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CRACKING BEHAVIOUR OF FRC MEMBERS REINFORCED WITH GFRP BARS UNDER SUSTAINED LOADS

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ABSTRACT

GFRP bars are regarded as an alternative to steel reinforcement in marine and aggressive environments. However, there are some shortfalls to the use of GFRP reinforced members in flexure, which the addition of fibres can redress. This paper is concerned with the effect of synthetic fibres on the cracking behaviour of GFRP reinforced members. A number of FRC beams reinforced with GFRP bars were tested in flexure, considering different synthetic fibre contents and GFRP bar diameters. The flexural loads applied were representative of service conditions and were sustained for 90 days. The short- and long-term cracking behaviour was analysed in terms of crack spacing, distribution and development in pure bending sections. It was concluded that synthetic fibres increased the cracking moment capacity by up to 20% and reduced the crack width and crack spacing by up to 63% and 31%, respectively.

The accuracy of the models available in current codes to predict crack width and crack spacing was assessed by comparing the experimental results to theoretical predicted values. The accuracy of crack spacing, and crack width predictions was found to vary with fibre content, and higher discrepancies were associated with higher fibre contents. This study shows that current prediction models for crack width and spacing need updating to make them better suited to elements reinforced with GFRP bars adequately considering the contribution of synthetic fibers.

KEYWORDS: Crack width, crack spacing, FRP, sustained load, synthetic fibres.

1. INTRODUCTION

Fibre-reinforced polymer (FRP) bars are increasingly used as reinforcement in concrete structures where the corrosion of steel reinforcement can be critical to their serviceability, being a competitive alternative to conventional steel in harsh environments [1, 2]. Serviceability conditions govern the design of FRP-reinforced members, and therefore the study of cracking and deformation is of fundamental importance. In service conditions, structural concrete elements reinforced with FRP bars operate at between 20 and 40% of their flexural capacity [3-6]. Due to its comparatively low modulus of elasticity, FRP reinforcement causes concrete members to exhibit larger deformations and bigger crack widths than their steel-reinforced equivalents [4, 7]. In consequence, cracks need to be controlled to avoid undesirable behaviour due to the degradation of bond between FRP bars and concrete over time. FRP bars are available in different types based on the material embedded in the resin matrix. This study considers glass fibre reinforced polymer (GFRP).

It is well known that fibre reinforced concrete (FRC) typically presents more distributed crack patterns and smaller crack widths [8, 9]. However, although previous studies report on ductility and toughness improvements achieved with different types of fibres, the majority of literature is concerned with the contribution of steel fibres and has paid little attention to non-metallic fibres.

There is abundant literature on the short-term cracking of structural concrete members reinforced with FRP bars [7, 10, 11]. However, there is limited research published on long-term cracking of FRC beams with FRP bars. This study is part of an experimental programme aimed at investigating the influence of synthetic fibres on the long-term flexural performance of GFRP reinforced beams. This paper presents the experimental investigation of the influence of synthetic fibres on the short- and long-term cracking of GFRP beams under sustained loads, and compares the experimental observations with the theoretical values based on the prediction models proposed by the Eurocode 2 [12], ACI 440.1R-15 [1], Model code 2010 [13] and RILEM TC 162-TDF [8].

2. EXPERIMENTAL PROGRAMME

2.1. Materials and mix designs

The same reference concrete mix, with a water-to-cement ratio of 0.29 and a mean compressive strength of 60 MPa at 28 days, was considered for all beams and control specimens. The type of cement used was CEM I (52.5N), and the reference concrete mix was designed so that it could accommodate different synthetic fibre contents by only adjusting the superplasticiser dosage (SikaViscoCrete 25MP was used). Synthetic macro-fibres with a length of 54 mm, a diameter of 0.34 mm and a tensile strength of 600 MPa were used. They were considered at three different dosages: 0, 5, and 10 kg/m^3, corresponding to volume fractions of 0%, 0.55% and 1.1%, and referred to as mix 1, mix 2 and mix 3, respectively in Table 1.

Table 1. Synthetic FRC mix designs.

Constituents	Quantity (kg/m^3)		
	Mix 1	Mix 2	Mix 3
Water	147	147	147
Cement	510	510	510
Fine aggregate	950	950	950
Coarse aggregate (20 mm)	300	300	300
Coarse aggregate (10 mm)	580	580	580
Synthetic fibres	0	5	10
Superplasticiser	9.4	12	14

Pultruded GFRP bars with diameters of 16 mm and 20 mm were used as flexural reinforcement for the beams produced in this study. Their tensile strength and modulus of elasticity were determined by testing five bars of each diameter to ACI 440.3R-04 [14]. It was confirmed that there were no significant differences between bars of different diameters. The average tensile strength and elastic modulus were 694 MPa and 40 GPa respectively, and the ultimate strain was 1.76%.

2.2. Flexural tests

A total of eight simply supported beams were produced. All beams had the same dimensions: the rectangular cross-section was 200 mm wide and 260 mm deep, and the clear span between supports was 3050 mm. These beams were tested in flexure following a four-point configuration, as shown in Figure 1. Steel stirrups were equally spaced to provide sufficient shear reinforcement in all sections of the beam apart from the central third of the span, in order to prevent shear failure.

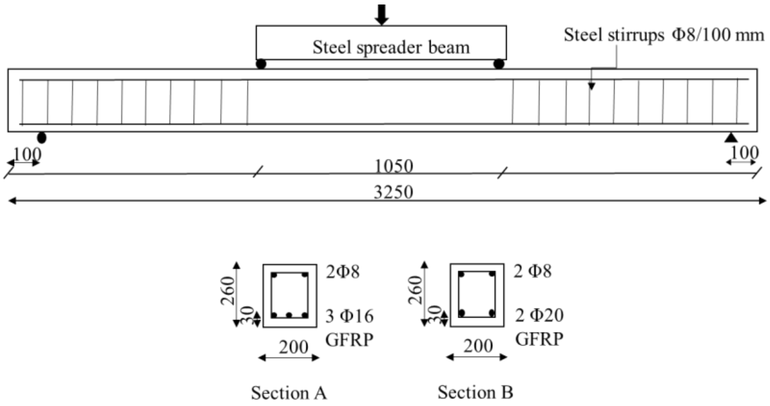

Figure 1. Beam dimensions and reinforcement details.

Two series of beams (A and B) were produced: four beams were reinforced with 16 mm GFRP bars, and four were reinforced with 20 mm GFRP. The number of GFRP bars in each case was adjusted so that all eight beams had practically the same reinforcement ratio. As shown in Table 2, each series comprised 4 beams: one was the reference beam without fibres; two identical beams with 5 kg/m^3 fibres content, and one beam with 10kg/m^3 of fibres. Beams with moderate synthetic fibre content (5kg/m^3) were replicated to get an indication of variability in the results. They were designated as F#D#, where F denotes the fibre content in kg/m^3, and D denotes the bar diameter in mm.

Table 2. Beams details.

Beam designation	Bar diameter (mm)	Fibre content (kg/m^3)	Section
F0D16	16	0	A
F5D16	16	5	A
F5D16 (replicate)	16	5	A
F10D16	16	10	A
F0D20	20	0	B
F5D20	20	5	B
F5D20 (replicate)	20	5	B
F10D20	20	10	B

2.3. Testing procedure

As illustrated in Figure 1, beams were supported by rollers and loaded at two points, each being 525 mm away from midspan. The load was applied at a constant rate of 2 kN/min until it reached the value of 37 kN, which was then sustained for 90 days. This load corresponded to 40% of the design flexural capacity of the section and was considered as representative of serviceability conditions.

Midspan deflection was monitored by means of an LVDT, and concrete surface strains were measured using DEMEC points installed in the constant bending moment zone, with a spacing of 150 mm between them. Strains on the GFRP bars were measured with strain gauges placed on their surface. Crack width, depth and spacing were measured manually and recorded immediately after the application of the load and regularly thereafter for 90 days. This paper focuses on the values observed right after the application of the load and after 90 days of sustained load.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Characterisation test results

The compressive strength, tensile strength and modulus of elasticity of the concrete mixes were determined by testing cylindrical (150x300 mm) and cubic (100-mm side) specimens. From each batch of concrete produced, 3 cylinders and 3 cubic specimens were produced and tested. This information was used to monitor consistency between batches. The average values are given in Table 3.

Table 3. Concrete mechanical properties.

Properties	Mechanical properties (MPa)		
	Mix 1	Mix 2	Mix 3
Compressive strength	60.3	60.1	59.7
Tensile strength	3.90	4.4	4.6
Modulus of elasticity	39.6	40.9	39.8

No significant differences were observed in relation to compressive strength or elastic modulus. Tensile strength improved with the addition of synthetic fibres, increasing by 13% when 5kg/m^3 fibres were used, and by 4.5% when the fibre content was increased from 5 to 10 kg/m^3. This was consistent with studies reporting improvements of up to 19% in tensile strength when using synthetic fibres [15, 16].

3.2. Influence of fibres on the cracking load and crack width

During the application of the load, flexural cracks appeared in the constant bending moment zone when the cracking load was reached. With the increasing load, new vertical cracks formed. The load levels at which cracks stabilised ranged between 1.5-2 times the cracking load, which was consistent with studies reporting that this occurs at load levels between 11% and 41% of the flexural capacity [17, 18].

The cracking load, number of cracks, crack width, depth and spacing were recorded. Crack width, depth and spacing were averaged taking into account the measurements from all cracks. Values at 90 days are given in Table 4, together with the average crack width right after the load was applied.

Table 4. Crack measurements recorded after 90 days sustained loading.

Beam designation	Cracking load (kN)	No. of cracks	Average spacing (mm)	Average depth (mm)	Average crack width (mm)	
					0 day	90 days
F0D16	21.1	10	201	212	0.53	0.72
F5D16	22.6	13	160	186	0.34	0.44
F5D16*	26.2	13	157	178	0.31	0.42
F10D16	25.2	15	125	147	0.18	0.31
F0D20	20.7	10	230	214	0.55	0.79
F5D20	22.3	11	180	188	0.35	0.51
F5D20*	24.0	11	183	180	0.34	0.53
F10D20	24.8	13	121	145	0.22	0.34

FRC beams exhibited higher cracking loads than the control beams. Fibres were found to improve the cracking load by up to 14% when dosed at 5 kg/m^3. Cracking loads were further increased when the fibre content increased from 5 kg/m^3 to 10 kg/m^3, but only by 4%. FRC beams developed more cracks and presented lower crack widths and depths than their control counterparts (Figure 2). The average short-term crack width was 0.34 mm and 0.20 mm in FRC beams with 5 and 10 kg/m^3 of synthetic fibres respectively, as opposed to 0.54 mm in the reference beams, without fibres.

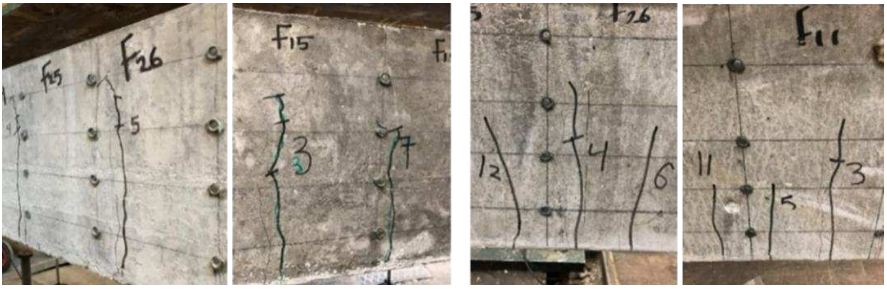

Figure 2. Crack detail in beams without fibres (left) and with synthetic fibres (right).

The average crack widths observed in the reference beams were higher than the limit values of 0.5-0.7 mm recommended by the ACI Committee 440. It is not uncommon that the crack widths observed in beams with GFRP bars exceed recommended limits [19]. However, the addition of 5 kg/m^3 of synthetic fibres sufficed to bring crack widths down to acceptable levels.

The reference beams without fibres developed new cracks along the span within the first week of sustained loading, which was consistent with previous reports [20]. The FRC beams, on the other hand, did not develop new visible cracks during the sustained loading period. Furthermore, the average crack depth was reduced by up to 14% and 31% with fibre dosages at 5 and 10 kg/m^3, respectively.

The crack width values measured after the 90 days of sustained loading were between 40-60% higher than the values registered right after the application of the flexural load. However, the crack widths significantly decreased with increasing fibre contents consistently at all ages, as shown in Figure 3. Reductions between 34% and 40% were observed for a synthetic fibre content of 5 kg/m^3, and between 57% and 66% for a synthetic fibre content of 10 kg/m^3.

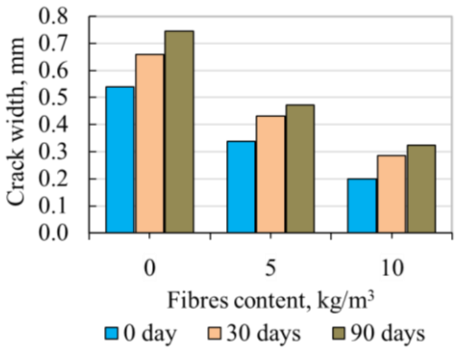

Figure 3. Average crack widths observed for different dosages of fibres.

The experimental crack width values were compared to the theoretical values shown in Table 5, whilst Table 6 presents the observed versus predicted ratios. Predicted values as per Eurocode 2 [12], CSA [21] and some other models [22-24] closely matched the experimental short-term crack widths of reference beams. The ACI 440.1R and Eurocode 2 models yielded good predictions for reference beams without fibres but overpredicted the long-term crack width values by 26% and 52% in FRC beams with fibre contents of 5 and 10 kg/m^3, respectively. This was attributed to these models considering higher bond coefficients and not adequately accounting for the fibres contribution in increasing the area of concrete active in the tension zone.

The model proposed by RILEM TC 162-TDF, on the other hand, underpredicted long-term crack widths. Although the model proposed by the Model Code 2010 accounts for the post-cracking tensile strength of FRC, it underpredicted crack width values by 45% and 34% for fibre contents of 0 and 5 kg/m^3, respectively, but the difference with the experimental values decreased to 9% for a fibre content of 10 kg/m^3. This was attributed to this model having been developed for steel FRC with steel reinforcement, not synthetic FRC with GFRP bars.

Table 5. Theoretical crack width values according to different models.

Models and provisions	Crack width (mm)	
	Bar 16 mm (short/long)	Bar 20 mm (short/long)
CSA [21]	0.56	0.58
ISIS Manual [23]	0.82	0.95
ACI 440.1R-015 [1]	0.71	0.71
Toutanji and Saafi [22]	0.55	0.66
Salib and Abdel-Sayed [24]	0.53	0.62
Wang and Belarbi [9]	0.53	0.61
EC2 [12]	0.56/0.69	0.62/0.77
RILEM TC 162-TDF [8]*	0.09/0.11	0.10/0.13
CEB-FIP Code [13]	0.28/0.37	0.35/0.46
CEB-FIP Code [13]*	0.20/0.30	0.26/0.35
CEB-FIP Code [13]**	0.18/0.26	0.24/0.32

* FRC with 5 kg/m^3
** FRC with 10 kg/m^3

Table 6. Long-term crack widths compared to theoretical values.

Beam	Exp.	EC2		MC2010		ACI 440.1R	
	$w_{exp.}$	w_{pred}	$w_{pred}/w_{exp.}$	$w_{pred.}$	w_{pred}/w_{exp}	w_{pred}	$w_{pred}/w_{exp.}$
F0D16	0.72	0.69	0.96	0.37	0.51	0.71	0.98
F5D16	0.44	0.69	1.74	0.28	0.68	0.71	1.61
F5D16*	0.42	0.69	1.65	0.28	0.71	0.71	1.68
F10D16	0.31	0.69	2.24	0.25	0.83	0.71	2.28
F0D20	0.79	0.77	0.88	0.46	0.59	0.71	0.89
F5D20	0.51	0.77	1.50	0.35	0.68	0.71	1.39
F5D20*	0.53	0.77	1.44	0.35	0.65	0.71	1.33
F10D20	0.34	0.77	2.25	0.32	0.95	0.71	2.08

The crack width values obtained experimentally were used to obtain an adjusted value for the bond coefficient (k_1 or k_b) for the different fibre contents considered. Table 7 shows the adjusted bond coefficient values and the corresponding long-term crack widths.

The plot in Figure 4 shows the ratio of theoretical to experimental crack width versus fibre contents using original and adjusted bond coefficients in the different models. It can be observed that the ACI, ISIS and CSA models, when used with the adjusted bond coefficients, led to predicted crack width values that were quite close to those experimentally observed for plain and FRC beams. On the other hand, predicted values using EC2 were higher, which was attributed to the lower bond coefficient originally proposed in the EC2 model (0.8).

Table 7. Crack width values using adjusted bond coefficients.

Fibre content (kg/m³)	Adjusted k_b	Crack width (mm)			
		ACI	EC2	ISIS	CSA
0	1.26	0.75	0.81	0.85	0.76
5	0.77	0.45	0.69	0.54	0.46
10	0.56	0.33	0.63	0.39	0.34

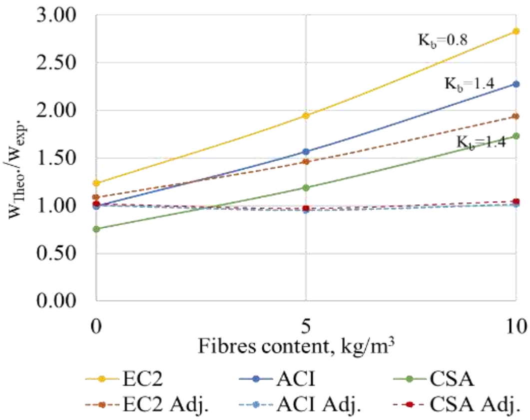

Figure 4. Ratio of theoretical to experimental crack widths versus fibre contents.

3.3. Influence of fibres on the crack spacing

The spacing between flexural cracks was measured in all tested beams. Table 8 presents the maximum, minimum and average values of crack spacing measured after 90 days of sustained load, together with the ratios of average to minimum and maximum to minimum crack spacing.

Table 8. Long-term maximum and average crack spacing.

Beam designation	Crack spacing (mm)			Ratios	
	$S_{max.}$	$S_{Aver.}$	$S_{Min.}$	$S_{ave.}/S_{Min.}$	$S_{max.}/S_{Min.}$
F0D16	250	201	170	1.18	1.47
F5D16	218	160	115	1.39	1.89
F5D16*	210	157	121	1.29	1.74
F10D16	156	125	78	1.60	2.00
F0D20	248	230	180	1.28	1.38
F5D20	220	180	123	1.46	1.79
F5D20*	222	183	113	1.62	1.96
F10D20	160	121	85	1.43	1.88

Using the expressions in Eurocode 2 for steel-reinforced beams, the maximum and average crack spacing would be 232 mm and 177 mm for a rebar diameter of 16 mm, and 255 mm and 201 mm for a diameter of 20 mm. Comparing these values to those in Table 8, the maximum crack spacing values predicted by the Eurocode were similar to those observed in the GFRP-reinforced beams without fibres. However, it overpredicted the crack spacings observed in FRC beams by up to 35%. This indicated that crack spacing estimates to Eurocode 2 reproduced well the observations with GFRP bars but failed to account for the effect of synthetic fibres.

The synthetic FRC beams presented significant reductions in crack spacing when compared to their counterparts without fibres, the maximum cracks spacing being reduced up to 37% for a synthetic fibre content of 10 kg/m^3. The ratio of maximum to average crack spacing was 1.16 for the beams without fibres, and 1.29 for FRC beams. Observed values of the ratios of maximum to average crack spacing and minimum to average crack spacing are plotted against average crack spacing in Figure 7. The average crack spacing was 1.39 times the minimum crack spacing, whilst the maximum crack spacing ranged between 1.35 and 2 times the minimum crack spacing. These observations were found to be in good agreement with the values reported in previous studies [25].

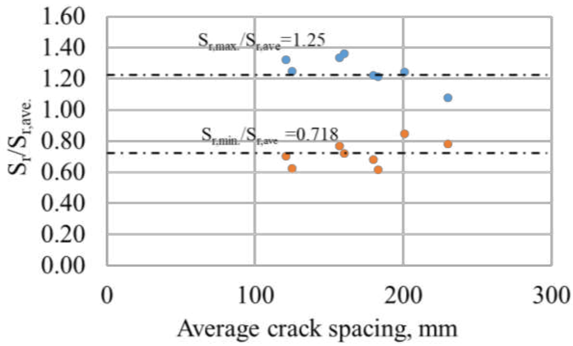

Figure 5. Relative maximum and minimum crack spacing with respect to average crack spacing.

According to the Model Code 2010, the maximum crack spacing corresponds to twice the length over which slip occurs between concrete and reinforcement. For 16 and 20 mm bar diameters, these values would be 111 mm and 139 mm, respectively, and as a result the maximum crack spacing is significantly underpredicted in GFRP-reinforced beams with synthetic fibres. Some researchers have proposed models to calculate the crack spacing in steel FRC, e.g. Moffatt [26] accounts for the residual flexural strength of the material. However, such models do not seem to work well for synthetic FRC beams with GFRP bars, significantly underestimating the crack spacing in GFRP reinforced beams, yielding values of 77 mm and 84 mm for 16- and 20 mm bar diameters, respectively.

4. SUMMARY AND CONCLUSIONS

This paper reports on the experimental results on the short- and long-term cracking behaviour of synthetic FRC beams reinforced with GFRP bars subject to sustained flexural load for a period of 90 days. The relative effect of the synthetic fibre content and bar diameter on crack width and spacing are discussed. Experimentally obtained values of crack width and crack spacing were compared to the theoretical values obtained by means of predictive models in a number of codes and reports. The main conclusions of this study can be summarised as follows:

- The incorporation of synthetic fibres to concrete at the volume fractions considered in this study resulted in an increased cracking capacity of GFRP beams. The observed cracking loads were increased by up to 14% and 20% in beams with 5 and 10 kg/m^3 of synthetic fibres, respectively.
- The average crack width in GFRP reinforced beams with 5 kg/m^3 of synthetic fibres were up to 37% lower than those corresponding to the reference beams without fibres. Higher reductions, up to 63%, were observed in beams with 10 kg/m^3 of synthetic fibres.
- The spacing between flexural cracks was reduced by 13% and 31% when synthetic fibres were dosed at 5 and 10kg/m^3, respectively. Similar reductions were observed in the crack depth values:

crack spacing observed in beams with 5 and 10kg/m^3 of synthetic fibres was 14% and 31% lower, respectively.

- The comparison of experimental results for crack width, depth and spacing against the values predicted by different models confirmed that these do not accurately represent the cracking of synthetic FRC beams reinforced with GFRP bars. This was attributed to the fact that existing models mostly assume steel reinforcement and steel fibres, when the contribution of fibres is accounted for.

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