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# Effect of hybrid fibres on the static load performance of concrete beams

Abdulrahman Abbadi [a,b,*], P.A.M. Basheer [a], John P. Forth [a]

[a] School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds, United Kingdom
[b] School of Civil Engineering, College of Engineering, Jazan University, Jazan, Saudi Arabia

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ABSTRACT

Fibre-reinforced concrete (FRC) has been increasingly used in construction for several decades to reduce crack growth by incorporating one or two types of fibre in reinforced concrete elements under the static load. This paper intends to investigate experimentally how hybrid fibre systems (micro and macro polypropylene fibres and steel fibres) can enhance the performance of RC beams subjected to static loading by restricting the development of micro-cracks and macro-cracks. The test programme consisted of testing six full-scale simply supported beams. The main parameters were fibres' addition (i.e. steel and polypropylene fibres) and volume fraction (i.e. 1 and 1.5% for steel and hybrid fibre system (1% steel, 0.1% micro, and 0.4% macro polypropylene fibres)). From the test data analysis, it was found that the hybrid fibre system decreased the deflection, reduced the strain in the steel reinforcement bars, and reduced the crack width. The splitting tensile strength and compressive strength of the hybrid fibre-reinforced concrete was greater than that of the single fibre-reinforced concrete. The addition of more than two types of fibres illustrates a pronounced beneficial hybrid effect.


## 1. Introduction

Concrete is a tension-weak construction material with a low strain capacity. As such, it is prone to cracking in both the short-term, due to plastic shrinkage and the restraint of imposed strains, for instance, and long-term, due to applied loading and degradation resulting from durability issues. To improve the cracking observed at the serviceability limit state and, hence, help control deflection and provide greater resistance to problems resulting from durability issues, traditional steel reinforced concrete can be strengthened with a range of fibres to help resist the different scales of cracking. This combination or hybrid fibre system can, through their different lengths and constitution, help control the propagation of cracks in both the short term and long term and at both the micro and macro scales.

Fibre-reinforced concrete (FRC) has been increasingly utilised in construction for several decades. It has been well-established that FRC can enhance the ductility of the concrete element. FRC also diminishes the growth and formation of cracks and can perform as shear reinforcement. FRC has numerous advantages when compared to reinforce concrete beams, such as decreasing the width and the number of cracks, enhancing the shear and flexure strengths, increasing ductility, and reducing deflection [1]. Moreover, the presence of discrete fibres enhances fracture toughness and fatigue resistance [2]. An FRC mix is usually used to enhance the serviceability of concrete and improve its fatigue resistance [3–5].

Hybrid fibres are where more than one type of fibre is used. The ductility and strength of concrete are enhanced by the hybridisation of different types of fibres; incorporating different types of fibres with different lengths helps control the propagation of micro and macro cracks [6]. There is a positive interaction between the fibres in well-designed hybrid composites and the consequent hybrid performance is better than the sum of the individual fibres' performance; for instance, the hybrid fibre system produced an increase in the compressive strength of between 2 and 13% and an increase in the tensile strength by up to 14.8% when compared to the results from the single fibre tests [7].

Previous studies [8–14] have reported the inclusion of one or two types of fibre to reduce cracking in reinforced concrete elements subjected to static loading. To the authors' best knowledge, none of the previous studies have been carried out to determine

* Corresponding author at: School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds, United Kingdom.
*E-mail address:* cnamia@leeds.ac.uk (A. Abbadi).

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the effects of a hybrid fibre system (micro and macro polypropylene fibres combined with macro steel fibres) on the cracking performance of reinforced concrete beams under static loading. The work reported in this paper aims to establish the benefit of hybrid fibre systems on the ultimate limit state (ULS) performance of beams subjected to static loading. The work presented here is the first phase of a study to assess how hybrid fibre reinforcement can restrict the development of micro and macro cracks in RC elements subjected to dynamic loading.

## 2. Experimental programme

### 2.1. Materials, mixing and specimen preparations

Portland cement (high strength cement 52.5 N) (CEM I) was used for all concrete mixes. Natural sand with a maximum particle size of 5 mm and natural coarse quartzite gravel aggregate with a maximum size of 20 mm were used. The grading of both types of aggregate was according to BS882: 1992 [15]. A high range water reducing admixture, Sika ® Visco Crete 25 MP, that complies with the requirements of BS EN 934-2: 2009 [16] was used to ensure that the concrete was workable. The water-cement ratio was 0.42 for all mixes. The proportions of the different concrete mixes are reported in Table 1.

Three types of fibres, namely, steel, macro and micro fibres, have been used due to their reported [17–18] positive contribution to decreasing the number of cracks and crack widths. The hooked end steel fibre (Dramix 3D) was obtained from Bekaert, whereas the fibrin and durus polypropylene fibres were obtained from Adfil; these are shown in Fig. 1(a), Fig. 1(b) and Fig. 1(c), respectively. The properties of the micro (fibrin) and macro (Durus) polypropylene fibres and steel fibres, as reported by the manufacturers, are given in Table 2.

The concrete mixes were made by following BS 1881-125: 2013 [19], using a drum mixer to mix the concrete. The drum mixer was grouted to make the mixer slightly wet and avoid the absorption of the mix water. The materials were placed in the drum mixer in the following order. 1) Fine and coarse aggregate were added and then mixed dry for 15 to 30 s. 2) The mixer was stopped, then the cement was added and mixed with the aggregate to ensure homogeneity of the mix and run it for 30 s. 3) Superplasticizer was added to the water and then the water/superplasticizer was added to the mix while the mixer was still running for two minutes or three minutes. For the fibre concrete mixes; 4) The fibres were added while the mixer was still running; the mixer was kept running for a couple of minutes to assure the regular distribution of all fibres.

The experimental programme consisted of testing six full-scale simply supported beams (150x300x4200 mm), details of which are provided in Table 3. They were manufactured in duplicates to study three concrete mixes: 1) normal concrete (NRC) with steel reinforcement bars; 2) steel fibre-reinforced concrete (SFRC) with steel reinforcement bars; and 3) hybrid steel and polypropylene fibre reinforced concrete (HyFRC) with steel reinforcement bars. Each beam was subjected to a static load (ST). In Table 3, the beam labels also include the fibre volume fraction (i.e., 0 for reference concrete specimens, 1 and 1.5% for steel and hybrid fibre system (1% steel, 0.1% micro, and 0.4% macro polypropylene fibres)). For each mix, accompanying concrete cylinders (150x300 mm) and cubes (100x100x100 mm) were tested to determine the tensile strength and compressive strength of the different concrete mixes as per British Standards and BS EN 12390-6 [20] and BS EN 12390-3 [21], respectively.

The slump test was used to determine the workability of the fresh concrete and was performed according to BS EN 12350-2 [22]; these results are shown in Table 4. After 24 h, all small concrete test specimens were removed from their moulds and stored for a further 27 days in a controlled environmental fog room, where the temperature was 20 ± 2 °C and the relative humidity was ≥ 95%. The full-scale beams were initially cured in their moulds, being covered with wet hessian and polythene sheet, before being demoulded after 4 days and placed in the fog room for a further 25 ± 1 days.

### 2.2. Test specimens and experimental set-up

Six full-scale beams were manufactured and tested using a static load at the age of 28 days to determine the flexural strength of the full-scale beams. Three deformed steel bars of diameter $\phi$ = 16 mm as bottom tensile longitudinal reinforcement were used. Two steel bars of $\phi$ = 10 mm acted as hangar bars for the shear links. For the shear links, deformed bars of $\phi$ = 8 mm were spaced at 150 mm along the length of the beam but omitted within the constant moment zone (see Fig. 2). Small pieces of concrete (packers) were placed under the reinforcement cage to maintain a clear concrete cover of 25 mm. All beams had a rectangular cross-section of 150x300 mm; the clear span between supports was 4000 mm and the distance between the applied loads was 1500 mm. All beams were simply supported and subjected to a four-point bending load, as shown in Fig. 2. A hydraulic jack was utilized to apply the load at two locations spaced 1500 mm apart. Chemical metal was used to 'bed' the loading and support plates to ensure the beams were level and the load acted vertically at the start of the test.

### 2.3. Instrumentation and measurements

Three, five millimetre long electrical wire strain gauges were attached to the tensile reinforcement steel bars at the mid-span of the beams. Electrical wires were soldered to the strain gauges' ends and connected to electrical terminals on the steel bar. Prior to testing, four rows of Demec gauges were installed on one side of the long (4.2 m) beam specimens within the constant moment zone (the spacing of the Demec points was 150 mm) to monitor the neutral axis depth and curvature; two rows of Demec points were placed level with the bottom and top reinforcement of the beam. The strain was monitored and measured using a handheld mechanical Demec gauge. Additionally, two ERS gauges were installed at the mid-span of the beam, on the opposite side to that with the Demec points and in line with the level of the top and bottom reinforcement. All electrical strain gauges were connected to a

**Table 1**
Mix proportions.

| Mix type | Quantity (kg/m$^3$) | | | | | Fibres | |
|---|---|---|---|---|---|---|---|
| | Cement | Water | Fine aggregate | Coarse aggregate | Superplasticizer | Volume fraction (%) | Fibre type |
| NRC | 422 | 177 | 754 | 1024 | – | – | – |
| SFRC | 422 | 177 | 754 | 1024 | 1 | 1% | Steel fibres |
| HyFRC | 422 | 177 | 754 | 1024 | 1.5 | 1.5% | 0.1% micro fibre, 0.4% macro-PP, and 1% steel fibre |

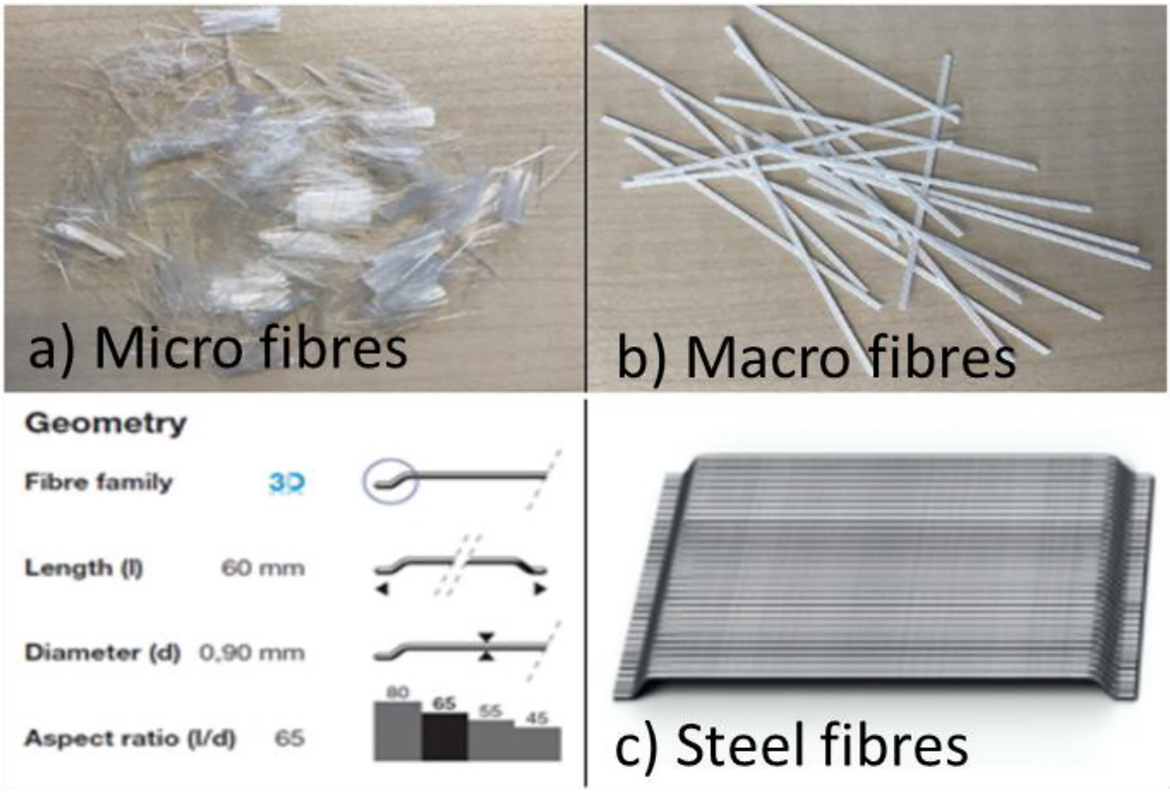


**Fig. 1.** Different fibres type: a) micro polypropylene fibres, b) macro polypropylene fibres and c) steel fibres.

**Table 2**
Properties of fibres.

| Fibre type | Specific gravity (kg/m$^3$) | Length (mm) | Diameter | Aspect ratio |
|---|---|---|---|---|
| Fibrin (micro 1960/650) | 910 | 18 | 50 µ | – |
| Durus (macro S500) | 922 | 48 | 0.7 | 69 |
| Steel (Dramix 3D 65/35BG) | 7850 | 60 | 0.9 | 65 |

**Table 3**
Summary of the experimental programme.

| No. | Beam labels | No. of bottom bars | No. of top bars | Volume fraction | Fibre type |
|---|---|---|---|---|---|
| 1 | NRC-ST-0 | 3–16 | 2–10 | 0 | – |
| 2 | SFRC-ST-1 | 3–16 | 2–10 | 1% | Steel fibre |
| 3 | HyFRC-ST-1.5 | 3–16 | 2–10 | 1.5% | 0.1% micro fibre, 0.4% macro-PP, and 1% steel fibre |

**Table 4**
Experimental results for normal and fibre reinforced concrete (fresh and hardened concrete).

| Concrete mix | Cube strength (MPa) and Coefficient of variation (%) | Cylinder strength (MPa) and Coefficient of variation (%) | Splitting tensile strength (MPa) and Coefficient of variation (%) | Modulus of elasticity (MPa) | Slump (mm) |
|---|---|---|---|---|---|
| NRC | 52.72 (0.85) | 40.51 (6.06) | 3.25 (9.34) | 30,172 | 100 |
| SFRC | 58.15 (1.68) | 43.48 (5.36) | 5.03 (0.39) | 31,069 | 75 |
| HyFRC | 59.58 (4.51) | 43.61 (3.53) | 5.86 (6.14) | 31,916 | 50 |

data logger and measured the steel and concrete strains during testing.

A linear variable displacement transducer (LVDT) located at the mid-span of the beams was utilized to measure the short-term deflection of the beams. The crack growth at the surface of the concrete was monitored during testing to investigate the influence of fibres on the development of the cracks. The crack width of the full-scale beams was recorded using a digitronic caliper or graduated magnifier.

## 3. Results and discussion

### 3.1. Fresh concrete properties

Table 4 shows the slump recorded for the different mixes used in this investigation. The normal concrete mix was designed to achieve an S3 slump class and its slump was measured at 100 mm. As expected, the introduction of fibres reduced the measured slump (as fibres tend to reduce the concrete workability

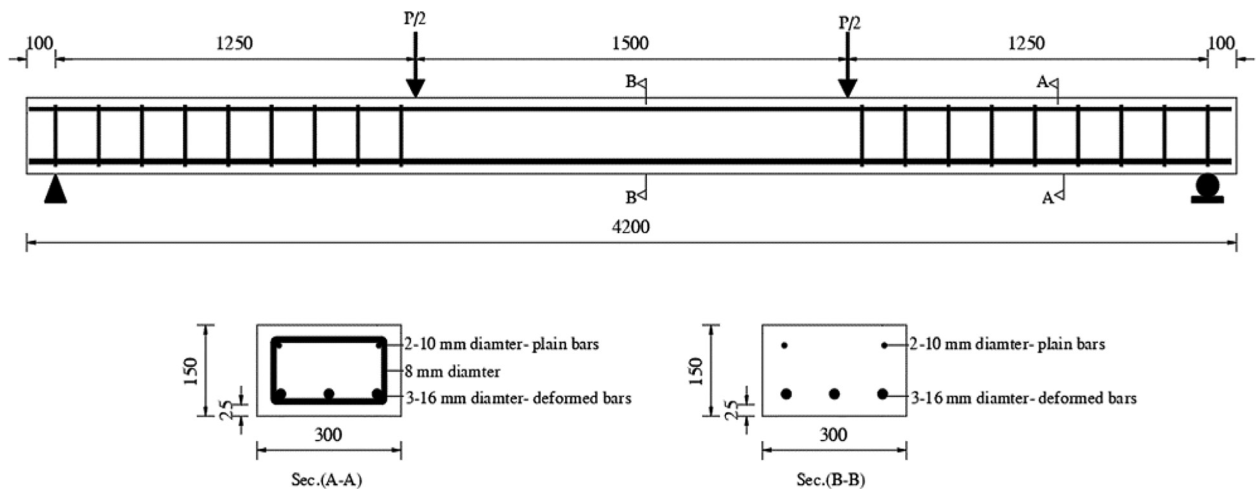


**Fig. 2.** The details of the beam specimens.

[12,23–24]); Steel fibres recorded a slump of 75 mm, whilst the hybrid steel-polypropylene fibres produced a slump of 50 mm.

### *3.2. Compressive strength, splitting tensile strength and modulus of elasticity*

Cube and cylinder concrete specimens with and without fibres were used to determine the 28-day compressive strength, splitting tensile strength and modulus of elasticity; these results are shown in Table 4. The test results indicated that the addition of different types of fibres and different volume fractions can result in higher compressive and splitting tensile concrete strengths, as shown in Table 4. The highest compressive strength was attained with the inclusion of 1.5% hybrid steel-polypropylene fibres (i.e. HyFRC); these strengths were about 11.31% and 5.52%, respectively, higher than the reference specimens without fibres. A similar observation was made by Afroughsabet et al. [25], who reported a higher compressive strength for the hybrid steel-polypropylene fibres (of about 18% more than the normal concrete). As reported by both Afroughsabet et al. [25] and Nia et al. [26], steel fibres had a greater influence on the compressive strength enhancement than polypropylene fibres. According to them, this is due to the longer length, higher tensile strength, and the hooked-ends of the steel fibres. The incorporation of hybrid steel-polypropylene fibres (i.e. HyFRC) also produced the greatest increase in the splitting tensile strength; it was approximately 37% greater than the reference specimens. The addition of 1% of steel fibres only produced an increase in the splitting tensile concrete strength of approximately 27%. According to Afroughsabet et al. [25] the incorporation of hybrid steel-polypropylene fibres increased the splitting tensile strength by between 23% and 52%; the extent of increase depended on the fibre replacement percentage and the testing age. The addition of either the hybrid fibres or the steel fibres produced an increase in the modulus of elasticity by about 5.46% and 2.88%, respectively. From these results, it can be seen that the hybrid fibre mix is more beneficial when compared to a single fibre mix.

### *3.3. Flexural behaviour*

#### *3.3.1. Crack pattern and mode of failure*

In all beams, the initial flexural cracks formed randomly at the bottom of the beams within the constant moment region and spread upwards on the side of the beams with no specific pattern during the test. At each increment of loading, a visual examination was performed to track the progression of cracks on the side of the beams. Vertical cracks developed upward towards the compressed concrete zone as the load was increased, and the crack width expanded until the failure of the tested beams occurred. The typical flexural failure of each type of beam is shown in Fig. 3. The failure mode of the normal concrete specimens was a brittle flexural failure; a similar observation was reported by Kim et al. [11]. With the incorporation of either the hybrid fibres or the steel fibres, the failure mode of the beams changed from a sudden and brittle concrete crushing failure to a ductile failure. Fibres can prevent brittle concrete crushing due to their ability to increase concrete toughness in compression as reported by Meda et al. [8]. The FRC beams had fewer cracks when compared to the reference beams without fibres at the same load level. Beams containing steel fibres and hybrid fibres exhibited smaller cracks, at the same load levels, when compared to the reference NRC beams.

#### *3.3.2. Load-deflection curve*

Fig. 4 shows the load–deflection curve of the three types of beams. Each curve is based on the average displacement of two replicate beams for each type that were tested. Table 5 summarizes the test results. The addition of either the steel fibres (SFRC) or the hybrid fibres (HyFRC) to the test beams produced an increase in the cracking load by 29% and 43%, respectively, greater than the reference specimen without any fibres. After the formation of the first visible crack, all the test beams showed a significant loss in their stiffness. The incorporation of steel and hybrid fibres to test beams showed a reduction in the deflection at failure of approximately 5.58% and 5.84%, respectively. Meda et al. [8] report that the fibres' ability to control the deflection before the failure load can decrease up to 17% when compared to reference specimens. As reported in Table 5, there was an increase in the failure load with the addition of steel fibres and hybrid fibres by 14% and 15% respectively compared to the reference beams without fibres. Furthermore, as seen in Fig. 4 and reported in Table 5, the addition of polypropylene fibres in the hybrid fibre system resulted in a 14% increase in load at the formation of the first visible crack and a modest 1% increase in the failure load compared to the SFRC beams. The incorporation of either the steel fibres or the hybrid fibres to the test beams produced an increase in first cracking load and the load just before the failure. This is in agreement with some of the other published work [9,12,13,27]; this increase is attributed to the fibres' bridging action at the fracture interfaces. The test results revealed that the addition of single or hybrid fibres reduced the deformation of the beams, as shown in Table 5 and Fig. 4,

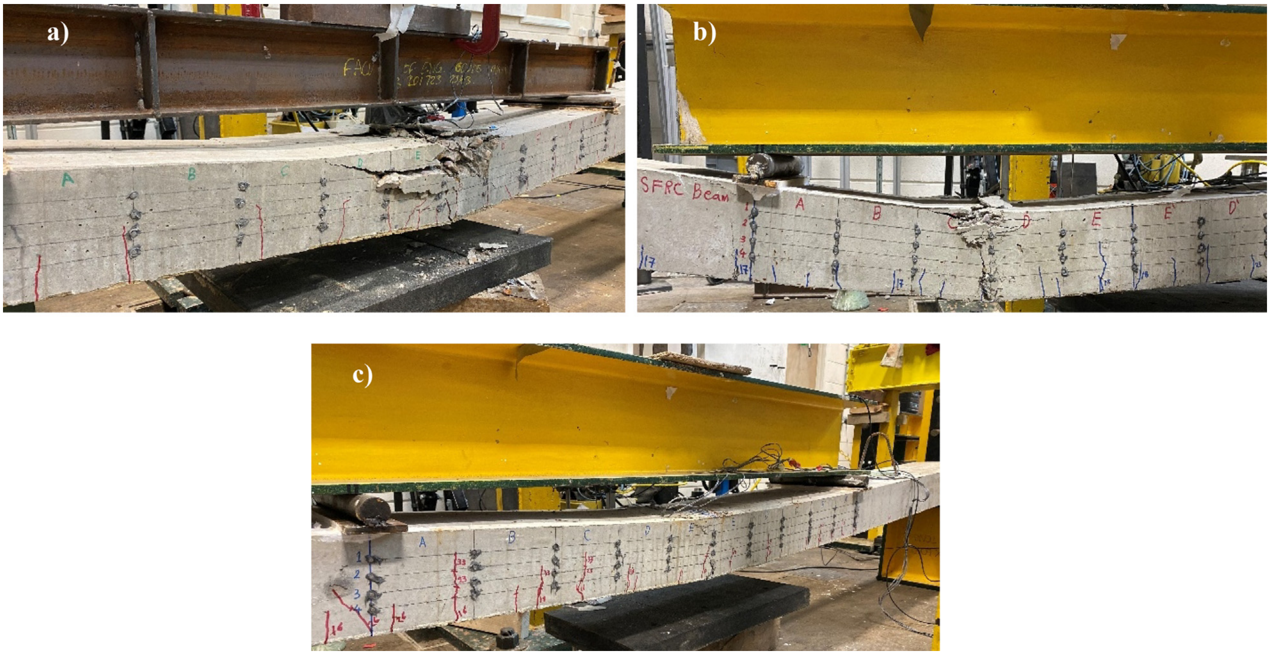


**Fig. 3.** Crack pattern and mode of failure for normal and fibre-reinforced concrete beams: (a) NRC, (b) SFRC, and (c) HyFRC.

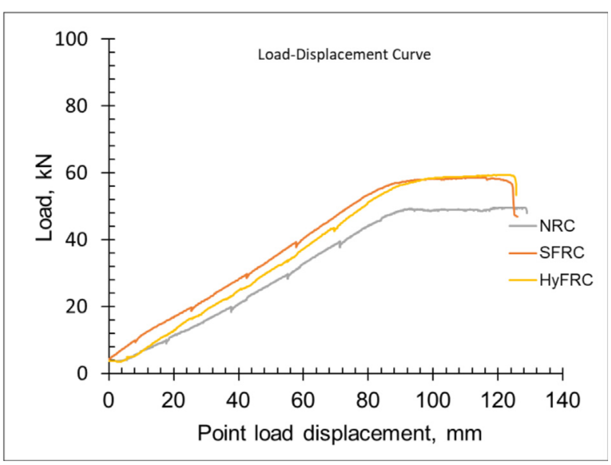


**Fig. 4.** Load-deflection curve for test beams.

demonstrating the effectiveness of fibres in enhancing the flexural stiffness.

### 3.3.3. Load strain response

Fig. 5 shows the surface strain of the concrete in the tension region and the strain response of the steel reinforcement bars at mid-span of the beams. The concrete and steel strains were measured at each loading step. Concrete surface strains were monitored and measured by using a hand-held mechanical strain gauge. Electrical strain gauges mounted on the steel bars were connected automatically to a data logger to track the steel bar strains during the test. From the data in Fig. 5, it is clear that the incorporation of single or hybrid fibres decreased both the concrete surface strain and the tensile steel reinforcement strain for a given load until the performance became non-linear. These data demonstrates that during the serviceability limit state, the addition of both steel fibres and the hybrid fibres enhances the flexural stiffness of reinforced concrete beams. The inclusion of 1% steel fibres and 1.5% hybrid fibres reduced the surface strain of the concrete in the tension zone by 36% and 43%, respectively, at the failure load, as shown in Fig. 5(a). However, both these types of beams showed almost similar tensile reinforcement strain at the failure load, as shown in Fig. 5(b).

### 3.3.4. Crack width and crack spacing

As reported in Table 5, a decrease in the crack width was observed in the SFRC and HyFRC beams; this decrease is mainly credited to the fibres' 'bridging' across the cracks [9,17,18]. The addition of fibres might have helped to mitigate crack openings and reduce their widths significantly. As reported in Table 5, there was a decrease in the crack width with an increase in the fibre volume fractions; these decreases were about 14% and 22% for SFRC and HyFRC, respectively. Moreover, the addition of polypropylene fibres in the hybrid fibre system resulted in 8% lower crack width. Steel fibres' ability to minimize beam crack widths might be due to

**Table 5**
Test results for normal and fibre reinforced concrete beams.

| Type of beam | Load at the formation of first visible crack (kN) | Percentage[1] (%) | Deflection at the formation of first visible crack (mm) | Failure load (kN) | Percentage[2] (%) | Crack width at Failure (mm) | Deflection just before reaching the failure load (mm) | Percentage[3] (%) |
|---|---|---|---|---|---|---|---|---|
| NRC-ST-0 | 8.5 | – | 9.08 | 50.43 | – | 4.5 | 122.47 | – |
| SFRC-ST-1 | 12 | 29% | 11.12 | 58.59 | 14% | 3.85 | 115.63 | 5.58 |
| HyFRC-ST-1.5 | 15 | 43% | 14.32 | 59.47 | 15% | 3.5 | 115.31 | 5.84 |

[1] Increase in load at first crack compared to NRC.
[2] Increase in failure load compared to NRC.
[3] Decrease in deflection at failure load.

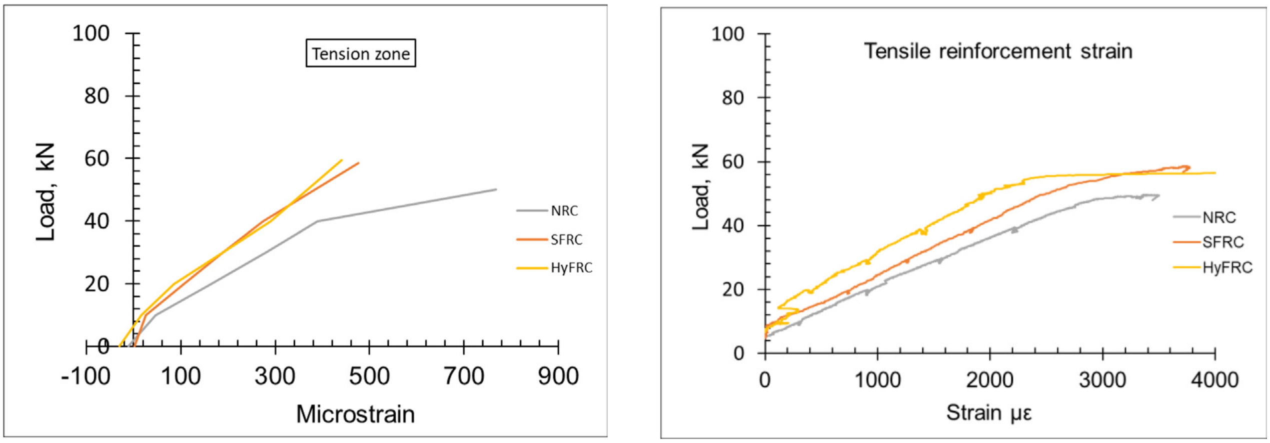


**Fig. 5.** Load strain behaviour: (a) Concrete surface strain and (b) Tensile reinforcement strain.

**Table 6**
Comparison of test results and predicted crack spacing values.

| Type of beams | Experimental results Exp (mm) | EC2 Exp/Pre | *fib* MC2010 Exp/Pre | RILEM TC 162-TDF Exp/Pre |
|---|---|---|---|---|
| NRC-ST-0 | 114.32 | 1.41 | 1.31 | 1.41 |
| SFRC-ST-1 | 86.00 | 1.06 | 0.99 | 1.17 |
| HyFRC-ST-1.5 | 88.52 | 1.09 | 1.02 | 1.32 |
| Mean | – | 1.18 | 1.11 | 1.30 |
| SD | – | 0.19 | 0.18 | 0.11 |
| Coefficient of Variation (%) | – | 16.28 | 16.27 | 9.20 |

their excellent characteristics in terms of high modulus, yielding capacity, and the presence of hooked-ends, which could improve the bond between the fibre and the surrounding concrete, as reported by Abbadi [28] and Bhosale and Prakash [29]. As a result of the steel fibre's ability to reduce tensile stresses across cracks, crack widths are reduced, which in turn arrests further propagation of cracks, as reported by Tan et al. [14], Pajak and Ponikiewski [27] and Deluce and Vecchio [30].

In this research paper, the crack spacing as per different design codes [31,32] and a RILEM recommendation [33] was determined. These values are compared with the experimental results of the tested beams in Table 6. The mean, standard deviation, and coefficient of variation for each beam type were determined and summarised in Table 6. The crack spacing was measured when the stress in the steel tensile reinforcement was about 200 MPa, which is associated with stabilized crack pattern. The data in this table indicate that the current crack spacing formulae underestimated the value of crack spacing compared to the experimental results. The reduction in the crack spacing, which reflects one of the significant benefits of adding fibres, can be observed in Table 6, and agrees with findings reported by others [34–35]. The present study's finding suggests that the current design formulas in Eurocode 2 neglect the effect of the fibres into account in their equations to calculate and predict the crack spacing, whereas the fib Model Code 2010 formula and RILEM recommendation incorporate the factors for fibres.

## 4. Conclusions

According to the test data, the hybrid fibre system considerably improved the behaviour of concrete beams by enhancing the stiffness in the crack development phase post cracking stage and, consequently, restricting the crack openings and deformations. From the analysis of the experimental data, it was found that the hybrid fibre system decreased the deflection, reduced the strain in the steel reinforcement bars and reduced the crack width. Furthermore, the splitting tensile strength and compressive strength of the hybrid fibre-reinforced concrete was greater than that of the single steel fibre-reinforced concrete. The incorporation of the hybrid fibre system also produced fewer and smaller cracks and reduced the visible width of cracks at failure. The addition of more than two types of fibres illustrated a pronounced beneficial hybrid effect. It was observed from the analysis of the test results that the current crack spacing formulae in the design codes (such as Eurocode 2, fib Model Code 2010) and other guidance documents, (RILEM TC 162-TDF) underestimated the value of crack spacing in comparison to the experimental results.

## 5. Future work

A comprehensive analysis is being conducted at present using different models to assess both the crack prediction and deflections with the aim of identifying any possible modifications required in design standards for RC structures when hybrid fibres are used. In the next phases of the study (to be presented at a later date), an analytical study will be conducted using Abaqus software to validate these results and additional testing of beams under repeated and sustained loads will be performed (followed by an analytical study to validate the results) and extend the work via a parametric study.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Abdulrahman Abbadi reports financial support was provided by Jazan University Faculty of Engineering.]

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