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Shear Capacity of Reinforced Concrete Beam with an Opening Retrofit Using Steel Fiber and Metakaolin

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Abstract: The presence of opening in the shear zone of beams can significantly affect the load-carrying capacity and the shear resistance of the beams. Previous research has shown that strengthening provides promising results in increasing the performance of the beams with opening. Therefore, this study presents the experimental work of five (5) reinforced concrete beam with opening at shear zone, added with steel fibre and metakaolin to increase the shear capacity of the beam. All beams were cast and tested under four-point bending test. One beam served as the control specimen, two beams had one and two opening respectively while the other two beams also had one and two opening but with added steel fibre and metakaolin. The type of steel fibre used was a hooked-end steel fiber with the dimensions of 0.9 mm in diameter, 60 mm in length. 0.5% of steel fiber was added by volume of beam, and 5% of metakaolin by volume of beam were used. From the experimental results, it was found that the two beams with added steel fibre and metakaolin shows an increase in shear capacity compared with the beams with opening without the steel fibre and metakaolin. The highest shear force recorded was 79.11 kN (beams with added steel fibre and metakaolin) which showed an increase of about 54.3 % compared with the same beam with opening without added steel fibre and metakaolin.

Keywords: Shear capacity, steel fiber, metakaolin, beam with opening

1. Introduction

One of the issues that modern structural engineering faces today is the strengthening, upgrading, and retrofitting of existing structures. Existing concrete constructions may be found to operate inadequately for a variety of reasons. This could present as poor service loading performance, such as excessive deflections and breakage, or as insufficient shear capacity. Furthermore, changes in structural design and loading requirements may declare many constructions previously perceived to be satisfactory noncompliant with current provisions. On the other hand, a facility that allows services to pass over the structure comprises reinforced concrete beams with a transverse opening. RC beams may also need to be designed with an opening for aesthetic purposes [1]. Because of the abrupt changes in the cross-section of the beam, the edges of the opening may be subjected to high-stress concentrations, potentially resulting in transverse cracks in the beam [2].

Beam openings can be of many forms and sizes, and they are typically situated near the supports where shear is greatest. In practice, it is frequently used to provide convenient passage of environmental services, which reduces the story heights of buildings and the weight of concrete beams as it improves the demand on the supporting frame both under gravity loading and seismic excitation, resulting in significant cost savings. Openings should be placed on the concrete beams to give chords enough concrete area to generate ultimate compression blocks in flexure and enough

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depth to offer efficient shear reinforcement. Although many different shapes are conceivable, the most typical are circular and rectangular openings [3].

The inclusion of openings in RC beams obviously changes the simple beam behavior to a more complex one. Opening areas are vulnerable to high-stress concentration due to abrupt changes in sectional configuration, which may result in undesired cracking from an aesthetic and durability perspective. In a continuous beam, the lower stiffness of the beam may also result in excessive deflection under service load and a significant redistribution of internal forces and moments. The strength and serviceability of such a beam may be substantially compromised unless particular reinforcement is provided in adequate quantity and with proper details [4].

On the other hand, brittle failure is an inherent feature of plain concrete, which means it has very low tensile strength and strain capacity at cracks. These flaws of plain concrete are remedied by the use of steel reinforcement bars. The main disadvantage of reinforcing steel is corrosion caused by chloride ion infiltration in the concrete. This issue is even worse in coastal places. Corrosion of steel bars causes rust to form over time. Because rust has a higher volume than iron, it expands. This expansion creates high tensile stresses on the concrete, causing cracks to form and propagate, resulting in concrete spalling. To compensate for this weakness, fibers are mixed into cement concrete [5]. Steel fibers are applied in this project because of their high tensile strength, ductility, capacity to stop crack propagation, enhanced bond strength, and other properties.

The current experimental study is primarily concerned with investigating the various strengths of steel fibre employing metakaolin as a retrofit material. Metakaolin is a manufactured substance that is made by calcining kaolin at temperatures ranging from 700 to 800 degrees Celsius [6]. It is a pozzolanic substance made from chosen kaolin after it has been improved under specified conditions. It is an efficient pozzolan that reacts effectively with the excess calcium hydroxide produced by the pozzolanic hydration of OPC (Ordinary Portland Cement) to create calcium silicate hydrate and calcium alumina silicate hydrate. Metakaolin is a fine white clay with a high amount of silica. Water combines with Portland cement during the hydration process, forming calcium-silicate-hydrate (CSH). Calcium hydroxide is also formed as a result of this reaction (lime). Since lime is weak in concrete, it reduces the action of CSH. According to John [7], when metakaolin is added to concrete, it combines with free lime to generate an additional CSH substance, making the concrete stronger and more lasting. Due to their potential to improve concrete performance, metakaolin was added in this study to investigate its effectiveness in enhancing the shear capacity of the beams.

2. Research Methodology

2.1 Details of Specimen

Table 1 below shows the details of specimens cast at the Heavy Structural Laboratory and tested at Jamilus Research Centre, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia. In this study, opening was located at the shear zone of the beam. Based on Table 1 and Figure 1, beam B-C was a control beam without opening, beam BO-1 was a beam with one opening, beam BO-2 was beam with two opening, beam BO-1-RSFM was beam with opening, added with steel fibre and metakaolin while beam BO-2-RSFM was a beam with two opening, added with steel fibre and metakaolin. All openings were located at the shear zone. The dimensions of each specimen, as well as the reinforcement details and cross-section, are shown in Figures 1, 2, 3 and 4.

Table 1 - Specimen characteristics

Specimen	No. of opening	Strengthening / Retrofit material
B-C	-	-
BO-1	1	-
BO-2	2	-
BO-1-RSFM	1	Steel Fiber and Metakaolin
BO-2-RSFM	2	Steel Fiber and Metakaolin

B-C: Control Beam
BO-1: Beam with one opening
BO-2: Beam with two opening
BO-1-RSFM: Beam with one opening retrofit using steel fiber and metakaolin
BO-2-RSFM: Beam with two opening retrofit using steel fiber and metakaolin

All beams were designed with the same dimensions of 150 mm width, 300 mm height and 1900 mm of total length. The beams were reinforced with three (3) number of high yield strength size 12 mm as main reinforcement (3H12) while mild yield strength of reinforcement was used as link with the spacing of 300 mm (R6-300). From the designed, compressive reinforcement is not required, therefore 2R6 is used to form the reinforcement cage. All beams were designed to fail in shear since this study is about the presence of opening in the shear zone. The type of opening is circular opening with the size of 100 mm diameter.

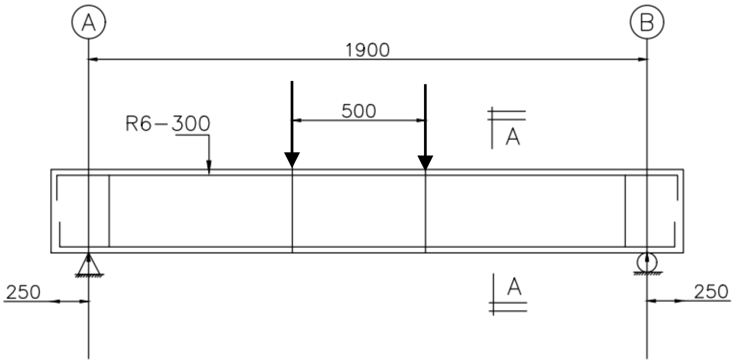

Fig. 1 - Beam B-C and reinforcement details (unit in mm)

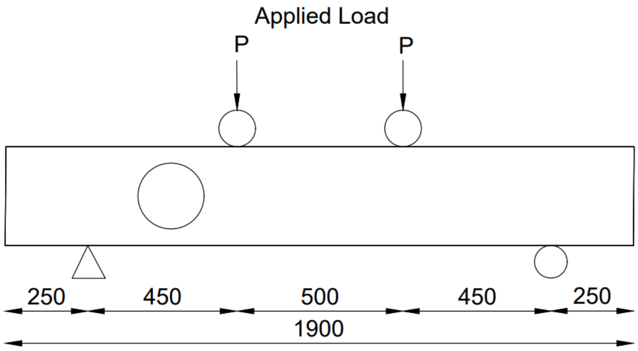

Fig. 2 - Beam BO-1 and BO-1-RSFM details (unit in mm)

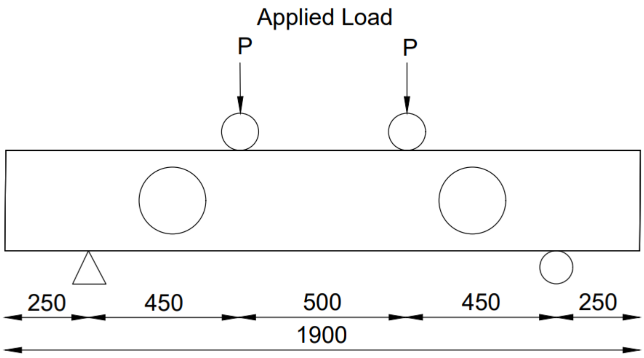

Fig. 3 - Beam BO-2 and BO-2-RSFM details (unit in mm)

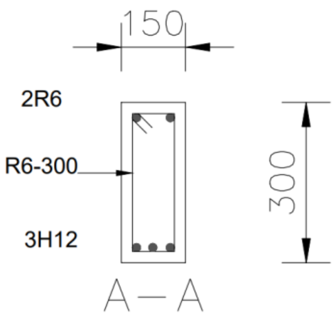

Fig. 4 - Cross section of all beams (unit in mm)

2.2 Properties of Materials

This research involved casting beams with the goal of analysing the shear capacity performance of reinforced concrete beams, as well as analysing the shear force, deflection profile, modes of failure, and crack pattern for reinforced concrete beams with opening retrofit material. The experimental study was strengthened by using the following methods:

i. Grade 30 ready mix concrete was used. Six 150×150×150 mm concrete cubes were cast for cube compressive testing. Three specimens were tested on the 7th day while the other three were tested on the 28th days.
ii. 5% of metakaolin by volume of cement was used.
iii. Hooked-end steel fibers with a length of 60 mm and diameter of 0.9 mm used and 0.5% of steel fibers was added by volume of concrete.

3. Experimental Results

3.1 Ultimate Shear Force, Modes of Failure, and Crack Pattern

The ultimate shear force, maximum deflections, modes of failure, and contribution of steel fiber and metakaolin in the beam relation of all beams, including the control beam, are shown in Table 2.

Table 2 - Experimental results of reinforced concrete beam

Beam	Ultimate shear force (kN)	Percentage increment / decrement (%)	Contribution of steel fiber and metakaolin (kN)	Maximum deflection (mm)	Percentage increment / decrement (%)	Modes of failure	Shear crack angle (°)
B-C	68.78	-	-	66.95	-	Shear	47.0
BO-1	64.34	- 6.46	-	46.95	- 29.87	Shear	32.1
BO-2	51.27	- 25.46	-	53.2	- 20.54	Shear	43.6
BO-1-RSFM	61.57	- 10.48	- 2.77	8.8	- 86.86	Shear	23.0
BO-2-RSFM	79.11	15.02	27.84	78.90	17.85	Shear	21.3

The data above shows that all beams except beam BO-2-RSFM recorded lower capacity compared with the control specimen, which has an ultimate shear force of 68.78 kN. The decreased of beams capacity is due to the presence of opening at the shear zone. On the other hand, beam BO-2-RSFM recorded the highest capacity with the addition of steel fibre and metakaolin. This is due to the steel fibres that act as a frame for the concrete matrix together with the fine aggregate to provide dimensional stability. Apart from that, steel fibre has higher elastic modulus compared with concrete [8]. In addition, metakaolin also plays an important role. A study bu Dhabbagi [9] reveals that the large quantity of reactive SiO2 and Al2O3 in metakaolin chemically reacts with the calcium hydroxide and produce C-S-H gel and aluminates. This resulted in an improved microstructure specifically at the weakest part of the concrete which is interfacial transition zone. Figure 5 displays the relationship between shear force, V, and deflection, δ for all beams (B-C, BO-1, BO-2, BO-1-RSFM, and BO-2-RSFM).

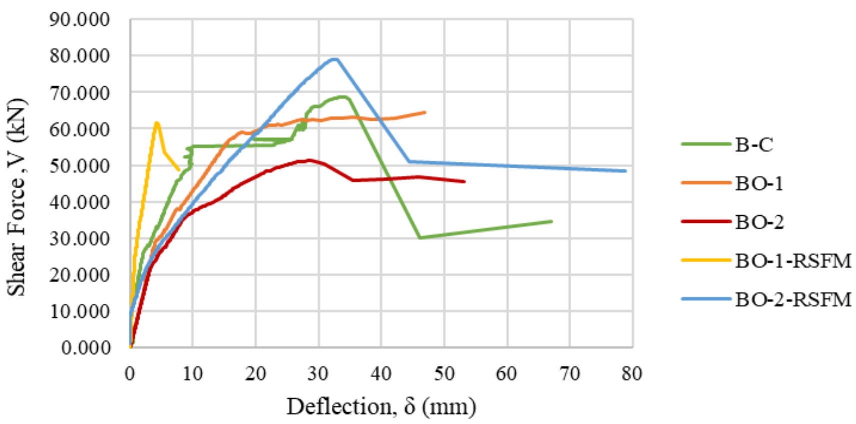

Fig. 5 - Shear force - deflection curve of beams B-C, BO-1, BO-2, BO-1-RSFM, and BO-2-RSFM

The Shear Force - Deflection graph for all proposed beams (B-C, BO-1, BO-2, BO-1-RSFM, and BO-2-RSFM) shows a linear elastic behavior at the start of testing. However, as load increased, the curve became non-linear due to cracks in the beam. The largest measured deflection was 78.90 mm, recorded for beam BO-2-RSFM. Although this beam recorded the highest deflection, it still shows stiffer behaviour compared to beam BO-2 which have the same number of opening. This is due to the presence of steel fibre and metakaolin that increased the shear capacity of the beam. Beam BO-2 and B-C exhibited varied Shear Force - Deflection profiles, with both beams forming a linear curve at the start of loading and becoming non-linear as they approached their elastic limit. After reaching a shear force of 51.27 kN, the deflection curve of beam BO-2 tended to decrease until failure, where it was found to be stiffer. The lowest deflection obtained was from beam BO-1-RSFM was 8.8 mm, a 96.53% deviation from the control beam, beam B-C.

3.2 Crack Pattern

3.2.1 Control Beam (B-C)

The bottom part of the middle support section was where the first shear crack (or diagonal crack) formed. The crack expanded as the load increased and moved diagonally to the point load. In addition to the first diagonal crack, further shear cracks were seen spreading in the same direction. The beam failed due to shear at a load of 137.50 kN as the shear cracks widened and propagated with increasing load. With a shear fracture angle of 47.0º, Figure 6 depicts beam B-C failing in shear. At the mid-span area, several vertical cracks were also observed. According to test observations, vertical cracks in the flexural zone ended their progression far sooner than cracks in the shear span. Since the specimen was made to have fewer stirrups than longitudinal reinforcements, the beam eventually failed in shear rather than flexure, as was to be predicted. The lack of adequate stirrups on the beam caused a diagonal shear crack where the principal tensile stress was greater than the concrete's tensile strength. The same failure was observed with the study from Samad *et. al* [10]. Figure 6 illustrates the crack pattern of the real constructed beam with dimensions of 150×300×1900 mm.

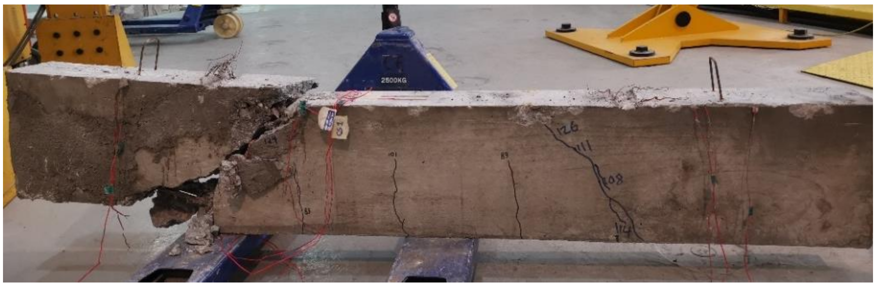

Fig. 6 - Crack pattern of beam B-C

3.2.2 Beam with One Opening (BO-1)

This beam (BO-1), which has one opening and was not reinforced with steel fiber and metakaolin, was put to the test and loaded until it failed. Within a load of 82 kN, it was noticed that flexural cracks first developed near the opening area. At a subsequent load of 104 kN, shear cracks developed. With increasing load, the flexural fractures (or vertical cracks) expanded and spread to the compression zone of the beam. As the shear cracks developed and spread with increasing load, the beam failed owing to shear at a load of 128.69 kN. Figure 7 shows beam BO-1 failing under shear with a 32.1º shear crack angle. Vertical cracks in the flexural zone ended their propagation far more quickly than cracks in the shear span, according to the results of the 4-point bending test. The specimen eventually collapsed in shear rather than flexure, as was expected, because there were fewer stirrups and the effect of openings on it.

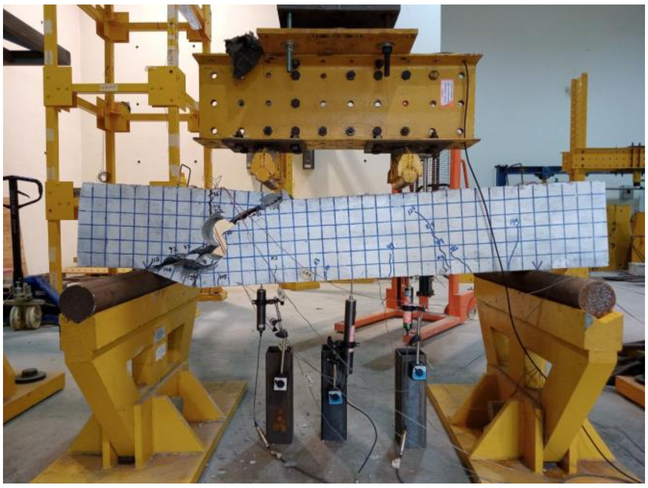

Fig. 7 - Crack pattern of beam BO-1

3.2.3 Beam with Two Opening (BO-2)

Figure 8 displays the crack patterns of the studied beam (BO-2). Since only flexural reinforcement was used for reinforcement, beam BO-2's failure under shear was expected. About 400 mm away from the load, the initial shear crack started and went diagonally in the direction of the beam's support. As a result, this beam experienced an extremely brittle failure (shear failure), which was similar to the other beams. According to Figures 8, the control beam (B-C) experienced about thirteen flexural cracks along with concrete crushing in the compression zone. As the bond length of the reinforcement was being reinforced, cracks began to appear close to the ends of the bond loss. The stress concentration in the area of the bonded zone where the concrete begins to transfer strains to the reinforcement may be the cause of this behavior. The beam failed due to shear at a load of 102.54 kN as the shear cracks widened and propagated with increasing load. With a shear crack angle of 43.6º, Figure 8 depicts beam BO-2 failing in shear.

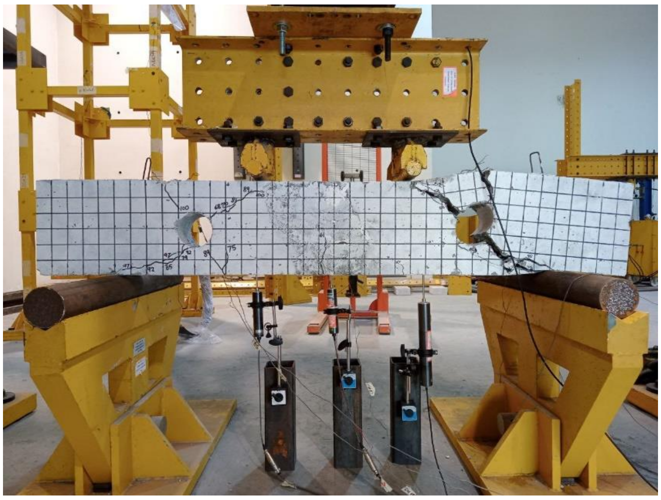

Fig. 8 - Crack pattern of beam BO-2

3.2.4 Beam with One Opening Retrofit Using Steel Fiber and Metakaolin (BO-1-RSFM)

The initial shear crack (50 kN) first appeared at the bottom of the middle support section. With increasing load, the crack widened and went diagonally to the point load. Along with the initial diagonal crack, more shear cracks could be detected extending in the same direction. As the shear cracks developed and spread with increasing load, the beam failed due to shear at a load of 123.14 kN. Figure 9 shows beam BO-1-RSFM failing under shear with a 23.0º shear crack angle. The 4-point bending test results showed that vertical cracks in the flexural zone stopped progressing much earlier than cracks in the shear span. The specimen ultimately failed in shear rather than flexure, as was anticipated since the beam was designed to fail in shear, also with the addition of opening at the shear zone.

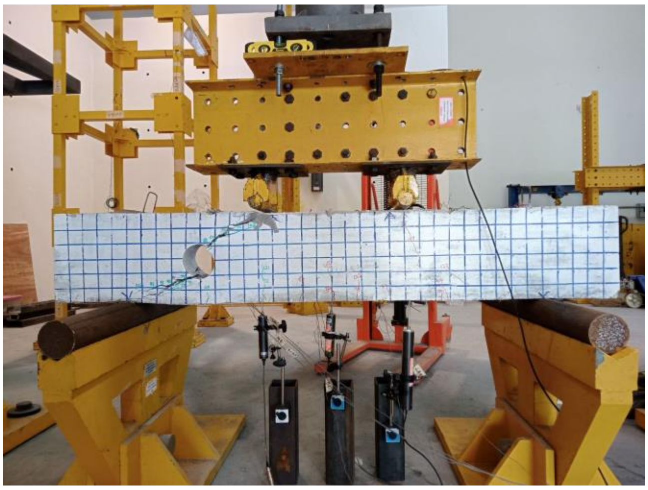

Fig. 9 - Crack pattern of beam BO-1-RSFM

3.2.5 Beam with Two Opening Retrofit Using Steel Fiber and Metakaolin (BO-2-RSFM)

The tested beam's (BO-2-RSFM) crack patterns are shown in Figure 10. It was anticipated that Beam BO-2-RSFM would break under shear as only flexural reinforcement was used for reinforcement. The initial shear crack began about 250 mm from the load and moved diagonally in the direction of the support of the beam. So, like the other beams, this beam also underwent an exceptionally brittle failure (shear failure). The control beam (B-C) had an ultimate shear force of approximately 137.55 kN and a shear crack angle of approximately 47.0º. This behavior may be caused by the stress concentration in the bonded zone, where the concrete starts to transfer strains to the reinforcement. The shear cracks expanded and spread with increasing load, causing the beam to deflect and failed at 158.21 kN. Figure 10 shows the failure of beam BO-2-RSFM in shear with a 41.3º shear fracture angle.

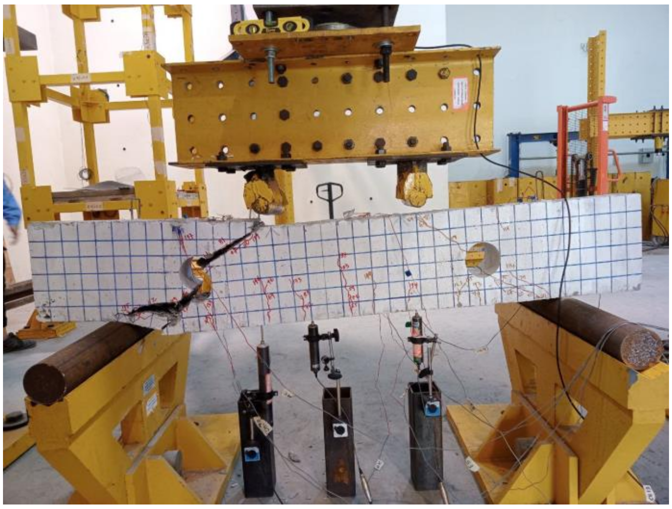

Fig. 10 - Crack pattern of beam BO-1-RSFM

3.3 Shear Force - Strain Relationship

3.3.1 Link Strain

The shear force versus strain of link is shown in Figure 11. The number and location of the strain gauges were the same for each beam, with strain gauges 1 and 2 being on the left side and 3 and 4 being on the right side of the beam. All stirrups for beam B-C displayed linear-elastic behavior up until a shear force of approximately 26.42 kN. The emergence of a diagonal crack in the concrete causes the slope of the strain gauge BO-1 graph to alter. This beam's link strain also had the highest strain, measuring 681.16 µ. At certain shear force levels, the strain gauge for BO-1 displayed plastic behavior, whereas the strain gauges for BO-2, BO-1-RSFM, and BO-2-RSFM had nearly linear behavior up until failure. Only beams B-C and BO-1 were broken at failure despite the fact that all of the beams had yielded and exceeded the yield strain value at 504.35 µ. At a shear force of approximately 51.11 kN for Beam BO-2, the strain gauge had abruptly decreased. The stirrup was compressed to a shear force of approximately 41.66 kN. Due to the presence of opening in beam BO-1-RSFM, link strain displayed a change in slope at early 10 kN of shear force. For beam BO-2-RSFM, it could be seen that a proportional increase of strain was recorded and it yielded at shear force of around 31.08 kN.

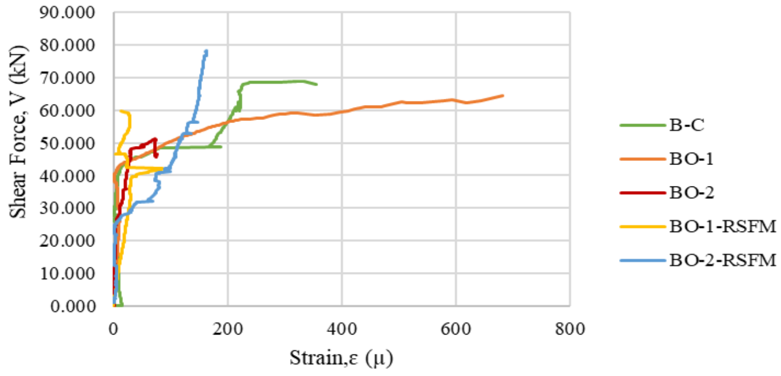

Fig. 11 - Shear force (V) vs link strain (ε) for all beams

3.3.2 Concrete Strain

Figure 12 shows the shear force versus strain in a concrete strain of beams. In each beam, two strain gauges of size 10mm were fixed to the surface of the concrete beam to monitor the strain during the loading applied to the beam. The strain gauges are located at mid-span with distances of 700 mm from the support. It could be seen that all beams had exhibited an elastic behavior at the beginning of the loading process until at a shear force of around 18 kN, curves B-C, BO-1, BO-2, and BO-1-RSFM showed a change of slope due to the appearance of a diagonal crack in the concrete. For curve BO-2-RSFM it can be seen that it is unstable at the beginning of the process. After the reading of shear force around 26 kN, as the loads increase it starts to become even more linear until failure at 253.14 µ. A maximum strain of 630.92 µ was recorded on beam B-C which exceeded the steel yield strain limit.

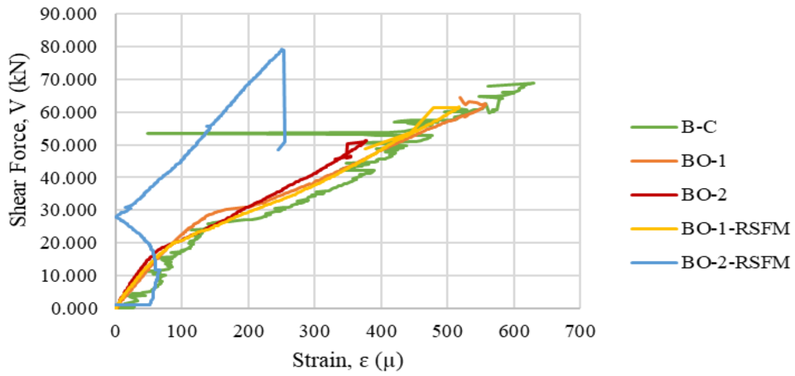

Fig. 12 - Shear force (V) vs concrete strain (ε) for all beams

4. Conclusions

Based on the study objectives, which particularly required some data to be analyzed, a reinforced concrete beam with an opening retrofit utilizing steel fiber and metakaolin was designed, with a dimension of 150×300×1900 mm and a circular opening size of 100 mm. All the objectives were accomplished by the time this study was finished, as shown in the list below:

- Based on the study, the beam that has been under curing for 28 days and tested for its compressive strength and 4-point bending test shows the data that can comply with the shear capacity of a reinforced concrete beam. From the experimental results, it can be seen that data from beam BO-2-RSFM recorded the highest shear capacity rather than the other beams. This is because of the influence and efficiency of the retrofit material (steel fiber and metakaolin) in the beam. This beam recorded the maximum load that it can resist, which is 158.21 kN, and the shear force is 79.11 kN compared to BO-2 (51.27 kN) and control beam, B-C (68.78 kN) which has a smaller value of shear force, V.
- From the analyzed data for the shear force-deflection profile, it can be concluded that beam BO-2-RSFM shows stiffer behaviour compared with beam BO-2 which have the same opening characteristics, but without the addition of steel fibre and metakaolin.

- On the other hand, the cracks pattern was influenced by the modes of failure where all beams experienced shear (diagonal cracks) and flexural (vertical cracks), especially to the beam that has an opening. From the data discussed in the results and analysis part, beam BO-2-RSFM creates more cracks than the other beams even though the beam consists of retrofit material of steel fiber and metakaolin. This complies with the number of openings in which it is designed to have 2 openings on the beam, it has the most crack pattern also due to the maximum value of the load of all beams that undergo the 4-point bending test.

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