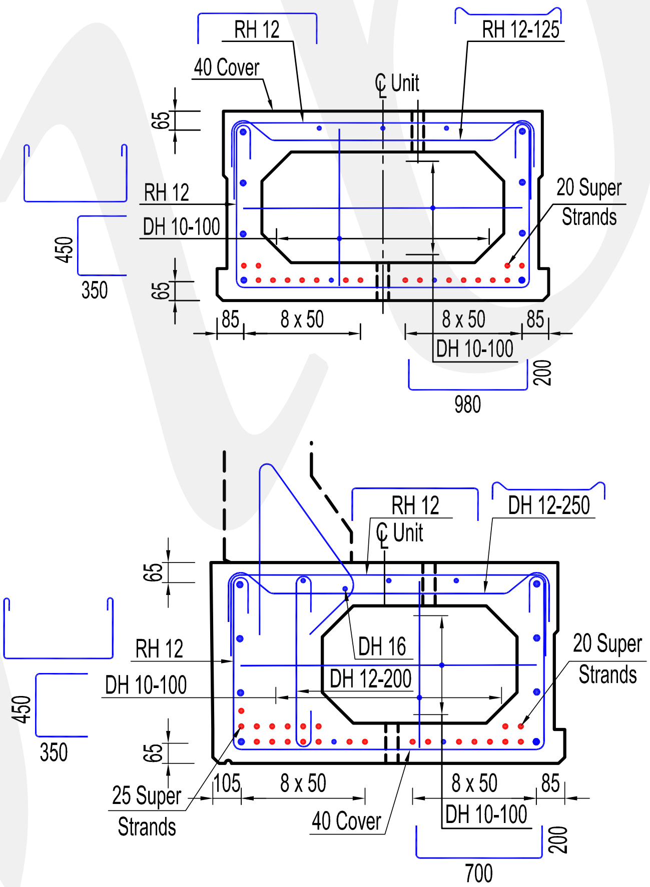


Fig. 5-220 Precast elements reinforcement detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.3.2 Deck slab

No deck slab is used with this solution.

5.19.3.3 Details

5.19.3.3.1 Continuity

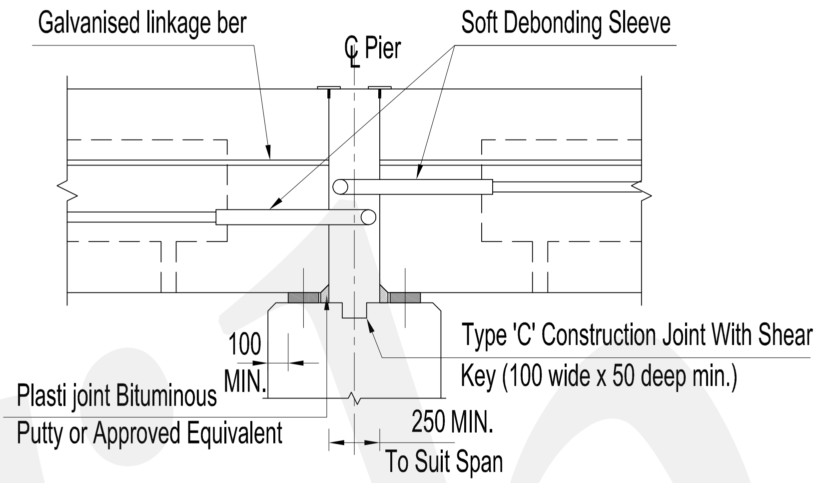


Fig. 5-221 Continuity detail over the piers. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.3.3.2 Transverse diaphragms

This solution uses post-tensioned diaphragms.

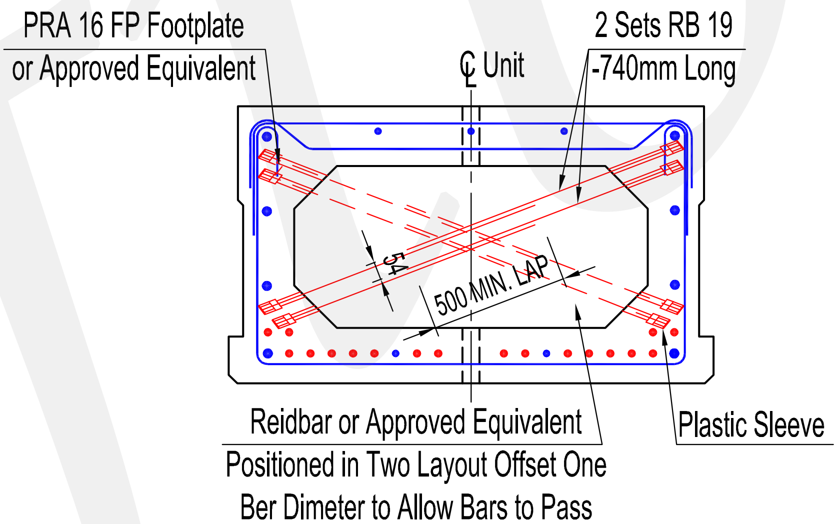


Fig. 5-222 Diaphragm detail at interior girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.19.3.4 Summary of the preliminary design

Number of spans	10
Continuity	Structural continuity
Span length *L*, m	15
Girder depth *G*, mm	650
Slab depth *H*, mm	0
Total depth *D* = *G* + *H*, mm	650
Web width *W*, mm	300
Girder spacing *S*, m	1.2
Precast concrete girder weight, tonnes	20
L/D	23.08
L/G	23.08

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

5.19.4 Substructure

5.19.4.1 Piers

This solution assumes precast concrete pier columns, 7 m (23 ft) tall. The columns are 1.5 m (4.9 ft) diameter with forty 32 mm (1.25 in.) reinforcing steel bars. The precast concrete piers weigh a total of 40 tonnes (44 tons).

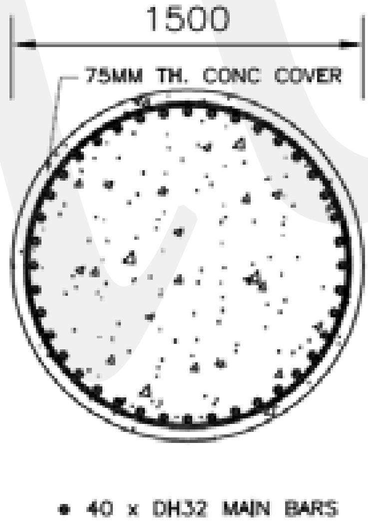


Fig. 5-223 Cross-section of piers. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20 Example 20: bridge with five 30 m (98 ft) long spans in New Zealand

This example was furnished by Alessandro Palermo.

5.20.1 Considerations identified

- Bridge layout: This example bridge has a total length of 150 m (492 ft) and a total width of 15 m (49 ft). The deck carries two lanes of traffic. There are sidewalks for pedestrians and cyclists on each side of the bridge. All spans are equal in length and all piers are the same height.
- Geological and geotechnical factors: The soil is Class D (soil) and the site is 20 km (93 mi) from any known fault.
- Codes: This example is governed by the action codes NZS 1170.5 (2004)[5-17],the concrete design code NZS 3101(2006)[5-18],and the New Zealand Transport Agency Bridge Manual[5-19].
- Environmental: The structure does not span flowing water.

5.20.2 Proposed solution

This solution has five spans, each with a length of 30 m (98 ft). The only precast concrete section commonly used for spans of this length in New Zealand is the 1'225 mm (48 in.) deep Super T girder. However, it should be noted that 900 mm (35 in.) deep single hollow-core units are used for spans up to 27 m (86 ft) and I-girders span up to 30 m. Super T girders were selected here as they are more common than I-girders. Many contractors have forms allowing for competitive pricing of the Super T. Aesthetics and health and safety were not explicitly considered in this design.

This solution adopts seven 1'225 mm (48 in.) deep, Super T girders designed as simply supported elements. There is a 180 mm (7 in.) thick CIP reinforced concrete deck slab. The bridge has 3% transverse slopes on both sides of centerline.

The structure uses internal web stiffeners at a 10 m (33 ft) spacing.

The spans are seated on elastomeric bearings, built-up with mortar as required.

At the supports, this solution uses reinforced concrete diaphragms.

5.20.2.1 Plan

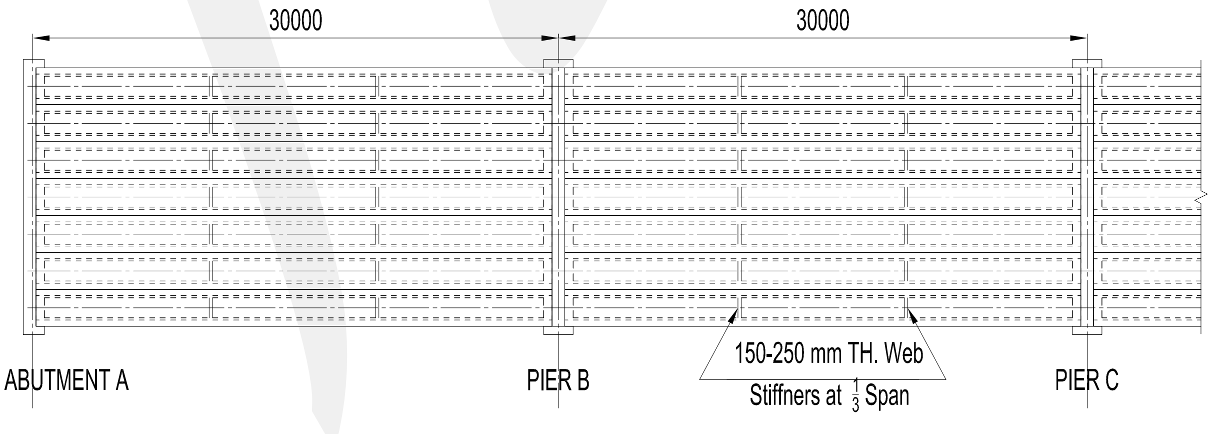


Fig. 5-224 One-half plan view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20.2.2 Elevation

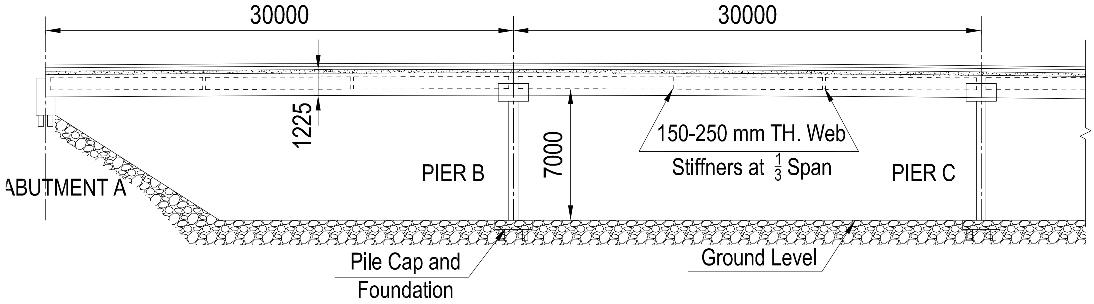


Fig. 5-225 One-half elevation view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20.2.3 Cross section

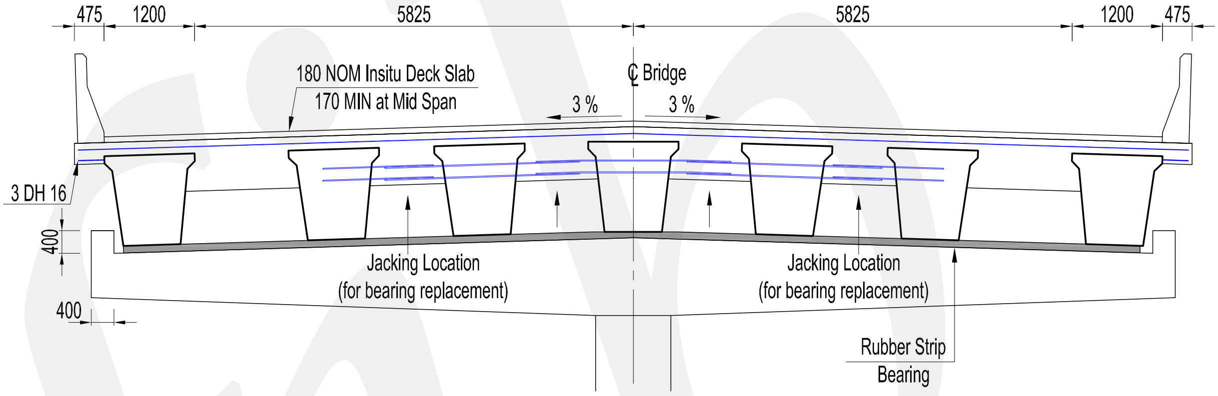


Fig. 5-226 Cross-section view of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20.3 Superstructure

5.20.3.1 Precast concrete girders

5.20.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1'840 MPa (269 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.203.1.2 Description of the cross section

This solution uses seven, 1225 mm (48 in.) deep Super T girders designed as simply supported. A precast concrete stay-in-place deck panel is placed in ledges cast into the interior edge of the top flanges to close the top of the girder. There is a 180 mm (7 in.) thick reinforced conventional concrete deck slab cast on the precast concrete panel and the top flanges. The bridge has 3% transverse slopes on both sides of centerline.

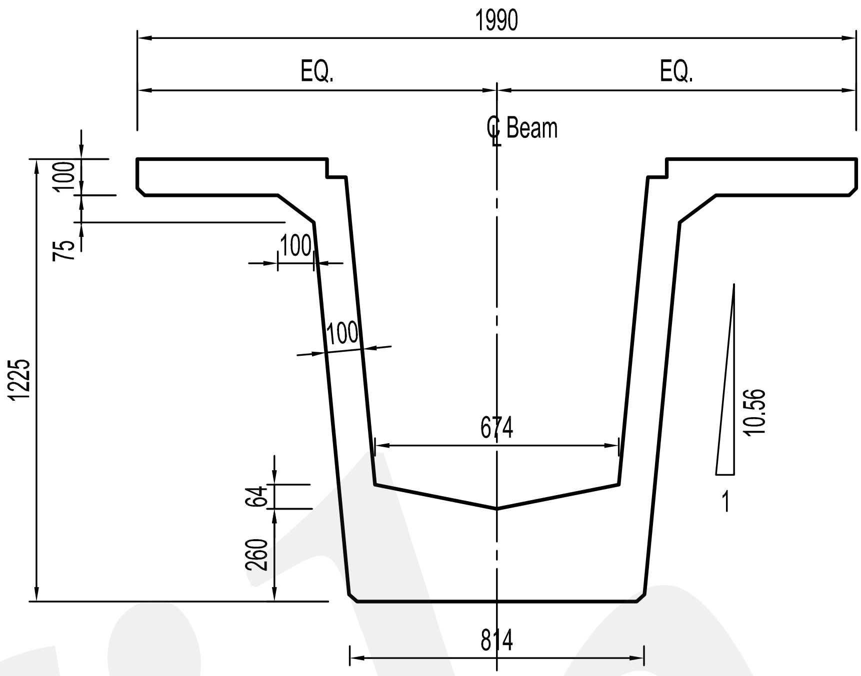


Fig. 5-227 Cross-section dimensions of precast concrete Super T girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20.3.1.3 *Prestressing*

Each girder is prestressed with a total of forty 15.2 mm (0.6 in.) diameter, super seven-wire, straight prestressing strands.

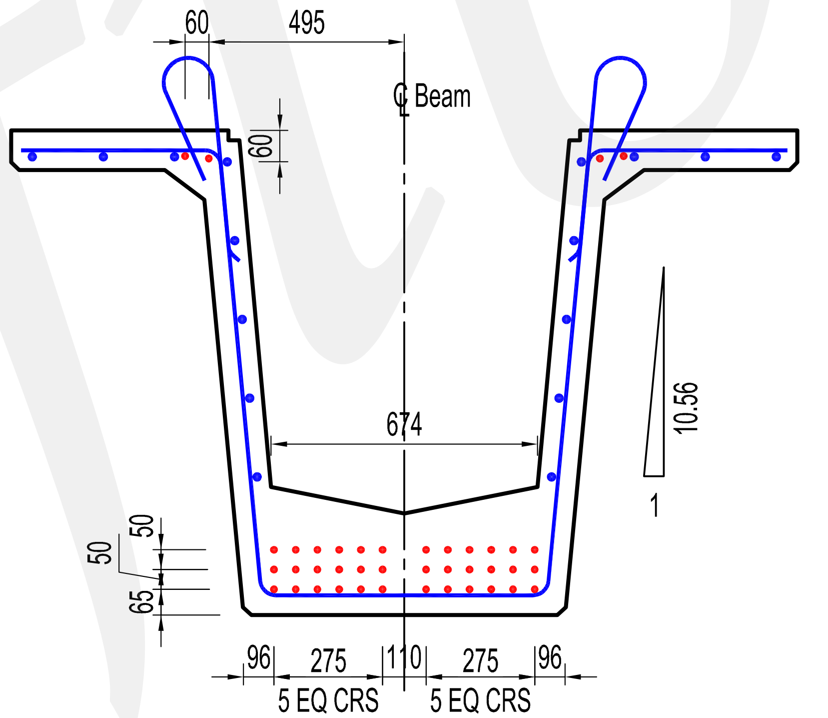


Fig. 5-228 Cross section of precast concrete Super T girder showing typical reinforcement and strand locations. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.20.3.2 Deck slab

The 180 mm (7 in.) thick CIP deck slab is reinforced with mild steel and uses conventional concrete.

5.20.3.3 Summary of the preliminary design

Number of spans	5
Continuity	Structural continuity
Span length *L*, m	30
Girder depth *G*, mm	1'225
Slab depth *H*, mm	180
Total depth *D* = *G* + *H*, mm	1'405
Web width *W*, mm	200
Girder spacing *S*, m	2.0
Precast concrete girder weight, tonnes	41
L/*D*	24.5
L/*G*	21.35

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

5.20.4 Substructure

5.20.4.1 Piers

This example assumes precast concrete piers 7 m (23 ft) tall. The piers are 1.5 m (4.9 ft) in diameter with forty 32 mm (1.25 in.) diameter reinforcing steel bars. The precast concrete piers weigh a total of 40 tonnes (44 tons).

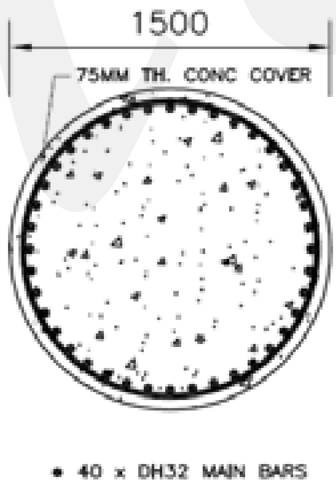


Fig. 5-229 Cross-section of piers. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.21 Example 21: bridge with two 30 m (98 ft) long spans in Spain

This example was furnished by David Fernández-Ordoñez.

5.21.1 Considerations identified

- Bridge layout: This example bridge has a total length of 60 m (197 ft) and a total width of 11.3 m (37 ft).
- Geological and geotechnical factors: The bridge is in an area of very low seismic activity.
- Code: This example is governed by the action codes EN 1990[5-4] and EN 1991-2[5-2], and the design codes EN 1992-1-1[5-5] and EN 1992-2[5-3].
- Construction factors: The speed of construction and erection is considered.
- Environmental factors: Consider a minimal use of materials.
- Maintenance: Low maintenance is desired. Check supports and for cracking in the beams regularly.
- Economy: Minimum cost for construction.
- Functional factors: There is a longitudinal gradient. Provide adequate clearance beneath.

5.21.2 Proposed solution

This example has two spans, each with a length of 30 m (98 ft). The cross section consists of five precast concrete I-girders with a depth of 1'400 mm (55 in.), spaced at 2.5 m (8.2 ft) on center. Precast concrete deck stay-in-place deck panels are proposed to facilitate casting the deck slab.

The two edge girders have an L-shaped top flange to minimize formwork for casting the deck slab.

The CIP deck slab is 250 mm (10 in.) deep and the superstructure has 2% transverse slopes on both sides of centerline formed by varying the height of the neoprene bearings and by varying the thickness of the CIP concrete deck.

This example assumes an area of very low seismic activity. Therefore, it does not use a diaphragm over the piers or the abutments. Intermediate diaphragms are not used. Transverse distribution of the load is considered to be achieved with the rigidity of the slab.

The precast concrete I-girders are pretensioned and the layout of the prestressed reinforcement consists of straight strands placed in the top and bottom flanges of the I-girders.

Expansion joints are used in the abutments and a link slab is used at the intermediate support.

5.21.2.1 Plan

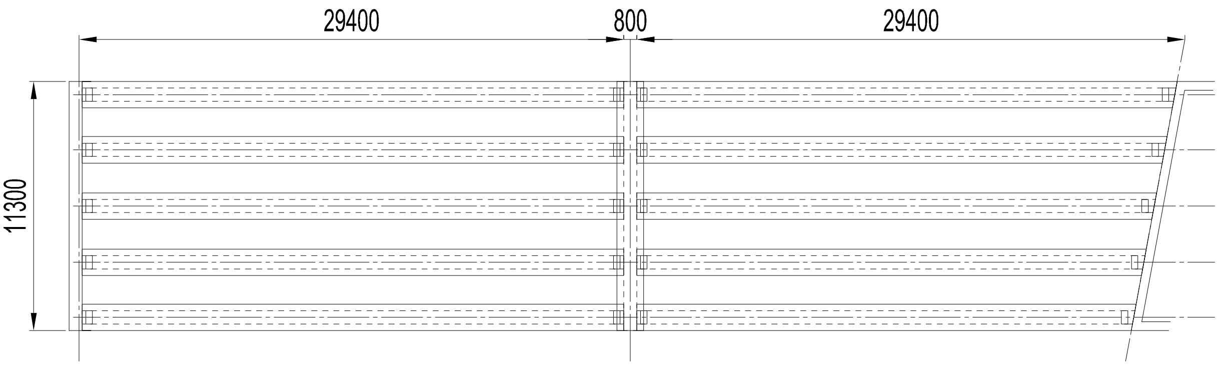


Fig. 5-230 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.21.2.2 Elevation

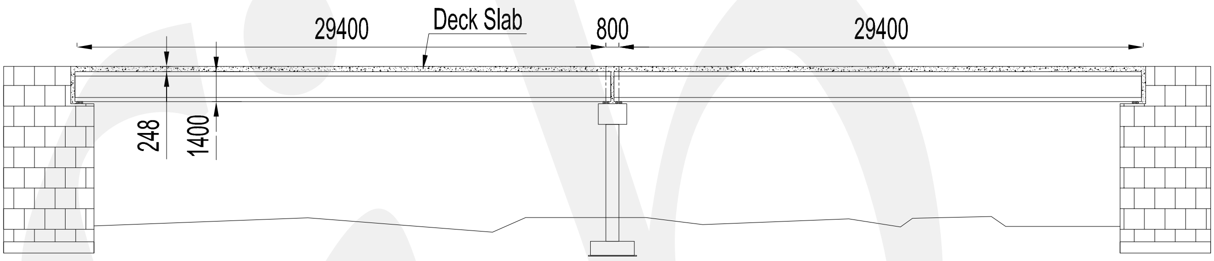


Fig. 5-231 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.21.2.3 Cross section

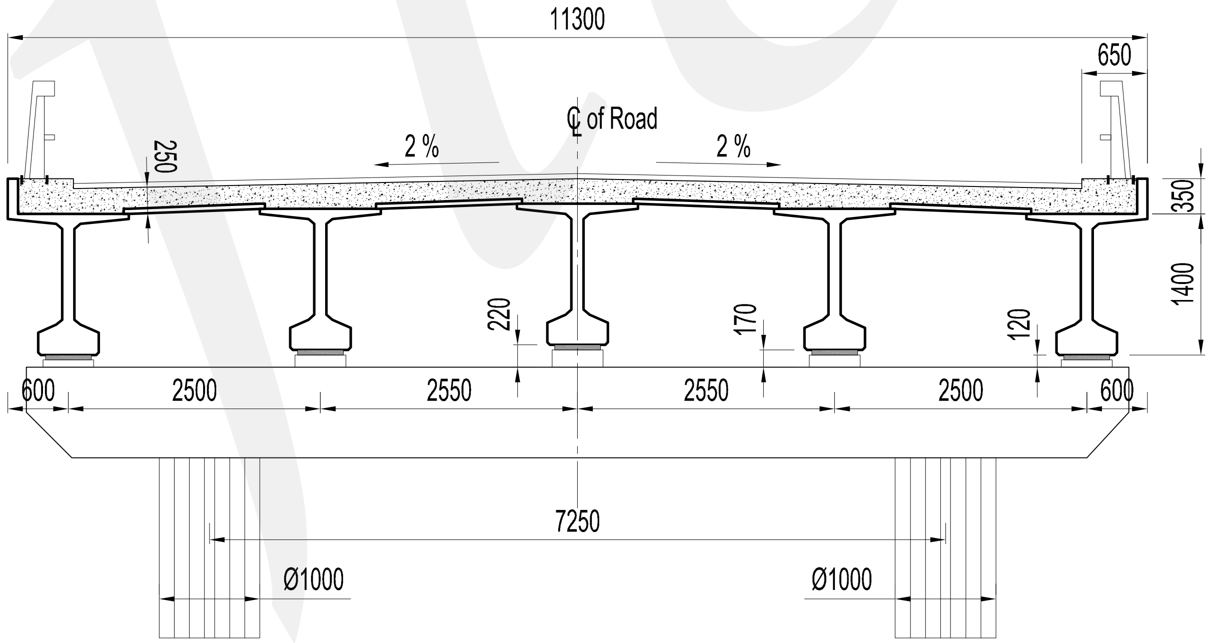


Fig. 5-232 Cross-section view of the bridge. No diaphragms are used in this bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.21.3 Superstructure

5.21.3.1 Precast concrete girders

5.21.3.1.1 Materials

Concrete:	55 MPa (8 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.21.3.1.2 Description of the cross section

Five I-girders, 1400 mm (55 in.) deep and 1200 mm (47 in.) wide, are spaced either 2.5 or 2.55 m (8.2 or 8.37 ft) on center. The two edge girders have an L-shaped top flange to facilitate the casting of the deck slab and reduce the need for formwork. There is no additional cantilever of the deck slab for ease of construction and economy.

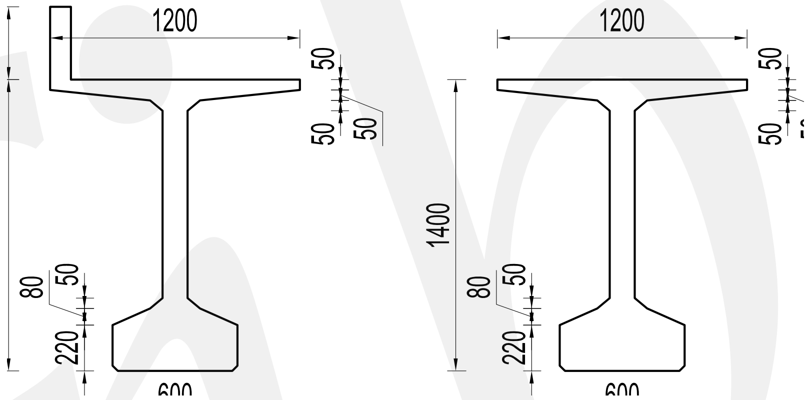


Fig. 5-233 Cross-section dimensions of precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.21.3.1.3 Prestressing

The I-girders are prestressed longitudinally with straight strands. In each girder there is a total of 28 15.2 mm (0.6 in.) diameter prestressing strands, 2 in the top flange and 26 in the bottom flange. Of these, eight strands are debonded near the ends.

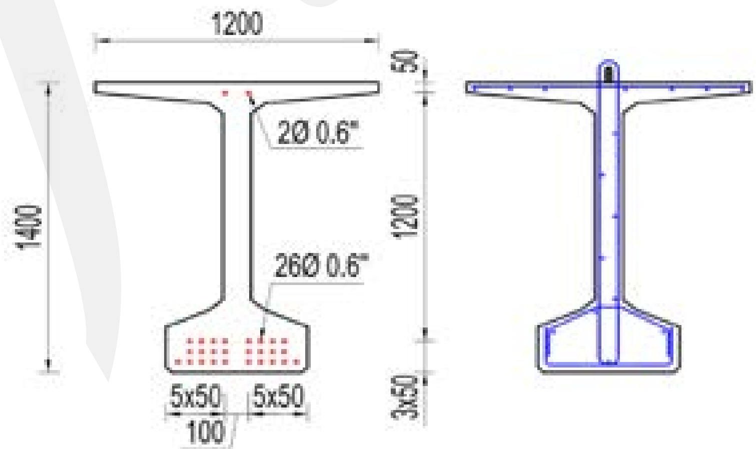


Fig. 5-234 Cross section of the I-girders showing typical reinforcement and location of the strands.

5.21.3.2 Deck slab

5.21.3.2.1 Materials

Concrete: 30 MPa (4 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.21.3.2.2 Deck slab description

The deck is a CIP slab with a minimum thickness of 250 mm (10 in.) and cast on top of the girders as well as on top of precast concrete stay-in-place deck panels bearing on the top edges of the girder flanges. The deck has 2% transverse slopes from the center of the deck.

5.21.3.3 Details

5.21.3.3.1 Bearings

The girders are placed on neoprene pads. Due to slab continuity at the center pier, the center of movements is at this pier. Therefore, the movements for creep, shrinkage, and temperature considered for the neoprene pads take into account the total length of the bridge. The movements at the abutments are related to the center pier.

5.21.3.3.2 Continuity

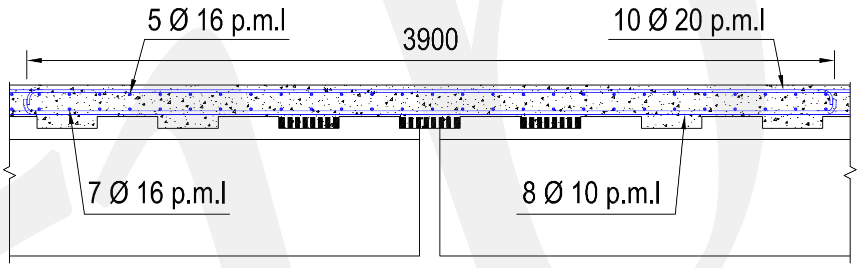


Fig. 5-235 Continuity detail over the pier. Note: p.m.l. = per linear meter. All dimensions are in millimeters. 1 mm = 0.0394 in.

Slab continuity is achieved with a fixed slab at both spans by taking into account the rotations of each deck and the local load of the design truck of 10 kN (2.25 kips). The slab is disconnected from the beams to achieve a higher flexibility and to take these deformations into account.

5.21.3.3.3 Transverse slopes

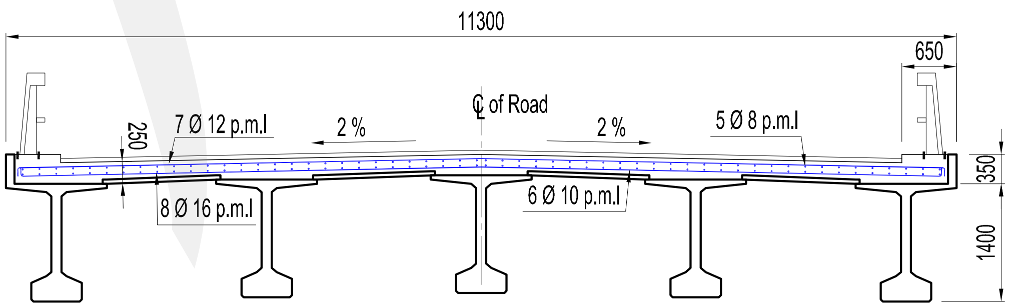


Fig. 5-236 Bridge superstructure with 2.0% transverse slopes. Note: p.m.l. = per linear meter. All dimensions are in millimeters. 1 mm = 0.0394 in.

The deck of the bridge has 2% transverse slopes formed by varying the height of the neoprene bearings under the precast concrete girders and the thickness of the deck slab.

5.21.3.3.4 Transverse diaphragms

This solution does not consider transverse diaphragms over the supports or between piers.

5.21.3.4 Summary of the preliminary design

Number of spans	2
Continuity	Partial using a link slab
Span length *L*, m	30
Girder depth *G*, mm	1'400
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	1'650
Web width *W*, mm	120
Girder spacing *S*, m	2.50 or 2.55
Precast concrete girder weight, tonnes	29
L/D	21.43
L/G	18.18
Prestressing steel, kg/m^2	+26 × 5/11.30 = 11.50
Reinforcing steel – girder, kg/m^2	+16(5/11.30) = 7.08
Reinforcing steel – top slab, kg/m^2	22

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.22 Example 22: bridges with 18.75 m (61.52 ft) long spans and 35 m (115 ft) long spans in the United Kingdom

This example was furnished by Robert Wheatley.

5.22.1 Considerations identified

- Bridge layout: This example bridge has a total length of 150 m (492 ft) and a total width of 15 m (49 ft). Headroom is not a constraint. There are no obstructions that require a special span arrangement. There is easy access for equipment and materials throughout the length of the bridge. There is no skew. Deck cross slopes are 2.5% equally about the centerline
- Geological and geotechnical factors: Foundation design is not considered in this example.
- Codes: This example is governed by the following action codes: EN 1991-1[5-20], EN 1991-2[5-2] and the following design codes: BS EN 1992-1-1[5-5] and EN 1992-2[5-3] and BS NA EN 1991-2[5-21], LM1 and LM3 (Special Vehicle SV196).
    - In addition, the following manufacturer's reference was considered: Bridge Beam Manual, 2nd ed. Banagher, Co. Offaly Ireland: Banagher Precast Concrete Ltd. Other manufacturers produce similar bridge girders.

- Construction factors:
  - The end spans would be simply supported at the abutments. Internal spans would be continuous over the piers.
  - Health and safety are increasingly important to both contractors and clients, with many initiatives to promote better site safety culture. The greater use of precast concrete elements is seen as a way of improving safety and this comes into consideration when selecting bridge designs and the use of precast concrete girders.
  - For example; SY girders (the largest type of Y-shaped girders) are seen by some as too tall and the potential for lateral instability during erection requires additional shoring and bracing. U girders are often preferred for stability and the interior can be used as a walkway for erecting permanent formwork.
  - Other safety practice that affects design includes:
    - Girders can be erected with cantilever formwork and edge protection already attached.
    - Girders can have parapet and edge details precast before lifting over railways.
    - Precast concrete deck panels are being adopted more widely for steel-concrete composite designs.
    - Precast concrete plinths on which to construct parapets help reduce the amount of work near the edge and reduce the risk of a workman falling during construction.
- Aesthetics: Aesthetic requirements are usually defined by bridge owners as high-level priorities. Details would be locally defined by the designer or architectural advisor. Consultation may be required with the citizen organizations that safeguard appearance. Good aesthetic practice is considered advisory, except for major structures.
- Environmental factors: Environmental conditions are an important set of constraints on designs from an early stage. They are considered in depth at the preliminary stage and become part of the evaluation of the design, often determined at ministerial level. Environmental conditions are not easily altered after the planning stage. Typically, the environmental conditions could dictate where a bridge is required, what must be crossed, and what clearance may be needed.
- Construction factors: Construction methods must limit or prevent disturbance to protected areas. However, the construction considerations do not usually dictate the materials or form of bridge, except where future painting of steel girders would be a major disruption of, or risk to, the environmentally protected area. In these cases, precast concrete is usually preferred.

5.22.2 Proposed solution

With a total length of 150 m (492 ft), this bridge is too long to be considered as an integral structure by typical UK practice. There are few integral bridges over 100 m (328 ft) in length in the UK, although this number may increase as design confidence is built up with this type. It would be preferable to have shorter end spans than interior spans, as the positive moment is higher in the end spans. The end span could be typically assumed to be two-thirds the length of the main span.

However, for the short-span bridge, it was preferred to resort to eight equal spans, each with a length of 18.75 m (61.52 ft). The simplicity and repetitive nature of the design make it cost effective, provided that substructure costs and appearance are not significant. For the 35 m (115 ft) span solution, it was preferred to resort to three spans, each with a length of 35 m (115 ft) and two spans, each with a length of 22.5 m (74 ft) because it is a reasonable balance of available girders that can be supplied and erected using standard techniques and equipment.

Selection of common types of UK precast concrete girders is based on the manufacturer's catalogue of available shapes. Span, available construction depth and girder spacing affect the choice. Equally important are the contractor's preferences over the cost, the available cranes, the erection plan, and the ease of securing road or railway possessions for the beams to be lifted into place. For most bridges, the choice is between Y and U girders, which have superseded the less efficient T and M girders. Special types exist for very shallow depth girders and for long-span girders.

U girders have some advantages over Y girders: they are more stable during construction, offer smaller spans for deck formwork, and are easier to fit formwork around. They can have longitudinally extended internal end diaphragms, which help with defining the extent of the beam considered as a prestressed beam design and the extent considered as a reinforced section design.

Solid deck construction is appreciated for smaller spans where the simplicity of avoiding formwork and having a simple top mat of reinforcement helps reduce costs. Transverse bottom bars are required, placed through regular holes in the web. This detail may need some careful reinforcement planning and detailing to get the bars in place during construction. Edge beams can have cast-in couplers to connect the transverse bars. Transverse post-tensioning is not typically used owing to historic concerns over durability and having to get access to the outer face of the girders.

Permits to use parts of the obstacle crossed by the bridge have a major influence in the choice of design solutions. Where the obstacle is a live road or railway, it is usually cost-effective to minimize the quantity of assets required for construction work to be completed. Erecting precast concrete girders that only need permanent formwork to be installed above the obstacle is a significant advantage compared to having transverse post-tensioning installed from outside the bridge. Taking the earliest opportunity to seal the interface between construction operations and the user below is often a cost-effective solution.

Edge cantilever dimensions are decided early in the design process. Aspect ratios of girder depth to cantilever distance are sometimes specified by owners. UK industry proprietary edge falsework system can work with deck cantilevers up to 2.5 m (8 ft) but are effective with a 2.0 m (6.6 ft) cantilever from the girder centerline and still leave room for construction access. Girders with integral bridge decks often have shorter cantilevers, typically with a cantilever length to girder depth ratio of 1:1. The edge formwork is often installed before girder erection for ease of access and to have the edge protection in place immediately when the girder is erected. The girder will require a check that it can carry the weight of the formwork without splitting (for example, U girders) or rotating.

Deck slope is typically chosen to match the highway alignment, except on narrow bridges, to reduce the additional surfacing material necessary to match the highway slopes. For UK highways, slopes can vary from 2.5% balanced slopes, up to 7% where highway superelevation is applied. Girders are often erected to match the cross slope and avoid step changes in the abutment construction joint. The stability of the girders that are super-elevated needs to be checked during deck erection. Where the girders follow the deck cross slope the deck can be kept at a constant depth.

Tight vertical curvature may need additional deck thickness to accommodate the difference between the nominally straight girders and the highway alignment. The additional thickness is usually included in the carriageway as a regulating course. The design needs to allow for the construction depth as a result of adding the regulating course.

Curvature and change in width can be accommodated by varying the width between girders or by having variable width edge cantilevers.

Changes in highway slopes as a result of application of superelevation, or the intersection of a ramp with different slopes, needs to be carefully checked so that the change in slope of the deck does not conflict with the straight girders.

Deck panels can be fabricated from several materials: glass-fiber-reinforced cement, glass-fiber-reinforced plastic, fiber-reinforced concrete, and reinforced concrete slabs have all been used as stay-in-place formwork. Key considerations are the span required between supporting beams, the deflection of the panel when the deck is cast and the thickness of the stiffening ribs above the panels affecting the position of the deck reinforcement. The deck reinforcement also needs to prevent longitudinal shear in precast concrete composite beam decks and the position of the deck reinforcing bars relative to both the beam shear links and the deck panel ribs influences the early sizing of the bridge deck.

Bridges that are continuous over intermediate piers are usually fully built into (integral with) the substructure. Continuity of bridge decks wherever possible has been a requirement since 1996 as a result of much better durability of continuous structures compared to simply supported spans. Options are available for achieving continuity, but by far the most common is to have full continuity with the pier and deck. The advantages of full continuity are:

- The structural framing helps redistribute moments at the support, provides greater robustness in case of collision, and acts as a restraint to thermal movement.
- The rigid diaphragm improves load distribution across the deck.
- Bearings and the means to replace them are not required. This reduces the need for lane closures for maintenance.
- There are fewer site operations, which simplifies construction although the risk of a clash with reinforcement needs to be addressed.
- The beams can be supported directly on the pier to reduce the need for temporary supports. Using the permanent support for the temporary condition can be safer than using temporary supports.

5.22.2.1 Plan

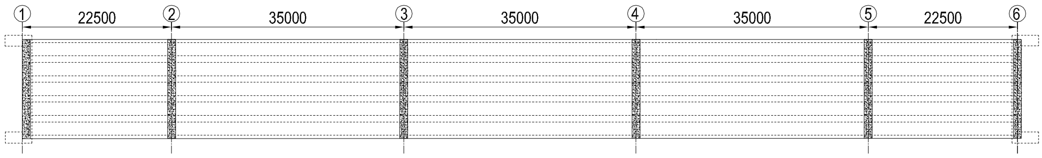


Fig. 5-237 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.22.2.2 Elevation

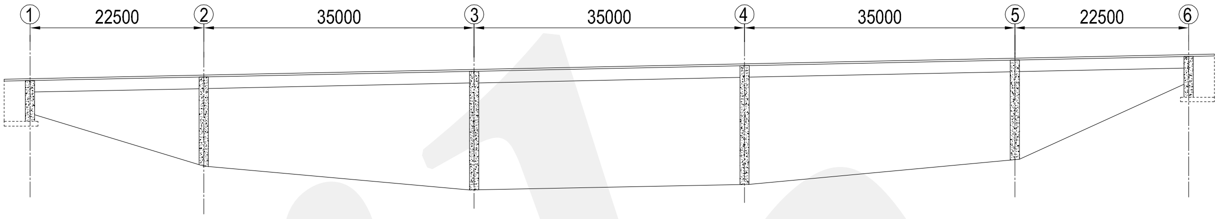
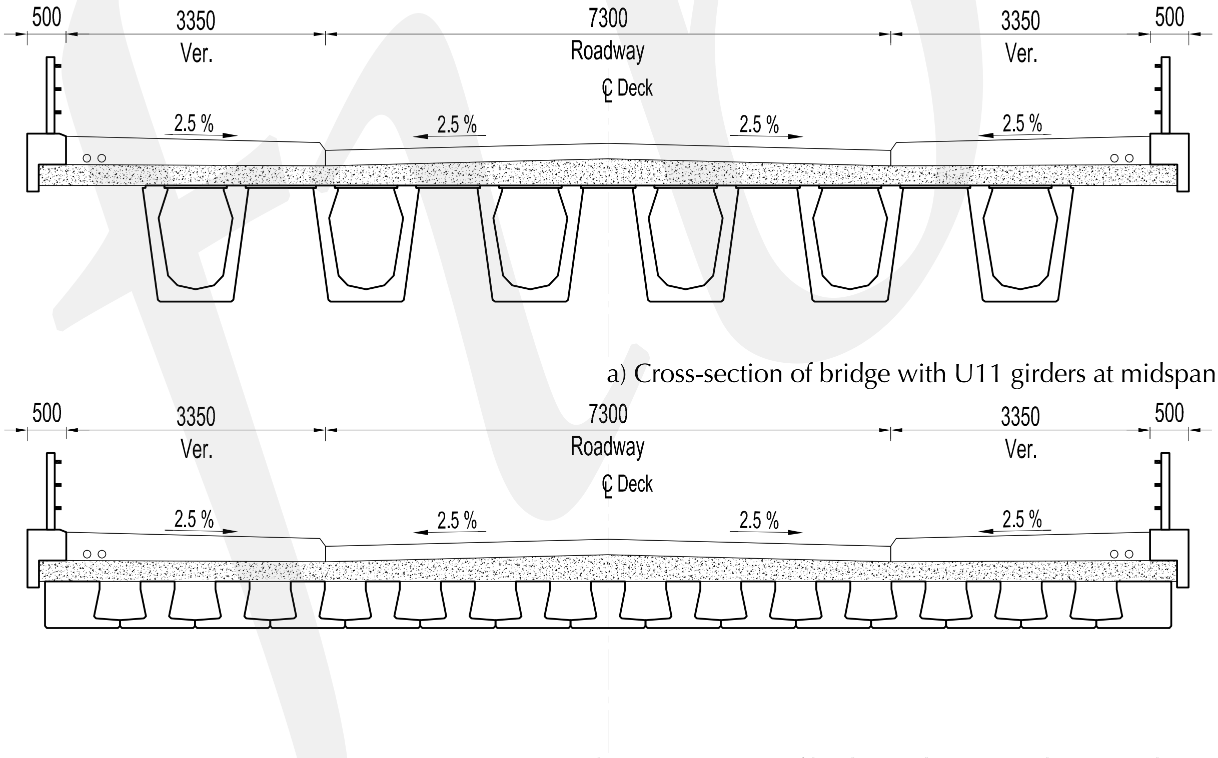


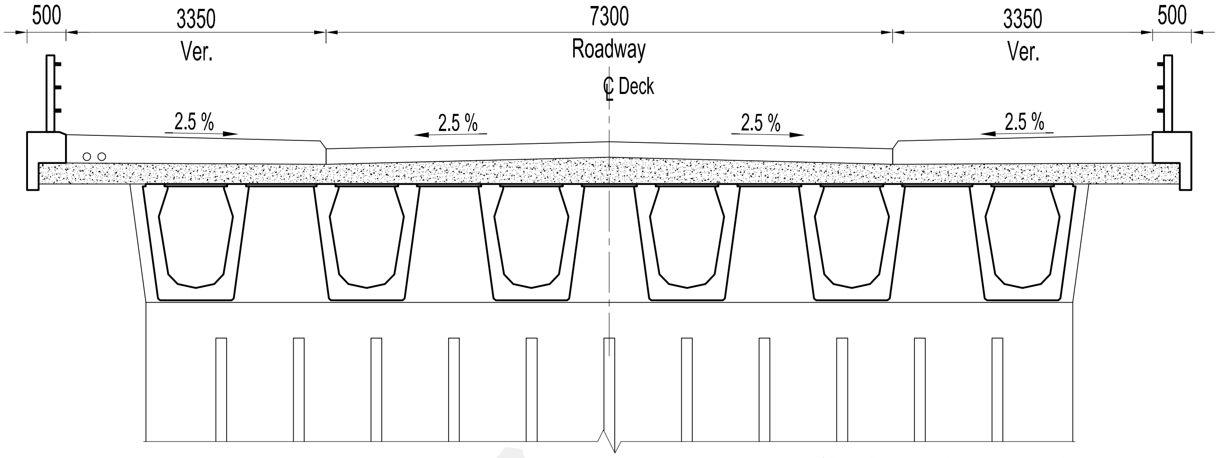
Fig. 5-238 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in

5.22.2.3 Cross section

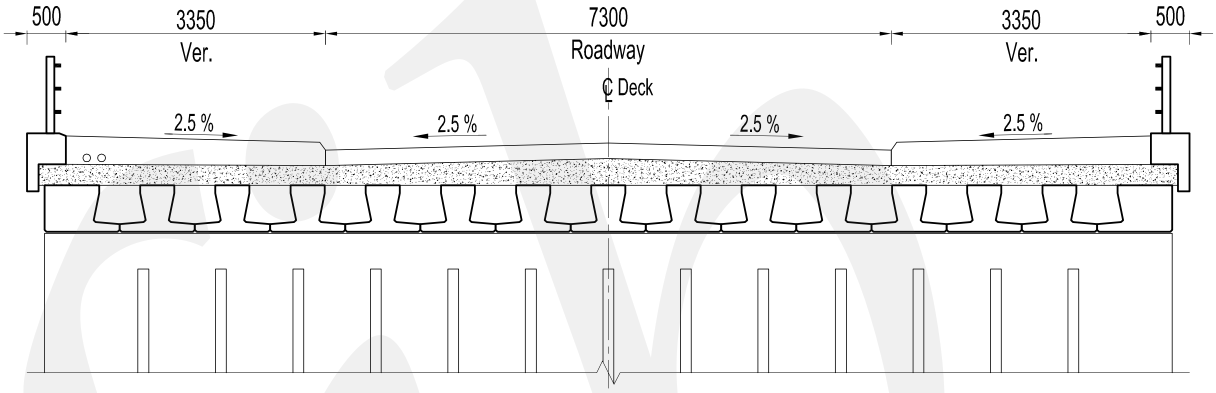


a) Cross-section of bridge with U11 girders at midspan

b) Cross-section of bridge with MY7 girders at midspan



c) Cross-section of bridge with U11 girders over piers



d) Cross-section of bridge with MY7 girders over piers

Fig. 5-239 Cross-section view of the proposed bridges. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.22.3 Superstructure

5.22.3.1 Precast concrete girders

5.22.3.1.1 Materials

Concrete:	50 MPa (7 ksi)
Prestressing steel:	1'860 MPa (20 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.22.3.1.2 Description of the cross section

For the U11 girders (35 m [115 ft] long spans): six beams at 2.12 m (6.96 ft) centers, using two 1.5 m (4.9 ft) long cantilevers.

For the MY7 girders (18.75 m [61.52 ft] long spans): 14 beams at 0.985 m (3.232 ft) centers, using two 0.61 m (2 ft) long cantilevers.

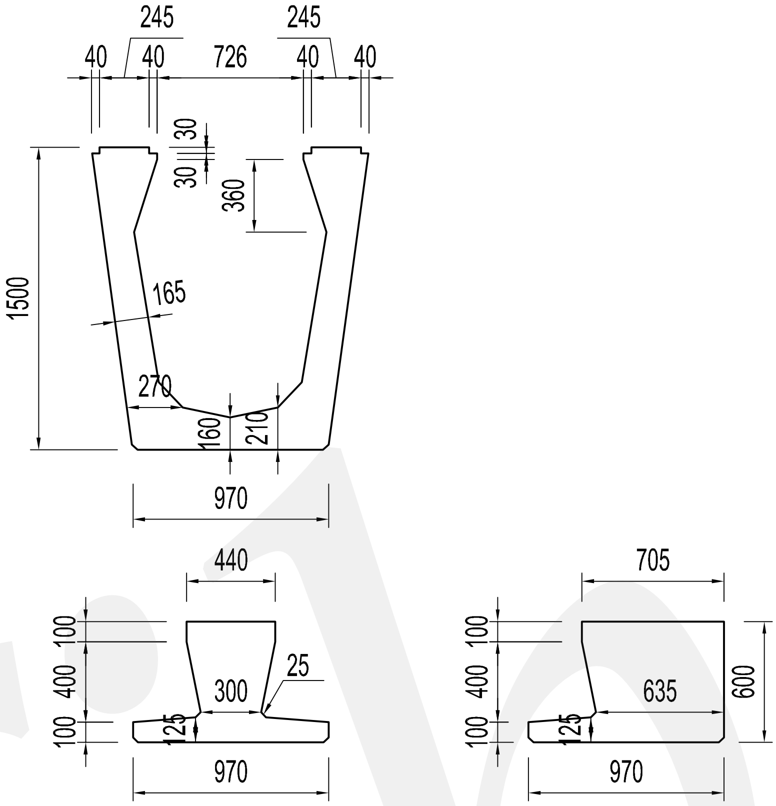


Fig. 5-240 Cross-section dimensions of the precast concrete girders. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.22.3.1.3 Prestressing

The seven-wire strands are typically 15.2 mm (0.6 in.) diameter standard or 15.7 mm (0.62 in.) special diameter drawn strands set at prescribed locations in the beam cross section in accordance with the manufacturer's catalogue. The strand complies with class 2 relaxation and is stressed to 174 kN (39 kip) for standard and 210 kN (47 kip) for drawn strand.

The prestress layouts comprise straight strands, with debonding used to change the prestress along the beam length.

Beams are pretensioned at the casting facility before truck transfer to the site. Post-tensioning is comparatively rare and used in box girder bridges either as segmental construction with external post-tensioning or CIP construction with internal post-tensioning.

5.22.3.2 Deck slab

5.22.3.2.1 Materials

Concrete:	40 MPa (6 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.22.3.2.2 Deck slab description

The CIP deck slab has a thickness of 200 mm (8 in.) for the 35 m (115 ft) long spans solution, and 100 mm (4 in.) CIP on top of the girders on deck slabs for the 18.75 m (62 ft) long spans solution.

5.22.3.3 Details

5.22.3.3.1 Bearings

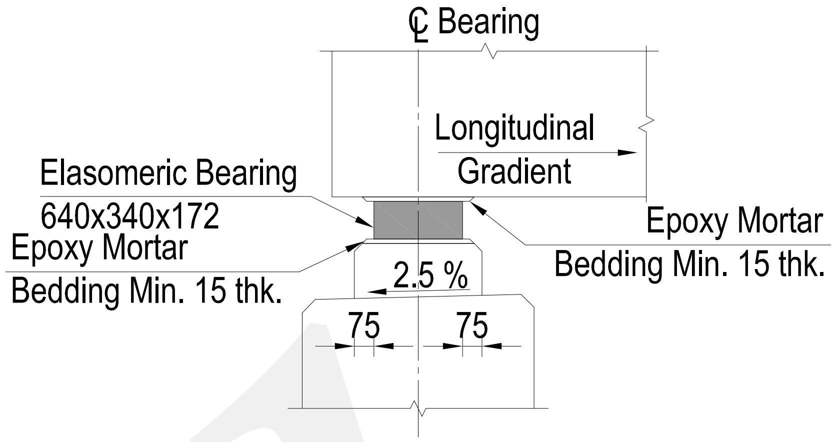


Fig. 5-241 Detail of the bearing and detailfor girder slopes. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

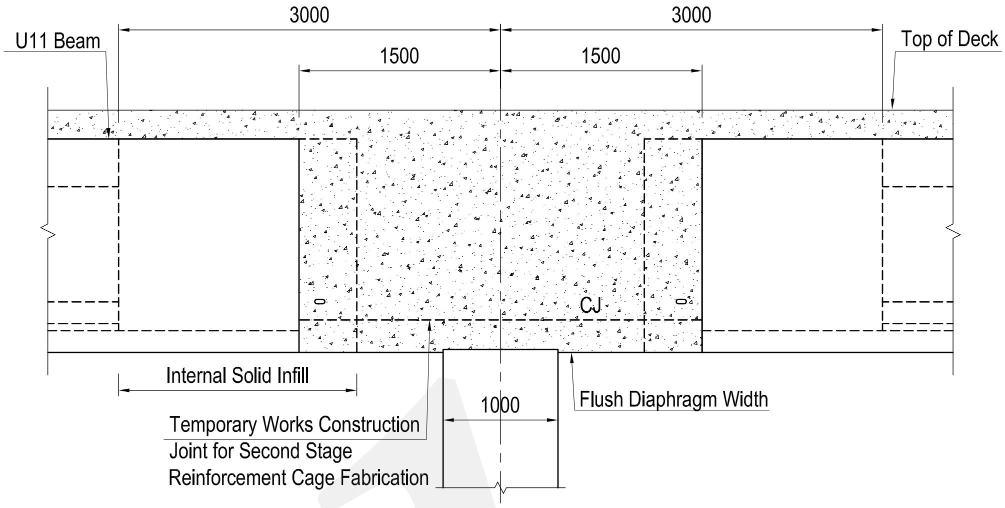
Some beams will need bearing supports where integral bridges cannot be used because of overall length or high skew. Typically, these are elastomeric bearings for the span ranges being considered. The elastomeric bearings will require positive fixity to the beams. Fixity through friction is permitted in some cases, but it is more usual to use an epoxy mortar to provide the positive fixity. Bearings glued down by epoxy mortar would need to have the mortar cut through if it were planned to replace the bearings at a future date.

For the case study, the bridge is considered too long to be an integral bridge, so expansion joints will be provided at each abutment.

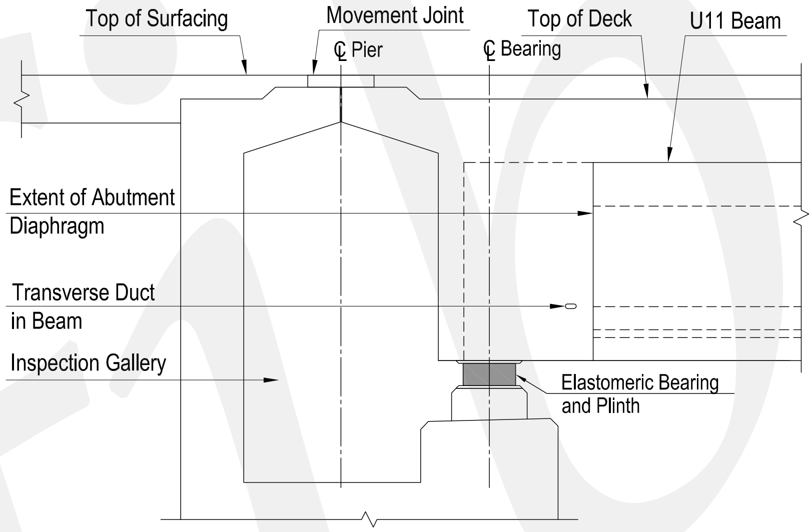
The bearing could be located on bearing plinths to lift the bearing above the bearing shelf that may be wet or have accumulated debris. It also allows space for jacks to be installed should the bearings require replacement. Where a pot bearing is used, the plinth is useful for final adjustment of the bolt anchorage cradle that is to be cast into the plinth. The bearing shelf can also serve as a place to locate jacks for supporting the deck when replacing the bearings.

The jacking arrangement needs to allow adequate space to free the bearing. This can be as little as 2 mm (0.08 in.), but the elastic recovery of the bearing also needs to be included, which may mean that a greater vertical allowance is required. The condition of the deck joint above the bearing also must be considered when the deck is lifted, if live traffic is permitted. The allowable vertical movement of the expansion joint may be small.

5.22.3.3.2 Details of the continuity connection over the piers



a) At the pier



b) At the abutment

Fig. 5-242 Section through the diaphragm at the pier and at the abutment. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Fully integral designs are common and mandatory for bridges less than 60 m (197 ft) long and that have a small skew angle. Integral bridges are regularly used up to 100 m (328 ft), and this length is expected to increase in the future. The field connections are full depth and extend into the span to deal with positive moments as reinforced sections and negative moments as precast concrete section (that is, prevent decompression). Intermediate diaphragms between piers are not used; the precast concrete manufacturers do not indicate that this is possible in their catalogues. The exception is for shallow construction depth solid slab bridges, where transverse reinforcement is placed through regularly spaced holes in the webs.

Connections at supports make use of holes cast in the girder web or couplers where holes are not permitted. Reinforced concrete is detailed around the beams and this can be difficult to detail and awkward to build. Continuity at the soffit of the girder is provided to cater for positive moments from creep rotation. Two methods are used: casting additional bars into the beams or leaving the prestressing strand protruding so that it can be cast into the diaphragm. Abutments are provided with diaphragms to enclose the ends of the beams, seal the ends of the prestressing strand, and provide jacking points for bearing replacement.

Some designers prefer not to have slabs extend between the carriageway and the integral bridge abutment.

5.22.3.3.3 Transverse diaphragms

These bridges have diaphragms over the supports but no intermediate transverse diaphragms.

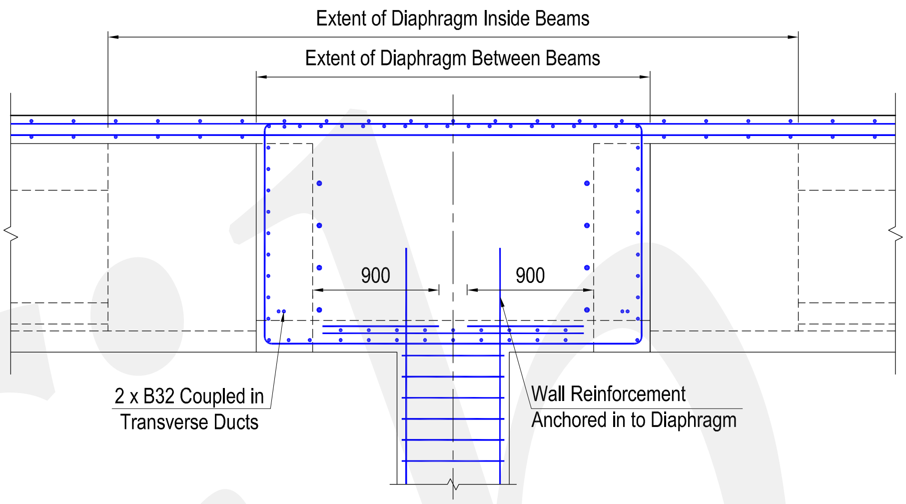


Fig. 5-243 Diaphragm detail. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.22.3.4 Summary of the preliminary design

First solution: Eight 18.75 m (61.52 ft) long spans

Number of spans	8
Continuity	Structural continuity
Span length *L*, m	18.75
Girder depth *G*, mm	600
Slab depth *H*, mm	100
Total depth *D* = *G* + *H*, mm	700
Web width *W*, mm	300
Girder spacing *S*, m	0.99
Precast concrete girder weight, tonnes	13.88
L/D	26.79
L/G	31.25

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

Second solution: Five 35 m (115 ft) long spans

Number of spans	5
Continuity	Structural continuity
Span length *L*, m	35
Girder depth *G*, mm	1'500
Slab depth *H*, mm	200
Total depth *D* = *G* + *H*, mm	1'700
Web width *W*, mm	165
Girder spacing *S*, m	2.12
Precast concrete girder weight, tonnes	62.3
L/D	20.59
L/G	23.33

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

5.22.4 Substructure

5.22.4.1 Piers

Few precast concrete piers and abutments have been used in the UK. These are normally cast in place and arranged to permit continuity over piers and abutments (where integral).

Pier heights normally suit the highway geometry and clearance required over the obstacle crossed. For instance, a crossing of a road would require minimum designed clearance of 5.3 m (17 ft). Additions arise from deck deflection, construction tolerance and vertical curvature of the road beneath. Construction tolerance is typically 100 mm (4 in.). The highway geometry will require that the clearance is calculated to take into account the gradient and superelevation of the road over as well as the road below, to come up with the critical dimension for the clearance.

Piers can come in many forms and are frequently used to express architectural intent as well as simple functionality.

Column structures are often capped with a pier beam that is wide enough to support the girders. This improves the practicality of construction but sometimes is considered to detract from the appearance. The owner's requirements for vehicle clearance beneath may also apply to the pier beam, which can affect the span or height of the bridge.

Circular column pier sections are typically at least 1.2 m (3.9 ft) in diameter for resistance to vehicle collision. Other variations such as leaf piers with patterned finishes depend on aesthetic choice. A plain finish to concrete is usually ruled out by the owner's specification. Vehicle restraint barriers affect the highway cross section at the base.

In the examples presented in this section, pier height is taken as 6 m (20 ft) from pile cap to deck soffit with piers cast in place.

5.22.4.1 Abutments

The abutment will be provided with a gallery to allow inspection access to the expansion joint and to the bearings. The inspection galleries and bearing shelves are waterproofed for improved durability and provided with drainage if water were to leak through a failed expansion joint. Where subsurface drains are provided, these would also discharge into the gallery drainage.

In the examples proposed in this section, the abutment is assumed as CIP concrete and its wing walls comprise mechanically stabilized (reinforced soil) earth walls with precast concrete facing. The facing can be reinforced precast concrete panels or unreinforced concrete blocks

5.22.4.3 Foundations

The column footing or pile cap would be buried. The depth of the footing is a design judgement. Starting from the principle that the least excavation required is best, other construction practicalities will often change this. Fitting in the necessary infrastructure (for example, highway drainage, communication ducts, or underground services) may require deeper footings or pile caps. Founding strata and piling platform level are also important considerations.

Precast concrete driven piles are typically limited to 355 mm (14 in.) square cross sections. The low bending capacity of these piles limits their use to areas that are not subject to impact forces. They are not commonly used in bridge design where integral designs increase bending capacity on piles. Continuous flight auger (CFA) piles are cost competitive with driven precast concrete piles and can carry greater moment.

5.23 Example 23: bridge with a single 25.9 m (85 ft) long span in the United States

This example was furnished by Maher Tadros and William Nickas.

This example is a completed project: the St. Clair Road Bridge Over the Maple River, Clinton County, Michigan, United States. The bridge was open to traffic in July 2014.

5.23.1 Considerations identified

- Bridge layout: The structure has a total span length of 25.9 m (85 ft) and a total width of 7.67 m (25.2 ft).
- Codes: The bridge was designed in accordance with the AASHTO LRFD specifications[5-1].

5.23.2 Proposed solution

This is a very shallow simple-span bridge with a length of 25.2 m (83 ft) and a width of 7.67 m (25.2 ft). The bridge superstructure has six adjacent precast concrete box beams (Fig. 5-245), 1.22 and 0.84 m (4 and 2.75 ft) wide. This results in a span-to-depth ratio of 31 (Fig. 5-244). It also includes a 100 mm (4 in.) thick hot mix asphalt (HMA) wearing surface installed over a waterproofing membrane. The bridge has a skew angle of 12 degrees (Fig. 5-245).

This bridge features an innovative transverse post-tensioning system. The tendons comprise three strands, each strand is encased in grease, then a polyethylene sheath, which is in turn encased in a polyvinyl chloride (PVC) tube. This duct-in-duct system is used to connect the top flanges of the boxes and the bottom flanges of the boxes. Not only is the post-tensioning placed where it is needed the most (the extreme fibers), but also the webs are free of ducts. This allows for total elimination of the heavy intermediate diaphragms and thus reduces the precast concrete weight, concrete quantities, and the final load on the bridge. The system also eliminates the need for a CIP deck slab in accordance with the bridge owner's standard practice for a low-volume bridge. No need for field concrete placement and curing results in accelerated bridge construction (ABC), as promoted by the U.S. Federal Highway Administration. Use of unbonded post-tensioning allows for possible removal of the post-tensioning and widening of the bridge in the future. Most importantly, the post-tensioning is not performed until the longitudinal joints are grouted. Thus, the joints are in permanent compression and fear of water leakage at the joints is essentially eliminated. More details on the system innovation are provided in Section 5.23.4.

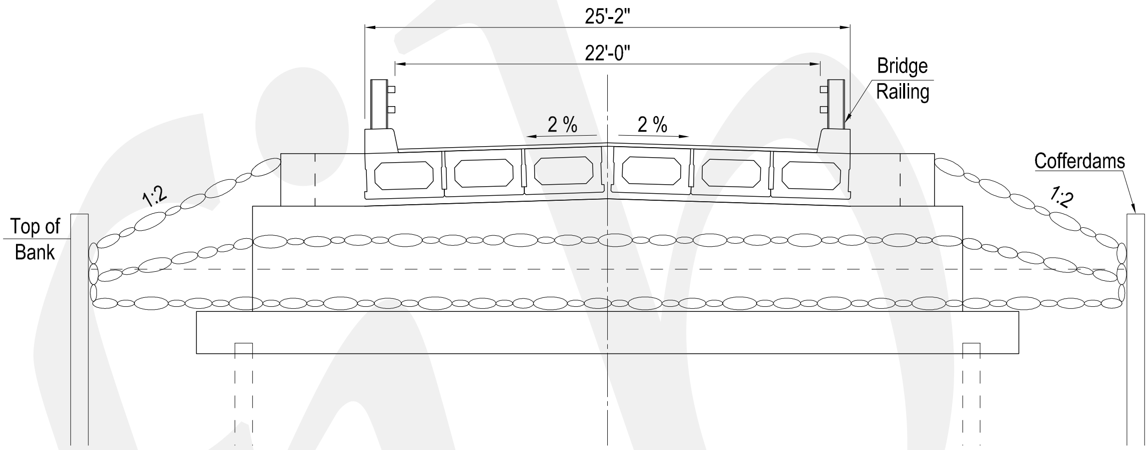


Fig. 5-244 Cross section of the bridge. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

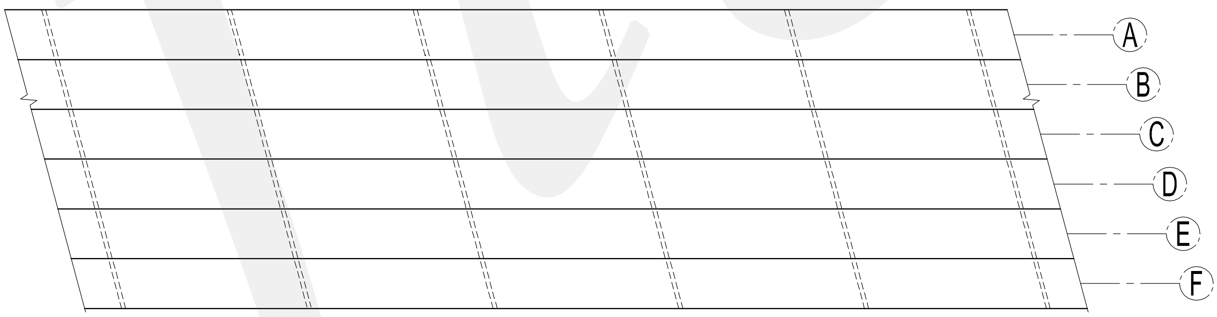


Fig. 5-245 Plan of the bridge.

5.23.2.1 Precast concrete box beam

Figure 5-246 shows a three-dimensional model of two beamlines, including an edge beam and its adjacent interior beam. Dimensions of the beams are illustrated in Figure 5-247 and Figure 5-248, away from the post-tensioning location and at the post-tensioning location, respectively.

The interior box beam is 1.22 m (4 ft) wide at the bottom flange and 1.17 m (3.83 ft) wide at the top flange. The flange thickness is 150 mm (6 in.) at the bottom and 165 (6.5 in.) at the top. Both webs are 125 mm (5 in.) thick at the interior beam.

The edge beam section is similar to the interior beam except the following:

- The width of its top flange is 1.19 m (3.92 ft), slightly wider than that of the interior beam, because the exterior face of the fascia beam does not have vertical shear keys.
- The top flange thickness is increased to 200 mm (8 in.), which allows for sufficient embedment of anchor bolts used for connecting the bridge railing.
- The exterior web is widened from 125 to 250 mm (5 to 10 in.) to accommodate the transverse post-tensioning anchorages.

The beam concrete strength is 55 MPa (8 ksi) at 28 days and 41 MPa (6 ksi) at prestress release. The interior beam includes 21 bottom strands in two rows and 2 top strands (Figure 5-249). The strands are 15.2 mm (0.6 in.) diameter, Grade 1860 MPa (270 ksi), low-relaxation strands. The edge beam includes 22 bottom strands in three rows and 2 top strands (Figure 5-250). The number and locations of the strands at the edge beam differ slightly from the interior beam. The strand locations are arranged to avoid conflicts with the post-tensioning anchorages while satisfying the unique loads on the edge beam. Also, it is intended to design the strand layout in the beams so that the calculated differential cambers between the interior and edge beams is no more than 3 mm (0.125 in.) at the time of beam erection.

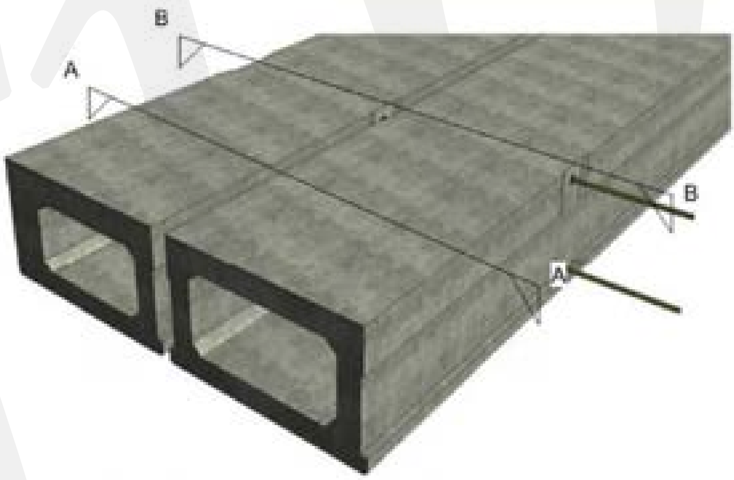


Fig. 5-246 Three-dimensional model of an edge and an interior beam.

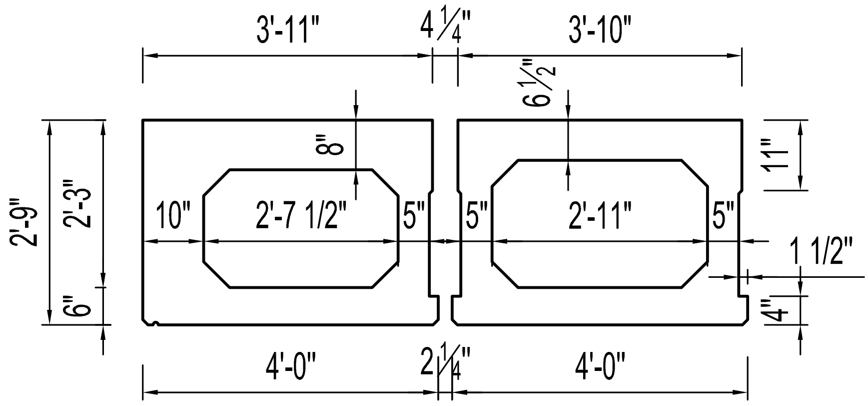


Fig. 5-247 Cross-section dimensions (in.) of an edge and an interior beam away from the post-tensioning location (section A-A). Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

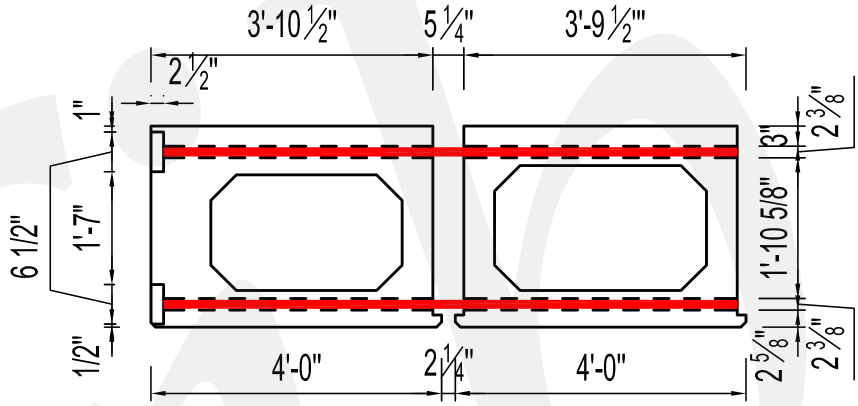


Fig. 5-248 Cross section of an edge and an interior beam at the post-tensioning location (section B-B). Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

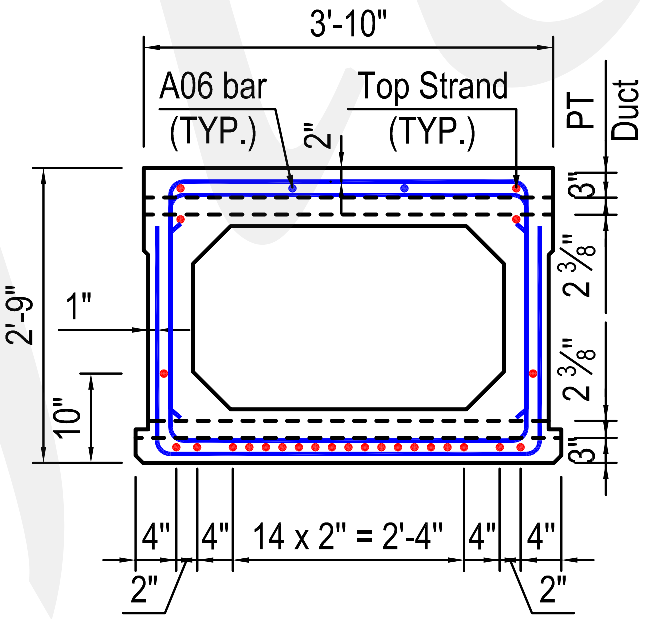


Fig. 5-249 Typical reinforcement and strand locations in an interior beam. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

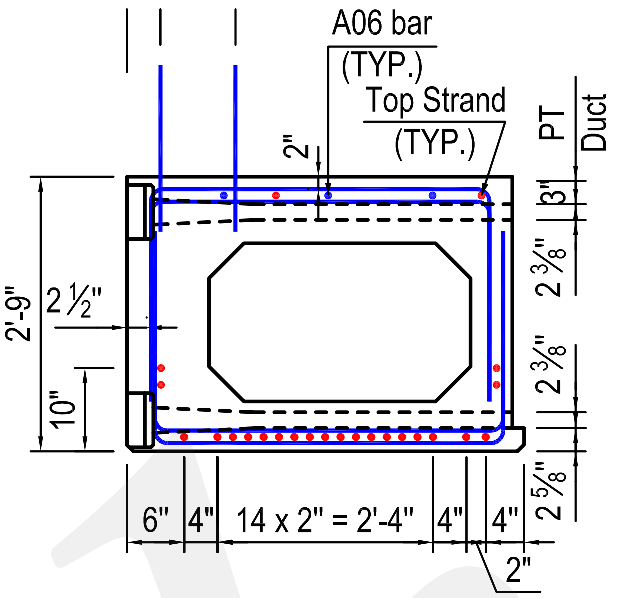


Fig. 5-250 Typical reinforcement and strand locations in an edge beam. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

5.23.2.2 Shear key

Both vertical and horizontal shear keys (Figure 5-253) are cast in the beams to allow for overall structural integrity. At the shear key locations away from the post-tensioning tendons, the width of the vertical shear key is 57 mm (2.25 in.) at the bottom of the beams and is widened to 133 mm (5.25 in.) at the beam webs (Figure 5-247). The width of the shear key is then reduced to 108 mm (4.25 in.) at the top of the beams. At the transverse post-tensioning locations, the shear key is 133 mm (5.25 in.) wide along most of the beam height (Figure 5-248). The shear key is widened at the post-tensioning locations to allow for access and space to maneuver the tendons at the joint so that they can be inserted through all beams properly. Furthermore, horizontal shear keys are created at the post-tensioning locations due to the widened joint as compared to the typical shear keys. The described system requires that the longitudinal joints be grouted fully before transverse PT is introduced. Some bridge contruction in the US, especially for small projects, still continues to apply transverse post-tensioning before the longitudinal joint is grouted. This practice has created considerable considerable leakage as the grout is not compressed in this sequencing of construction.

5.23.2.3 Unbonded post-tensioning system

A total of six pairs of transverse post-tensioning tendons are used in this bridge. The tendons are spaced at approximately 4.9 m (16 ft) along the beam length. Each pair of tendons consists of one tendon at the beam top and bottom flanges. Each tendon comprises three 15.2 mm (0.6 in.) diameter monostrands (Figure 5-251). The individual seven-wire strands are coated with corrosion-inhibiting grease and encased in polyethylene sheaths in accordance with ASTM 416 (Figure 5-252).

Corrugated steel ducts, 60 mm (2.375 in.) outside diameter, were originally specified in the Contract Drawings. To reduce the fabrication cost, the corrugated steel ducts were replaced by PVC pipes after consultation with the precaster. Also, PVC ducts are much stiffer than the corrugated steel ducts, which avoids possible deformation along the ducts during concrete placement. The ends of the PVC ducts were firmly secured by attaching them to the steel forms. It is critical to place the PVC ducts properly in the box beams to ensure proper installation of tendons at the site. The location tolerance of PVC ducts was specified to be ±6 mm (0.25 in.) in the Contract Drawings. Before placement in the forms, the ends of the ducts were required to be sealed to prevent entry of water and debris.

Because the post-tensioning tendons are located at the beam top and bottom flanges only, no intermediate diaphragms are required in this bridge. The most important advantage of this post-tensioning system is that the longitudinal joints are grouted before post-tensioning without locking the strands in place, which allows the joints to be in permanent compression and therefore essentially eliminates possible water leakage at the joints (Figure 5-253). In addition, no grouting is required in the PVC ducts after the transverse post-tensioning.

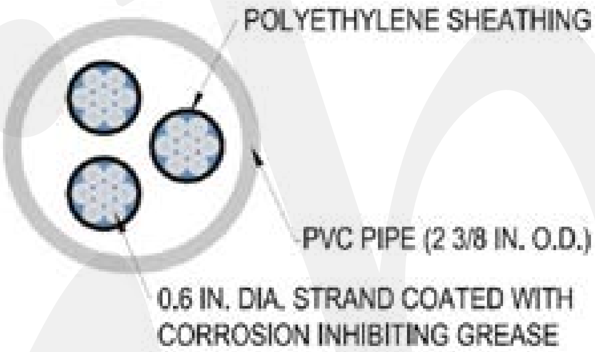


Fig. 5-251 Unbonded post-tensioning monostrand tendon. Note: 1 in. = 25.4 mm.

Fig. 5-252 Monostrand tendon: 0.6 in (15.2 mm). diameter strand coated with corrosion-inhibiting grease and encased in a polyethylene sheath.

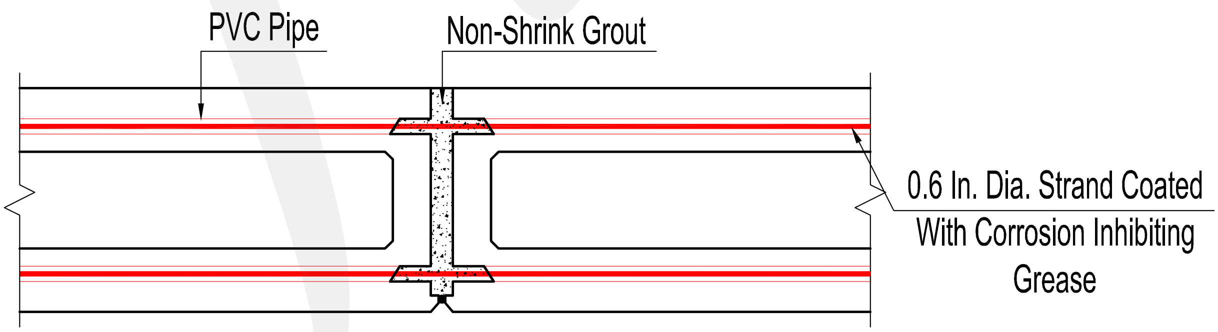


Fig. 5-253 The shear key is grouted before post-tensioning. Note: 1 in. = 25.4 mm.

5.23.2.3.1 Beam fabrication

Figure 5-254 shows the reinforcement being tied in a box beam before concrete placement. Also shown are the PVC ducts that house the transverse post-tensioning tendons. Figure 5-255 illustrates a side view of two interior beams that are stored in the precast concrete yard. Figure 5-256 shows the shear key at the location of the transverse post-tensioning.

Fig. 5-254 Partial reinforcement setup in a beam form before concrete placement. Top and bottom PVC post-tensioning ducts are visible.

Fig. 5-255 Side view of interior beams in the precast concrete storage yard.

Fig. 5-256 Vertical and horizontal shear keys at the post-tensioning location.

5.23.2.3.2 Construction sequence

The superstructure construction sequence is listed as follows:

- Install the precast concrete box beams (Figure 5-257).
- Seal the longitudinal joints between beams.
- Insert the transverse post-tensioning tendons.
- Grout the longitudinal joints.
- Tension the transverse tendons.
- Encapsulate the post-tensioning anchorages with high-strength nonshrinkage grout.
- Pour concrete brush block for bridge railing.
- Place the bridge railings (Figure 5-258).
- Install the waterproofing membrane and HMA wearing surface.

The most critical construction step is related to the transverse post-tensioning, particularly installation of the post-tensioning tendons. Every post-tensioning tendon was inserted after each individual beam was installed in its position. As a result, the transverse post-tensioning procedure was performed successfully (Figure 5-259 and Figure 5-260).

Fig. 5-257 Erection of the first edge beam.

Fig. 5-258 Subsequent beams are installed.

Fig. 5-259 The completed bridge.

Fig. 5-260 The bridge open to traffic.

5.23.3 Key design challenges

5.23.3.1 Need for intermediate diaphragms for transverse post-tensioning

The bridge owner’s standard practice for a conventional adjacent box beam system requires the use of transverse post-tensioning tendons or high-strength threaded rods that are housed in the intermediate diaphragms and are located at or near middepth of the box beams. These heavy intermediate diaphragms increase the precast concrete weight, concrete quantities, and the final load on the bridge.

5.23.3.2 Dilemma of including a composite deck slab

The bridge owner specifies a 150 mm (6 in.) thick reinforced concrete deck that is made composite with the box beams unless the bridge carries a low volume of traffic. Even though this composite deck requirement can be waived for this bridge due to its low traffic volume, the designers are concerned about potential water leakage between box beams. A composite deck slab provides a reasonable insurance against longitudinal joint cracking. However, it introduces an extra step of placing the deck slab, and therefore, it slows down the construction and increases the construction cost.

5.23.3.3 Construction complexities related to grouting longitudinal joints

Because the adjacent box girders are erected edge to edge, they do not allow for sufficient space for splicing the post-tensioning ducts in the field. Before the longitudinal joints are grouted, extreme caution must be exercised to prevent grout from entering post-tensioning ducts. A possible method includes the placement of seal washers to seal the post-tensioning tendons at the shear keys, which is not construction-friendly and is sometimes ineffective.

To overcome these challenges, the designers were motivated to develop a unique transverse post-tensioning system that allowed enhanced structural performance, increased durability, and accelerated bridge construction.

5.23.4 Innovations and accomplishments

Precast concrete adjacent box beams were used in this bridge due to their relatively shallow structural depth and low cost. An innovative transverse post-tensioning system was successfully implemented. The innovations and accomplishments in this project are summarized as follows:

- The transverse post-tensioning strands are each coated with grease and encased in a polyethylene sheath, which in turn is encased in a PVC duct. This unique duct-in-duct system is used to connect the top flanges as well as the bottom flanges of the box beams.
- The box beam webs are free of post-tensioning ducts; therefore, intermediate diaphragms are unnecessary, which reduces the precast concrete weight, concrete quantities, and the final load on the bridge.
- Elimination of intermediate diaphragms makes it possible to include a reusable steel hollow box forming system instead of sacrificial expanded polystyrene (EPS), which can result in a significant improvement in production economy.
- This system facilitates the bridge construction due to the use of unbonded post-tensioning tendons without the need for grouting transverse post-tensioning ducts.
- This system accelerates the bridge construction by eliminating the need to form and cast a concrete deck on top of the box beams.
- The transverse post-tensioning is not performed until after the longitudinal joints are grouted and reach a required minimum compressive strength. Therefore, the joints are in permanent compression and the risk of water leakage at the joints is essentially eliminated.

- This post-tensioning system greatly enhances the ability to control differential twisting between adjacent boxes and eliminates reflective cracking above the longitudinal joints, which results in a virtually maintenance-free structure.
- This simple-span bridge features an extraordinarily economical solution that results in a span-to-depth ratio of 31.
- This innovative system achieves better cost effectiveness, higher structural performance, and improved durability.

5.23.5 Summary of the preliminary design

Number of spans	1
Continuity	None: simply supported
Span length *L*, m	25.9
Girder depth *G*, mm	840
Slab depth *H*, mm	n/a
Total depth $D = G + H$, mm	840
Web width *W*, mm	250
Girder spacing *S*, m	1.33
Precast concrete girder weight, tonnes	37.8
L/D	30.83

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

5.24 Example 24: bridge with six spans, two 41.15 m (135 ft) and four 53.54 m (175.6 ft) in the United States

This example was furnished by Maher Tadros and William Nickas.

This example is a completed project: the Platte River East Bridge, located on the east side of Interstate Highway 80 between the cities of Omaha and Lincoln, Nebraska, United States.

Fig. 5-261 Photo of the completed Platte River East Bridge.

5.24.1 Considerations identified

- Bridge layout: The structure has a total length of 295.7 m (970 ft) and a total width of 14.12 m (46.33 ft).
  - A nearly level alignment required the use of the shallowest possible structural depth to avoid the maximum flood levels.
- Codes: The design is governed by the AASHTO LRFD Bridge Design Specifications[5-1].
- Traffic: The bridge is on a very busy interstate highway. Minimizing traffic interruption during construction was a priority.
- Community: The bridge serves a large community. Accelerated bridge construction (ABC) techniques were used to reduce roadway closures.
- Geological and geotechnical factors: The bridge crosses a very wide but shallow river. Reducing the number of piers would accelerate construction and reduce the cost of foundations in the water.

5.24.2 Proposed solution

This bridge length was divided into six spans. Because there were no specified locations for piers, the spans were selected for optimum structural efficiency. The spans were: one 41.15 m (135 ft), four 53.54 m (175.65 ft), and one 41.15 m. The design team also decided to use only four girder lines in the bridge cross section, resulting in girder spacing of 3.80 m (12.5 ft) and deck overhangs of 1.35 m (4.43 ft). A special continuity system to make the girders continuous for deck weight and live loads allowed the girders to be only 1.8 m (5.91 ft) deep. This corresponded to a slender span-to-depth ratio of nearly 30.

5.24.2.1 Plan

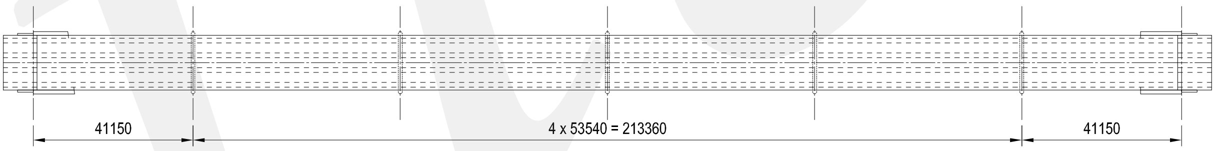


Fig. 5-262 Plan of the Platte River East Bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.24.2.2 Elevation

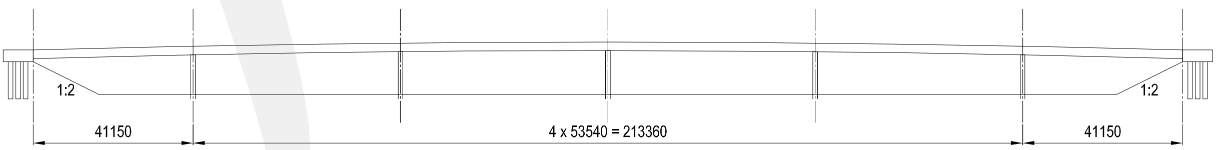


Fig. 5-263 Elevation of the Platte River East Bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.24.2.3 Cross section

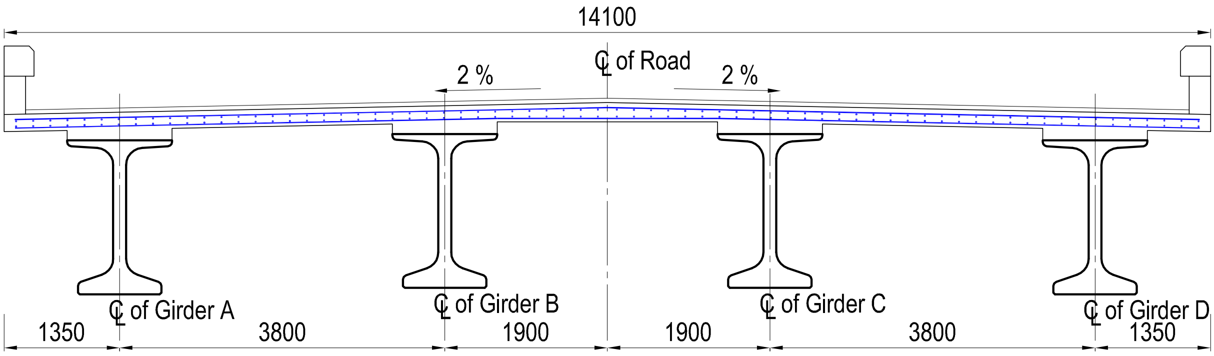


Fig. 5-264 Cross-section drawing of the Platter River East Bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

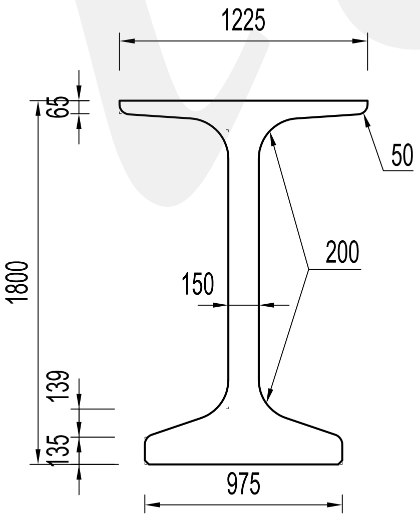
5.24.2.4 Superstructure

5.24.2.4.1 Precast concrete girders

Concrete strength at 56 days:	65 MPa (9.5 ksi)
Concrete strength at prestress release:	38 MPa (5.5 ksi)
Prestressing steel, 15.2 mm (0.6 in.) diameter strands:	1'862 MPa (270 ksi)
Mild reinforcing steel:	414 MPa (60 ksi)
Threaded rods Grade 150:	827 MPa (150 ksi)

5.24.2.5 Description of the cross section

The cross section of the superstructure consists of four I-girders, Type NU1800, 1800 mm (71 in.) deep. The precast concrete cross section is constant throughout the girder length.

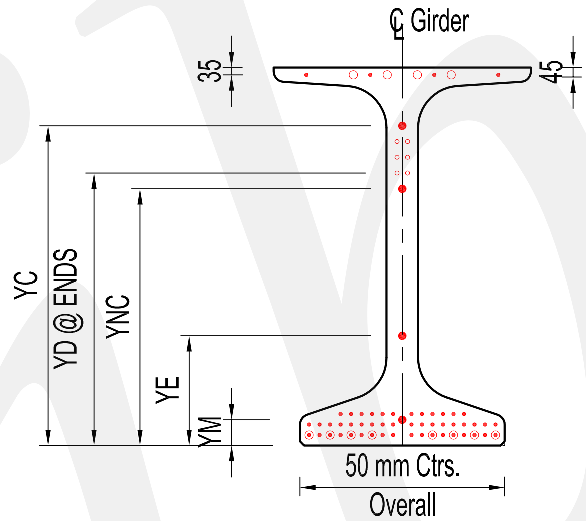


H, mm	Weight, kg/m	Area, mm²	Y_{bottom}, mm	Inertia, mm⁴
1'800	1'331	554×10^3	814	255×10^9

Fig. 5-265 Cross-section dimensions of precast concrete girders. Note: Y_{bottom} = distance from centroid to bottom fiber. Diagram dimensions are in millimeters. 1 mm = 0.0394 in.; 1 kg/m = 0.67 lb/ft; 1 mm² = 0.00155 in.².

5.24.2.6 Prestressing

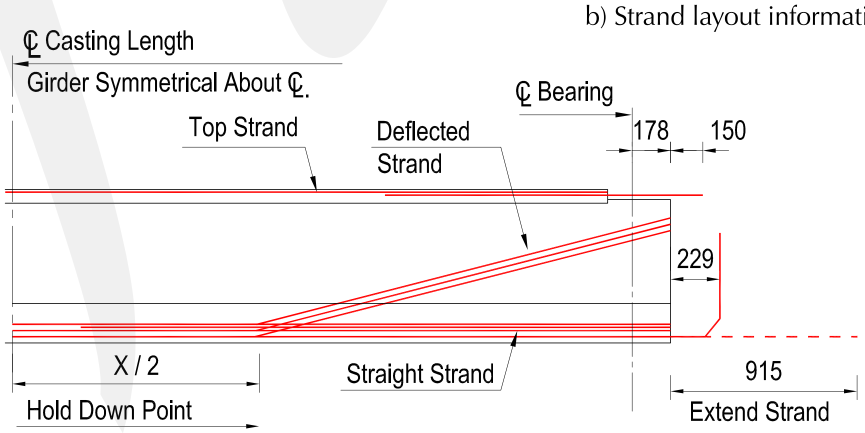
The precast concrete girders are pretensioned. The prestressing steel is low-relaxation, 15.2 mm (0.60 in.) diameter strands with yield strength of 1676 MPa (240 ksi), and ultimate strength of 1862 MPa (270 ksi). For a typical 53.34 m (175 ft) interior span, 46 bottom strands are required in three rows. Of the 46 strands, six are draped upward at the ends, and eight are extended and bent into a CIP diaphragm over the pier support. There are four partially tensioned strands in the top flange to control concrete release stresses and to support reinforcement in the girder. In addition, four high-strength, 35 mm (1 3/8 in.) diameter, untensioned threaded rods are embedded in the negative moment zone at the ends of the girder (Figure 5-268). These bars are coupled with loose bars over the pier diaphragms to create continuous negative moment capacity for deck weight. For this goal to be achieved, the loose bars are embedded in a CIP concrete strip, cast at the same time as the diaphragm concrete and before the deck concrete.



a) Locations of strands in the cross

SPAN NO.	GIRDER CASTING LENGTH (m)	CONCRETE STRENGTH (MPa) AT RELEASE	CONCRETE STRENGTH (MPa) AT 56 DAYS	NO. OF STRANDS PER GIRDER	STRANDS PER ROW AT MIDSPAN R1	R2	R3	R4	R5	R6	NUMBER of DEFLECTED STRANDS	STRAND CENTROID ENDS YE	STRAND CENTROID MIDSPAN YM	STRAND DEFLECTION AT ENDS YD	DISTANCE BETWEEN HOLDDOWN PNTS. X
1&6	39.953	38	65	36	18	18					4	240	76	60.28	1531
2&5	53.036	38	65	46	18	18	10				6	272	92	58.28	884
3&4	53.036	38	65	46	18	18	10				6	272	92	58.28	884

b) Strand layout information



c) Strand profile details

Fig. 5-266 Locations of strands in the cross section, strand layout information, and strand profile details. Note: Diagram dimensions are in millimeters 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

5.24.2.7 Deck slab

5.24.2.7.1 Materials

Concrete: 31 MPa (4.5 ksi)

Mild reinforcing steel: 414 MPa (60 ksi)

5.24.2.7.2 Deck slab description

The slab is CIP concrete with a uniform thickness of 215 mm (8.5 in.). The slab thickness varies between the two interior girders from 215 to 240 mm (8.5 to 9.84 in.) to form a crown at the center of the bridge cross section.

5.24.2.7.3 Transverse slopes

The deck of the bridge has a crown with 2% transverse slopes each direction formed by the deck slab. The slope is achieved by lowering the elevations of the two exterior girders compared to the two interior girders, and by sloping the top surface of the deck.

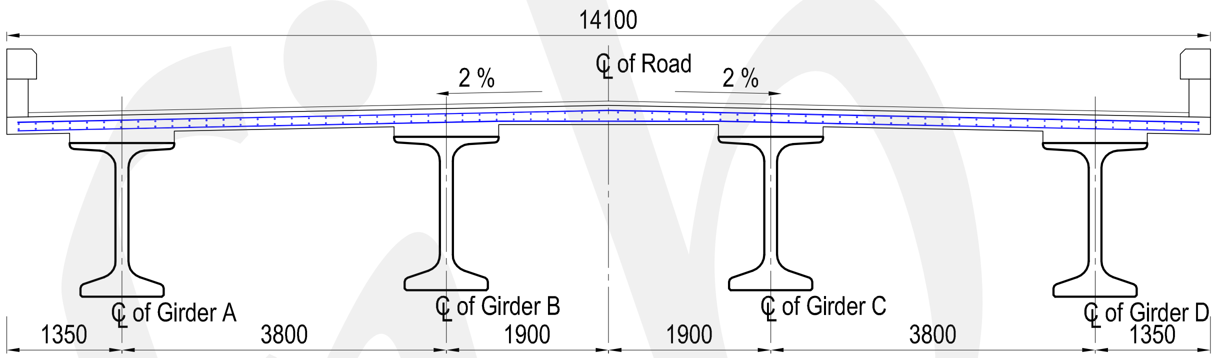
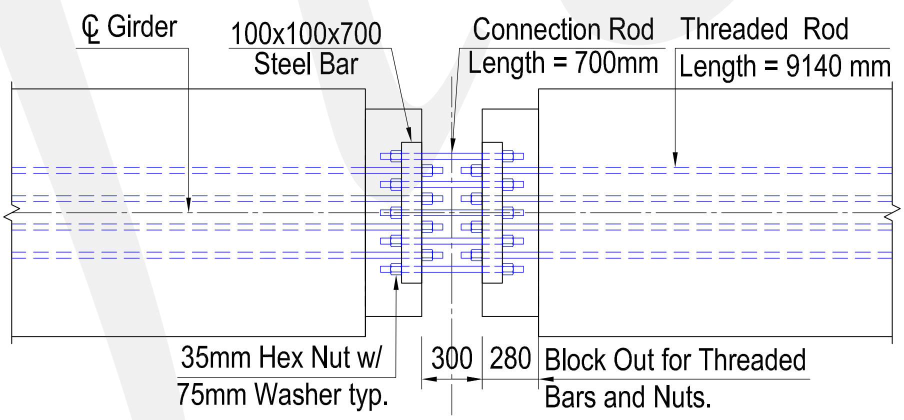


Fig. 5-267 Bridge cross section. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.24.2.7.4 Details of the continuity connection over the piers



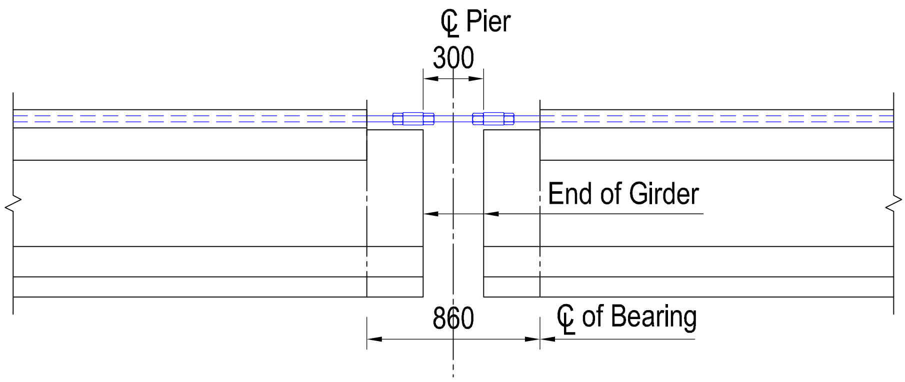


Fig. 5-268 Continuity detail over the piers. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

This example uses the threaded rod continuity system, which allows the structure to be continuous for deck weight. In this system, the precast concrete girders are fabricated with high-strength threaded rods located in the top flange and projecting from the ends of the girders. The threaded rods are mechanically spliced in the field at the diaphragms over the piers. The diaphragm concrete is then placed, and the deck slab is cast after the diaphragm gains the required strength. This continuity reinforcement is designed to resist the negative moment due to the weight of the top slab. This system is only used in Nebraska and several other states. It is not as common as the system where all the continuity reinforcement is placed in the deck and is designed as simple span for the deck weight and continuous for all additional loads. The Platter River East Bridge with the continuity system described here allowed for further optimization of the I-girders. It allowed for relatively wider girder spacing, reduced demand for prestressing, and for reduction of concrete strength at prestress release. However, it required accuracy of placement of the threaded rods. It also required an extra step of coupling the rods and placing the diaphragm and joint concrete before placing

Fig. 5-269 Photo showing the threaded rod connection over the pier.

5.24.2.8 Transverse diaphragms

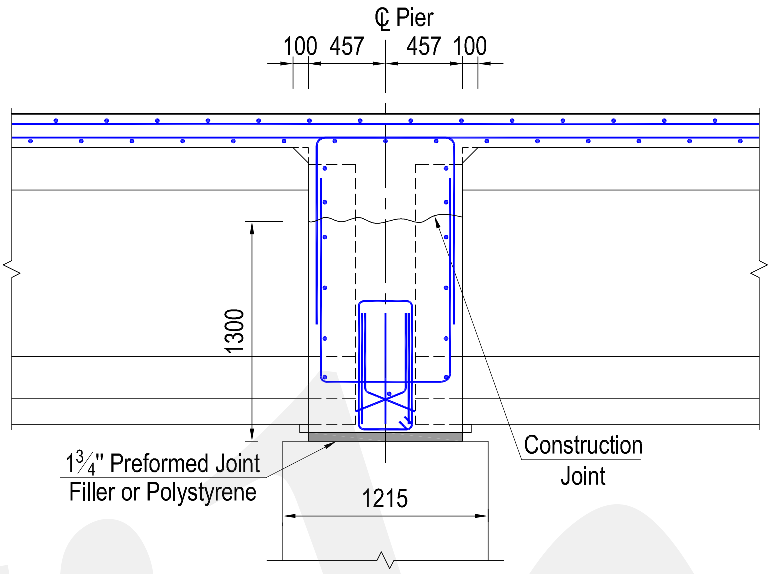


Fig. 5-270 Detail of a cast-in-place diaphragm. Note: All dimensions are in millimeters. 1 mm = 0.0394 in. 1" = 1 in. = 25.4 mm.

5.24.2.9 Construction sequence

- Construct CIP abutments and piers.
- Place bearing pads on top of the abutments and piers.
- Erect girders and couple threaded rods over piers.
- Form and cast the diaphragm, enclosing the threaded rods.
- Form and cast the deck slab.
- Form and cast the railing.

5.24.2.10 Substructure

The substructure of this bridge was constructed with CIP concrete. The piers are CIP wall piers that are supported by steel piles. This is the type used in stream crossings to suit hydraulics of the flowing water in the stream.

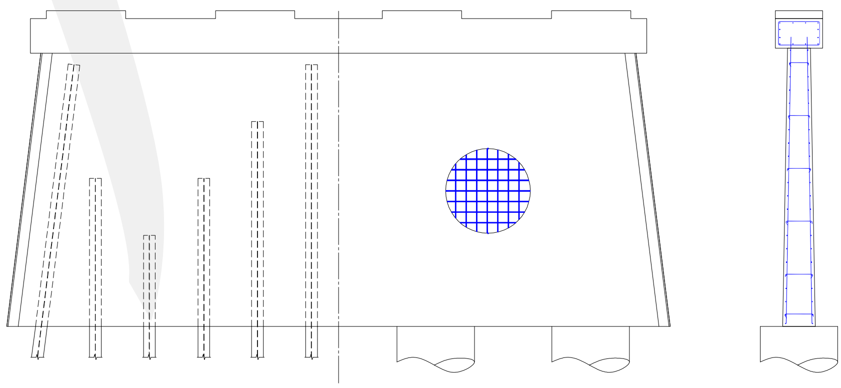


Fig. 5-271 Pier details.

The abutments are CIP reinforced concrete typically supported by steel piles. The backwall helps retain the earth beyond the bridge.

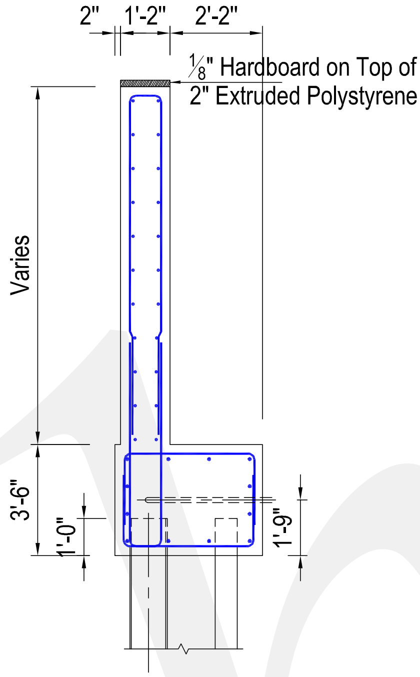


Fig. 5-272 Abutment details. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

5.24.3 Summary of the preliminary design

Number of spans	6
Continuity	Continuous for deck dead load and live load: threaded rods and reinforcement in the deck slab
Span lengths *L*, m	41.15 and 53.34
Girder depth *G*, mm	1'800
Slab depth *H*, mm	215
Total depth *D* = *G* + *H*, mm	2015
Web width *W*, mm	150
Girder spacing *S*, m	3.8
Precast concrete girder weight, tonnes	52 and 68
L/D	23 and 30

5.25 Example 25: bridge with two 40 m (131 ft) long spans in South Korea

This example was furnished by Manyop Han.

Precast, prestressed concrete I-girders are widely used in short- and medium-span bridges. Prestressing in the form of post-tensioning is usually applied once at the first stage of construction. The magnitude of the prestressing force is limited within allowable stresses at various construction stages. Consequently, for longer spans, a deeper girder is required.

To achieve shallower and more economical girders for a given span, or a longer span for a given girder depth, multistage prestressing at different loading stages is used here. When prestressing forces are introduced incrementally in multiple steps according to the applied loading sequence, larger moment capacity of the girder can be achieved. At the first stage, prestressing force which compensates for self-weight is introduced. After the concrete deck slab is cast and cured, more prestressing force is applied to compensate for the total design loads. In this way, final load-carrying capacity increases quite a lot compared to the traditional one-time prestressing method

5.25.1 Considerations identified

- Bridge layout: This example is a bridge with a total length of 80 m (262 ft) and a total width of 11.4 m (37.4 ft).
- Codes: This example is governed by the "Korean Highway Bridge Design Code"[5-22].

5.25.2 Proposed solution

This example has two spans, each with a length of 40 m (131 ft). The cross section of the superstructure consists of eight precast concrete girders with a depth of 1900 mm (75 in.).

The CIP deck slab is 24 cm (9 in.) thick and the bridge has 2.0% transverse slopes, on both sides of centerline formed by the concrete slab.

The precast concrete girders are post-tensioned, and the layout of the tendons are both straight and draped, placed in both the top and bottom flanges.

5.25.2.1 Plan

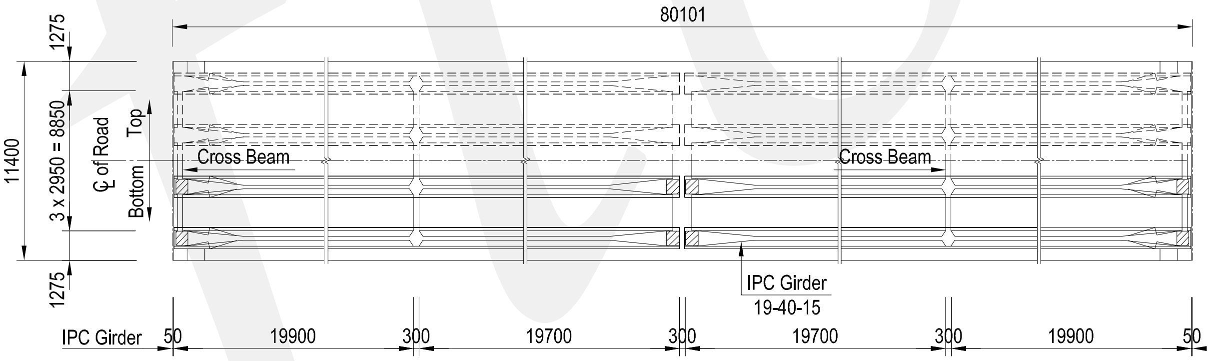


Fig. 5-273 Abutment details. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

5.25.2.2 Elevation

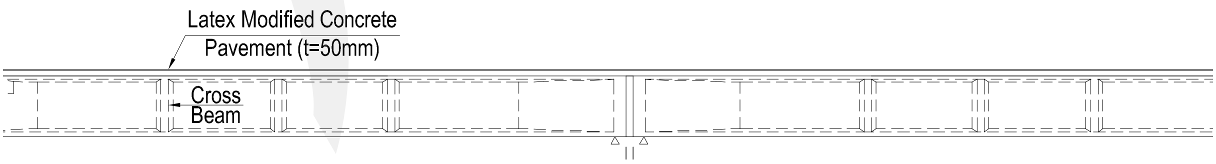


Fig. 5-274 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.25.2.3 Cross section

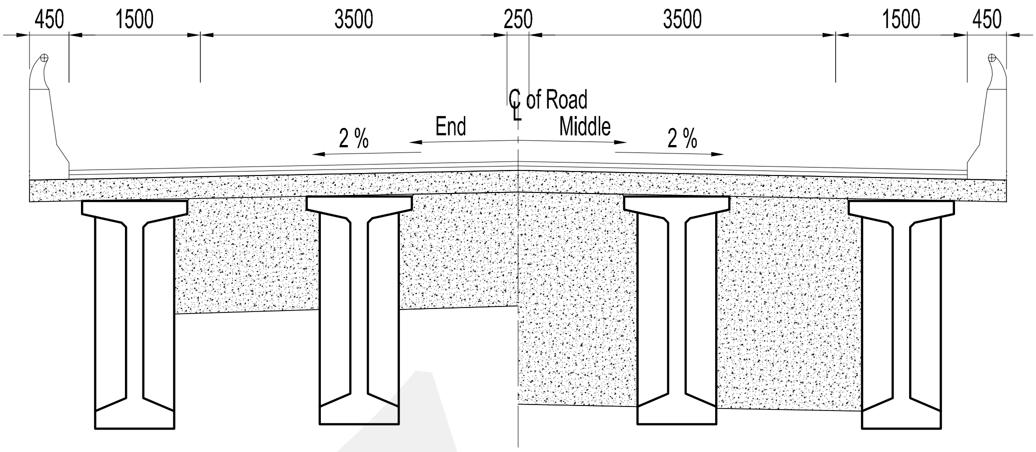


Fig. 5-275 Cross section of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.25.3 Superstructure

5.25.3.1 Precast concrete girders

5.25.3.1.1 Materials

Concrete:	40 MPa (6 ksi)
Prestressing steel:	1'900 MPa (276 ksi)
Mild reinforcing steel:	300 MPa (44 ksi)

5.25.3.1.2 Description of the cross section

The cross section consists of four I-girders, 1'900 mm (75 in.) deep spaced at 2.9 m (9.5 ft) on center.

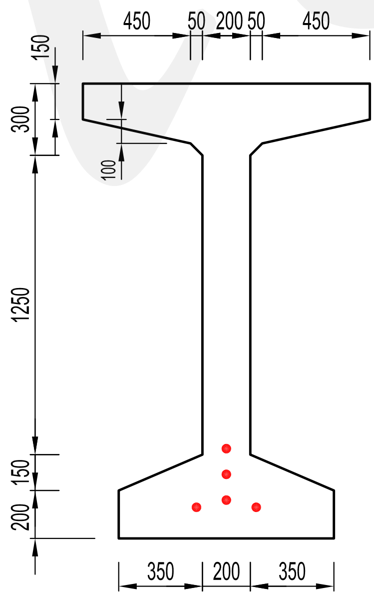


Fig. 5-276 Cross-section dimensions of precast concrete girder All dimensions are in centimeters. 1 cm = 0.3937 in.

5.25.3.1.3 Prestressing

The precast concrete girders are post-tensioned. The method of multistage tensioning at different loading stages is introduced8. For each girder there is a total of 70 15.2 mm (0.6 in.) diameter prestressing strands. In the first stage, 48 strands are tensioned before casting deck slab. For the second stage, 22 strands are tensioned after the deck slab has reached the required strength.

5.25.3.2 Deck slab

5.25.3.2.1 Materials

Concrete: 27 MPa (4 ksi)

Mild reinforcing steel: 400 MPa (58 ksi)

5.25.3.2.2 Deck slab description

The deck is a 240 mm (9 in.) thick CIP concrete slab that also spans between girders. The deck has a transverse slope of 2%, achieved by installing each girder at a different elevation.

5.25.3.3 Summary of the preliminary design

Number of spans	2
Continuity	Link slab
Span length *L*, m	40
Girder height *G*, mm	1'900
Slab depth *H*, mm	240
Total depth $D = G + H$, mm	2'140
Web width *W*, mm	200
Girder spacing *S*, m	2.7
Precast concrete girder weight, tonnes	19.5
L/D	18.7
L/G	21.1
Prestressing steel, kg/m^2	29.9
Reinforcing steel – girder, kg/m^2	55.2
Reinforcing steel – top slab, kg/m^2	48.2
Reinforcing steel in a diaphragm, kg	108.6

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m2 = 0.2048 lb/ft2; 1 tonne = 1.102 tons.

5.25.4 Construction sequence

- After the CIP construction of the piers, neoprene bearing pads are installed on a bed of adjusting mortar.
- Typically, girders are transported by truck and erected with cranes.
- Girders are placed on temporary devices on top of the piers, allowing casting of variable-depth bedding mortar on the neoprene pads.

- Reinforcement is installed for the deck slab and concrete is placed, completing the superstructure.
- When the deck concrete is sufficiently strong, post-tensioning tendons are installed and tensioned in each diaphragm.

5.26 Example 26: bridge with two 50 m (164 ft) long spans in South Korea

This example was furnished by Manyop Han.

5.26.1 Considerations identified

- Bridge layout: This example bridge has a total length of 100 m (328 ft) and a total width of 20.4 m (66.9 ft).
- Codes: This example is governed by the "Korean Highway Bridge Design Code"[5-22].

5.26.2 Proposed solution

This example has two spans each with a length of 50 m (164 ft). The cross section of the superstructure consists of eight precast concrete I-girders with a depth of 2'600 mm (102 in.).

The CIP deck slab is 24 cm (9 in.) thick. The bridge has 2.0% transverse slopes on both sides of centerline formed by the concrete deck slab.

5.26.2.1 Plan

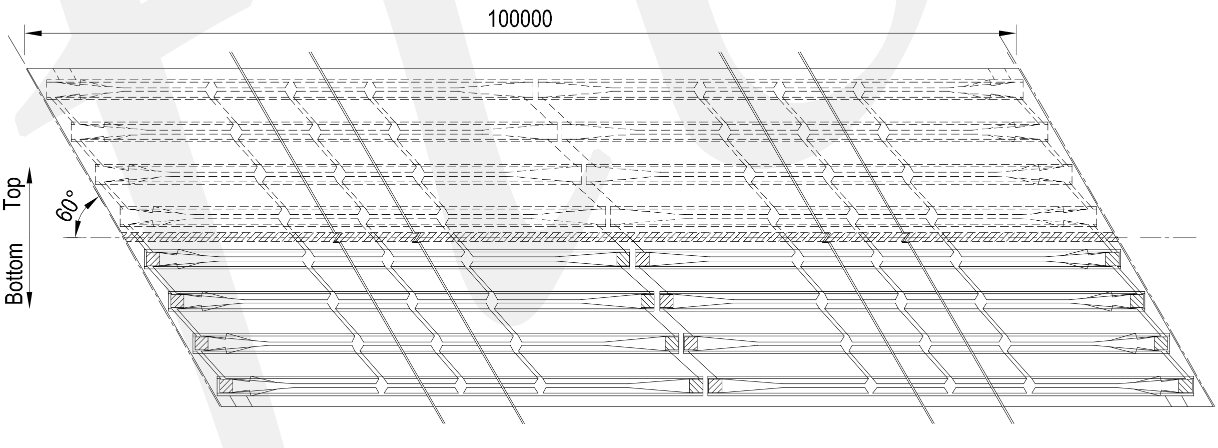


Fig. 5-277 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.26.2.2 Elevation

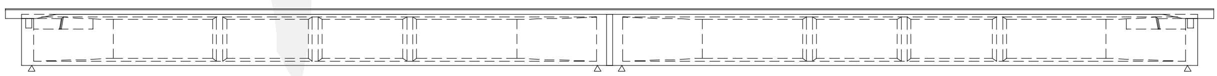


Fig. 5-278 Elevation of the bridge.

5.26.2.3 Cross section

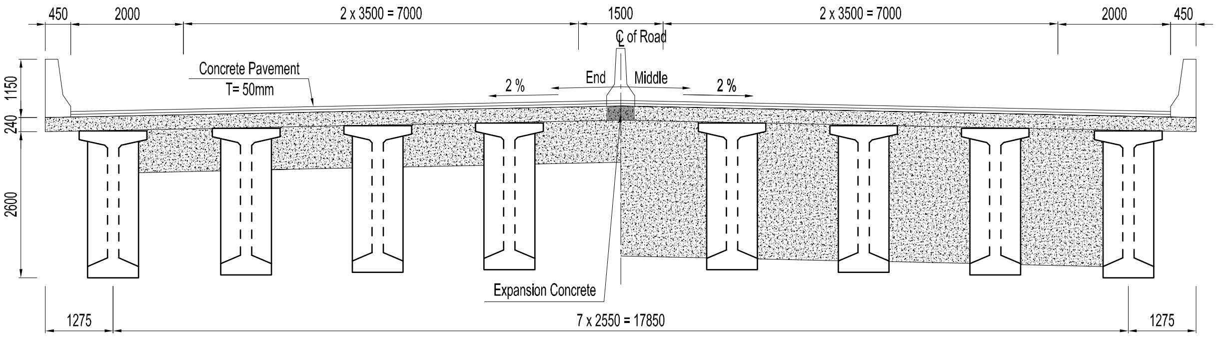


Fig. 5-279 Cross section of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.26.3 Superstructure

5.26.3.1 Precast concrete girders

5.26.3.1.1 Materials

Concrete:	40 MPa (6 ksi)
Prestressing steel:	1'900 MPa (276 ksi)
Mild reinforcing steel:	300 MPa (44 ksi)

5.26.3.1.2 Description of the cross section

There are eight I-girders, 2'600 mm (102 in.) deep spaced at 2.55 m (8.37 ft) on center.

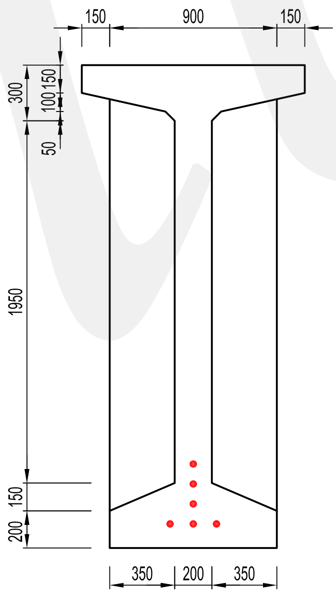


Fig. 5-280 Cross-section dimensions of precast concrete girder. All dimensions are in centimeters. 1 cm = 0.3937 in.

5.26.3.1.3 *Prestressing*

The precast concrete girders are post-tensioned. The method of multistage tensioning at different loading stages is employed[5-23]. For each girder, there is a total of 84 15.2 mm (0.6 in.) prestressing strands in a total of six post-tensioning tendons. The first stage of prestressing tensions 58 strands before casting the deck slab. The second stage of tensioning the remaining 26 strands occurs after the deck slab has reached the required strength. Each CIP concrete diaphragm contains two straight post-tensioning tendons.

5.26.3.2 Deck slab

5.26.3.2.1 *Materials*

Concrete: 27 MPa (4 ksi)

Mild reinforcing steel: 400 MPa (58 ksi)

5.26.3.2.2 *Deck slab description*

The deck is a 240 mm (9 in.) thick CIP concrete slab that also spans between girders. The deck has a transverse slope of 2%, achieved by installing each girder at a different elevation.

5.26.3.3 Summary of the preliminary design

Number of spans	2
Continuity	Link slab
Span length *L*, m	50
Girder depth *G*, mm	2'600
Slab depth *H*, mm	240
Total depth *D* = *G* + *H*, mm	2'840
Web width *W*, mm	200
Girder spacing *S*, m	2.55
Precast concrete girder weight, tonnes	23.0
L/D	17.61
L/G	19.23
Prestressing steel, kg/m^2	31.3
Reinforcing steel – girder, kg/m^2	47.4
Reinforcing steel – top slab, kg/m^2	39.2
Reinforcing steel in a diaphragm, kg	196.4

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.26.4 Construction sequence

- After completing the CIP piers, neoprene bearing pads are installed on a bed of adjusting mortar.
- Typically, girders are transported by truck and erected with cranes.
- Girders are placed on temporary devices on top of the piers, allowing placement of variable-depth mortar on neoprene pads.

- Reinforcement is installed for the deck slab and concrete is placed to complete the superstructure.
- When the deck concrete is sufficiently strong, post-tensioning tendons are installed and tensioned in each diaphragm.

5.27 Example 27: bridge with a single 60 m (197 ft) long span in South Korea

This example was furnished by Manyop Han.

In this project, the concept for a "holed," incrementally prestressed concrete (H-IPC) girder represents various advanced design ideas. First, the entire self-weight can be considerably reduced by casting holes in the web, with minimal effect on the moment of inertia. Also, prestress can be efficiently introduced in an incremental way by distributing some post-tensioning anchorages to the holes. The girder can maintain the same section throughout the span by preventing concentration of the anchorage forces. This can further reduce self-weight, fabricating time, and cost. Furthermore, the spliced girder system makes it possible to extend the span to more than the conventional length because the segments can be transported and assembled on-site.

5.27.1 Considerations identified

Bridge layout: This example bridge has a total length of 60 m (197 ft) and a total width of 25.5 m (83.7 ft). The structure is over a highway, which made the 60 m span necessary.

Codes: This example is governed by the "Korean Highway Bridge Design Code"[5-22].

5.27.2 Proposed solution

This solution is a bridge with a single span of 60 m (197 ft). The cross section of the superstructure uses eight precast, prestressed concrete girders with a depth of 2500 mm (98 in.).

Three important concepts were implemented in the design of these I-girders:

- The girders are fabricated as segments and assembled at the site using post-tensioning before they are erected on the piers.
- In this example, 18 1 m (3 ft) diameter holes were formed in the web of the girder during manufacture. This reduces not only the self-weight of the girder but also the wind load acting on the girder. An additional benefit is some of the post-tensioning anchorages can be moved from the ends of the girder into the openings. In this way, the magnitude of negative moment developed at girder ends will be reduced. Furthermore, because anchorage stresses are reduced at ends, the size of diaphragms may be reduced.
- The prestressing force was applied to the girder in multiple stages[5-23]. This technique overcomes the limitation of prestressing force due to allowable concrete stresses.

The CIP top slab is 24 cm (9 in.) thick and the deck of the bridge has 2.0% transverse slopes formed by the concrete deck slab.

5.27.2.1 Plan

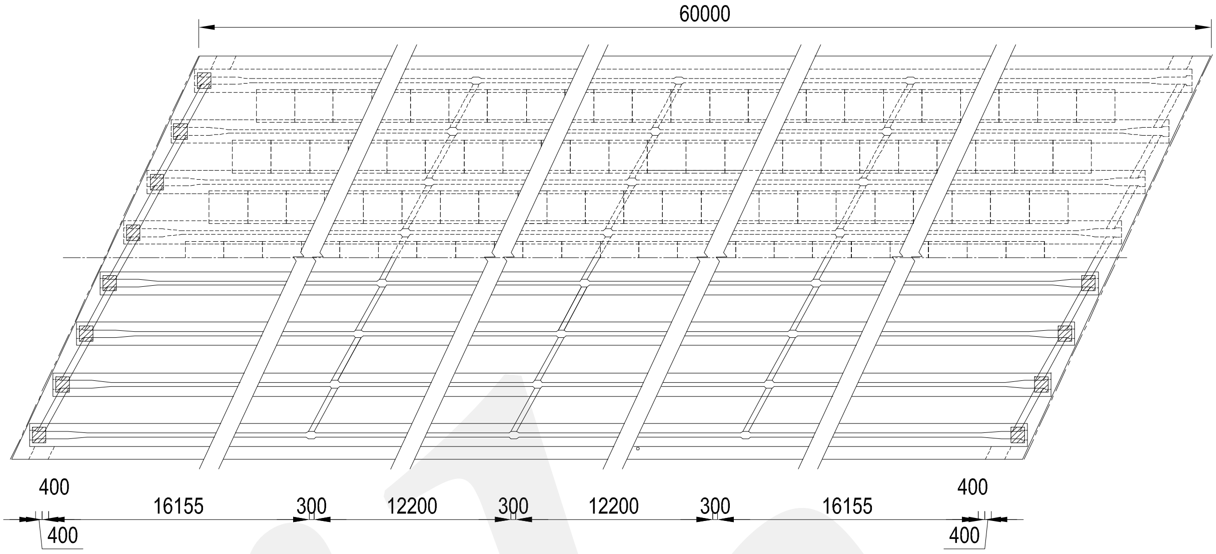


Fig. 5-281 Plan of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.27.2.2 Elevation

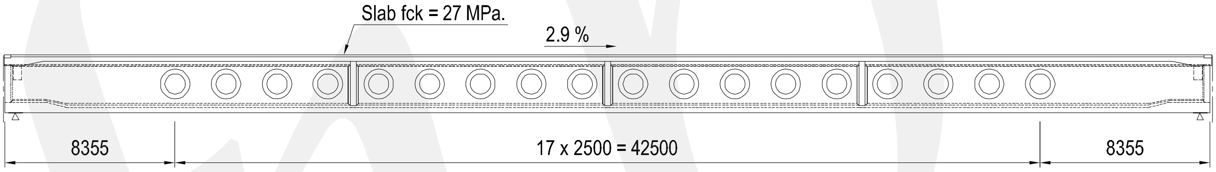


Fig. 5-282 Elevation of a girder. Note: fck = 28 day characteristics strength of concrete. All dimensions are in millimeters. 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi.

5.27.2.3 Cross section

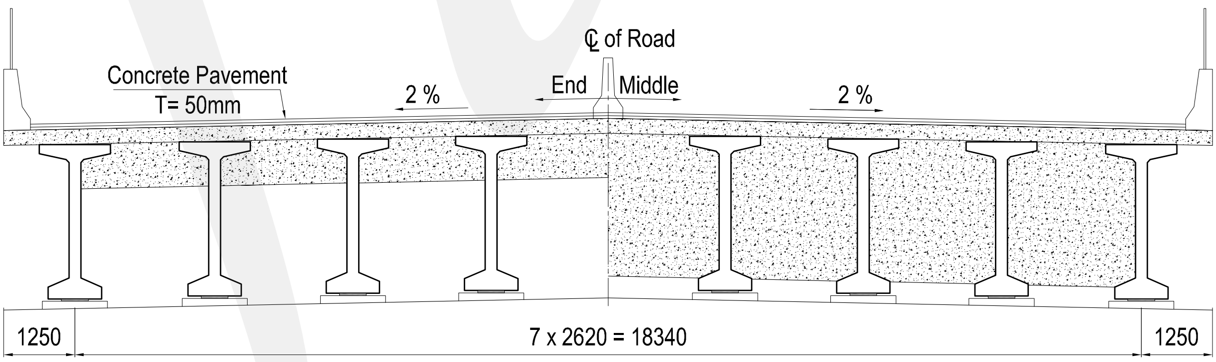


Fig. 5-283 Cross section of the superstructure. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.27.3 Superstructure

5.27.3.1 Precast concrete girders

5.27.3.1.1 Materials

Concrete:	80 MPa (12 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	400 MPa (58 ksi)

5.27.3.1.2 Description of the cross section

Eight I-girders, 2'500 mm (98 in.) deep spaced at 2.62 m (8.6 ft) on center. Holes with 1 m (3 ft) diameter are cast through the webs every 2.5 m (8.2 ft) on center.

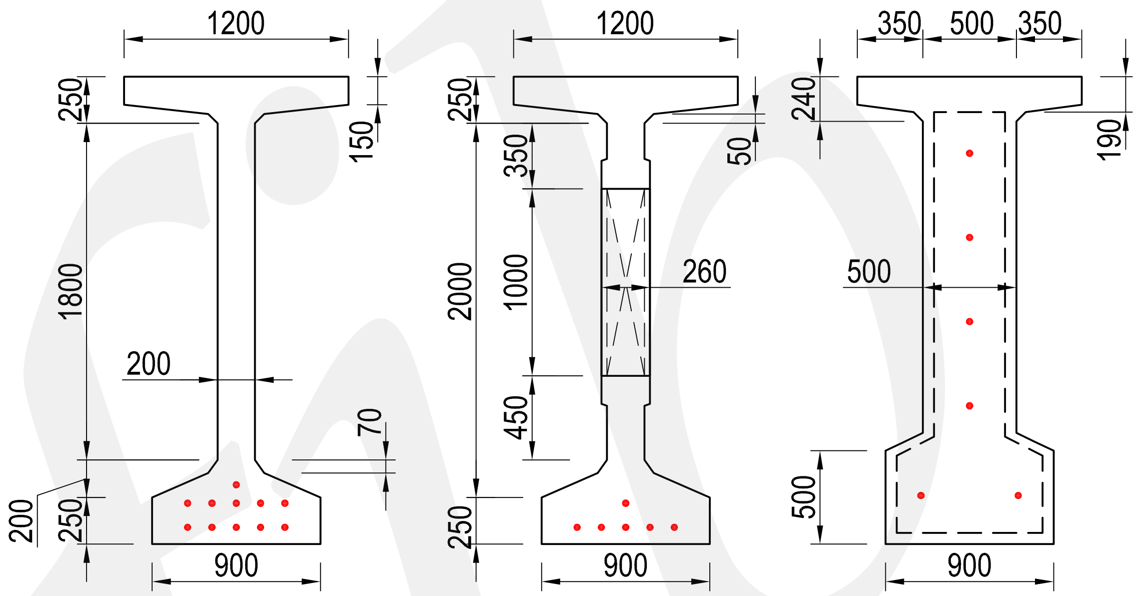


Fig. 5-284 Cross-section dimensions of precast concrete girder. All dimensions are in centimeters. 1 cm = 0.3937 in.

5.27.3.1.3 Prestressing

The precast concrete girders are post-tensioned. Multistage tensioning at various loading stages is used. For each girder there is a total of 100 15.2 mm (0.6 in.) diameter prestressing strands per girder (72 strands are tensioned in the first stage from anchorages installed at the ends before casting the deck slab; 28 strands are installed in ducts anchored in a hole for the second stage tensioning after the deck slab has attained the required strength).

5.27.3.2 Deck slab

5.27.3.2.1 Materials

Concrete:	30 MPa (4 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.27.3.2.2 Deck slab description

The deck slab is cast in place, 24 cm (9 in.) thick.

5.27.3.3 Summary of the preliminary design

Number of spans	1
Continuity	n/a
Span length *L*, m	60
Girder height *G*, mm	2'500
Slab depth *H*, mm	240
Total depth *D* = *G* + *H*, mm	2'740
Web width *W*, mm	200
Girder spacing *S*, m	2.62
Precast concrete girder weight, tonnes	21.2
L/*D*	21.9
L/*G*	24.0
Prestressing steel, kg/m^2	32.5
Reinforcing steel – girder, kg/m^2	59.8
Reinforcing steel – top slab, kg/m^2	33.3
Reinforcing steel in a diaphragm, kg	196.2

Note: n/a = not applicable. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 kg = 2.205 lb; 1 kg/m^2 = 0.2048 lb/ft^2; 1 tonne = 1.102 tons.

5.28 Example 28: bridge with ten 35 m (115 ft) long spans in Portugal

This example was furnished by Luis Matute and Helder Figueiredo.

The bridge presented in this example is in the city of Valongo in the northern region of Portugal crossing over the A4 freeway. It has both vertical and horizontal curvature.

Fig. 5-285 Partial elevation of the finished bridge.

5.28.1 Considerations identified

- Bridge layout: This example is a bridge with a total length of 350 m (1148 ft) and a total width of 13.1 m (43 ft).
- Codes: This example is governed by the standard code: “Regulamento de Segurança e Ações” (Portuguese standard)[5-24].

5.28.2 Proposed solution

Precast concrete superstructures are used in Spain and Portugal in a wide range of spans and geometric configurations (constant or variable width, straight, skewed or curved alignment). For spans up to 35 m (115 ft) they are the most used solution in both countries, either using I-girders or U girders. Traditionally, simply supported solutions are preferred in Spain, while in Portugal continuous solutions are more common.

The viaduct in this example has two parallel decks with a continuous precast concrete superstructure. It has 10 continuous spans, each with a length of 35 m. The cross section of the superstructure consists of four precast concrete I-girders with a depth of 2'000 mm (79 in.).

The CIP top slab is 250 mm (10 in.) thick and the bridge has a minimum 2% transverse slope.

The precast concrete girders are pretensioned and the strands are all straight and located in the bottom flange.

5.28.2.1 Plan

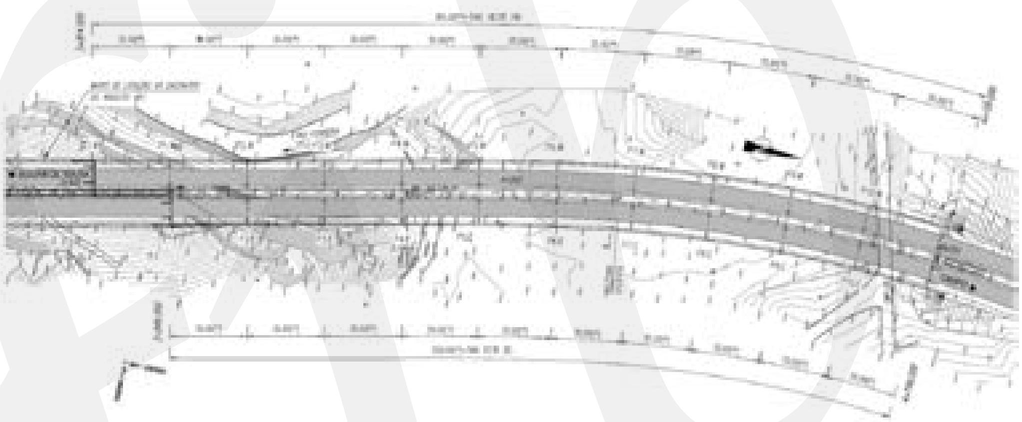


Fig. 5-286 Plan of the bridge.

5.28.2.2 Elevation

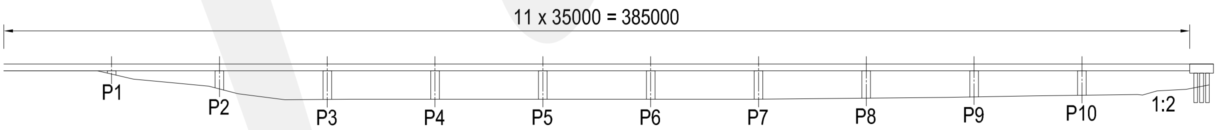


Fig. 5-287 Elevation of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.28.2.2 Elevation

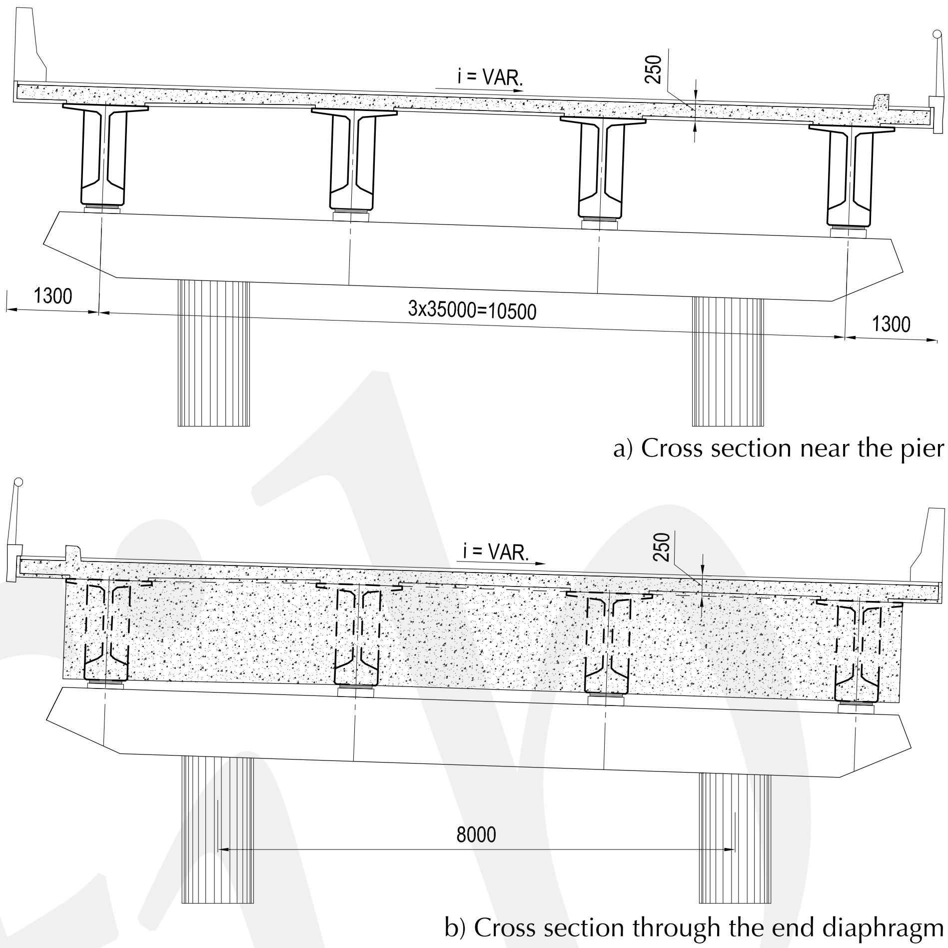


Fig. 5-288 Cross sections of the bridge. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.28.3 Superstructure

5.28.3.1 Precast concrete girders

5.28.3.1.1 Materials

Concrete:	40 MPa (6 ksi)
Prestressing steel:	1'860 MPa (270 ksi)
Mild reinforcing steel:	500 MPa (73 ksi)

5.28.3.1.2 Description of the cross section

Four I-girders, 2000 mm (79 in.) deep, spaced at 3.5 m (11.5 ft) on center.

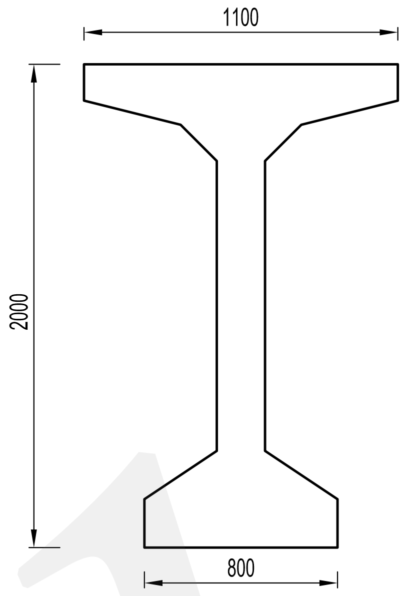


Fig. 5-289 Cross-section dimensions of precast concrete girder. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.28.3.1.3 Prestressing

The precast concrete girders are pretensioned. There are 32 straight prestressing straight strands in the bottom flange. Several strands are debonded up to 4 m (13 ft) from the supports.

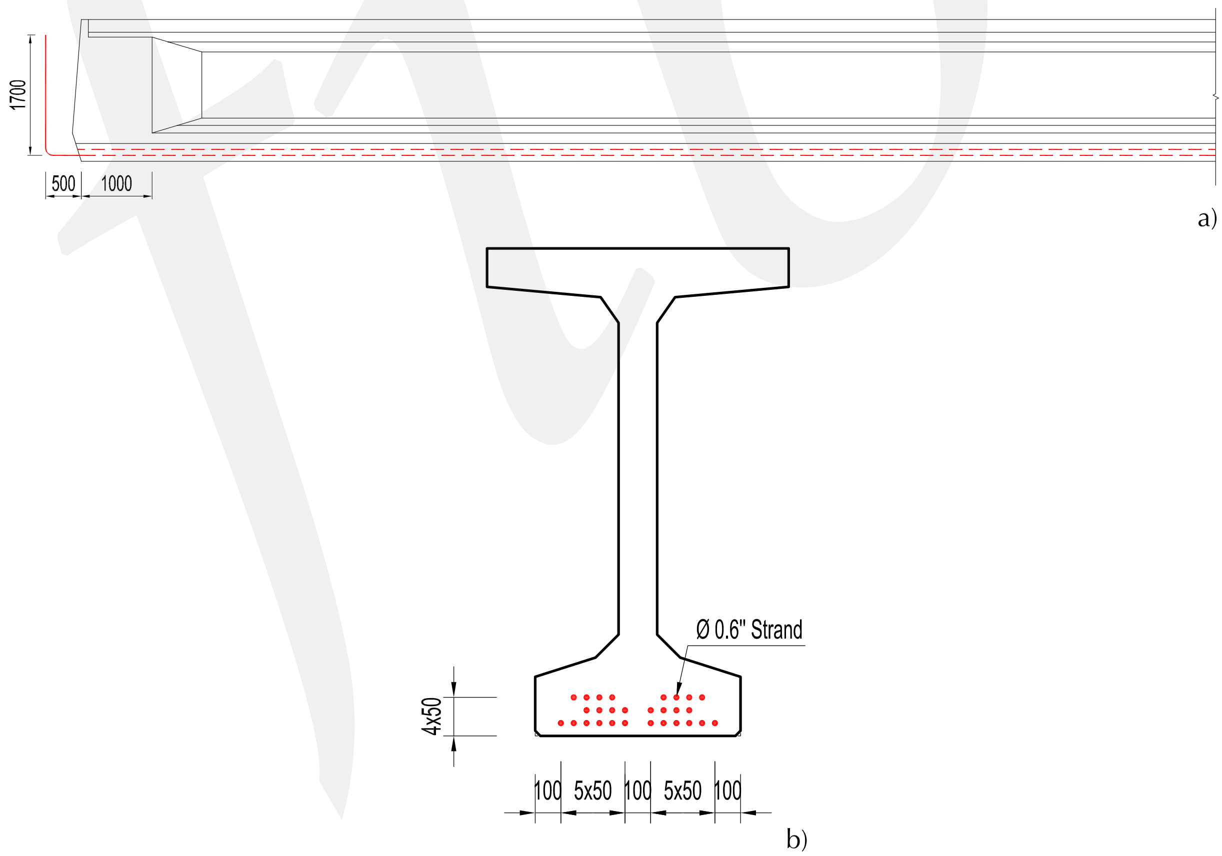


Fig. 5-290 Prestressing strand layout, (a) side view, and (b) strand locations at the ends. Note: Dimensions are in centimeters. 1 cm = 0.3937 in. 1" = 1 in. = 25.4 mm.

5.28.3.2 Deck slab

5.28.3.2.1 Materials

Concrete: 35 MPa (5 ksi)

Mild reinforcing steel: 500 MPa (73 ksi)

5.28.3.2.2 Deck slab description

The deck slab has a thickness of 250 mm (10 in.) and is cast on precast concrete deck panels placed on the edges of the top flanges of the girders.

5.28.3.3 Continuity

Following the casting of the deck slab, continuity is established for superimposed dead load and live loads only. The negative bending is resisted with mild steel reinforcement placed in the slab. The positive bending that can develop due to upward long-term camber is resisted by reinforcement placed in the bottom of the pier diaphragms.

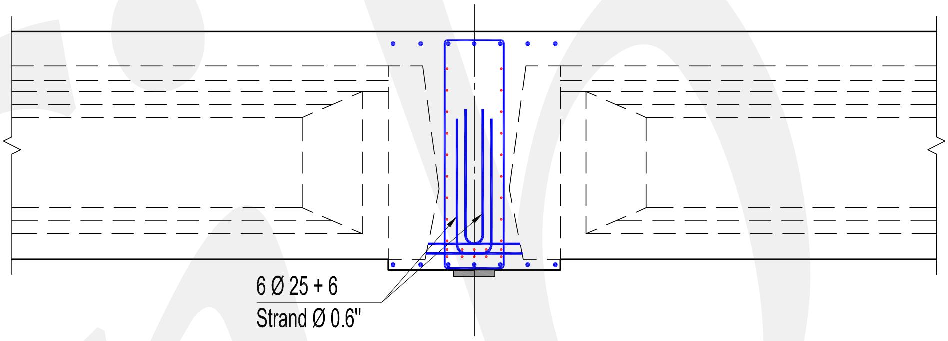


Fig. 5-291 Continuity detail over the pier. Note: 1" = 1 in. = 25.4 mm.

5.28.3.4 Diaphragms

Diaphragms are CIP reinforced concrete over the piers and abutments.

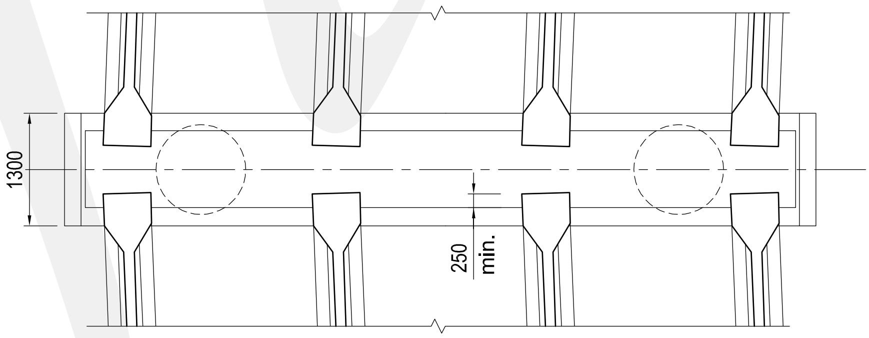


Fig. 5-292 Transverse diaphragm over intermediate pier. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

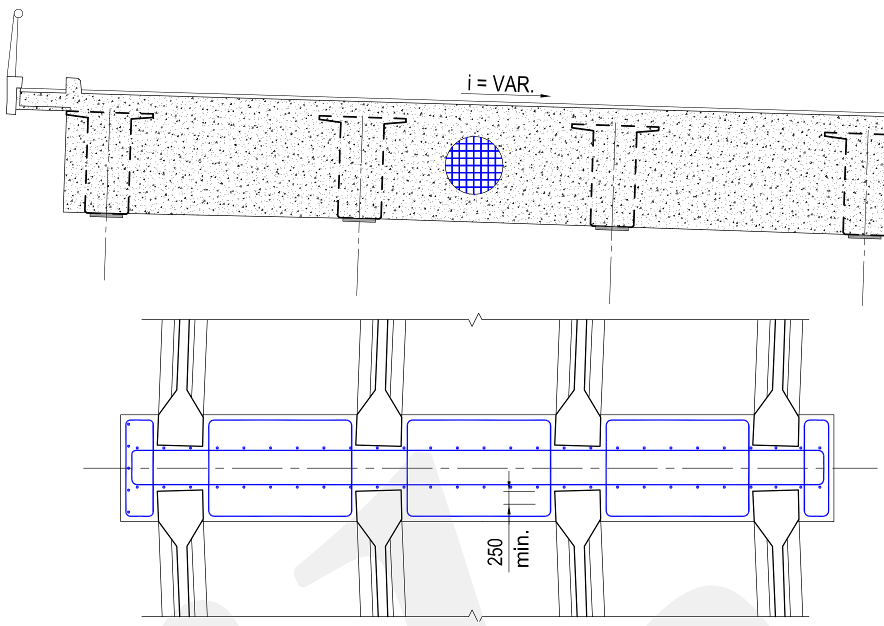


Fig. 5-293 Reinforcement of the diaphragms. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

5.28.3.5 Summary of the preliminary design

Number of spans	10
Continuity	Partial structural continuity
Span length *L*, m	35
Girder height *G*, mm	2'000
Slab depth *H*, mm	250
Total depth *D* = *G* + *H*, mm	2'250
Web width *W*, mm	170
Girder spacing *S*, m	3.5
Precast concrete girder weight, tonnes	64.2
L/D	15.6
L/G	17.5

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.102 tons.

5.28.4 Construction sequence

- Phase 1: Erect precast concrete girders on temporary supports (located on pier beams and abutments).
- Phase 2: Place precast concrete stay-in-place deck panels on the girders over their total length (with the exception of over the diaphragms on the piers, which are cast with conventional formwork).

  Place deck slab reinforcement; cast and cure the deck concrete.
- Phase 3: Construct the transverse diaphragms over the intermediate piers and abutments.
- Phase 4: Remove temporary supports and perform final finishing work.

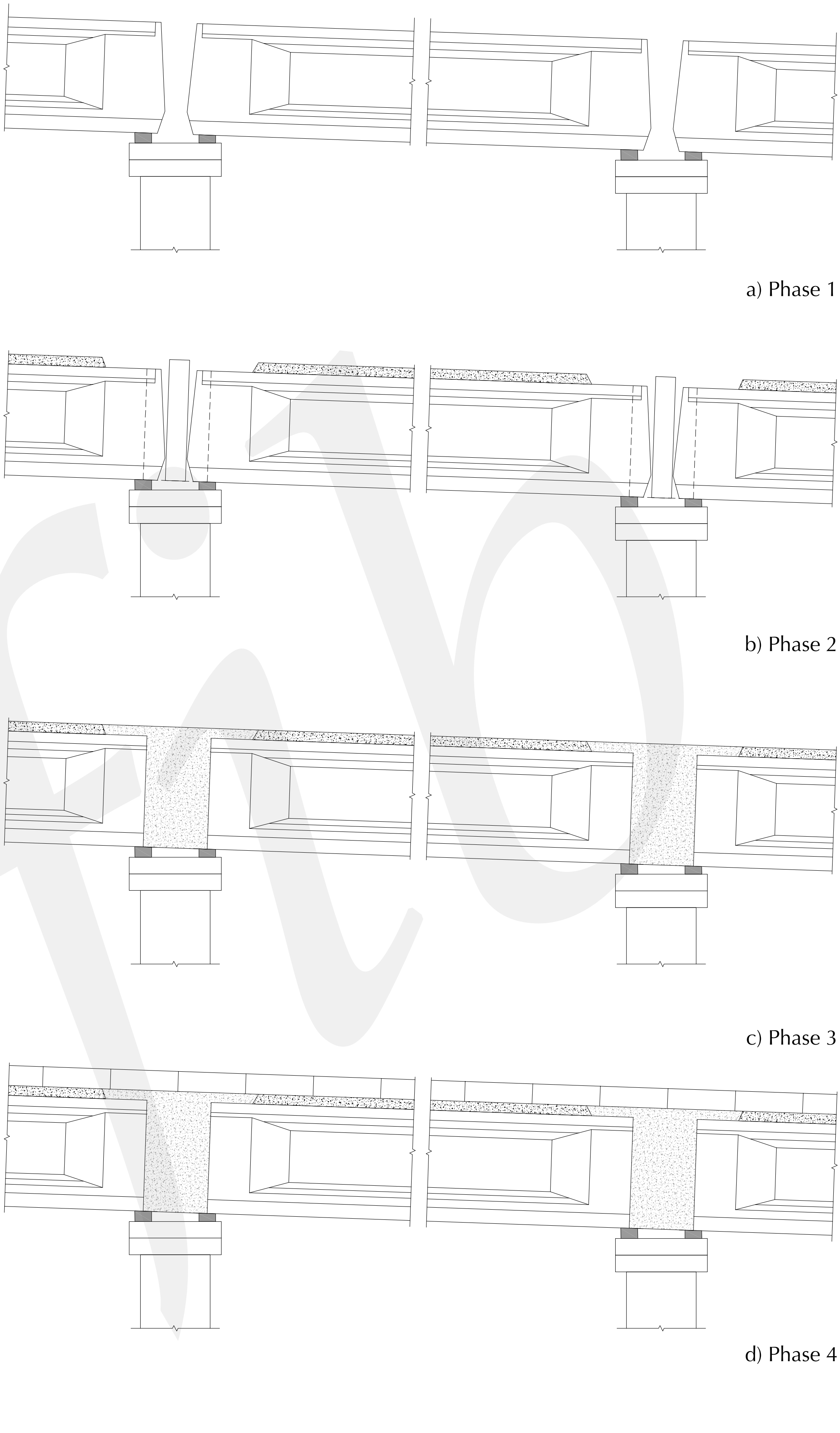


Fig. 5-294 Phases of the construction sequence.

6. Final Considerations

Structural design involves a process to determine the best and most suitable solution. The most important step in the process is preliminary/conceptual design, where precast concrete is considered and structure type is determined.

Bridge engineers often face unique challenges. Experience and skill are important, but it is often necessary to be creative and develop an ad hoc solution to address the problem encountered. It is important to begin every design at the conceptual level, then progress and refine to a final solution. Appropriate conceptual solutions have shown to be the best assurance of a successful process.

Decisions made during the important preliminary design phase set the stage and typically direct the outcome of the final solution. The opportunity for creativity is also available and bridge engineers should capitalize on this.

This document presents a variety of solutions to various structural challenges from many different countries. Technical aspects and the reasoning behind the solutions are made available.

https://doi.org/10.35789/fib.BULL.0099.Ch06

A. Appendix A: Preliminary design charts for different precast concrete sections used in the United States[A-1]

A.1 Assumed data for preliminary design charts

A.1.1 Bridge data

Girder spacing: 1.829, 2.438, 3.048, and 3.658 m (6, 8, 10, and 12 ft).

Number of traffic lanes: 4.

Deck slab thickness: 190 mm (7.5 in.) for 1.829 to 3.048 m (6 to 10 ft) spacing, 196 mm (7.7 in.) for 3.658 m (12 ft) spacing. 13 mm (0.5 in.) reduction of deck slab thickness is assumed in computing composite properties to allow for long-term wear. No significant loss of accuracy occurs if designers use 196 mm thick slabs with 1.829 to 3.048 m spacing.

Effective top flange width (B) is 1'830, 2'438, 3'048, and 3'658 mm (72, 96, 120, and 144 in.) for girder spacing of 1.829, 2.438, 3.048, and 3.658 m (6, 8, 10, and 12 ft), respectively.

A.1.2 Load data

Superimposed dead load: Future wearing surface is 1.2 kN/m^2 (0.025 kip/ft^2); barrier load 2.92 kN/m per girder; design live load: AASHTO LRFD HL-93[A-2].

A.1.3 Concrete data

Precast: compressive strength varies, see charts; unit weight = 24.03 kN/m^3 (0.153 kip/ft^3)

Deck slab (topping): 28-day compressive strength = 28 MPa (4 ksi); unit weight = 22.43 kN/m^3 (0.143 kip/ft^3)

A.1.4 Reinforcement data

Strands: Low-relaxation Grade 1'862 MPa (270 ksi) 13 mm (0.5 in.) diameter for voided slabs and 15 mm (0.6 in.) diameter for box girders and I-girders. Yield strength = 1'675 MPa (243 ksi). Ultimate strength = 1'862 MPa and E_s = 1.96 × 105 MPa (28,427 ksi) Modulus of elasticity of steel.

Mild reinforcing steel: Grade 60, yield strength = 414 MPa (60 ksi) and E_s = 2 × 105 MPa (29,007 ksi)

Threaded rods: Grade 150, yield strength = 827 MPa; ultimate strength = 1'034 MPa (150 ksi) and E_s = 2 × 105 MPa

A.2 Girder profiles

The following tables show the geometric properties of the various girder types used to develop the charts.

A.2.1 AASHTO solid and voided slab beams

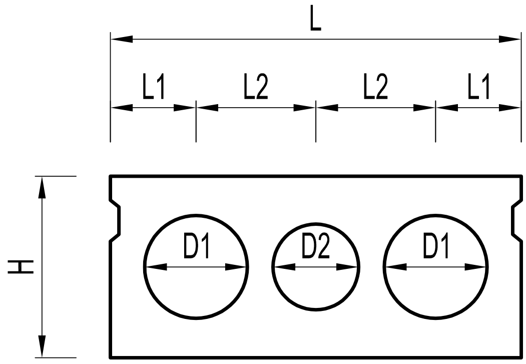


Fig. A-1 Geometry of AASHTO solid and voided slab beams.

Table A-1 Dimensions and properties of solid and voided slab beams

Type	*L*, mm	*H*, mm	*L1*, mm	*L2*, mm	No. of voids	*D1*, mm	*D2*, mm	Area, mm²	y_{bottom}, mm	Inertia, mm⁴
SI-36	900	300	n.d.	n.d.	0	n.d.	n.d.	279×10^3	150	2.15×10^9
SII-36	900	380	265	190	2	200	n.d.	283×10^3	190	4.05×10^9
SIII-36	900	460	265	190	2	250	n.d.	317×10^3	230	6.87×10^9
SIV-36	900	530	265	200	2	300	n.d.	342×10^3	265	10.72×10^9
SI-48	1'200	300	n.d.	n.d.	0	n.d.	n.d.	372×10^3	150	2.88×10^9
SII-48	1'200	380	250	350	3	200	200	367×10^3	190	5.37×10^9
SIII-48	1'200	460	240	370	3	250	250	405×10^3	230	9.10×10^9
SIV-48	1'200	530	250	350	3	300	250	453×10^3	265	14.37×10^9

Note: y_{bottom} = distance from centroid to bottom fiber; n.d. = no data available. 1 mm = 0.0394 in.; 1 mm² = 0.00155 in.²; 1 mm⁴ = 2.4025 × 10-6 in.⁴

A.2.2 AASHTO box girders

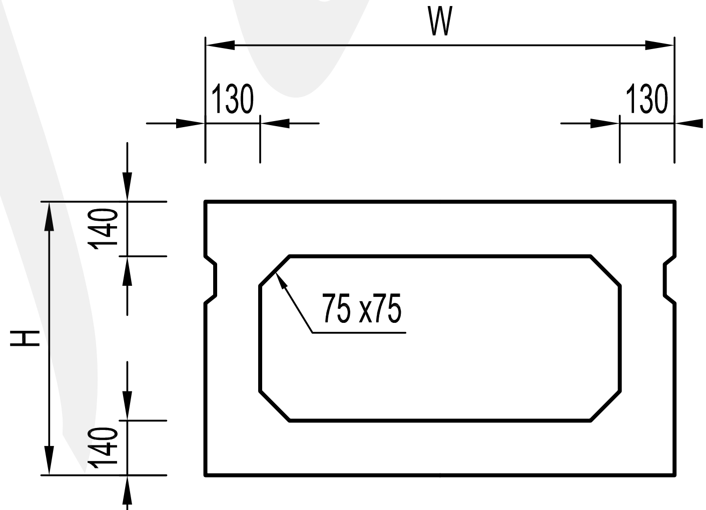


Fig. A-2 Geometry of AASHTO box girders. Note: 1 mm = 0.0394 in

Table A-2 Dimensions and properties of box girders

Type	*W*, mm	*H*, mm	Area, mm²	y_{bottom}, mm	Inertia, mm⁴	Weight, kg/m
BI-36	900	685	362×10^3	340	23.03×10^9	835.234
BI-48	1'200	685	447×10^3	340	27.44×10^9	1'031.171
BII-36	900	840	400×10^3	415	35.44×10^9	923.907
BII-48	1'200	840	485×10^3	415	45.99×10^9	1'121.274
BIII-36	900	990	439×10^3	490	54.58×10^9	1'014.009
BIII-48	1'200	990	524×10^3	490	70.07×10^9	1'209.946
BIV-36	900	1'060	458×10^3	525	66.03×10^9	1'058.345
BIV-48	1'200	1'060	543×10^3	525	84.53×10^9	1'255.712

Note: y_{bottom} = distance from centroid to bottom fiber. 1 mm = 0.0394 in.; 1 mm² = 0.00155 in.²; 1 mm⁴ = 2.4025 × 10-6 in.4; 1 kg/m = 0.67197 lb/ft.

A.2.3 AASHTO I-girders

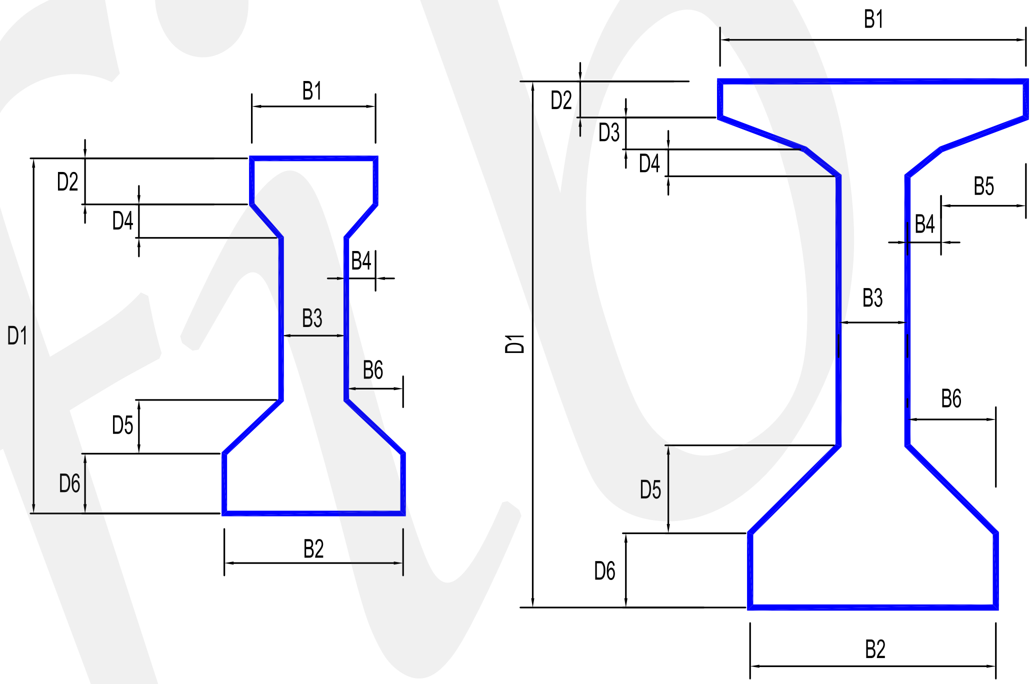


Fig. A-3 Geometry of AASHTO I-girders.

Table A-3 Dimensions and properties of AASHTO I-girders

Type	D1	D2	D3	D4	D5	D6	B1	B2	B3	B4	B5	B6	Area, mm^2	y_{bottom}, mm	Inertia, mm^4	Weight, kg/m
I	700	100	0	75	130	130	305	405	150	75	0	130	178×10^3	320	9.46×10^9	410.46
II	900	150	0	75	150	150	305	460	150	75	0	150	238×10^3	402	21.21×10^9	549.19
III	1'140	180	0	115	190	180	405	560	180	115	0	190	361×10^3	515	52.19×10^9	833.80
IV	1'370	200	0	150	230	200	510	660	200	150	0	230	509×10^3	630	108.52×10^9	1'175.62
V	1'600	130	75	100	250	200	1'070	700	200	100	330	250	653×10^3	810	216.93×10^9	1'508.85
VI	1'830	130	75	100	250	200	1'070	700	200	100	330	250	700×10^3	925	305.23×10^9	1'616.12

Note: y_{bottom} = distance from centroid to bottom fiber 1 mm = 0.0394 in.; 1 mm^2 = 0.00155 $in.^2$; 1 mm^4 = 2.4025×10^{-6} $in.^4$

A.2.4 AASHTO-PCI bulb tees

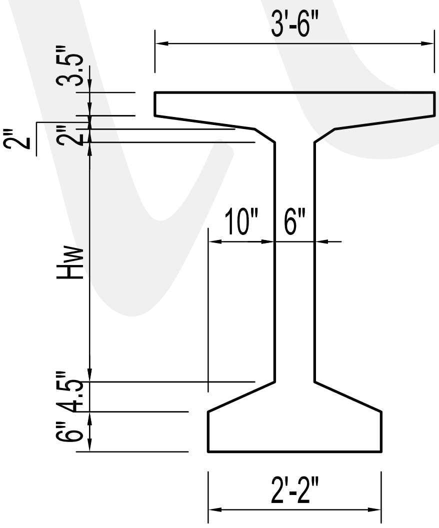


Fig. A-4 Geometry of AASHTO-PCI bulb tees. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

Table A-4 Dimensions and properties of AASHTO-PCI bulb tees

Type	H, mm	H_w, mm	Area, mm²	Inertia, mm⁴	y_{bottom}, mm	Weight, kg/ m
BT-54	1'370	910	425×10^3	111.60×10^9	700	981.11
BT-63	1'600	1'140	460×10^3	163.42×10^9	815	1'062.63
BT-72	1'830	1'370	495×10^3	227.21×10^9	930	1'142 .72

Note: y_{bottom} = distance from centroid to bottom fiber 1 mm = 0.0394 in.; 1 mm² = 0.00155 in.²; 1 mm⁴ = 2.4025 × 10-6 in.⁴.

A.2.5 PCEF bulb tees (XB yy 47)

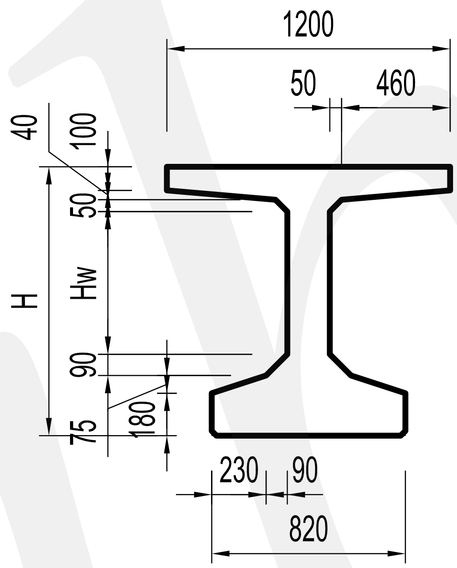


Fig. A-5 Geometry of PCEF bulb tees (XB yy 47). Note: 1 mm = 0.0394 in

Table A-5 Dimensions and properties of PCEF bulb tees (XA yy 46)

Type	H, mm	Hw, mm	Area, mm²	Y_{bottom}, mm	Inertia, mm⁴	Weight, kg/m
XA 31 46	785	200	430×10^3	385	32.71×10^9	995.41
XA 39 46	990	405	462×10^3	475	59.60×10^9	1'066.92
XA 47 46	1'200	610	493×10^3	565	95.89×10^9	1'138.43
XA 55 46	1'400	810	524×10^3	660	142.26×10^9	1'209.95
XA 63 46	1'600	1'015	555×10^3	750	199.37×10^9	1'281.45
XA 71 46	1'800	1'220	586×10^3	850	267.84×10^9	1'352.96
XA 79 46	2'000	1'420	616×10^3	940	348.38×10^9	1'424.47
XA 87 46	2'200	1'625	648×10^3	1'040	441.58×10^9	1'495.98
XA 95 46	2'400	1'830	678×10^3	1'135	548.09×10^9	1'567.49

Note: Y_{bottom} = distance from centroid to bottom fiber 1 mm = 0.0394 in.; 1 mm² = 0.00155 in.²; 1 mm⁴ = 2.4025 × 10-6 in.⁴; 1 kg/m = 0.67197 lb/ft.

A.2.7 NU I-girder

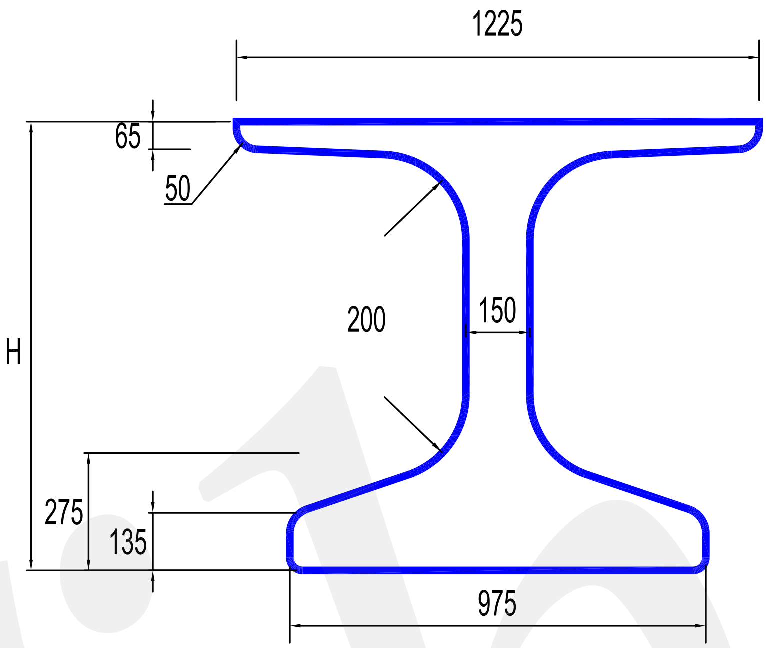


Fig. A-6 Geometry of NU I-girder. Note: 1 mm = 0.0394 in.

Table A-6 Dimensions and properties of NU I-girder

Type	H, mm	Area, mm²	Y_{bottom}, mm	Inertia, mm⁴	Weight, kg/m
NU 900	900	418×10^3	410	45.89×10^9	972.53
NU 1100	1'100	448×10^3	500	75.87×10^9	1'035.46
NU 1350	1'350	485×10^3	610	125.84×10^9	1'120.70
NU 1600	1'600	523×10^3	720	190.83×10^9	1'201.36
NU 1800	1'800	553×10^3	815	254.45×10^9	1'278.59
NU 2000	2'000	583×10^3	905	329.06×10^9	1'347.24

Note: Y_{bottom} = distance from centroid to bottom fiber 1 mm = 0.0394 in.; 1 mm² = 0.00155 in.²; 1 mm⁴ = 2.4025 × 10-6 in.⁴; 1 kg/m = 0.67197 lb/ft.

A.3 Description of charts

Four design criteria were used to develop the preliminary design charts:

Strength I, Service III, shear strength, and strength at release.

Shear strength calculations were performed based on a maximum value design shear strength equal to $0.18f_c$ at the support centerline.

Note that the 0.18 is lower than the previously allowed 0.25 coefficient due to 2007 revisions to the AASHTO LRFD specifications. Strength at release calculations were performed at the midspan, with the assumption that strands can be draped or debonded at the precast concrete member ends.

AASHTO LRFD Service III calculations were performed at midspan with tensile limit stress of 0.5(f_c)1/2 factor. The charts in the following sections were developed for simple spans. Adjustments for various continuity types are given following the chart presentation.

A.3.1 Voided slab beams

Voided slab beams are commonly used with bridge spans from 6 to 20 m (20 to 66 ft). The analysis was performed for 0.914 m (3 ft) wide and 1.219 m (4 ft) wide slabs. The analysis shows that the span length is slightly different between the 0.914 and 1.219 m widths. Two levels of concrete strength were used at the time of release to create the preliminary design charts: 42 and 55 MPa (6 and 8 ksi). The corresponding service life (final) strengths are 55 and 69 MPa (8 and 10 ksi), respectively. Figure A-7 shows span ranges for voided slabs of 0.914 m width in the following four different depths: 305, 380, 460, and 535 mm (12, 15, 18, and 21 in.).

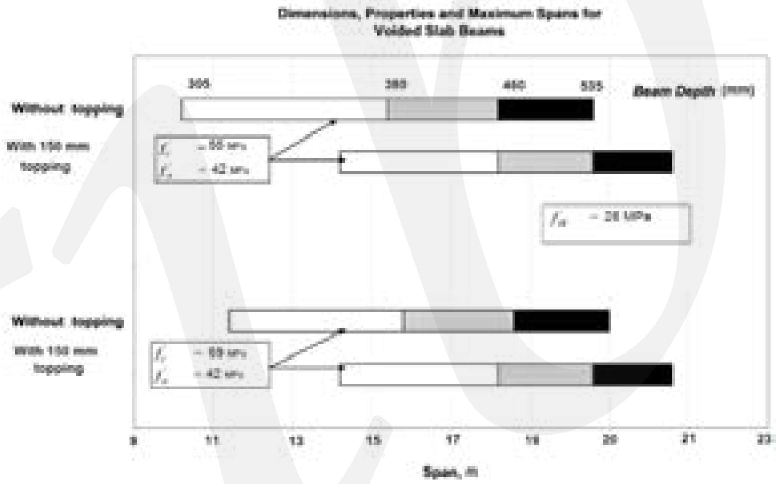


Fig. A-7 Voided slab beams. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

AASHTO box girders

Box girders are commonly used for spans from 15 to 45 m (49 to 148 ft). The following charts were developed assuming adjacent box beams. Figure A-8 shows the possible span lengths of AASHTO box girders with depths of 685, 840, 990, and 1'070 mm (27, 33, 39, and 42 in.).

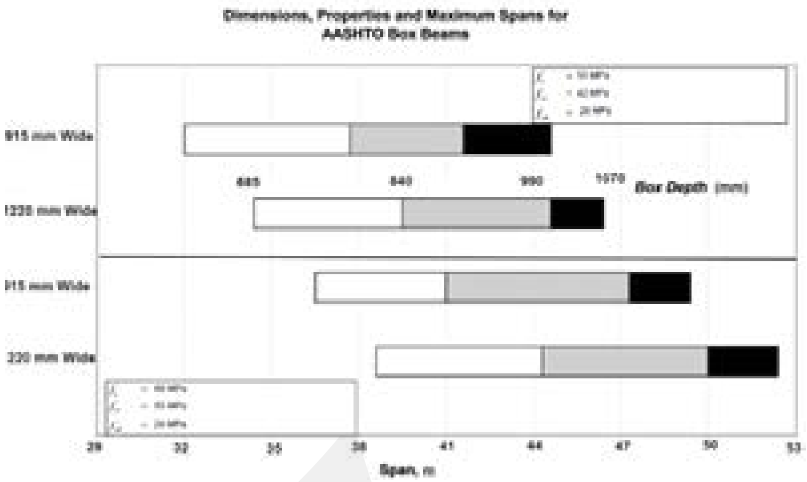


Fig. A-8 AASHTO box girders. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

A.3.3 I-girders

Three types of I-girders were assumed for these charts: AASHTO I-girders, AASHTO-PCI bulb tees and Mid-Atlantic (PCEF) I-girders. I-girders are commonly used for spans from 9 to 60 m (30 to 197 ft).

The maximum number of strands used to develop the span charts is 62 15.2 mm (0.6 in.) diameter strands, which is the practical prestressing bed design capacity for most precasters in the United States. Designers are cautioned to check the capabilities of their local producers before accepting this assumed limit.

A.3.4 AASHTO I-girder

Figures A-9 and A-10 show the maximum spans for AASHTO I-girders.

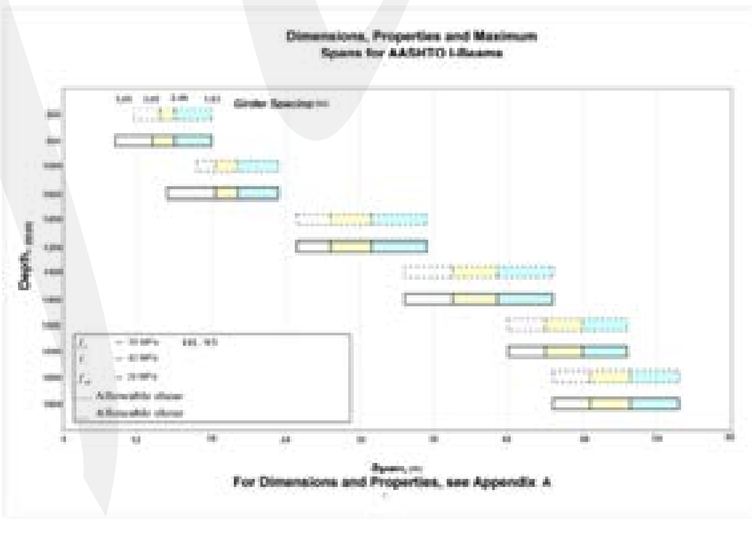


Fig. A-9 Spans for AASHTO I-girders, f_c = 55 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

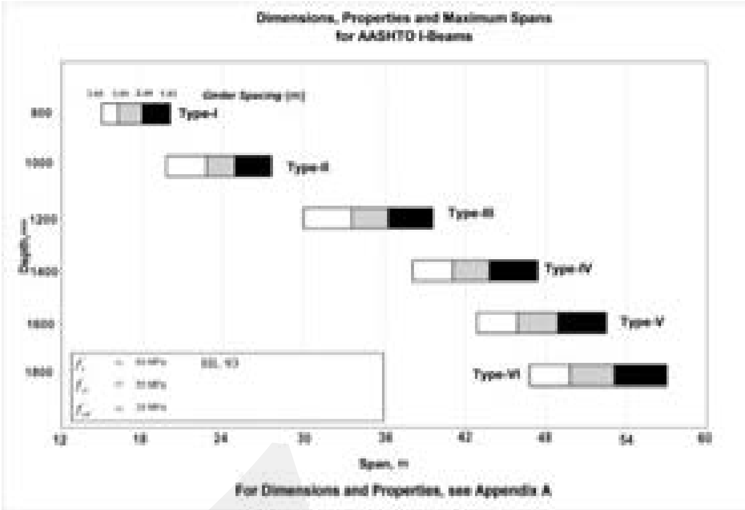


Fig. A-10 Spans for AASHTO I-girders, f_c = 70 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

A.3.5 AASHTO-PCI bulb tee

Figure A-11 shows the span ranges for the AASHTO-PCI bulb tees.

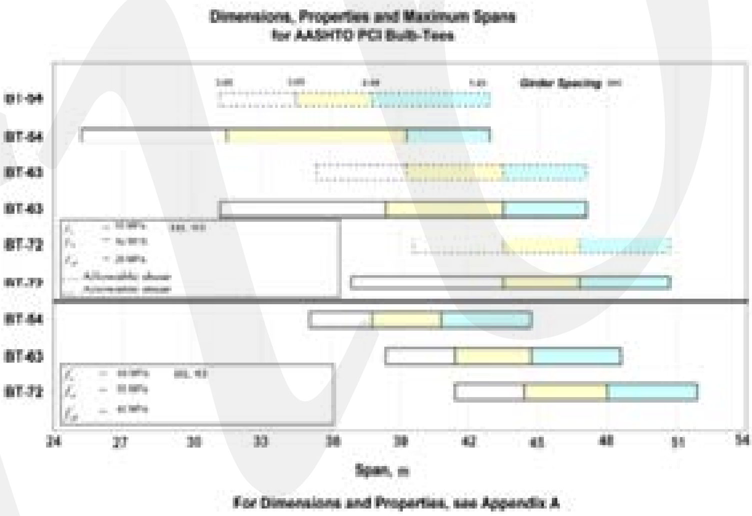


Fig. A-11 AASHTO-PCI bulb tees. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

A.3.6 PCEF bulb tee

The PCEF bulb tee has been introduced in the Mid-Atlantic region of the United States. It has reportedly been used, or is planned to be used, in the states of Virginia, Maryland, New Jersey, Tennessee, Pennsylvania, and Massachusetts. Its general shape represents a new efficient generation of I-girders that started with the introduction of the NU (Nebraska University) I-girders in the early 1990s. There are 162 variations of the basic PCEF I-girder section. The span charts for two series of the PCEF are given here. The first series is the one already adopted by the Virginia Department of Transportation and is labeled the XB yy 47 series. It has a 180 mm (7 in.) thick bottom flange and a 180 mm wide web. Its results are shown in Fig. A-12 and A-13. The second series has reportedly not been adopted yet by any highway agency. It is named the XA yy 46 series and it features a 230 mm (9 in.) thick bottom flange and a 150 mm (6 in.) wide web. Its span ranges are given in Fig. A-14 and A-15. The significant difference in capacity between the two series is primarily a result of two effects:

- a 150 mm web is more efficient than a wider web as it results in reduction of weight without much reduction is section properties, and
- the larger bottom flange allows for placement of more strands and thus the ability to carry more superimposed loads.

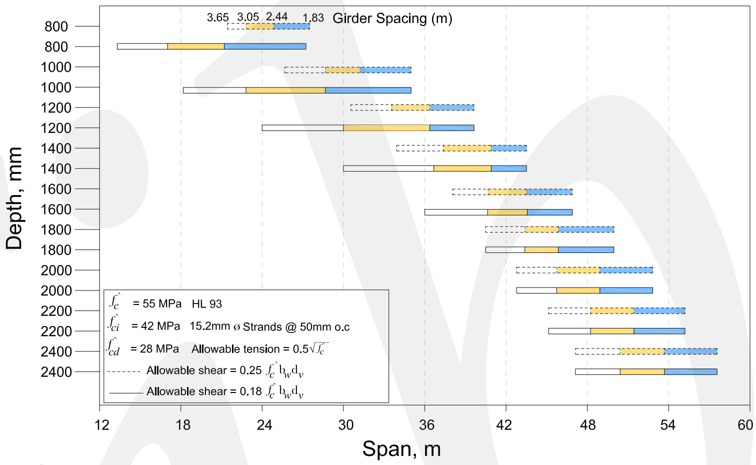


Fig. A-12 PCEF bulb tee, series XB yy 47, f_c = 55 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

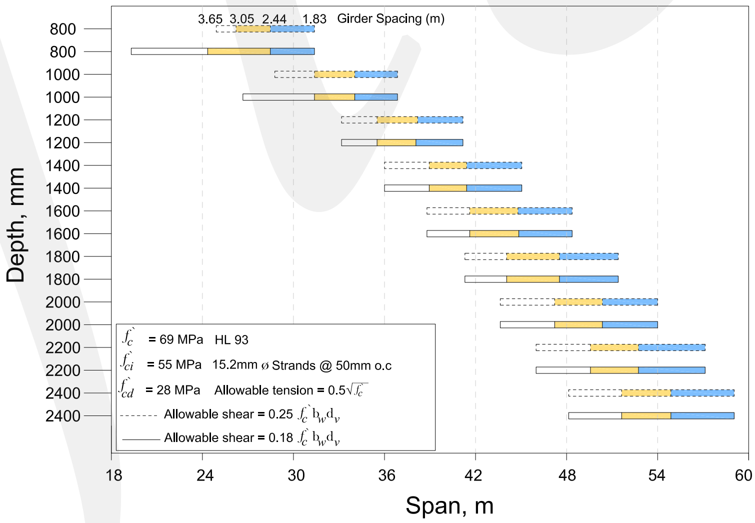


Fig. A-13 PCEF bulb tee, series XB yy 47, f_c = 70 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

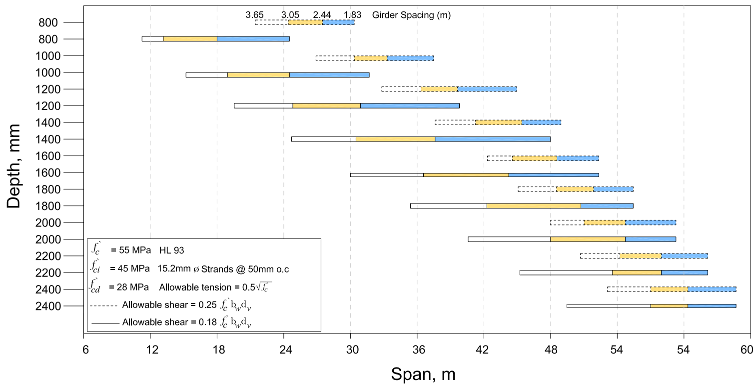


Fig. A-14 PCEF bulb tees, series XA yy 46, f_c = 55 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

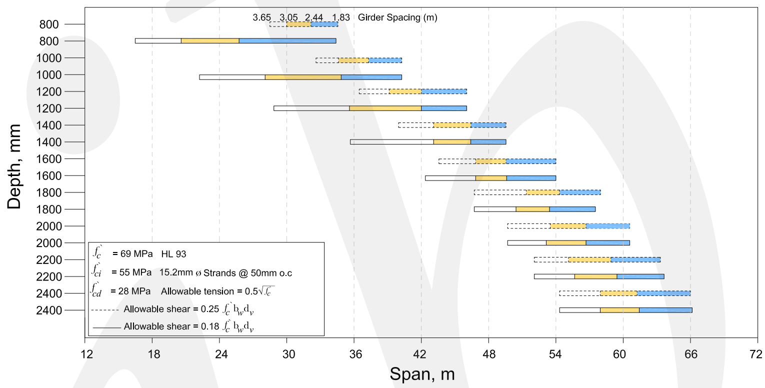


Fig. A-15 PCEF bulb tees, series XA yy 46, f_c = 70 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

A.3.7 NU I-girders

The NU I-girders were the first in a series of new generation precast, prestressed concrete I-girders that have generated considerable popularity since the mid-1990s. The NU I-girder was developed in hard metric units in anticipation of the U.S. conversion to the SI system of units, which has not yet materialized. The dimensions of the series of sections are given in section A2.7. It is noted that the top and bottom flanges are the same for all girder depths. Therefore, the side forms can be used with proper web form height extensions to produce any of the sizes. This concept was followed by other regions in generating unique regional shapes. The NU girder has been adopted with minor or no changes by other agencies and given local names such as the New England bulb tee, the Washington super girder, and the Michigan I-girder. The shape has been also in use in several other countries, including Canada, Mexico, India, and Panama. Canada has wide experience with the girder in various provinces. The record longest, single piece NU I-girder was used for construction of the Bow River Bridge in Calgary. It is an NU2800, 2.8 m (9.2 ft) deep, 65 m (213 ft) long, and weighs 123 tonnes (136 tons).

States including Iowa, Wisconsin, Minnesota, and the Mid-Atlantic states have developed similar sections with similar features to the NU I-girder. Because of the slight changes from one section to the other, it is more convenient to show examples of regional girders. Two series of the PCEF are described in the preceding section. This section covers the NU I-girder. With its limited coverage, it is hoped that the reader will explore the features and span capacities of this series of girders.

The NU I-girders are distinguishable by their wide bottom flange, which is beneficial for stability during shipping and handling, and results in long span capabilities due to the available space for a large number of prestressing strands (a larger prestress force) while enjoying a relatively low centroid of the force. The relatively thin 150 mm (5.9 in.) wide web aids in reducing the weight, improving the structural efficiency. The wide, thin top flange helps improve girder handling stability, and bridge deck forming. The span charts of the NU I-girder are shown in Fig. A-16 and A-17.

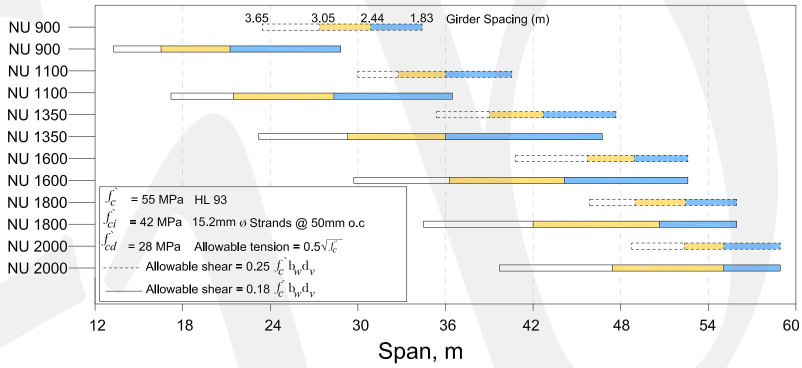


Fig. A-16 NU I-girder, f_c = 55 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

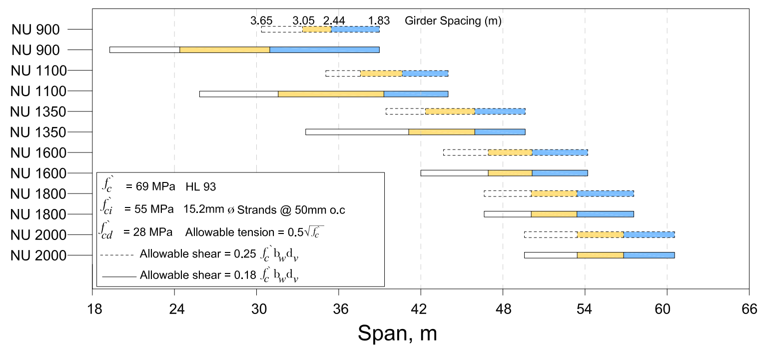


Fig. A-17 NU I-girder, f_c = 70 MPa. Note: f'_c = compressive strength of concrete for use in design; f'_{cd} = compressive strength of concrete at time of initial loading; f'_{ci} = compressive strength of concrete at time of prestress release. 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 MPa = 0.145 ksi.

B. Appendix B: Preliminary design criteria used in Spain[B-1]

The use of precast concrete girders in the construction of concrete bridges is a technique that has been extensively used for some time. These elements are either made in a permanent precast concrete yard or on-site in temporary precast concrete yards set up for only one project, due to the expenses and difficulties related to truck transportation.

The superstructure is often completed with a CIP concrete deck slab, although it is also common to use of full-depth precast concrete deck panels, or a combination solution such as the use of precast concrete stay-in-place deck panels that serve as formwork and become composite with a partial-depth CIP slab.

To minimize the maintenance of the structure, the top slab should have the least possible number of joints compatible with the flexibility of the substructure and with the characteristics of the supports. In any case, unlike other sections that can reach greater lengths, the maximum distance between expansion joints usually is less than 100 m (328 ft).

It is very important to adequately determine the camber to prevent functional and structural problems produced by creep, once the structure has been opened to traffic.

The current trend in Spain consists of the construction of integral bridges using precast concrete girders and precasting some elements of the substructure such as the piers, abutments, walls, etc. The trend is to consider ever larger and heavier precast concrete pieces, limited by the capacity of the installation cranes. In this sense, for longer spans, there are solutions that facilitate the execution of continuous (statically indeterminate) structures, for example, using mild reinforcement or prestressing reinforcement to develop the continuity of the structure.

B.1 Sections and slenderness

A. Side-by-side girders
B. I-girders
C. U girders

Side-by-side girders form cross sections similar to those of slabs with reduced depths (therefore with high slenderness). The most common cross sections are shown in Fig. B-1.

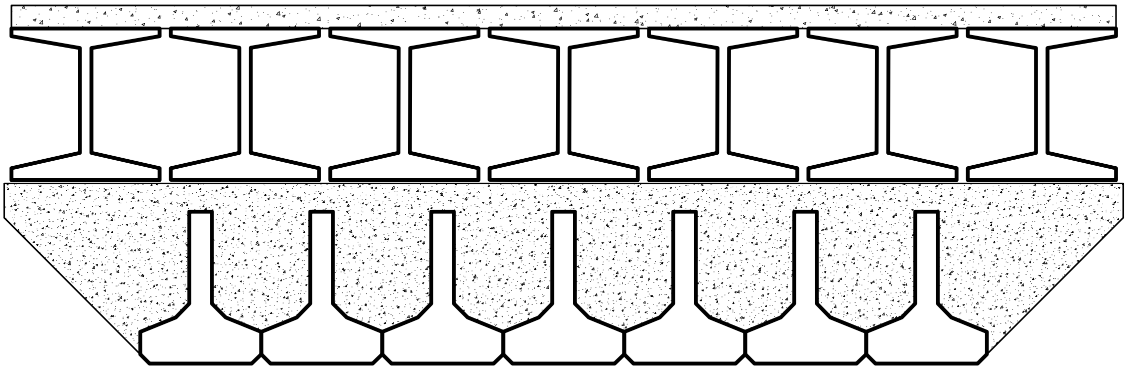


Fig. B-1 Common superstructure cross sections – Types A and B.

Cross section A corresponds to traditional I-girders placed side by side with a top slab cast in place on the girders. Cross section B corresponds to inverted T girders that are monolithically joined to the top slab with CIP infill concrete. This section, although it can be used for spans of almost 20 m (66 ft), is not often used for spans longer than 10 to 12 m (33 to 39 ft).

Nowadays, the most used profiles are the I-girders shown in Fig. B-2. Section C corresponds to girders with a normal depth and section D to girders with reduced depth.

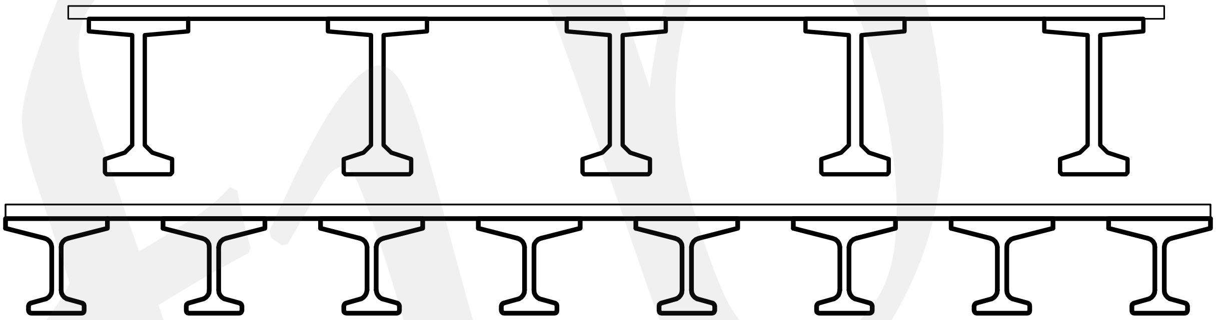


Fig. B-2 Common I-girder and double-tee girder cross sections – Types C and D.

Many U girders, shown in Fig. B-3, are used increasingly in practice.

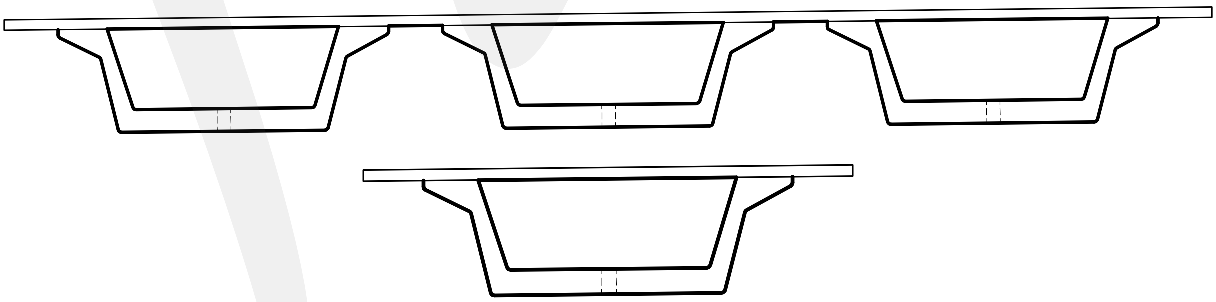


Fig. B-3 Common U girder cross sections – Types E and F.

The most common solutions are simply supported with the following depth-to-span ratio:

Table B-1 Span length/depth ratios

Cross section type	Span length/depth ratio
A	20
B	22
C	16
D	20

In the case of Types C and D these values are conditioned by the number of girders that form the superstructure. If there are no geometric constraints (that is, restricted vertical clearances), it is common to use few deeper girders instead of many shallow girders because the former is, in general, more cost-effective than the latter.

It is important to highlight how important it is for U girders and box-girders to have openings, with the drainage devices in the correct places in their bottom flanges, depending on their geometry. This intends to prevent water stagnation inside the girder and initiate the deterioration of the structure, which is particularly worrisome in the cases of elements with external prestressing.

B.2 Construction procedures

The most usual construction methods for the installation of precast concrete girder superstructures are one or more of the following:

- use one or two cranes
- use a launching gantry
- install on the closest edge and move laterally into final position
- hoist from above

The use of one procedure over the other depends on the accessibility to the jobsite, the height of the superstructure, the length of the bridge, etc.

Precast concrete girder superstructures are, in general, the section type that leads to better performance regarding the speed of construction.

B.3 Application range

Precast concrete elements can be used for spans that range from 5 to 50 m (16 to 164 ft). Nevertheless, in normal practice in Spain, it is uncommon to work with spans longer than 45 m (148 ft).

B.4 Reinforcement ratios

The reinforcement ratios of the CIP deck slabs, in the case of types C, D, and E, assume girder separation and might range from 100 to 175 kg/m^3 (6 to 11 lb/ft^3). In the case of U-girder solutions, the reinforcement ratio can be up to 250 to 300 kg/m^3 (16 to 19 lb/ft^3).

C. Appendix C: Comparison of Vertical Live loads

A comparison of the effects due to live load on a 37.5 m (123 ft) long (36.5 m (120 ft) between piers) and a 15 m (49 ft) wide deck comprising precast concrete girders was carried out according to the provisions of three different codes and is presented in the following example.

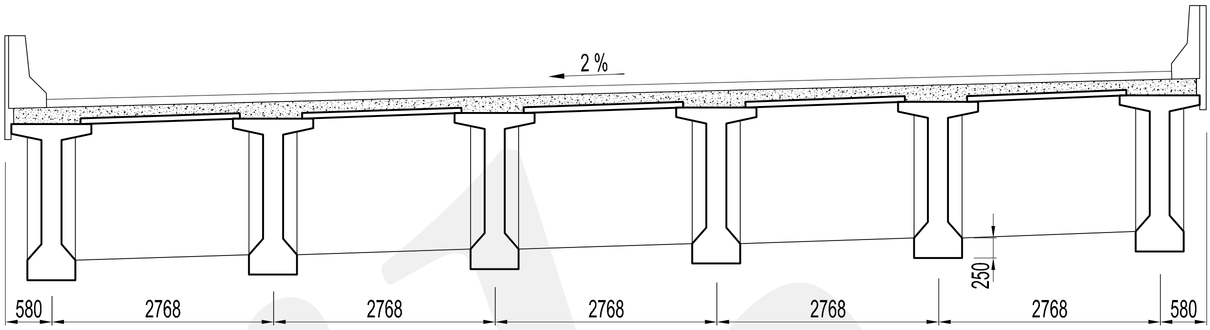


Fig. C-1 Cross section used in the comparison. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.

Different countries have very different road traffic conditions, differences in economic development, transport mode shares and roads network.

Therefore, local codes vary in the way they define live loads to be applied to bridge design, to produce the expected effects on those structures.

The purpose of this comparison is to show how these differences affect internal forces on the superstructure, calculated with its characteristic values.

This study should not be taken by itself as an indication of materials consumption or justification to evaluate preliminary design issues. Determination of preliminary design questions relies on a much larger number of factors, such as ultimate limit state factors, resistance factors, and the effect of dead load, just to name a few.

Although every code has numerous specific conditions for application, the general provisions of the load models of Eurocode 1[C-1], the AASHTO LRFD specifications[C-2], and the Brazilian standard NBR 7178[C-3] are described in the following sections.

C.1 Eurocode 1

According to load model 1, a maximum of three notional lanes are loaded with one tandem system per lane and a uniformly distributed load is applied on unfavorable parts of the deck. Loads values and distribution are as shown in Fig. C-2 and C-3.

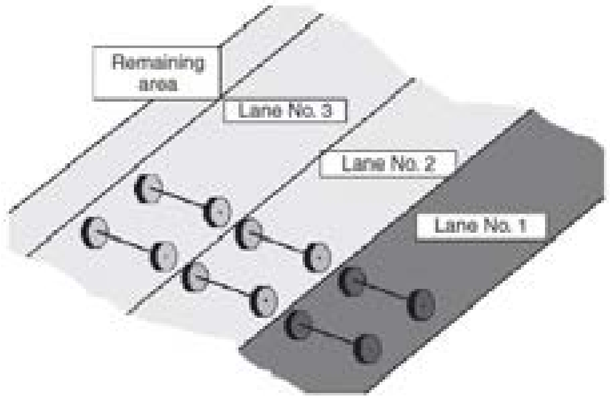


Fig. C-2 Distribution of design trucks according to Eurocode 1.

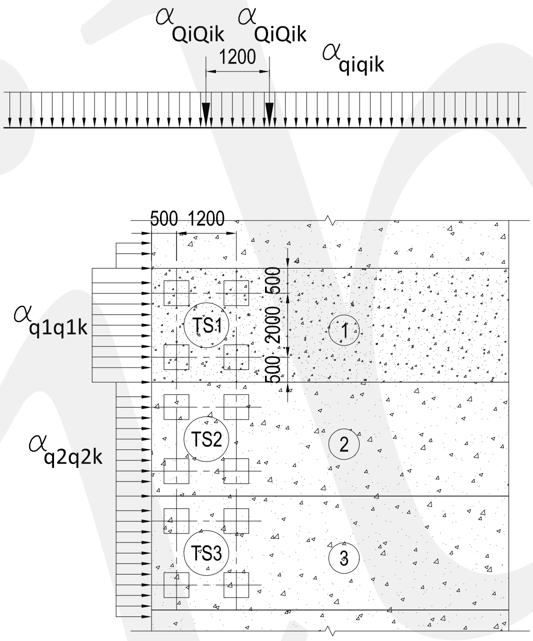


Fig. C-3 Vertical live load according to Eurocode 1. Note: α_{QiQik}; α_{qiqik}; α_{q1q1k}; α_{q2q2k} are adjustment load factors defined in EC1-2[C-4]. All dimensions are in millimeters. 1 mm = 0.0394 in.

To account for a 1000-year return period, these loads should be considered as follows:

Table C-1 Vertical live loads in Eurocode 1

Location	Tandem system (TS) Axle loads, Q_{ik} (kN)	UDL system q_{ik} (or q_{rk}) (kN/m²)
Lane No. 1	300	9
Lane No. 2	200	2.5
Lane No. 3	100	2.5
Other lanes	0	2.5
Remaining area (q_{rk})	0	2.5

Note: 1 kN = 0.225 kip; 1 kN/m² = 0.02 kip/ft².

No additional factors should be applied to these loads to account for impact and dynamic effects on the deck.

It should be understood that Eurocode 1 is the basic document; however, the values in the different national annexes may vary.

C.2 AASHTO

The so-called HL-93, design vehicular live load, consists of a truck or a tandem combined with a uniform load per traffic lane. The distance between rear axles should be taken as to produce maximum effects on the structure, as indicated below.

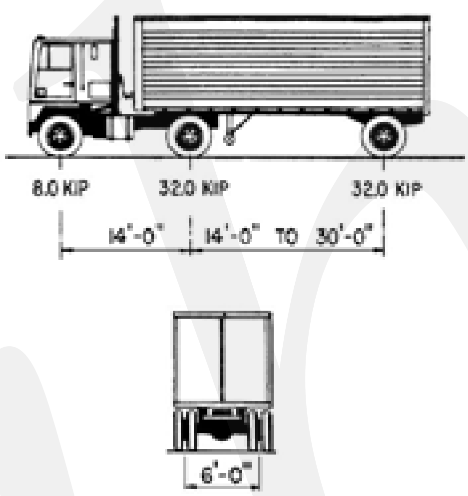


Fig. C-4 HL-93 Truck AASHTO LRFD. Note: 1 mm = 0.0394 in.; 1 N = 0.225 lb.

The tandem load consists of a pair of 110 kN (25 kip) axles, 1.2 m (3.9 ft) apart. As for the truck load, the transverse distance between wheels should be taken as 1.8 m (5.9 ft).

For both truck and tandem loads, an impact coefficient (dynamic load allowance) should be considered to account for dynamic effects on the structure. For every limit state on deck elements other than joints, except for fatigue, this coefficient should be taken as 1.33.

The uniform lane load is 9.3 kN/m (637 lbf/ft). This load should not be factored by any impact coefficient and is distributed on a 3.0 m (9.8 ft) width.

An adjusting coefficient should be considered to account for the probability of the presence of the live load on multiple lanes at a time, as indicated in Table C-2.

Table C-2 Multiple presence factors AASHTO LRFD

Number of Loaded Lanes	Multiple Presence Factors m
1	1.20
2	1.00
3	0.85
>3	0.65

The loads considered here correspond to a 75-year return period.

C.3 NBR 7178

This live load, the so-called TT-450, consists of a 450 kN (101 kip), three-axle truck, with six wheels weighing 75 kN (16 kip) each, surrounded by a 5 kN/m² (0.1 kip/ft²) uniform load (Fig. C-5). Such values correspond to a 140-year return period.

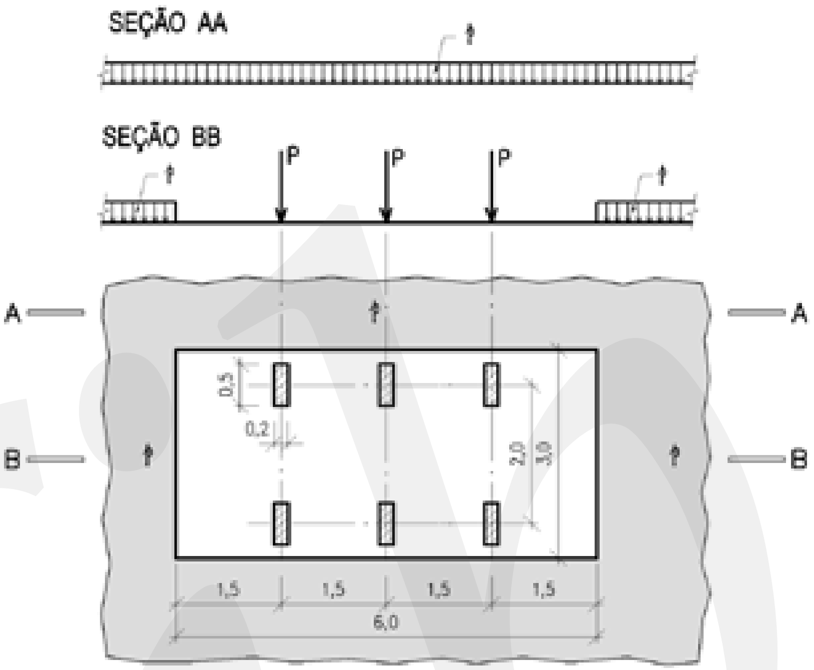


Fig. C-5 Vertical live load in NBR 7178. Note: All dimensions are in meters. 1 m = 3.281 ft.

To account for the dynamic effect on structures, an impact coefficient for vertical loads should be considered as follows:

$$CIV = 1 + 1.06\left(\frac{20}{Liv + 50}\right)$$

For isostatic structures, Liv is the span of the structure, in meters.

According to the number of traffic lanes n, a reduction coefficient may also be considered:

$$CNF = 1 - 0.05(n-2) > 0.9$$

In this example, maximum *n* was taken equal to 3, because shoulders should not be considered (only for *CNF* calculation).

C.4 Results

The following charts show the difference between maximum values of internal forces on each girder due to live load according to the three load models.

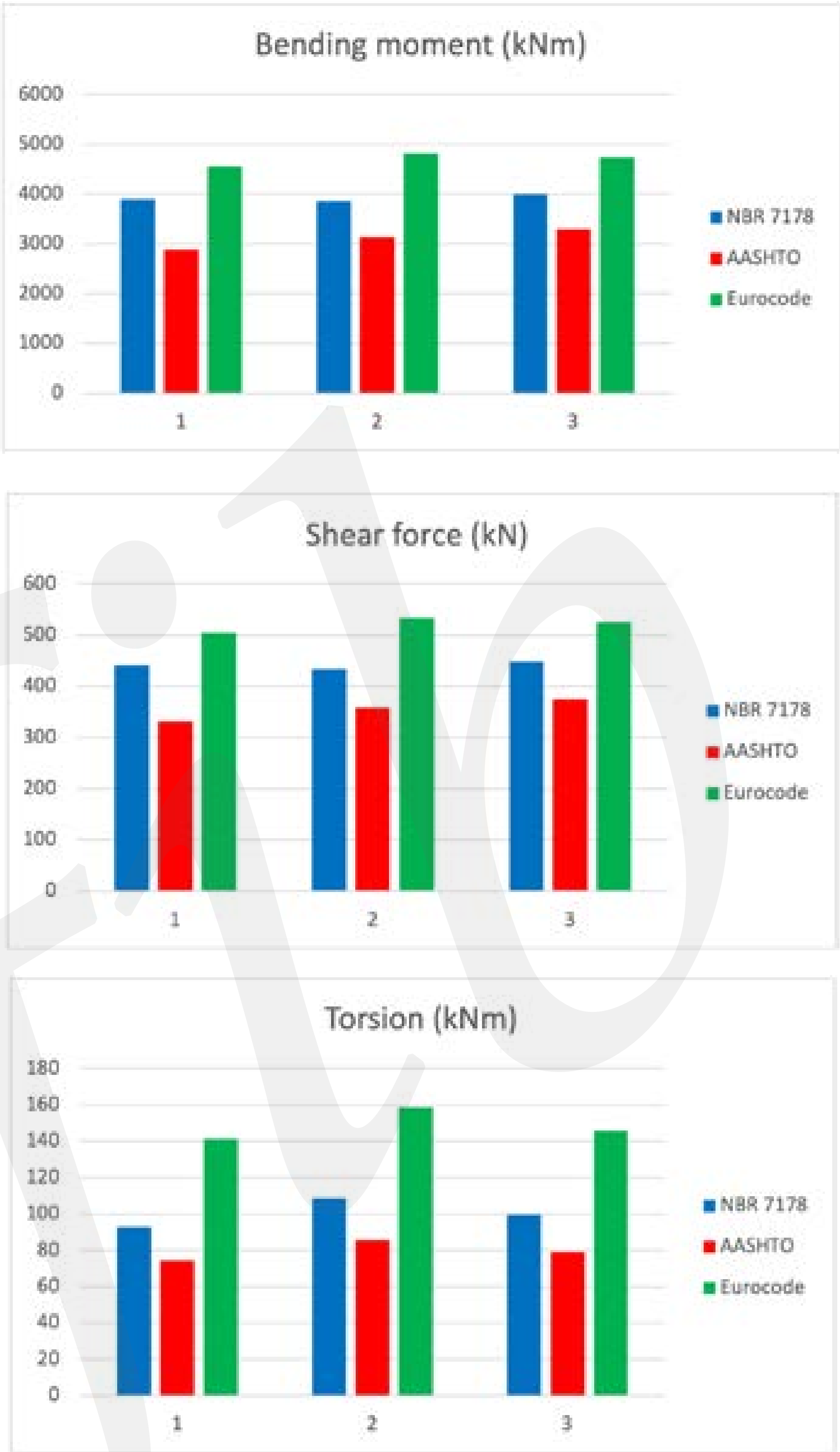


Fig. C-6 Comparison of maximum values of internal forces on each girder due to live load. Note: 1 kN = 0.225 kip; 1 kN-m = 0.738 kip-ft.

C.4.1 Bending moments

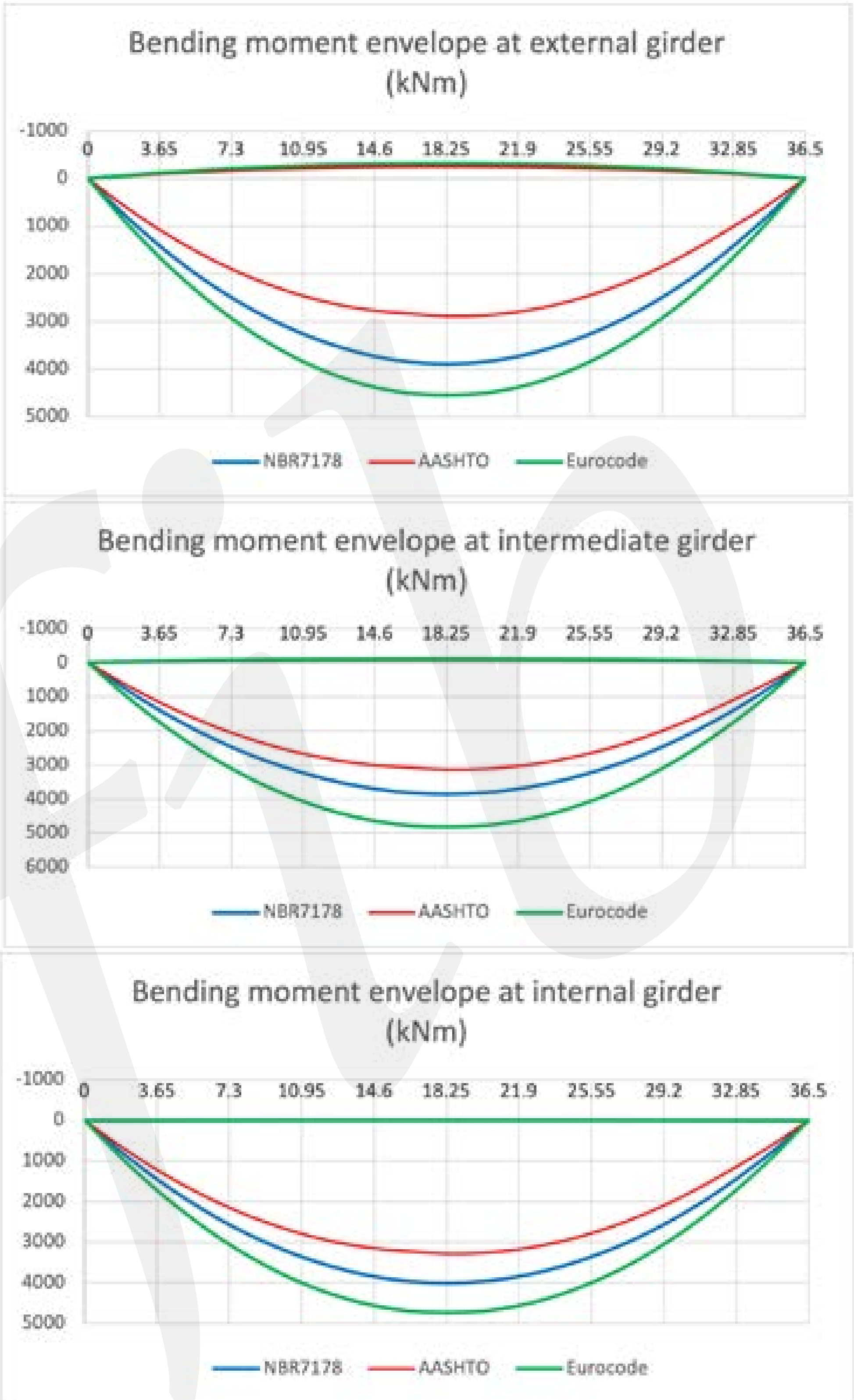


Fig. C-7 Comparison of bending moment envelopes. Note: 1 kN-m = 0.738 kip-ft.

C.4.2 Shear force

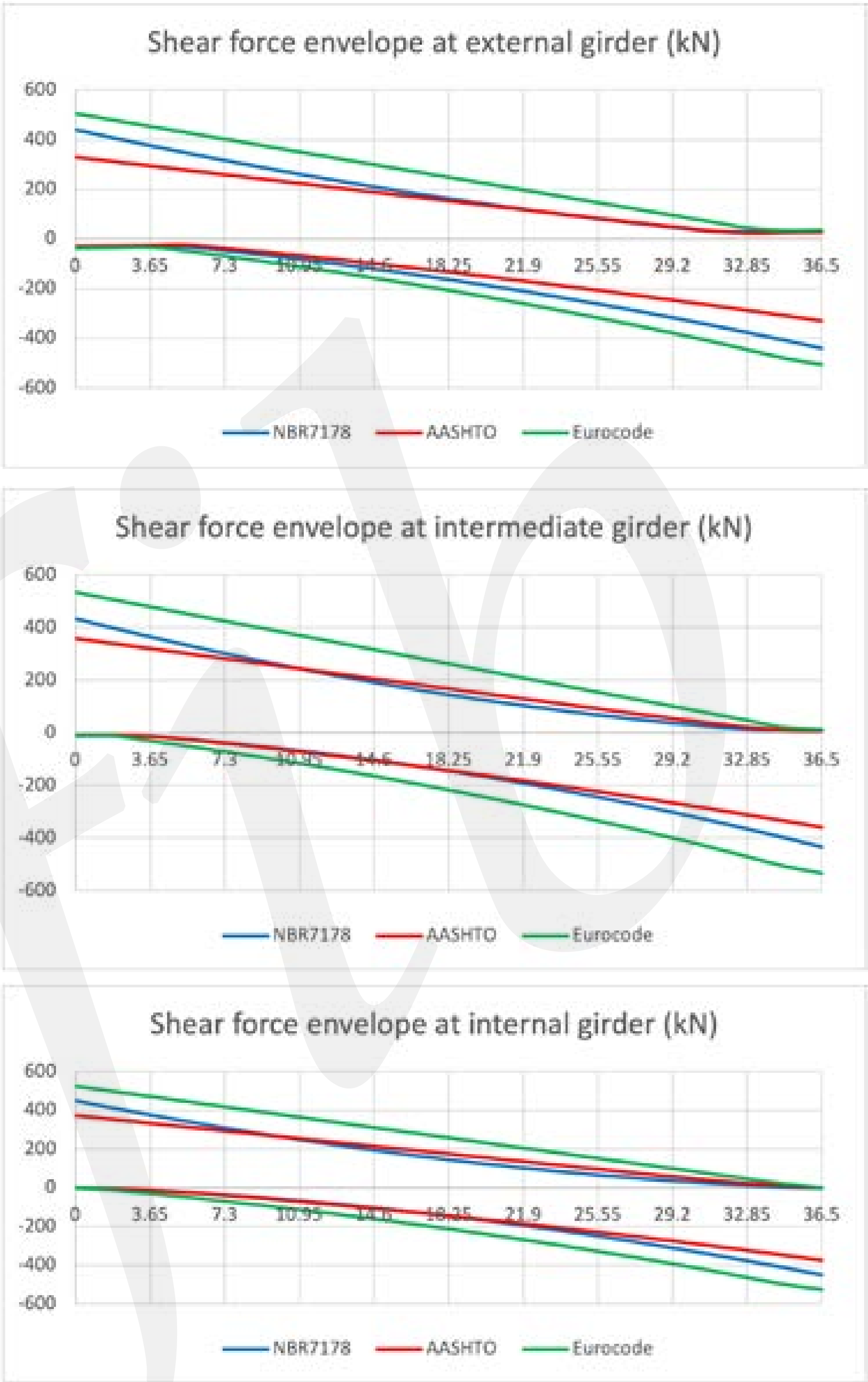


Fig. C-8 Comparison of shear force envelopes. Note: 1 kN = 0.225 kip.

C.4.3 Torsion

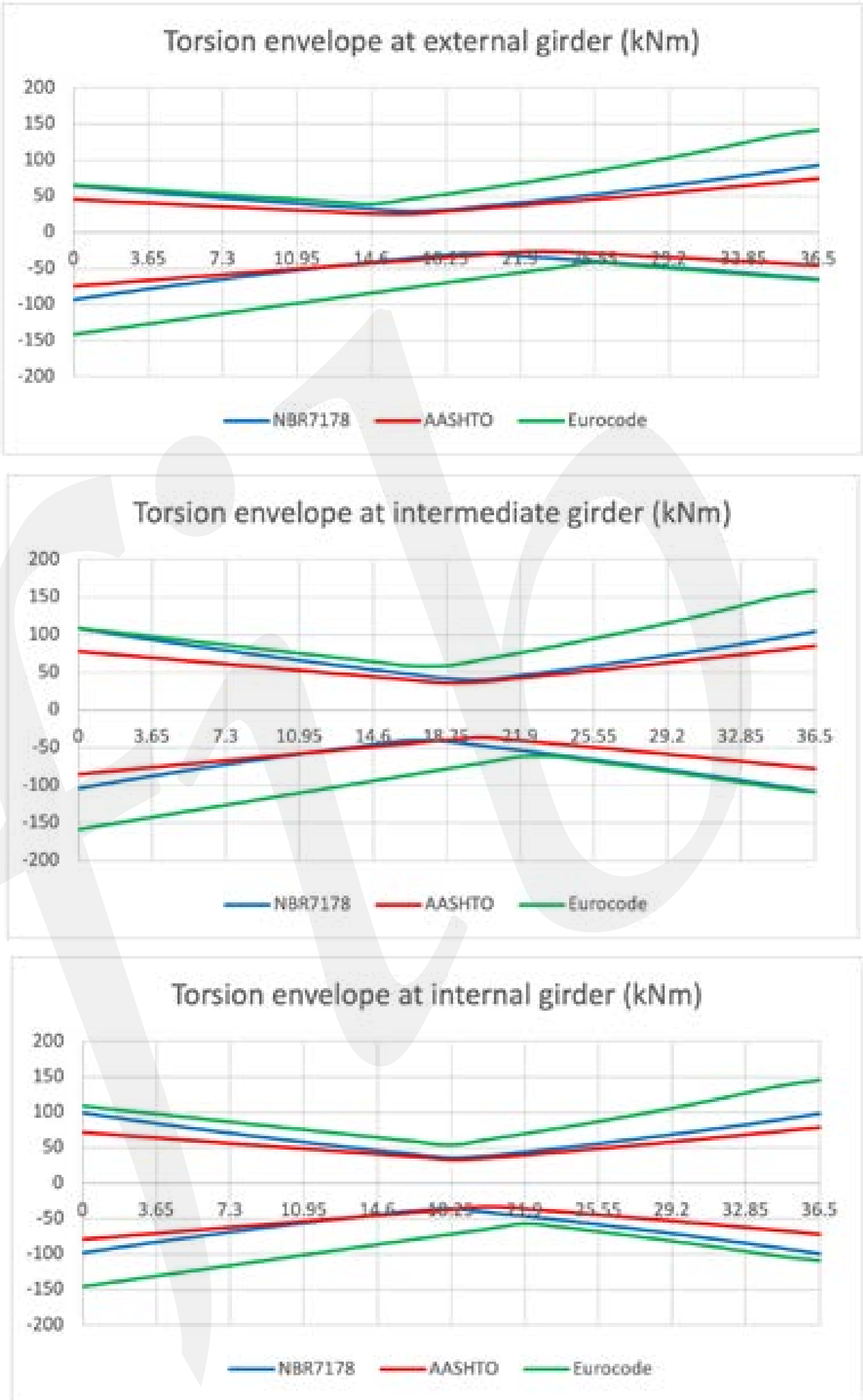


Fig. C-9 Comparison of torsion envelopes. Note: 1 kN-m = 0.738 kip-ft.

D. Appendix D: Summary Table of Preliminary Design Examples

Example Number	Authors	Country	Number of Spans	Span Length (L) [m]	Girder depth (G) [mm]	Slab depth (H) [mm]	Total depth (D) G+H [mm]
1	Pieter van der Zee	Belgium	7	36	1'000	250	1'250
2	Pieter van der Zee	Belgium	10	15	600	250	850
3	Pieter van der Zee	Belgium	3	50	1'600	250	1'850
4	Fernado Stucchi and Marcelo Waimberg	Brazil	10	15	550	100	650
5	Fernado Stucchi and Marcelo Waimberg	Brazil	6	25	1'500	200	1'700
6	Fernado Stucchi and Marcelo Waimberg	Brazil	4	37.5	1'950	200	2'150
7	BaoChun Chen	China	10	16	800	180	980
8	BaoChun Chen	China	5	30	2'000	80	2'080
9	BaoChun Chen	China	4	40	2'000	180	2'180
10	Andre de Chefdebien	France	6	25	1'000	250	1'250
11	Mario Petrangeli	Italy	5	30	1'600	250	1'850
12	Kenichi Kata	Japan	10	15	600	N/A	600
13	Kenichi Kata	Japan	6	25	1'300	150	1'450
14	Kenichi Kata	Japan	4	40	2'600	200	2'800
15	Voo Yen Lei	Malaysia	10	15	650	200	850
16	Voo Yen Lei	Malaysia	10	15	875	N/A	875
17	Voo Yen Lei	Malaysia	10	25	1'325	N/A	1'325
18	Voo Yen Lei	Malaysia	3	50	2'000	200	2'200
19	Alessandro Palermo	New Zealand	10	15	650	N/A	650
20	Alessandro Palermo	New Zealand	5	30	1'225	180	1'405
21	David Fernández-Ordoñez	Spain	2	30	1'400	250	1'650
22A	Robert Wheatly	UK	5	35	1'500	200	1'700
22B	Robert Wheatly	UK	8	18.75	600	100	700
23	Maher Tadros and William Nickas	USA	1	25.9	840	N/A	840
24	Maher Tadros and William Nickas	USA	6	53.34	1'800	215	2'015
25	Manyop Han	South Korea	2	40	1'900	240	2'140
26	Manyop Han	South Korea	2	50	2'600	240	2'840
27	Manyop Han	South Korea	1	60	2'500	240	2'740
28	Luis Matute and Helder Figueiredo	Spain	10	35	2'000	250	2'250

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft.

Example Number	Authors	Country	L/D	L/G	Web width (W) [mm]	Girder Separation (S) [m]	Precast girder weight [t]
1	Pieter van der Zee	Belgium	28.80	36.00	160	1	38.2
2	Pieter van der Zee	Belgium	17.65	25.00	200	1	11
3	Pieter van der Zee	Belgium	27.03	31.25	160	1	76.8
4	Fernado Stucchi and Marcelo Waimberg	Brazil	23.08	27.27	150	5.6	6
5	Fernado Stucchi and Marcelo Waimberg	Brazil	14.70	16.67	400	2.7	49
6	Fernado Stucchi and Marcelo Waimberg	Brazil	17.44	19.23	250	2.77	68
7	BaoChun Chen	China	13.33	16.32	270	1.25	28.9
8	BaoChun Chen	China	14.42	15.00	240	2.4	76.5
9	BaoChun Chen	China	13.76	15.00	200	2.9	153.1
10	Andre de Chefdebien	France	20.00	25.00	150	1.25	19.3
11	Mario Petrangeli	Italy	16.22	18.75	380	4.98	110
12	Kenichi Kata	Japan	25.00	25.00	240	0.77	11
13	Kenichi Kata	Japan	17.24	19.23	300	1	29.4
14	Kenichi Kata	Japan	14.29	15.38	600	4.65	24
15	Voo Yen Lei	Malaysia	17.65	23.08	100	1.5	4.93
16	Voo Yen Lei	Malaysia	17.14	17.14	100	1.5	12
17	Voo Yen Lei	Malaysia	18.87	18.87	100	1.5	24.5
18	Voo Yen Lei	Malaysia	22.73	25.00	300	5	114
19	Alessandro Palermo	New Zealand	23.08	23.08	300	1.20	20
20	Alessandro Palermo	New Zealand	21.35	24.49	200	2	41
21	David Fernández-Ordoñez	Spain	18.18	21.43	120	2.5	29
22A	Robert Wheatly	UK	20.59	23.33	165	2.12	62.3
22B	Robert Wheatly	UK	26.79	31.25	300	0.99	13.88
23	Maher Tadros and William Nickas	USA	30.83	30.83	250	1.33	37.8
24	Maher Tadros and William Nickas	USA	26.47	29.63	150	3.8	68
25	Manyop Han	South Korea	18.7	21.1	200	2.7	19.5
26	Manyop Han	South Korea	17.6	19.2	200	2.55	23
27	Manyop Han	South Korea	21.9	24.0	200	2.62	21.2
28	Luis Matute and Helder Figueiredo	Spain	15.60	17.5	170	3.5	64.2

Note: 1 mm = 0.0394 in.; 1 m = 3.281 ft; 1 tonne = 1.1 ton.

Example Number	Authors	Country	Prestress layout	fc (Girder) [MPa]	fc (slab) [MPa]	Prestressing steel [MPa]	Reinforcing steel [MPa]
1	Pieter van der Zee	Belgium	Straight	50	30	1'860	500
2	Pieter van der Zee	Belgium	Straight	50	30	1'860	500
3	Pieter van der Zee	Belgium	Draped	50	30	1'860	500
4	Fernado Stucchi and Marcelo Waimberg	Brazil	Straight	35	35	1'900	500
5	Fernado Stucchi and Marcelo Waimberg	Brazil	Straight	40	40	1'900	500
6	Fernado Stucchi and Marcelo Waimberg	Brazil	Straight	35	35	1'900	500
7	BaoChun Chen	China	Straight	40	40	1'860	335
8	BaoChun Chen	China	Straight	50	50	1'860	335
9	BaoChun Chen	China	Draped	50	50	1'860	335
10	Andre de Chefdebien	France	Straight	60	35	1'860	500
11	Mario Petrangeli	Italy	Straight	45	32	1'860	450
12	Kenichi Kata	Japan	Straight	50	30	1'860	295
13	Kenichi Kata	Japan	Draped	50	30	1'860	345
14	Kenichi Kata	Japan	Draped	40	36	1'860	345
15	Voo Yen Lei	Malaysia	Straight	min 150	40	1'860	460
16	Voo Yen Lei	Malaysia	Straight	min 150	N/A	1'860	460
17	Voo Yen Lei	Malaysia	Straight	min 150	N/A	1'860	460
18	Voo Yen Lei	Malaysia	Straight	min 150	40	1'860	460
19	Alessandro Palermo	New Zealand	Straight	50	N/A	1'840	500
20	Alessandro Palermo	New Zealand	Straight	50	50	1'840	500
21	David Fernández-Ordoñez	Spain	Straight	55	30	1'860	500
22A	Robert Wheatly	UK	Straight	50	40	1'860	500
22B	Robert Wheatly	UK	Straight	50	40	1'860	500
23	Maher Tadros and William Nickas	USA	Straight	55	N/A	1'860	414
24	Maher Tadros and William Nickas	USA	Straight	65	31	1'862	414
25	Manyop Han	South Korea	Straight	40	27	1'900	400
26	Manyop Han	South Korea	Straight	40	27	1'900	400
27	Manyop Han	South Korea	Straight	80	30	1'860	400
28	Luis Matute and Helder Figueiredo	Spain	Straight	40	35	1'860	500

Note: fc = compressive design strength of concrete ; N/A = not applicable. 1 MPa = 0.145 ksi.

Example Number	Authors	Country	Continuity System	Intermediate Transversal Diaphragms	Supports Diaphragms
1	Pieter van der Zee	Belgium	Structural Continuity	YES	YES
2	Pieter van der Zee	Belgium	Structural Continuity	YES	YES
3	Pieter van der Zee	Belgium	Structural Continuity	YES	YES
4	Fernado Stucchi and Marcelo Waimberg	Brazil	Link Slab	NO	YES
5	Fernado Stucchi and Marcelo Waimberg	Brazil	Link Slab	NO	YES
6	Fernado Stucchi and Marcelo Waimberg	Brazil	Partial structural continuity	NO	YES
7	BaoChun Chen	China	Simply Supported	NO	YES
8	BaoChun Chen	China	Link slab	YES	NO
9	BaoChun Chen	China	Structural Continuity	YES	YES
10	Andre de Chefdebien	France	Structural Continuity	NO	YES
11	Mario Petrangeli	Italy	Link Slab	YES	YES
12	Kenichi Kata	Japan	Structural Continuity	NO	YES
13	Kenichi Kata	Japan	Structural Continuity	NO	YES
14	Kenichi Kata	Japan	Structural Continuity	NO	YES
15	Voo Yen Lei	Malaysia	Structural Continuity	NO	YES
16	Voo Yen Lei	Malaysia	Structural Continuity	NO	YES
17	Voo Yen Lei	Malaysia	Structural Continuity	YES	YES
18	Voo Yen Lei	Malaysia	Structural Continuity	NO	YES
19	Alessandro Palermo	New Zealand	Structural Continuity	YES	YES
20	Alessandro Palermo	New Zealand	Structural Continuity	YES	YES
21	David Fernández-Ordoñez	Spain	Link Slab	NO	NO
22A	Robert Wheatly	UK	Structural Continuity	NO	YES
22B	Robert Wheatly	UK	Structural Continuity	NO	YES
23	Maher Tadros and William Nickas	USA	Simply Supported	NO	NO

24	Maher Tadros and William Nickas	USA	Threaded rod continuity system	NO	YES
25	Manyop Han	South Korea	Link slab	NO	YES
26	Manyop Han	South Korea	Link slab	NO	YES
27	Manyop Han	South Korea	Simply Supported	NO	YES
28	Luis Matute and Helder Figueiredo	Spain	Structural Continuity	NO	YES

References

Chapter 2

[2-1] *fib* (fédération internationale du béton). 2013. *fib Model Code for Concrete Structures 2010*. Berlin: Ernst & Sohn Verlag.

[2-2] *fib*. 2009. *Structural Concrete Textbook on behaviour, design and performance, second edition*, Volume 1. Bulletin 51. Lausanne, Switzerland: *fib*.

[2-3] Corres, H. 2013. "Sound engineering through conceptual design according to the *fib* Model Code 2010." *Structural Concrete* 14 (2): 89–98.

[2-4] Tadros, M. 2007. *Preliminary Design of Precast Prestressed Concrete Bridge Superstructures*. Skokie, IL: Portland Cement Association.

[2-5] Ministerio de Fomento. 2000. *Obras de paso de nueva construcción: Conceptos generales*. Madrid, Spain: Centro de Publicaciones, Secretaría General Téchnica, Ministerio de Fomento.

Chapter 3

[3-1] *fib*. 2004. *Precast Concrete Bridges*. Bulletin 29. Lausanne, Switzerland: *fib*.

[3-2] Tadros, M., and L. Y. Voo. 2016. "Taking Ultra-High-Performance Concrete to New Heights: The Malaysian Experience." *ASPIRE* 10 (3): 36–38.

[3-3] Han, M., E. Hwang, and C. Lee. 2003."Prestressed Concrete Girder with Multistage Prestressing Concept." *Structural Journal* 100 (6): 1723–1731.

[3-4] *fib* (fédération internationale du béton). 2013. *fib Model Code for Concrete Structures 2010*. Berlin: Ernst & Sohn Verlag.

[3-5] CEN (European Committee for Standardization)/Technical Committee (TC) 250. 2002. *Eurocode – Basis of structural design*. EN 1990. Brussels, Belgium: CEN.

[3-6] CEN/TC 250. 2003. *Eurocode 1 – Actions on structures – Part 2: Traffic loads on bridges*. EN 1991-2. Brussels, Belgium: CEN.

[3-7] AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

[3-8] CEN/TC 250. 2005. *Eurocode 2 – Design of concrete structures – Concrete bridges – Design and detailing rules*. EN 1992-2. Brussels, Belgium: CEN.

[3-9] L. Y. Voo and S. J. Foster 2010. "Characteristics of ultra-high performance 'ductile' concrete and its impact on sustainable construction." *The IES Journal Part A: Civil & Structural Engineering* 3 (3): 168-18737.

Chapter 4

[4-1] PCI Committee on Bridges. 2016. *Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*. CB-02-16. Chicago, IL: PCI.

[4-2] *fib*. Forthcoming bulletin. *Lateral girder stability of precast girders*. Lausanne, Switzerland: *fib*

[4-3] R. F. Mast. 1989. "Lateral stability of long prestressed concrete beams part 1." *PCI Journal* 34 (1): 34-53.

[4-4] R. F. Mast. 1993. "Lateral stability of long prestressed concrete beams part 2." *PCI Journal* 38 (1): 70-88.

[4-5] A. De la Fuente, et al. 2018. "Lateral stability of prestressed precast concrete girders during lifting: study case." *High Tech Concrete: Where Technology and Engineering Meet*: 1530-1537.

[4-6] PCI Committee on Bridges. 2012. *Curved Precast Concrete Bridges State-of-the-Art Report*. CB-01-12. Chicago, IL: PCI.

[4-7] *fib*. 2004. *Precast Concrete Bridges*. Bulletin 29. Lausanne, Switzerland: *fib*.

[4-8] AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

[4-9] CEN/TC 250. 2003. *Eurocode 1 – Actions on structures – Part 2: Traffic loads on bridges*. EN 1991-2. Brussels, Belgium: CEN.

[4-10] Sun, C. Wang, N., Tadros, M.K. and Girgis, A.F.M., "Threaded Rod Continuity for Bridge deck Weight," *PCI Journal*, May-June 2016, pp. 47-67.

[4-11] Castrodale, R. W., and C. D. White. 2004. *Extending Span Ranges of Precast Prestressed Concrete Girders*. National Cooperative Highway Research Program Report 517. Washington, DC: Transportation Research Board.

Chapter 5

[5-1] AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

[5-2] CEN/TC 250. 2003. *Eurocode 1 – Actions on structures – Part 2: Traffic loads on bridges*. EN 1991-2. Brussels, Belgium: CEN.

[5-3] CEN/TC 250. 2005. *Eurocode 2 – Design of concrete structures – Concrete bridges – Design and detailing rules*. EN 1992-2. Brussels, Belgium: CEN.

[5-4] CEN (European Committee for Standardization)/Technical Committee (TC) 250. 2002. *Eurocode – Basis of structural design*. EN 1990. Brussels, Belgium: CEN.

[5-5] CEN/TC250. 2004. *Eurocode 2 – Design of concrete structures – Part 1-1: General rules and rules for buildings*. EN 1992-1-1. Brussels, Belgium: CEN.

[5-6] ABNT (Brazilian Technical Standards Association). 2013. *Road and Pedestrian Live Load on Bridges, Viaducts, Footbridges and Other Structures*. NBR 7188. Rio de Janeiro, Brazil: ABNT.

[5-7] ABNT. 2014. *Design of structural concrete – Procedure*. NBR 6118. Rio de Janeiro, Brazil: ABNT.

[5-8] ABNT. 2004. *Actions and safety of structures – Procedure*. NBR 8681. Rio de Janeiro, Brazil: ABNT.

[5-9] China Ministry of Transport. 2003. *Technical Standard of Highway Engineering*. JTG B01-2003.

[5-10] China Ministry of Transport. 2004. *General Code for Design of Highway Bridges and Culverts*. JTG D60-2004. China.

[5-11] China Ministry of Transport. 2004. *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts*. JTG D62-2004. China.

[5-12] China Ministry of Transport. 2000. *Technical Specification for Construction of Highway Bridge and Culverts*. JTJ041-2000. China.

[5-13] China Ministry of Transport. 2006. *Guidelines for Design of Highway Safety Facilities*. JTG D81-2006. China.

[5-14] Japan Road Association. *Specifications for Highway Bridges in Japan*.

[5-15] BSI (British Standards Institution). BS 5400. *Steel, concrete and composite bridges – Parts 1 to 10*. London, UK: BIS

[5-16] Design Manual for Roads and Bridges Volume 1, Section 3 Part 14 BD37/01 Loads for Highway Bridge: 2001. London, United Kingdom: Stationery Office UK.

[5-17] Standards New Zealand Committee BD/6/4. 2004. *Structural design actions – Part 5: Earthquake actions – New Zealand*. NZS 1170.5:2004. Wellington, New Zealand: Standards New Zealand.

[5-18] Standards New Zealand Committee P3101. 2006. *Concrete Structures Standard*. NZS 3101.1&2:2006. Wellington, New Zealand: Standards New Zealand.

[5-19] New Zealand Transport Agency. 2016. *Bridge Manual*, 3rd ed. SP/M/022. Wellington, New Zealand: New Zealand Transport Agency.

[5-20] CEN/TC 250. 2002. *Eurocode 1 – Actions on structures – General actions*. EN 1991-1. Brussels, Belgium: CEN.

[5-21] BS NA EN 1991-2. *UK National Annex to Eurocode 1. Actions on structures. Traffic loads on bridges*. UK.

[5-22] MOLIT (Ministry of Land, Infrastructure, and Transport). Korean Highway Bridge Design Code. South Korea

[5-23] Han, M., E. Hwang, and C. Lee. 2003."Prestressed Concrete Girder with Multistage Prestressing Concept." *Structural Journal* 100 (6): 1723–1731.

[5-24] Regulamento de Segurança e Ações para Estruturas de Edifícios e Pontes. Brazil.

Appendix A

[A-1] Tadros, M. 2007. *Preliminary Design of Precast Prestressed Concrete Bridge Superstructures*. Skokie, IL: Portland Cement Association.

[A-2] AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

Appendix B

[B-1] Ministerio de Fomento. 2000. *Obras de paso de nueva construcción: Conceptos generales*. Madrid, Spain: Centro de Publicaciones, Secretaría General Téchnica, Ministerio de Fomento.

Appendix C

[C-1] CEN/TC 250. 2002. *Eurocode 1 – Actions on structures – General actions*. EN 1991-1. Brussels, Belgium: CEN.

[C-2] AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

[C-3] ABNT. 1997. *Full mortise hinge – Specification and performance*. NBR 7178. Rio de Janeiro, Brazil: ABNT.

[C-4] CEN/TC 250. 2003. *Eurocode 1 – Actions on structures – Part 2: Traffic loads on bridges*. EN 1991-2. Brussels, Belgium: CEN.

The *fib* (International Federation for Structural Concrete - Fédération internationale du béton) is grateful for the invaluable support of the following national member groups and sponsoring members, which contributes to the publication of *fib* technical bulletins, the *Structural Concrete* journal and *fib*-news.

National member groups

UNNOBA - Universidad Nacional del Nor Oeste de la Provincia de Buenos Aires, Argentina
CIA - Concrete Institute of Australia
ÖBV - Österreichische Bautechnik Vereinigung, Austria
GBB-BBG - Groupement Belge du Béton, Belgium
ABCIC - Associação Brasileira da Construção Industrializada de Concreto, Brazil
ABECE - Associação Brasileira de Engenharia e Consultoria Estrutural, Brazil
IBRACON - Instituto Brasileiro do Concreto, Brazil
CPCI (Canadian Precast Prestressed Concrete Institute)
Université Laval, Canada
CCES - China Civil Engineering Society
Cyprus University of Technology
Cyprus Association of Civil Engineers
Česká Betonářská Společnost, Czech Republic
DBF - Dansk Betonforening, Denmark
SB - Suomen Betoniyhdistys, Finland
AFGC - Association Française de Génie Civil, France
DAfStb - Deutscher Ausschuss für Stahlbeton, Germany
Technical Chamber of Greece
University of Patras, Department of Civil Engineering, Greece
Hungarian Group of the *fib*
The Institution of Engineers, India
fib-Indonesia
University of Amirkabir, Iran
IACIE - Israeli Association of Construction and Infrastructure Engineers
AICAP - Associazione Italiana Calcestruzzo, Armato e Precompresso, Italy
CTE - Collegio dei tecnici della industrializzazione edilizia, Italy
ITC - CNR, Istituto per le Tecnologie della Costruzione, Italy
ReLUIS, Italy
JCI - Japan Concrete Institute
JPCI - Japan Prestressed Concrete Institute
Administration des Ponts et Chaussées, Luxembourg
fib Netherlands
NZCS - New Zealand Concrete Society
NB - Norsk Betongforening / Norwegian Concrete Association
Polish Academy of Sciences, Committee for Civil Engineering, Poland
GPBE - Grupo Portugês de Betão Estrutural, Portugal
Polytechnic University of Timisoara, Romania
Technical University of Civil Engineering, Romania
University of Transylvania Brasov, Faculty of Civil Engineering, Romania
Association for Structural Concrete, Russia
SNK *fib*, Slovakia
Slovenian Society of Structural Engineers, Slovenia

The Concrete Institute, South Africa
KCI - Korean Concrete Institute, South Korea
ACHE - Asociación Cientifico-Técnica del Hormigon Estructural, Spain
SB - Svenska Betongföreningen, Sweden
Délégation nationale suisse de la *fib*, Switzerland
ITU - Istanbul Technical University, Turkey
NIISK - Research Institute of Building Constructions, Ukraine
Society of Engineers, United Arab Emirates
fib UK, United Kingdom
ASBI - American Segmental Bridge Institute, United States of America
PCI - Precast/Prestressed Concrete Institute, United States of America
PTI - Post-Tensioning Institute, United States of America

Sponsoring members

Strong Force-MGC W.L.L., Bahrain
Liuzhou OVM Machinery Company, China
Shenzhen University, China
Peikko Group Corp., Finland
Consolis, France
ECS - European Engineered Construction Systems Association, Germany
FBF - Betondienst, Germany
ISB - Institut für Stahlbetonbewehrung, Germany
MKT - Metall-Kunststoff-Technik, Germany
Progress Group GmbH, Germany
Larsen & Toubro Ltd, ECC Division, India
FUJI P. S. Corporation, Japan
IHI Construction Service Company, Japan
Oriental Shiraishi Corporation, Japan
P. S. Mitsubishi Construction Company, Japan
SE Corporation, Japan
Sumitomo Mitsui Construction Company, Civil Engineering Division, Japan
Cimenterie Nationale S.A.L., Lebanon
Hilti, Liechtenstein
BBR VT International, Switzerland
Sika Schweiz, Switzerland
VSL International, Switzerland
PBL Group, Thailand
CEG – The Consulting Engineers Group, United States of America

fib Bulletins published since 1998

1 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 1: *Introduction, Design Process, Materials*
Manual - textbook (244 pages, ISBN 978-2-88394-041-3, July 1999)

2 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 2: *Basis of Design*
Manual - textbook (324 pages, ISBN 978-2-88394-042-0, July 1999)

3 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 3: *Durability, Design for Fire Resistance; Member Design, Maintenance; Assessment and Repair, Practical aspects*
Manual - textbook (292 pages, ISBN 978-2-88394-043-7, December 1999)

4 *Lightweight aggregate concrete: Extracts from codes and standards*
State-of-the-art report (46 pages, ISBN 978-2-88394-044-4, August 1999)

5 *Protective systems against hazards: Nature and extent of the problem*
Technical report (64 pages, ISBN 978-2-88394-045-1, October 1999)

6 *Special design considerations for precast prestressed hollow core floors*
Guide to good practice (180 pages, ISBN 978-2-88394-046-8, January 2000)

7 *Corrugated plastic ducts for internal bonded post-tensioning*
Technical report (50 pages, ISBN 978-2-88394-047-5, January 2000)

8 *Lightweight aggregate concrete*: Part 1 (guide) – *Recommended extensions to Model Code 90*; Part 2 (technical report) – *Identification of research needs*; Part 3 (state-of-art report) – *Application of lightweight aggregate concrete* (118 pages, ISBN 978-2-88394-048-2, May 2000)

9 *Guidance for good bridge design*: Part 1 – Introduction, Part 2 – *Design and construction aspects*
Guide to good practice (190 pages, ISBN 978-2-88394-049-9, July 2000)

10 *Bond of reinforcement in concrete*
State-of-art report (434 pages, ISBN 978-2-88394-050-5, August 2000)

11 *Factory applied corrosion protection of prestressing steel*
State-of-art report (20 pages, ISBN 978-2-88394-051-2, January 2001)

12 *Punching of structural concrete slabs*
Technical report (314 pages, ISBN 978-2-88394-052-9, August 2001)

13 *Nuclear containments*
State-of-art report (130 pages, 1 CD, ISBN 978-2-88394-053-6, September 2001)

14 *Externally bonded FRP reinforcement for RC structures*
Technical report (138 pages, ISBN 978-2-88394-054-3, October 2001)

15 *Durability of post-tensioning tendons*
Technical report (284 pages, ISBN 978-2-88394-055-0, November 2001)

16 *Design Examples for the 1996 FIP recommendations Practical design of structural concrete*
Technical report (198 pages, ISBN 978-2-88394-056-7, January 2002)

17 *Management, maintenance and strengthening of concrete structures*
Technical report (180 pages, ISBN 978-2-88394-057-4, April 2002)

18 *Recycling of offshore concrete structures*
State-of-art report (33 pages, ISBN 978-2-88394-058-1, April 2002)

19 *Precast concrete in mixed construction*
State-of-art report (68 pages, ISBN 978-2-88394-059-8, April 2002)

20 *Grouting of tendons in prestressed concrete*
Guide to good practice (52 pages, ISBN 978-2-88394-060-4, July 2002)

21 *Environmental issues in prefabrication*
State-of-art report (56 pages, ISBN 978-2-88394-061-1, March 2003)

22 *Monitoring and safety evaluation of existing concrete structures*
State-of-art report (304 pages, ISBN 978-2-88394-062-8, May 2003)

23 *Environmental effects of concrete*
State-of-art report (68 pages, ISBN 978-2-88394-063-5, June 2003)

24 *Seismic assessment and retrofit of reinforced concrete buildings*
State-of-art report (312 pages, ISBN 978-2-88394-064-2, August 2003)

25 *Displacement-based seismic design of reinforced concrete buildings*
State-of-art report (196 pages, ISBN 978-2-88394-065-9, August 2003)

26 *Influence of material and processing on stress corrosion cracking of prestressing steel – case studies*
Technical report (44 pages, ISBN 978-2-88394-066-6, October 2003)

27 *Seismic design of precast concrete building structures*
State-of-art report (262 pages, ISBN 978-2-88394-067-3, October 2003)

28 *Environmental design*
State-of-art report (86 pages, ISBN 978-2-88394-068-0, February 2004)

29 *Precast concrete bridges*
State-of-art report (83 pages, ISBN 978-2-88394-069-7, November 2004)

30 *Acceptance of stay cable systems using prestressing steels*
Recommendation (80 pages, ISBN 978-2-88394-070-3, January 2005)

31 *Post-tensioning in buildings*
Technical report (116 pages, ISBN 978-2-88394-071-0, February 2005)

32 *Guidelines for the design of footbridges*
Guide to good practice (160 pages, ISBN 978-2-88394-072-7, November 2005)

33 *Durability of post-tensioning tendons*
Recommendation (74 pages, ISBN 978-2-88394-073-4, December 2005)

34 *Model Code for Service Life Design*
Model Code (116 pages, ISBN 978-2-88394-074-1, February 2006)

35 *Retrofitting of concrete structures by externally bonded FRPs*
Technical Report (224 pages, ISBN 978-2-88394-075-8, April 2006)

36 *2006 fib Awards for Outstanding Concrete Structures*
Bulletin (40 pages, ISBN 978-2-88394-076-5, May 2006)

37 *Precast concrete railway track systems*
State-of-art report (38 pages, ISBN 978-2-88394-077-2, September 2006)

38 *Fire design of concrete structures – materials, structures and modelling*
State-of-art report (106 pages, ISBN 978-2-88394-078-9, April 2007)

39 *Seismic bridge design and retrofit – structural solutions*
State-of-art report (300 pages, ISBN 978-2-88394-079-6, May 2007)

40 *FRP reinforcement in RC structures*
Technical report (160 pages, ISBN 978-2-88394-080-2, September 2007)

41 *Treatment of imperfections in precast structural elements*
State-of-art report (74 pages, ISBN 978-2-88394-081-9, November 2007)

42 *Constitutive modelling of high strength / high performance concrete*
State-of-art report (130 pages, ISBN 978-2-88394-082-6, January 2008)

43 *Structural connections for precast concrete buildings*
Guide to good practice (370 pages, ISBN 978-2-88394-083-3, February 2008)

44 *Concrete structure management: Guide to ownership and good practice*
Guide to good practice (208 pages, ISBN 978-2-88394-084-0, February 2008)

45 *Practitioners' guide to finite element modelling of reinforced concrete structures*
State-of-art report (344 pages, ISBN 978-2-88394-085-7, June 2008)

46 *Fire design of concrete structures —structural behaviour and assessment*
State-of-art report (214 pages, ISBN 978-2-88394-086-4, July 2008)

47 *Environmental design of concrete structures – general principles*
Technical report (48 pages, ISBN 978-2-88394-087-1, August 2008)

48 *Formwork and falsework for heavy construction*
Guide to good practice (96 pages, ISBN 978-2-88394-088-8, January 2009)

49 *Corrosion protection for reinforcing steels*
Technical report (122 pages, ISBN 978-2-88394-089-5, February 2009)

50 *Concrete structures for oil and gas fields in hostile marine environments*
State-of-art report (36 pages, IBSN 978-2-88394-090-1, October 2009)

51 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 1
Manual – textbook (304 pages, ISBN 978-2-88394-091-8, November 2009)

52 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 2
Manual – textbook (350 pages, ISBN 978-2-88394-092-5, January 2010)

53 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 3
Manual – textbook (390 pages, ISBN 978-2-88394-093-2, December 2009)

54 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 4
Manual – textbook (196 pages, ISBN 978-2-88394-094-9, October 2010)

55 *fib Model Code 2010, First complete draft* – Volume 1
Draft Model Code (318 pages, ISBN 978-2-88394-095-6, March 2010)

56 *fib Model Code 2010, First complete draft* – Volume 2
Draft Model Code (312 pages, ISBN 978-2-88394-096-3, April 2010)

57 *Shear and punching shear in RC and FRC elements - Workshop proceedings*
Technical report (268 pages, ISBN 978-2-88394-097-0, October 2010)

58 *Design of anchorages in concrete*
Guide to good practice (282 pages, ISBN 978-2-88394-098-7, July 2011)

59 *Condition control and assessment of reinforced concrete structures exposed to corrosive environments (carbonation/chlorides)*
State-of-art report (80 pages, ISBN 978-2-88394-099-4, May 2011)

60 *Prefabrication for affordable housing*
State-of-art report (130 pages, ISBN 978-2-88394-100-7, August 2011)

61 *Design examples for strut-and-tie models*
Technical report (220 pages, ISBN 978-2-88394-101-4, September 2011)

62 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 5
Manual – textbook (476 pages, ISBN 978-2-88394-102-1, January 2012)

63 *Design of precast concrete structures against accidental actions*
Guide to good practice (78 pages, ISBN 978-2-88394-103-8, January 2012)

64 *Effect of zinc on prestressing steel*
Technical report (22 pages, ISBN 978-2-88394-104-5, February 2012)

65 *fib Model Code 2010*, Final draft – Volume 1
Model Code (350 pages, ISBN 978-2-88394-105-2, March 2012)

66 *fib Model Code 2010*, Final draft – Volume 2
Model Code (370 pages, ISBN 978-2-88394-106-9, April 2012)

67 *Guidelines for green concrete structures*
Guide to good practice (56 pages, ISBN 978-2-88394-107-6, May 2012)

68 *Probabilistic performance-based seismic design*
Technical report (118 pages, ISBN 978-2-88394-108-3, July 2012)

69 *Critical comparison of major seismic codes for buildings*
Technical report (216 pages, ISBN 978-2-88394-109-0, August 2013)

70 *Code-type models for structural behaviour of concrete*
State-of-art report (196 pages, ISBN 978-2-88394-110-6, November 2013)

71 *Integrated life cycle assessment of concrete structures*
State-of-art report (62 pages, ISBN 978-2-88394-111-3, December 2013)

72 *Bond and anchorage of embedded reinforcement: Background to the fib Model Code for Concrete Structures 2010*
Technical report (170 pages, ISBN 978-2-88394-112-0, May 2014)

73 *Tall buildings: Structural design of concrete buildings up to 300m tall*
State-of-the-art report (158) pages, ISBN 978-2-88394-113-7, August 2014)

74 *Planning and design handbook on precast building structures*
Manual – textbook (313 pages, ISBN 978-2-88394-114-4, September 2014)

75 *Polymer-duct systems for internal bonded post-tensioning*
Recommendation (172 pages, ISBN 978-2-88394-115-1, December 2014)

76 *Benchmarking of deemed-to-satisfy provisions in standards: Durability of Reinforced Concrete Structures Exposed to Chlorides*
State-of-the-art-report (191 pages, ISBN 978-2-88394-116-8, May 2015)

77 *Corrugated-steel-web bridges*
State-of-the-art-report (110 pages, ISBN 978-2-88394-117-5, December 2015)

78 *Precast-concrete buildings in seismic areas*
State-of-the-art-report (273 pages, ISBN 978-2-88394-118-2, March 2016)

79 *Fibre-reinforced concrete - From design to structural applications*
ACI-*fib* workshop proceedings (480 pages, ISBN 978-2-88394-119-9, May 2016)

80 *Partial factor methods for existing concrete structures*
Recommendation (129 pages, ISBN 978-2-88394-120-5, December 2016)

81 *Punching of structural concrete slabs: Honoring Neil M. Hawkins*
ACI SP-315, ACI-*fib* symposium proceedings (378 pages, ISBN 978-2-88394-121-2, April 2017)

82 *Precast segmental bridges*
Guide to good practice (183 pages, ISBN 978-2-88394-122-9, August 2017)

83 *Precast Tunnel Segments in Fibre-Reinforced Concrete*
State-of-the-art report (162 pages, ISBN 978-2-88394-123-6, November 2017)

84 *Precast insulated sandwich panels*
State-of-the-art report (129 pages, ISBN 978-2-88394-124-3, December 2017)

85 *Towards a rational understanding of shear in beams and slabs*
Technical Report (338 pages, ISBN 978-2-88394-125-0, May 2018)

86 *Safety and performance concepts*
Guide to good practice (357 pages, ISBN 978-2-88394-126-7, August 2018)

87 *2018 fib Awards for Outstanding Concrete Structures*
Bulletin (39 pages, ISBN 978-2-88394-127-4, October 2018)

88 *Sustainability of precast structures*
State-of-the-art report (153 pages, ISBN 978-2-88394-128-1, December 2018)
89 *Acceptance of cable systems using prestressing steels*
Recommendation (153 pages, ISBN 978-2-88394-129-8, March 2019)
90 *Externally applied FRP reinforcement for concrete structures*
Technical report (229 pages, ISBN 978-2-88394-131-1, May 2019)
91 *Floating concrete structures*
State-of-the-art report (100 pages, ISBN 978-2-88394-133-5, August 2019)
92 *Serviceability Limit State of Concrete Structures*
Technical report (209 pages, ISBN 978-2-88394-135-9, September 2019)
93 *Birth Certificate and Through-Life Management Documentation*
Technical report (90 pages, ISBN 978-2-88394-137-3, June 2020)
94 *Precast concrete bridge continuity over piers*
Technical report (44 pages, ISBN 978-2-88394-140-3, July 2020)
95 *Fibre Reinforced Concrete: From Design to Structural Applications*
ACI SP-343, ACI-*fib* workshop proceedings (539 pages, ISBN 978-2-88394-141-0, August 2020)
96 *Guidelines for Submerged Floating Tube Bridges*
Guide to good practice (119 pages, ISBN 978-2-88394-143-4, October 2020)
97 *External Tendons for Bridges*
State-of-the-art-report (108 pages, ISBN 978-2-88394-145-8, December 2020)
98 *Acceptance of post-tensioning systems for cryogenic applications*
Recommendation, (106 pages, ISBN 978-2-88394-148-9, April 2021)

Abstracts for *fib* Bulletins and lists of available CEB Bulletins and FIP Reports are available on the *fib* website at www.fib-international.org/publications.

fib CEB-FIP

PCI
Precast/Prestressed Concrete Institute

Conceptual Design of Precast Concrete Bridge Superstructures

Contents

ISBN 978-2-88394-150-2
9 782883 941502

International Federation for Structural Concrete
Fédération internationale du béton
www.fib-international.org

ISSN: 1562-3610