Experimental and analytical study of fatigue behaviour of Reinforced UHPC beams

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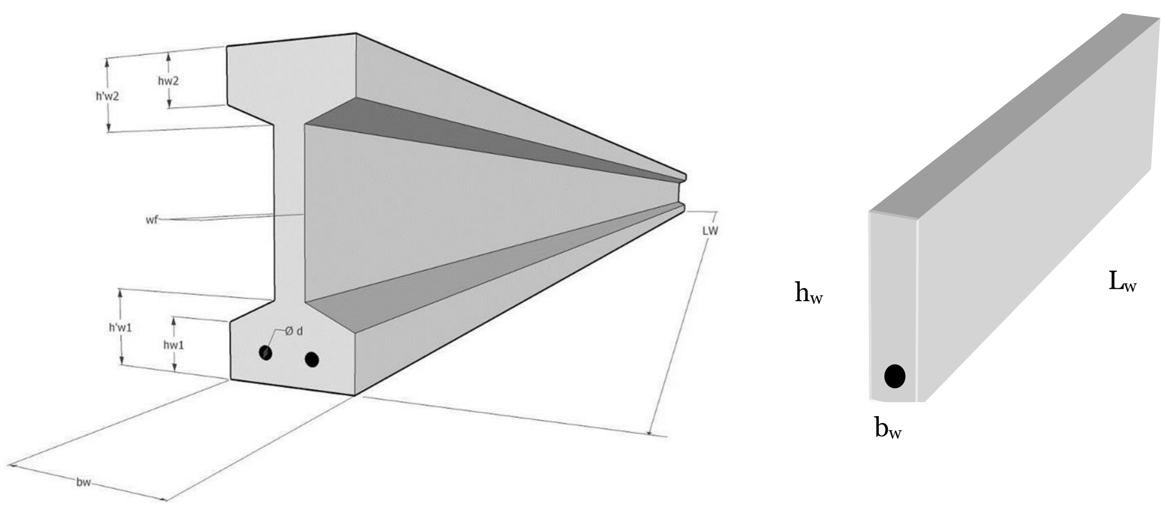
Abstract: The main objective of the research project reported in this paper is to develop a new type of high performance light beam that will increase the performance of usual beams (timber steel or RC beams) by combining FRP rebars cast in a ultra-high-performance concrete with short fibre reinforcement (UHPC-SFR). The beam is obtained to get a light beam with a high compressive and tensile capacity to sustain high bending moment and to be also shear resistant. The hybrid beam thus obtained possesses a lower bending stiffness than a glulam beam or steel beam of similar overall dimensions but a higher ultimate load capacity. One model is developed to validate this concept is presented in this paper. It is an analytical model based on the usual force equilibrium hypotheses. The load-displacement and moment-curvature relationships are compared to experimental results obtained from 5 large scales specimens. The results show good correlation between analytical and experimental results, and illustrate the potential interest of such composite beam configurations for civil engineering structures. Fatigue behaviour is also investigate UHPC and on 6 large scale beams.

Keywords: CFRP bars, Ultra-High-Performance Concrete, Reinforced concrete, beams, Fatigue

1. **Introduction**

Construction with ultra high performance short fibers has increased significantly in Europe and all over the world in recent years. Since the materials strength are very high in compression and very interesting in tension combined with a capacity to mitigate the effects of environmental exposure thanks to a low permeability, its increased use is predictable when sustainable development principles are taken in consideration (In Hwan et al., 2010 Behloul, 1998). Use of this technology enables the designer to create thinner sections and longer spans that are lighter, more graceful and innovative in geometry and form, with improved durability and impermeability against corrosion, abrasion and impact (AFGC, 2002). The material technology permits it to be used without passive reinforcing (rebar) and reductions in formwork, labor and maintenance further add to economy (Acker, 2004). The elimination of shear stirrups framework improves safety, the reduction of weight speeds construction, and the improved durability reduces maintenance and extends the usage-life. As a consequence, the consumption of UHPC has increased significantly for construction all over the world, to such a level that new ways to optimize its use are now necessary (Perry, 2007, Amin Kamal 2010). This paper presents the analytical and experimental results of an investigation on a new type of hybrid beam. On the one hand, as shown in Figure 1, the hybrid beam is obtained by casting FRP rebars in the bottom of a beam made of ultra-high-performance concrete with short fiber with a length of 10 mm (UHPC-SFR). The high performance concrete, with a compressive strength of 150 MPa and a tensile strength of 15 MPa, are cast in mould to get the lighter beam as possible. The Young modulus of UHPC- SFR is approximately 50 000 MPa. The UHPC-SFR layers are internally reinforced with FRP bars in order to increase the tensile strength of the bottom portion of the hybrid beam (El-Hacha, 2011). On the other hand, the objective of the modelling was to develop a modelling which consider concrete cracking and post pic behaviour and then allowing to optimize the configuration of the section, by selecting the most appropriate thickness of UHPC for shear and flexure, FPR properties (rebars area, Young modulus), thus increasing the bending stiffness and the ultimate load capacity. The experimental testing was done on beams with a 2- or 4-meter span. The performance of this innovative hybrid structural configuration is confirmed in this paper. A I type section was considered. The objective is to develop different failure modes; the geometry of the section has been adapted to each case study. The objective was either to reach the tensile FRP reinforcement failure (beam with a 4 meter span) or to reach the compressive strength failure (beam with a 4 meters span) or by retaining a smaller span length (2 meters) to get a shear failure. A typical hybrid beam such as the one described above is shown in Fig. 1. The beam of length L_w has a width b_w and height h_w. The tensile bottom of the beam has a thickness of h_{w1} which is reinforced with FRP. At the top of the section, the compressive part of the beam has a thickness of h_{w1}. For the sake of comparison, the total depth of the specimen is selected to be identical for all the beams. In order to evaluate the efficiency of this beam, a limited number of depth and span, depth-to-width ratio, volume percentage of concrete versus short steel fibers, volume ratio of the tensile rebars and their mechanical properties including axial stiffness of rebars, and mechanical properties of concrete and FRP are all significant. In this study, the parameters that were investigated are the beam span, depth-to-width ratio, and the tensile strength of the rebars incorporated in the lower part (Fig. 1).



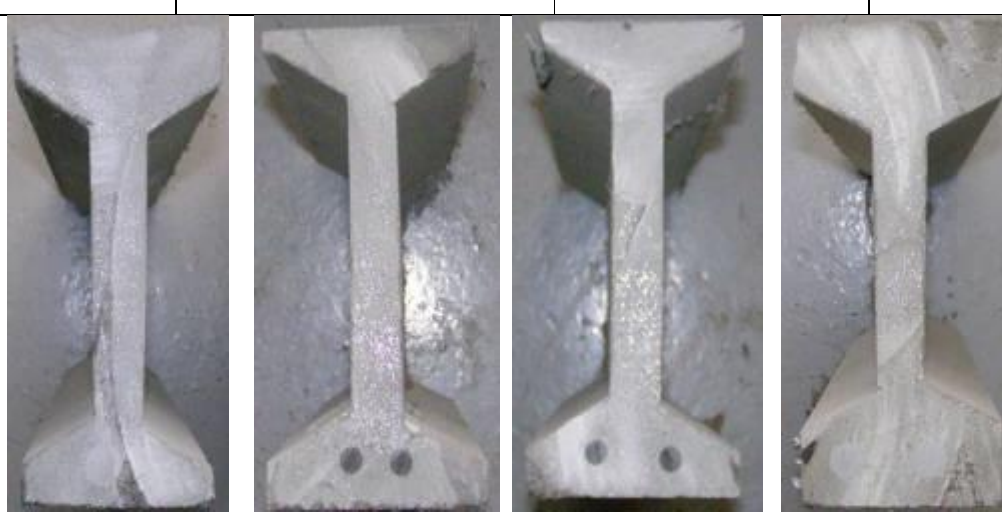
Beam 1-5 Beam 6-11

Figure 1. Geometrical parameters of beams

The mechanical properties of the material studied are given in Table 1. For the five beams the volume percentage of short metallic fibers is 2 % and the axial stiffness E_rA_r of the rebars was fixed to range from 20 MN to 30 MN for carbon FRP rebars and to range from 9 to 18 MN for glass FRP rebars. The material properties of the rebars, made of, glass (G) or carbon (C) fiber-reinforced polymers, are given in table 1 and 2. The depth-to-width ratio h/b_w was fixed to range from 8 to 9.7 to obtain the wanted failure modes. The beam span-to-depth ratio L_w/h_w was taken as 9 for the four 2-metre beams to get a shear failure and 20 to 22 for the four 4-metre beams to obtain a flexural failure. The highest value for this ratio is anticipated to favor the flexural behavior rather than the shear behavior more likely to control the shorter beams. The L_{span}/h value of 20 corresponds to the standard value proposed by ASTM D3737 (2008) test procedure used for glulam beams. The short span beam 5 has been lighten thanks to 50 mm diagonal void in the flange (Fig. 2).

Table 1. Parameters of mechanical behaviour law

Material		**Parameters**	**Value**
Ultra high performance concrete	**Tension**	f_{ctj} [MPa]	9
		ε_e [%]	0.02
		f_{ct} [MPa]	17
		$\varepsilon_{0.3\%}$ [%]	0.3
		$\varepsilon_{1\%}$ [%]	1
		ε_{lim} [%]	10
	Compression	ε_{bc} [%]	0.3
		f_{cc} [MPa]	150
	Young's modulus	E_c [MPa]	50000
FRP Rebars	**Tension**	$f_{FRP\ r}$ [MPa]	1900
		ε_{re} [%]	1.35
	Young's Modulus	E_r [MPa]	140000



Beam 1 Beam 2 Beam 3 Beam 4 -5

Figure 2. Beams section after testing

2. Material

As described above, the hybrid beam is made of an ultra high performance concrete. The UHP concrete is a premix. In order to evaluate the mechanical properties, mechanical tests were performed on each concrete batch. The 11 beams were cast in four different batches. No specific curing conditions were applied. Nine cylindrical concrete specimens were tested under compression 90 days after casting, according to the specifications of UHPC standart (Japan society of civil engineers, 2006). A mean compressive strength f_c of 174 ± 7.4 MPa was found. For FRP rebars, we did not perform specific mechanical testing in the laboratory and we used the properties provided by the suppliers in our calculations (Table 1).

Table 2 . Materials and geometrical parameter definitions

	h_{w1}	h'_{w1}	h_{w2}	h'_{w2}	b_w	b_f	h_w	$\frac{h_w}{L}$	FRP TYPE	Diameter	number	Area
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]		CF/GF	[mm]	[u.]	[mm^2]
Beam 1	23	40	32	48	90	22	200	1/20	Glass	16	1	201
Beam 2	17	33	10	21	90	22	176	1/22	Carbon	9.6	3	217
Beam 3	17	33	10	21	90	22	192	1/21	Carbon	9.6	2	144
Beam 4	38	55	35	50	90	22	215	1/9	Glass	16	2	402
Beam 5	38	55	35	50	90	22	215	1/9	Glass	16	2	402
Beam 6-9	-	-	-	-	70	-	250	1/8	Glass	16	1	201
Beam 10-11	-	-	-	-	70	-	250	1/8	Steel	25	2	490

3. Specimen preparation

The FRP-concrete composite beams used in this research were fabricated using casting as mentioned earlier. FRP rebars were fixed in the mould because of their low density. The beams were cast vertically.

4. Experimental Result

4.1 *Mechanical testing*

The tests done in order to obtain the bending stiffness and the load bearing capacity of the composite beam and moment-curvature relation are illustrated in Fig. 3. The beams specimens prepared according to the above detailed procedure were subjected to a four-point loading test according to ASTM standards D 3737-04 and D 4761-05. The distance between support and applied load was higher than twice the depth of the beam, as required by the standard. For the 2.0-metre beams, this distance is 0.7 m while for the 4.0-metre beams, it is 1.3 m. The loading was displacement-controlled and, as requested by the standard ASTM D4761-05, the total test duration was always between 10 s and 10 min. The exact speed rate was 9 mm/min for the beam with a span/depth ratio of 20 and 1 mm/min for the beams with a span/depth ratio of 9. The loads and displacements were recorded at 1 s intervals by data logger using load cells and LVDT transducers. In order to obtain strain distribution in the mid-span section, four strain gauges were bonded on the lateral face of the beam. Rebar strains were also measured during the loading with gauges bonded before the beams were cast.

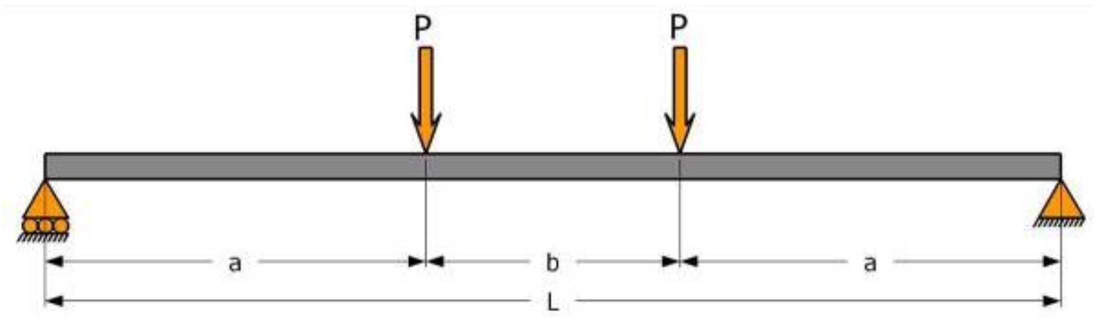


Figure 3 . Testing device

4.2 *Load-deflection response of composite beams*

The analysis of the load-displacement curves indicates that there are two or three stages of distinct behavior during the test, corresponding to the progressive damages in the constitutive materials (concrete, rebars). The curves showing the load-displacement relationship for the three 4.0-metre beams are given in Fig. 4 and, for the two 2-metre beams, in Fig. 5. For all beams with UHPC reinforced with GFRP or CFRP, the first stage of behavior corresponds to that of the uncracked section and the beam exhibits an important bending stiffness. The second stage of behavior is attained when the load reaches about 11 kN for the 2.0-metre span beams and for a load of 5 kN in the case of the 4-metre span beams. At this point, the bottom UHPC of the beam begins to crack, and a reduction of the bending stiffness is observed.

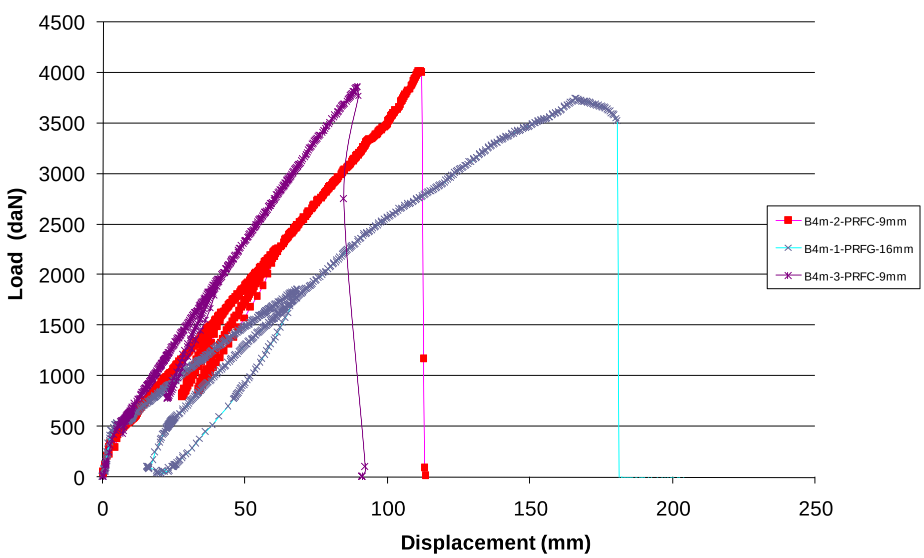


Figure 4. Load –displacement curve Beam 1 to 3

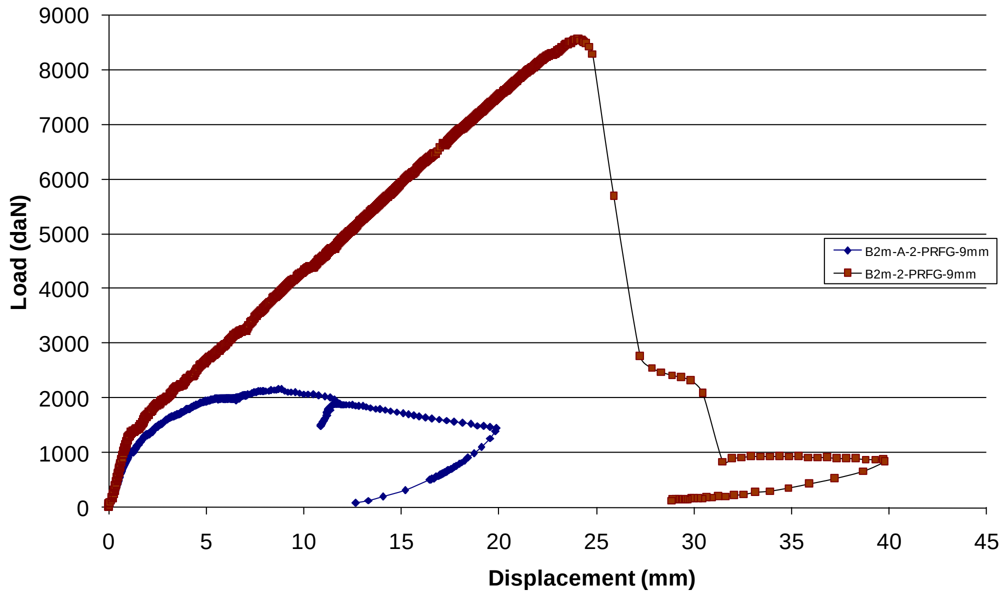


Figure 5. Load –displacement curve, Beam 4 to 5

The behavior of the composite beam remains linear but with a reduced stiffness until the third stage of behavior may occurs (beam 1). This corresponds to the yielding of tensile steel short fibers that occurs at loads of about 35 kN for the beam 1. After the cracking load the behavior remains elastic with a constant stiffness until failure. This emphasizes the interest of using FRP rebars to allow an increase of the tensile capacity of the lower beam part and to increase the ultimate capacity of the beam (Table 3).

Table 3. Experimental results

			Elastic limit load	Displacement at elastic load	Load at failure	Displacement at failure
			[kN]	[mm]	[kN]	[mm]
Beam	1	B4m-1-PRFG-16 mm	5.20	5.29	37.42	166
Beam	2	B4m-3-PRFC-9 mm	5.50	5.12	38.62	90
Beam	3	B4m-2-PRFC-9 mm	4.57	3.21	40.15	112
Beam	4	B2m-2-PRFG-16 mm	13.62	1.20	85.55	24.13
Beam	5	B2m-A-2-PRFG-16 mm	10.62	1.35	21.62	9

4.3 *Behaviour at failure*

Using the mid section strain measurements, an evaluation of the mechanical behavior of the composite beams and of the efficiency of the hybrid solution at failure can be performed. For the upper UHPC section in compression, the strain rate at failure was higher than 2500 µm/m for beam 3 and nearly 2300 µm/m for beam 1. For FRP rebars, ultimate strength was attained in beam 1 with GFRP bars while 80 % of the CFRP strength was reached at failure for Beam 3. For 2-meter beams, the range of tensile stress in CFRP or GFRP varied from 20 to 50 % of the ultimate FRP strength due to the premature shear failure of the beam (Table 3). From this observation, it was concluded that this new innovative hybrid beams allows to get higher stress at failure in each material at failure and increase then the performances of the beam. It can be stated that the hybrid configuration of the beam allows each material to reach a high strain at failure in the concrete in compression; this confirms the interest of this approach. At the ultimate load level, various failure modes were observed, depending on the span and characteristics of the beam.

(a) Beam 1 *(b) Beam 2*

(c) Beam 4 (d) Beam 5

Figure 6. Failure modes

The 2.0-metre beams failed in shear (Fig. 7c and d), while the 4-metre beams exhibited compressive (Fig. 7b) or tensile failure (Fig. 7a). The failure load of the hybrid beams occurred between 18 kN (beam 1) and 85 kN (beam 5) (Table 3). It is important to note that there was no debonding of the FRP rebars from UHPC from any of the beams. The use of Carbon composite rebars seems to be the most appropriate in relation to reduce span displacement. This can be explained by the fact that Carbon FRP Young modulus is higher than GFRP Young Modulus (Table 1). For structure design purpose, the main design criterion will be related to service condition (deflection criterion) as for glulam or steel beams. The design properties should consider the axial stiffness of FRP rebars.

4.4 *Fatigue behaviour of UHPC*

Fatigue tests are done on concrete specimen in order to obtain the fatigue resistance of UHPC in tension. The size of the specimen is 140x140x560 mm with a notch of 10 mm on the bottom central tension side. Twelve fatigue tests are done on specimen in order to obtain the fatigue resistance of UHPC used for beams shear strengthening. Wöhler curve for UHPC is obtained.

The Wöhler curve is the oldest diagram that allows to estimate the resistance of the structure or materials in the field of fatigue. This curve defines a relationship between the applied stress σ and the number of cycles at failure NR (actual number of cycles for which P% of failure was observed). In practice, the Wöhler curve is usually given for a probability of rupture P = 0.5.
In order to trace it, simple tests are carried out which consist of submitting each test specimen to periodic cycles of effort, of constant load amplitude fluctuating around a fixed average value and to note the number of cycles at the end which the initiation of a crack is observed, called here number of cycles with rupture NR; This is done for several values of the alternating amplitude Sa and R; The load ratio R is the ratio of the minimum stress to the maximum stress of the periodic cycle. For our study R=0.8, 0.6 and 0.4 for three specimens of each fatigue stress ratio.
Thus, at each structure tested, thus corresponds a point of the plane (NR, Sa) and from a number of tests with generally decreasing stress, one can establish the curve of Wöhler. The characterization of a material in the field of conventional fatigue can be made by the Wöhler curves, according to the load ratio R, from tests on smooth specimens. Tests on notched test specimens can also be carried out to validate the fatigue calculation methods of the structures.

4.1 *Fatigue behaviour of UHPC/ FRP Beams*

In order to confirm the fatigue test done on UHPC material, fatigue test are done on beams. A comparison is done between Beams reinforced by FRP bars and beams reinforced by steel rebars. According to the fatigue test, if tensile stress is lower than 7 MPa in the shear area or tension zone, the fatigue effect may be neglected. There no increase in crack width and or mid span displacement. Main objective is first to investigate the tensile strength of UHPC according to fatigue loading. A 3 point bending test is done to obtain the fatigue Wölher curve of UHPC. Since previous study (Makita el al. Song et al., Chena et al.), have shown that UHPC fatigue behaviour is good if the stress limit is under the crack strength, it is decided to do the test under several cracking load. The test is done under a crack load of 0.1, 0.15, 0.20, 0.25, 0.3, 0.4 mm crack opening. Twelve specimens are tested. The size of the specimen is 140x140x560 mm (Figure 7).

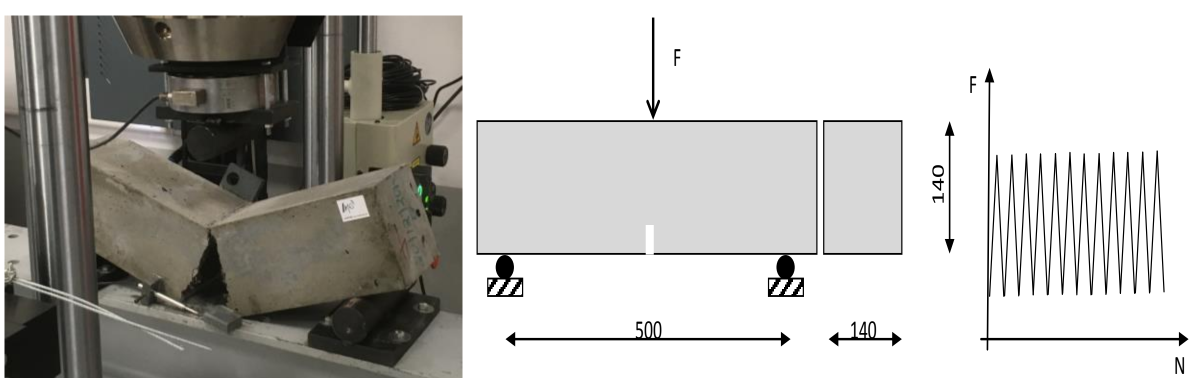


Figure 7. Fatigue test under UHPC

The fatigue of UHPC above a flexural test that allows a crack opening of 0.2 mm do not allows to obtain an extensive fatigue life since the number of cycle before failure is low. The wölher curve (Figure 9) is bi linear allowing to conclude for beam fatigue test should limit the fatigue loading is limit the UPHC crack opening to 0.10 mm. This study will be used for the next stage of the study.

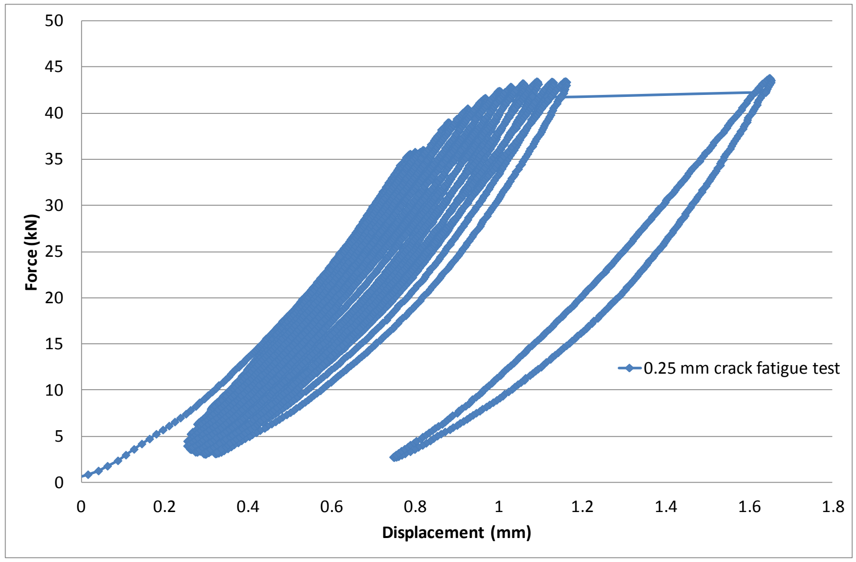


Figure 8. Wöhler Curve

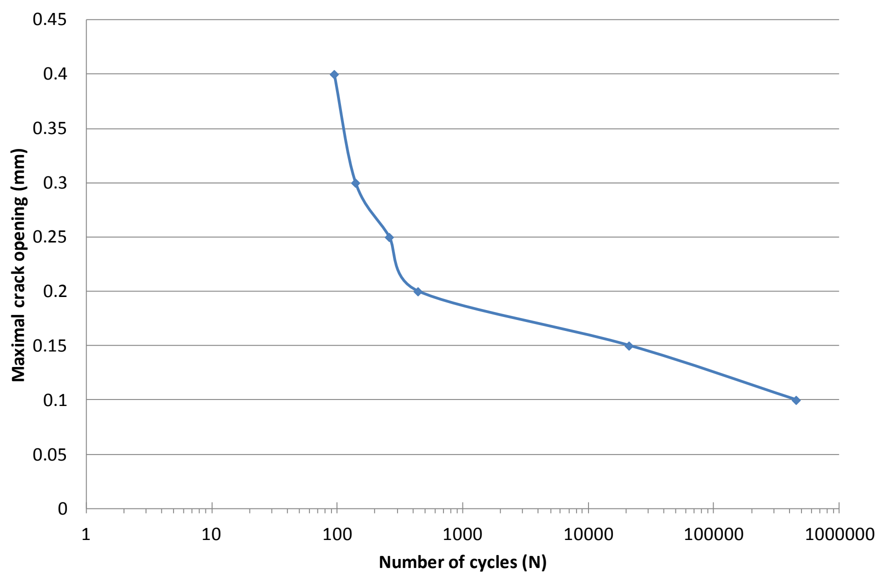


Figure 9. Wöhler Curve

5. Conclusions

This study presents an innovative hybrid beam constructed of ultra-high performance concrete with short fibres and FRP reinforcing bars. Results from an analytical procedure are compared to a preliminary experimental study. The bending stiffness and the ultimate load of the hybrid beam investigated are improved over those of conventional beams of similar dimensions. The combination of materials allows a control of the ultimate load and ductility. The results of this study should be confirmed by an extensive experimental program with large-scale beams and more specimens. Repeated stresses (traction-traction for example) are to be distinguished from alternating stresses (traction-compression). In repeated stresses, the BFM do not show a fatigue fracture, when the maximum tensile stress of the fatigue cycle does not exceed 0.5 times the tensile stress which generated, in static, the service crack. Alternating stresses are the most severe mechanical stresses for BFM. The fibre/concrete bond "suffers" immensely and, due to the discontinuous nature of the fibre, its anchorage is deteriorated fairly quickly. BFM behave poorly when fatigue stress is alternated. In a so-called "mixed" structure of bundle reinforced concrete, the fatigue behaviour of the UHPC also depends on the synergy between the reinforcements and the fibres. When a structure is subjected to repeated stresses of fatigue, even at a high level of stress such as an earthquake, the mixed structures of bundle reinforced concrete have better behaviour than conventional reinforced concrete structures.

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