Technical Guidelines for Structural Use of Ultra-High Performance Concrete

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FOREWORD

The Civil Engineering and Development Department (CEDD) is committed to embracing innovation and technology to build a smart and liveable city. In recent years, Ultra-High Performance Concrete (UHPC) has emerged globally as a revolutionary cementitious composite known for its exceptional compressive and tensile strengths, unparalleled toughness, enhanced ductility, and extraordinary durability. Ranging from major infrastructure in Chinese Mainland, Europe, and North America to iconic landmarks in Japan and Malaysia, UHPC has proven its transformative value through diverse field applications and advancements in material science.

In a steadfast commitment to expedite the use of UHPC for Hong Kong’s infrastructure development, CEDD set up a Joint Task Force with the Highways Department (HyD) in January 2025 with an aim of propelling UHPC adoption by implementing pilot projects in the Northern Metropolis. Complementing this initiative, CEDD collaborated with the Building Technology Research Institute (BTRi) to author the Technical Guidelines and Particular Specifications for Structural Use of UHPC. These documents present the necessary design principles, construction methodologies, material specifications, and quality assurance protocols required for the application of UHPC in civil engineering work.

Capitalizing on Hong Kong's strategic role as an international hub for infrastructure development, CEDD fosters a collaborative platform for experts across Chinese Mainland, Hong Kong, and the international engineering community to contribute in the alignment of China national standards with local requirements and prevailing global practice. I earnestly invite practitioners and stakeholders to share valuable insights and refinements by leveraging valuable experience gained and technological advancements adopted in your projects for establishment and continuous refinement of the design standard for broader application of UHPC in Hong Kong, the Greater Bay Area and beyond.

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LIST OF SYMBOLS

A_c	Cross-sectional area of UHPC
$A_{c,eff}$	Effective tension area of UHPC
A_k	Area enclosed by the centre line of wall elements including the inner hollow areas
A_p	Total areas of prestressing tendons located in $A_{c,eff}$
A_s	Total areas of reinforcing steel located in $A_{c,eff}$
A_{sl}	Cross-sectional area of the longitudinal torsion reinforcement
A_{sw}	Cross-sectional area of shear reinforcement
D_{Sup}	Nominal upper dimension of the largest aggregate
E_{cm}	Mean value of modulus of elasticity
E_s	Design value of modulus of elasticity of reinforcing steel
F_{bt}	Design tensile force in a bar or bundled bars at the start of the bend
K	Factor accounting the effect of fibre orientation to UHPC post-cracking behaviour under tension
K'_{global}	Global factor for considering the fibre orientation effects to the transverse direction of the reinforcement
K_{global}	Global factor for considering the fibre orientation effects
K_{local}	Local factor for considering the fibre orientation effects
L_c	Characteristic length
L_f	Length of the longest fibres
N_{Ed}	Design value of the applied axial force (tension or compression)
RH	Relative humidity of environment
T_{Ed}	Design value of the applied torsional moment
$T_{Rd,max}$	Limit resisting torsional moment
V_{Ed}	Design value of the applied shear force
$V_{Ed,i}$	Force acting parallel to wall member i, resulting from shear forces
V_{Rd}	Superposition of the three resistance terms $V_{Rd,c} + V_{Rd,s} + V_{Rd,f}$
$V_{Rd,c}$	Shear resistance provided by UHPC without considering the fibres inside
$V_{Rd,f}$	Shear resistance provided by fibres inside UHPC
$V_{Rd,max}$	Limit force for the compressive strength of the concrete compression struts in the truss diagram
$V_{Rd,s}$	Shear resistance provided by transverse reinforcement
$V_{Rd,total}$	Total shear resistance
b_w	Width of the web on T, I or L beams or smallest width of the cross-section in tensile area
c	Concrete cover
c_{min}	Minimum concrete cover
d	Effective depth of cross-section
e_d	Design eccentricity
e_h	Clear horizontal distance between reinforcement bar
e_o	Assumed minimum eccentricity
e_v	Clear vertical distance between reinforcement bar
f_{bd}	Design value of ultimate bond stress
f_{bpd}	Ultimate bond stress for anchorage
$f_{ck,cube}$	Characteristic cube strength of concrete
f_{cbd}	Constant bond stress
f_{cd}	Design compressive strength of UHPC
f_{ck}	Characteristic value of UHPC compressive strength
f_{cm}	Mean value of UHPC compressive strength
$f_{ctd,el}$	Design tensile limit of elasticity of UHPC at ULS
f_{ctfd}	Design post-cracking tensile strength of UHPC

f_{ctfk}	Characteristic value of post-cracking tensile strength of UHPC
f_{ctfm}	Mean value of post-cracking tensile strength of UHPC
$f_{ctk,el}$	Characteristic value of tensile limit of elasticity of UHPC
$f_{ctm,el}$	Mean value of tensile limit of elasticity of UHPC
$f_{p0.1k}$	characteristic 0.1% proof-stress of prestressing steel
f_{yd}	Design yield strength of reinforcement
f_{ywd}	Design yield strength of shear reinforcement
h	Height of a cross-section
$h_{c,eff}$	Effective height of UHPC around tensioned reinforcement
h_o	Equivalent radius of the cross-section
k_t	Factor dependent on the duration of the load or its repetition
l_{bd}	Design anchorage length
$l_{bd,min}$	Minimum anchorage length
$l_{b,rqd}$	Basic required anchorage length
l_o	Concrete coating term
$l_{o,d}$	Design lap length
$l_{o,min}$	Minimum lap length
l_t	Transmission length term
l_{tol}	Allowance for the increased in anchorage length
s	Spacing of links
$s_{r,max,f}$	Maximum spacing between cracks
t	Concrete age
t_{eff}	Effective wall thickness
$t_{eff,i}$	Effective wall thickness of wall member i
t_o	Age of UHPC at loading
t_s	Age of UHPC at the beginning of drying
u_k	Perimeter of the area A_k
w_{max}	Limiting calculated crack width
w_s	Crack width at the most tensioned reinforcement
$w_{t,a}$ / $w_{t,b}$	Crack width at the most tensioned fibre
z	Lever arm for shear stress calculation
z_i	Length of the wall member i
α	Inclination of the reinforcement on the longitudinal axis
α_{cc}	Coefficient which takes account of long-term effects on compressive strength and adverse effects resulting from the way the load is applied.
γ_c	Partial factor for UHPC under compression
γ_{cf}	Partial factor for UHPC under tension
γ_E	Safety factor taken such that $\gamma_{cf} \times \gamma_E$ is equal to 1.5
γ_p	Partial factor for prestressing steel
γ_s	Partial factor for reinforcing steel
δ	Fibre contribution factor for UHPC cover performance and reinforcement bond
ε_{c0d}	Design strain corresponding to compressive elastic limit of UHPC
ε_{ca}	Autogenous shrinkage strain
ε_{cd}	Drying shrinkage strain
$\varepsilon_{cm,f}$	Mean strain in UHPC between cracks
ε_{cud}	Ultimate compressive strain of UHPC
ε_{lim}	Tensile strain limit of UHPC
$\varepsilon_{sm,f}$	Mean strain in the reinforcement under the relevant combination of loads
ε_u	Strain of reinforcement or prestressing steel at maximum load
$\varepsilon_{u,lim}$	Ultimate tensile strain of UHPC
ε_{ud}	Design strain of reinforcing steel and prestressing steel at maximum load
ε_{uk}	Characteristic strain of reinforcement or pre-stressing steel at maximum load
η	Factor accounting the effect of different bond behaviour of prestressing and reinforcing steel in calculating f_{cbd}

η_s	Factor accounting bond behaviour of prestressing and reinforcing steel in calculating l_t
θ	Angle between the principle diagonal compressive stresses (struts) and the longitudinal axis of the member
ξ	Ratio of bond strength of prestressing and reinforcing steel
σ_{cp}	Compressive stress in UHPC from axial load or prestressing
$\sigma_{Rd,f}$	Mean value of the post-cracking strength along the shear crack at an angle θ
σ_s	Stress in the tension reinforcement closest to the tensioned concrete surface assuming crack section
σ_{sd}	Design stress of the bar at the position from where the anchorage is measured from
τ_{max}	Maximum shear stress
τ_t	Torsional shear stress in wall elements
φ_b	Basic creep coefficient
φ_d	Drying creep coefficient
ϕ_m	Mandrel diameter
ϕ_p	Nominal diameter of prestressing tendons
ϕ_s	Nominal diameter of reinforcing steel

ABBREVIATIONS

BS	British Standard
BTRi	Building Technology Research Institute
CEDD	Civil Engineering and Development Department
CS1	Construction Standard CS1 – Testing Concrete (CS1:1990 version)
CS2	Construction Standard – Steel Reinforcing Bars for the Reinforcement of Concrete (CS2:2012 version)
GS	General Specification of Civil Engineering Works
NA	National Annex
PD	Published Document
PS	Particular Specification for Structural Use of Ultra-High Performance Concrete
HKSDMHR	Structures Design Manual for Highways and Railways (2013 Edition)
SLS	Serviceability Limit State
TG	Technical Guidelines for Structural Use of Ultra-High Performance Concrete
UHPC	Ultra-High Performance Concrete
UK	United Kingdom
ULS	Ultimate Limit State

1 GENERAL

1.1 Scope

(1) This "Technical Guidelines for Structural Use of Ultra-High Performance Concrete" (TG) provides guidance and requirements for the design and construction of civil engineering structures using unreinforced Ultra-High Performance Concrete (UHPC), reinforced UHPC, prestressed UHPC, or their combination. For applications such as road pavements, water-retaining structures, tunnels and structural works with fire engineering considerations, additional design and construction requirements beyond the scope of this TG should be considered where necessary. The TG shall be used in conjunction with the following codes and standards.

BS EN 1992 Eurocode 2: Design of Concrete Structures

NF P18-710 National addition to Eurocode 2 - Design of concrete structures: specific rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC)

DG/TJ 08-2401-2022 Technical standard for application of ultra-high performance concrete in bridges

Structures Design Manual for Highways and Railway (2013 Edition) (HKSDMHR)

(2) This TG complies with the general principles and local requirements for structural safety and serviceability in Hong Kong. The relevant references considered in this TG are listed in Appendix A.

(3) This TG only deals with the requirements for strength, reliability, serviceability, durability of relevant UHPC structures.

(4) In case of conflict, the provisions contained in this TG shall prevail over the codes and standards mentioned in Section 1.1 (1).

(5) The structural design requirements for relevant reinforced and prestressed UHPC structures are specified in this TG. Designers shall be obligated to ensure that provisions given in this TG are applicable to their designs. For any other design aspects not covered by this TG, design criteria and standards to be adopted shall be agreed with the appropriate authority.

(6) UHPC structures designed in accordance with this TG shall be constructed in compliance with the "Particular Specification for Structural Use of Ultra-High Performance Concrete" (PS), jointly published by the Civil Engineering and Development Department (CEDD) and the Building Technology Research Institute (BTRi).

1.2 Reference

(1) Unless otherwise stated, references in this TG and other similar design standards and manuals shall be to that edition of the document stated in **Appendix A**. For dated references, subsequent amendments to or revisions of any of these documents shall not apply. For undated references, the latest editions of the documents referred to apply (including amendments).

(2) In the absence of test results of UHPC material properties, the *Designer* may consider adopting the indicative design values presented in **Appendix B** to carry out scheme design or preliminary design.

(3) Three worked examples (i.e., design of unreinforced UHPC slab, reinforced UHPC beam and prestressed UHPC beam) are provided in **Appendix C** as a guidance for using this TG.

(4) A sample framework of quality assurance (QA) / quality control (QC) plan is provided in **Appendix D** for a reference purpose

1.3 Definition

1.3.1 UHPC

In this TG, UHPC is defined as a steel-fibre-reinforced, cement-based composite, characterized by a minimum compressive cube strength of 120 MPa, a minimum direct tensile strength of 5 MPa, and superior ductility, durability and toughness.

1.3.2 Project Office

Project Office is the relevant government department in Hong Kong SAR government in charge of the project.

1.3.3 Designer

Designer is a team of professionals, the company or the organization being responsible for the design.

1.3.4 Checking Engineer

Checking Engineer is the professional, the team of professionals, the company or the organization separate from the *Designer* and being responsible for the independent check of the design.

1.3.5 Project Manager

Project Manager is the person named in the Contract Data Part One who is appointed to administer the contract. The *Project Manager* has authority to issue instructions, notifications, and communications required under the contract, and is responsible for managing the contract procedures, including acceptance of programmes, assessment of compensation events, and other key decisions.

1.4 Design Working Life

Unless otherwise stated, the design working life of UHPC structures shall follow relevant prevailing codes and standards.

1.5 Design Checking

1.5.1 General

Unless otherwise stated, the requirements of design checking for normal strength concrete structures as stated in the Section 2.4 of HKSDMHR shall be followed for design checking of UHPC structures.

1.5.2 Classification of UHPC Structures

For design checking purpose, all UHPC structures shall be classified as Structure Categories II or III, as refer to Table 2.2 of HKSDMHR. The *Designer* shall determine and agree with the Project Office the proposed Category for UHPC structures being designed having regard to the cost, complexity, safety, durability and consequences of failure.

1.6 Design Checking Actions and Combination of actions

(1) Unless otherwise stated, the requirements for action and their combination effects on the using UHPC structures are the same as those mentioned in relevant prevailing code and standards, including dead load, superimposed dead load, wind actions, temperature effects, accidental actions, traffic actions, seismic action and its combination.

(2) In addition to the limit states, design situations and combinations of actions given in BS EN 1990, the following two combinations of actions which are specifically defined for Hong Kong conditions shall also be considered:

(a) Crack width verification in accordance with the provisions on effects of actions and combinations of actions set out in Section 3.2.2 of the HKSDMHR for UHPC members; and

(b) Tensile stress verification for prestressed UHPC members, as defined in Section 3.2.3 of HKSDMHR, including:
(i) Case 1: No tensile stress permitted; and
(ii) Case 2: Tensile stress permitted.

2 MATERIALS

2.1 General

(1) The requirements for materials, products, execution and workmanship given in the PS shall be complied with.

(2) For any other requirements not stated in the PS, the "General Specification of Civil Engineering Works" (GS) of the Government of the Hong Kong Special Administrative Region shall be complied with. Where considered necessary for a particular project, the *Designer* shall make reference to any applicable standards related to structural use of UHPC in proposing addition or alternative specification of UHPC, and seek agreement with relevant authority.

2.2 Material Properties of UHPC

2.2.1 Strength

(1) UHPC shall be designated by compressive strength classes in accordance with **Table 2.1**. The compressive strength grade of UHPC shall be determined based on the standard compressive strength of cubic specimens with a side length of 100mm. The standard values of UHPC cubic compressive strength shall not be less than 120MPa, as shown in **Table 2.1**.

Table 2.1 – Compressive strength grade for UHPC

Compressive Strength Class	**C120**	**C130**	**C140**	**C150**	**C160**	**C170**	**C180**	**C190**	**C200**
f_{ck}[(1)] (MPa)	120	130	140	150	160	170	180	190	200

(1) f_{ck} has the same definition of $f_{ck,cube}$ in HKSDMHR

(2) The direct tensile strength of UHPC, not less than 5 MPa, shall be specified by the *Designer* and justified by test results. Requirements for the direct tensile strength testing shall be referred to the PS.

(3) The concrete strength grades to be used shall be limited to a minimum grade of Grade C120 for the design of UHPC structures. Unlike normal strength concrete, UHPC of any strength grade is not subject to a prescribed maximum limit on shear strength.

(4) Similar to normal strength concrete for prestressing work, strict control shall be exercised with adequate provisions in the contract to ensure the reliability and consistency of the UHPC.

(5) The strength gain after 28 days of UHPC shall not be considered in the design.

2.2.2 Elastic Deformation

(1) The elastic modulus of UHPC under compression (E_{cm}) shall be obtained by testing according to the requirements in the PS. If test result is not available at the time of design, the elastic modulus shall be taken as 45 GPa, which is the minimum requirements of elastic modulus of UHPC as specified in the PS.

(2) The elastic modulus of UHPC under tension shall be taken the same as that for compression.

(3) Poisson's ratio of UHPC shall be taken as 0.2.

(4) The linear coefficient of thermal expansion of UHPC can be taken as 11×10^{-6} per °C.

2.2.3 Curing Method

(1) In this TG, UHPC structures may be cured with or without steam curing.

(2) If steam curing is adopted, the mean 28-day compressive strength shall not be less than the mean 28-day compressive strength of the same UHPC produced and kept at 20 °C ± 2 °C without any steam curing process.

2.2.4 Tensile Behaviour in UHPC

Given the critical nature of civil engineering structures, this TG specifies UHPC must exhibits tensile strain hardening. Specifically, the mean post-cracking tensile strength (f_{ctfm}) shall be at least 1.25 times the mean tensile limit of elasticity ($f_{ctm,el}$).

2.2.5 Thickness of Structural Member

The scope of this TG is limited to thick structural members; thin-walled elements are excluded. A UHPC member is defined as thick when its minimum thickness is at least three times the length of the longest steel fibres (L_f).

2.2.6 Orientation Factors

(1) Since fibres distribution in actual structural members may differ from the idealized, isotropic distribution found in standard moulded specimens, a so-called global factor K_{global} or and a local factor K_{local} are introduced to quantify the impact of fibre distribution on the material properties of UHPC.

(2) K_{global} is the ratio of the mean flexural strength of a set of moulded specimens to that of a set of sawn specimens from structures. It may be taken as 1.25 in the absence of test results.

(3) K_{local} is the ratio of the mean flexural strength of a set of moulded specimens to the minimum flexural strength of a set of sawn specimens from structures. It may be taken as 1.75 in the absence of test results.

2.2.7 Shrinkage

(1) In the absence of test data, the following indicative values of shrinkage of UHPC shall be used:

(a) For UHPC without steam curing, a total shrinkage of 700×10^{-6} shall be used. Of this total, autogenous shrinkage (ε_{ca}) shall be taken as 550×10^{-6} and drying shrinkage(ε_{cd}) as 150×10^{-6}.

(b) For UHPC with steam curing, a total shrinkage of 550×10^{-6} shall be used, representing the final shrinkage value upon completion of steam curing.

(2) In the absence of test data, the time-evolution of shrinkage of UHPC without steam curing shall be assessed by autogenous and drying shrinkage separately.

(a) For UHPC without steam curing, the autogenous shrinkage (ε_{ca}) at the age of UHPC (t) is determined by Eq. 2.1.

$$\varepsilon_{ca}(t) = \begin{cases} 0 & \dfrac{f_{cm}(t)}{f_{ck}} < 0.1 \\ \beta_{ca}\left[1 - e^{-\frac{t}{T_{ca}}}\right] 10^{-6} & \dfrac{f_{cm}(t)}{f_{ck}} \geq 0.1 \end{cases} \quad \text{(Eq. 2.1)}$$

where

ε_{ca} = Autogenous shrinkage strain
f_{cm} = Mean compressive cube strength
f_{ck} = Characteristic compressive cube strength
β_{ca} = 300×10^{-6} to 600×10^{-6}
t = Concrete age (days)
T_{ca} = Autogenous shrinkage time constant, taken as 100 days

(b) The drying shrinkage (ε_{cd}) at the concrete age (t) for UHPC without steam curing is determined by Eq. 2.2.

$$\varepsilon_{cd}(t) = \begin{cases} \dfrac{5\,[80\,\% - RH]\,(t - t_s) \times 10^{-6}}{(t - t_s) + \beta_{cd}\, h_0^2} & RH \leq 80\% \\ 0 & RH > 80\% \end{cases} \quad \text{(Eq. 2.2)}$$

where

ε_{cd} = Drying shrinkage strain
RH = Relative humidity of environment
t_s = Concrete age at the beginning of drying (days)
β_{cd} = 0.003 to 0.01 days/mm^2
h_o = Equivalent radius of the cross-section (mm)

(3) The time-dependent evolution of shrinkage is not addressed for steam-cured UHPC because the thermal treatment effectively accelerates and completes the primary shrinkage mechanisms (autogenous and drying) before the element is put into service.

2.2.8 Creep

(1) In the absence of test data, the following indicative values of creep of UHPC shall be used:

(a) For UHPC without steam curing, a creep factor of 0.8, or 1.0 if loads are applied at early age.

(b) For UHPC with steam curing, a creep factor of 0.2 for loads applied after steam curing.

(2) In the absence of test data, the time-evolution of creep of UHPC shall be assessed based on two components, namely, basic creep (φ_b) and drying creep (φ_d).

(a) The basic creep (φ_b) at the age of UHPC (t) is determined by the following equations:

$$\varphi_b(t, t_0) = \begin{cases} \beta_{bc1}\varphi_{b0}\dfrac{\sqrt{t - t_0}}{\sqrt{t - t_0} + \beta_{bc}} & \text{UHPC without Steam Curing} \\ \beta_{bc3}\dfrac{\sqrt{t - t_0}}{\sqrt{t - t_0} + 10} & \text{UHPC with Steam Curing} \end{cases} \qquad \text{(Eq. 2.3)}$$

$$\varphi_{b0} = \frac{3.6}{f_{cm}(t_0)^{0.37}} \qquad \text{(Eq. 2.4)}$$

$$\beta_{bc} = \beta_{bc2}e^{2.8\frac{f_{cm}(t_0)}{f_{ck}}} \qquad \text{(Eq. 2.5)}$$

where

φ_b	=	Basic creep coefficient
t_o	=	Age of UHPC at the time of loading (days)
β_{bc1}	=	1.5 to 2.5
β_{bc2}	=	0.7
β_{bc3}	=	0.2 to 0.5

(b) For UHPC with or without steam curing, the drying creep (φ_d) at the specific day (t) can be determined by Eq. 2.6 in the condition that the environmental relative humidities (RH) are less than or equal to 80 %.

$$\varphi_d(t, t_0) = \varphi_{do}[\varepsilon_{cd}(t) - \varepsilon_{cd}(t_0)] \qquad \text{(Eq. 2.6)}$$

where

φ_d	=	Drying creep coefficient
φ_{do}	=	20

2.2.9 Design Stress-Strain Curve of UHPC in Compression

(1) The stress-strain curve of UHPC in compression to be used for designing at Ultimate Limit State (ULS) is illustrated in **Figure 2.1**:

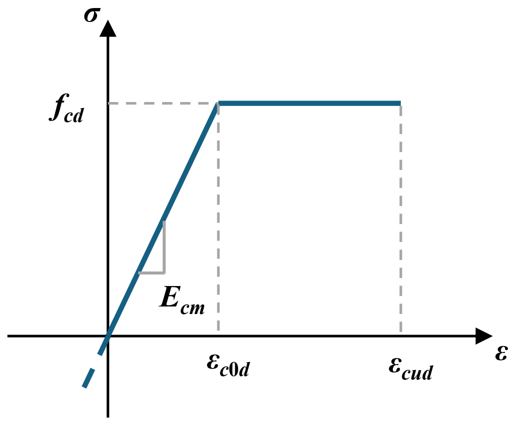


Figure 2.1 – Design stress-strain curve of UHPC in compression at ULS

(2) The design compressive strength of UHPC shall be determined by:

$$f_{cd} = 0.67 f_{ck} \;/\; \gamma_c \qquad \text{(Eq. 2.7)}$$

where

f_{cd} = Design value of compressive strength

γ_c = Partial factor for UHPC under compression (See **Table 2.4)**

(3) The compressive strain corresponds to the start of assumed perfect plasticity plateau (ε_{c0d}) is defined by the following expression:

$$\varepsilon_{c0d} = f_{cd} \;/\; E_{cm} \qquad \text{(Eq. 2.8)}$$

where

ε_{c0d} = Design strain corresponding to compressive elastic limit of UHPC

E_{cm} = Mean static modulus of elasticity

(4) The ultimate compressive strain (ε_{cud}) is defined by the following expression:

$$\varepsilon_{cud} = \left(1 + 14 \frac{f_{ctfm}}{K_{global}\, f_{cm}}\right) \times \varepsilon_{c0d} \qquad \text{(Eq. 2.9)}$$

where

ε_{cud}	=	Ultimate compressive strain
f_{ctfm}	=	Mean post-cracking tensile strength
K_{global}	=	Global factor, taken as 1.25

2.2.10 Design Stress-Strain Curve of UHPC in Tension

(1) The design stress-strain curve of UHPC in tension at ULS is illustrated in **Figure 2.2**:

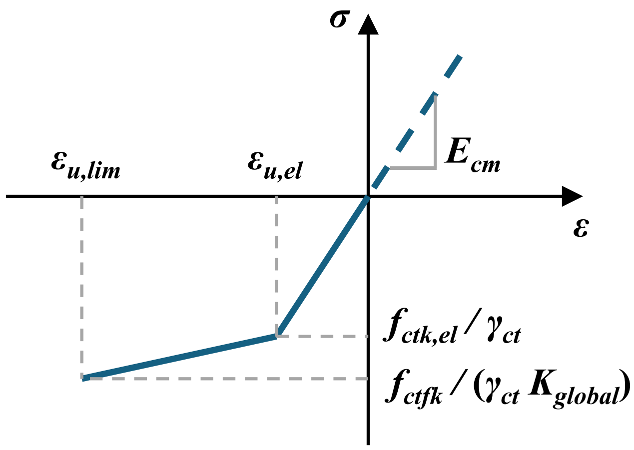


Figure 2.2 Design stress-strain curve of UHPC in tension at ULS

(2) The design tensile limit of elasticity of UHPC at ULS shall be determined by:

$$f_{ctd,el} = \frac{f_{ctk,el}}{\gamma_{cf}} \qquad \text{(Eq. 2.10)}$$

where

$f_{ctd,el}$	=	Design tensile limit of elasticity of UHPC at ULS
$f_{ctk,el}$	=	Characteristic value of the tensile limit of elasticity
γ_{cf}	=	Partial factor for UHPC under tension (See **Table 2.4)**

(3) The design post-cracking tensile strength of UHPC at ULS shall be determined by:

$$f_{ctfd} = \frac{f_{ctfk}}{\gamma_{cf} K_{global}} \qquad \text{(Eq. 2.11)}$$

where

f_{ctfd}	=	Design post-cracking tensile strength
f_{ctfk}	=	Characteristic value of the post-cracking tensile strength
K_{global}	=	Global factor

(4) The tensile strain at design tensile limit of elasticity at ULS shall be determined by:

$$\varepsilon_{u.el} = f_{ctd.el} \,/\, E_{cm} \qquad \text{(Eq. 2.12)}$$

(5) The ultimate tensile strain of UHPC at ULS shall be determined by:

$$\varepsilon_{u.lim} = \frac{L_f}{4\, L_c} \qquad \text{(Eq. 2.13)}$$

where

$\varepsilon_{u,lim}$	=	Ultimate tensile strain
L_f	=	Length of the longest fibres contributing to ensuring non-brittleness
L_c	=	$2/3 \times h$
h	=	Height of the cross-section

2.3 Reinforcing Steel

(1) If reinforcement is added in UHPC structures, reinforcing steel shall comply with the standards specified in the GS and Construction Standard CS2. References in the Eurocodes to reinforcing steel Class B and Class C shall be replaced by grade 500B and grade 500C of CS2:2012 respectively.

(2) As similar to the reinforced normal strength concrete, welding to the hot rolled high yield steel bars shall not be used.

(3) The requirements and provisions given in Clause 3.2 of BS EN 1991, Clause 3.2.4(101)P of BS EN 1992-2 and the associated clauses in the UK NAs and PD 6687-2 that are in conflict with (1) and (2) above shall not be followed.

2.4 Durability

2.4.1 Concrete Cover to Reinforcement

The provisions related to the minimum cover (c_{min}) for reinforced UHPC and prestressed UHPC structures as shown in **Table 2.2** and **Table 2.3** respectively shall be adopted, with the following key points to be noted:

(a) The nominal value of cover for design shall be used in the calculations and stated on the design drawings.

(b) The exposure conditions for reinforced UHPC and prestressed UHPC structures shall follow Table 5.2 of HKSDMHR for the envisaged condition of exposure.

(c) The provision in Clause 4.4.1.3(3) of BS EN 1992-1-1 on reduction of allowance in design for deviation C_{dev} is not applicable. The C_{dev} refer to the allowance in reduction of concrete cover to reinforcement during design development.

Table 2.2 –Minimum concrete cover (c_{min}) for reinforced UHPC structures

Environmental Requirements for c_{min} (mm)							
Design Life	Exposure Class according to Table 5.2 of HKSDMHR						
	X0	XC1	XC2/XC3	XC4	SD1/XS1	SD2/XS2	XD3/XS3
50 Years	-	10	15	15	20	20	25
120 Years		20	25	25	25	30	30

Table 2.3 – Minimum concrete cover (c_{min}) for Prestressed UHPC structures

Environmental Requirements for c_{min} (mm)							
Design Life	Exposure Class according to Table 5.2 of HKSDMHR						
	X0	XC1	XC2/XC3	XC4	SD1/XS1	SD2/XS2	XD3/XS3
50 Years	-	15	20	20	20	25	25
120 Years		25	25	30	30	35	35

2.5 Prestressing

2.5.1 General

(1) Prestressing steel and devices shall comply with the standards specified in the Section 17 of GS.

(2) For design, stress-strain curve with a horizontal branch as given Clause 3.3.6(7) of BS EN 1992-1-1 shall be assumed. The assumption of an inclined top branch shall only be used with prestressing steels complying with prEN 10138.

2.5.2 Post-tensioning Systems

For post-tensioning system of UHPC structures, the specific requirements as stated in Section 5.6.2 of HKSDMHR are applicable.

2.5.3 External Prestressing

For external prestressing for UHPC structures, the specific requirements as stated in Section 5.6.3 of HKSDMHR are applicable.

2.5.4 Specialist Prestressing Contractors

(1) All prestressed UHPC works shall be carried out by specialist contractors in the Prestressed Concrete Works for Highway Structure Category of the List of Approved Suppliers of Materials and Specialist Contractors for Public Works.

(2) The Prestressed Concrete Works for Highway Structures Category consists of two classes:

Class I – Supply and Installation of Prestressing Systems; and

Class II – Supply of Prestressed Concrete Units.

(3) The supply and installation of on-site prestressing work shall be carried out by a contractor in Class I. Precast prestressed units manufactured off-site shall be supplied by a contractor in Class II.

2.5.5 Compressive Strength Limitation for Prestressing Design

(1) The yield strength f_{yk} (or the 0.2% proof stress, $f_{0.2k}$) and the tensile strength f_{tk} are defined respectively as the characteristic value of the yield load, and the characteristic maximum load in direct axial tension, each divided by the nominal sectional area.

(2) In addition to those indicated in the preceding sections, some additional modifications to HKSDMHR shall be followed.

(a) Limiting value of the angles θ between the UHPC compression strut and the beam axis perpendicular to the shear force for the shear truss model shall be 30°.

(b) Limiting value of the angle of strut inclination θ in torsion design shall be 30°.

2.5.6 Anchorage Zones of Post-tensioned UHPC Members

Tensile forces due to concentrated forces should be assessed by a strut and tie model, or other appropriate representation. Reinforcement should be detailed assuming that it acts at its design strength. If the stress in this reinforcement is limited to 250 MPa no check of crack widths is necessary.

2.6 Partial Factors for Materials

For unreinforced UHPC structures, reinforced UHPC structures and prestressed UHPC structures, the partial factors for materials at the ULS shall be taken in the **Table 2.4**:

Table 2.4 Partial factors for materials at ULS

Design Situations	γ_c (Compressed UHPC)	γ_{cf} (Tensioned UHPC)	γ_s (Reinforcing steel)	γ_p (Prestressing steel)
Persistent & Transient	1.5	1.3	1.15	1.15
Accidental	1.2	1.05	1.0	1.0

3 DESIGN OF UHPC STRUCTURES

3.1 Ultimate Limit State (ULS)

3.1.1 Bending with / without Axial Force

(1) This section applies to general design of beams, slabs and similar types of members for which sections remain approximately plane before and after loading.

(2) When determining the ultimate moment resistance of reinforced or prestressed UHPC cross-sections, the following assumptions are made:

(a) plane sections remain plane.

(b) for a given deformation state, the compressive stress and tensile stress of UHPC shall be determined in accordance with Sections 2.2.9 to 2.2.10.

(c) the strain in bonded reinforcement or bonded prestressing tendons, whether in tension or in compression, is the same as that in the surrounding UHPC.

(d) the stresses in the reinforcing or prestressing steel are derived from the design curves in Clauses 3.2.7 and 3.3.6 in BS EN 1992-1-1.

(e) the initial strain in prestressing tendons is taken into account when assessing the stresses in the tendons.

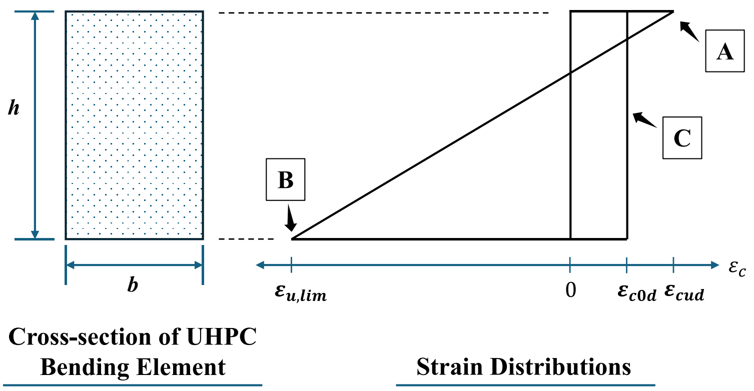
(3) The strains in the reinforcing steel and the prestressing steel shall be limited to ε_{ud} (where applicable), see Clauses 3.2.7(2) and 3.3.6(7) of BS EN 1992-1-1 respectively.

(4) For cross-sections loaded by the compression force (excluding the prestressing force), it is necessary to assume the minimum eccentricity, $e_o = h / 30$ but not less than 20 mm, where h is the depth of the section.

(5) In parts of cross-sections which are subjected to approximately concentric loading ($e_d / h \leq 0.1$, e_d is the design eccentricity), such as compression flanges of box girders, the mean compressive strain in that part of the section shall be limited to ε_{c0d}.

(6) The resisting forces of the sections are calculated from a linear deformation diagram included in a domain defined by the limiting deformations known as pivots defined below.

(a) In the case of unreinforced UHPC structures, the pivot strain limits are illustrated in **Figure 3.1**.



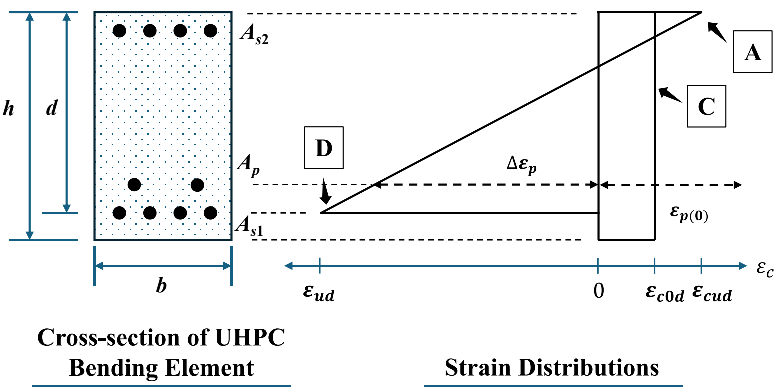
i. Pivot A relates to the state where the compressive strain of UHPC at the extreme compression fibre reaches its ultimate limit, i.e., ε_{cud}.

ii. Pivot B relates to the state where the tensile strain of UHPC at the extreme tensile fibre reaching its ultimate limit, i.e., $\varepsilon_{u,lim}$.

iii. Pivot C relates to the state where the cross-section is under pure axial compression and the compressive strain level reaches its elastic limit, i.e., ε_{c0d}.

Figure 3.1 – Possible strain distributions of unreinforced UHPC in ULS

(b) In the case of reinforced and/or prestressed UHPC structures, the pivot limits are illustrated in **Figure 3.2**.



i. Pivot A relates to the state where the compressive strain of UHPC at the extreme compression fibre reaches its ultimate limit, i.e., ε_{cud}.

ii. Pivot C relates to the state where the cross-section is under pure axial compression and the compressive strain level reaches its elastic limit, i.e., ε_{c0d}

iii. Pivot D relates to the state where the outer reinforcement reaches its ultimate limit, i.e., ε_{ud}, if applicable, in accordance with Clause 3.2.7 of BS EN 1992-1-1

Figure 3.2 – Possible strain distributions of reinforced and/or prestressed UHPC in ULS

3.1.2 Shear

3.1.2.1 General

(1) For checking of design for UHPC structures, the design shear force, V_{Ed} must be less than the total shear resistance $V_{Rd,total}$. The total shear resistance $V_{Rd,total}$ is equal to the smallest of V_{Rd} and $V_{Rd,max}$.

$$V_{Ed} < V_{Rd.total} \quad \text{(Eq. 3.1)}$$

$$V_{Rd,total} < Min\ (V_{Rd}\ , V_{Rd,max}) \quad \text{(Eq. 3.2)}$$

where

V_{Ed}	=	Design value of the applied shear force
$V_{Rd,total}$	=	Total shear resistance
V_{Rd}	=	Superposition of the three resistance components $V_{Rd,c} + V_{Rd,s} + V_{Rd,f}$
$V_{Rd,max}$	=	Limit force for the compressive strength of the concrete compression struts in the truss diagram
$V_{Rd,c}$	=	Shear resistance provided by UHPC without considering the fibres inside
$V_{Rd,s}$	=	Shear resistance provided by transverse reinforcement
$V_{Rd,f}$	=	Shear resistance provided by fibres inside UHPC

(2) The following clauses describe the shear checking based on the members loaded on their upper surface. If the loads are applied from below, vertical suspension reinforcement must be provided in addition.

(3) The tensioned longitudinal reinforcement should be able to resist the additional tensile force generated by the shear force.

(4) In the case of members mainly subject to uniformly distributed loads, there is no need to carry out a shear force verification at a distance to the reference surface of the support less than h for unreinforced UHPC members or d for reinforced or prestressed UHPC members but design checking should be made that the shear force acting on the support does not exceed the value $V_{Rd,max}$.

3.1.2.2 UHPC resistance component $V_{Rd,c}$

(1) For a reinforced section, the design shear resistance $V_{Rd,c}$ provided by the UHPC members is given by the following equations:

$$V_{Rd,c} = \frac{0.21}{\gamma_{cf}\gamma_E} k \sqrt{f_{ck}}\, b_w\, d \qquad \text{(Eq. 3.3)}$$

$$k = 1 + 3\frac{\sigma_{cp}}{f_{ck}} \qquad \text{(Eq. 3.4)}$$

$$\sigma_{cp} = N_{Ed} \,/\, A_c \qquad \text{(Eq. 3.5)}$$

where

b_w	=	Minimum width of the cross-section in tensile area. If the cross-section is circular, b_w shall be taken as 0.55 of the diameter, ϕ;
d	=	Distance between the most compressed fibre and the longitudinal reinforcement;
γ_E	=	γ_E is a safety factor taken such that $\gamma_{cf} \times \gamma_E$ is equal to 1.5;
σ_{cp}	=	Axial compressive stress (0 to 0.4f_{ck} under Eq. 3.4)
N_{Ed}	=	Design value of the applied axial force
A_c	=	Cross-sectional area of UHPC

(2) For a reinforced or an unreinforced prestressed section, $V_{Rd,c}$ is given by:

$$V_{Rd,c} = \frac{0.24}{\gamma_{cf}\gamma_E} k \sqrt{f_{ck}}\, b_w\, z \qquad \text{(Eq. 3.6)}$$

where

z	=	Lever arm for shear stress calculation = 0.9 d and d = 7/8 × h for unreinforced case

(3) For a non-prestressed and an unreinforced section, $V_{Rd,c}$ is given by:

$$V_{Rd,c} = \frac{0.18}{\gamma_{cf}\gamma_E} k \sqrt{f_{ck}}\, b_w\, h \qquad \text{(Eq. 3.7)}$$

3.1.2.3 Reinforcement resistance component $V_{Rd,s}$

(1) The resistance to the shearing force from the vertical reinforcement is determined by:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta \qquad \text{(Eq. 3.8)}$$

where

A_{sw}	=	Cross-sectional area of shear reinforcement
s	=	Spacing of shear reinforcement
f_{ywd}	=	Design yield strength of shear reinforcement
θ	=	The inclination of the main compression stress on the longitudinal axis

(2) In the case where the member includes inclined reinforcement, the term for the resistance to the shearing force provided by the reinforcement is:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} (\cot\theta + \cot\alpha) \sin\alpha \qquad \text{(Eq. 3.9)}$$

where

α	=	The inclination of the reinforcement on the longitudinal axis

(3) In circular sections reinforced with hoops or circular frames, $V_{Rd,s}$ should be reduced by 30% to take account of the fact that the reinforcement does not work directly in the direction of the tie parallel to the shear force, unlike with frames.

3.1.2.4 Fibre Contribution Term $V_{Rd,f}$

(1) The design resisting shear force $V_{Rd,f}$ contributed by the fibres is determined by:

$$V_{Rd,f} = A_{fv}\sigma_{Rd,f} \cot\theta \quad \text{(Eq. 3.10)}$$

where

A_{fv}	=	$b_w z$ for rectangular sections or T sections $0.58 \times \phi$ for a circular section of diameter, ϕ

(2) For UHPC exhibiting strain hardening, $\sigma_{Rd,f}$ is determined by:

$$\sigma_{Rd,f} = \frac{1}{K\,\gamma_{cf}} \times \frac{1}{\varepsilon^* - \varepsilon_{el}} \times \int_{\varepsilon_{el}}^{\varepsilon^*} \sigma_f(\varepsilon)\,d\varepsilon \quad \text{(Eq. 3.11)}$$

where

$\sigma_{Rd,f}$	=	Mean post-cracking tensile strength across the shear crack
K	=	K_{global} for members with a dimension larger than 5 L_f; K_{local} for members with a dimension smaller than 5 L_f
$\sigma_f(\varepsilon)$	=	Design stress-strain curve of UHPC
ε^*	=	Max (ε_u , $\varepsilon_{u,lim}$)
ε_{el}	=	Elastic tensile strain
ε_u	=	Maximum tensile strain of UHPC in the ULS calculation of bending with axial force

3.1.2.5 *Term $V_{Rd,max}$*

(1) For UHPC members without shear reinforcement, the resistance limit of the compression struts is:

$$V_{Rd,max} = 2.3\frac{\alpha_{cc}}{\gamma_c}b_w z f_{ck}^{2/3} tan\theta \quad \text{(Eq. 3.12)}$$

where

α_{cc} = Coefficient which takes account of long-term effects on compressive strength and adverse effects resulting from the way the load is applied, taken as 0.85

(2) For UHPC members with shear reinforcement inclined at α, the resistance limit of the compression struts is:

$$V_{Rd,max} = 2.3\frac{\alpha_{cc}}{\gamma_c}b_w z f_{ck}^{2/3}\left[\frac{V_{Rds}\times(cot\ \theta + cot\ \alpha)}{(1 + cot^2\ \theta)} + V_{Rdf} tan\ \theta\right]\left[\frac{1}{V_{Rds} + V_{Rdf}}\right] \quad \text{(Eq. 3.13)}$$

3.1.2.6 *Other considerations*

Regarding the checking for complementary tensile force due to the shear force, concentrated loads near supports, shear between web and flanges and shear at the interface between concrete cast at different times, the requirements given in Clauses 6.2.1.6, 6.2.1.7, 6.2.4 and 6.2.5 of NF P18-710 shall be followed.

3.1.3 Torsion

3.1.3.1 General

(1) Where the static equilibrium and stability of a structure depend on the torsional resistance of its elements, a full torsional design at the ULS shall be performed.

(2) In statically indeterminate structures where torsion arises solely from compatibility of deformations, and the stability of the structure does not rely on torsional resistance, it is generally unnecessary to verify torsion at the ULS. However, the non-brittleness condition given in Clause 9.1(3) of NF P18-710 shall be fulfilled to prevent brittle failure.

(3) When calculating the torsional resistance, solid sections may be modelled as equivalent thin-walled sections with an effective wall thickness (t_{eff}), in which equilibrium is satisfied by a closed shear flow. For hollow sections, the effective wall thickness (t_{eff}) shall not exceed the actual thickness.

(4) Cross-sections with complex shapes (e.g., T sections) may be divided into a series of sub-sections, each one of which is modelled as an equivalent thin-walled section. The total torsional resistance is the sum of the resistances of the sub-sections.

(5) The distribution of the acting torsional moments over the sub-sections may be in proportion to their uncracked torsional stiffness.

(6) Each sub-section shall be verified by superimposing the shear stresses caused by torsion with those caused by vertical shear forces. To carry out superimposition of hollow and convex solid sections, the wall may need to be broken down into a number of members. A distinction must also be made between compressed and tensioned sections at ULS for bending with axial force.

3.1.3.2 Design procedure

(1) The shear stress in a wall element *i* of a section subject to a torsional moment T_{Ed} shall be calculated from:

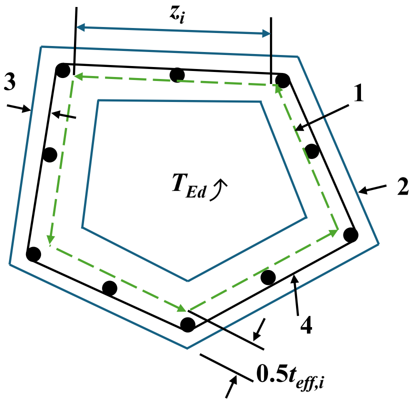
$$\tau_{t,i} t_{eff,i} = T_{Ed}/(2A_k) \quad \text{(Eq. 3.14)}$$

where

$\tau_{t,i}$	=	Torsional shear stress in wall element *i*
$t_{eff,i}$	=	Effective wall thickness of wall element *i*, may be taken as one-sixth of the diameter of the largest inscribed circle within the outer contour of the section
A_k	=	Area enclosed by the centre-lines of the connecting wall elements, including inner hollow areas

(2) The shear force $V_{Ed,i}$ in a wall element duo to torsion is given by:

$$V_{Ed,i} = \tau_{t,i} t_{eff,i} z_i \qquad \text{(Eq. 3.15)}$$



1 – Centre line
2 – Outer edge of effective cross-section
3 – Concrete cover
4 – Torsional web reinforcement A_{sw}

Figure 3.3 – Notations and definitions used in Section 3.1.3

(3) The effects of torsion and shear for both hollow and solid members may be superimposed, assuming the same value for the strut inclination θ.

(4) The cross-sectional area of the transverse reinforcement A_{sw}, required to supplement the torsional resistance of the fibres to torsional resistant moment only, shall be calculated by

$$t_{eff}\sigma_{Rd,f} + \frac{A_{sw}f_{yd}}{s} = \frac{T_{Ed}}{2A_k cot\theta} \qquad \text{(Eq. 3.16)}$$

where

f_{yd} = Design yield strength of the reinforcement

$\sigma_{Rd,f}$ = See Eq. 3.11

(5) Each wall element i of length z_i shall be verified for combined shear and torsion forces. Eq. 3.17 shall be applied to check each wall element:

$$V_{Rd,c} + V_{Rd,f} + V_{Rd,s} \geq V_{Ed,i} + \frac{T_{Ed}}{2A_k} z_i \qquad \text{(Eq. 3.17)}$$

(6) The cross-sectional area of the longitudinal reinforcement for torsion ΣA_{sl} shall be calculated by:

$$\frac{A_k\sigma_{Rd,f} + \sum A_{sd}f_{yd}}{u_k} = \frac{T_{Ed}}{2A_k} cot\theta \qquad \text{(Eq. 3.18)}$$

where

A_{sl} = Cross-sectional area of the longitudinal torsion reinforcement

u_k = Perimeter of the area A_k

(7) The maximum resistance of a member subjected to torsion and shear is limited by the capacity of the concrete struts. In order not to exceed this resistance, the following condition shall be satisfied:

:

$$\frac{T_{Ed}}{T_{Rd,max}} + \frac{V_{Ed}}{V_{Rd,max}} \leq 1 \qquad \text{(Eq. 3.19)}$$

(8) The design torsional resistance moment ($T_{Rd,max}$) is given by:

$$T_{Rd,max} = 2.3\frac{\alpha_{cc}}{\gamma_c} \times 2A_k t_{eff,i} f_{ck}^{2/3} tan\theta \qquad \text{(Eq. 3.20)}$$

3.1.4 Punching

For unreinforced, reinforced or prestressed UHPC structures, the reference contour located at a distance h / 2 from the loaded area, the mean shear stress τ in the UHPC must be less than the limit τ_{max}:

$$\tau_{max} = \frac{0.8}{\gamma_{cf}} Min\left(\frac{f_{ctfk}}{K_{local}}; f_{ctk,el}\right) \qquad \text{(Eq. 3.21)}$$

3.1.5 Design with Strut and Tie Models

3.1.5.1 General

Where a non-linear strain distribution exists (e.g. supports, near concentrated loads or planar stress) strut -and-tie models shall be used. The strut and tie method can be used if it is demonstrated that the forces path in the strut and tie model relates to forces path in an elastic analysis.

3.1.5.2 Struts

The maximum stress in a compressed strut is set to $0.8 f_{ck} / \gamma_c$ where the strut is subject to a positive or null transverse stress and to $2.3\ \alpha_{cc}\ (0.8 f_{ck})^{2/3} / \gamma_c$ when the strut is subject to a negative transverse stress (tensile) for consistency with the term $V_{Rd,max}$ using in verifying shear.

3.1.5.3 Ties

Ties shall be comprised of reinforcing steel, but may also be implemented through the friction force contributed by the fibres. In the latter case, the force on the tie is $A_t \times \sigma_{Rd,f}$ where A_t is the area of the tie considered.

3.1.5.4 Nodes

When the node is subject to compression only, the maximum stress is taken as $0.8 f_{ck} / \gamma_c$. When the node is subject to compression and traction, the maximum stress is set to $2.3\ \alpha_{cc}\ (0.8 f_{ck})^{2/3} / \gamma_c$.

3.2 Serviceability Limit State (SLS)

3.2.1 Crack Control

3.2.1.1 General

(1) Reinforced UHPC structures or structural elements shall be designed so that the calculated crack width under the Crack Width Verification Combination specified in Section 1.6 does not exceed the limiting calculated crack width w_{max} given in **Table 3.1**.

(2) At permanent stage, prestressed UHPC structures shall be designed so that:

(a) Decompression in the tension face of UHPC structures does not occur under the Tensile Stress Verification Combination for Prestressed Concrete Members Case 1 as specified in Clause 1.6(2); and

(b) Design tensile stresses in the tension face of UHPC structures under the Tensile Stress Verification Combination for Prestressed UHPC Members Case 2 as specified in Clause 1.6(2), do not exceed 3.5 N/mm^2 for pre-tensioned members and 2.8 N/mm^2 for post-tensioned members.

(3) At execution stage, prestressed UHPC structures shall be designed so that:

(a) Tensile stress in UHPC structures under the quasi-permanent combination of actions during execution should be limited to $f_{ctm,el}(t)$ where $f_{ctm,el}(t)$ is the mean value of the tensile limit of elasticity of the UHPC at the time t when it is subjected to the prestressing force.

(b) Compressive stress in UHPC structures resulting from the prestressing force and other loads acting at the time of tensioning or release of prestress should be limited to 0.6 $f_{ck}(t)$ where $f_{ck}(t)$ is the characteristic compressive strength of the UHPC at the time t when it is subjected to the prestressing force.

(4) Crack width due to early thermal movement in UHPC structures is deemed to be negligible.

3.2.1.2 *Crack Width Requirements*

The limiting calculated crack width w_{max} (mm) is shown in **Table 3.1** below.

Table 3.1 Limiting calculated crack width w_{max} (mm)

Exposure Class#	Members in Reinforced UHPC and Prestressed UHPC	Members in Unreinforced UHPC
X0	0.30	Crack is not allowed
XC1, XC2 XC3, XC4	0.25	
XD1, XD2 XD3	0.25	
XS1	0.25	
XS2	0.15	
XS3	0.15 (0.10)*	

The exposure classes follow the definition given in HKSDMHR
* The crack width of 0.10 mm applies to the cases exposed to abrasive action by sea water.

3.2.1.3 *Early Thermal Movement*

Unlike normal strength concrete, UHPC members do not require a minimum quantity of steel reinforcement to control cracking in early thermal movement.

3.2.1.4 *Minimum Reinforcement Areas*

UHPC members do not require a minimum quantity of steel reinforcement to control cracking. This is assumed to be provided by the checks in Clause 3.2.4(101)P of BS EN 1992-2 and the sufficiently ductile character under tension of the UHPC covered by this TG.

3.2.1.5 *Calculation of Crack Widths*

(1) For unreinforced UHPC structures, the following inequality shall be satisfied:

$$w_{t,a} = \left[\varepsilon_{t,a} - \frac{f_{ctm,el}}{K_{global} E_{cm}}\right] L_c \leq w_{max} \qquad \text{(Eq. 3.22)}$$

where

w_{max}	=	Limiting calculated crack width
$w_{t,a}$	=	Crack width calculated at the most tensioned fibre
$\varepsilon_{t,a}$	=	Maximum strain value in tension size
$f_{ctm,el}$	=	Mean tensile limit of elasticity

(2) For reinforced or prestressed UHPC structures, the crack width at the most tensioned fibre can be calculated by the Eq. 3.22 and the following inequality shall be satisfied:

$$w_{t,b} = w_s(h - x - x')/(d - x - x') \leq w_{max} \qquad \text{(Eq. 3.23)}$$

where

$w_{t,b}$	=	Crack width calculated at the most tensioned fibre
w_s	=	Crack width at the most tensioned reinforcement
d	=	Effective depth of a cross-section
x	=	Depth of the neutral axis
x'	=	Uncracked tensioned height (stress between 0 and $f_{ctm,el}$)

The crack width at the most tensioned reinforcement w_s shall be determined by:

$$w_s = s_{r,max,f} \times (\varepsilon_{sm,f} - \varepsilon_{cm,f}) \qquad \text{(Eq. 3.24)}$$

where

$s_{r,max,f}$	=	Maximum spacing between cracks
$\varepsilon_{sm,f}$	=	Mean strain in the reinforcement under the relevant combination of loads
$\varepsilon_{cm,f}$	=	Mean strain in UHPC between cracks

($\varepsilon_{sm,f} - \varepsilon_{cm,f}$) is calculated by:

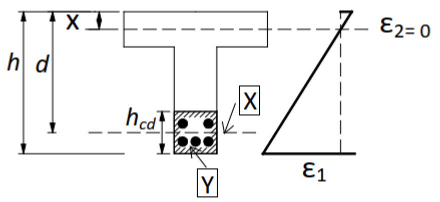
$$\varepsilon_{sm,f} - \varepsilon_{cm,f} = \frac{\sigma_s}{E_s} - \frac{f_{ctfm}}{K_{global}E_{cm}} - \frac{1}{E_s} \times \left[k_t\left(f_{ctm,el} - \frac{f_{ctfm}}{K_{global}}\right)\left(\frac{1}{\rho_{eff}} + \frac{E_s}{E_{cm}}\right)\right] \quad \text{(Eq. 3.25)}$$

where

σ_s	=	Stress in the tension reinforcement closest to the tensioned concrete surface assuming crack section. For member with bonded tendons, σ_s may be replaced by $\Delta\sigma_p$, i.e., the stress variation in prestressing tendons from the state of zero strain of the concrete at the same level, up to characteristic 0.1% proof-stress of prestressing steel $f_{p0.1k}$
E_s	=	Design value of modulus of elasticity of reinforcing steel
k_t	=	0.6 in the case of a short duration load 0.4 in the case of a long duration load applied while the concrete is still new, or in the case of repeated high amplitude loads.
ρ_{eff}	=	A_s / $A_{c,eff}$ for reinforcing steel A_p / $A_{c,eff}$ for prestressing tendons
A_s	=	Total areas of reinforcing steel located in $A_{c,eff}$
A_p	=	Total areas of prestressing tendons located in $A_{c,eff}$
$A_{c,eff}$	=	Effective tension area of UHPC with a height of $h_{c,eff}$ surrounding the reinforcement or prestressing tendons (See **Figure 3.4**)

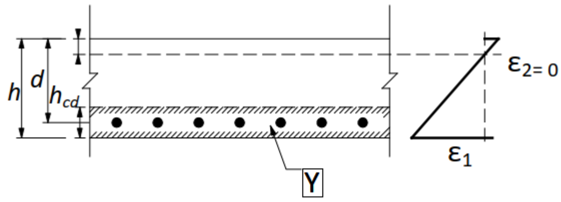
The height of the effective tension area around reinforcement $h_{c,eff}$ shall be calculated as follows:

$$h_{c,eff} = \text{Min}(2.5(h - d); h/2) \quad \text{(Eq. 3.26)}$$



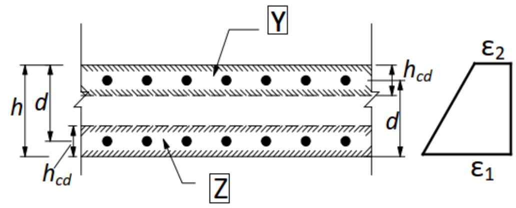
a) **Beam**

X: Level of steel centroid; Y: Effective tension area of UHPC, $A_{c,eff}$



b) **Slab**

Y: Effective tension area of UHPC, $A_{c,eff}$



c) **Member in tension**

Y: Effective tension area of UHPC for upper surface, $A_{c,eff}$; Z: Effective tension area of UHPC for lower surface

Figure 3.4 – Effective tension area (typical cases)

(3) The maximum spacing between cracks shall be calculated using the following equations, which adds a concrete coating term l_o and a transmission length l_t, in the case where all reinforcement has the same diameter and same bonding:

$$s_{r,max,f} = 2.55(l_o + l_t) \qquad \text{(Eq. 3.27)}$$

$$l_o = 1.33\,\frac{c}{\delta} \qquad \text{(Eq. 3.28)}$$

$$l_t = 2\left[0.3k_2\left(1 - \frac{f_{ctfm}}{K_{global} f_{ctm,el}}\right)\frac{1}{\delta\,\eta_s}\right]\frac{\phi}{\rho_{eff}} \geq \frac{L_f}{2} \qquad \text{(Eq. 3.29)}$$

$$\delta = 1 + 0.4 \times \left(\frac{f_{ctfm}}{K'_{global} f_{ctm,el}}\right) \leq 1.5 \qquad \text{(Eq. 3.30)}$$

where

l_o	=	Concrete coating term
l_t	=	Transmission length term
c	=	Concrete cover
δ	=	Fibre contribution factor for UHPC cover performance and reinforcement bond
K'_{global}	=	Corresponds to the transverse direction of the reinforcement, taken as 1.25.
k_2	=	1 for pure tension; 0.5 for bending with or without axial force with a partially compressed section; $(\varepsilon_1 + \varepsilon_2) / (2 \times \varepsilon_1)$ for bending with axial force with the section fully tensioned, ε_1 and ε_2 being respectively the longest and shortest elongation of the end fibres in the section
η_s	=	2.25 for steel reinforcements; 2.25ξ for prestressing tendons
ξ	=	Ratio of bond strength of prestressing and reinforcing steel. The values given in Table 3.2 may be used in the absence of test data.

Table 3.2 Ratio of bond strength between tendons and reinforcing steel

Prestressing steel	Ratio of bond strength ξ	
	Pre-tensioned	Bonded, post-tensioned
Smooth bars and wires	0.35	0.11
Strands	0.6	0.18
Indented wires	0.7	0.22
Ribbed bars	0.8	0.24

4 DETAILING OF REINFORCEMENT

4.1 General

(1) This TG applies for reinforcing steel bars with a diameter between 8mm and 32mm. For steel bar of other size, reference should made to other applicable design standards, codes of practice, guidelines and literatures.

(2) The detailing of reinforcement for normal strength concrete could be applied to UHPC except the following provisions as stated in this TG.

4.2 Spacing of Reinforcing Bars

The clear horizontal distance (e_h) and clear vertical distance (e_v) between individual parallel bars or horizontal layers of parallel bars must satisfy the following equations:

$$e_h \geq \text{Max}\left[\phi_s, \left(D_{sup} + 5\right), 1.5L_f, 20\right] \quad \text{(Eq. 4.1)}$$

$$e_v \geq \text{Max}\left[\phi_s, (D_{sup} + 5); 1.5L_f; 20\right] \quad \text{(Eq. 4.2)}$$

where

e_h	=	Clear horizontal distance between reinforcement bars (mm)
e_v	=	Clear vertical distance between reinforcement bars (mm)
ϕ_s	=	Nominal diameter of reinforcement bars
D_{sup}	=	Nominal upper dimension of the largest aggregate

4.3 Permissible Mandrel Diameter for Bent Bars

Similar to normal strength concrete, the mandrel diameter for bent bar shall be controlled to avoid bending cracks in the bar and to avoid failure of UHPC inside the bend of the bar. However, the mandrel diameter for bent bar need not be checked to avoid failure of UHPC inside the bend if the following conditions are met:

(a) The anchorage of the reinforcement bar does not exceed Max($5\phi_s / \delta$, $2.5\phi_s$).

(b) The bar is not positioned in the surface (plane of bend close to concrete face) and there is a cross reinforcement bar of diameter greater than or equal to Max(ϕ_s / δ , 2.5 ϕ_s) inside the bend.

(c) The mandrel diameter is at least equal to $4\phi_s$ for diameter of reinforcement bar equal and smaller than 16mm and $7\phi_s$ for diameter of reinforcement bar greater than 16mm.

Otherwise, the mandrel diameter (ϕ_m) should be increased in accordance with the Eq. 4.3:

$$\phi_m = F_{bt} \frac{\frac{1}{a_b} + \frac{a}{2\phi}}{2.7\, \delta f_{ck}^{2/3}} \qquad \text{(Eq. 4.3)}$$

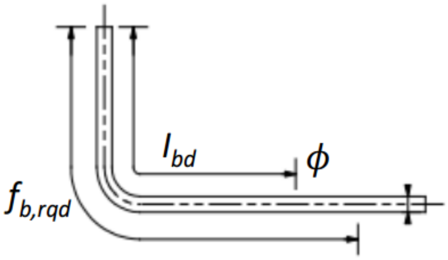
where

ϕ_m	=	Mandrel diameter
F_{bt}	=	Design tensile force in a bar or bundled bars at the start of the bend
a	=	Clear distance between bars
a_b	=	For a given bar (or groups of bars in contact), is half of the centre-to-centre distance bars (or groups of bars) perpendicular to the plane of the bend. For a bar or group of bars adjacent to the face of the member, a_b should be taken as the cover plus $\phi_s/2$
δ	=	Defined in Eq. 3.30

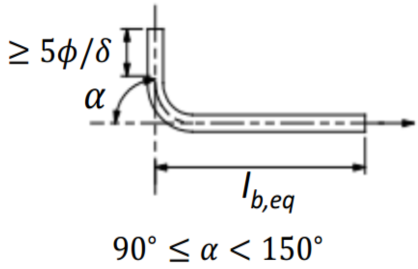
4.4 Anchorage of Longitudinal Reinforcement

(1) Reinforcing bars shall be so anchored that the bond forces are safely transmitted to the concrete avoiding longitudinal cracking or spalling. Transverse reinforcement shall be provided, if necessary.

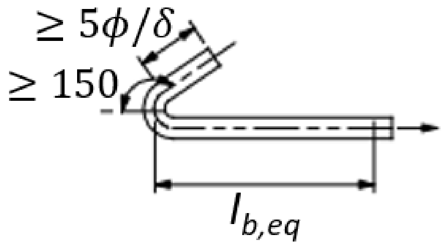
(2) Method of anchorage are shown in **Figure 4.1**:



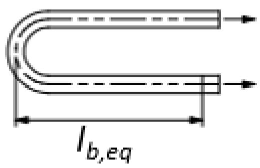
(a) Basic tension anchorage length, $l_{b,rqd,}$ for any shape measured along the centreline



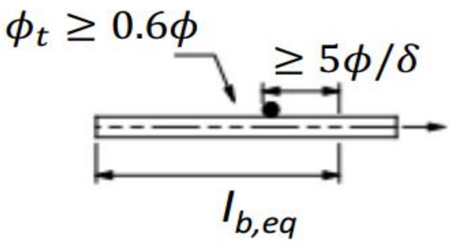
(b) Equivalent anchorage length for standard bend



(c) Equivalent anchorage length for standard hook



(d) Equivalent anchorage length for standard loop



(e) Equivalent anchorage length for welded transverse bar

Figure 4.1 – Methods of anchorage other than by a straight bar

(3) The design value of ultimate bond stress (f_{bd}) for ribbed bars shall be taken as:

$$f_{bd} = \eta\delta f_{ctk,el}/\gamma_c \qquad \text{(Eq. 4.4)}$$

(4) The calculation of the required anchorage length shall take into consideration the type of steel and bond properties of the bars. The basic required anchorage length, $l_{b,rqd}$ shall be calculated using the Eq. 4.5:

$$l_{b,rqd} = (\phi_s/4) \times (\sigma_{sd}/f_{bd}) \qquad \text{(Eq. 4.5)}$$

where

$l_{b,rqd}$	=	Basic required anchorage length
σ_{sd}	=	Design stress of the bar at the position from where the anchorage is measured from

(5) The design anchorage length (l_{bd}) shall be determined by the following equations:

$$l_{bd} = \sigma_1\sigma_2\sigma_3\sigma_4\sigma_5 l_{b,rqd} + l_{to1} \geq l_{b,min} + l_{tol} \qquad \text{(Eq. 4.6)}$$

$$l_{tol} = \mathrm{Max}(\phi_s, 10) \qquad \text{(Eq. 4.7)}$$

$$0.80 \leq \sigma_2 = 1.6 - 0.4 \times \left(\frac{c}{\phi_s} - 1\right) \leq 1.6 \qquad \text{(Eq. 4.8)}$$

where

l_{bd}	=	Design anchorage length (mm)
σ_1	=	Coefficient for the effect of the form of the bars assuming adequate cover (See Table 4.1).
σ_2	=	Coefficient for the effect of concrete minimum cover (See Eq. 4.8)
σ_3	=	Coefficient for the effect of the pressure transverse to the plant of splitting along the design anchorage length (See Table 4.1)
σ_4	=	Coefficient for influence of one or more welded transverse bars ($\phi_t > 0.6 \times \phi_s$) along the design anchorage length l_{bd} (See Table 4.1).
σ_5	=	Coefficient for the effect of the pressure transverse to the plane of splitting along the design anchorage length (See Table 4.1).
l_{tol}	=	Allowance for the increased in anchorage taking into account possible positioning imperfections
$l_{b,min}$	=	Minimum anchorage length
c	=	Concrete cover

Table 4.1 – Values of coefficients σ_1, σ_2, σ_3, σ_4 and σ_5

Coefficient	Influencing factor	Type of anchorage	Reinforcement bar	
			In tension	**In Compression**
σ_1	Shape of bars	Straight	$\sigma_1 = 1.0$	$\sigma_1 = 1.0$
		Other than straight	$\sigma_1 = 0.7$ if $c_d > 3\phi_s$ otherwise $\sigma_1 = 1.0$	$\sigma_1 = 1.0$
σ_2	Concrete Cover	All types	Eq. 4.8	Eq. 4.8
σ_3	Confinement by transverse reinforcement not welded to main reinforcement	All types	$\sigma_3 = 1 - K_\sigma \times \lambda$ $(0.7 \leq \sigma_3 \leq 1.0)$	$\sigma_3 = 1.0$
σ_4	Confinement by welded transverse reinforcement	All types	$\sigma_4 = 0.7$	$\sigma_4 = 0.7$
σ_5	Confinement by transverse pressure	All types	$\sigma_5 = 1 - 0.04p$ $(0.7 \leq \sigma_5 \leq 1.0)$	-

where

λ	=	$(\Sigma A_{st} - \Sigma A_{st,min}) / A_s$
ΣA_{st}	=	Cross-sectional area of the transverse reinforcement along the design anchorage length, l_{bd}
$\Sigma A_{st,min}$	=	Cross-sectional area of the minimum transverse reinforcement $= 0.25A_s$ for beams and 0 for slabs
A_s	=	Area of a single anchored bar with maximum bar diameter
K_σ	=	Values shown in **Figure 4.2**
c_d	=	Definition follows Clause 8.4.4 of BS EN 1992-1-1 2004
p	=	Transverse pressure (MPa) at ULS along l_{bd}

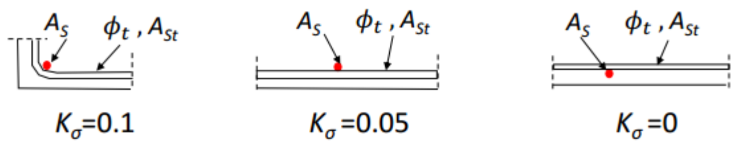


Figure 4.2 – Values of K_σ for beams and slabs

(6) The minimum anchorage length ($l_{bd,min}$) shall be determined by the following equations:

(a) For anchorage in tension:

$$l_{bd,min} = \text{Max}(0.3l_{b,rqd}, (\frac{1}{\delta} - 0.15) \times 10\phi_s, (\frac{1}{\delta} - 0.15) \times 100) \quad \text{(Eq. 4.9)}$$

(b) For anchorage in compression:

$$l_{bd,min} = \text{Max}(0.7l_{b,rqd}, (\frac{1}{\delta} - 0.15) \times 10\phi_s, (\frac{1}{\delta} - 0.15) \times 100) \quad \text{(Eq. 4.10)}$$

(7) The anchorage of links and shear reinforcement shall comply with **Figure 4.3**.

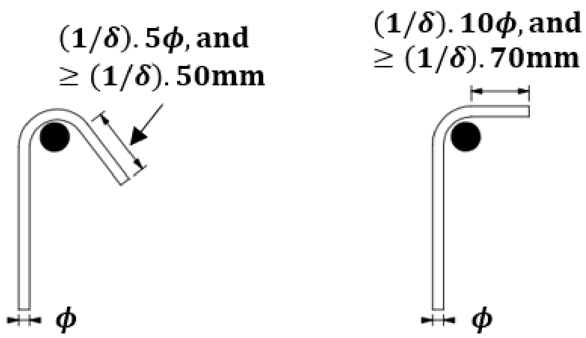


Figure 4.3 – Anchorage of links

4.5 Laps

(1) The requirements of laps are same as the conventional concrete, except the minimum lap length ($l_{o,min}$) shall be calculated using the Eq. 4.11:

$$l_{0,min} \geq \text{Max}(0.3\sigma_6 l_{b,rqd}, 15\phi_s/\delta, (1/\delta) \times 200) \quad \text{(Eq. 4.11)}$$

where

$l_{o,min}$ = Minimum lap length (mm)

σ_6 = $(p_1/25)^{0.5}$ but not exceeding 1.5 nor less than 1.0, where p_1 is the percentage of reinforcement lapped within 0.65 $l_{o,d}$ from the centre of the lap length considered.

(2) Therefore, the design lap length ($l_{o,d}$) shall be calculated using the Eq. 4.12:

$$l_{o,d} = \sigma_1\, \sigma_2\, \sigma_3\, \sigma_4\, \sigma_5\, \sigma_6\, l_{b,rqd} \geq l_{o,min} \quad \text{(Eq. 4.12)}$$

where

$l_{o,d}$ = Design lap length

4.6 Connection Details for Precast Elements and Structures

(1) When UHPC is used for connecting precast members, reinforcement may be connected using lap splices. The minimum lap length shall satisfy the following requirements:

(a) For diameter of reinforcing steel (ϕ_s) equal to and less than 25mm, the minimum lap length shall be greater than $10\phi_s$.

(b) For diameter of reinforcing bar (ϕ_s) greater than 25mm and equal to and less than 32mm, the minimum lap length shall be greater than 12 ϕ_s.

(c) When the reinforcement consists of bundled bars, the minimum lap length shall be calculated based on the equivalent diameter of the bundled bars.

(2) When UHPC is used for connecting precast members, the clear spacing between lap-spliced bars shall not be less than 20mm.

4.7 Prestressing Tendons/Ducts

(1) The requirements of pre-tensioned tendons/ducts for conventional concrete also applies to UHPC. However, the spacing between reinforcement must greater than 1.5 time the length of the longest fibre (L_f) for the UHPC to flow satisfactorily.

(2) At release of tendons, the prestress may be assumed to be transferred to the concrete by a constant bond stress (f_{cbd}) and the bond stress shall be calculated by the following equations:

$$f_{cbd} = \eta \delta f_{ctk,el}(t)/\gamma_c \quad \text{(Eq. 4.13)}$$

$$\eta = \frac{A_s + A_p}{A_s + A_p\sqrt{\xi(\phi_s/\phi_p)}} \quad \text{(Eq. 4.14)}$$

where

f_{cbd}	=	Constant bond stress
ϕ_s	=	Largest diameter of reinforcing steel
ϕ_p	=	Nominal diameter or equivalent diameter of prestressing steel $\phi_p = 1.60A_p^{0.5}$ for bundles $\phi_p = 1.75\phi_{wire}$ for single 7 wire strands where ϕ_{wire} is the wire diameter $\phi_p = 1.20\phi_{wire}$ for single 3 wire strands
η	=	Factor for bond behaviour of prestressing and reinforcing steel
$f_{ctk,el}(t)$	=	Characteristic tensile limit of elasticity at time of release tendon

(3) The bond strength for anchorage in the ULS (f_{bpd}) shall be calculated using the following equation:

$$f_{bpd} = 0.5\eta \delta f_{ctk,el}(t)/\gamma_c \quad \text{(Eq. 4.15)}$$

5 CONSTRUCTION OF UHPC STRUCTURES

5.1 Materials Management

5.1.1 Storage, Handling and Processing

(1) Raw materials, including aggregates, cement, binders, chemical admixtures, and steel fibre, shall be stored, handled, and processed to prevent moisture, contamination or deterioration.

(2) All liquid raw materials shall be protected from changes in moisture content. Any liquid material exhibiting signs of segregation shall be thoroughly re-mixed to ensure uniformity prior to use.

5.1.2 Pre-batching Checks

(1) An inspection shall be carried out prior to UHPC batching and shall include the following check:

(a) Verify that a screen is installed at the mixer's charging point to sieve out lumps.

(b) Ensure the mixer is free from excessive wear of blades, fins, or paddles and from hardened concrete build-up.

(c) Confirm that the correct raw materials are being used.

(d) Inspect for any colour changes indicating potential deterioration of fibres or admixtures.

(e) Verify specific gravity of liquid materials.

(f) Confirm that steel fibres comply with the requirements specified in the PS.

(g) Check pre-blended materials for signs of lumps or ageing.

(h) Ensure inspection personnel and laboratory equipment meet the requirements from PS.

(i) Confirm that sufficient quantities of all required materials are available to complete the batching process.

(j) Inspect raw materials and packaging for any signs of damage or deterioration.

5.2 Mixing

5.2.1 Mixing Equipment

(1) The batching of UHPC shall be carried out using one of the following mixer types: pan, planetary, horizontal shaft drum, or ready-mix truck.

(2) The mixer shall be capable of delivering adequate torque to facilitate the transition of UHPC from dry to fluid state.

(3) The mixer shall be equipped with a screen at the charging point to filter out any lumps.

(4) Mixers shall be inspected daily for concrete build-up and any accumulation on the fins or blades shall be thoroughly removed.

(5) Daily inspections shall be conducted to assess wear on mixer components. Blades, fins, or paddles with wear exceeding 15% shall not be used.

(6) For pans, planetary, and horizontal shaft drum mixers, the clearance between paddles and the mixer wall and floor shall conform to the supplier's specifications.

5.2.2 Mix Adjustments and Retempering

(1) Adjustments to the UHPC mix and any retempering during batching shall only be performed by personnel who are appropriately qualified and possess demonstrable experience in UHPC mixing.

(2) A qualified person refers to an experienced technician who has been adequately trained by an individual possessing comprehensive knowledge of UHPC constituents, mixing equipment, mixing procedures, temperature control, and all other aspects relevant to the UHPC mixing process.

(3) The adjusted water content shall not exceed the quantity specified by the supplier. If any adjustment or retempering results in a water-to-cementitious materials ratio exceeding the design limit, the entire batch shall be discarded.

(4) Admixture dosages used for UHPC retempering shall not exceed the limits specified by the supplier.

(5) The addition of water or admixtures to UHPC after discharge from the mixer is strictly prohibited.

5.3 Delivery and Placement

5.3.1 Delivery of UHPC

(1) UHPC batched off-site shall be transported by ready-mix concrete truck and delivered from the mixer to the point of placement as promptly as practicable to preserve mix integrity and workability.

(2) Equipment used to transport UHPC shall consist of smooth, watertight metal or plastic containers capable of directing the flow of UHPC during placement. Protective covers shall be provided to shield the material from inclement weather and prevent moisture loss.

(3) Each load of UHPC shall be documented and tested in accordance with the PS.

(4) The Contractor shall conduct pre-pour flow testing to establish the maximum allowable delivery time for each batch.

5.3.2 Placement of UHPC

(1) UHPC shall be positioned as close as practicable to its final location.

(2) UHPC placing methods and equipment shall convey and deposit the material without segregation, ensuring that the fibres maintain a continuous overlap, and without changing or adversely affecting the specified fresh or hardened properties.

(3) UHPC placing methods shall account for internal reinforcement and embedded elements, as conventional reinforcement such as rebars or strands may obstruct flow and cause fibre segregation.

(4) UHPC is recommended to be placed monolithically. If monolithic placement is not feasible, casting procedures shall be adjusted to ensure that the interface between successive pours behaves monolithically.

(5) The UHPC pour point shall not advance ahead of the leading edge of the wave front within the formwork. UHPC shall be placed from one end of the form or just behind the progressing wave front to maintain uniform flow and prevent entrapment

(6) Elevation drops for UHPC placement shall not exceed 1 meter and must be validated by both contractor and the supplier prior to use. To minimize the risk of fibre segregation associated with free-fall, alternative methods such as bottom-up injection, use of a tremie pipe, or gravity-fed pressure injection may be employed, particularly in confined spaces.

(7) When bonding fresh UHPC to hardened UHPC, the existing surface shall be roughened to expose the fibre matrix, cleaned to create mechanical bond, and pre-wetted to a saturated surface dry (SSD) condition prior to placement of the fresh UHPC. Dowel bars, mechanical bonds (such as shear keys or grooves) or verified chemical agents such as epoxy-based compounds, may be used to enhance bond performance.

(8) When bonding fresh UHPC to normal strength concrete, the existing surface shall be roughened to expose the aggregate by removing matrix material and cleaned to create a

mechanical bond, then pre-wetted to SSD condition prior to placing the fresh UHPC. Dowel bars or mechanical bond (such as shear keys or grooves) may also be used to enhance bond performance.

(9) UHPC in place shall not be subjected to harmful vibration or shock that could cause fibre segregation or misalignment. The preferred approach for placement is to provide adequate flow with proper mix design to fill the formwork and moulds while maintaining isotropic fibre orientation. Placement shall proceed as continuously as practicable until the section is fully cast.

(10) When UHPC is placed by pumping, the entire length of pipeline shall be lubricated by passing UHPC mix without steel fibres through the pipeline before the UHPC is pumped. The pipeline length shall not exceed 3 meters unless prior validation demonstrates that longer lengths do not adversely affect the fresh or hardened properties of the UHPC.

5.3.3 Placing Temperature

(1) The recommended placing temperature of the UHPC shall be between 5 and 30°C.

(2) To adjust placing temperature, pre-heating of the pre-mix and extended batching durations may be employed to raise it, while chilled pre-mix or ice may be introduced into the mixer to lower it.

(3) Control of the material temperature during batching will provide the ability to accelerate or slow the working time, setting times, and rate of early strength gain.

(4) Cooler placing temperatures increase workability. Flows should be adjusted to avoid segregation or fibre settlement during cooler placing temperatures.

5.4 Protection and Curing

5.4.1 Protection after Placing

(1) UHPC shall be protected against excessive moisture loss. Acceptable measures include:

(a) Lowering the temperature of the UHPC or surrounding environment;

(b) Increasing surface humidity; or

(c) Immediately covering the UHPC surface with waterproof sheeting in full contact, or applying a roll-on or spray-applied curing compound at the rate recommended by the manufacturer and deemed appropriate for the application.

(2) UHPC shall be protected against differential thermal stresses that may lead to cracking, including the following formwork considerations:

(a) Due to its composition and the nature or mould construction, UHPC can generate high internal temperatures, comparable to mass concrete, even in elements with relatively small volumes or cross-sectional areas.

(b) Measures shall be taken to limit internal heat build-up.

(c) Elements with varying mass-to-surface-area ratios dissipate heat at different rates; care shall be taken to minimize differential thermal stresses throughout the element.

(d) The use of ice as a partial or full replacement for mixing water may be considered to control temperature rise and support the development of UHPC's strength, durability, and other performance properties.

5.4.2 Curing Method and Duration

(1) Curing for in-situ cast and precast UHPC shall begin following the placing and finishing operations and shall provide the temperature and moisture conditions for the period of time necessary for UHPC to develop its strength, durability, and other properties.

(2) All materials and equipment needed for adequate protection and curing shall be in place and ready for use before each UHPC placement is started.

(3) Curing of UHPC surfaces may be initiated using one or more of the following methods, including:

(a) Application of curing compounds of a type, method, and rate approved by the *Project Manager*;

(b) Placement of waterproof plastic sheeting in full contact with the UHPC surface; or

(c) Formwork in full contact with the UHPC surface.

5.4.3 Demoulding

The timing and sequencing of the demoulding phase in UHPC construction shall account for the material's high early-age shrinkage characteristics and ensure that the element has attained sufficient strength to support its self-weight without compromising its integrity.

5.5 Finishes and Quality Control

5.5.1 Surface finishes

(1) The application of surface treatments after demoulding shall be validated for bond, performance, and compliance with the supplier's recommendations.

(2) All external surfaces of the UHPC components shall be painted with a self-cleaning or superhydrophobic coatings to prevent staining.

5.5.2 Inspection and Acceptance Criteria

(1) All UHPC shall be subject to inspection and acceptance by the *Project Manager*. Inspection shall verify compliance with the PS and relevant standard, codes of practice and guidance as required under the Contract.

(2) Acceptance shall be based on documented evidence of conformity, including test results, certificates and inspection records.

(3) Dimensional tolerances, surface finishes, and alignment shall be inspected against design drawings. Any defects (cracks, spalling, surface irregularities) shall be assessed and rectified before acceptance.

(4) Testing, including but not limited to workability (slump flow), compressive strength, direct tensile strength, static modulus of elasticity in compression, permeability, and if required, abrasion resistance, shall be carried out in accordance with the PS. Acceptance requires all test results to meet or exceed the specified criteria in the PS. Complete records of inspections, tests, and approvals shall be submitted prior to acceptance.

6 MAINTENANCE OF UHPC STRUCTURES

6.1 General

(1) It is recommended that the same maintenance schedule for normal strength concrete civil engineering structures could be adopted for corresponding UHPC structures.

(2) For the inspection of UHPC structures, all inspections shall be carried out by professional engineer with at least 3 years' relevant post qualification experience in design, construction and maintenance work for relevant structures.

6.2 Routine Inspection

(1) Due to the extremely low permeability, UHPC is highly resistant to the primary causes of conventional concrete deterioration, such as chloride-induced corrosion, chemical attack, etc. Unless noticeable defects, such cracks or other damages, are identified during the routine inspection, no specific tests on concrete condition, such as carbonation, coring, chloride, or sulphate tests, are required for UHPC structures in service for less than 10 years.

(2) The wearing surface over the UHPC, including the asphalt, concrete or other types of overlaid materials (if present) shall be inspected for wear, rutting, or damage.

(3) Surface appearance shall be inspected for any staining. Although often aesthetic, staining may indicate drainage deficiencies or overhead leakage.

(4) The field-cast UHPC joints and connections between prefabricated elements (such as deck panels and girders) shall be inspected for defects, including but not limiting to, hairline cracking or debonding.

6.3 Cleaning

(1) UHPC usually requires very little maintenance due to its exceptional durability and toughness and usually no periodic cleaning is required.

(2) In general, the least aggressive cleaning method (low pressure, soft brushes, water) is recommended.

6.4 Repair Method

(1) For minor repairs of UHPC structures, a proprietary UHPC repair mortar in equivalent compressive strength or high strength epoxy shall be used for repair in accordance with the supplier's requirements.

(2) For large scale damage such as traffic accidents on deck or piers, the repair method shall be carefully assessed, and structural stability assessment shall be carried out such that the proposed repair works shall not affect the structural integrity and stability.

APPENDIX A

LIST OF REFERENCES

ACKNOWLEDGEMENT

A full list of standards, specifications, design codes, and Published Documents (PDs) which form the basis of this Technical Guideline is provided below.

LIST OF REFERENCES

(1) Structures Design Manual for Highways and Railways, 2013 Editions, and its amendments up to Amendment No. 2/2025, published by Highways Department, Hong Kong SAR Government.

(2) General Specification for Civil Engineering Works, 2020 Edition, and its amendments up to Amendment No. 3/2025, published by Civil Engineering and Development Department, Hong Kong SAR Government.

(3) Construction Standard CS1, 1990 Testing Concrete Volume 1 (May 2001) and its amendments up to Amendment 1102, published by Hong Kong SAR Government

(4) Construction Standard CS1, 1990 Testing Concrete Volume 2 (January 2002) and its amendment up to Amendment 1206, published by Hong Kong SAR Government.

(5) DG/TJ 08-2401-2022, Technical Standard for Application of Ultra-High Performance Concrete in Bridges, published by Shanghai Municipal Commission of Housing and Urban-rural Development, China

(6) NF P 18-451 (December 2018), Concrete – Execution of concrete structures – Specific rules for UHPRFC, published by French Standardization Association (AFNPR), French

(7) NF P 18-470 (July 2016), Concrete – Ultra-High Performance Fibre-Reinforced Concrete – Specifications, Performance, Production and Conformity, published by AFNPR, French

(8) NF P 18-710 (April 2016), National addition to Eurocode 2 – Design of Concrete Structures: Specific Rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC), published by AFNPR, French

(9) Eurocode: Basis of Structural Design – BS EN 1990:2002+A1:2005 incorporating Corrigenda December 2009 and April 2010

(10) Eurocode 1: Actions on Structures - BS EN 1990:2002+A1:2005 Eurocode: Basis of Structural Design, incorporating Corrigenda December 2009 and April 2010, published by BSI, United Kingdom

(11) Eurocode 2: Design of Concrete Structures - BS EN 1992-1-1:2004 Part 1-1: General rules and rules for buildings, incorporating Corrigenda January 2008 and November 2021, published by BSI, United Kingdom

(12) Eurocode 4: Design of Composite Steel and Concrete Structures - BS EN 1994-1-1:2004

Part 1-1: General rules and rules for buildings incorporating Corrigendum April 2009, published by BSI, United Kingdom

(13) National Standard of Canada CSA A23.1:24/CSA A23.2:24 (June 2024) – Concrete Materials and methods of concrete construction / Test Methods and Standard Practices for concrete

(14) Particular Specification for Structural Use of Ultra-High Performance Concrete (December 2025), published by CEDD/BTRi

APPENDIX B

INDICATIVE VALUES FOR DESIGN OF UHPC STRUCTURES

Appendix B – Indicative Values for Design of UHPC Structures

B1 General

In the absence of laboratory test, the *Designer* may consider to adopt the following indicative design values to carry out scheme design or preliminary design for purposes of material quantity or cost estimation.

A detailed design shall be carried out based on the laboratory testing or supplier information to conduct a comprehensive structural design calculation with proper checking.

B2 Design Values

UHPC shall be designated by strength grades which relate to the characteristic cube strength, f_{cd}, in accordance with the GS. The corresponding Eurocode strength classes, characteristic cylinder strength, f_{ck}, and other mechanical characteristics necessary for design shall be obtained from **Table B1** by interpolation between the lower bound limits for C120 and upper bound limit for C200 UHPC.

Table B1 – Indicative Values for UHPC Design

Mean modulus of elasticity, E_{cm}	45 GPa
Characteristic compressive strength, f_{ck}	120 - 200 MPa
Mean compressive strength, f_{cm}	130 - 230 MPa
Characteristic tensile limit of elasticity, $f_{ctk,el}$	5.0 - 10.0 MPa
Mean tensile limit of elasticity, $f_{ctm,el}$	6.0 - 12.0 MPa
Characteristic post-cracking strength, f_{ctfk}	6.0 - 10.0 MPa
Mean post-cracking strength, f_{ctfm}	7.5 - 15.0 MPa
Length of the longest fibre, L_f	6 - 25 mm

APPENDIX C

WORKED EXAMPLES

APPENDIX C1

UNREINFORCED UHPC SLAB DESIGN

UNREINFORCED UHPC SLAB DESIGN

A Calculation Principles

A1 Design Assumptions

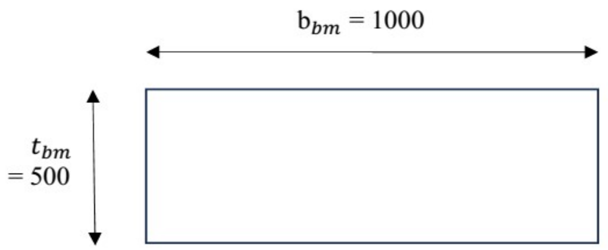
1. This example adopts a simplified load combination for illustrative purpose. Comprehensive design shall be made against the complete set of load combinations required by the applicable codes.
2. Steam curing will be not used.
3. SI Units are adopted. [i.e. Moment (kNm), Shear (kN), Dimensions (mm), Area (mm^2), Moment of Inertia (mm^4), Stress / Modulus of Elasticity / Strength (N/mm^2 or MPa) etc].

A2 Design Forces

ULS Design Moment $M_{Ed.ULS} := 400$

SLS Design Moment (Characteristic Load Comb.) $M_{Ed.SLS} := 300$

ULS Design Shear $V_{Ed.ULS} := 150$



A3 Configuration

Member Width $b_{bm} := 1000$

Member Thickness $t_{bm} := 500$

Span Length (Simply Supported) $L_{span} := 10 \cdot 10^3$

Exposure Class $XC4$

Max. Crack Width Requirement $w_{max} := 0.1$ TG Cl. 3.2.1.2 Table 3.1

B Materials & Strength

B1 Materials - Fibres

Length of Fibres $L_f := 13$ TG Appendix B Table B1

Global Fibre Orientation $K_{global} := 1.25$ TG Appendix B Table B1

Local Fibre Orientation $K_{local} := 1.75$ TG Appendix B Table B1

B2 Materials - UHPC

ULS Partial Factor for Compressed UHPC $\gamma_c := 1.5$ TG Cl. 2.6 Table 2.4

ULS Partial Factor for Tensioned UHPC $\gamma_{cf} := 1.3$ TG Cl. 2.6 Table 2.4

Characteristics Compressive Cylinder Strength $f_{ck} := 190$ TG Appendix B Table B1

Characteristics Post-cracking Strength $f_{ctfk} := 9$ TG Appendix B Table B1

Characteristic Tensile Limit of Elasticity $f_{ctk.el} := 7$ TG Appendix B Table B1

Mean Compressive Strength $f_{cm} := 160$ TG Appendix B Table B1

Mean Post-cracking Strength $f_{ctfm} := 11$ TG Appendix B Table B1

Mean Tensile Limit of Elasticity $f_{ctm.el} := 8$ TG Appendix B Table B1

Mean Modulus of Elasticity $E_{cm} := 45 \cdot 10^3$ TG Cl. 2.2.2(1)

Creep Coefficient (w/o Steam Curing) $\varphi_{ef} := 0.8$ TG Cl. 2.2.8(1)(a)

B3 Strength - UHPC - Compressive Strength

Design Compressive Strength $f_{cd} := \frac{0.67 \cdot f_{ck}}{\gamma_c} = 84.87$ TG Cl. 2.2.9(2) Eq. 2.7

Design Ultimate Elastic Shortening Strain $\varepsilon_{c0d} := \frac{f_{cd}}{E_{cm}} = 0.189 \cdot \%$ TG Cl. 2.2.9(3) Eq. 2.8

Design Ultimate Shortening Strain $\varepsilon_{cud} := \left(1 + 14 \cdot \frac{f_{ctfm}}{K_{global} \cdot f_{cm}}\right) \cdot \varepsilon_{c0d} = 0.334 \cdot \%$ TG Cl. 2.2.9(4) Eq. 2.9

B4 Strength - UHPC - Tensile Behaviour

B.4.1 Check Tensile Behaviour

$$Check_{tensile.behaviour} := \begin{cases} \text{"Strain Hardening"} & \text{if } \frac{f_{ctfm}}{1.25} \geq f_{ctm.el} \wedge \frac{f_{ctfk}}{1.25} \geq f_{ctk.el} \\ \text{"Not Applicable"} & \text{otherwise} \end{cases} = \text{"Strain Hardening"}$$

TG Cl. 2.2.4

B4.2 Check Thick / Thin Member

$$Check_{conventional.law} := \begin{cases} \text{"Thick Member"} & \text{if } t_{bm} \geq 3 \cdot L_f \\ \text{"Thin Member"} & \text{otherwise} \end{cases} = \text{"Thick Member"}$$

TG Cl. 2.2.5

Characteristic Length $L_c := \frac{2 \cdot t_{bm}}{3} = 333.3$ TG Cl. 2.2.10(5)

ULS Design Tensile Limit of Elasticity $f_{ctd.el} := \frac{f_{ctk.el}}{\gamma_{cf}} = 5.38$

ULS Strain at Max. Limit of Elasticity $\varepsilon_{u.el} := \frac{f_{ctd.el}}{E_{cm}} = 0.012 \cdot \%$ TG Cl. 2.2.10(4) Eq. 2.12

ULS Design Post-cracking Strength $f_{ctfd} := \frac{f_{ctfk}}{\gamma_{cf} \cdot K_{global}} = 5.54$

ULS Ultimate Strain in Tension $\varepsilon_{u.lim} := \frac{L_f}{4 \cdot L_c} = 0.975 \cdot \%$ TG Cl. 2.2.10(5) Eq. 2.13

SLS Design Tensile Limit of Elasticity $f_{ctd.el.SLS} := f_{ctk.el} = 7.00$

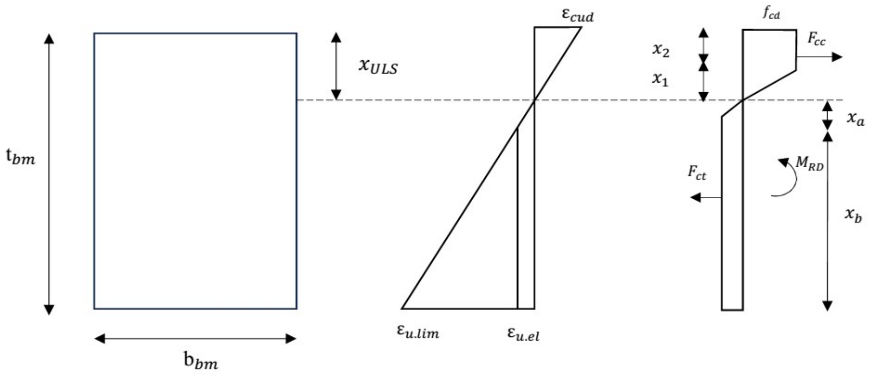
SLS Strain at Max. Limit of Elasticity $\varepsilon_{el} := \frac{f_{ctd.el.SLS}}{E_{cm}} = 0.016 \cdot \%$

SLS Design Post-cracking Strength $f_{ctfd.SLS} := \frac{f_{ctfk}}{K_{global}} = 7.20$

SLS Ultimate Strain in Tension $\varepsilon_{lim} := \varepsilon_{u.lim} = 0.975 \cdot \%$

C ULS Bending Resistance

C1 UHPC Bending Resistance



Horizontal Equilibrium between the Forces, find compressive depth (i.e. N.A.) $x := 1$ Try x from 1 until x_{ULS} at equilibrium

$$f_1(x) := f_{cd}\cdot\left[\frac{1}{2}\cdot\frac{\varepsilon_{c0d}}{\varepsilon_{cud}} + \left(1 - \frac{\varepsilon_{c0d}}{\varepsilon_{cud}}\right)\right]\cdot x\cdot b_{bm}\cdot\frac{1}{10^3} - f_{ctd.el}\left[\left(\frac{1}{2}\cdot\frac{\varepsilon_{u.el}}{\varepsilon_{cud}}\right)\cdot x + \left(t_{bm} - x - \frac{\varepsilon_{u.el}}{\varepsilon_{cud}}\cdot x\right)\right]\cdot b_{bm}\cdot\frac{1}{10^3}$$

Compressive Depth of UHPC (N.A.) $x_{ULS} := root(f_1(x), x) = 40.6$

Depth $x_1 := \frac{\varepsilon_{c0d}}{\varepsilon_{cud}}\cdot x_{ULS} = 22.9$ $x_2 := x_{ULS} - x_1 = 17.6$

$x_a := x_1\cdot\frac{\varepsilon_{u.el}}{\varepsilon_{c0d}} = 1.5$ $x_b := t_{bm} - x_{ULS} - x_a = 458.0$

Compressive Force in UHPC $F_{cc} := f_{cd}\cdot\left(\frac{x_1}{2} + x_2\right)\cdot b_{bm}\cdot\frac{1}{10^3} = 2470$

Moment Resistance in UHPC $M_{cc} := f_{cd}\cdot\left[\frac{x_1^2}{3} + x_2\cdot\left(x_1 + \frac{x_2}{2}\right)\right]\cdot b_{bm}\cdot\frac{1}{10^6} = 62$

Tensile Force in UHPC $F_{ct} := f_{ctd.el}\left(\frac{x_a}{2} + x_b\right)\cdot b_{bm}\cdot\frac{1}{10^3} = 2470$

Moment Resistance in UHPC $M_{ct} := f_{ctd.el}\cdot\left[\frac{x_a^2}{3} + x_b\cdot\left(x_a + \frac{x_b}{2}\right)\right]\cdot b_{bm}\cdot\frac{1}{10^6} = 568$

C1.1 Check Horizontal Force Equilibrium

Resultant Horizontal Force $F_{cc} - F_{ct} = 0.00$

$Check_{force.equilibrium} :=$ "Close Enough" if $|F_{cc} - F_{ct}| \le 1$ = "Close Enough"
"Retry Compressive Depth, x" otherwise

C1.2 Check Ultimate Moment Resistance

ULS Design Moment Resistance $M_{Rd} := M_{cc} + M_{ct} = 631$

$Check_{moment} :=$ "ULS Moment Reistance O.K." if $M_{Rd} \ge M_{Ed.ULS}$ = "ULS Moment Reistance O.K."
"Retry Section" otherwise

D ULS Shear Resistance

D1 UHPC Shear Resistance

Long-term effects Coefficient	$\alpha_{cc} := 0.85$	TG Cl. 3.1.2.5
	$k := 1$ where $\sigma_{cp} = 0$ N/mm^2	TG Cl. 3.1.2.2(1) Eq. 3.4
Safety Factor	$\gamma_E := \frac{1.5}{\gamma_{cf}} = 1.15$	TG Cl. 3.1.2.2(1)
Lever Arm	$z := 0.9\cdot\left(\frac{7}{8}\cdot t_{bm}\right) = 393.8$	TG Cl. 3.1.2.2(2)
UHPC Contribution Term	$V_{Rd.c} := \frac{0.18}{\gamma_{cf}\cdot\gamma_E}\cdot k\cdot\sqrt{f_{ck}}\cdot b_{bm}\cdot t_{bm}\cdot\frac{1}{10^3} = 827$	TG Cl. 3.1.2.2(1) Eq. 3.7
Reinforcement Contribution Term	$V_{Rd.s} := 0$	TG Cl. 3.1.2.3
Strain Limit at ULS	$\varepsilon_x := \varepsilon_{u.lim} = 0.975\cdot\%$	
Compression Area	$A_{fv} := b_{bm}\cdot z = 393.750\times 10^3$	TG Cl. 3.1.2.4
Integration of Stress-Strain Function	$\sigma_f := \left(f_{ctd.el.SLS} + f_{ctfd.SLS}\right)\cdot\left(\frac{\varepsilon_{u.lim} - \varepsilon_{el}}{2}\right)\cdot 10^2 = 6.81$	
Mean Post-cracking Strength Value	$\sigma_{Rd.f} := \frac{1}{K_{global}\cdot\gamma_{cf}}\cdot\frac{1}{\left(\varepsilon_x - \varepsilon_{el}\right)}\cdot\sigma_f\cdot\frac{1}{10^2} = 4.37$	TG Cl. 3.1.2.4(2) Eq. 3.11
Inclination of Main Compression Stress on Long. Axis	$\theta := 30\cdot deg$	TG Cl. 2.5.5(2)(a)
Fibre Contribution Term	$V_{Rd.f} := A_{fv}\cdot\sigma_{Rd.f}\cdot\cot(\theta)\cdot\frac{1}{10^3} = 2980$	TG Cl. 3.1.2.4(1) Eq. 3.10
Superposition of Three Resistance Term	$V_{Rd} := V_{Rd.c} + V_{Rd.s} + V_{Rd.f} = 3807$	TG Cl. 3.1.2.1(1)
Limit Force for Compressive Strength	$V_{Rd.max} := 2.3\cdot\frac{\alpha_{cc}}{\gamma_c}\cdot b_{bm}\cdot z\cdot f_{ck}^{\frac{2}{3}}\cdot\tan(\theta)\cdot\frac{1}{10^3} = 9792$	TG Cl. 3.1.2.5(1) Eq. 3.12
ULS Design Shear Resistance	$V_{Ed.total} := \min\left(V_{Rd}, V_{Rd.max}\right) = 3807$	TG Cl. 3.1.2.1(1) Eq. 3.2

$Check_{shear} :=$ | "ULS Shear Resistance O.K." if $V_{Ed.total} \geq V_{Ed.ULS}$ = "ULS Shear Resistance O.K."
"Retry Section" otherwise

E Crack Control

E1 Verification of Crack

UHPC Gross Area $A_c := b_{bm} \cdot t_{bm} = 500.000 \times 10^3$

Effective Modulus of Elasticity of UHPC with Creep $E_{c.eff} := \frac{E_{cm}}{1 + \varphi_{ef}} = 25.000 \times 10^3$ NF P18-710 Cl. 7.4.3 Eq. 7.221

Moment of Inertia $I_c := \frac{b_{bm} \cdot t_{bm}^3}{12} = 10.417 \times 10^9$

Centre of Gravity $y_{cg} := \frac{t_{bm}}{2} = 250.0$

Tensile Stress at the Bottom $\sigma_{ct} := \frac{M_{Ed.SLS}}{I_c} \cdot (t_{bm} - y_{cg}) \cdot 10^6 = 7.20$

$$Check_{tensile.stress} := \begin{cases} \text{"Not Cracked Section"} & \text{if } \sigma_{ct} \le f_{ctd.el.SLS} \\ \text{"Cracked Section"} & \text{otherwise} \end{cases} = \text{"Cracked Section"}$$

E2 Crack Width Control

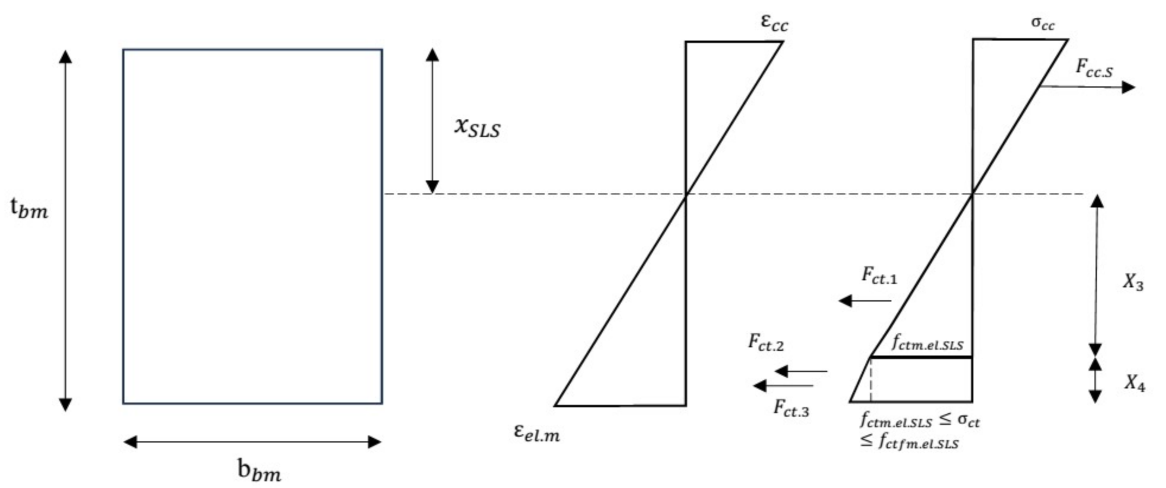
Load Duration Factor $k_t := 0.4$ TG Cl. 3.2.1.5(2)

SLS Mean Design Tensile Limit of Elasticity $f_{ctm.el.SLS} := f_{ctm.el} = 8.00$

SLS Mean Max. Limit of Elasticity $\varepsilon_{el.m} := \frac{f_{ctm.el.SLS}}{E_{c.eff}} = 0.032 \cdot \%$

SLS Mean Design Post-cracking Strength $f_{ctm.SLS} := \frac{f_{ctfm}}{K_{global}} = 8.80$

SLS Mean Ultimate Strain in Tension $\varepsilon_{lim.m} := \varepsilon_{lim} = 0.975 \cdot \%$



Compressive Depth of UHPC (i.e. N.A.) $x_{SLS} := 249.40$

Compressive Strain of UHPC $\varepsilon_{cc} := 0.029 \cdot \%$

Strain of Tensioned UHPC $\varepsilon_{ct} := \varepsilon_{cc} \cdot \frac{t_{bm} - x_{SLS}}{x_{SLS}} = 0.029 \cdot \%$

UHPC under Compression

Compressive Stress of UHPC $\sigma_{cc} := \varepsilon_{cc} \cdot E_{c.eff} = 7.25$

Compressive Force of UHPC $F_{cc.S} := \sigma_{cc} \cdot \frac{x_{SLS} \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = 904$

Lever Arm for UHPC under Compression $x_{cc.S} := x_{SLS} \cdot \frac{2}{3} = 166.3$

UHPC under Tension

Height that is Uncracked $x_3 := (t_{bm} - x_{SLS}) \cdot \frac{\varepsilon_{el.m}}{\varepsilon_{ct}} = 275.2$

Height that is Cracked $x_4 := t_{bm} - x_{SLS} - x_3 = -24.6$

Tensile Force of Uncracked UHPC $F_{ct.1} := f_{ctm.el.SLS} \cdot \frac{x_3 \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = 1101$

Lever Arm of Uncracked UHPC $x_{ct.1.S} := x_3 \cdot \frac{2}{3} = 183.5$

Tensile Force of Cracked UHPC $F_{ct.2} := f_{ctm.el.SLS} \cdot x_4 \cdot b_{bm} \cdot \frac{1}{10^3} = -197$

Lever Arm for Cracked UHPC $x_{ct.2.S} := x_3 + \frac{x_4}{2} = 262.9$

Tensile Force of Cracked UHPC $F_{ct.3} := (f_{ctm.SLS} - f_{ctm.el.SLS}) \cdot \frac{\varepsilon_{ct}}{\varepsilon_{lim.m}} \cdot \frac{x_4 \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = -0$

Lever Arm for Cracked UHPC $x_{ct.3.S} := x_3 + x_4 \cdot \frac{2}{3} = 258.8$

E2.1 Check Horizontal Force Equilibrium

Resultant Horizontal Force $F_{cc.S} - F_{ct.1} - F_{ct.2} - F_{ct.3} = 0.37$

$Check_{SLS.force.equilibrium} :=$ "Close Enough" if $|F_{cc.S} - F_{ct.1} - F_{ct.2} - F_{ct.3}| \le \frac{F_{cc.S}}{100}$ = "Close Enough"

"Retry Compressive Depth, x_SLS" otherwise

E2.2 Check Moment Equilibrium

SLS Moment Resistance $M_{cr} := (F_{cc.S} \cdot x_{cc.S} + F_{ct.1} \cdot x_{ct.1.S} + F_{ct.2} \cdot x_{ct.2.S} + F_{ct.3} \cdot x_{ct.3.S}) \cdot \frac{1}{10^3} = 300$

Resultant Moment $M_{Ed.SLS} - M_{cr} = -0.46$

$Check_{SLS.moment.equilibrium} :=$ "Close Enough" if $|M_{Ed.SLS} - M_{cr}| \le \frac{M_{Ed.SLS}}{100}$ = "Close Enough"

"Retry Compressive Strain, ε_cc" otherwise

E3 Crack Width

Crack Width at the Most Tensioned Fibre $w_{t.a} := \left(\varepsilon_{ct} - \frac{f_{ctm.el}}{K_{global} \cdot E_{cm}}\right) \cdot L_c = 0.05$ TG Cl. 3.2.1.5(1) Eq. 3.22

$Check_{crack.width} :=$ "Crack Width O.K." if $w_{t.a} \le w_{max}$ = "Crack Width O.K."

"Not O.K. !" otherwise

APPENDIX C2

REINFORCED UHPC BEAM DESIGN

REINFORCED UHPC BEAM DESIGN

A Calculation Principles

A1 Design Assumptions

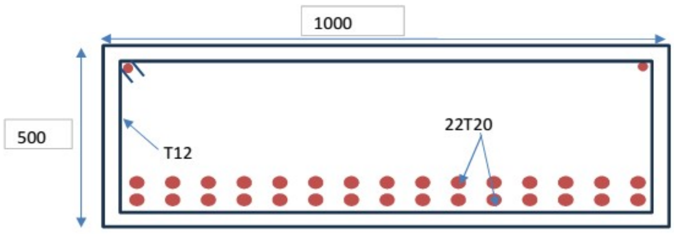
1. This example adopts a simplified load combination for illustrative purpose. Comprehensive design shall be made against the complete set of load combinations required by the applicable codes.
2. Steam curing will not be used.
3. The compressive strain ε_{cc} is at ε_{cud} and steel reinforcement has yield and the reinforcement stress is at f_{yd} at ULS.
4. The strain in the reinforcement, tension or compression, is the same as the surrounding UHPC and strain is zero after the reinforcement in the bottom.
5. SI Units are adopted. [i.e. Moment (kNm), Shear (kN), Dimensions (mm), Area (mm^2), Moment of Inertia (mm^4), Stress / Modulus of Elasticity / Strength (N/mm^2 or MPa)].

A2 Design Forces

ULS Design Moment $M_{Ed.ULS} := 1000$

SLS Design Moment (Characteristic Load Comb.) $M_{Ed.SLS} := 750$

ULS Design Shear $V_{Ed.ULS} := 250$



A3 Configuration

Member Width $b_{bm} := 1000$

Member Thickness $t_{bm} := 500$

Span Length $L_{span} := 19 \cdot 10^3$

Exposure Class $XC4$

Max. Crack Width Requirement $w_{max} := 0.25$ TG Cl. 3.2.1.2 Table 3.1

Min. Cover Requirement $c_{min} := 25$ TG Cl. 2.4.1 Table 2.2

A4 Reinforcement

Longitudinal Bottom 1st Layer Reinforcement $\phi_{b1} := 20$

Longitudinal Bottom 2nd Layer Reinforcement $\phi_{b2} := 20$

Link $\phi_{link} := 12$

No. of 1st Layer Reinforcement $Nr_{b1} := 22$

No. of 2nd Layer Reinforcement $Nr_{b2} := Nr_{b1} = 22$

Area of 1st Layer Reinforcement $A_{b1} := Nr_{b1} \cdot \dfrac{\pi \cdot \phi_{b1}^2}{4} = 6912$

Area of 2nd Layer Reinforcement $A_{b2} := Nr_{b2} \cdot \dfrac{\pi \cdot \phi_{b2}^2}{4} = 6912$

B Materials & Strength

B1 Materials - Reinforcement

Partial Factor for Reinforcement in ULS	$\gamma_s := 1.15$	TG Cl. 2.6 Table 2.4
Characteristic Reinforcement Stress	$f_{yk} := 500$	
Design Modulus of Elasticity	$E_s := 200 \cdot 10^3$	BS EN 1992 Cal. 3.2.7(4)
Characteristic Ultimate Strain of Reinforcement	$\varepsilon_{uk} := 7.5 \cdot \%$	TG Cl. 3.1.1(3)

B2 Materials - Fibres

Length of Fibres	$L_f := 13$	TG Appendix B Table B1
Global Fibre Orientation	$K_{global} := 1.25$	TG Appendix B Table B1
Local Fibre Orientation	$K_{local} := 1.75$	TG Appendix B Table B1

B3 Materials - UHPC

ULS Partial Factor for Compressed UHPC	$\gamma_c := 1.5$	TG Cl. 2.6 Table 2.4
ULS Partial Factor for Tensioned UHPC	$\gamma_{cf} := 1.3$	TG Cl. 2.6 Table 2.4
Characteristics Compressive Cylinder Strength	$f_{ck} := 190$	TG Appendix B Table B1
Characteristics Post-cracking Strength	$f_{ctfk} := 9$	TG Appendix B Table B1
Characteristic Tensile Limit of Elasticity	$f_{ctk.el} := 7$	TG Appendix B Table B1
Mean Compressive Strength	$f_{cm} := 160$	TG Appendix B Table B1
Mean Post-cracking Strength	$f_{ctfm} := 11$	TG Appendix B Table B1
Mean Tensile Limit of Elasticity	$f_{ctm.el} := 8$	TG Appendix B Table B1
Mean Modulus of Elasticity	$E_{cm} := 45 \cdot 10^3$	TG Cl. 2.2.2(1)
Creep Coefficient (w/o Steam Curing)	$\varphi_{ef} := 0.8$	TG Cl. 2.2.8(1)(a)

B4 Strength - Reinforcement

Design Stress of Reinforcement $$f_{yd} := \frac{f_{yk}}{\gamma_s} = 434.78$$

Design Strain of Reinforcement $$\varepsilon_{ys} := \frac{f_{yd}}{E_s} = 0.217 \cdot \%$$

Design Ultimate Strain of Reinforcement $$\varepsilon_{ud} := 0.9 \cdot \varepsilon_{uk} = 6.750 \cdot \%$$

B5 Strength - UHPC - Compressive Strength

Design Compressive Strength $$f_{cd} := \frac{0.67 \cdot f_{ck}}{\gamma_c} = 84.87$$ TG Cl. 2.2.9(2) Eq. 2.7

Design Ultimate Elastic Shortening Strain $$\varepsilon_{c0d} := \frac{f_{cd}}{E_{cm}} = 0.189 \cdot \%$$ TG Cl. 2.2.9(3) Eq. 2.8

Design Ultimate Shortening Strain $$\varepsilon_{cud} := \left(1 + 14 \cdot \frac{f_{ctfm}}{K_{global} \cdot f_{cm}}\right) \cdot \varepsilon_{c0d} = 0.334 \cdot \%$$ TG Cl. 2.2.9(4) Eq. 2.9

B6 Strength - UHPC - Tensile Strength

B.6.1 Check Tensile Behaviour

$Check_{tensile.behaviour} :=$ "Strain Hardening" if $\frac{f_{ctfm}}{K_{global}} \geq f_{ctm.el}$ and $\frac{f_{ctfk}}{K_{global}} \geq f_{ctk.el}$; "Not Applicable" otherwise $=$ "Strain Hardening"

TG Cl. 2.2.4

B6.2 Check Thick / Thin Member

$Check_{conventional.law} :=$ "Thick Member" if $t_{bm} \geq 3 \cdot L_f$; "Thin Member" otherwise $=$ "Thick Member"

TG Cl. 2.2.5

Characteristic Length	$L_c := \frac{2 \cdot t_{bm}}{3} = 333.3$	TG Cl. 2.2.10(5)
ULS Design Tensile Limit of Elasticity	$f_{ctd.el} := \frac{f_{ctk.el}}{\gamma_{cf}} = 5.38$	
ULS Strain at Max. Limit of Elasticity	$\varepsilon_{u.el} := \frac{f_{ctd.el}}{E_{cm}} = 0.012 \cdot \%$	TG Cl. 2.2.10(4) Eq. 2.12
ULS Design Post-cracking Strength	$f_{ctfd} := \frac{f_{ctfk}}{\gamma_{cf} \cdot K_{global}} = 5.54$	
ULS Ultimate Strain in Tension	$\varepsilon_{u.lim} := \frac{L_f}{4 \cdot L_c} = 0.975 \cdot \%$	TG Cl. 2.2.10(5) Eq. 2.13
SLS Design Tensile Limit of Elasticity	$f_{ctd.el.SLS} := f_{ctk.el} = 7.00$	
SLS Strain at Max. Limit of Elasticity	$\varepsilon_{el} := \frac{f_{ctd.el.SLS}}{E_{cm}} = 0.016 \cdot \%$	
SLS Design Post-cracking Strength	$f_{ctfd.SLS} := \frac{f_{ctfk}}{K_{global}} = 7.20$	
SLS Ultimate Strain in Tension	$\varepsilon_{lim} := \varepsilon_{u.lim} = 0.975 \cdot \%$	

C Cover & Spacing of Bars

C1 UHPC Cover

Additive Safety Element — $\Delta c_{dur.\gamma} := 0$ — NF P18-710 Cl. 4.4.1.2(6)

Reduction of Min. Cover for Use of Stainless Steel — $\Delta c_{dur.st} := 0$ — NF P18-710 Cl. 4.4.1.2(7)

Additional Protection — $\Delta c_{dur.add} := 0$ — NF P18-710 Cl. 4.4.1.2(8)

Max. Aggregate Size — $D_{sup} := 14$

Min. Cover for Bond — $c_{min.b} := max(\phi_{b1}, \phi_{b2}) = 20.0$ — NF P18-710 Cl. 4.4.1.2(3)

Min. Cover that Take Placement Conditions into Account — $c_{min.p} := max(1.5 \cdot L_f, 1.5 \cdot D_{sup}, max(\phi_{b1}, \phi_{b2})) = 21.0$ — NF P18-710 Cl. 4.4.1.2(2)

Min. Cover Required — $c_{min.req} := max(c_{min.b}, c_{min} + \Delta c_{dur.\gamma} - \Delta c_{dur.st} - \Delta c_{dur.add}, c_{min.p}, 10) = 25.0$

UHPC Nominal Cover — $c_{nom} := max(c_{min}, c_{min.req}) = 25.0$

C2 UHPC Spacing of Reinforcement

Min. Clear Distance — $e_{min} := max(\phi_{b1}, \phi_{b2}, D_{sup} + 5, 1.5L_f, 20) = 20.0$ — TG Cl 4.2 Eq. 4.1 & Eq. 4.2

Horizontal Clear Distance — $e_h := e_{min} = 20.0$ — TG Cl. 4.2 Eq. 4.1

Vertical Clear Distance — $e_v := e_{min} = 20.0$ — TG Cl. 4.2 Eq. 4.2

C2.1 Check Spacing of Longitudinal Reinforcement

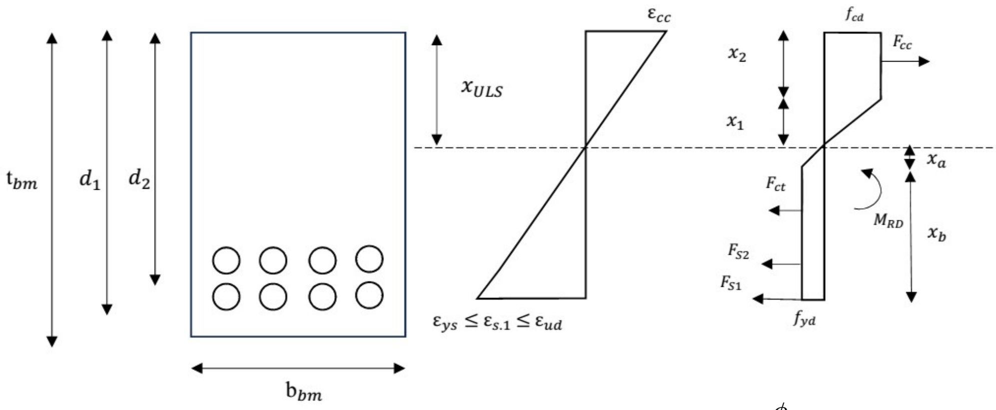
Longitudinal Bottom 1st Layer Reinforcement Spacing

$$S_d := \frac{b_{bm} - 2 \cdot c_{min} - 2 \cdot \phi_{link} - max(\phi_{b1}, \phi_{b2})}{Nr_{b1}} = 41.2$$

$$Check_{long.bar.spacing} := \begin{cases} \text{"Long. Rebar Spacing O.K."} & \text{if } S_d \geq \phi_{b1} + e_h \wedge \phi_{b2} + e_h \\ \text{"Long. Rebar Spacing Fail !"} & \text{otherwise} \end{cases} = \text{"Long. Rebar Spacing O.K."}$$

D ULS Bending Resistance

D1 UHPC Bending Resistance



Effective Depth for 1st Layer $$d_1 := t_{bm} - c_{nom} - \phi_{link} - \frac{\phi_{b1}}{2} = 453.0$$

Effective Depth for 2nd Layer $$d_2 := t_{bm} - c_{nom} - \phi_{link} - \phi_{b1} - e_v - \frac{\phi_{b2}}{2} = 413.0$$

Horizontal Equilibrium between the Forces, find compressive depth (i.e. N.A.) $x := 1$ Try x from 1 until x_{ULS} at equilibrium

$$f_1(x) := f_{cd} \cdot \left[\frac{1}{2} \cdot \frac{\varepsilon_{c0d}}{\varepsilon_{cud}} + \left(1 - \frac{\varepsilon_{c0d}}{\varepsilon_{cud}}\right)\right] \cdot x \cdot b_{bm} \cdot \frac{1}{10^3} - f_{yd} \cdot A_{b1} \cdot \frac{1}{10^3} - f_{yd} \cdot A_{b2} \cdot \frac{1}{10^3} - f_{ctd.el}\left[\left(\frac{1}{2} \cdot \frac{\varepsilon_{u.el}}{\varepsilon_{cud}}\right) \cdot x + \left(d_1 - x - \frac{\varepsilon_{u.el}}{\varepsilon_{cud}} \cdot x\right)\right] \cdot b_{bm} \cdot \frac{1}{10^3}$$

Compressive Depth of UHPC (N.A.) $$x_{ULS} := root(f_1(x), x) = 127.3$$

Depth

$$x_1 := \frac{\varepsilon_{c0d}}{\varepsilon_{cud}} \cdot x_{ULS} = 71.9 \qquad x_2 := x_{ULS} - x_1 = 55.4 \qquad x_a := x_1 \cdot \frac{\varepsilon_{u.el}}{\varepsilon_{c0d}} = 4.6 \qquad x_b := d_1 - x_{ULS} - x_a = 321.1$$

Compressive Force in UHPC $$F_{cc} := f_{cd} \cdot \left(\frac{x_1}{2} + x_2\right) \cdot b_{bm} \cdot \frac{1}{10^3} = 7752$$

Moment Resistance in UHPC $$M_{cc} := f_{cd} \cdot \left[\frac{x_1^2}{3} + x_2 \cdot \left(x_1 + \frac{x_2}{2}\right)\right] \cdot b_{bm} \cdot \frac{1}{10^6} = 614$$

Tensile Force in Layer 1 Reinforcement $$F_{s.1} := f_{yd} \cdot A_{b1} \cdot \frac{1}{10^3} = 3005$$

Moment Resistance in Layer 1 Reinforcement $$M_{s.1} := F_{s.1} \cdot \left(d_1 - x_{ULS}\right) \cdot \frac{1}{10^3} = 979$$

Tensile Force in Layer 2 Reinforcement $$F_{s.2} := f_{yd} \cdot A_{b2} \cdot \frac{1}{10^3} = 3005$$

Moment Resistance in Layer 2 Reinforcement $$M_{s.2} := F_{s.2} \cdot \left(d_2 - x_{ULS}\right) \cdot \frac{1}{10^3} = 859$$

Tensile Force in UHPC $$F_{ct} := f_{ctd.el} \left(\frac{x_a}{2} + x_b\right) \cdot b_{bm} \cdot \frac{1}{10^3} = 1741$$

Moment Resistance in UHPC $$M_{ct} := f_{ctd.el} \cdot \left[\frac{x_a^2}{3} + x_b \cdot \left(x_a + \frac{x_b}{2}\right)\right] \cdot b_{bm} \cdot \frac{1}{10^6} = 286$$

D1.1 Check Strain Limit of Reinforcement

Strain of 1st Layer Reinforcement

$$\varepsilon_{s.1} := \frac{\varepsilon_{cud} \cdot (d_1 - x_{ULS})}{x_{ULS}} = 0.854 \cdot \%$$

$$Check_{strain.layer.1} := \begin{cases} \text{"Normal reinforced"} & \text{if } \varepsilon_{ys} \le \varepsilon_{s.1} \wedge \varepsilon_{s.1} \le \varepsilon_{ud} \\ \text{"Not normal reinforced"} & \text{otherwise} \end{cases} = \text{"Normal reinforced"}$$

D1.2 Check Strain Limit of UHPC in Tension

$$Check_{strain.uhpc.tensile} := \begin{cases} \text{"No Tensile Contribution by UHPC "} & \text{if } \varepsilon_{s.1} \ge \varepsilon_{u.lim} \\ \text{"Tensile Contribution added by UHPC"} & \text{otherwise} \end{cases} = \text{"Tensile Contribution added by UHPC"}$$

D1.3 Check Horizontal Force Equilibrium

Resultant Horizontal Force

$$F_{cc} - F_{s.1} - F_{s.2} - F_{ct} = -0.00$$

$$Check_{force.equilibrium} := \begin{cases} \text{"Close Enough"} & \text{if } \left| F_{cc} - F_{s.1} - F_{s.2} - F_{ct} \right| \le 1 \\ \text{"Retry Compressive Depth, x"} & \text{otherwise} \end{cases} = \text{"Close Enough"}$$

D1.4 Check Ultimate Moment Resistance

ULS Design Moment Resistance

$$M_{Rd} := M_{cc} + M_{s.1} + M_{s.2} + M_{ct} = 2737$$

$$Check_{moment} := \begin{cases} \text{"ULS Moment Reistance O.K."} & \text{if } M_{Rd} \ge M_{Ed.ULS} \\ \text{"Retry Section or Reinforcement"} & \text{otherwise} \end{cases} = \text{"ULS Moment Reistance O.K."}$$

E ULS Shear Resistance

E1 UHPC Shear Resistance

Long-term effects Coefficient	$\alpha_{cc} := 0.85$	TG Cl. 3.1.2.5
	$k := 1$ where $\sigma_{cp} = 0\ N/mm^2$	TG Cl. 3.1.2.2(1) Eq. 3.4
Safety Factor	$\gamma_E := \frac{1.5}{\gamma_{cf}} = 1.15$	TG Cl. 3.1.2.2(1)
Distance from Top to Reinforcements Centroid	$d := \frac{Nr_{b1} \cdot A_{b1} \cdot d_1 + Nr_{b2} \cdot A_{b2} \cdot d_2}{Nr_{b1} \cdot A_{b1} + Nr_{b2} \cdot A_{b2}} = 433.0$	TG Cl. 3.1.2.2(1)
Lever Arm	$z := 0.9 \cdot d = 389.7$	TG Cl. 3.1.2.2(2)
UHPC Contribution Term	$V_{Rd.c} := \frac{0.21}{\gamma_{cf} \cdot \gamma_E} \cdot k \cdot \sqrt{f_{ck}} \cdot b_{bm} \cdot d \cdot \frac{1}{10^3} = 836$	TG Cl. 3.1.2.2(1) Eq. 3.3
Reinforcement Contribution Term	$V_{Rd.s} := 0$	TG Cl. 3.1.2.3
Strain Limit at ULS	$\varepsilon_x := \varepsilon_{u.lim} = 0.975 \cdot \%$	
Compression Area	$A_{fv} := b_{bm} \cdot z = 389700$	TG Cl. 3.1.2.4
Integration of Stress-Strain Function	$\sigma_f := \left(f_{ctd.el.SLS} + f_{ctfd.SLS}\right) \cdot \left(\frac{\varepsilon_{u.lim} - \varepsilon_{el}}{2}\right) \cdot 10^2 = 6.81$	
Mean Post-cracking Strength Value	$\sigma_{Rd.f} := \frac{1}{K_{global} \cdot \gamma_{cf}} \cdot \frac{1}{\left(\varepsilon_x - \varepsilon_{el}\right)} \cdot \sigma_f \cdot \frac{1}{10^2} = 4.37$	TG Cl. 3.1.2.4(2) Eq. 3.11
Inclination of Main Compression Stress on Long. Axis	$\theta := 30 \cdot deg$	TG Cl. 2.5.5(2)(a)
Fibre Contribution Term	$V_{Rd.f} := A_{fv} \cdot \sigma_{Rd.f} \cdot cot(\theta) \cdot \frac{1}{10^3} = 2949$	TG Cl. 3.1.2.4(1) Eq. 3.10
Superposition of Three Resistance Term	$V_{Rd} := V_{Rd.c} + V_{Rd.s} + V_{Rd.f} = 3785$	TG Cl. 3.1.2.1(1)
Limit Force for Compressive Strength	$V_{Rd.max} := 2.3 \cdot \frac{\alpha_{cc}}{\gamma_c} \cdot b_{bm} \cdot z \cdot f_{ck}^{\frac{2}{3}} \cdot tan(\theta) \cdot \frac{1}{10^3} = 9692$	TG Cl. 3.1.2.5(1) Eq. 3.12
ULS Design Shear Resistance	$V_{Ed.total} := min\left(V_{Rd}, V_{Rd.max}\right) = 3785$	TG Cl. 3.1.2.1(1) Eq. 3.2

$Check_{shear} :=$ "ULS Shear Resistance O.K." if $V_{Ed.total} \geq V_{Ed.ULS}$ = "ULS Shear Resistance O.K."
"Retry Section or Reinforcement" otherwise

F Crack Control

F1 Verification of Crack

UHPC Gross Area $A_c := b_{bm} \cdot t_{bm} = 500000$

Effective Modulus of Elasticity of UHPC with Creep $E_{c.eff} := \frac{E_{cm}}{1 + \varphi_{ef}} = 25.000 \times 10^3$ NF P18-710 Cl. 7.4.3 Eq. 7.221

Modular Ratio $\alpha_c := \frac{E_s}{E_{c.eff}} = 8.00$

Moment of Inertia $I_c := \frac{b_{bm} \cdot t_{bm}^3}{12} = 10.417 \times 10^9$

C.G. $y_{cg} := \frac{t_{bm}}{2} = 250.0$

Transformed Gross Area $A_{tr} := A_c + (\alpha_c - 1) \cdot (A_{b1} + A_{b2}) = 596761$

Transformed C.G. $y_{tr} := \frac{A_c \cdot y_{cg} + (\alpha_c - 1) \cdot (A_{b1} \cdot d_1 + A_{b2} \cdot d_2)}{A_{tr}} = 279.7$

Transformed Moment of Inertia $I_{tr} := I_c + A_c \cdot (y_{cg} - y_{tr})^2 + (\alpha_c - 1) \cdot \left[A_{b1} \cdot (d_1 - y_{tr})^2 + A_{b2} \cdot (d_2 - y_{tr})^2\right] = 13.170 \times 10^9$

Tensile Stress at the Bottom $\sigma_{ct} := \frac{M_{Ed.SLS}}{I_{tr}} \cdot (t_{bm} - y_{tr}) \cdot 10^6 = 12.55$

$Check_{tensile.stress} :=$ | "Not Cracked Section" if $\sigma_{ct} \le f_{ctd.el.SLS}$ = "Cracked Section"
"Cracked Section" otherwise

F2 Crack Width Control

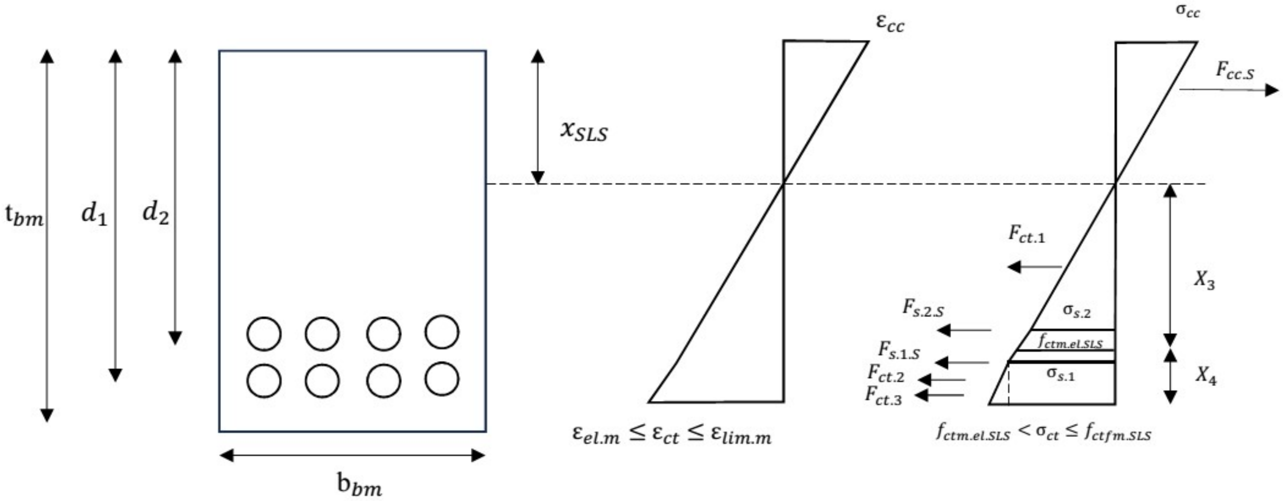
Load Duration Factor $k_t := 0.4$ TG Cl. 3.2.1.5(2)

SLS Mean Design Tensile Limit of Elasticity $f_{ctm.el.SLS} := f_{ctm.el} = 8.00$

SLS Mean Max. Limit of Elasticity $\varepsilon_{el.m} := \frac{f_{ctm.el.SLS}}{E_{c.eff}} = 0.032 \cdot \%$

SLS Mean Design Post-cracking Strength $f_{ctm.SLS} := \frac{f_{ctfm}}{K_{global}} = 8.80$

SLS Mean Ultimate Strain in Tension $\varepsilon_{lim.m} := \varepsilon_{lim} = 0.975 \cdot \%$



Compressive Depth of UHPC (i.e. N.A.) $x_{SLS} := 277.06$

Compressive Strain of UHPC $\varepsilon_{cc} := 0.065 \cdot \%$

Strain of Tensioned UHPC $\varepsilon_{ct} := \varepsilon_{cc} \cdot \frac{t_{bm} - x_{SLS}}{x_{SLS}} = 0.052 \cdot \%$

F2.1 Check Strain Limit of Reinforcement

$Check_{strain.limit} := \begin{cases} \text{"Strain Limit O.K."} & \text{if } \varepsilon_{el.m} \le \varepsilon_{ct} \wedge \varepsilon_{ct} \le \varepsilon_{lim.m} \\ \text{"Not O.K."} & \text{otherwise} \end{cases} = \text{"Strain Limit O.K."}$

UHPC under Compression

Compressive Stress of UHPC $\sigma_{cc} := \varepsilon_{cc} \cdot E_{c.eff} = 16.25$

Compressive Force of UHPC $F_{cc.S} := \sigma_{cc} \cdot \frac{x_{SLS} \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = 2251$

Lever Arm for UHPC under Compression $x_{cc.S} := x_{SLS} \cdot \frac{2}{3} = 184.7$

Reinforcement	***1st Layer***	***2nd Layer***
Strain @ Reinforcement	$\varepsilon_{s.1.S} := \varepsilon_{cc} \cdot \frac{d_1 - x_{SLS}}{x_{SLS}} = 0.041 \cdot \%$	$\varepsilon_{s.2.S} := \varepsilon_{cc} \cdot \frac{d_2 - x_{SLS}}{x_{SLS}} = 0.032 \cdot \%$
Stress @ Reinforcement	$\sigma_{s.1} := \varepsilon_{s.1.S} \cdot E_s = 82.55$	$\sigma_{s.2} := \varepsilon_{s.2.S} \cdot E_s = 63.78$
Force @ Reinforcement	$F_{s.1.S} := \sigma_{s.1} \cdot Nr_{b1} \cdot \pi \cdot \frac{\phi_{b1}^2}{4} \cdot \frac{1}{10^3} = 571$	$F_{s.2.S} := \sigma_{s.2} \cdot Nr_{b2} \cdot \pi \cdot \frac{\phi_{b2}^2}{4} \cdot \frac{1}{10^3} = 441$
Lever Arm @ Reinforcement	$x_{s.1.S} := d_1 - x_{SLS} = 175.9$	$x_{s.2.S} := d_2 - x_{SLS} = 135.9$

UHPC under Tension

Height that is Uncracked $x_3 := (t_{bm} - x_{SLS}) \cdot \frac{\varepsilon_{el.m}}{\varepsilon_{ct}} = 136.4$

Height that is Cracked $x_4 := t_{bm} - x_{SLS} - x_3 = 86.5$

Tensile Force of Uncracked UHPC $F_{ct.1} := f_{ctm.el.SLS} \cdot \frac{x_3 \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = 546$

Lever Arm of Uncracked UHPC $x_{ct.1.S} := x_3 \cdot \frac{2}{3} = 90.9$

Tensile Force of Cracked UHPC $F_{ct.2} := f_{ctm.el.SLS} \cdot x_4 \cdot b_{bm} \cdot \frac{1}{10^3} = 692$

Lever Arm for Cracked UHPC $x_{ct.2.S} := x_3 + \frac{x_4}{2} = 179.7$

Tensile Force of Cracked UHPC $F_{ct.3} := (f_{ctm.SLS} - f_{ctm.el.SLS}) \cdot \frac{\varepsilon_{ct}}{\varepsilon_{lim.m}} \cdot \frac{x_4 \cdot b_{bm}}{2} \cdot \frac{1}{10^3} = 2$

Lever Arm for Cracked UHPC $x_{ct.3.S} := x_3 + x_4 \cdot \frac{2}{3} = 194.1$

F2.2 Check Horizontal Force Equilibrium

Resultant Horizontal Force $F_{cc.S} - F_{s.1.S} - F_{s.2.S} - F_{ct.1} - F_{ct.2} - F_{ct.3} = -0.08$

$Check_{SLS.force.equilibrium} :=$ "Close Enough" if $|F_{cc.S} - F_{s.1.S} - F_{s.2.S} - F_{ct.1} - F_{ct.2} - F_{ct.3}| \le \frac{F_{cc.S}}{100}$ = "Close Enough"
"Retry Compressive Depth, x_SLS" otherwise

F2.3 Check Moment Equilibrium

SLS Moment Resistance $M_{cr} := (F_{cc.S} \cdot x_{cc.S} + F_{s.1.S} \cdot x_{s.1.S} + F_{s.2.S} \cdot x_{s.2.S} + F_{ct.1} \cdot x_{ct.1.S} + F_{ct.2} \cdot x_{ct.2.S} + F_{ct.3} \cdot x_{ct.3.S}) \cdot \frac{1}{10^3} = 750$

Resultant Moment $M_{Ed.SLS} - M_{cr} = -0.47$

$Check_{SLS.moment.equilibrium} :=$ "Close Enough" if $|M_{Ed.SLS} - M_{cr}| \le \frac{M_{Ed.SLS}}{100}$ = "Close Enough"
"Retry Compressive Strain, ε_cc" otherwise

Stress in Tensioned Reinforcement $\sigma_s := \sigma_{s.1} = 82.55$

Effective Height $h_{c.ef} := \min\left[2.5(t_{bm} - d), \frac{t_{bm}}{2}\right] = 167.5$ TG Cl. 3.2.1.5(2) Eq. 3.26

Effective Cross-sectional Area $A_{c.eff} := h_{c.ef} \cdot b_{bm} = 167500$ TG Cl. 3.2.1.5(2)

Ratio of Reinforcement to Effective Area. $\rho_{p.eff} := \frac{A_{b1} + A_{b2}}{A_{c.eff}} = 0.083$ TG Cl. 3.2.1.5(2)

$$\varepsilon_{sm.f\_\varepsilon.cm.f} := \frac{\sigma_s}{E_s} - \frac{f_{ctfm}}{K_{global} \cdot E_{cm}} - \frac{1}{E_s}\left[k_t \cdot \left(f_{ctm.el} - \frac{f_{ctfm}}{K_{local}}\right) \cdot \left(\frac{1}{\rho_{p.eff}} + \frac{E_s}{E_{cm}}\right)\right] = 160.427 \times 10^{-6}$$ TG Cl. 3.2.1.5(2) Eq. 3.25

F3 Crack Width Spacing

Contribution from Fibres $\delta_o := min\left(1 + 0.4 \cdot \frac{f_{ctfm}}{K_{global} \cdot f_{ctm.el}}, 1.5\right) = 1.44$ TG Cl. 3.2.1.5(3) Eq. 3.30

Concrete Coating Term $l_o := 1.33 \cdot \frac{c_{nom}}{\delta_o} = 23.1$ TG Cl. 3.2.1.5(3) Eq. 3.28

For Steel Reinforcement $\eta := 2.25$ TG Cl. 3.2.1.5(3)

For Bending w/ or w/o Axial Force $k_2 := 0.5$ TG Cl. 3.2.1.5(3)

Transmission Length $l_t := max\left[\frac{L_f}{2}, 2 \cdot 0.3 \cdot k_2 \cdot \left(1 - \frac{f_{ctfm}}{K_{global} \cdot f_{ctm.el}}\right) \cdot \frac{1}{\delta_o \cdot \eta} \cdot \frac{\phi_{b1}}{\rho_{p.eff}}\right] = 6.5$ TG Cl. 3.2.1.5(3) Eq. 3.29

Max. Crack Width Spacing $s_{r.max.f} := 2.55 \cdot (l_o + l_t) = 75.5$ TG Cl. 3.2.1.5(3) Eq. 3.27

Crack Width at the Most Tensioned Reinforcement $w_s := s_{r.max.f} \cdot \varepsilon_{sm.f\_\varepsilon.cm.f} = 0.01$ TG Cl. 3.2.1.5(2) Eq. 3.24

F4 Correction of Crack Width

F5.1 Check Correction of Crack Width

$Check_{crack.spacing} :=$ "Correction." if $S_d > 5 \cdot \left(c_{nom} + \frac{\phi_{b1}}{2}\right)$ = "No Correction"
"No Correction" otherwise

NF P18-710 Cl. 7.3.4(4)

F5 Crack Width

Crack Width at the Most Tensioned Fibre $w_{t.b} := w_s \cdot \frac{(t_{bm} - x_{SLS} - x_3)}{(d - x_{SLS} - x_3)} = 0.05$ TG Cl. 3.2.1.5(2) Eq. 3.23

$Check_{crack.width} :=$ "Crack Width O.K." if $w_{t.b} \le w_{max}$ = "Crack Width O.K."
"Not O.K. !" otherwise

APPENDIX C3

PRESTRESSED UHPC BEAM DESIGN

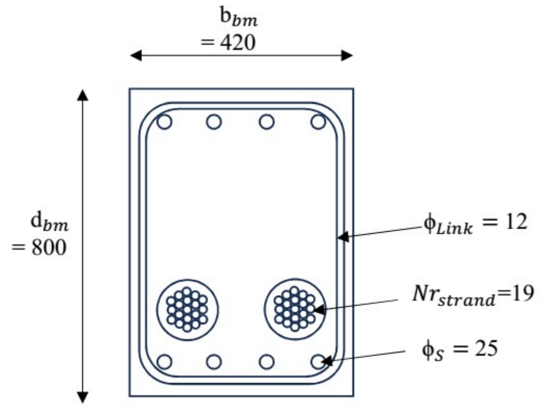
PRESTRESSED UHPC BEAM DESIGN

A Calculation Principles

A1 Design Assumptions

1. This example adopts a simplified load combination for illustrative purpose. Comprehensive design shall be made against the complete set of load combinations required by the applicable codes.
2. Steam curing will not be used.
3. The compressive strain ε_{cc} is at ε_{cud} and steel reinforcement has yield and the reinforcement stress is at f_{yd} at ULS.
4. The strain in the reinforcement, tension or compression, is the same as the surrounding UHPC and strain is zero after the reinforcement in the bottom.
5. SI Units are adopted. [i.e. Moment (kNm), Shear (kN), Dimensions (mm), Area (mm^2), Moment of Inertia (mm^4), Stress / Modulus of Elasticity / Strength (N/mm^2 or MPa)].

A2 Design Forces



ULS Design Moment $M_{Ed.ULS} := 1500$

SLS Design Moment (@ Transfer) $M_{Ed.SLS.tran} := 500$

SLS Design Moment (@ Service) $M_{Ed.SLS.ser} := 800$

ULS Design Shear $V_{Ed.ULS} := 500$

ULS Design Torsion $T_{Ed.ULS} := 300$

A3 Configuration

Beam Width $b_{bm} := 420$

Beam Depth $d_{bm} := 800$

Span Length $L_{span} := 45 \cdot 10^3$

Exposure Class XC4

Min. Cover Requirement $c_{min} := 30$

TG Cl. 2.4.1 Table 2.3

A4 Reinforcement

No. of Longitudinal Reinforcement (Bottom) $Nr_s := 4$

Longitudinal Reinforcement Diameter (Bottom) $\phi_s := 25$

Link $\phi_{link} := 12$

Link Spacing $S_{link} := 300$

A5 Prestressing Steel (Tendon)

Partial Factor for Tendon in ULS $\gamma_p := 1.15$

TG Cl. 2.6 Table 2.4

Modulus of Elasticity $E_{ps} := 195 \cdot 10^3$

Total No. of Tendon $Nr_{tendon} := 2$

Total No. of Strand $Nr_{strand} := 19$

Nominal Area of Strand $A_p := 150$

Characteristic Yield Strength $f_{p0.1k} := 1640$

Nominal Tensile Strength $f_{pk} := 1860$

Initial Prestress $PT_{\%} := 70 \cdot \%$

Relaxation (1000h at 20 Deg & 70% f_{pk}) $\rho_{1000} := 2.5 \cdot \%$ HKSDMHR Item 5.7.6

Friction Coefficient $\mu_{tendon} := 0.19$

Wobble Factor $k_{tendon} := 0.0075$

Tendon Curvature $\theta_{tendon} := 0$

Wedge Draw-in $\Delta_{tendon} := 6$

Depth of Tendon (measured from Top) $d_{pt} := 600$

B Materials & Strength

B1 Materials - Reinforcement

Partial Factor for Reinforcement in ULS	$\gamma_s := 1.15$	TG Cl. 2.6 Table 2.4
Characteristic Reinforcement Stress	$f_{yk} := 500$	
Design Modulus of Elasticity	$E_s := 200 \cdot 10^3$	BS EN 1992 Cal. 3.2.7(4)
Characteristic Ultimate Strain of Reinforcement	$\varepsilon_{uk} := 7.5 \cdot \%$	TG Cl. 3.1.1(3)

B2 Materials - Fibres

Length of Fibres	$L_f := 13$	TG Appendix B Table B1
Global Fibre Orientation	$K_{global} := 1.25$	TG Appendix B Table B1
Local Fibre Orientation	$K_{local} := 1.75$	TG Appendix B Table B1

B3 Materials - UHPC

ULS Partial Factor for Compressed UHPC	$\gamma_c := 1.5$	TG Cl. 2.6 Table 2.4
ULS Partial Factor for Tensioned UHPC	$\gamma_{cf} := 1.3$	TG Cl. 2.6 Table 2.4
Characteristics Compressive Cylinder Strength	$f_{ck} := 190$	TG Appendix B Table B1
Characteristics Post-cracking Strength	$f_{ctfk} := 9$	TG Appendix B Table B1
Characteristic Tensile Limit of Elasticity	$f_{ctk.el} := 7$	TG Appendix B Table B1
Mean Compressive Strength	$f_{cm} := 160$	TG Appendix B Table B1
Mean Post-cracking Strength	$f_{ctfm} := 11$	TG Appendix B Table B1
Mean Tensile Limit of Elasticity	$f_{ctm.el} := 8$	TG Appendix B Table B1
Mean Modulus of Elasticity	$E_{cm} := 45 \cdot 10^3$	TG Cl. 2.2.2(1)
Creep Coefficient (w/o Steam Curing)	$\varphi_{ef} := 0.8$	TG Cl. 2.2.8(1)(a)
Shrinkage (w/o Steam Curing)	$\varepsilon_{sh} := 700 \cdot 10^{-6}$	TG Cl. 2.2.7(1)(a)

B4 Strength - Reinforcement

Design Stress of Reinforcement $\quad f_{yd} := \frac{f_{yk}}{\gamma_s} = 434.78$

Design Strain of Reinforcement $\quad \varepsilon_{ys} := \frac{f_{yd}}{E_s} = 0.217 \cdot \%$

Design Ultimate Strain of Reinforcement $\quad \varepsilon_{ud} := 0.9 \cdot \varepsilon_{uk} = 6.750 \cdot \%$

B5 Strength - Tendon

Design Stress of Tendon $\quad f_{pd} := \frac{f_{pk}}{\gamma_p} = 1617.39$

Design Strain of Tendon $\quad \varepsilon_{ps} := \frac{f_{yd}}{E_{ps}} = 0.223 \cdot \%$

B6 Strength - UHPC - Compressive Strength

Design Compressive Strength	$f_{cd} := \frac{0.67 \cdot f_{ck}}{\gamma_c} = 84.87$	TG Cl. 2.2.9(2) Eq. 2.7
Design Ultimate Elastic Shortening Strain	$\varepsilon_{c0d} := \frac{f_{cd}}{E_{cm}} = 0.189 \cdot \%$	TG Cl. 2.2.9(3) Eq. 2.8
Design Ultimate Shortening Strain	$\varepsilon_{cud} := \left(1 + 14 \cdot \frac{f_{ctfm}}{K_{global} \cdot f_{cm}}\right) \cdot \varepsilon_{c0d} = 0.334 \cdot \%$	TG Cl. 2.2.9(4) Eq. 2.9

B7 Strength - UHPC - Tensile Strength

B.7.1 Check Tensile Behaviour

$$Check_{tensile.behaviour} := \begin{cases} \text{"Strain Hardening"} & \text{if } \frac{f_{ctfm}}{K_{global}} \geq f_{ctm.el} \wedge \frac{f_{ctfk}}{K_{global}} \geq f_{ctk.el} \\ \text{"Not Applicable"} & \text{otherwise} \end{cases} = \text{"Strain Hardening"}$$

TG Cl. 2.2.4

B7.2 Check Thick / Thin Member

$$Check_{conventional.law} := \begin{cases} \text{"Thick Member"} & \text{if } d_{bm} \geq 3 \cdot L_f \\ \text{"Thin Member"} & \text{otherwise} \end{cases} = \text{"Thick Member"}$$

TG Cl. 2.2.5

Characteristic Length	$L_c := \frac{2 \cdot d_{bm}}{3} = 533.3$	TG Cl. 2.2.10(5)
ULS Design Tensile Limit of Elasticity	$f_{ctd.el} := \frac{f_{ctk.el}}{\gamma_{cf}} = 5.38$	
ULS Strain at Max. Limit of Elasticity	$\varepsilon_{u.el} := \frac{f_{ctd.el}}{E_{cm}} = 0.012 \cdot \%$	TG Cl. 2.2.10(4) Eq. 2.12
ULS Design Post-cracking Strength	$f_{ctfd} := \frac{f_{ctfk}}{\gamma_{cf} \cdot K_{global}} = 5.54$	
ULS Ultimate Strain in Tension	$\varepsilon_{u.lim} := \frac{L_f}{4 \cdot L_c} = 0.609 \cdot \%$	TG Cl. 2.2.10(5) Eq. 2.13
SLS Design Tensile Limit of Elasticity	$f_{ctd.el.SLS} := f_{ctk.el} = 7.00$	
SLS Strain at Max. Limit of Elasticity	$\varepsilon_{el} := \frac{f_{ctd.el.SLS}}{E_{cm}} = 0.016 \cdot \%$	
SLS Design Post-cracking Strength	$f_{ctfd.SLS} := \frac{f_{ctfk}}{K_{global}} = 7.20$	
SLS Ultimate Strain in Tension	$\varepsilon_{lim} := \varepsilon_{u.lim} = 0.609 \cdot \%$	

C Cover & Spacing of Bars

C1 UHPC Cover

Additive Safety Element	$\Delta c_{dur.\gamma} := 0$	NF P18-710 Cl. 4.4.1.2(6)
Reduction of Min. Cover for Use of Stainless Steel	$\Delta c_{dur.st} := 0$	NF P18-710 Cl. 4.4.1.2(7)
Additional Protection	$\Delta c_{dur.add} := 0$	NF P18-710 Cl. 4.4.1.2(8)
Min. Upper Dim. of Largest Aggregate	$D_{sup} := 14$	
Min. Cover for Bond	$c_{min.b} := \phi_s = 25.0$	NF P18-710 Cl. 4.4.1.2(3)
Min. Cover that Take Placement Conditions into Account	$c_{min.p} := max(1.5 \cdot L_f, 1.5 \cdot D_{sup}, \phi_s) = 25.0$	NF P18-710 Cl. 4.4.1.2(2)
Min. Cover Required	$c_{min.req} := max(c_{min.b}, c_{min} + \Delta c_{dur.\gamma} - \Delta c_{dur.st} - \Delta c_{dur.add}, c_{min.p}, 10) = 30.0$	
UHPC Nominal Cover	$c_{nom} := max(c_{min}, c_{min.req}) = 30.0$	

C2 UHPC Spacing of Reinforcement

Min. Clear Distance	$e_{min} := max[\phi_s, (D_{sup} + 5), 1.5L_f, 20] = 25.0$	TG Cl. 4.2 Eq. 4.1
Horizontal Clear Distance	$e_h := \dfrac{b_{bm} - 2 \cdot c_{nom} - 2 \cdot \phi_{link} - Nr_s \cdot \phi_s}{(Nr_s - 1)} = 78.7$	

C2.1 Check Spacing of Longitudinal Reinforcement

$$Check_{long.bar.spacing} := \begin{cases} \text{"Long. Rebar Spacing O.K."} & \text{if } e_h \geq e_{min} \\ \text{"Long. Rebar Spacing Fail !"} & \text{otherwise} \end{cases} = \text{"Long. Rebar Spacing O.K."}$$

D SLS Stress Limitation

D1 Beam Section Properties

Area of Reinforcement $A_s := Nr_s \cdot \frac{\pi \cdot \phi_s^2}{4} = 1963$

Area of Link (2 Legs) $A_{sw} := 2 \cdot \frac{\pi \cdot \phi_{link}^2}{4} = 226$ TG Cl. 3.1.2.3(1)

Area of Strand (Total) $A_{ps.total} := Nr_{tendon} \cdot Nr_{strand} \cdot A_p = 5700$

Area of Concrete (Beam) $A_{bm} := b_{bm} \cdot d_{bm} = 336000$

Section Modulus (Top) $Z_{top} := \frac{b_{bm} \cdot d_{bm}^2}{6} = 44.800 \times 10^6$

Section Modulus (Bottom) $Z_{bot} := Z_{top} = 44.800 \times 10^6$

Moment of Inertia $I_{bm} := \frac{b_{bm} \cdot d_{bm}^3}{12} = 17.920 \times 10^9$

D2 Prestress Losses

Effective Modulus of Elasticity of UHPC with Creep $E_{c.eff} := \frac{E_{cm}}{1 + \varphi_{ef}} = 25.0 \times 10^3$ NF P18-710 Cl. 7.4.3 Eq. 7.221

Initial Prestress $\sigma_{pi} := PT_{\%} \cdot f_{pk} = 1302$

Ratio of Initial Prestress / Char. Yield Strength $\mu := \frac{\sigma_{pi}}{f_{p0.1k}} = 0.79$

Average Normal Compressive Stress $\sigma_{bm} := \frac{\sigma_{pi} \cdot A_{ps.total}}{A_{bm}} = 22.09$

Prestress Loss due to Friction (Short Term) $\%_{friction} := 1 - e^{-\mu_{tendon} \cdot \left(\theta_{tendon} + k_{tendon} \cdot \frac{L_{span}}{1000}\right)} = 6.21 \cdot \%$

Prestress Loss due to Wedge Draw-in (Short Term) $\%_{draw.in} := \frac{\Delta_{tendon} \cdot E_{ps}}{L_{span}} \cdot \frac{1}{\sigma_{pi}} = 2.00 \cdot \%$

Prestress Loss due to Elastic Shortening (Short Term) $\%_{elastic} := \frac{\sigma_{bm}}{\sigma_{pi}} = 1.70 \cdot \%$

Prestress Loss due to Creep (Long Term) $\%_{creep} := \frac{\frac{E_{ps}}{E_{cm}} \cdot \sigma_{bm} \cdot \varphi_{ef}}{1 + \frac{E_{ps}}{E_{c.eff}} \cdot \frac{A_{ps.total}}{A_{bm}} \cdot \left[1 + \frac{A_{bm}}{I_{bm}} \cdot \left(d_{pt} - \frac{d_{bm}}{2}\right)^2\right]} \cdot \frac{1}{\sigma_{pi}} = 4.78 \cdot \%$

Prestress Loss due to Shrinkage (Long Term) $\%_{shrinkage} := \varepsilon_{sh} \cdot E_{cm} \cdot \frac{1}{\sigma_{pi}} = 2.42 \cdot \%$

Prestress Loss due to Relaxation of Steel (Long Term) $\%_{relax} := 0.66 \cdot \rho_{1000} \cdot e^{9.1 \cdot \mu} \cdot \left(\frac{120 \cdot 365 \cdot 24}{1000}\right)^{0.75 \cdot (1-\mu)} \cdot 10^{-3} = 6.64 \cdot \%$

Total Prestress Loss (at Transfer) $\%_{ST} := \%_{friction} + \%_{draw.in} + \%_{elastic} = 9.90 \cdot \%$

Total Prestress Loss (at Service) $\%_{LT} := \%_{ST} + \%_{creep} + \%_{shrinkage} + \%_{relax} = 23.74 \cdot \%$

D3 SLS Stress Check (Case I: No Tensile Stress Permitted)

Design Compressive Strength (SLS) $f_{cd.sls} := 0.67 \cdot f_{ck} = 127.30$ where $\gamma_c = 1.0$ for SLS TG Cl. 2.2.9(2) Eq. 2.7

Compressive Stress Limit (SLS) $f_{cd.sls.lim} := 0.6 \cdot f_{cd.sls} = 76.38$ TG Cl. 3.2.1.1(3)(b)

Top Fibre Stress at Transfer

$$\sigma_{top.tran} := (1 - \%_{ST}) \cdot \sigma_{bm} - \frac{(1 - \%_{ST}) \cdot \sigma_{pi} \cdot A_{ps.total} \cdot \left(d_{pt} - \frac{d_{bm}}{2}\right)}{Z_{top}} + \frac{M_{Ed.SLS.tran}}{Z_{top}} \cdot 10^6 = 1.21$$

$Check_{top.stress.transfer} :=$ | "Top Stress within Stress Limit at Transfer" if $f_{cd.sls.lim} \geq \sigma_{top.tran} \geq 0$ = "Top Stress within Stress Limit at Transfer"
"Retry Section or Prestress !" otherwise

Bottom Fibre Stress at Transfer

$$\sigma_{bot.tran} := (1 - \%_{ST}) \cdot \sigma_{bm} + \frac{(1 - \%_{ST}) \cdot \sigma_{pi} \cdot A_{ps.total} \cdot \left(d_{pt} - \frac{d_{bm}}{2}\right)}{Z_{top}} - \frac{M_{Ed.SLS.tran}}{Z_{top}} \cdot 10^6 = 38.59$$

$Check_{bottom.stress.transfer} :=$ | "Bottom Stress within Stress Limit at Transfer" if $f_{cd.sls.lim} \geq \sigma_{bot.tran} \geq 0$ = "Bottom Stress within Stress Limit at Transfer"
"Retry Section or Prestress !" otherwise

Top Fibre Stress at Service

$$\sigma_{top.ser} := (1 - \%_{LT}) \cdot \sigma_{bm} - \frac{(1 - \%_{LT}) \cdot \sigma_{pi} \cdot A_{ps.total} \cdot \left(d_{pt} - \frac{d_{bm}}{2}\right)}{Z_{top}} + \frac{M_{Ed.SLS.ser}}{Z_{top}} \cdot 10^6 = 9.44$$

$Check_{top.stress.service} :=$ | "Top Stress within Stress Limit at Service" if $f_{cd.sls.lim} \geq \sigma_{top.ser} \geq 0$ = "Top Stress within Stress Limit at Service"
"Retry Section or Prestress !" otherwise

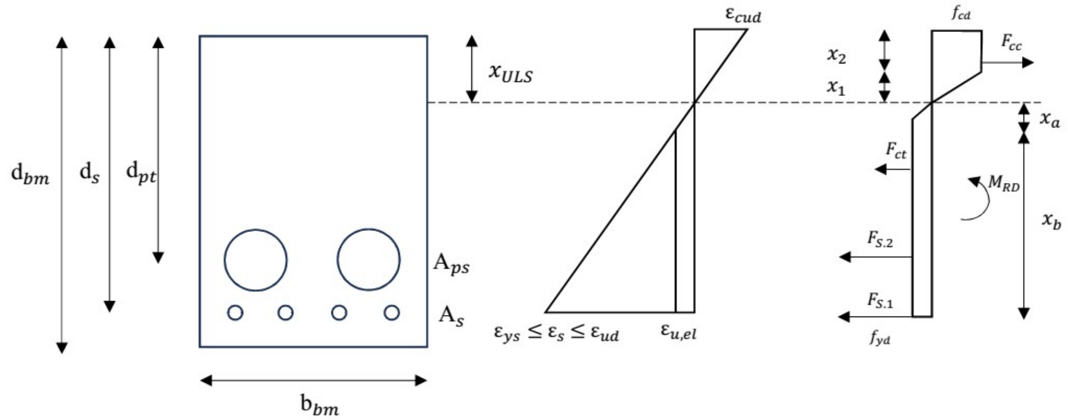
Bottom Fibre Stress at Service

$$\sigma_{bot.ser} := (1 - \%_{LT}) \cdot \sigma_{bm} + \frac{(1 - \%_{LT}) \cdot \sigma_{pi} \cdot A_{ps.total} \cdot \left(d_{pt} - \frac{d_{bm}}{2}\right)}{Z_{top}} - \frac{M_{Ed.SLS.ser}}{Z_{top}} \cdot 10^6 = 24.25$$

$Check_{bottom.stress.service} :=$ | "Bottom Stress within Stress Limit at Service" if $f_{cd.sls.lim} \geq \sigma_{bot.ser} \geq 0$ = "Bottom Stress within Stress Limit at Service"
"Retry Section or Prestress !" otherwise

E ULS Bending Resistance

E1 UHPC Bending Resistance



Effective Depth for Reinforcement $\quad d_s := d_{bm} - c_{nom} - \phi_{link} - \frac{\phi_s}{2} = 745.5$

Horizontal Equilibrium between the Forces, find compressive depth (i.e. N.A.) $\quad x := 1 \quad$ Try x from 1 until x_{ULS} at equilibrium

$$f_1(x) := f_{cd} \cdot \left[\frac{1}{2} \cdot \frac{\varepsilon_{c0d}}{\varepsilon_{cud}} + \left(1 - \frac{\varepsilon_{c0d}}{\varepsilon_{cud}}\right)\right] \cdot x \cdot b_{bm} \cdot \frac{1}{10^3} - f_{yd} \cdot A_s \cdot \frac{1}{10^3} - f_{pd} \cdot A_{ps.total} \cdot \frac{1}{10^3} - f_{ctd.el}\left[\left(\frac{1}{2} \cdot \frac{\varepsilon_{u.el}}{\varepsilon_{cud}}\right) \cdot x + \left(d_s - x - \frac{\varepsilon_{u.el}}{\varepsilon_{cud}} \cdot x\right)\right] \cdot b_{bm} \cdot \frac{1}{10^3}$$

Compressive Depth of UHPC (N.A.) $\quad x_{ULS} := root(f_1(x), x) = 421.8$

Depth $\quad x_1 := \frac{\varepsilon_{c0d}}{\varepsilon_{cud}} \cdot x_{ULS} = 238.3 \qquad x_2 := x_{ULS} - x_1 = 183.5$

$x_a := x_1 \cdot \frac{\varepsilon_{u.el}}{\varepsilon_{c0d}} = 15.1 \qquad x_b := d_s - x_{ULS} - x_a = 308.6$

Compressive Force in UHPC $\quad F_{cc} := f_{cd} \cdot \left(\frac{x_1}{2} + x_2\right) \cdot b_{bm} \cdot \frac{1}{10^3} = 10788$

Moment Resistance in UHPC $\quad M_{cc} := f_{cd} \cdot \left[\frac{x_1^2}{3} + x_2 \cdot \left(x_1 + \frac{x_2}{2}\right)\right] \cdot b_{bm} \cdot \frac{1}{10^6} = 2834$

Tensile Force in Bottom Reinforcement $\quad F_{s.1} := f_{yd} \cdot A_s \cdot \frac{1}{10^3} = 854$

Moment Resistance in Bottom Reinforcement $\quad M_{s.1} := F_{s.1} \cdot \left(d_s - x_{ULS}\right) \cdot \frac{1}{10^3} = 276$

Tensile Force in Tendon $\quad F_{s.2} := f_{pd} \cdot A_{ps.total} \cdot \frac{1}{10^3} = 9219$

Moment Resistance in Tendon $\quad M_{s.2} := F_{s.2} \cdot \left(d_{pt} - x_{ULS}\right) \cdot \frac{1}{10^3} = 1643$

Tensile Force in UHPC $\quad F_{ct} := f_{ctd.el} \left(\frac{x_a}{2} + x_b\right) \cdot b_{bm} \cdot \frac{1}{10^3} = 715$

Moment Resistance in UHPC $\quad M_{ct} := f_{ctd.el} \cdot \left[\frac{x_a^2}{3} + x_b \cdot \left(x_a + \frac{x_b}{2}\right)\right] \cdot b_{bm} \cdot \frac{1}{10^6} = 118$

E1.1 Check Strain Limit of Reinforcement

Strain of Bottom Reinforcement

$$\varepsilon_s := \frac{\varepsilon_{cud} \cdot (d_s - x_{ULS})}{x_{ULS}} = 0.256 \cdot \%$$

$$Check_{strain.layer.1} := \begin{cases} \text{"Normal reinforced"} & \text{if } \varepsilon_{ys} \le \varepsilon_s \wedge \varepsilon_s \le \varepsilon_{ud} \\ \text{"Not normal reinforced"} & \text{otherwise} \end{cases} = \text{"Normal reinforced"}$$

E1.2 Check Strain Limit of UHPC in Tension

$$Check_{strain.uhpc.tensile} := \begin{cases} \text{"No Tensile Contribution by UHPC "} & \text{if } \varepsilon_s \ge \varepsilon_{u.lim} \\ \text{"Tensile Contribution added by UHPC"} & \text{otherwise} \end{cases} = \text{"Tensile Contribution added by UHPC"}$$

E1.3 Check Horizontal Force Equilibrium

Resultant Horizontal Force

$$F_{cc} - F_{s.1} - F_{s.2} - F_{ct} = 0.00$$

$$Check_{force.equilibrium} := \begin{cases} \text{"Close Enough"} & \text{if } \left|F_{cc} - F_{s.1} - F_{s.2} - F_{ct}\right| \le 1 \\ \text{"Retry Compressive Depth, x"} & \text{otherwise} \end{cases} = \text{"Close Enough"}$$

E1.4 Check Ultimate Moment Resistance

ULS Design Moment Resistance

$$M_{Rd} := M_{cc} + M_{s.1} + M_{s.2} + M_{ct} = 4871$$

$$Check_{moment} := \begin{cases} \text{"ULS Moment Reistance O.K."} & \text{if } M_{Rd} \ge M_{Ed.ULS} \\ \text{"Retry Section or Reinforcement"} & \text{otherwise} \end{cases} = \text{"ULS Moment Reistance O.K."}$$

F ULS Shear Resistance

F1 UHPC Shear Resistance

Long-term effects Coefficient	$\alpha_{cc} := 0.85$	TG 3.1.2.5
	$k := 1 + 3 \cdot \frac{(1 - \%_{LT}) \cdot \sigma_{bm}}{f_{ck}} = 1.27$	TG Cl. 3.1.2.2(1) Eq. 3.4
Safety Factor	$\gamma_E := \frac{1.5}{\gamma_{cf}} = 1.15$	TG Cl. 3.1.2.2(1)
UHPC Contribution Term	$V_{Rd.c} := \frac{0.24}{\gamma_{cf} \cdot \gamma_E} \cdot k \cdot \sqrt{f_{ck}} \cdot b_{bm} \cdot d_s \cdot \frac{1}{10^3} = 874$	TG Cl. 3.1.2.2(1) Eq. 3.6
Inclination of Main Compression Stress on Long. Axis	$\theta := 30 \cdot deg$	TG Cl. 3.1.2.3(1)
Lever Arm	$z := 0.9 \cdot d_s = 671.0$	TG Cl. 3.1.2.2(2)
Reinforcement Contribution Term	$V_{Rd.s} := \frac{A_{sw}}{S_{link}} \cdot z \cdot f_{yd} \cdot cot(\theta) \cdot \frac{1}{10^3} = 381$	TG Cl. 3.1.2.3(1) Eq. 3.8
Strain Limit at ULS	$\varepsilon_x := \varepsilon_{u.lim} = 0.609 \cdot \%$	
Compression Area	$A_{fv} := b_{bm} \cdot z = 281799$	TG Cl. 3.1.2.4(1)
Integration of Stress-Strain Function	$\sigma_f := (f_{ctd.el.SLS} + f_{ctfd.SLS}) \cdot \left(\frac{\varepsilon_{u.lim} - \varepsilon_{el}}{2}\right) \cdot 10^2 = 4.22$	
Mean Post-cracking Strength Value	$\sigma_{Rd.f} := \frac{1}{K_{global} \cdot \gamma_{cf}} \cdot \frac{1}{(\varepsilon_x - \varepsilon_{el})} \cdot \sigma_f \cdot \frac{1}{10^2} = 4.37$	TG Cl. 3.1.2.4(2) Eq. 3.11
Fibre Contribution Term	$V_{Rd.f} := A_{fv} \cdot \sigma_{Rd.f} \cdot cot(\theta) \cdot \frac{1}{10^3} = 2133$	TG Cl. 3.1.2.4(1) Eq. 3.10
Superposition of Three Resistance Term	$V_{Rd} := V_{Rd.c} + V_{Rd.s} + V_{Rd.f} = 3388$	TG Cl. 3.1.2.1(1)
Limit Force for Compressive Strength	$V_{Rd.max} := 2.3 \cdot \frac{\alpha_{cc}}{\gamma_c} \cdot b_{bm} \cdot z \cdot f_{ck}^{\frac{2}{3}} \cdot tan(\theta) \cdot \frac{1}{10^3} = 7008$	TG Cl. 3.1.2.5(1) Eq. 3.12
ULS Design Shear Resistance	$V_{Ed.total} := min(V_{Rd}, V_{Rd.max}) = 3388$	TG Cl. 3.1.2.1(1) Eq. 3.2

$Check_{shear} :=$ "ULS Shear Resistance O.K." if $V_{Ed.total} \geq V_{Ed.ULS}$ = "ULS Shear Resistance O.K."
"Retry Section or Reinforcement" otherwise

G ULS Torsional Resistance

G1 UHPC Torsional Resistance

Thickness of Dummy Wall $t_{ef} := \frac{min(b_{bm}, d_{bm})}{6} = 70.0$ TG Cl. 3.1.3.2

Enclosed Area by Dummy Tubular Section $A_k := (b_{bm} - t_{ef})\cdot(d_{bm} - t_{ef}) = 255500$ TG Cl. 3.1.3.2

ULS Design Torsional Moment Resistance $T_{Rd.max} := 2.3\cdot\frac{\alpha_{cc}}{\gamma_c}\cdot 2\cdot A_k\cdot t_{ef}\cdot f_{ck}^{\frac{2}{3}}\cdot tan(\theta)\cdot\frac{1}{10^6} = 890$ TG Cl. 3.1.3.2(8) Eq. 3.20

Utilisation for Torsional Moment + Shear $\frac{T_{Ed.ULS}}{T_{Rd.max}} + \frac{V_{Ed.ULS}}{V_{Rd.max}} = 0.409$

$Check_{torsion} :=$ "ULS Torsion Resistance O.K." if $\frac{T_{Ed.ULS}}{T_{Rd.max}} + \frac{V_{Ed.ULS}}{V_{Rd.max}} \le 1$ = "ULS Torsion Resistance O.K."
"Retry Section or Reinforcement" otherwise

TG Cl. 3.1.3.2(7) Eq. 3.19

APPENDIX D

SAMPLE CONTENTS OF QA/QC PLAN

Appendix D – Sample Framework of QA/QC Plan

Quality Assurance / Quality Control (QA/QC) Plan
for
Production and Supply of Ultra-High Performance Concrete

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10. Review of the Quality Management System
11. Quality Records

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D. List of Testing Requirements