

CEN/TC 250

Date: 2021-01

prEN 1992-1-1:2021

Secretariat: BSI

**Eurocode 2: Design of concrete structures — Part 1-1: General rules —
Rules for buildings, bridges and civil engineering structures**

**Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und
Spannbetontragwerken — Teil 1-1: Allgemeine Regeln — Regeln für Hochbauten,
Brücken und Ingenieurbauwerke**

**Eurocode 2: Calcul des structures en béton — Partie 1-1: Règles générales — Règles
pour les bâtiments, règles pour les bâtiments, les ponts et les ouvrages de génie civil**

ICS:

CCMC will prepare and attach the official title page.

Annex J (informative)

Strengthening of Existing Concrete Structures with CFRP

J.1 Use of this annex

(1) Annex J contains rules for strengthening of existing structures assessed in accordance with this Eurocode comprising plain, reinforced, and/or prestressed normal weight concrete with Carbon Fibre Reinforced Polymer (CFRP) reinforcement adhesively bonded to the concrete surface.

NOTE 1 The reinforcement can be externally bonded to the surface (EBR) or near surface mounted in the concrete (NSM).

NOTE 2 The reinforcement material can be in the form of

- Prefabricated carbon FRP (CFRP) strips (EBR or NSM) or bars (NSM),
- In-situ lay-up carbon fibre (CF) sheets (EBR).

NOTE 3 National choice on the application of this Informative Annex is given in a National Annex. If a National Annex contains no information on the application of this Informative Annex, it can be used.

J.2 Scope and field of application

(1) All clauses of this Eurocode apply unless specifically omitted or supplemented in Annex J.

NOTE For general aspects of existing structures, Annex I can be considered.

J.3 General

NOTE Unless noted otherwise, in Annex J all section/sub-section numbers and titles are similar as the relevant of the main part of this Eurocode. The prefix 'J' is added to subclauses/clauses numbers to distinguish content that pertain to strengthening of existing concrete structures with CFRP. Annex J contains only sections/subsections of the main part of this Eurocode that include specific clauses for the strengthening of existing concrete structures with CFRP.

J.4 Basis of design - Partial factors for materials

(1) Partial factors for ABR CFRP reinforcement γ_f and γ_{BA} shall be applied.

NOTE The values γ_f and γ_{BA} are those given in Table J.1(NDP) unless a National Annex gives different values.

Table J.1(NDP) — Partial factors for ABR CFRP strengthening

Design situation	Tensile strength		Bond strength
	CFRP strips and bars	In-situ lay-up CF sheets	Failure in concrete or adhesive
Designation	γ_f		γ_{BA}
Persistent and transient	1,30	1,40	1,50
Accidental	1,05	1,10	1,20
Serviceability	1,00	1,00	1,00
Fatigue	1,30	1,40	1,30

J.5 Materials - Properties and related conditions

(1) Specified properties and related conditions of adhesively bonded CFRP reinforcement systems that are required for design to this Eurocode shall include at least:

For CFRP polymer:

- characteristic short-term tensile strength of the ABR CFRP f_{fuk} , determined in accordance with ISO 10406 (all parts);
- mean modulus of elasticity in longitudinal direction of adhesively bonded CFRP E_f , determined in accordance with ISO 10406 (all parts);

For adhesive:

- characteristic compressive strength of the adhesive f_{Ack} determined in accordance with EN 1504-4;
- characteristic tensile strength of the adhesive f_{Atk} , determined in accordance with EN 1504-4; which shall be $f_{Atk} \geq 14 \text{ N/mm}^2$ for design to Annex J.

NOTE 1 Variations in material properties with temperature may occur. The producer should be informed of the maximum and minimum temperatures for the design life of the CFRP system, calculated in accordance with prEN 1991-4 for the application of the system to be used for execution.

NOTE 2 Variations in material properties with environmental conditions may occur. The producer should be informed of the environmental conditions that will be encountered through the design life of the CFRP for the application of the system to be used for execution.

NOTE 3 Variations in alkali resistance between CFRP systems may occur. The producer should be informed where exposure to an alkali -environment is probable through the design life of the CFRP.

(2) The value of design tensile strength of adhesively bonded CFRP reinforcement shall be taken as

$$f_{fud} = \frac{\eta_f \cdot f_{fuk}}{\gamma_f} \quad (J.1)$$

where

η_f is a reduction factor applied to the tensile strength of the ABR CFRP reinforcement calculated in accordance with ISO 10406 (all parts) as appropriate.

(3) η_f may be taken as 0,7 unless more accurate information is available based on test data for the CFRP reinforcement.

(4) The strain corresponding to the short-term design strength, ε_{fud} , shall be calculated according to the following Formula (J.2):

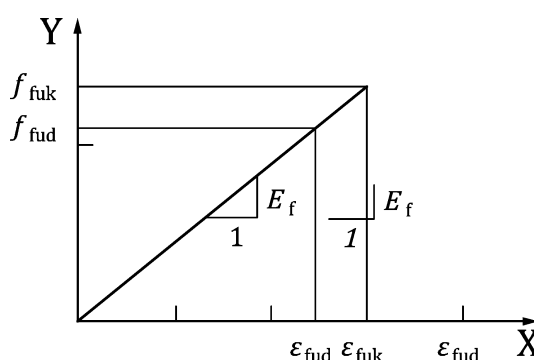
$$\varepsilon_{fud} = \frac{f_{fud}}{E_f} \quad (J.2)$$

(5) The mean modulus of elasticity, E_f , of the CFRP reinforcement strips shall be in a range of 150 000 MPa to 230 000 MPa for design to Annex J.

(6) The elastic stiffness $E_f \cdot A_f$ per unit width for CFRP reinforcement sheets for design to this Annex J shall be limited to values from 20 N/mm to 400 N/mm, and the total CFRP cross section per unit width of CFRP reinforcement sheets in the total of all layers shall be between 100 mm²/m and 1 800 mm²/m.

(7) The design stress-strain diagram for CFRP reinforcement should be taken as in Figure J.1.

(8) ABR CFRP shall not be used for concrete where deterioration is present.



Key

x Strain
y Stress

Figure J.1 — Design stress- strain diagram for CFRP reinforcement

J.6 Durability - Environmental exposure conditions

(1) Without additional measures to protect the CFRP system and its adhesive, for the design life of the structure, strengthening with adhesively bonded CFRP reinforcement should only be applied in exposure classes X0, XC1 (dry), XC3, XC4, or XF1 in accordance with Table 6.1. In addition, ABR CFRP reinforcement should not be exposed to direct UV radiation (direct sun radiation or indirect sun from snow or water reflection) or alternating or permanent penetration of moisture. Thermal effects shall be considered from e.g. asphalt on a strengthened bridge deck.

J.7 Structural analysis

(1) Unless more rigorous analysis is undertaken, members strengthened with CFRP should not be analysed using linear elastic analysis with limited redistribution or plastic analysis.

(2) A member should be assessed against accidental loss of adhesively bonded CFRP reinforcement, including the following situations:

- The FRP should not be designed to withstand permanent action effects in a manner that the structure would not be able to withstand collapse without FRP, unless the following is addressed in design:
 - The ABR CFRP strengthening is detailed in a manner that protects it against damage from vandalism or accidental mechanical damage;

- Member collapse will not result in progressive collapse of the structure;
- Protection from fire damage is provided.

J.8 Ultimate limit states (ULS)

J.8.1 Bending with or without axial force

J.8.1.1 General

(1) When determining the ultimate moment resistance of reinforced or prestressed concrete cross sections strengthened in flexure with adhesively bonded CFRP reinforcement, the following assumptions in addition to 8.1.1(2) should be made:

- the compressive strength of ABR CFRP is ignored;
- the slip between CFRP reinforcement and the concrete substrate is neglected.

(2) The strain state of the existing reinforcement and concrete members being strengthened shall be determined prior to strengthening under the relevant effects of actions. Strains arising from additional action effects after strengthening should be superimposed to these when verifying the capacity of the strengthened member.

(3) Unless more rigorous analysis is undertaken, the provisions in this Eurocode should not be applied to concrete with $f_{ck} \leq 12$ MPa or $f_{ck} > 50$ MPa.

(4) Subject to the provisions of 8.1 and J.11 being satisfied, the tension contribution of the adhesively bonded CFRP should be included in calculation of ultimate moment resistance using the limiting strain distribution shown in 8.1.1(6) where the strain limit in the ABR CFRP is limited by the bond capacity determined in J.11.

J.8.1.2 Concrete columns confined with fully wrapped CFRP

(1) The confining effect provided by adhesively bonded CFRP may be considered in design of axially-loaded members under the following conditions, where:

- the characteristic concrete strength f_{ck} is less than 50 MPa;
- the diameter of a circular column, D , or effective diameter of a rectangular or square column, D_{eq} is greater than 150 mm;
- the first order eccentricity satisfies the condition $\frac{e_0}{D_{eq}} \leq 0,25$;
- the slenderness of satisfies the condition $l_0/D_{eq} \leq 40$;
- the corner radius for rectangular cross sections is $r_c \geq 20$ mm;
- $t_{f,eff} = n_f^{af} \cdot t_f$, with $a_f = 0,85$ for $n_f > 3$, or 1 otherwise.

The increase in compressive strength from FRP confinement shall be considered in determining slenderness effects.

(2) The increase in compressive strength of concrete Δf_{cd} in columns resulting from confinement using FRP may be calculated as follows:

For circular columns:

$$\Delta f_{cd} = 0 \quad \text{for } \frac{2t_{f,eff} \cdot f_{fud}}{D \cdot f_{cd}} < 0,07 \quad (J.3)$$

$$\Delta f_{cd} = 3,3 \cdot \frac{2 \cdot t_f}{D} \cdot k_r \cdot f_{fud} \quad \text{for } \frac{2t_{f,eff} \cdot k_r \cdot f_{fud}}{D \cdot f_{cd}} \geq 0,07 \quad (J.4)$$

where D is the diameter of the circular column.

$$k_r = \begin{cases} 0,5 \cdot \left(\frac{r_c}{50}\right) \cdot \left(2 - \frac{r_c}{50}\right) & \text{for } r_c < 50 \text{ mm} \\ 0,5 & \text{for } r_c \geq 50 \text{ mm} \end{cases} \quad (J.5)$$

$$r_c = 0,5 \cdot D \quad (J.6)$$

For rectangular columns:

$$\Delta f_{cd} = 0 \quad \text{for } \left(\frac{b}{h}\right)^2 k_e \frac{2t_{f,eff} \cdot k_r \cdot f_{fud}}{D_{eq} \cdot f_{cd}} < 0,07 \quad (J.7)$$

$$\Delta f_{cd} = 3,3 \cdot \left(\frac{b}{h}\right)^2 \cdot k_e \cdot \frac{2t_f}{D_{eq}} \cdot k_r \cdot f_{fud} \quad \text{for } \left(\frac{b}{h}\right)^2 k_e \frac{2t_f \cdot k_r \cdot f_{fud}}{D_{eq} \cdot f_{cd}} \geq 0,07 \quad (J.8)$$

where

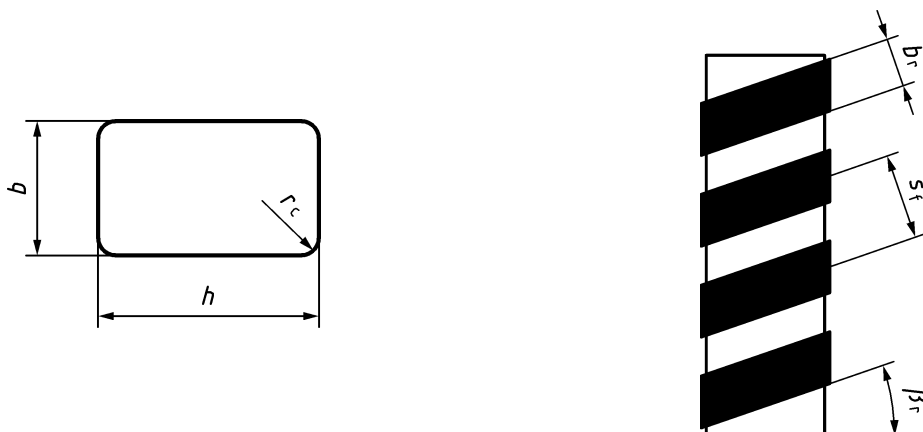
$$D_{eq} = \frac{2 \cdot b \cdot h}{b + h} \quad (J.9)$$

$$k_e = 1 - \frac{(b - 2 \cdot r_c)^2 + (h - 2 \cdot r_c)^2}{3 \cdot b \cdot h} \quad (J.10)$$

Where helical wrapping is used on rectangular or square columns (see Figure J.2), the value of k_e calculated in Formula (J.10) should be factored by k_h in Formula (J.11), where geometrical parameters are defined in Figure J.2a) and b).

$$k_h = \left(1 - \frac{(s_f - b_f)}{2 \cdot b}\right) \cdot \left(1 - \frac{(s_f - b_f)}{2 \cdot h}\right) \cdot \left(\frac{1}{1 + (\tan \beta_f)^2}\right) \quad (J.11)$$

(3) The confining effect of CFRP may be ignored in creep calculations for concrete columns.



a) cross sectional dimensions of rectangular column

b) helical wrapping configuration

Figure J.2 — Configuration of CFRP wrapping

J.8.2 Shear

J.8.2.1 General verification procedure

(1) The shear resistance of a section strengthened with CFRP may be taken as:

$$V_{Rd,CFRP} = V_{Rd} + V_{Rd,f} \leq \frac{V_{fcd}}{2} b_w \cdot z \leq (0,5 \cdot v \cdot f_{cd}) \cdot b_w \cdot z \quad (J.12)$$

where

$$V_{Rd} = \tau_{Rd} \cdot b_w \cdot z \quad (J.13)$$

$$V_{Rd,f} = \frac{A_f}{s_f} \cdot z_f \cdot f_{fwd} \cdot (\cot\theta + \cot\alpha_f) \sin\alpha_f \quad (J.14)$$

$$\frac{A_f}{s_f} = \begin{cases} \frac{2 \cdot t_f \cdot b_f}{s_f} & \text{for discrete CFRP strips} \\ 2 \cdot t_f & \text{for CFRP sheets} \end{cases} \quad (J.15)$$

α_f is the angle formed between the CFRP system;

z_f is the height of CFRP crossed by the shear crack.

f_{fwd} is design shear strength of the CFRP system calculated in accordance with J.8.2.2 and J.8.2.3.

Unless more rigorous analysis is undertaken, θ should be taken as 45 degrees for the calculation of V_{Rd} and $V_{Rd,f}$.

J.8.2.2 Fully Wrapped CFRP Systems

(1) The following may be used to determine the design shear strength of fully wrapped CFRP systems as defined in Figure J.3.

$$f_{fwd} = 0,8 \cdot k_r \cdot f_{fud} \quad (J.16)$$

where

f_{fud} should be determined using Formula (J.1) and k_r should be determined using Formula (J.5).

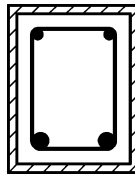


Figure J.3 — Illustration of fully wrapped CFRP system covered by this code

J.8.2.3 Open CFRP Systems

(1) The following may be used to determine the design shear strength of open CFRP systems as defined in Figure J.4.

Where the anchorage length into the compression zone of the member of all CFRP strips, l_{bf} , is less than $l_{bf,max,k}$, f_{fwd} should be determined using the Formula (J.17), where θ and α_f are defined in Figure J.5.

$$f_{\text{fwd}} = \frac{2(n \cdot s_f / [(\cot\theta + \cot\alpha_f)\sin\alpha_f]}{3 l_{\text{bf,max,k}}} f_{\text{bfRd}} \quad (\text{J.17})$$

Where the anchorage length into the compression zone of the member of some CFRP strips, l_{bf} , is less than $l_{\text{bf,max,k}}$, f_{fwd} should be determined using Formula (J.18):

$$f_{\text{fwd}} = \left[1 - \left(1 - \frac{2m \cdot s_f}{3 \cdot l_{\text{bf,max,k}}} \right) \frac{m}{n} \right] f_{\text{bfRd}} \quad (\text{J.18})$$

Where the parameters α_f , m and n are defined in Figure J.5 and f_{bfRd} shall be determined using 11.1.1.

(2) Formulae (J.17) and (J.18) may be applied with CFRP sheets by substituting s_f with $b_f/\sin\alpha$.

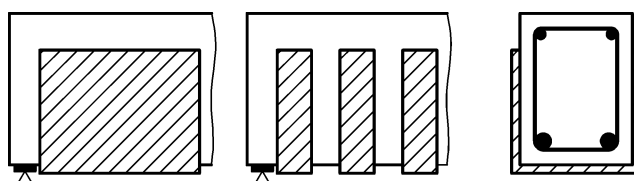
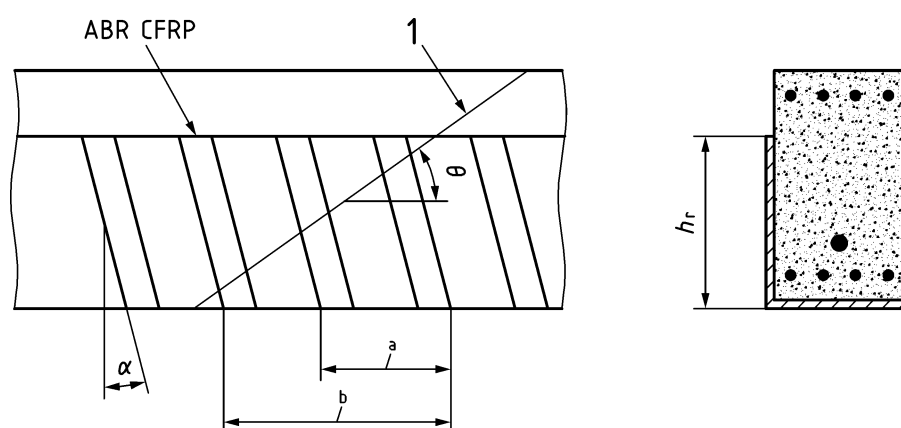


Figure J.4 — Illustration of open CFRP shear strengthening systems covered by this code



Key

- 1 Shear crack
- a m stirrups with $l_{\text{bl}} < l_{\text{bl,k,max}}$
- b n stirrups intersecting shear crack

Figure J.5 — Illustration of ABR CFRP stirrups intersecting shear crack

J.8.3 Punching

- (1) This Eurocode does not apply for strengthening for punching shear with CFRP.

J.8.4 Design with strut-and-tie models and stress fields

- (1) ABR CFRP systems may be used as tension reinforcing in ties according to the provisions of 8.5 and J.11 subject to strain compatibility being demonstrated.

J.9 Serviceability limit states (SLS)

- (1) Deflections of beams or slabs strengthened with CFRP may be estimated by ignoring the slip between the CFRP and concrete and transforming the area of CFRP to steel by taking account of the

modular ratio. Pre-existing deflections shall be considered by using the appropriate provisions of prEN 1990.

J.10 Fatigue

J.10.1 Basic fatigue analysis for externally bonded CFRP systems

(1) A fatigue check for externally bonded CFRP systems may be omitted where the following condition is satisfied:

$$\Delta F_{fEd, equ} \leq \Delta F_{fRd, fat1} = 0,25 \cdot f_{ctm, surf}^{1/4} \cdot f_{bfRd} \cdot b_f \cdot t_f \quad (J.19)$$

where

$\Delta F_{fRd, fat1}$ is the basic fatigue resistance;

f_{bfRd} is the limiting design strength of the bond in the area being considered calculated in accordance with J.11;

$f_{ctm, surf}$ is defined by Formula (J.36);

$$\Delta F_{fEd, equ} = \max\{b_f \cdot t_f \cdot \Delta f_{fEd, max}, F_{fEd, cr}\} \quad (J.20)$$

$\Delta f_{fEd, max}$ is the maximum difference in CFRP stress under the relevant load combination between cracks (refer to Figure J.5) within the strengthened area. $F_{fEd, cr}$ is the force in CFRP at first crack in the strengthened area.

J.10.2 Refined fatigue analysis for externally bonded CFRP systems

(1) If the condition in Formula (J.19) cannot be satisfied, the following condition shall be assessed under the frequent combination stated in Clause 10 according to:

$$\Delta F_{fEd, fat} \leq \Delta F_{fRd, fat2} = \alpha_{fat2} \cdot \frac{\Delta F_{fk, B}}{\gamma_{BA}} \quad (J.21)$$

where

$\Delta F_{fEd, fat}$ is the design force range due to forces at the crack edge, $\Delta F_{f, max} - \Delta F_{f, min}$, and;

$\Delta F_{f, min}$ is the minimum value of $b_f \cdot t_f \cdot \Delta f_{fEd}$ under the relevant fatigue load combination specified in 10.2;

$\Delta F_{f, max}$ is the maximum value of $b_f \cdot t_f \cdot \Delta f_{fEd}$ under the relevant fatigue load combination specified in 10.2.

The difference in CFRP tension stress between cracks Δf_{fEd} calculated according to Formula (J.22) is defined in Figure J.6.

$$\Delta f_{fEd} = \frac{F_{fEd, b} - F_{fEd, a}}{b_f \cdot t_f} \quad (J.22)$$

where

$\Delta F_{fk, B} = b_f \cdot t_f \cdot \Delta f_{fk, B}$ and $\Delta f_{fk, B}$ is calculated according to Formula (J.39);

$$\alpha_{fat2} = -c_{fat} \cdot \frac{\Delta F_{f, max}}{\Delta F_{fRd}} + c_{fat} \quad (J.23)$$

$\Delta F_{f, max}$ is the maximum value of ΔF_f under the fatigue load combination according to 10.2;

$$c_{\text{fat}} = 0,35 \cdot \left(\frac{N^*}{2 \cdot 10^6} \right)^{-\frac{1}{k_{f3}}} \quad (\text{J.24})$$

N^* the number of stress cycles;

$k_{f3} = 23,2$ for $N^* < 2 \cdot 10^6$;

$k_{f3} = 45,4$ for $N^* \geq 2 \cdot 10^6$.

J.10.3 Near surface mounted CFRP strips

(1) Near surface mounted strips that satisfy the following conditions under the frequent combination stated in Clause 10 may be deemed adequate in fatigue.

1. The number of stress cycles is less than $2 \cdot 10^6$;
2. The maximum force in the NSM CFRP system, taking the shift of the tension envelope into account, does not exceed $F_{f,\text{NSM},\text{max}}$, where $F_{f,\text{NSM},\text{max}}$ is calculated using Formula (J.25);
3. The strip stress range $\Delta\sigma_f$ complies with the provisions stated in Formula (J.26).

$$F_{f,\text{NSM},\text{max}} = 0,6 \cdot f_{\text{bfRd}} \cdot b_f \cdot t_f \quad (\text{J.25})$$

$$\Delta\sigma_f \leq \frac{500}{t_f} \quad (\text{J.26})$$

where

$$\Delta\sigma_f = \frac{\Delta F_{f,\text{max}} - \Delta F_{f,\text{min}}}{b_f \cdot t_f} \quad (\text{J.27})$$

J.11 Bond and anchorage of CFRP systems

J.11.1 Anchorage of ABR CFRP strengthening systems

J.11.1.1 Basic anchorage resistance — CFRP to concrete for EBR CFRP strengthening

J.11.1.1.1 General

(1) The required anchorage length of externally bonded CFRP reinforcement, calculated in accordance with J.11.1.1, should be curtailed as described in J.11.1.2.

J.11.1.1.2 Simplified method

(1) The following simplified method may be used to determine the anchorage resistance for externally bonded CFRP.

$$f_{\text{bfRd}} = \frac{0,17}{\gamma_{\text{BA}}} k_b \beta_1 \sqrt{\frac{2E_f}{t_f} f_{\text{cm}}^{2/3}} \quad (\text{J.28})$$

where

$$k_b = \sqrt{\frac{2 - b_f/b}{1 + b_f/b}} \quad (\text{J.29})$$

$$\beta_1 = \begin{cases} \frac{l_{bf}}{l_{bf,max,k}} \left(2 - \frac{l_{bf}}{l_{bf,max,k}} \right) < 1 & \text{if } l_{bf} < l_{bf,max,k} \\ 1 & \text{if } l_{bf} \geq l_{bf,max,k} \end{cases} \quad (J.30)$$

$$l_{bf,max,k} = \frac{1.5\pi}{k_b} \sqrt{\frac{E_f \cdot t_f}{8f_{cm}^{2/3}}} \quad (J.31)$$

J.11.1.1.3 Refined method

(1) If more accurate data for the EBR CFRP reinforcement system is known based on production data, the following more refined analysis may be used to determine anchorage resistance. The design bond strength of the anchorage, of the EBR CFRP reinforcement system may be taken as the following:

$$f_{bfRd} = \frac{\sqrt{\eta_{cc} \cdot k_{tc} \cdot k_{tt}}}{\gamma_{BA}} \cdot \begin{cases} f_{bfk,max} \cdot \frac{l_{bf}}{l_{bf,max}} \left(2 - \frac{l_{bf}}{l_{bf,max}} \right) & \text{where } l_{bf} < l_{bf,max} \\ f_{bfk,max} & \text{where } l_{bf} \geq l_{bf,max} \end{cases} \quad (J.32)$$

where

$$l_{bf,max} = \frac{\pi}{2} \cdot \frac{\sqrt{E_f \cdot t_f \cdot S_{f0k}}}{\tau_{f1k}} \quad (J.33)$$

$$f_{bfk,max} = \sqrt{\frac{E_f \cdot \tau_{f1k} \cdot S_{f0k}}{t_f}} \quad (J.34)$$

$$S_{f0k} = 0,2 \cdot k_{sys,b2} \quad (J.35)$$

$$\tau_{f1k} = 0,37 \cdot k_{sys,b1} \cdot (f_{cm} \cdot f_{ctm,surf})^{0,5} \quad (J.36)$$

$$f_{ctm,surf} = 0,7 \cdot f_{ctm} \quad (J.37)$$

NOTE 1 The value of $k_{sys,b1}$ can be taken as 1,0 unless the more accurate information is available based on production data of EBR CFRP sheets or strips.

NOTE 2 The value of $k_{sys,b2}$ can be taken as 1,0 unless the more accurate information is available based on production data of EBR CFRP sheets or strips.

NOTE 3 The value of $f_{ctm,surf}$ from Formula (J.37) can only be used where it cannot be obtained using EN 1542.

J.11.1.2 EBR CFRP anchorage requirements — flexure

J.11.1.2.1 General

(1) Anchorage of the strengthening system to the concrete surface of a member in flexure shall be provided to avoid the following failure mechanisms:

- End Anchorage as described in J.11.1.2.2;
- Intermediate Crack Debonding as described in J.11.1.2.3;
- End Cover Separation as described in J.11.1.2.4;
- Shear Induced Crack Separation as described in J.11.1.2.5.

J.11.1.2.2 End anchorage

(1) The CFRP strengthening shall be anchored by an anchorage length beyond the section where the design resistance of the unstrengthened existing section is at least as great as the design effects resulting from the relevant limit state.

(2) Externally bonded CFRP reinforcement shall be curtailed according to one of the following conditions:

- where member strengthening is undertaken, the curtailment shall take account of a_l , calculated in accordance with 12.3.3;
- where local strengthening is undertaken, the CFRP strengthening should extend a distance $l_{bf} + h$ beyond the section where it is needed.

(3) The anchorage resistance f_{bFRd} shall be calculated using Formulae (J.28) or (J.32).

J.11.1.2.3 Intermediate crack debonding

(1) Where J.11.1.1.3 is used to determine the anchorage length of adhesively bonded CFRP, the capacity of the anchorage capacity between flexural cracks shall be sufficient to resist the difference in tensile forces in the system between cracks.

(2) Formula (J.38) may be used to determine the capacity of the CFRP strengthening system between adjacent flexural cracks.

(3) Formula (J.38) should not be applied where the strain in the CFRP exceeds 10 mm/m.

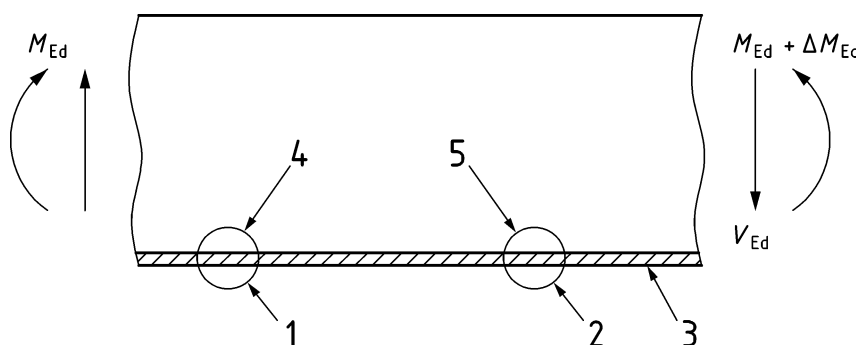
$$\Delta f_{fEd} \leq \Delta f_{fRd} \quad (J.38)$$

where

Δf_{fEd} is calculated according to Formula (J.22);

Δf_{fRd} is the bond resistance between adjacent cracks.

(4) Unless a more accurate analysis is undertaken, Δf_{fRd} and Δf_{fEd} should be calculated using the minimum crack spacing, $s_{cr,min}$, where $s_{cr,min} = 0,75 \cdot s_{cr,max}$ (see Figure J.6).



Key

- 1 $f_{fEd,a}$ in FRP at Crack A
- 2 $f_{fEd,b}$ in FRP at Crack B
- 3 FRP
- 4 Crack A

5 Crack B

Figure J.6 — CFRP Between Flexural Cracks

(5) The bond resistance between adjacent cracks, Δf_{fRd} may be determined using Formula (J.39) by taking account of the beneficial effects of bond friction, $\Delta f_{fk,F}$, and clamping from curvature of the beam, $\Delta f_{fk,C}$, in addition to the adhesive bond resistance between the cracks, $\Delta f_{fk,B}$ as follows:

$$\Delta f_{fRd} = 1/\gamma_{BA} \cdot ((\eta_{cc} \cdot k_{tc} \cdot k_{tt})^{0,5} \cdot \Delta f_{fk,B} + \Delta f_{fk,F} + \Delta f_{fk,C}) \quad (J.39)$$

$$\Delta f_{fk,B} = 0,84 \cdot k_{sys,b1} \cdot \sqrt{f_{cm} \cdot f_{ctm,surf}} \cdot \frac{\sqrt{S_{cr,min}}}{t_f} \quad (J.40)$$

$$\Delta f_{fk,F} = 0,1 \cdot f_{cm}^{0,9} \cdot \frac{S_{cr,min}^{4/3}}{t_f} \quad (J.41)$$

$$\Delta f_{fk,C} = \frac{\kappa_h}{h_f} \cdot \frac{S_{cr,min}^{1/3}}{t_f} \quad (J.42)$$

where

$\kappa_h = 2\,000$ for reinforced concrete members;

$\kappa_h = 0$ for prestressed concrete members;

$h_f = \min\{100\text{ mm}, h\}$.

(6) Unless a more accurate analysis is undertaken, Δf_{fEd} may be calculated by ignoring slip of the CFRP.

J.11.1.2.4 End cover separation

(1) The maximum design shear force (V_{ED}) at the support of the member subjected to strengthening shall be less than the design resistance value against concrete cover separation $V_{Rd,cFE}$ calculated in accordance to Formula (J.43):

$$V_{ED} \leq V_{Rd,cFE} = 0,75 \cdot \left(1 + 19,6 \cdot \frac{(100\rho_l)^{0,15}}{a_{fE}} \right) \cdot \tau_{Rd,c} \cdot b_w \cdot z \quad (J.43)$$

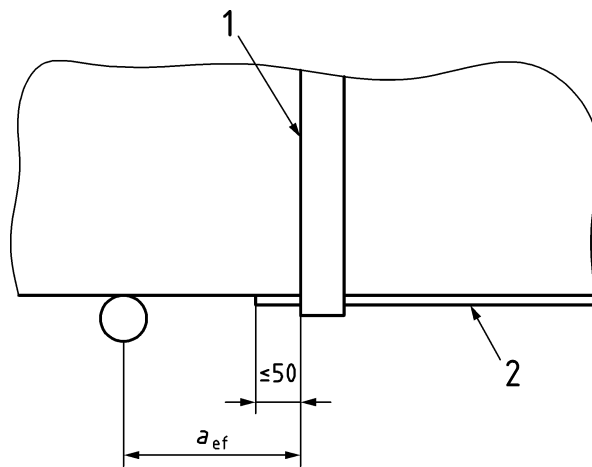
Where the condition in Formula (J.43) is not met, shear strengthening at the end of the longitudinal strengthening shall be provided in accordance with Formula (J.44) with anchorage satisfying the provisions of this Eurocode.

$$f_{fwd} \leq f_{bfRd} \cdot \tan\theta \quad (J.44)$$

where f_{bfRd} is the CFRP anchorage capacity for the flexural strengthening system being designed.

Stirrups for end cover separation shall be detailed as shown in Figure J.7.

In millimetres



Key

- 1 End stirrup
2 Flexural strengthening

Figure J.7 — CFRP shear stirrup arrangement to avoid end cover separation**J.11.1.2.5 Shear Induced Crack Separation**

(1) Where the limits in Formula (J.45) or (J.46) are exceeded for members strengthened with EBR in flexure, additional CFRP stirrups shall be provided.

$$\frac{V_{Ed} \cdot \sigma_{sw}}{\tau_{Rd} \cdot b \cdot d_w} \leq \begin{cases} 75 \text{ MPa} & \text{for ribbed steel bars} \\ 25 \text{ MPa} & \text{for plain round steel bars} \end{cases} \quad (\text{J.45})$$

where τ_{Rd} is calculated according to Formula (8.47).

$$V_{Ed} \leq 0,33 \cdot f_{ck}^{\frac{2}{3}} \cdot b_w \cdot z \quad (\text{J.46})$$

Where stirrups are required in accordance with Formulae (J.45) or (J.46), additional transverse EBR CFRP stirrups should be provided to resist the shear force in Formula (J.47) with adequate anchorage.

$$V_{Ed,f} = \max \left\{ \begin{array}{l} \frac{E_f A_f}{E_f A_f + E_s A_s} \cdot V_{Ed} \\ V_{Ed} - b_w \cdot z \cdot \tau_{Rd,sy} \end{array} \right. \quad (\text{J.47})$$

J.11.1.3 Basic anchorage resistance — CFRP to concrete for NSM CFRP strengthening

(1) The design bond load capacity per strip shall be according to Formula (J.48) or (J.49) for anchorage lengths according to Formula (J.48) or (J.50).

For $l_{bf} \leq 115 \text{ mm}$:

$$F_{bfRd} = 0,95 \cdot b_f \cdot \tau_{bfd} \cdot \sqrt[4]{a_r} \cdot l_{bf} \cdot (0,4 - 0,0015 \cdot l_{bf}) \quad (\text{J.48})$$

For $l_{bf} > 115 \text{ mm}$:

$$F_{bfRd} = 0,95 \cdot b_f \cdot \tau_{bAd} \cdot \sqrt[4]{a_r} \cdot \left(26,2 + 0,065 \cdot \tan h \left(\frac{a_r}{70} \right) \cdot (l_{bf} - 115) \right) \quad (\text{J.49})$$

where

$$a_r = \max\{100 \text{ mm}, a_r\}. \quad (\text{J.50})$$

The maximum design strength of the adhesive according for NSM CFRP systems may be obtained from Formula (J.51):

$$\tau_{bAd} = \frac{1}{\gamma_{BE}} \cdot \min \left\{ \begin{array}{l} \tau_{bAk} \cdot \alpha_{bA} \\ \tau_{bck} \cdot \alpha_{bc} \end{array} \right. \quad (\text{J.51})$$

where the maximum characteristic bond strength of the adhesive may be obtained from Formula (J.52), where the definitions of f_{Ack} and f_{Atk} are given in J.5.1.2.1.

$$\tau_{bAk} = 0,6 \cdot \sqrt{\left(2 \cdot f_{Atk} - 2 \cdot \sqrt{f_{Atk}^2 + f_{Ack} \cdot f_{Atk} + f_{Ack}} \right) \cdot f_{Atk}} \quad (\text{J.52})$$

$$\tau_{\text{bck}} = 4,5 \cdot f_{\text{cm}}^{0,5} \quad (\text{J.53})$$

The value of α_{bA} may be taken as 0,5 unless the more accurate information is available based on production data of EBR CFRP sheets or strips.

The value of α_{bc} may be taken as $(\eta_{\text{cc}} \cdot k_{\text{tc}} \cdot k_{\text{tt}})^{0,5}$ unless the more accurate information is available based on production data of EBR CFRP sheets or strips.

J.12 Detailing of Members and Particular rules – Detailing of CFRP

J.12.1 Flexural strengthening with externally bonded CFRP

(1) The following should be applied to the centre-to-centre spacing (a_f), in mm, of ABR CFRP strips:

$$a_{f,\text{max}} \leq 0,2 \quad \text{times distance between points of zero moments;}$$

$$a_{f,\text{max}} \leq 4 \quad \text{times slab thickness;}$$

$$a_{f,\text{max}} \leq 0,4 \quad \text{times cantilever length.}$$

(2) The distance of the longitudinal edge of the strip from the member edge should be at least equivalent to the nominal concrete cover c_{nom} of the internal reinforcement.

J.12.2 Flexural strengthening with NSM reinforcement bars

(1) Where slots are cut into the cover concrete for bonding of NSM CFRP systems, they should be located such that the cover is not adversely compromised when considering the accuracy of installation equipment along with adequate tolerance for installation.

(2) The geometrical limits for slots and edge distances and spacing [mm], for NSM CFRP bars and strips shall be in accordance with Table (J.2).

Table J.2 — Geometrical limits for slots and edge distances and spacing, in mm.

Geometrical limits	Square NSM CFRP bars	Round NSM CFRP bars	NSM CFRP bars or strips
The slot width b_{slot} [mm]	$t_f + 2 \text{ mm} \leq b_{\text{slot}} \leq t_f + 4 \text{ mm}$	$\phi_s + 2 \text{ mm} \leq b_{\text{slot}} \leq \phi_s + 4 \text{ mm}$	—
The slot depth t_{slot} [mm]	$b_f + 1 \text{ mm} \leq t_{\text{slot}} \leq b_f + 2 \text{ mm}$ $t_f \leq b_f$	$\phi_s + 1 \text{ mm} \leq t_{\text{slot}} \leq \phi_s + 1 \text{ mm}$	—
Distance from slot to edge in accordance with Figure J.8	$a_r \geq 4 \cdot b_f$	$a_r \geq 4 \cdot b_f$	$e_{f,\text{min}} \geq 1,5 \cdot t_{\text{slot}}$
The centre-to-centre spacing of adhesively bonded CFRP reinforcement a_f	—	—	$3 \cdot t_{\text{slot}} \leq a_f \leq \min\{0,2 \cdot l_{\text{ob}}; 4 \cdot h\}$ $l_{\text{ob}} = 2 \cdot l_k$

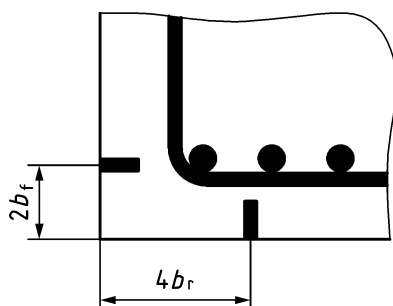


Figure J.8 — Edge distances in arrangement of strips on both sides of an edge

(3) Near curved edges of slabs and beams with ABR CFRP bars, a minimum edge distance of 150 mm in the direction of centre of curvature should be maintained. For all other cases, the radius of curvature of the near surface mounted CFRP strips shall be at least 2 m.

J.12.3 Permissible mandrel diameters for bending of FRP

(1) Straight prefabricated ABR CFRP bars should not be designed to be arranged at a radius that is less than 1 000 times their thickness, unless stresses that arise from the bending process are considered in the design.

J.12.4 Permissible layers of bonded CFRP sheets and strips

(1) CF sheets shall be bonded in no more than five layers for flexural or shear strengthening and a maximum of ten layers for strengthening columns.

(2) CFRP strips shall be bonded in no more than two layers. The maximum thickness of the CFRP strip cross section excluding the adhesive shall not exceed 3 mm.

(3) No more than a single NSM strip or bar shall be bonded into one slot.

Annex JA (informative)

Embedded FRP Reinforcement

JA.1 Use of this annex

(1) This Informative Annex contains supplementary guidance for the design of new structures reinforced with non-prestressed glass and carbon fibre reinforcement. The provisions of this Eurocode apply for concrete members with FRP reinforcement unless modified in this Annex JA.

NOTE: National choice on the application of this Informative Annex is given in a National Annex. If a National Annex contains no information on the application of this Informative Annex, it can be used.

JA.2 Scope and field of application

(1) This Informative Annex applies to profiled or roughened fibre reinforced polymer (FRP) reinforcement bars and mesh.

(2) This Informative Annex does not apply to lightweight aggregate and to recycled aggregate concrete structures, i.e. Annexes M and N do not apply to members with FRP reinforcement.

(3) This Informative Annex applies to members with FRP reinforcement subjected to predominantly static loads, i.e. Clause 10 and Annex E do not apply to members with FRP reinforcement.

JA.3 General

NOTE Unless noted otherwise, in Annex JA all clauses/subclauses numbers and titles are similar as the relevant of the main part of this Eurocode. The prefix 'JA' is added to section/sub-sections numbers to distinguish content that pertain embedded FRP reinforcement. Annex JA contains only sections/subsections of the main part of this Eurocode that include specific clauses for embedded FRP reinforcement.

JA.4 Verification- Partial Factors for FRP reinforcement

(1) The partial factor for material γ_{FRP} shall be used for FRP reinforcement.

NOTE The values of the partial factors for FRP reinforcement are those in Table JA.1 (NDP), unless a National Annex gives different values.

Table JA.1 (NDP) — Partial Factors for FRP Reinforcing

Design Situation	γ_{FRP}
Ultimate Limit States (Persistent and transient design situation)	1,50
Accidental Actions	1,10
Serviceability	1,00

JA.5 Materials - FRP reinforcement

JA.5.1 General

(1) Annex JA provides design rules for member reinforced with embedded FRP reinforcement within the following limits of applicability:

- Minimum long term tensile strength of $f_{\text{ftk},100a} \geq 300$ MPa,
- Minimum modulus of elasticity of $E_{\text{fR}} \geq 40\,000$ MPa,
- Ratio of $f_{\text{ftk},100a}/E_{\text{fR}} \geq 0,005$,
- characteristic compressive strength of concrete $f_{\text{ck}} \geq 20$ MPa,
- members with $\rho_{\text{lf}} \leq 0,05$.

JA.5.2 Properties

(1) Specified properties and related conditions of fibre reinforced polymer systems that are required for design to this Eurocode shall include at least the following:

- $f_{\text{ftk}0}$ determined in accordance with ISO 10406-1,
- E_{fR} determined in accordance with ISO 10406-1,
- diameter and size.

(2) The following properties of the FRP reinforcement should be provided to the FRP reinforcement supplier to ensure a performance as assumed in design:

- section sizes and tolerance on size,
- minimum characteristic short-term tensile strength,
- minimum long-term characteristic tensile strength,
- Youngs modulus,
- long term bond strength $f_{\text{bd},100a}$,
- installation temperature,
- maximum temperature of the FRP reinforcement for the design life of the structure,
- minimum temperature of the FRP reinforcement for the design life of the structure,
- exposure classification, in accordance with Table 6.1,
- durability requirements.

JA.5.3 Design assumptions

(1) Design should be based on the nominal cross section area of the reinforcement.

(2) The stress-strain relationship should be taken as illustrated in Figure JA.1 and Formula (JA.1).

$$f_{\text{ftd}} = \frac{f_{\text{ftk},100a0}}{\gamma_{\text{FRP}}} \quad (\text{JA.1})$$

where

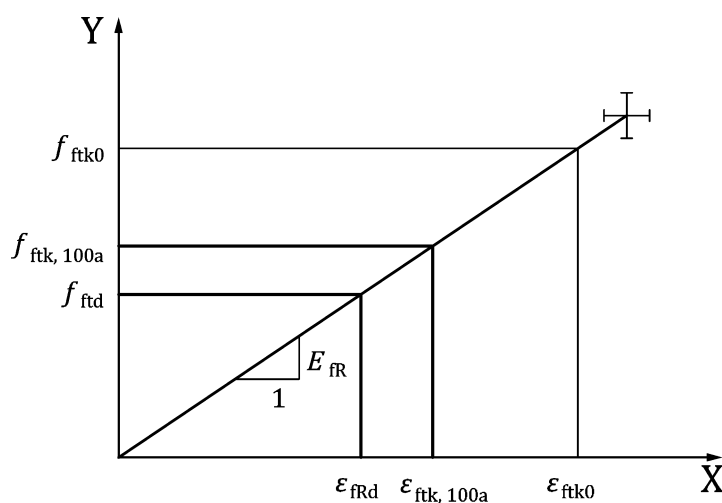
$$f_{\text{ftk},100a} = C_t \cdot C_C \cdot C_e \cdot f_{\text{ftk}0} \quad (\text{JA.2})$$

C_t is the influence factor for temperature. Unless more accurate information is available from production data, or more accurate values are determined in accordance with ISO 10406-1, the following values may be used for C_t :

- $C_t = 1,0$ for indoor and underground environments,
- $C_t = 0,8$ for exterior environments where the FRP reinforcement is subject to large temperature variations;

C_c is the influence factor for service life which may be taken as $C_c = 0,35$ unless more accurate values are determined in accordance with ISO 10406-1;

C_e is the influence factor for environmental attack which may be taken as $C_e = 0,7$ unless more accurate values are determined in accordance with ISO 10406-1.



Key

- x Strain
y Stress

Figure JA.1 — Design stress-strain-diagram for FRP Reinforcement

- (3) FRP reinforcement shall be used as tension reinforcement only.
- (4) The mean density of FRP for the purposes of design may be taken as 2 000 kg/m³.
- (5) The coefficient of thermal expansion $\alpha_{FRP,th}$ in longitudinal direction may be taken as $5 \cdot 10^{-6} \text{ K}^{-1}$ for GFRP bars and 0 for CFRP bars.

JA.6 Durability - Concrete cover - Special rules for FRP reinforcement

- (1) The value of $c_{min,dur}$ for FRP reinforcement in Formula (6.2) may be taken as zero.
- (2) Unless more accurate information is available based on test data, the cover for bond for FRP reinforcement should be taken as $c_{min,b} \geq 2\phi$. But at least the minimum cover for FRP reinforcement shall be taken as $c_{min,b} \geq 1,5\phi$.
- (3) Direct contact of carbon FRP reinforcement bars with steel reinforcement should be avoided.

JA.7 Structural analysis - Special rules for FRP reinforcement

- (1) For straight FRP-bars installed in a curved shape the bending stress shall be taken into account as permanent action.

- (2) Linear elastic analysis with limited redistribution according to 7.3.2 shall not be undertaken for members with FRP reinforcement.
- (3) Plastic analysis according to 7.3.3 shall not be undertaken for members with FRP reinforcement.
- (4) Non-linear analysis according to 7.3.4 may be undertaken using the model outlined in Figure JA.1 with design strength, f_{td} , and corresponding design rupture strain, ε_{fRd} .

JA.8 Ultimate Limit States (ULS) - Special rules for FRP reinforcement

JA.8.1 Bending with or without axial forces

- (1) The tensile strain in FRP reinforcement shall be limited to the design rupture strain, ε_{fRd} .
- (2) Unless more rigorous analysis is undertaken the benefit of the confining effect of FRP reinforcement should be reduced by the ratio E_{fR}/E_s in any direction that confinement is considered.

JA.8.2 Shear

- (1) For members reinforced with FRP reinforcement, the minimum shear resistance in 8.2.1(4) may be calculated as:

$$\tau_{Rdc,min} = \frac{0.29}{\gamma_c} \sqrt{f_{ck} \cdot \frac{E_{fR}}{E_s} \cdot \frac{d_{dg}}{d}} \quad (JA.3)$$

- (2) The provisions in 8.2.2 may be used provided that the ρ_l of longitudinal FRP reinforcement in Formula (8.17) is reduced by the ratio E_{fR}/E_s .
- (3) The provisions outlined in 8.2.3 of this Eurocode may be used subject to the following modifications:

— Formula (8.26) for the inclination of the compression field shall be replaced by:

$$\cot\theta = 0,8 \quad (JA.4)$$

— Formula (8.28) shall be replaced by

$$\tau_{Rd,f} = \tau_{Rd,c} + \rho_w \cdot f_{fWRd} \cdot \cot\theta \leq 0,17 \cdot f_{cd} \quad (JA.5)$$

where

$$f_{fWRd} = \min\{0,004 \cdot E_f; f_{ftd}^*\} \quad (JA.6)$$

where f_{ftd}^* is calculated in accordance with JA.11.4.3.

- (4) The provision outlined in 8.2.5 may be used subject to the following alterations:

- f_{yd} is replaced by f_{td} ,
- $\cot\theta$ is taken as 1,0,
- ν is taken as 0,35.

- (5) For members reinforced with FRP reinforcement, the shear resistance at an interface may be calculated as:

$$\tau_{Rdi} = c_{v1} \cdot f_{ctd} + \mu_v \cdot \sigma_n \leq 0,5 \cdot \nu \cdot f_{cd} \quad (JA.7)$$

where ν may be taken as 0,35.

JA.8.3 Torsion

(1) The provisions of 8.3.4 may be used for members with FRP reinforcement subject to the following alterations:

- f_{yd} is replaced by f_{ftd} , where f_{ftd} should be limited by $f_{ftd} \leq 0,004 \cdot E_f$,
- $\cot\theta$ is taken as 1,0,
- ν is taken as 0,35,
- ρ_i is factored by the ratio E_F/E_S .

JA.8.4 Punching

(1) The provisions in 8.4.3 may be used provided that ρ_l of longitudinal FRP reinforcement in Formula (8.78) is reduced by the ratio E_{FR}/E_S .

(2) The provisions in 8.4.4 shall not be applied to concrete members with FRP reinforcement.

JA.8.5 Design with strut-and-tie models and stress fields

(1) Design with strut and tie models and stress fields for concrete structure reinforced with FRP reinforcement are not covered by this Eurocode.

JA.9 Serviceability Limit States (SLS) - Special rules for FRP reinforcement

JA.9.1 Crack control

(1) Table 9.2(NDP) in 9.2.1(6) does not apply for members reinforced only with FRP reinforcement. A crack limit of $w_{lim,cal} = 0,4$ mm should be used in such members.

(2) The provisions relevant to steel reinforcement in 9.2.2(6), 9.2.3(3), 9.2.4(8) may be applied to concrete with FRP reinforcement where the value of E_s is replaced by E_{FR} , and A_s is replaced by $A_f \cdot (E_{FR}/E_s)$ in all relevant formulae in these clauses.

JA.9.2 Deflection control

(1) Table 9.3 in 9.3.2(1) should not be used for structures with FRP reinforcement.

(2) The provisions relevant to steel reinforcement in 9.3.3(3), 9.3.4(8) may be applied to concrete with FRP reinforcement where the value of E_s is replaced by E_{FR} in all relevant formulae in these clauses.

JA.10 Fatigue

(1) This Eurocode does not provide rules for fatigue utilising FRP reinforcement.

JA.11 Detailing of FRP reinforcement

JA.11.1 Spacing of bars

(1) Where the clear distance between FRP reinforcement bars $c_s < 7,5 \cdot \phi$, concrete cover spalling shall be prevented by limiting the design strain to $\varepsilon_{FRd} \leq 0,0035$ in straight bars.

JA.11.2 Permissible mandrel diameters for bent bars

(1) The minimum diameter to which a bar may be bent shall be such as to avoid:

- damaging the reinforcement (see (2)) and
- failure of the concrete inside the bend of the bar (crushing, splitting or spalling of reinforcement cover), see (3) and (4).

(2) The mandrel diameter of FRP reinforcement is given by the supplier. Bending on site is not permitted.

The mandrel diameter should be at least:

- $\phi_{\text{mand,min}} = 4\phi$ for $\phi \leq 16$ mm
- $\phi_{\text{mand,min}} = 7\phi$ for $\phi > 16$ mm

(3) Provided that $f_{\text{ftd}} \leq 25f_{\text{cd}}$ and $\gamma_c \leq 1,5$, verification of the concrete inside the bend may be omitted for :

- stirrups in compliance with 12.3.3(4),
- standard hook and bend anchorages complying with Figure 11.6 at a clear distance
- $c_x \geq 1,5\phi$ from an edge parallel to the bent and a clear distance between bars $c_s \geq 3\phi$ according to Figure 11.6c and
- all bends with an angle $\alpha_{\text{bend}} \leq 45^\circ$ at a clear distance $c_x \geq 2,5\phi$ from an edge parallel to the bent, a clear distance between bars $c_s \geq 5\phi$ and a length $\geq 2\phi$ of the straight segments between multiple bends.

(4) In cases not complying with (3) the stress in the FRP bar σ_{ftd} should be verified to avoid concrete failures inside the bend according to Formula (JA.8):

$$\sigma_f \leq 25 \cdot f_{\text{cd}} \quad (\text{JA.8})$$

JA.11.3 Anchorage of FRP reinforcement in tension and compression

(1) Provisions for anchorage in 11.4 may be applied to determining the anchorage lengths of FRP reinforcement only where additions and modifications in Annex JA are used in the determination of relevant parameters.

(2) Only the methods of anchorage according to Figure 11.2a), b) and c) in 11.4.1(6) may be used for FRP reinforcement.

(3) Formula (JA.9) may be applied to determine the anchorage length of FRP reinforcement:

$$l_{\text{bd}} = k_{\text{lb}} \cdot k_{\text{cp}} \cdot \phi \cdot \left(\frac{\sigma_{\text{ftd}}}{217} \right)^{\eta_\sigma} \cdot \left(\frac{25}{f_{\text{ck}^*}} \right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20} \right)^{\frac{1}{3}} \cdot \left(\frac{1,5 \cdot \phi}{c_d} \right)^{\frac{1}{2}} \geq 10\phi \quad (\text{JA.9})$$

Where

$$f_{\text{ck}^*} = \left(\frac{f_{\text{bd},100\text{a}}}{0,315} \right)^{1,5} \leq 1,1 \cdot f_{\text{ck}} \quad (\text{JA.10})$$

l_{bd} shall be limited also to

$$l_{\text{bd}} \geq (\phi/4) \cdot (\sigma_{\text{ftd}}/f_{\text{bd},100\text{a}}) \quad (\text{JA.11})$$

NOTE The value of $f_{\text{bd},100\text{a}}$ may be taken as 1,5 MPa unless the more accurate information is available based on production data.

(4) The reduction according to Formula (JA.12) in design tensile strength should be considered at a bend bar or if anchoring of FRP reinforcement with bends or hooks according to 11.4.4:

$$f_{\text{ftd}}^* = \left(0,3 + 0,05 \cdot \frac{r_f}{d_f} \right) \cdot f_{\text{ftd}} \leq f_{\text{ftd}} \quad (\text{JA.12})$$

Provisions of Formula (JA.12) shall only be applied where:

- the bend radius is within the range $3 \cdot d_f \leq r_f \leq 4 \cdot d_f$ and
- the bar diameter $d_f \leq 25\text{mm}$.

(5) Following clauses should not be used for FRP reinforcement: 11.4.4, 11.4.5, 11.4.6, 11.4.7.

(6) Provisions for laps in 11.5 should only be used for FRP reinforcement within the provisions stated in Annex JA.

(7) Laps of FRP reinforcement to FRP reinforcement or other reinforcement types shall be situated in zones where the stress in the reinforcement at ultimate limit state is less than 80 % of the design strength and the strain of the FRP reinforcement is less than 0,006.

(8) Table 11.3 should only be applied to members with FRP reinforcement within the provisions stated in Annex JA.

JA.12 Additional rules for precast concrete elements and structures

(1) Unless information is available from production data, Clause 13 for steel reinforcement is not applicable to FRP reinforcement.

JA.13 Lightly reinforced concrete structures

(1) This Eurocode does not provide rules for lightly reinforced concrete structures utilising FRP reinforcement.