

# Working Example on 70m Long Ultra High Performance Fiber-Reinforced Concrete (UHPFRC) Composite Bridge

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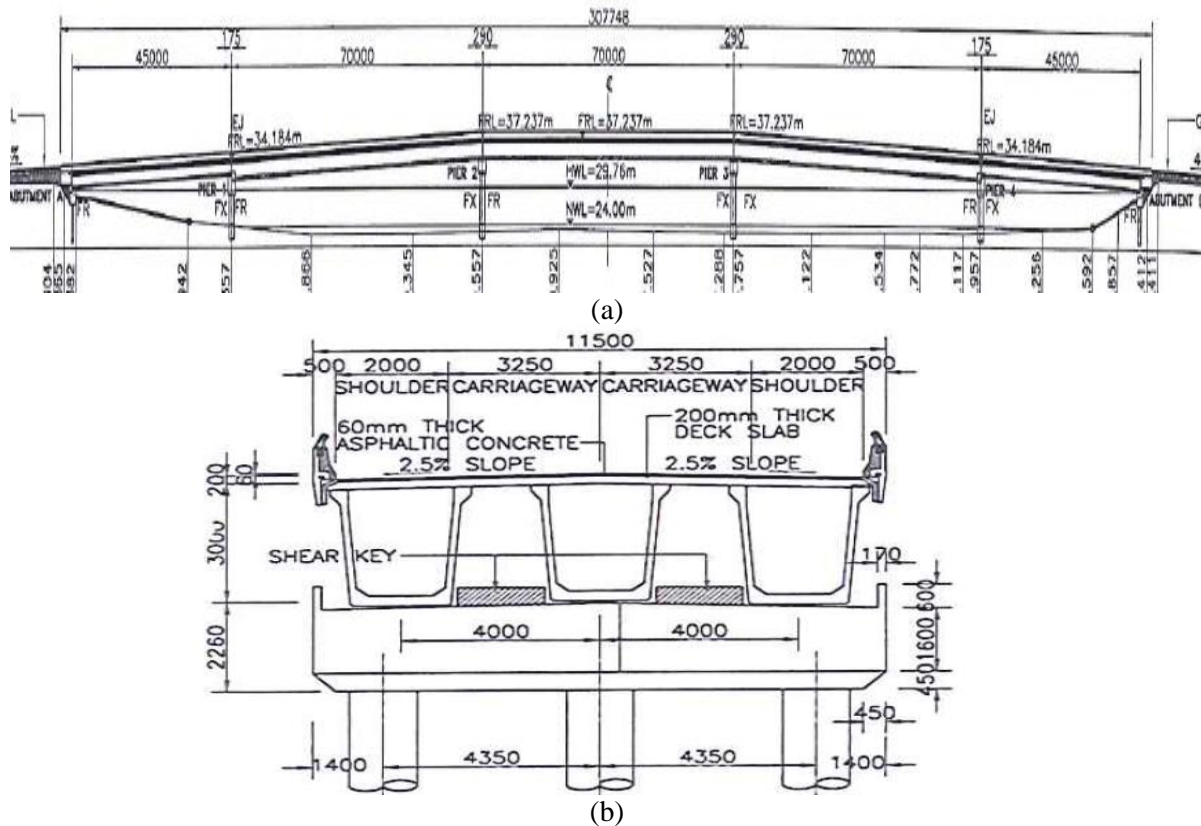
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**Abstract.** In 2016 the Association Française de Normalisation (AFNOR — French Standard Institute) has published the world first design standards for ultra-high-performance fibre reinforced concrete (UHPFRC) structures (i.e. NF P18-710:2016). This document is the national additional to Eurocode 2 for concrete structure design. To-date, there are several UHPFRC bridges have been designed using this standard. The design approach for UHPFRC structures are relatively similar to conventional concrete design. This paper presents the working example on the design of 70m span ultra-high-performance fibre reinforced concrete (UHPFRC) composite bridges. The working example mainly focus on (i) the material properties used in the structural analysis software – MIDAS CIVIL; (ii) the output results on the design forces at the critical sections (i.e. design moment effect,  $M_{Ed}$  and shear force effect,  $V_{Ed}$ ); (iii) the stresses and midspan displacement of the post-tension UHPFRC U-girder at transfer and at different construction load history and (iv) the design moment resistance ( $M_{Rd}$ ) and design shear resistance ( $V_{Rd}$ ) of the composite section.

## 1. Introduction

Since 1990's, UHPFRC has continuously received recognition and acceptance in many areas, especially in the bridge applications, due to this advanced concrete technology has proven provides several advantages to the asset owners and contractors such as reduction in overall project/construction cost, shorten construction duration, enhanced design and service life of structure and provide high quality of works. This paper gives the design example of 70m long UHPFRC composite bridge. In SLS condition, the calculation sample illustrated the stresses of the precast/prestressed girder at transfer stage, at different construction load history and at service stage. In ULS condition, the design moment and shear resistances are presented. The example used is a concrete bridge (known as Manung bridge) which is currently under construction at Perak state, near Kuala Kangsar. **Figure 1a** show the Manung Bridge consists of five continuous spans with the total length of 308m and total width of 11.5m. **Figure 1b** shows the typical cross-section of the 70m span and it shows each span consists of three UHPFRC U-girders and topped with a 11.5m wide and 200mm thick cast in-situ RC deck. The RC deck will later cover with 50mm thick asphalt wearing surface. The first and fifth spans are 45m long whereas the second to fourth spans are 70m length. The UHPFRC used for the U-girder has characteristic compressive strength of  $f_{ck} = f_{ck,cyl} = 140\text{MPa}$  and characteristic post-cracking tensile strength of  $f_{ctfk} = 8\text{MPa}$ . The composite bridge was designed as simply supported span and seated on elastomeric rubber bearings.





**Figure 1.** (a) Elevation view and (b) typical cross-section of Manung Bridge.

The bridge is designed with the following specification:

- i. Design life of 120 years.
- ii. Number of notional lane: 4 (three notional lanes with 3m per lane and one remaining area with 1.5m).
- iii. Design traffic load: Combination of LM 1 and LM 3 with SV80.
- iv. Superstructure: Precast UHPFRC U-girder composite with 200mm thick in-situ RC deck.
- v. Total Bridge length: 308m.
- vi. Overall bridge width: 115m.

Construction sequence of UHPFRC composite bridge:

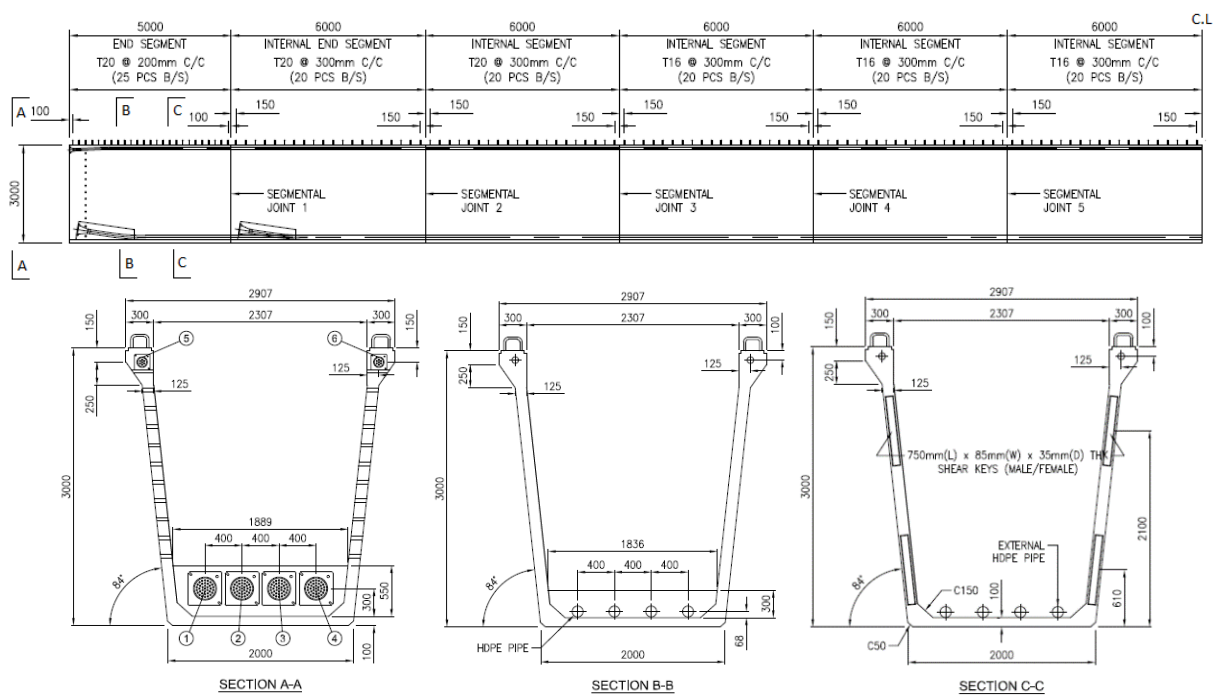
- a. Fabrication of UHPFRC U-girder segments in factory.
- b. Delivered U-girder to site.
- c. Assembling segments at site.
- d. Post-tensioned all segments into full monolithic 70m beam.
- e. Launched the 70m beams to elastomeric rubber bearings.
- f. Cast in-situ deck.
- g. Install parapets and then lay premix.
- h. Completion of composite UHPFRC bridge.

## 2. Description of UHPFRC U-Girder

### 2.1. General

**Figure 2** present the detail of UHPFRC UBG3000. Each 70m precast UHPFRC post-tensioned U-girder consists of twelve segments: two anchorage end segments (i.e. 5m long and weight 15.7 tonnes each); two anchorage end-internal segments (i.e. 6m long and weight 18.2 tonnes each) and eight internal

segments (i.e. 6m long and weight 15 tonnes each). The U-girder consists of two 125mm thin webs, a 100mm thick bottom flange and there are post-tensioned with six external tendons of 27K15 strands and two internal tendons of 7K15 strands at the top flanges to ensure the joints are always in compression during prestressed transfer and service stages, no tensile stress is permitted in all the joints. The strands used are a seven-wire, low-relaxation type with diameter of 15.24mm with minimum breaking load of 260kN per strands. All the tendons to be stressed up to 75% of the breaking load and the 5% of immediate losses during stressing is taken into design. Unlike conventional concrete beam, this UHPFRC U-girder does not have any shear reinforcement at any part of its thin webs. There is only bursting links at the anchorage zones and horizontal shear studs at the top flanges which act as a shear connection to the cast in-situ deck and U girders. **Figure 3** shows the typical look of a fully assembled UHPFRC U-girder during beam launching.



**Figure 2.** Detail of UHPFRC UBG3000 U-girder.



**Figure 3.** Typical view of UHPFRC precast/prestressed U-girder.

## 2.2. Mechanical properties of UHPFRC

To-date, UHPFRC has become a popular cementitious-based material to be used in precast construction, because UHPFRC can reduced overall construction time and cost whereas produce a high-quality finished product than cast in-situ concrete structure. The high durability of UHPFRC can increase the service life without any special major maintenance and repair. One of the unique properties of UHPFRC are it can achieve a high early mean cube compressive strength above 80 MPa after 1 day and above 160 MPa after 28 days. Heat curing on the girders were applied for a period of 48 hours at a temperature of 90°C and 100 percent humidity to result maximum strengths following by the further hydrating of cementitious material and densifying the mixing. The brief mechanical properties of the Malaysia blend UHPFRC are represented in Table 1.

## 2.3. Material Properties

The type of UHPFRC used in the design of the U-girder is Grade140/155 and come with 2% by volume of steel fibre with tensile strength above 2700 MPa. The characteristic cylinder and cube compressive strengths used are  $f_{ck,cyl} = 140$  MPa and  $f_{ck,cube} = 155$  MPa, respectively. The characteristics tensile limit of elasticity and post-cracking tensile strength used are taken as  $f_{ctk,el} = 7$  MPa and  $f_{ctfk} = 8$  MPa. On other hand, the term  $f_{ctm,el}$  and  $f_{ctfk}$  are the mean tensile limit of elasticity and mean post-cracking tensile strength, respectively [5]. In the checking of extreme fibres stresses at SLS conditions, tensile stresses developed in the sections should not greater than tensile stress limit of  $0.6f_{ctk,el} = 0.6 \times 7 = 4.2$  MPa and no tensile stresses are permitted at the segmental joint sections. The compressive stress limit is taken as  $0.6f_{ck} = 0.6 \times 140 = 84$  MPa. The modulus of elasticity is taken as  $E_{cm} = 50$  GPa. Steam curing was undertaken on the U-girder and therefore the total shrinkage after the steam curing process is minimal and therefore shrinkage is considered to be negligible ( $\epsilon_{sh}(t) = 0$ ) [6].

**Table 1.** Mechanical properties of UHPFRC

Characteristic	Unit	DURA® UHPFRC
Specify Density	kg/m <sup>3</sup>	2450
Cylinder Compressive Strength	MPa	130-160
Cube Compressive Strength	MPa	140-170
Creep Coefficient		0.2
Post Cured Shrinkage	µε	0
Modulus of Elasticity	GPa	50
Poison Ratio		0.2
Elastic Tensile Strength	MPa	> 7
Post-Cracking Tensile Strength	MPa	> 8
Modulus of Rapture	MPa	> 25
Rapid Chloride Permeability	coulomb	< 100
Chloride Diffusion Coefficient	m <sup>2</sup> /s	0.05 – 0.1 x 10 <sup>-12</sup>

## 2.4. Section Properties

The effective width of RC deck of the composite section is taken as 3.6 m and 4 m for the edge beam and internal beam respectively. The sectional properties of the U-girder and the composite section are presented in **Table 2**. The composite section was used to calculate elastic response of the bridge at certain load histories of the bridges.

**Table 2.** Transformed section properties of U-girder only and composite section

	Girder only	Composite section (Edge Beam)	Composite section (Internal Beam)
Sectional area, A (x 10 <sup>3</sup> mm <sup>2</sup> )	1116.6	1602.1	1656
Second moment of inertia, I <sub>xx</sub> (x 10 <sup>9</sup> mm <sup>4</sup> )	1229.4	2340.41	2423.70
Distance from N.A (Top), y <sub>top</sub> (mm)	1711	1362	1321
Distance from N.A (Bottom), y <sub>bot</sub> (mm)	1289	1838	1879
Section modulus (Top), Z <sub>top</sub> (x 10 <sup>6</sup> mm <sup>3</sup> )	718.6	1718.19	1834.71
Section modulus (Bottom), Z <sub>bot</sub> (x 10 <sup>6</sup> mm <sup>3</sup> )	953.65	1273.44	1289.90



### 3. Design Method

#### 3.1. General

The applied design loads in this work example according to BS: EN 1991-2-2003 [2] are presented in **Table 3** and the design bending moments and shear forces are presented in **Table 4**. The partial factor for the load cases are taken according BS: EN 1990:2002 [1]. The load cases were analyzed by using the MIDAS civil software to get the bending moment and shear forces.

**Table 3.** Applied design load on bridge girder

	Load History	Load (kN/m)	SLS Factor [1]	ULS Factor [1]
G1	Self-weight of U-girder	27.0	1	1.35
G2a	Self-weight of internal slab (B=4m)	19.60	1	1.35
G2b	Self-weight of external slab (B=3.6m)	17.64	1	1.35
G3	Parapet load	10.0	1	1.35
G4a	Internal deck surfacing (premix)	5.52	1	2.0925
G4b	External deck surfacing (premix)	4.485	1	2.0925
Q	LM1+LM3 SV80	Refer to [2]	1	1.35

**Table 4.** Design bending moments and shear forces

	Load History	Edge Beam (Governing Values)			
		SLS		ULS	
		Moment (kNm)	Shear (kN)	Moment (kNm)	Shear (kN)
G1	SW of U-girder	16537.5	945	22325.6	1275.8
G2a	SW of slab	10804.5	631.3	14586	833.5
G3	Parapet load	4195.9	363.1	5664.5	490.2
G4a	SIDL (premix)	2950.3	164.2	6173.5	343.6
Q	LM1+LM3 SV80	19884.1	1414.1	26843.5	1909
	Total SLS	$M_{SLS}^+ = 54372$	$V_{SLS} = 3518$	-	-
	Total ULS	-	-	$M_{Ed} = 75593$	$V_{Ed} = 4852$
	Load History	Internal Beam			
		SLS		ULS	
		Moment (kNm)	Shear (kN)	Moment (kNm)	Shear (kN)
G1	SW of U-girder	16537.5	945	22325.6	1276
G2b	SW of slab	12005	658.2	16206.8	926
G3	Parapet load	3858.2	-26.2	5208.6	316
G4b	SIDL (premix)	2962.3	178.1	6198.6	490
Q	LM1+LM3 SV80	13193.3	1247.6	17811	1752
	Total SLS	$M_{SLS}^+ = 48556$	$V_{SLS} = 3003$	-	-
	Total ULS	-	-	$M_{Ed} = 67751$	$V_{Ed} = 4760$

#### 3.2. Serviceability Limit State (SLS)

The total number of strands used are  $6 \times 27 = 162$  nos. for bottom row and  $2 \times 7 = 14$  nos. for top row, thus the total initial prestressing force applied to one U-girder is  $P_i = P_i \times (100\% - 5\% \text{ immediate losses}) = (162 + 14) \times \frac{260 \text{ kN}}{\text{strands}} \times 75\% \times 95\% = 32604 \text{ kN}$ . In SLS check, the edge beam is considered due to it is the more critical case (refer to Table 4). The transformed sectional moduli used for the UHPFRC U-girder only are  $Z_{top,beam} = 718.6 \times 10^6 \text{ mm}^3$  and  $Z_{bot,beam} = 953.65 \times 10^6 \text{ mm}^3$ ; whereas for the composited section are taken as  $Z_{top,edge,bridge} = 1718.19 \times 10^6 \text{ mm}^3$  and  $Z_{bot,edge,bridge} = 1273.44 \times 10^6 \text{ mm}^3$ . Table 5 presents the stresses at the top / bottom extreme fibers and midspan deflection of the UHPFRC composite bridge at transfer stage and at different load histories during the construction. Calculation shows after the transfer of prestressing forces, the precast UHPFRC U-beam will experience an instantaneous net hog deflection of 155.7mm at the midspan whereas the top and bottom extreme fibers will have stresses of -11.3 MPa and -42.7 MPa, respectively. After the RC wet deck is casted, the precast U-beam will experience a reduced net hog deflection of 65.9mm whereas

the top and bottom extreme fibers results stresses of -26.3 MPa and -31.4 MPa, respectively. During casting of the wet topping, it is assuming only the none-composited precast U-beam is taken the full dead load of the RC deck. The next stage will be the additional load due to the RC parapet and the wearing course. Calculation shows at this stage the composited edge beam will has remaining net hog deflection of 34.8mm whereas the top and bottom extreme fibers will have stresses of -29.9MPa and -25.7 MPa respectively. Finally, at instantaneous transient live load, the composite edge beam will experience an instantaneous midspan deflection of 86.7mm (*i.e.*  $\frac{70,000}{86.7} = \frac{span}{807} < \frac{span}{500}$ , OK!). At the full-service stage, the edge beam will face a midspan sag deflection of 52mm whereas the top and bottom extreme fibers will have stresses of -39.8MPa and -10.12 MPa respectively. The bottom flange will remain in compression, thus none of the segmental joints were decompressed, thus none of the joints will be opened under SLS condition. According to BS EN 1991-1-1-2004 [3] the instantaneous live load deflection should be limited to less than  $\frac{span}{500} = 140mm$ . Table 5 shows all parts of the UHPFRC girder is below the stress limits, this is particularly true also for the in-situ RC deck (*i.e.*  $-11MPa < 0.6 \times 40 = 24MPa$ ). Therefore, the UHPFRC composite bridge has sufficient stiffness under SLS loadings.

**Table 5.** Stresses and midspan deflection at SLS

	Load Histories	Section Type	Stress at U-girder (MPa)		Stress at RC Deck	Midspan deflection (mm)
			Top	Bottom	Top	
(1)	SW of girder	None-Composited	-23.02	+17.34	-	+137.0
(2)	Prestressing force	None-Composited	+11.72	-60.03	-	-293.0
(3) = (1) + (2)	After transfer	None-Composited	-11.30	-42.69	-	-155.7
(4)	Inc. In-situ RC deck	None-Composited	-15.04	+11.33	-	+89.7
(5) = (3) + (4)	After RC deck Casted	Composited	-26.34	-31.36	-	-65.9
(6)	Inc. SIDL + Parapet	Composited	-3.55	+5.62	-2.91	+31.2
(7) = (5) + (6)	Inc. Under Permanent DL	Composited	-29.89	-25.74	-2.91	-34.8
(8)	Inc. Live Load	Composited	-9.87	+15.62	-8.10	+86.7
(9) = (7) + (8)	At Full Service Stage	Composited	-39.76	-10.12	-11.0	+52.0

Notes: - value means stress in compression and + value mean stress in tension

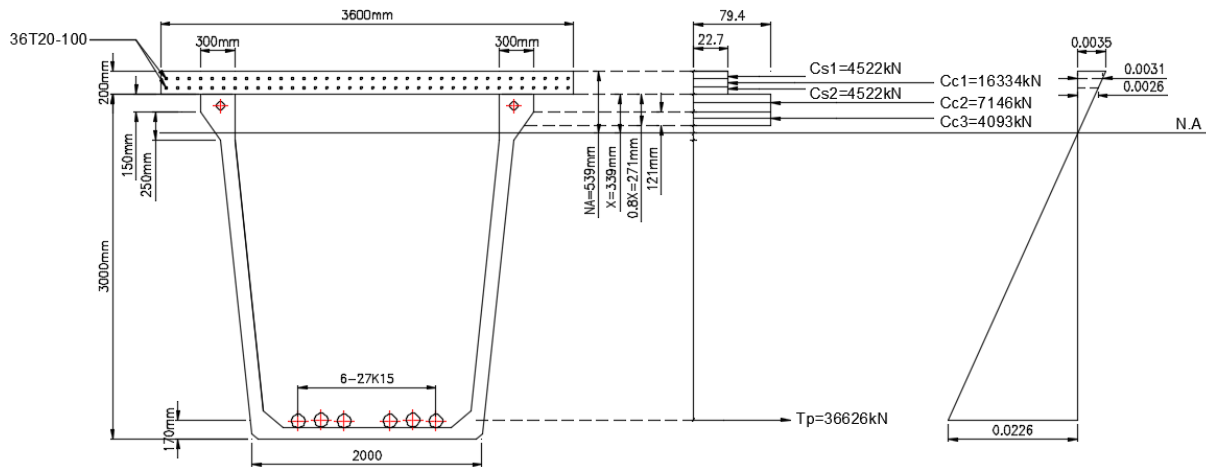
The design positive cracking moment capacity ( $M_{cr}$ ) of the edge beam can be approximated as the decompression moment capacity ( $M_o$ ) of the elastic composite transformed section:

$$M_{cr} = \text{decompression moment} = M_o = M_{SLS} + [\sigma_{bot.edge.bridge.full SLS} \times (100\% - \text{assume } 5\% \text{ time - effect losses}) \times Z_{bot.edge.bridge}] = 54372kNm + (10.12 \times 0.95 \times 1273.44 = 66615kNm > M_{SLS}^+ = 54372kNm.$$

### 3.3. Ultimate limit state (ULS)

The calculation of the design moment resistance ( $M_{Rd}$ ) of the UHPFRC composite bridge is similar to the conventional concrete bridges. The theory of strains compatibility and forces equilibrium acting on the cross-section of the bridge were used and the resultant strains and resisting internal forces of each components are presented in Figure 4. The calculated neutral axis depth is  $X = 539.1$  mm, which is located outside the in-situ Grade 40 RC deck. Because the full 70 m U-beam is come with several segments which were then joined by using prestressing, the weakest sections are the segmental joint sections, therefore the sections are consider do not developed any tensile stress at any level of the sections. The top tendons acted to make sure the joints closed and no tensile stress happen on the joint sections during transfer stage and the tendons forces can be neglected during ultimate stage. The composited RC deck comes with four layers of reinforcements whereas the longitudinal and transverse direction reinforced with T20-100mm c/c. The concrete cover used is 30 mm. For linear strain compatibility, the concrete top extreme fibre strain is a taken as 0.0035 as per EC2 [3]. The top and bottom reinforcement strains can be written as  $\varepsilon_{s1} = 0.0035 \times \frac{(X-60)}{X} = 0.00311 > 0.002$  (yielded)

and  $\varepsilon_{s2} = 0.0035 \times \frac{(X-140)}{X} = 0.00259 > 0.002$  (*yielded*) respectively. The top tendon is ignored in the ULS calculation. The bottom tendon strains can be expressed  $\varepsilon_{p2} = \left(0.0035 \times \frac{3030-539.1}{539.1}\right) + \frac{1860 \times 0.75 \times 0.95 \times 0.95}{195000} = 0.02262 > 0.0083$  (*yielded*) respectively. It is obvious that the top layer of the reinforcement has yielded. Therefore the internal forces can be calculated as: Compressive force of RC deck,  $C_{c1} = 3600 \times 22.7 \times 200 = 16344kN$ ; Compressive force of UHPFRC section 1,  $C_{c2} = 2sides \times 300 \times 150 \times \frac{79.4}{1000} = 7146kN$ ; Compressive force of UHPFRC section 2,  $C_{c3} = 2sides \times 212.5 \times (0.8 \times 339.1 - 150) \times 79.4/1000 = 4093kN$ ; compressive force of top reinforcement,  $C_{s1} = 36 \times 314 \times 460/(1.15 \times 1000) = 4521.6kN$ ; compressive force of bottom reinforcement,  $C_{s2} = 36 \times 314 \times 460/(1.15 \times 1000) = 4521.6kN$ . Therefore the total internal compressive force is  $C = 36626 kN$ . The tensile force of the bottom tendon is  $T_{p2} = 162 \times 260/1.15/1000 = 36626kN$ . The total internal tensile force is calculated as  $T = 36626kN$ . Therefore, the sum of forces is equal to zero. Lastly the design moment resistance can be calculated by taking moment about the top extreme fiber which gives  $M_{Rd} = 104,792 kNm > M_{Ed} = 75593 kNm$ , which is greater than the design moment effect. Thus, the section has adequate flexural resistance.



**Figure 4.** Strain distribution and equilibrium of the forces acting on the section

Since no shear reinforcement is used in the vertical web of the U-girders, the design shear resistance ( $V_{Rd}$ ) can be calculated from the design provision as given in the French Standard [4]. As explained in clause 6.2 of French Standard for UHPFRC [4],  $V_{Rd}$  can be calculated as follows:

$$V_{Rd} = V_{Rd,c} + V_{Rd,s} + V_{Rd,f} \quad (1)$$

where  $V_{Rd,c}$ ,  $V_{Rd,s}$ , and  $V_{Rd,f}$  are design shear resistances provided by UHPFRC, steel stirrups, and steel fibers, respectively. Due to there is no stirrup used in the UHPFRC girder, thus the term  $V_{Rd,s}$  is zero.

Design shear resistance provided by UHPFRC ( $V_{Rd,c}$ ) is calculated as:

$$V_{Rd,c} = \frac{0.24}{\gamma_{cf}\gamma_E} k f_{ck,UHPFRC}^{1/2} b_w \cdot z = \frac{0.24}{1.5} * 1.63 * 140^{1/2} * 250 * 2727 = 2110 kN \quad (2)$$

where material safety factor,  $\gamma_{cf}\gamma_E = 1.5$ ;  $b_w = 125 mm \times 2 sides = 250 mm$  is the total web thickness; lever arm of external force,  $z = 0.9d = 0.9 \times 3030mm = 2727 mm$ ;  $d = 3000 + 200 - 170 = 3030 mm$  is the effective depth of composite section, and  $k$  factor is determined as:

$$k = 1 + 3 \sigma_{cp} / f_{ck,UHPFRC} = 1 + 3 * 29.6/140 = 1.634 \quad (3)$$

where  $\sigma_{cp}$  is average confining stress due to prestress and is equal to  $\sigma_{cp} = N_{Ed}/A_c = 30974/1.0452 = 29.6 MPa$ . Total axial force due to prestressing in the cross-section is  $N_{Ed} = (2 \times 7 + 6 \times 27) \times 260 kN \times 0.75 \times 0.95 \times 0.95 = 30974 kN$  and  $A_c = 1.0452m^2$  is gross cross section area of UHPFRC girder.

Design shear resistance provided by steel fibers ( $V_{Rd,f}$ ) is determined as:

$$V_{Rd,f} = A_{fv} \sigma_{Rd,f} \cot \theta = 250 * 2727 * 4.923 \cot(30) = 5813 \text{ kN} \quad (4)$$

where  $A_{fv}$  is effective vertical web area and is equal to  $b_w \times z$ ,  $\theta$  is angle of inclination of the main compression stress on the longitudinal axis (which is taken as  $\theta = 30^\circ$ ),  $\sigma_{Rd,f}$  which is the design value of post cracking strength and calculated as below.

$$\sigma_{Rd,f} = f_{ctfk} / K \cdot \gamma_{cf} = 8.0 / 1.25 * 1.3 = 4.923 \text{ MPa} \quad (5)$$

where  $K = 1.25$  is global fiber orientation factor and  $\gamma_{cf} = 1.25$  is the partial factor of UHPFRC under tension.

Finally, the design shear resistance is determined as:

$$V_{Rd} = V_{Rd,c} + V_{Rd,s} + V_{Rd,f} = 2110 + 0 + 5813 = 7923 \text{ kN} > V_{Ed} = 4852 \text{ kN}.$$

Therefore, the girder has adequate shear resistance ( $V_{Rd}$ ) to withstand the design shear force ( $V_{Ed}$ ).

Furthermore, according to the French Standard [5],  $V_{Rd}$  must be smaller than the design limit force for the compressive strength of UHPFRC ( $V_{Rd,max}$ ) which is calculated as follows:

$$V_{Rd,max} = 2.3 \frac{\alpha_{cc}}{\gamma_c} b_w z f_{ck,UHPFRC}^{2/3} \tan \theta = 2.3 \frac{0.85}{1.5} * 250 * 2727 * 140^{2/3} * \tan(30) = 13832 \text{ kN} \quad (6)$$

#### 4. Conclusion

This paper presents the properties and design method of an UHPFRC composite bridge span 70m long. In the SLS check, the UHPFRC composite bridge has satisfied all the stress limit criteria. The instantaneous deflection due to live load is less than the allowance deflection limit. The design cracking moment capacity is  $M_{cr} = 66615 \text{ kNm}$  which is larger than the SLS maximum moment  $M_{SLS} = 54372 \text{ kNm}$ . The design moment resistance is  $M_{Rd} = 104,792 \text{ kNm}$  which is greater than the design moment effect  $M_{Ed} = 75593 \text{ kNm}$ . The design shear resistance is  $V_{Rd} = 7923 \text{ kN}$  which is greater than the design shear force effect  $V_{Ed} = 4852 \text{ kN}$ . The use of UHPFRC girder in the bridge construction have enhanced the construction technology in the aspect of time and cost efficiency. The UHPFRC girder can achieve a long span with the shallower girder depth and reduce number of pier which can significantly reduce the construction cost. UHPFRC is resistance to chemical attack, in result it can maximize the service life of the bridge.

#### 5. Reference

- [1] BS EN 1990:2002: Eurocode-Basic of structural design, European Standard *European Committee for Standardization*
- [2] BS EN 1991-2:2003: Eurocode 1– Action on structure - part 2: traffic loads on bridges, European Standard *European Committee for Standardization*
- [3] BS EN 1992-1-1:2004: Eurocode 2– Design of concrete structure – part 1-1: general rules and rules building, European Standard *European Committee for Standardization*
- [4] NF P18-710 2016: National addition to Eurocode 2 – Design of concrete structure: specific rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) *AFNOR-French standard institute*
- [5] NF 18-470 2016 Concrete-Ultra-High Performance Fiber-Reinforced Concrete-Specifications, performance, production and conformity *AFNOR-French standard institute*
- [6] Voo Y L, Augustin P, and Thamboe T 2011 Construction and design of a 50m single span UHP ductile concrete composite road bridge *The Structural Engineer* **89**(15) pp 24–31