Analysing existing structures: a brief introduction

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Introduction

There has never been a more pressing time to improve our understanding of existing structures. Each one represents an 'investment' of carbon emissions at some point in the past. Being able to analyse and modify them for new uses maximises the return on this investment and reduces the need for present-day emissions, particularly if this can be done without extensive strengthening works.

Engineers working with existing structures will need to be familiar with the behaviour and construction of a wide variety of materials and structural types, both modern and historic. They will need to exercise engineering judgement more frequently and possess a firm grasp of first principles to ensure such judgements are sound.

When is analysis necessary?

The general aim of analysis, with both existing and new structures, is to demonstrate that applied loads are exceeded by calculated resistances.

If the proposals for a particular existing building involve neither increasing loads nor decreasing resistances, then analysis is often not necessary. The structure may be deemed functionally adequate on the grounds that it has performed acceptably over an extended period of time under its current loading.

However, there are some exceptions to this principle and analysis will be required if the structure:

- is in poor condition, indicating that its original resistance may have been compromised
- shows signs of distress, indicating that its original resistance may have been inadequate
- contains obvious defects, such as absent load paths, modifications that have weakened load paths, or grossly undersized elements.

Redundancy, and where it may be found

Where the proposals do involve increasing loads or decreasing resistances, the engineer is reliant on finding redundancy in the existing structure. Sources of redundancy common to both modern and historic structures include:

- rationalisation – where a critical design section has been applied to non-critical members, usually to simplify design and construction
- conservatism – where sections that work 'comfortably' have been specified, or unnecessarily high allowances for finishes, etc. were used in the original design
- practicality – where the size of a section is governed by ease of construction, rather than structural demand (often the case with concrete walls)
- availability – even the most efficient section for a given scenario may not be at full utilisation, since section sizes are not on a continuum.

Further sources of redundancy are available with historic structures, though some care is necessary in determining whether it is appropriate to make use of them:

- Historic live load allowances are sometimes higher than modern requirements.
- In the UK, live load reductions for the design of multistorey buildings appear to have been first considered in BS 449:1932[1].
- Factors of safety used in historic design are sometimes more conservative than present-day equivalents.

The engineer should bear in mind that not all historic structures will have been designed and constructed in accordance with the codes, guidance and best practice of the time. It is necessary to judge the likelihood of this based on the age and nature of the building and evidence from desk studies, surveys and investigations.

The proposed development may itself contribute to redundancy:

- Changes of use can lead to reduced live loads.
- Removal and replacement of existing heavy finishes such as screeds and levelling compounds can lead to reduced dead loads. Removal of existing partitions or replacing solid loadbearing walls with lighter alternatives can have a similar effect.
- Existing sections which were previously governed by serviceability limits may have spare capacity if it is possible to relax those limits, e.g. by using more deflection-tolerant finishes.

What are the prospects?

The fact that utilisation ratios of around 80% are common for critical elements, and even as low as 60% on average[2], indicates that the first four factors alone can yield significant spare capacity to accommodate new development.

Legal constraints notwithstanding, the author's experience is that most medium-to-large city-centre structures have been found to possess adequate redundancy to make some form of redevelopment commercially viable with minimal intervention.

All the same, the greatest potential, at least in the UK, is to be found in iron, steel and concrete buildings dating from the early 19th to early 20th century. This is for two reasons – the vast stock of surviving buildings from this period, and the degree of redundancy which they often exhibit. This article is written predominantly with this type of structure in mind.

Approaches to analysis

Comprehensive analysis of any structure involves a large quantity of data, much of which is usually absent for existing buildings. Often, the only information available is an idea as to the approximate age and original use of the building, limited investigation results and a topographic survey.

1) When little information is available, or the client's brief is modest, the simplest approach is a **load balance**. If it can be demonstrated that an increase in loads due to one aspect of the proposals can be offset by a decrease due to another, with the result that there is no overall increase, the existing structure must be adequate and existing margins of safety are maintained.

A common example occurs with rear extensions. Consider a beam supporting the rear elevation of a Victorian brick building with floor beams spaced at 4.8m (16'). The client's brief is to extend the existing floor plate rearward using a steel and composite frame:

$$\text{Load added (new slab + SDL)} = 4.25\text{kN/m}^2 \times 2.4\text{m} = 11.5\text{kN/m (15.5 ultimate)}$$

$$\text{Load added (imposed + partitions)} = 3.50\text{kN/m}^2 \times 2.4\text{m} = 8.4\text{kN/m (12.6 ultimate)}$$

$$\text{Load removed (original rear wall)} = 13\tfrac{1}{2}" \times 21\text{kN/m}^3 \times 3\text{m} = 22.0\text{kN/m (30.8 ultimate)}$$

In this case, it can be seen that removing a single storey of masonry can offset the new floor loads entirely. Other than its condition, very little information on the existing beam or adjacent construction is necessary.

2) If the age of the original building is known and sizes of existing elements are confirmed, the strength of the existing structure may be assessed in accordance with **contemporary codes of practice**.

For historic iron and steel structures, this is a substantial topic in its own right, well covered in the BCSA's *Historical Structural Steelwork Handbook*[3], with allowable stresses traced as far back as 1879.

Historic concrete structures are typically assessed with modern limit state design methods, using appropriately low cube and yield strengths based on records and/or testing wherever possible.

Existing timber structures are commonly checked using allowable stress design, which many UK engineers still use. If in good condition, it is normal to assume that old, slow-grown timber is of high quality, usually no less than C24 equivalent, although this should be corroborated by visual inspection.

Elsewhere in this issue, Jess Foster describes using a combination of these two approaches to justify extensions to an existing concrete frame[4].

3) If, in addition to section sizing, it is practical to test material properties, the engineer can attempt to assess the structure in accordance with modern **limit state design** principles. Strictly speaking, material properties to be determined by testing include not only characteristic material strength and stiffness, but also the variability of these parameters, from which the engineer can derive appropriate material safety factors.

In practice, it is often not possible to obtain enough samples for meaningful statistical analysis and, particularly for historic structures, it falls to the engineer to make an educated judgement about appropriate values for γ_m. Reference may be made to the IStructE's *Appraisal of existing structures*[5], which describes the basis of modern values for γ_m for various materials as well as circumstances in which adjustments might be appropriate.

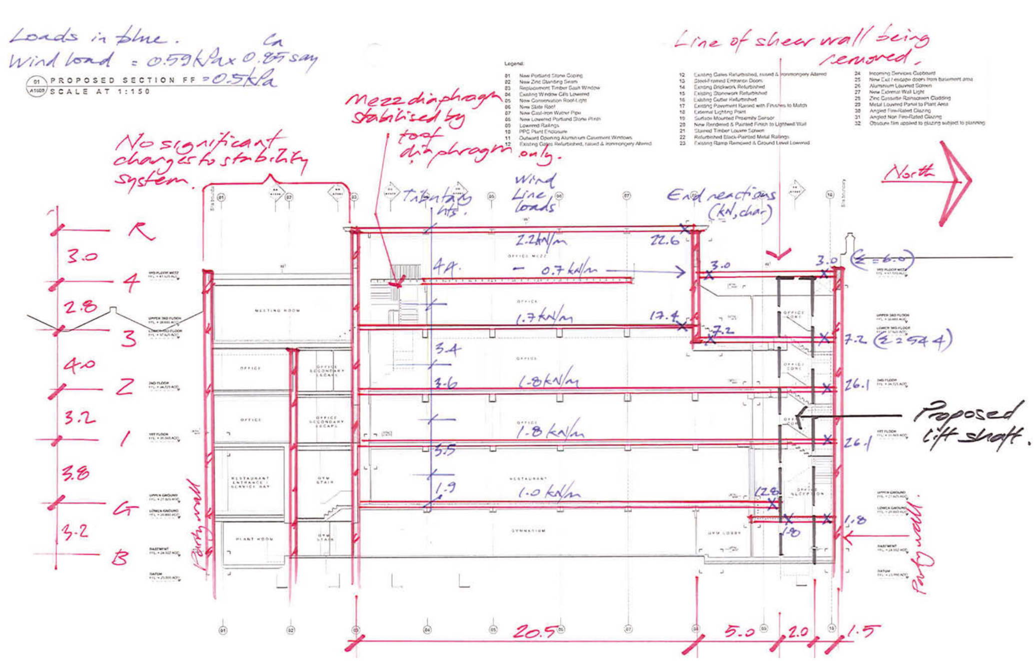
Modern limit state design codes tend to go into great detail with buckling checks. Historic construction tends to be quite robust against buckling, more by virtue of construction and detailing rather than refinement of structural analysis. Beams are often well restrained by slabs, and sections are often stockier than we might use today. Where simple slenderness checks can be employed, these are usually sufficient.

4) Lastly, in certain very limited circumstances, non-destructive **load testing** might be a valuable tool. It can be both expensive and time-consuming, and an estimate of strength derived by analysis is a prerequisite. It is usually a last resort, when analysis alone is not expected to provide a reliable prediction of a structure's behaviour.

Unsurprisingly, simpler analyses will tend to yield more conservative results and more sophisticated methods will tend to yield more favourable results. The brief and information available will vary from one project to another, so an appropriate method should be chosen in each case.

If any residual uncertainty remains in the analyses, proposed loading should be limited to whatever can be justified with confidence.

FIGURE 1: Arrangement of horizontal and vertical diaphragms in 1920s office building



Common pitfalls

One of the easiest issues to trip up on is **lateral stability**. Firstly, the relationship between building height and stability forces is quadratic – a 10% increase in height entails a 20% increase in bracing forces. Secondly, stability systems in older buildings can be idiosyncratic and poorly conditioned, with the result that very little works 'by inspection' and almost the entire load path needs to be checked explicitly.

It is doubtful that much analysis was applied to stability systems before the 1930s. BS 449:1932 devotes 123 words to wind loads and concludes that, *'If the height of a building is less than twice its width, wind pressure may be neglected, provided that the building is adequately stiffened by floors and walls'*[1]. The latter check, it seems, falls to the present-day engineer.

In the 1920s office building shown in **Figure 1**, existing floor diaphragms consisted of 1½" (38mm) thick, low-strength concrete toppings to hollow pot slabs. The fourth floor had no direct connection to shear walls but relied on the roof to transfer lateral loads, and the third floor was discontinuous across levels. The client's brief included removing one of the main shear walls and cutting large new openings into the floor plates. A lateral stability nightmare!

Increasing the height or use of a building can also change its **disproportionate collapse** consequence class, which may dramatically affect its structural adequacy. In the same example **(Figure 2)**, the addition of a mezzanine floor within an existing roof space resulted in consequence class 2B, requiring effective horizontal and vertical ties.

This had a significant effect on detailing – how does one go about demonstrating that a loadbearing masonry building provides 'effective vertical ties'? It was necessary to devise a strategy for disproportionate collapse and agree it with the approved inspector at an early stage. In this case, the strategy included notional removal of supports and key element design.

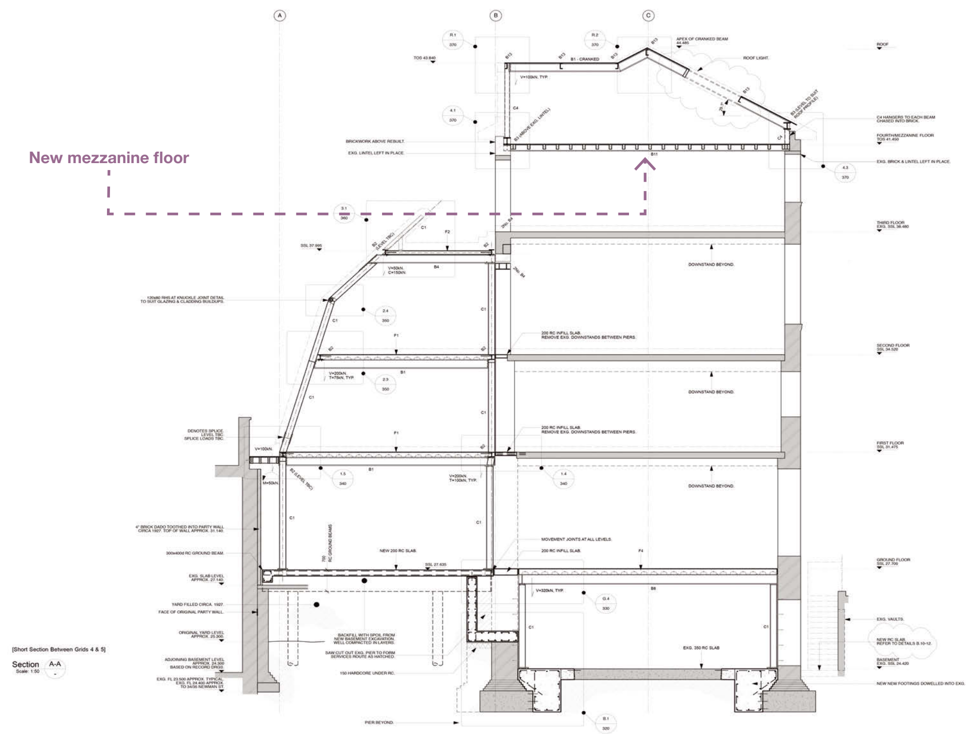


FIGURE 2: Cross-section through early 1920s building showing vertical and horizontal extensions

Safety factors should be used with care to compare loads and resistances like for like. With some minor exceptions, prior to limit state design, virtually all factors of safety were 'global' – i.e. load and material factors rolled into one – and applied to the resistance side of the equation only. Furthermore, these might have been intended for use with ultimate strengths or average strengths rather than characteristic strengths.

A related point is that modern structures are designed with **ductility** to avoid sudden failure, whereas this is not always the case for historic structures. Higher factors of safety may be necessary where sudden failure is a possibility.

Removal of existing beams or formation of new floor openings near columns or piers can result in a temporary or permanent **loss of restraint** to those columns, which usually rely on floor diaphragms to limit their effective length. In heavily loaded or massive masonry buildings, column restraint loads can exceed wind loads applied to the diaphragm. In such cases, checks should be made to verify the diaphragm's residual capacity or waling beams provided to replicate its restraint **(Figure 3)**.

Most larger buildings have a typical framing layout which is replicated across several floors, but the engineer should be wary of existing **transfer beams**, which are not always obvious on

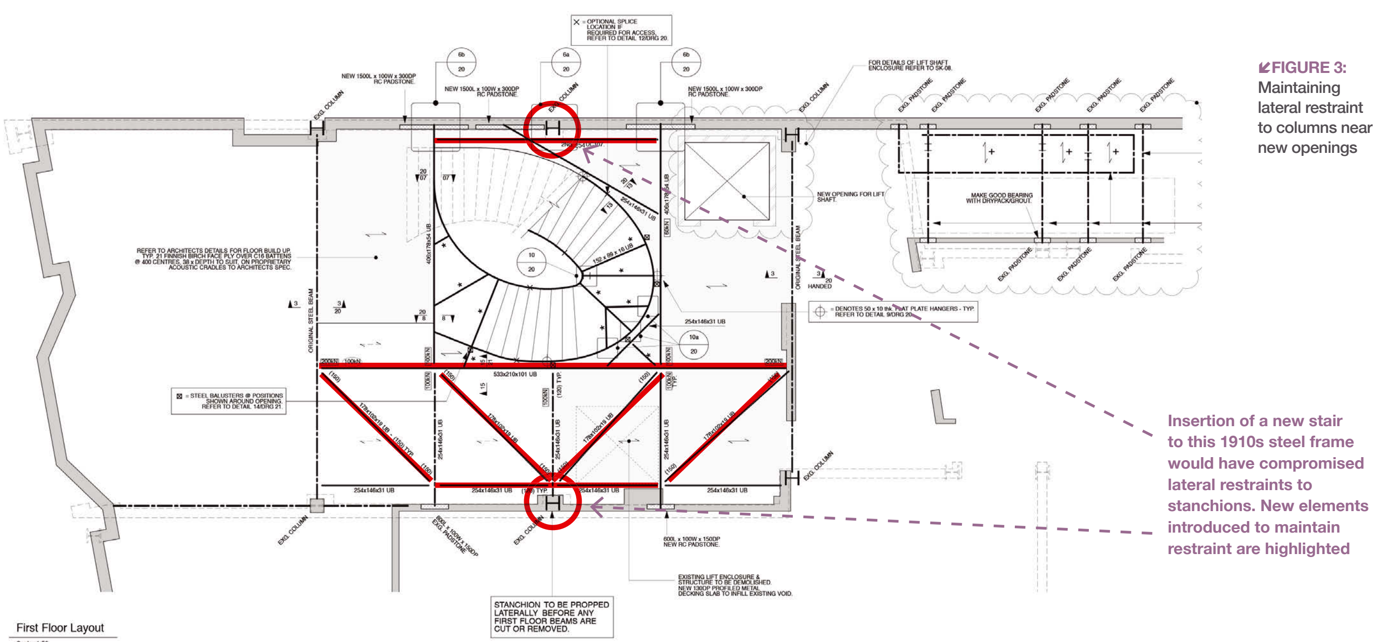


FIGURE 3: Maintaining lateral restraint to columns near new openings

older drawings, and even harder to detect in the finished building. Transfer beams often have high utilisation ratios.

Conclusion

Existing structures provide significant opportunities to reduce emissions and costs through reuse and refurbishment.

Analysing them need not be daunting, although it involves a different set of challenges than new buildings. Design methods have evolved over the years, not so much because structures have changed (they have), but because we have developed more accurate ways of predicting their behaviour. For the most part, existing structures behave similarly to new structures. Gravity acts identically for both.

REFERENCES

1) British Standards Institution (1932) *BS 449:1932 The use of structural steel in building*, London: BSI (withdrawn)

2) Poole I. (2020) 'Rationalisation versus optimisation – getting the balance right in changing times', *The Structural Engineer*, 98 (10), pp. 18–21

3) Bates W. (1984) *Historical Structural Steelwork Handbook*, London: BCSA

4) Foster J. (2021) 'What do you do when you are convinced the structure will work but can't prove it to code?', *The Structural Engineer*, 99 (6), pp. 18–22

5) Institution of Structural Engineers (2010) *Appraisal of existing structures* (3rd ed.), London: IStructE Ltd

USEFUL RESOURCES

Structural Engineer's Pocket Book	This book by Fiona Cobb draws together guidance from many superseded codes and contains a useful timeline of historic construction forms
Historical Structural Steelwork Handbook	This BCSA publication is a gold mine for historic section sizes in iron and steel and permissible stresses from a variety of historic codes from before 1900 to 1948. The manner in which section stability and buckling were dealt with in these codes is also described. Perhaps most usefully, it also tracks changes in live load allowances in this period
Handbook of Steel Sections	Dorman Long's 1895 handbook may be freely downloaded from its website and contains section properties and span tables for an enormous range of monolithic and compound steel girders
Historical approaches to the design of concrete buildings and structures	Concrete Society Technical Report 70 describes UK elastic design methods, material strengths and safety factors from the early 20th century
Office floor loading in historic buildings	This English Heritage publication has successfully been used to argue in favour of lower live load allowances in historic buildings, particularly where adherence to BS 6399 or EN 1991 would result in disruption of listed fabric
Structural renovation of traditional buildings	CIRIA R111 is a concise but invaluable guide to traditional construction materials and techniques, with many useful diagrams and isometrics showing how some details and concepts were intended to work – something that's not always legible *in situ* after a century or more of wear and weathering
Appraisal of existing structures (3rd ed.)	This IStructE publication also contains comprehensive, step-by-step guidance for structural engineers needing to check and report on the adequacy of an existing structure