Impact of Web Openings on the Shear Behavior of Lightweight Deep Beams

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ABSTRACT

An experimental program was conducted to investigate the shear behavior of simply supported deep beams made of reinforced lightweight concrete (LWC), both with and without web openings. The test program consisted of four simply supported, deep beams made of reinforced concrete. The dimensions and placement of the openings were the primary variables. The results of the experiment show that adding web openings to the load path lowers the ultimate shear strength of LWC simply supported deep beams. More precisely, the findings indicated that web openings measuring 20% of the total web height resulted in a decrease of about 15% in the maximum shear strength when compared to a beam without any openings of the same type. Web openings that had a height equivalent to 40% of the overall web height resulted in a significantly larger decrease in the ultimate shear strength, roughly 62%, compared to a beam without similar openings. This result can be utilized to guide the development of reinforced concrete simply supported deep beams in the future, specifically in relation to the dimensions and placement of web openings.

Keywords: Lightweight concrete, Deep Beams, Web opening, Shear.

I. Introduction

The majority of the current concrete research is on high- and ultra-performance concrete, which is intended to be a cost-effective material that meets stringent performance standards, such as durability. The importance of lightweight concrete (LWC) to the construction industry is based on its cheaper cost and lighter weight.

The fundamental benefit of utilising LWC is the decrease of the dead load of the concrete structure, which in turn reduces the dimensions of columns, footings, and other load-bearing parts. Lightweight foamed concrete is a new type of LWC that combines the benefits of normal density concrete, cellular concrete, and self-compacting concrete by partially replacing normal weight aggregates with polystyrene foam, resulting in a decreased in concrete unit weight while maintaining adequate strength. Therefore, this material, which has a dry unit weight of 18.5 kN/m3, may be manufactured using normal construction industry practises.

The use of lightweight foamed concrete reduces the dead load by 15–20%. which helps reduce the overall cost of the construction, making it a viable alternative to normal density concrete (NDC) with a dry unit weight of 25 kN/m3.

Eleven deep beams were fabricated and experimentally tested by Moussa, A., et al. [3] to investigate the effect of the existence of openings on the behaviour of the deep beams as well as the size and nature of the stress distribution. According to the test results, expanding the size of the opening increased the top deflection. Due to the deviation of the arch action, raising the opening causes an increase in the top deflection and a decrease in the bottom deflection. For solid beams and beams with openings not in the load path, the shear capabilities estimated by the Egyptian and ACI codes are relatively comparable.

Haque, M., et al. [4] investigated the stress distribution in deep beams with and without web openings using photoelastic techniques. The general shape of the stress diffusion was determined, as were the critical zones. The sensitivity of the critical tensile and shear stresses to the span-to-depth ratio and opening position along the span was determined. On the basis of the stress flow pattern and contour lines of the primary tensile stresses, failure mechanisms and design suggestions for reinforced concrete deep beams were projected.

Danile F. Jensen [5] conducted research titled "Reliability Analysis for Shear in Lightweight Reinforced Concrete Bridges Using Shear Beam Database" (2014). The purpose of the study was to analyse and verify the shear reliability indices for reinforced concrete bridge girders. Existing statistical models are based on experimental data from a small number of tests.

Existing models demonstrated that current analysis methods are approximately 10 to 15% less cautious for LWC than for standard weight concrete. To determine shear and moment envelopes for loads applied to bridges, precise load models were employed. The shear behaviour of full-size reinforced LWC beams was investigated by C. H. Huang, L. H. Chen, Y. C. Kan, C. H. Wu, and T. Yen [6]. (2011). This study provided the outcomes of centre load bending tests conducted on three lightweight aggregate concrete (LWAC) beams and three normal weight concrete (NWC) beams designed and cast for shear investigations. The test findings demonstrated that the shear failure modes of LWAC beams are comparable to those of NWC beams, including shear-tension failure and shear-compression failure.

II. Methodology

The considered methodology in this research begins with collecting, sorting, and analyzing the previous work regarding LWC for deep beams.

The output of this stage indicated a gap study regarding the impact of opening size and location on the capacity of LWC deep beams. Accordingly, the next stage is to design an experimental test program to investigate this gap.

The developed test program contains four LWC deep beams: a control beam (B1), one beam with a different opening location (B2), and two beams with different opening sizes (B3, B4).

The impact of opening location is investigated by comparing the testing results of B1, B2, and B3, while the effect of opening size is investigated using the results of B1, B3, and B4. Finally, the recorded results are discussed, and the research conclusions are summarized, including the study limitations and further research recommendations. Fig. 1 shows the considered methodology.

III. Experimental Program

Four reinforced concretes simply supported deep beams with and without web openings constructed from LWC were designed and fabricated to investigate the shear behavior under incremental vertical loading. All beams had the same geometry (80mm width x 400mm height x 800mm span). Same main longitudinal top and bottom reinforcements 2Ø10 and 4Ø16 respectively. Mild stirrups reinforcement was constant for all specimens Ø6 @ 100mm spacing.

Fig. 2 shows the concrete dimensions and Reinforcement details for all the tested beams.

Two parameters were studied in this research, opening sizes, and opening location. two different opening size were considered:

(80x80mm) and (160x80mm) for specimens B3 and B4 in order.

The influence of opening location on the shear strength was studied using three specimens (B1, B2, and B3) for without opening, with opening in location 2 and with opening in location 1 respectively as shown in Fig. 3 and Fig. 4.

All beams were gradually loaded with vertical hydraulic jack on a steel plate placed at the center of the beam. The characteristics of each beam are summarized in Table 1.

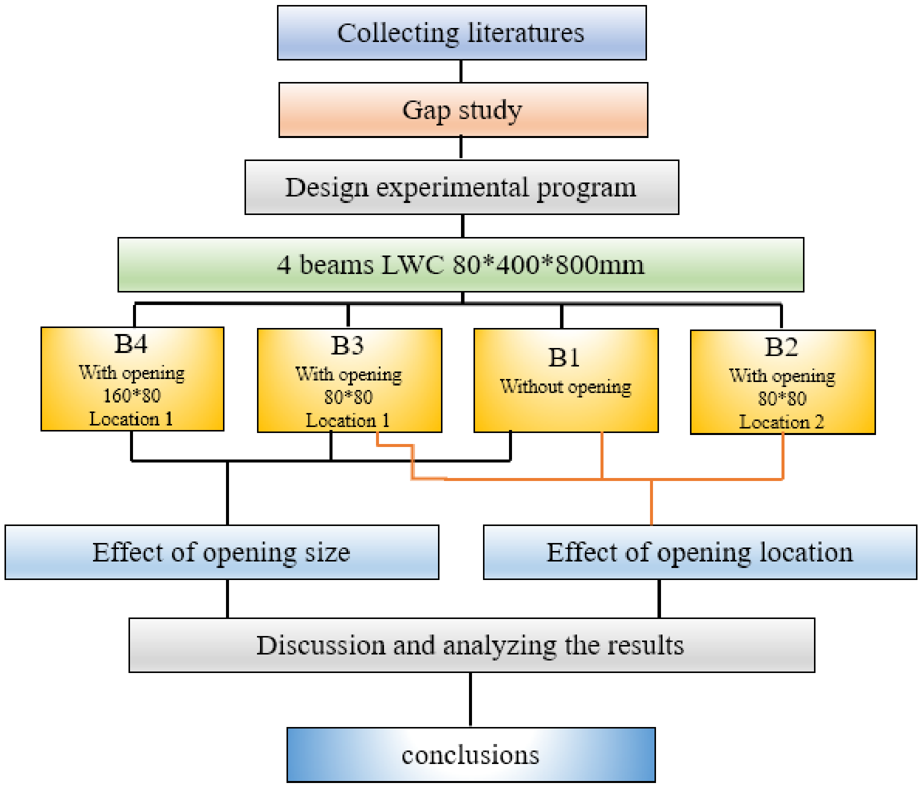

Fig. 1: The considered methodology

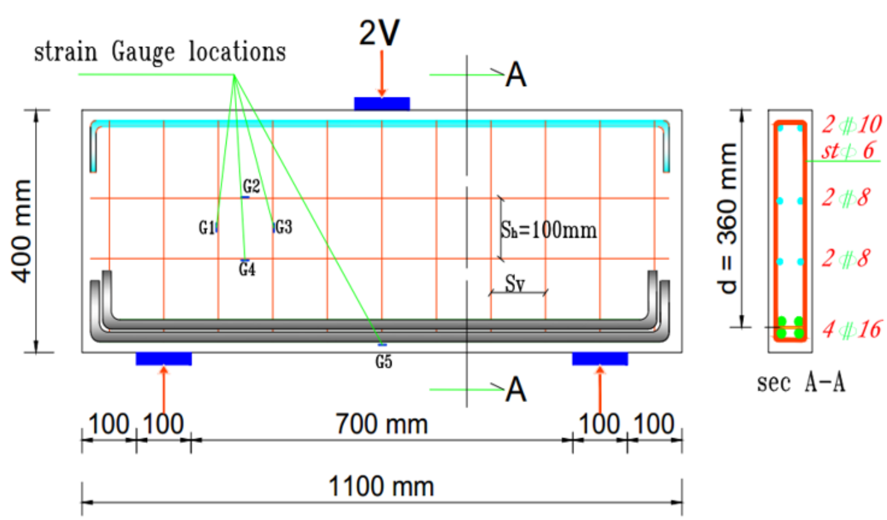

Fig. 2 Reinforcement details

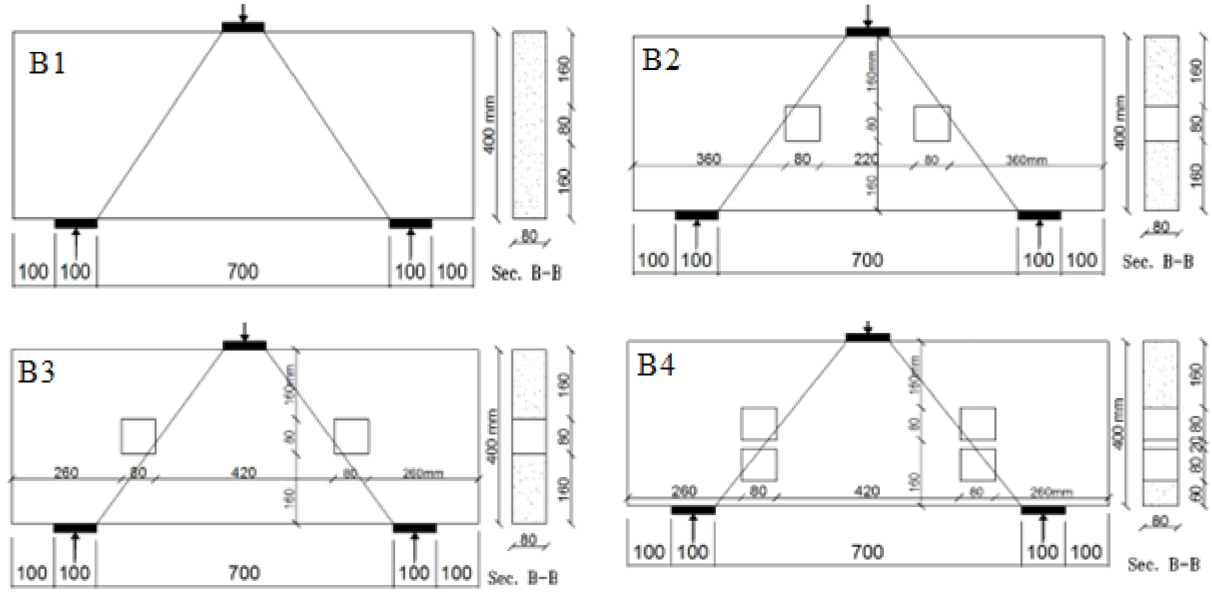

Fig. 3 Typical dimensions of the tested beams

Table 1 Designation of experimental test specimens

<table>
<tr><th>Beam</th><th>Dimensions (mm)</th><th>Span (mm)</th><th>Shear span-to-depth ratio a/d</th><th>Top Longitudinal Bars</th><th>Bottom Longitudinal Bars</th><th>Stirrups Ø6 S_v(mm)</th><th>Opening Size (mm)</th><th>Opening Location</th></tr>
<tr><td>B1</td><td rowspan="4">80 x 400</td><td rowspan="4">800</td><td rowspan="4">0.97</td><td rowspan="4">2Ø10</td><td rowspan="4">4Ø16</td><td rowspan="4">100</td><td>---</td><td>---</td></tr>
<tr><td>B2</td><td>80*80</td><td>2</td></tr>
<tr><td>B3</td><td>80*80</td><td>1</td></tr>
<tr><td>B4</td><td>160*80</td><td>1</td></tr>
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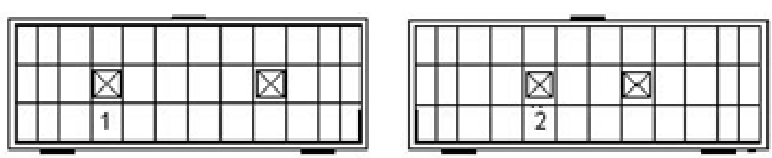

Fig. 4 Location of openings

III.1 Material

From the mix design, the quantities required by weight for one cubic metre of fresh concrete for the LWC specimens are given in Table 2. The longitudinal reinforcements for the beams were high-grade steel bars (fy=550 N/mm2, fult=700 N/mm2).

Table 2 Specimen material properties

Cement Kg/m^3	Sand Kg/m^3	Gravel Kg/m^3	w/c ratio	Super-plasticizer Litre/m^3	Silica fume Litre/m^3	Polystyrene foam Litre/m^3
450	630	630	0.308	13.5	40	330

Table 3 Mechanical properties of LWC mix (N/mm^2)

Concrete type	Concrete strength *(N/mm^2)*	Cube strength 7 days	Cube strength 28 days	Cylindrical compressive strength N/mm^2 after 28 days
Lightweight	25	19.7	28.9	23.3

III.2 Loading of specimens

The specimens were loaded in increments to failure. The tested specimens were instrumented to measure the deformation behaviour after each load increment. The recorded data included measurements of the strain, deflection and crack propagation in the concrete, main steel, transverse reinforcement (stirrups) and longitudinal bars. After each load increase, the cracks were traced and marked on the painted surfaces of the specimen according to their sequence of appearance.

III.3 Test procedure

The specimens were tested using a hydraulic jack. At the beginning of each test, the specimen was installed on the two supports as a simply supported beam. The reading of the hydraulic jacks and the steel strain gauges were taken by special instruments.

IV. Experimental Results

The foer tested models behaved differently, and the following remarks can be made:

IV.1 Crack pattern and failure mode of tested beams

At the end of the testing of each deep beam, the marked crack pattern was used to obtain the information required for defining the failure mechanism of each specimen. Fig. 5 shows the failure modes of all tested specimens. For all specimens, flexural cracks initiated on the tension side at the middle of the beam span, and the cracks propagated upwards with increasing load. For the solid beam, the first diagonal crack suddenly developed at the mid-depth within the shear span.

Diagonal cracks were observed parallel to the compression strut and propagated towards the loading region and supports. For the beams with a small opening size, with an increase in the applied load, shear diagonal cracks began to appear and extend from the support plates to the edges of the openings. For the tested deep beams with large openings, diagonal cracks first initiated at the opening corners and propagated with increasing load towards the loading zone and supports. With increasing load, more diagonal cracks appeared parallel to the strut, passing through the opening corners, and propagating in both directions towards the loading region and the support plates. Table 4 shows the cracking and failure loads for all tested beams.

IV.2 The following points can be made:

The effect of the opening size on the failure load was studied by comparing beams B3 and B4. The failure loads were determined relative to that of the solid beam B1. The failure loads of B3 and B4 with respect to that of B1 were 0.80 and 0.60, respectively.

The effect of the opening location on the failure load was studied by comparing beams B2 and B3. The failure loads were determined relative to that of the solid beam B1. The failure loads of B2 and B3 were 0.86 and 0.80 times that of B1, respectively.

Table 4 Beam loading test results

Specimen	**B1**	**B2**	**B3**	**B4**
Failure load (kN)	250	215	200	150
Cracking load (kN)	100	70	80	60

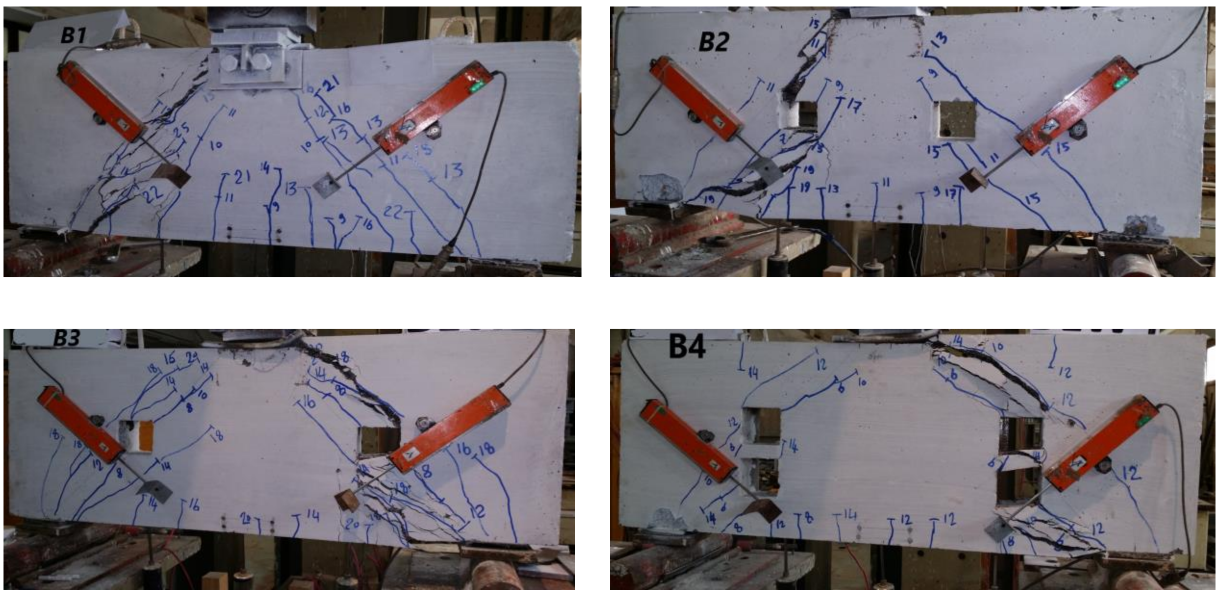

Fig. 5 Failure modes of the tested beams

IV.3 Deflection

During the testing of each beam, the deflection at the mid-span was measured at the end of each load increment. The measured load-deflection curves are shown in Fig. 6. From the figure, the following points can be made:

The mid-span deflection curves of LWC deep beams with and without web openings are reported here. In the early stages of loading, the beams behaved in a truly elastic manner. At higher loading, beams with large web openings exhibited the highest deflection among all beams at the same level of loading. Beams with small web openings showed load deflection behaviour very similar to that of the solid beam.

The effect of the opening size on the mid-span deflection clearly indicates that openings reduce the deep beam stiffness. The effect of the opening size is also clear when the response of beams B3, B4. The comparisons of beams B3 and B4 are shown in Fig. 6. The mid-span deflection of beam B3 with small opening 80*80mm is smaller than that of beam B4 with opening 160*80mm.

The effect of the opening location on the mid-span deflection was studied. The load-deflection curves of beams B2 and B3 indicate that moving the opening towards the beam centre reduces the deflection.

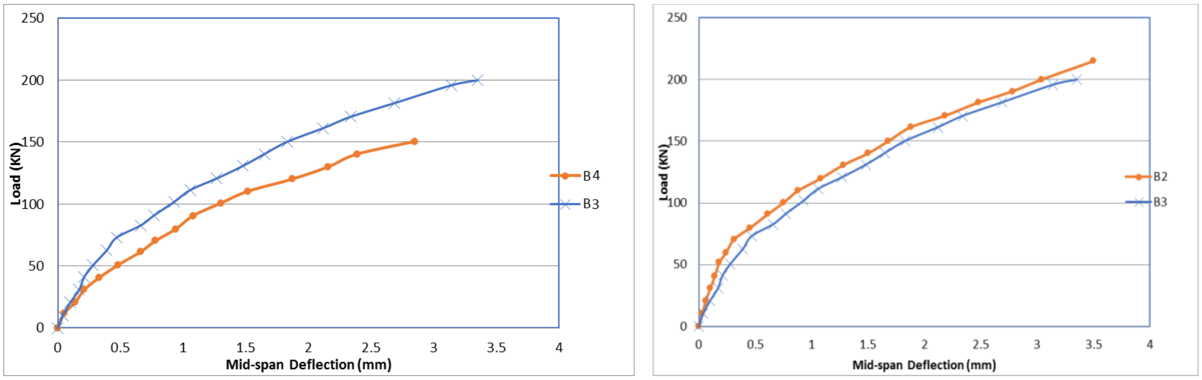

Fig.6 Load-Deflection relationships for the tested beams

IV.4 STEEL STRAIN

The steel strain occurs in three locations. The first location is at the bottom steel bars (main steel) in the mid-span of the beam. The second location is at the vertical stirrups around the web opening. The third location is at the horizontal stirrups (longitudinal bars) around the web opening.

Fig. 7 shows the measured load-main steel strain curves until failure for the beams. From the figure, the following observations can be made:

Failure of all the tested deep beams with and without web opening occurred before yielding of the longitudinal bars. The formation of inclined diagonal cracks had no effect on the strain readings in the longitudinal bars.

The effect of the opening size on the main steel strain was determined by comparing beams B3 and B4. From these comparisons, we note that the main steel strain increases as the opening size increases at the same load. The effect of the opening location on the main steel strain for beams B3 and B2 indicates that moving the opening towards the beam centre reduces the main steel strain at the same load.

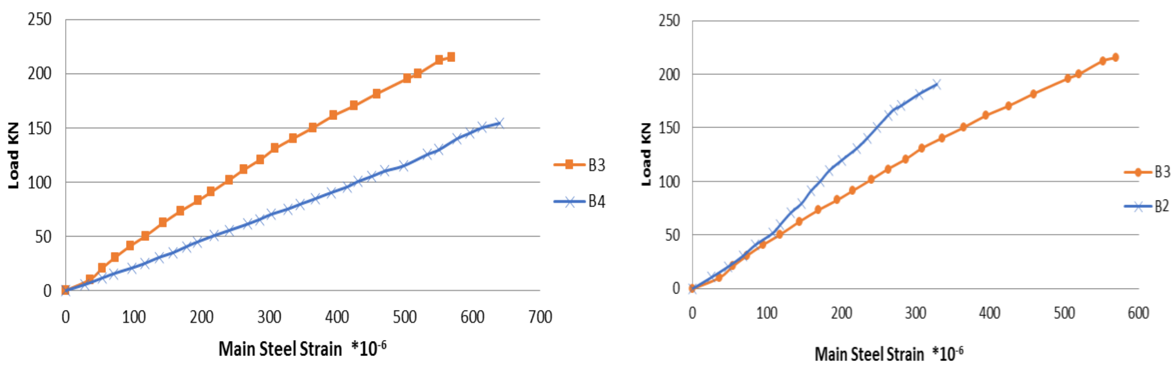

Fig. 7 Load-Steel strain relationships of main steel for the tested beams

Fig. 8 shows the measured load-vertical stirrup strain curves until failure for the beams. From the figure, the following observations can be made:

The strains in the stirrups before the initial diagonal crack occurred were very small and increased suddenly after the formation of this crack.

The effect of the opening size on the vertical stirrup strain was determined by comparing beams B3 and B4. From these comparisons, we note that the vertical stirrup strain of beam B3 with a small opening size is higher than that of beam B4 with a large opening size; however, the strain of B3 was expected to be lower than that of B4. This result could be attributed to the small opening size decreasing the vertical stirrup strain.

The effect of the opening location on the vertical stirrup strain for beams B3 and B2 shows that moving the opening towards the beam centre reduces the vertical stirrup strain at the same load.

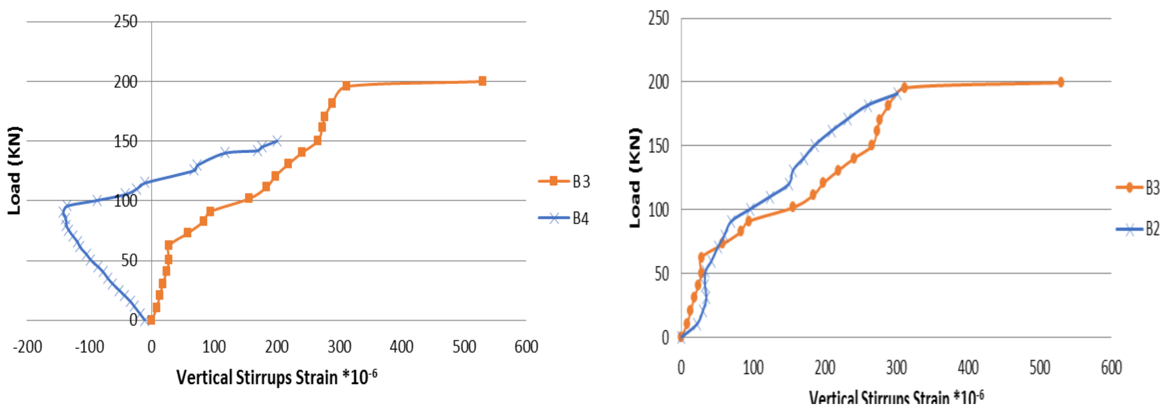

Fig. 8 Load-Steel strain relationships of vertical stirrups for the tested beams

Fig. 9 shows the measured load-longitudinal bar strain curves until failure for the beams. From the figure, the following observations can be made:

The effect of the opening size on the longitudinal bar strain was determined by comparing beams B3 and B4 From these comparisons, we note that the longitudinal bar strain increases as the opening size increases at the same load.

The effect of the opening location on the longitudinal bar strain for beams B3 and B2 shows that moving the opening towards the beam centre reduces the longitudinal bar strain at the same load.

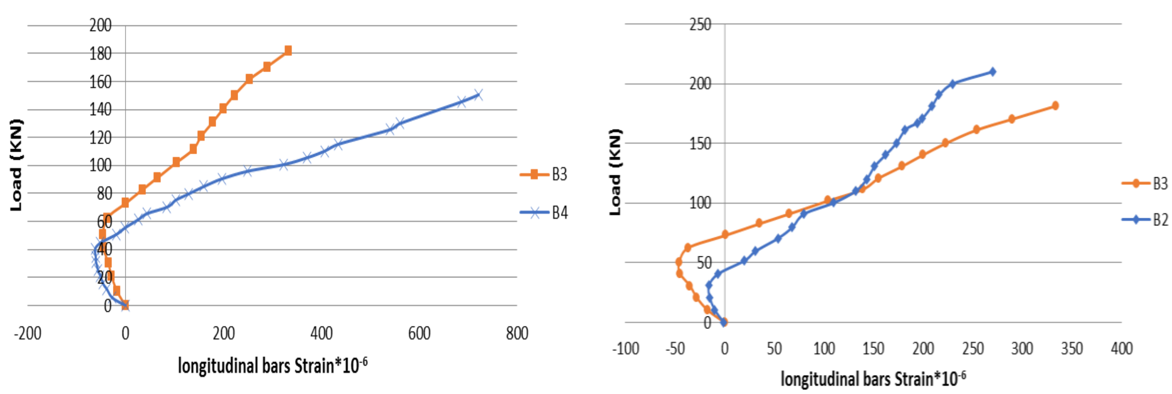

Fig. 9 Load-Steel strain relationships of longitudinal bars for the tested beams

V. CONCLUSIONS

- The presence of web openings (of height equal to 20% and 40% of the total web height) in the load path leads to a reduction in the ultimate shear strength of LWC deep beams by approximately 15% and 62%, respectively, compared with a similar beam without openings.
- When an opening exists near the support region of the LWC deep beam, early cracking and a reduction in the strength and stiffness of the beam occur.
- Openings in the shear span of deep beams reduce the shear strength compared to that of the solid deep beam.
- Openings in the shear span of deep beams increase deflection and concrete and steel strains.

VI. REFERENCES

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