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Effect of Polyethylene Terephthalate Fibres on the Structural Performance of Beams with Openings in the Shear Region

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***Abstract*—** the provision of transverse openings in beams to allow passage of services reduces the cracking and ultimate load capacities of the beams and increases deflection under the openings. Strengthening of the pre-planned opening regions by use of special steel reinforcements causes reinforcement congestion and difficulties in compaction, calling for alternative ways of strengthening beams with openings. In this study, concrete material was modified by the use of Polyethylene Terephthalate (PET) fibres produced from waste plastic bottles to improve the tensile properties and hence reduce the cracking around the openings and improve the overall performance of the beams. To evaluate the performance of PET fibres in beams with openings, eight (8) reinforced concrete beams with and without fibres of dimensions (150*250*2000 mm) were cast with varying opening sizes. The horizontal position of the openings was fixed at 300 mm from the support while the vertical position was maintained at the mid-depth of all beams. This performance was evaluated in terms of ultimate and first cracking loads, mid-span deflections, ductility, crack patterns and failure modes, and strain behavior. Test data showed that incorporating PET fibres in beams with openings resulted in a slight increase in ultimate load of 4.1% and 5.82% for 0.25 h and 0.35 h beam opening sizes respectively, beyond which the strength was reduced by 9.57% for beams with 0.45 h opening size, where h was the overall depth of the beam. The first cracking loads increased by 44.12%, 48.48%, and 9.38% for 0.25 h, 0.35 h, and 0.45 h opening sizes, respectively. In addition, a slight improvement in the ductility of PET fibre beams for all opening sizes was observed. The PET fibre beams exhibited a slight change in the mode of failure from dominant shear failure to combined shear and flexure failure characterized by multiple cracks in the flexure region with minimal spacing. An increase in the concrete compressive and tensile strains accompanied by a reduction in concrete and steel shear strains was observed because of the tension stiffening effects of the fibres. The incorporation of PET fibres, therefore, showed a significant improvement in strengthening beams with openings.

***Keywords*—** Beams with openings, first cracking load Polyethylene Terephthalate fibres, ultimate load.

I. INTRODUCTION

Modern construction of multi-story buildings requires a network of pipes and ducts to allow for the passage of service lines such as electricity, water supply, air conditioning, sewage, telephone lines, and computer networks. When these ducts and pipes are placed underneath the soffit of the beam, a suspended ceiling is required to cover the ducts and pipes for aesthetic reasons, creating a dead space [1]. Transverse openings in reinforced concrete beams are therefore provided to allow passage of these utility pipes and ducts, reducing the total height of the structure, the length of electrical and air-conditioning ducts, and the overall load on the foundation, thus leading to a highly economical design [2].

The provision of openings of different configurations in reinforced concrete beams alters the beam behavior under loading, making it more complex due to the abrupt change in the cross-section of the beam [2], [3]. The stress transfer discontinuities in the normal stress flow produced by the openings may lead to stress concentration and premature cracking of the beam around the opening region, which might not meet the required durability requirements [4]. Openings reduce the ultimate strength, the shear capacity, and the stiffness of the beam, which may cause unacceptable deflection under service loads in beams [3].

For pre-planned openings, internal strengthening is adopted where the top and bottom chords are designed to resist internal forces and provided with special steel reinforcement around the opening edges to resist stress concentration before casting. Since there are no specific guidelines provided in the codes of practice to design beams with large openings, complex methods have been developed including the Modified ACI traditional approach, the Plasticity truss model approach, and the Strut and Tie Method. When these methods are used, the resulting design requires the provision of a special reinforcement scheme on the top and bottom chords and diagonally on the sides of the opening, which leads to reinforcement congestion. The small dimensions of the upper and bottom chord members do not permit providing a sufficient quantity of steel reinforcements to limit crack propagation and prevent potential premature shear failure of the beam. Alternate solutions to the internal strengthening of beams with pre-planned openings, therefore, need to be explored to improve their performance and reduce the amount of shear reinforcement required around the opening.

The shear region, in a reinforced concrete beam, experiences both compressive and tensile forces, which are magnified when an opening is introduced. Attempts have been made to modify the concrete material by use of high strength

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and ultra-performance concrete to increase the compressive resistance of the concrete in compression but findings show that this does not affect the ultimate strength of the beams and might not be sustainable given its high cost [5]. Since concrete has a very low tensile strength, when an opening is introduced in the shear region, early cracking occurs, which eventually causes premature failure. The concrete material can therefore be modified by incorporating fibres, which increase its tensile and flexural strength, reduces cracks, and improve the ductility of RC beams and hence their performance [6].

Several types of fibres can be used ranging from steel fibres, synthetic fibres, glass fibres, and natural fibres to pre or post-consumer waste fibres. Steel fibres have a high risk of corrosion that can lead to a rapid deterioration of concrete structures while glass fibres show a poor alkali resistance. While natural fibres are cheap and easily available, they have poor durability and can lead to the degradation of concrete structures [7]. In the recent past, many studies have been conducted to reuse waste plastics as fibres in concrete and mortar composites to overcome the challenges experienced with other types of fibres as well as reduce the environmental degradation caused by plastic wastes.

The use of PET fibres in solid concrete beams has shown an improvement in the first crack and ultimate loads, ductility, and delayed appearance of cracks [8]–[12]. However, some studies show that PET fibres do not give a significant increase in ultimate strength owing to their reduction in the compressive strength of PET fibre concrete [13]–[15]. Some studies show that incorporating PET fibres in concrete beams slightly changes the failure mode from shear to flexure [9], [11], [15]. However, for beams designed in flexure, the mode of failure is not altered and the beams fail similarly to the control beams [13], [14]. Since these fibres improve the tensile properties of concrete, they can be used to reduce cracking in regions of high stress concentration like opening corners and hence improve the performance of these beams.

The use of fibres in beams with openings has mainly focused on deep beams in which steel fibres have been predominantly used [16]–[18]. Few studies have been carried out on the use of fibres in normal/shallow beams with openings [19], [20]. The study by Varghese and Jacob (2017) [19] was not conclusive since it only considered the ultimate load capacity, first crack, and ductility performance of self-compacting concrete beams, using commercial polypropylene fibres. On the other hand, Smarzewski (2018) [20] used hybrid fibres (steel and polypropylene) in high-performance concrete beams with openings with the focus of replacing shear reinforcements with hybrid fibres.

Even though the use of PET fibres has shown a good performance in solid beams [9]–[11], [21], [22], their use in beams with openings has not been explored. This study, therefore, sought to strengthen beams with openings in the shear region by modifying the concrete tensile properties through the incorporation of waste PET fibres, providing a cost-effective and environmentally friendly solution, which the current solutions do not offer. The size of the openings was varied to understand the contribution of fibres, as the opening size was increased while the horizontal position was fixed at the mid-section of the shear span to simulate the worst-case scenario. Since polymeric fibres have poor adhesion with a concrete mix [23], the PET fibres were coated with a thin layer of sand to improve their bonding properties.

II. EXPERIMENTAL PROGRAM

Materials and mix design

Materials used in this study include Ordinary Portland Cement (OPC) class 42.5N conforming to standard [24], fine aggregates (ordinary river sand) obtained locally, coarse aggregates which were mixed thoroughly on arrival, and clean portable water. Material characterization was carried out to ensure conformance with codes of practice.

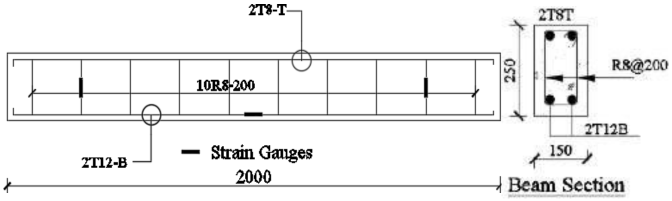
High-strength tensile steel bars were adopted for use in this project. Longitudinal steel bars type T12 with a yield strength of 424 MPa and R8 stirrups with a yield strength of 293 MPa were used. PET fibres were obtained from waste 5-litre PET bottles obtained from a local plastic handling company in Nairobi, Kenya. The PET fibres were coated with a thin layer of sand to improve their bonding capacity. Figure 1 shows the fibres used in the study. The fibres had a width of 2 mm, a length of 75 mm, an average tensile strength of 348.8 MPa, and elongation of 9.34 mm. A fibre dosage of 1.25% by weight of cement and 75 mm length obtained from a preliminary optimization study was maintained in all specimens.

A mix design of 30 MPa characteristic strength was carried out according to the Building Research Enterprise (BRE) method with a mix ratio of 1:1.9:3.5 and a constant water-cement ratio of 0.55. The compressive strength accompanying the control beam at 28 days was 40.54 MPa while that of the PET fibre reinforced beam was 34.68 MPa. The characteristic strength of 30 MPa was therefore exceeded in all mixes. However, the introduction of fibres reduced the compressive strength of the concrete by 14.45%. PET fibres made the mix more porous, creating weak zones inside the concrete, which resulted in the propagation of cracks and hence the reduction in strength.

Figure 1: PET fibres used in this study

Methods

The design of the reinforced concrete beam was carried out as per BS 8110-1:1997 [25] and ACI 318:95 [26], using assumed loading. The model specimen was 2 m in span, 150 mm in width, and 250 mm deep. A preliminary design for the beam was carried out to determine the reinforcement scheme and the positioning of the openings, which was verified after material characterization and the mix design results. Figure 2 shows the specimen dimensions and reinforcement scheme.



(a) Reinforcement details

(b) Formwork and reinforcement cage

Figure 2: Beam formwork and reinforcement details

To study the effects of PET fibres on beams with openings, eight (8) beams were prepared and tested for combined shear and flexural performance. The beams had uniform geometric dimensions and the same reinforcement scheme. To simulate a worst-case scenario, openings of square geometry were adopted due to their high load reduction capacity resulting from stress concentrations at the corners compared to circular openings [27]–[29]. Two sets of beams with varying opening sizes of 0.25h (62.5 mm), 0.35h (87.5 mm), and 0.45h (112.5 mm), where h was the overall depth of the beam, were prepared. The first set (control) did not have fibres, while the second set had fibres to allow for comparison. In addition, two-reference beams without openings, one with fibres and the other without fibres, were prepared to act as the controls.

The samples were assigned codes for easy reference as shown in table I. Beams without fibres were denoted as CB while beams with fibres were denoted as FCB, all followed by the opening size in mm. Control beams without fibres were represented as CB while the control beam with fibres was represented as FCB only. Table I shows the test matrix for the beam specimens and their corresponding code references.

The openings were located in the shear zone close to the supports since this reduces the concrete area responsible for resisting diagonal tensile stresses that develop in the shear region. Besides, providing an opening in this region is likely to intercept the load path between the point of load application and the supports. This position was kept constant at 300 mm from the supports where the highest shear forces were expected to occur. The study by Aziz (2016) [2] showed that a beam with an opening located at a distance L/6 (where L is the length of the beam) from the edge of the beam gave the highest reduction in the ultimate strengths. The vertical position was maintained at the mid-depth of all beams to avoid reducing the concrete area necessary for the full development of the compressive stress block.

TABLE I: BEAM SPECIMENS

Beams without fibres			Beams with fibres		
	Size of openings			Size of openings	
	% of depth	mm		% of depth	mm
CB	0	0	FCB	0	0
CB 62.5	0.25h	62.5	FCB 62.5	0.25h	62.5
CB 87.5	0.35h	87.5	FCB 87.5	0.35h	78.5
CB 112.5	0.45h	112.5	FCB 112.5	0.45h	112.5

In the table, h is the overall depth of the beam.

All the samples were subjected to a four-point loading arrangement to expose the beam to both shear and flexure failure. A hydraulic jack was used to apply the load at the top of the beam and a load cell with a capacity of 200 kN was used to measure the applied load accurately. A Dial gauge type Displacement Transducer was used to measure the deformation at the beam's mid-span. The loading set-up is presented in Figure 3.

Electrical resistance strain gauges were mounted on the tensile and shear reinforcements, before casting. These were also mounted on the concrete surfaces at the top and bottom faces of the concrete beam and adjacent to the opening corners with high chances of crack formation as illustrated in Figures 2 & 3. The strain gauges were then connected to a data logger during the loading phase to record the strain in both the concrete and reinforcements during loading. Observations and measurements were carried out to identify the first cracking and ultimate loads, and the cracking attributes (pattern, propagation, and behavior). Failure modes, deflection capacities, and ductility values, of the beams were also determined.

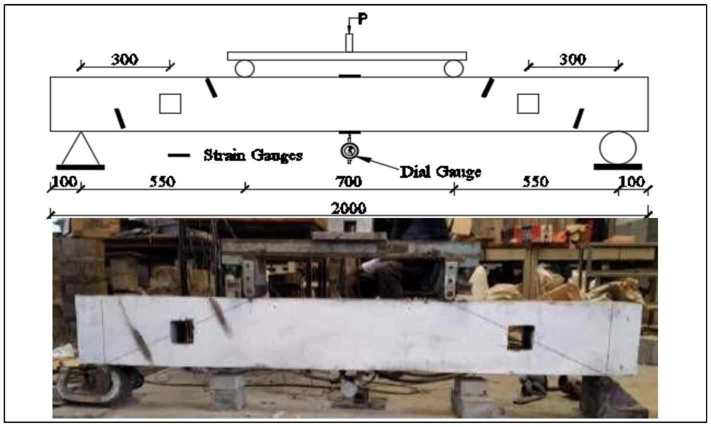


Figure 3: Beam loading and instrumentation set-up

III. RESULTS AND DISCUSSION

A. Ultimate and first cracking loads

Ultimate loads

Figure 4 shows a comparison of the ultimate and first cracking loads for beams with and without fibres when the opening sizes were varied. The control beam CB (without openings) failed at an ultimate load of 84 kN which was 8.24% higher than the corresponding beam with fibres, FCB. The reduction in ultimate loads for the beam with fibres could be attributed to the reduction in the compressive strength of concrete by introducing PET fibres. The compressive strength of concrete affects the ability of concrete beams to resist compressive forces in the compression zone, and the shear forces induced in the shear span.

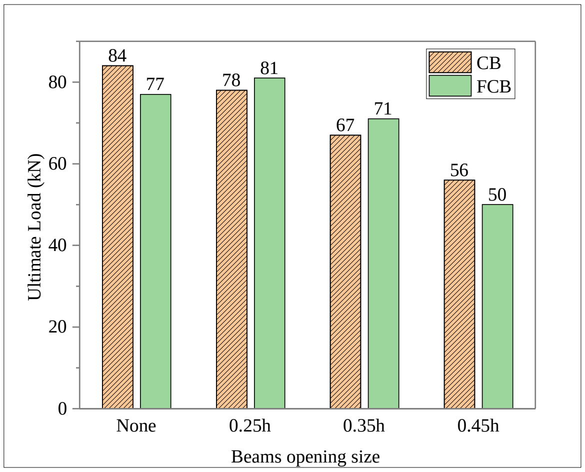


Figure 4: Ultimate Loads

On the introduction of an opening of 0.25 h (62.5 mm) in the shear span, beam CB 62.5 failed at a slightly lower ultimate load of 78 kN (7.15 % reduction) compared to the control beam CB due to the reduction in the area of concrete required to carry shear forces in the shear region. Beam FCB 62.5 with fibres failed at an ultimate load of 81 kN, which is slightly higher than beam CB 62.5 (4.10% increase) corresponding to a 3.35% reduction in strength compared to the control beam CB. This value is 5.19% higher than beam FCB with no opening, showing that the action of fibres is more pronounced when an opening is introduced in the shear region.

Beam CB 87.5 with an opening size of 0.35 h failed at an ultimate load of 67 kN corresponding to a 20.22% reduction compared to the control beam CB. However, its counterpart, beam FCB 87.5 failed at a slightly higher loading of 71 kN corresponding to a 5.82% increase in strength compared to beam CB 87.5. This corresponds to a 15.58% reduction in strength compared to the control beam CB. Beam CB 112.5 with an opening size of 0.45 h failed at an ultimate load of 56 kN corresponding to a 33.71% reduction in strength compared to the control beam CB. On the other hand, a 9.57% reduction in strength by beam FCB 112.5 was recorded, which corresponds to a 40.05% reduction compared to the control beam.

The introduction of openings in the shear region reduces the concrete area responsible for carrying loads and hence the reduction in the ultimate and cracking loads. The positioning of the openings in the shear region subjects the opening periphery to a strain concentration as observed in Figure 8 in section D, leading to the development of an early shear crack through the opening and subsequent reduction in the ultimate and first crack loads. This has been observed especially in beams CB 87.5 and CB 112.5. The presence of an opening of height less than 25% of the beam’s overall depth did not result in a high reduction of ultimate load capacity, findings supported by Jen Hua, Tang, Leong and Sia (2020) for circular openings. Further, [28] noted a 15.65% reduction in strength for square openings with 0.16 H size located in the shear zone. In his study, an opening of size 0.32 H gave a higher reduction in strength of up to 32.44%, where H was the overall depth of the beam.

The introduction of fibres in a beam with openings slightly improved its load-carrying capacity for beams with opening sizes up to 0.35 h, beyond which there was no improvement in the load-carrying capacity of the beams. Fibres increase the tensile capacity of concrete through crack control and therefore assist in redistributing the dominant tensile forces that build up around the opening region. When the opening size exceeds 0.35 h, the stress concentrations are too high for the PET fibres to resist given their low tensile strength. The slight contribution of fibres to the ultimate load was only experienced when the openings were introduced due to the change in failure from flexure dominated to shear dominated but only up to a certain opening size.

A slight improvement in the ultimate loads for solid beams without openings has been noted by several authors. Rasheed, Alyhya and Kadhim (2021) noted an improvement in the ultimate loads ranging from 1% to 2.86% while Khan and Ayub (2020) noted a 13% increase in ultimate loads. On the other hand, a reduction in the ultimate loads of 1.71% has been noted by Mohammed and Rahim (2020) and 12.12% reduction by Adnan and Dawood (2020). The slight improvement as well as the reduction in ultimate strength in some studies has been mainly attributed to the reduction of concrete compressive strength by PET fibres and the low tensile strength of virgin PET fibres. Despite the fact that fibres increase the tensile strength of the matrix, this is accompanied by a reduction in the compressive strength of concrete.

In conclusion, there was no improvement in the ultimate loads for control beams on the introduction of fibres owing to the reduction of the compressive strength of the PET concrete. However, a slight improvement was noted for beams with small opening sizes (0.25 h and 0.35 h) due to the ability of the fibres to resist the shear stresses that build up in the region around the openings.

First cracking loads

External loads applied on a beam result in bending and direct stresses, which initiate bond, flexural, and shear cracks. Internal micro-cracks occur when the tensile stress in concrete exceeds its tensile strength, which grow into macro cracks, spreading to the external edges of the member. The stress in the concrete at the cracking zone is reduced to zero and is assumed by the steel reinforcement once the first crack appears in the RC beam [20]. Figure 5 shows a comparison of the first cracking loads for beams with and without fibres as the opening size was increased.

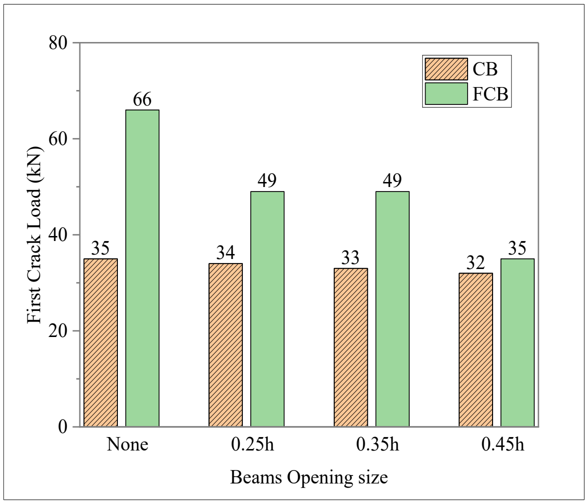


Figure 5: First Cracking Load

As seen in Figure 5, the first crack in the beam FCB appeared at a load of 66 kN, 88.57% higher compared to the control beam CB with a first cracking load of 35 kN. A similar trend in the appearance of the first crack was observed for the subsequent beams with increasing opening size. The first crack in beams FCB 62.5 and FCB 87.5 occurred at a load of 49 kN, 44.12%, and 48.48% higher in beams CB 62.5 and CB 87.5 respectively. There was a slight improvement in the first cracking load of 9.38% in beam FCB 112.5 compared to CB 112.5. In the control beams, increasing the opening size had little effect on the reduction of the first crack loading since the failure began from the flexure zone before shifting to the opening region as explained in section 3.3. Similar results have been noted by Hamzah and Ali (2020) [31].

The increase in the first cracking load for all beams with PET fibres is attributed to the improvement in the tensile strength of the concrete, which increases the serviceability load of the beams. Once the fibre reinforced beam starts to crack, several fibres continue to carry and transfer loads, maintaining the structural integrity of the beam, with an increase in deflection as observed by Khalid et al. (2018) [13]. Virgin PET fibres, therefore, play a significant role in increasing the first cracking loads, especially on the introduction of openings, which tend to lower the cracking load.

B. Load-deflection behavior

Deflection in beams is a function of the applied load, the length of span, the flexural rigidity, and ductility. Figure 6 shows the load-deflection history of all the beams with the subsequent opening sizes.

The load-deflection behavior of the control beam depicted the three stages of collapse: the elastic stage, elastoplastic, and plastic stage. On load application, the deflection increased gradually until the first crack appeared at a loading of 35 kN. This was followed by a series of flexural and shear flexural cracks until failure at an ultimate load of 84 kN with a maximum deflection of 28 mm. Beam FCB failed identically, with the control beam CB showing an extended plastic deformation up to the failure load of 77 kN at a maximum deflection of 34 mm. It can be observed that the beam experienced an oscillatory plastic deformation with successive increases and decreases in loads until the ultimate failure load, a factor that can be attributed to the tension stiffening action of the fibres.

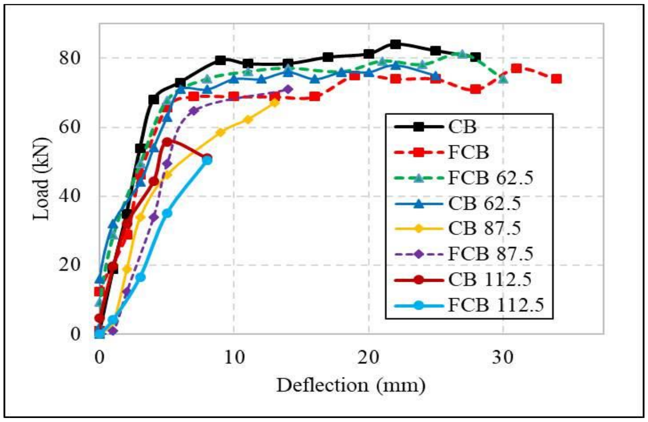


Figure 6: Load-deflection curves

Beams with 0.25 h opening size, beams CB 62.5 and FCB 62.5 also experienced a ductile failure with an extended plastic region before collapse, although there was a slight reduction in the maximum deflection, which were 25 mm and 30 mm, respectively. The action of the fibres in beam FCB 62.5 slightly increased the loading capacity of the beam and extended the plastic region of the beam, causing final collapse at a slightly greater deflection compared to beam CB 62.5. The failure loads were within a close range compared to the control beams and thus it can be concluded that an opening less than 0.25 h has a minimal effect on the performance of the beam.

Beams CB 87.5 and FCB 87.5 with an opening size of 0.35 h showed a more elastic deformation with little plastic deformation, indicating a reduction in the rigidity of these beams and hence a reduced stiffness as shown in Figure 8. Although beam FCB 87.5 failed at a slightly higher loading, there was no significant increase in the maximum deflection owing to the rupture of the fibres at the maximum failure load. The maximum deflection of beam CB 87.5 was 13 mm, while that of FCB 87.5 was 14 mm. Similarly, beams CB 112.5 and FCB 112.5 failed abruptly with a greater elastic deformation and little plastic deformation. The maximum deflection at failure for both beams was 8 mm, and the fibres did not have any significant ductility enhancement on the beam. Material and geometric properties affect the rigidity of a beam. The provision of openings reduced the moment of inertia, making the beams less rigid with a large deflection in the opening region.

Ductility

Uniform ductility is measured as the ratio of deflection at the ultimate load to deflection at the yield point while total ductility is taken as the ratio of the failure load to the yield deflection. The yield displacement was obtained from the load-deflection curves using the general yielding method.

Table II summarizes the yielding, cracking, and ultimate loads with the corresponding displacements. The ductility index, the initial and secant stiffness, and the relative ductility and stiffness indices have also been included. In general, the ductility of the beams reduced with the introduction and subsequent increase in the size of the openings. Introducing the openings reduced the ability of the beams to deform excessively along the mid-span due to the sudden brittle failure experienced. Using PET fibres in the beams slightly improved their ductility owing to the ability of the fibres to carry part of the stresses before failure.

When the size of the openings was increased, an abrupt shear failure was experienced, causing a sudden fibre rupture, which resulted in an early beam failure. For instance, for beam FCB 112.5 with the largest opening size (0.45 h), the fibres did not improve the ductility of the beam in any way. According to BS 8110, the serviceability deflection should be limited to span/250, which in this experiment translates to 7.2 mm. The serviceability deflection for all beams tested was lower than the limiting value, hence meeting the requirements.

Stiffness

The stiffness of a beam is its ability to resist deflection on load application and is dependent on the material properties and geometry of the beam. The initial stiffness can be calculated by dividing the ultimate load by the yield deflection. Similarly, secant stiffness, also known as effective stiffness can also be calculated by dividing the ultimate load by the ultimate deflection [15]. Table II also shows the values of the initial, and secant stiffness, and their relative stiffness. In general, as the opening size increased, the initial stiffness of the beams reduced. On the contrary, the secant stiffness increased with an increase in the opening size because of the successive reduction in the mid-span deflections. The incorporation of fibres reduced both the initial and secant stiffness due to the successive increase in the yielding load and deflection.

Visual observation of the slopes of the load-deflection curves in figure 8 showed that beam CB was stiffer compared to its counterpart beam FCB. Beam FCB 62.5 and FCB 87.5 were stiffer than their counterpart beams CB 62.5 and CB 87.5 while beam CB 112.5 was stiffer than beam FCB 112.5. The proposed method of calculating initial and secant stiffness does not faithfully capture the behavior of beams when fibres are introduced due to their effect of increasing the yield and ultimate deflections.

C. Crack patterns and failure modes

Crack pattern and failure modes for the beams were also observed with strains at critical positions monitored with subsequent load increment. The control beam CB experienced a combined shear and flexural failure at 84 kN loading, characterized by the yielding of steel reinforcement and concrete crushing at the compression zone with a large deflection. Beam FCB failed in almost the same manner as the beam without the fibres except that the ultimate failure was characterized by yielding of steel reinforcement but no crushing of the concrete in the compressive zone. The first crack appeared at the mid-span of the beam at a higher loading of 66 kN, followed by several flexural cracks extending towards the neutral axis of the beam. With subsequent loading, shear-flexural cracks extended towards the loading point, causing ultimate failure at a reduced loading of 77 kN. Diagonal shear cracks were observed at 45^{o} in the shear span in both beams. The significant difference in the failure mode between the two beams was that the beam with fibres did not experience concrete crushing. This could be attributed to the ability of fibres to improve concrete toughness in the compression zone [32].

Beam CB 62.5 with an opening of 0.25 h had almost a similar mode of failure to the control beam characterized by the yielding of steel and minor concrete crushing of the compressive zone compared to the control beam. The diagonal tension crack through the openings indicated a beam-type failure in which a diagonal crack passes through the opening, maintaining the usual beam theory. The ultimate failure was caused by the flexural tension cracks, which widened and extended towards the neutral axis. The similarity in the mode of failure between this beam and the control, besides the minimal reduction in ultimate loads, supports the claim that an opening of 0.25 h or less does not significantly affect the performance of the beam [30].

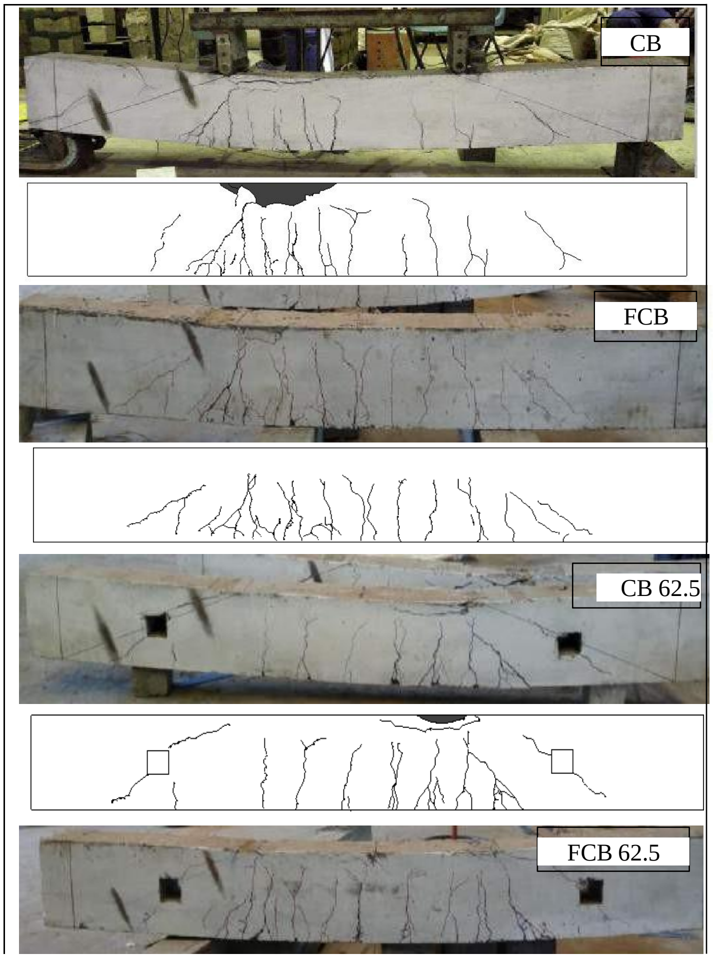
Beam FCB 62.5 experienced a flexural failure mode characterized by steel yielding with no visible crushing of concrete in the compressive zone. The incorporation of fibres therefore slightly changed the mode of failure of the beam from a more pronounced flexure + shear failure to a dominant flexure failure, with cracks more distributed within the flexure zone. This behavior is to be attributed to the tension-stiffening action of PET fibres, which offer more shear resistance.

In beam CB 87.5 with an opening of 0.35 h, the large dimensions of the opening resulted in stress concentrations at the corners of the opening, leading to a brittle diagonal tension failure with wide cracks extending from the supports to the load application points characterized by a small mid-span deflection. This resulted in a brittle shear failure at a load of 67 kN. The mode of failure around the opening has been classified as a frame-type failure unlike beam CB 62.5, which showed a beam-type failure. In a frame–type failure, the top and bottom chords fail independently, changing the load-carrying mechanism of a normal beam under bending and shear as observed with this beam.

Beam FCB 87.5, failed in an almost similar manner, characterized by several flexural cracks along the flexural zone before the beam experienced an abrupt frame-type failure. This beam failed at a relatively higher loading, with several flexural cracks before failure. The formation of several flexural cracks is attributed to the action of the fibres to change the mode of failure from shear to flexure failure. However, given the large size of the opening and the low tensile strength of the fibres, stress concentration caused fibre rupture and eventual failure.

In Beam CB 112.5 with 0.45 h opening size, initial cracks appeared below the opening at early loading stages, with only two fissures observed in the flexure region. The beam experienced a diagonal tension failure through the opening characterized by its brittle nature and minimum mid-span deflection. As the size of the opening increased, the stress discontinuity around the corners of the opening was magnified, not to mention the greater reduction there was in the concrete area required to carry shear forces. Similar to beam CB 87.5, a frame-type failure was observed where the bottom and top chords failed independently.

Beam FCB 112.5 failed in almost a similar manner to beam CB 112.5 except that the first crack appeared in the mid-span of the beam at the early loading stages, followed by shear cracks through the opening. The beam then experienced a frame-type failure through the opening at a lower loading of 50 kN compared to its counterpart beam CB 112.5. Beam FCB 112.5 depicted an increased number of flexural cracks compared to beam CB 112.5 due to the action of fibres. Figure 11 shows the failure modes and crack propagation of all tested beams with increasing opening sizes.



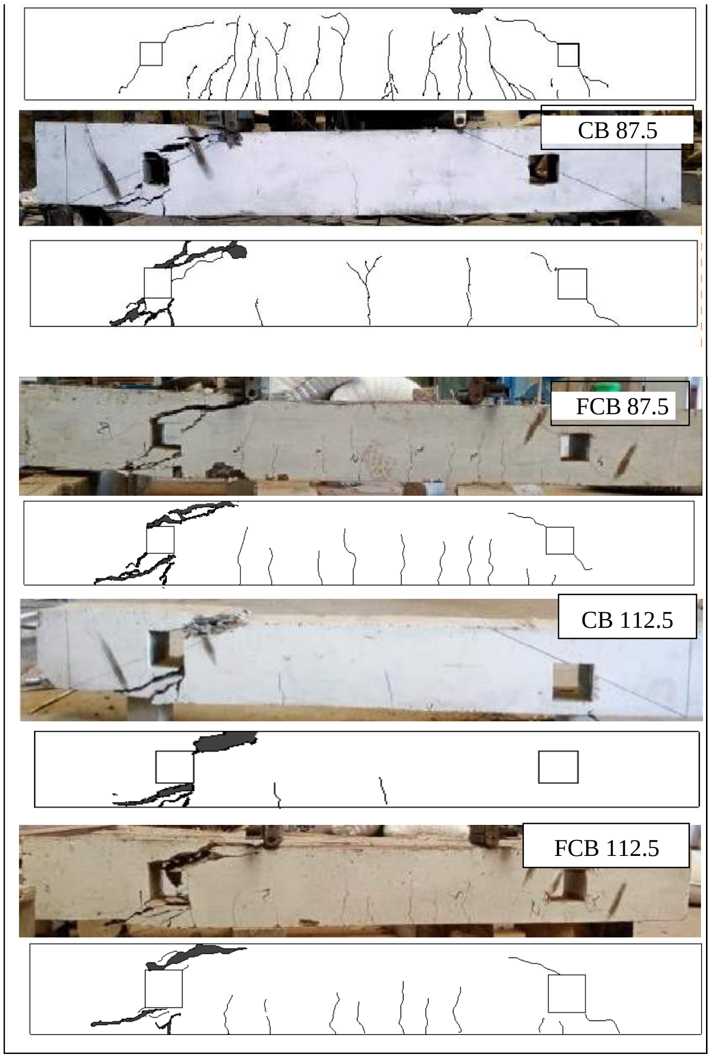


Figure 7: Failure modes and crack patterns of tested beams

D.Strain behavior

The strain at critical locations was examined using strain gauges mounted on both the steel reinforcement and the concrete surface. For the steel reinforcement, the strain was monitored both in the mid-section of the flexural reinforcement and the shear reinforcement. In concrete, the compressive, tensile, and shear strains were monitored.

Concrete strain behavior

Figure 7 shows the compressive and tensile strain response for the concrete beams of various opening sizes respectively. In general, the compressive strain of the concrete was lower than the tensile strain of concrete for all beams since their ultimate failure was caused by the yielding of steel with some beams showing minor concrete compression failure. All the beams experienced a considerable mid-span deflection and hence the pronounced tensile strain. This was highest in beams with larger bending (Beam CB, FCB and FCB 62.5). In beam FCB at the onset of the first crack (at 66 kN), exaggerated strain measurements were recorded until failure. Carmona and Aguado (2012) [33] noted that the ultimate indirect tensile strain for concrete ranges from 0.015% to 0.025%.

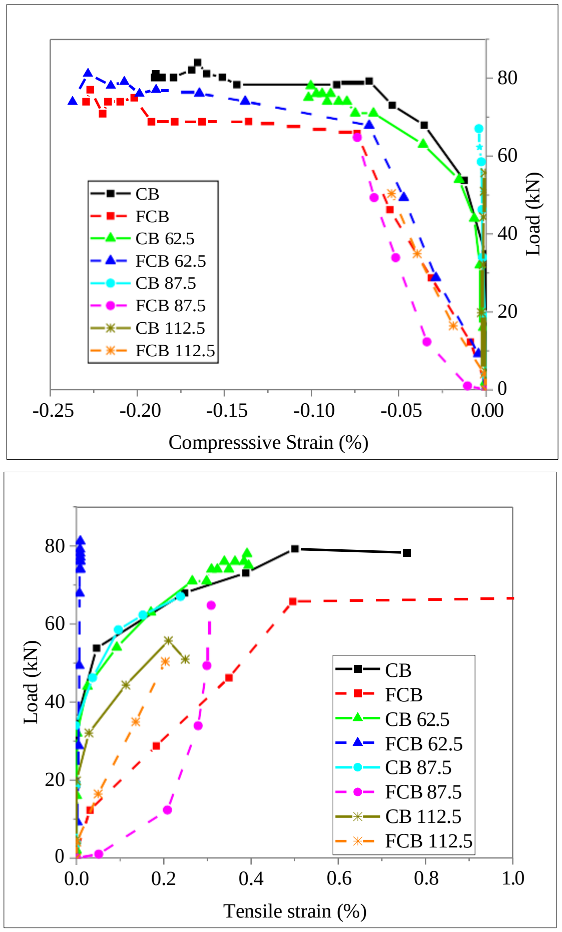


Figure 8: Concrete compressive and tensile strains

The strain gauge mounted on the tensile side of beam CB was damaged at 50% of the loading and hence the relatively lower strain readings. The strain gauge for beam FCB 62.5 slipped from the concrete surface during testing and hence the low tensile strain values. The strain values for the beams with an opening of size 0.45 h were close, since the fibres did not have a considerable increase in the mid-span deflections as in other beams.

The reduction in compressive and tensile strains as the opening size increased can be explained by the change in the mode of failure from more pronounced flexure and shear failure to pure shear failure, which was characterized by low mid-span deflections. However, on introducing PET fibres, it was observed that there was an increase in both the compressive and tensile strain values. This can be attributed to the ability of fibres to relatively change the mode of failure from a flexure + shear/pure shear failure to a flexure failure which is characterized by the formation of more flexural cracks and increased mid-span deflection as has been noted in section C above. The composite action of the fibres and concrete produced a more ductile material. The relative strain values are shown in Table III.

Shear strain gauges were also mounted on the concrete surface to monitor the shear response of the beams on the adjacent corners of the openings where failure would likely occur, intercepting the load path from the loading point to the supports. The same position was maintained for all the beams tested for uniformity. Figure 8 shows the strain curves for the strain gauge above the opening.

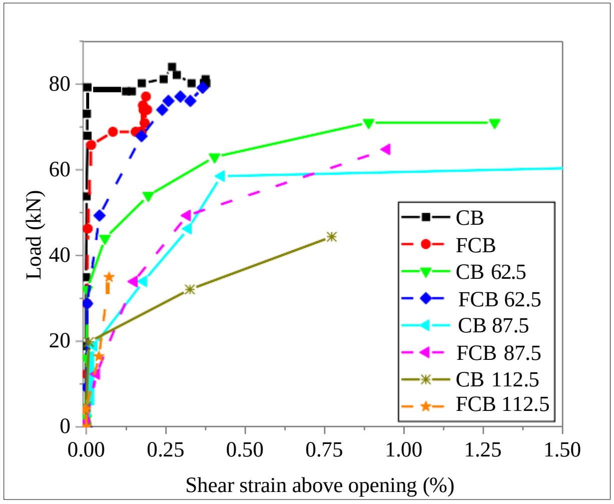


Figure 9: Concrete shear strain

The strain above the opening increased as the size of the opening was increased, since the failure mode changed to a more pronounced brittle shear failure. All beams with fibres showed progressively reduced strain values except for Beam FCB 87.5, which showed a slightly higher value, compared to its counterpart beam CB 87.5, owing to the shear crack having passed through the position of the strain gauge. The fibres in the shear region have the effect of tension stiffening and hence the reduced strain values.

Reinforcement strain behavior

Monitoring the strain on the steel reinforcements, helps understand the type of failure that is experienced based on its yielding strains and the effect of the fibres on the yielding of steel. Figure 9 shows the strain response of tension reinforcements.

The steel tensile strains indicated that all the beams experienced yielding of tensile steel before failure. The beam with the largest opening showed the smallest strain values of 0.144% for beam CB 112.5 and 0.176% for beam FCB 112.5 since the failure was abrupt and did not allow enough time for the steel to yield. Beams that experienced a more balanced failure like the control beam and beam FCB 62.5 gave high ultimate strains owing to their large bending. The strain gauges on the tensile reinforcements of beam CB 62.5 were damaged, making it difficult to obtain ultimate strains. In general, it can be deduced that fibres reduced the strains in the tensile strain reinforcements due to their ability to carry part of the tensile stress after concrete cracking, unlike the beams without fibres where all the stresses were transferred to the steel reinforcements after concrete cracking. This is except for beam FCB 112.5 whose strain values were close to that of the control beam CB 112.5 due to similar mid-span deflections.

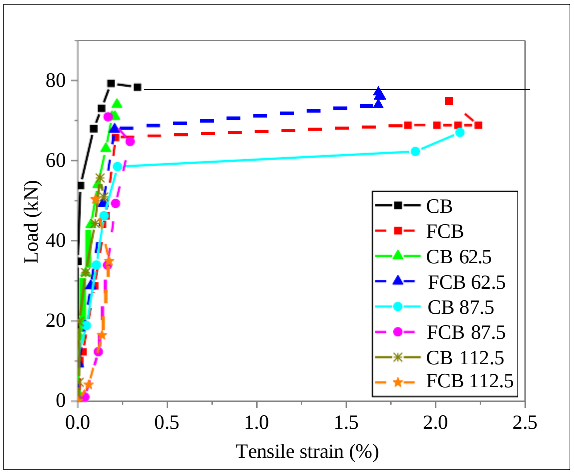


Figure 10: Steel tensile strain

Figure 10 shows the strain measurements taken from the shear stirrups. It can be seen from this Figure that as the mode of failure changed from flexure + shear to pure shear failure due to an increase in the size of the opening, the stress on the stirrups increased. On the introduction of fibres, there was a reduction in the shear strains on the shear reinforcements. The slightly high strain value in beam FCB 87.5 is as explained in above section. The shear stirrups experience both tensile and compressive stresses and hence the peculiar strain patterns.

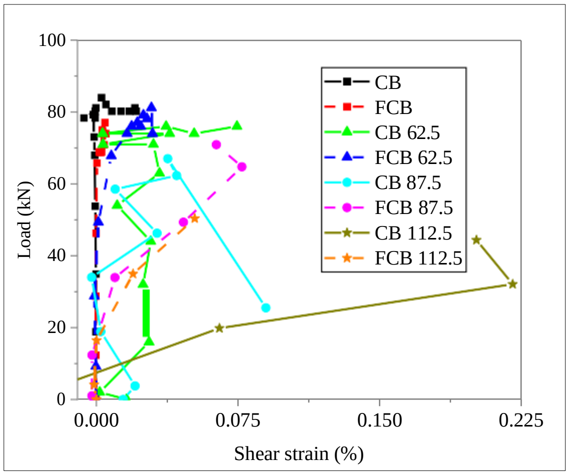


Figure 11: Steel stirrup shear strain

Results from the strain gauges show the local response of the beams under loading. Incorporating fibres in beams relieves the shear and tensile reinforcement's part of the induced stresses as well as reduces the shear stresses on the concrete material, hence better performance of the beams. Table III shows the ultimate strain values for the concrete and steel reinforcements for all beams.

TABLE II: DUCTILITY AND STIFFNESS OF THE BEAMS

Beam Code	Pu (kN)	Δu (mm)	Pcr (kN)	Δcr (mm)	Py (kN)	Δy (mm)	Ductility Index (Δu/ Δy)	Pcr/Pu (%)	Relative Ductility index	Initial Stiffness (Pu /Δy)	Relative initial stiffness	Secant Stiffness (Pu/ Δu)	Relative secant stiffness
CB	84	28	35	2	73	6	4.67	41.67		14		3.00	
FCB	77	34	66	5	69	7	4.86	85.71	1.04	11	0.79	2.26	0.75
CB 62.5	78	25	34	1	71	6	4.17	43.59		13		3.12	
FCB 62.5	81	28	49	3	72	6.5	4.31	60.49	1.03	12.5	0.96	2.89	0.93
CB 87.5	67	13	33	3	55	7	1.86	49.25		9.6		5.15	
FCB 87.5	71	14	49	5	65	7	2.00	69.01	1.08	10.1	1.06	5.07	0.98
CB 112.5	56	8	32	2	44	4	2.00	57.14		14		7.00	
FCB 112.5	50	8	35	5	47	7.2	1.11	70.00	0.56	6.9	0.50	6.25	0.89

In the table, Pu is the ultimate load; Δu is the ultimate deflection; Pcr is the cracking load; Δcr is the cracking deflection; Py is the yield load and Δy is the yielding deflection.

TABLE III: CONCRETE AND STEEL REINFORCEMENT STRAIN VALUES

Beam code	Concrete strain								Steel strain			
	Compressive	Rel. strain	Tensile	Rel. strain	Shear (above opening)	Rel. strain	Shear (below opening)	Rel. strain	Tensile	Rel. strain	Shear	Rel. strain
CB	-0.179	1.279	0.758	8.681	0.331	0.581	0.010	0.330	3.684	0.564	0.008	0.617
FCB	-0.229		6.577		0.192		0.003		2.077		0.005	
CB 62.5	-0.102	2.330	0.394	0.023	1.285	0.285	0.113	0.066	0.219	7.741	0.074	0.339
FCB 62.5	-0.237		0.009		0.366		0.008		1.694		0.030	
CB 87.5	-0.00	8.892	0.238	1.296	2.628	0.360	0.147	1.195	2.136	0.137	0.026	3.008
FCB 87.5	-0.074		0.309		0.946		0.175		0.292		0.077	
CB 112.5	-0.004	14.263	0.249	0.818	1.392	0.052	0.048	0.021	0.145	1.214	0.220	0.236
FCB 112.5	-0.054		0.203		0.072		0.001		0.176		0.052	

In the table, Rel. is the relative strain values obtained by dividing strain values from PET fibre reinforced beams to those of the control beams

IV. CONCLUSIONS

Conclusions

This study has the following findings.

i. Introduction of PET fibres in beams with openings slightly improved the load carrying capacity by 4.1% and 5.82% for 0.25h and 0.35h beam opening sizes respectively, beyond which the strength reduced by 9.57% for beams with 0.45h opening size. In addition, PET fibres increased the first cracking load by 44.12%, 48.48% and 9.38% for 0.25h, 0.35h and 0.45h opening sizes, respectively.

ii. A good convergence between the theoretical and experimental shear strengths was observed, with the relative shear values between 0.85 and 1.12 and hence the experimental work was adequately validated.

iii. For beams with an opening size less than 0.35h, an improvement in the ductility index between 1.08 and 1.03 was observed, and the failure mode slightly changed from a more pronounced shear + flexure to a flexure mode with multiple cracks.

iv. PET fibres increased the compressive and tensile strains due to the slight change in failure modes. In addition, the shear strains in the concrete reduced progressively due to the tension stiffening effects of the fibres.

PET fibres should therefore only be used to reinforce beams with openings less than 0.35h opening size. Even though they do not restore the original capacity of the beam, the reduction in strength is only 15.58% and the serviceability performance of the beams is improved.

Other Recommendations

i. PET fibres should only be used to reinforce beams with opening sizes not more than 0.35h. To reduce the effect of compressive strength reduction, these fibres can be provided around the opening region only.

ii. In this study, the beams were under designed in shear to isolate the contribution of fibres in strength enhancement. Further studies could be done where only the diagonal reinforcements around the opening region are avoided.

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