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# Flexural Performance of Composite Ultra-High-Performance Concrete-Encased Steel Hollow Beams

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**Abstract**

Composite members have been widely used in the construction of medium- and high-rise buildings. The results of the development of a new structural member by experimental investigation of the flexural behavior of hollow composite beams are presented in this paper. This research aims to exploit the properties of composite sections and their strength in developing a new approach for overcoming the problems of service pipes in buildings. A hollow steel section encased fully in concrete is used to form a composite hollow beam. The structural benefit provided by the steel section (composite part) is adopted to increase the stiffness of the member. The hollow part is employed to provide services and economic benefits by reducing the amount of expensive ultra-high-performance concrete (UHPC) used and decreasing the self-weight of the member. The flexural strength of 11 UHPC beams is tested under two-point loads. The variables in this investigation include the type of hollow core mold material and the size, location, and shape of steel hollow sections in the middle and tension zones of the cross-section. Experimental results are compared and discussed. The tested results show that the flexural capacity and stiffness of the UHPC-encased steel hollow beams are 109% and 23.5% higher than those solid beams, respectively.

*Keywords:* Ultra-High Performance Concrete; Hollow Beams; Composite Beams; Longitudinal Opening; Position of Hole.

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## 1. Introduction

Generally, studies on structural engineering aim to search for materials whose properties can be effectively used in construction. Therefore, materials characterized by strength, stiffness, workability, and economic feasibility are utilized to obtain the best performance of concrete structures. Given that no single material can satisfy all structural requirements, two or more materials are combined to take full advantage of their properties and obtain one structural element with desirable properties. The advantages of different materials are combined to produce a member with high carrying capacity known as a composite member.

The most common composite member in structural engineering usually consists of a concrete slab attached to a steel I-section beam, as shown in Figure 1a. However, recent studies have focused on the use of a composite member (composite-encased beam) composed of a steel I-section embedded in the middle of the concrete section, as shown in Figure 1b, to take advantage of the bonding between the steel and surrounding concrete and to allow them to act as one unit.

In the design of the high reinforced concrete structures, (1) hollow concrete beam is usually used to reduce the self-

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weight of members. However, it is possible that these hollow member does not have sufficient plastic deformation to absorb the applied energy. Therefore, in order to ensure the safety of these elements, many investigations should be made upon it (Susumu et al. 1996) [1]. So In the present research, a new type of composite section was developed; this section is completely different from the composite sections studied in previous research. This section provides benefits in addition to the structural benefit by using a hollow steel section and embedding it in the concrete section. The existing hollow core provides a safe outlet for service runs (plumbing pipes, electrical ducts, etc.). This new type of encased composite beams (hollow composite beams) is shown in Figure 1c. This section provides another important benefit (economic benefit) because the existence of the hollow core reduces the amount of required concrete, thereby reducing the weight of the structural element. An ultra-high-performance concrete (UHPC) mixture is used in the present research. However, despite the useful properties of UHPC, the cost of its materials is relatively high.

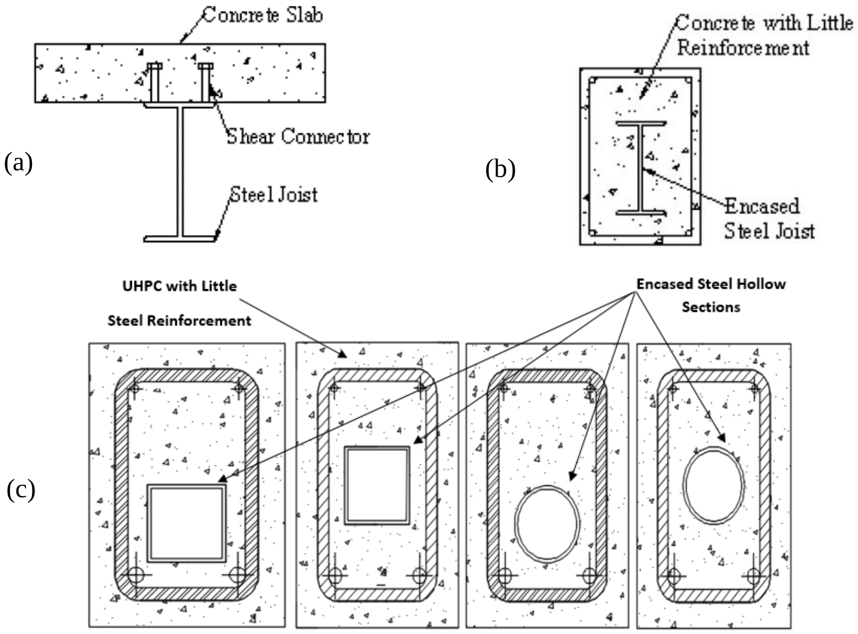



**Figure 1. (a) Traditional composite beam; (b) Composite encased beam; (c) Composite hollow beams (developed in the present work)**

### 1.1. Literature review

- **On the Composite Sections:**

Through a literature review, we found that a composite hollow beam that consists of a hollow steel section embedded in the concrete section has not been studied recently.

Neelima (2016) investigate the flexural and shear behavior of fully encased composite beams. The study compares beams were reinforced with traditional steel rebars and models reinforced using steel sections instead of steel rebars. The resulting load-deflection curve shows that the use of the steel section in reinforcing gave higher ultimate load and less deflection rather than the rebars reinforcing [2].

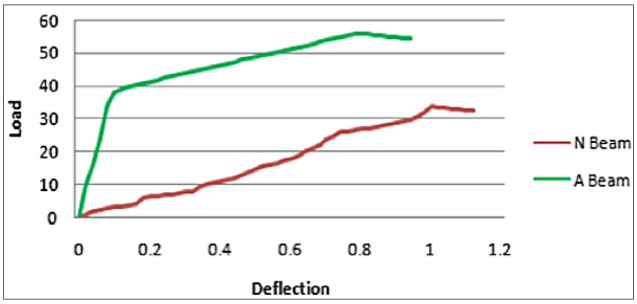



**Figure 2. Load-deflection curves comparison.**

Samer (2018) investigated the effect of using composite sections in flexural behavior. His study included the use of different percentages of the areas of the steel sections embedded. The study concluded that the composite section containing the percentage of steel section ratio 3% gave higher capacity than the sections with percentages of 1% and 1% [3].

Shingade (2016) investigated the removal of the shear reinforcement from the composite sections to determine the flexural and shear behavior with/without shear reinforcement. The study variables were (B1: using conventional shear reinforcement, B2: using rolled steel angle sections as reinforcement and B3: using rolled steel channel sections as reinforcement). Results showed that width of the cracks was increased by the absence of shear reinforcement compared to the models with shear reinforcement and failing by crushing the concrete in diagonal tension [4].

Shallal (2018) studied the flexural behavior of a composite beam consisting of tubular square sections filled with concrete. The depth-to-thickness ratios (D/t) of the tubular sections were 33.34 and 37.5. These composite beams were subjected to bending load, and the tests results were compared with those of a tubular steel section without concrete. The comparison showed that filling a tubular section with concrete increases the maximum moment strength from 47.15% to 87.07% [5].

Elnawawy (2018) investigate the efficiency of hollow reinforced concrete encased steel tube composite beams. The study consisted of testing three solid reinforced concrete beams specimens and six hollow reinforced concrete encased steel tube composite beams specimens. The purpose of the study is to investigate the possibility of reducing the depth of the composite beam using steel tubes without affecting the overall stiffness and strength requirements. The target depth of the composite beams was selected as 480 mm which is 20% less than the conventional beam. The results showed that the usage of concrete encased steel tube system increases the ductility of the beams as compared with traditional solid beams. The ultimate flexural strength, ductility, and energy absorption capacity can be enhanced by providing the hollow steel tube embedded in the beam as a heavy reinforcement [6].

- **On UHPC Mixture:**

Richard and Cheyrezy were the first to develop UHPC in the 1990s in a laboratory in France, where they made several attempts to reach the compressive strength of 200 Mpa. After that, other attempts were made to develop the tensile properties of this mixture and increase the ductility ratio [7]. For example, Oh [8] and Ashour et al. [9] added steel fibers to the mixture's components. Also, Pengtao (2019) studied the performance of UHPC reinforced with steel fibers. The fibers were a straight-type with 125 aspect ratio. He found that the strength and ductility of UHPC were enhanced significantly using micro steel fibers [10].

The mechanical properties of this mixture were investigated by Wille et al. [11], who used two types of UHPC, namely, containing steel fiber (fiber reinforced) and not containing steel fiber (plain). They used glass powder in addition to the commercial components (fine sand and silica fume). After moist curing, the maximum compressive strength gained by a cube (50, 50, and 100 mm) was 201 Mpa for fiber-reinforced UHPC and 192 Mpa for plain UHPC. They also investigated the flexural strength of this type of concrete by testing 100, 100, and 400 mm prisms. The obtained flexural strength was 13.95 Mpa for fiber-reinforced UHPC and 7.5 Mpa for plain UHPC. During the test, the plain UHPC failed directly after the first crack, and this failure provides a sufficient impression of the effect of steel fibers on the ductility of this type of concrete.

Shafieifar (2017) made an experimental study on mechanical properties of (UHPC). The purpose of the study was to determine the basic behaviors of UHPC and NC. Results obtained from the experimental study showed that the compressive strength of commercial UHPC was three or four times higher than normal concrete [12].

Shamsad (2019) studied the Influence of admixing microsilica in UHPC mixtures. He used several replacement ratios for silica fume instead of cement. He concluded that the increase of silica fume ratios significantly reduced the workability of UHPC mixtures [13].

Lin (2019) studied the effect of adding silica fume on the flow of UHPC mixture; use five types of silica fume as mineral admixtures to test the fluidity. The findings of the study showed that the following factors of silica fume (high packing density, Low void ratio, wide particle size span, and low carbon content) affect the fluidity of UHPC [14].

## 2. Materials and Methods

### 2.1. Details of Test Specimens

The experimental program for studying the flexural behavior of beams consisted of 11 directly supported beams that were cast and tested to failure by being subjected to two-point loads. The studied parameters were divided into five groups. The first group included a solid beam, a hollow beam fabricated using a cork material, and a hollow composite beam fabricated using a hollow steel box. The second group included three composite beams containing a steel box with different area sections (60×60, 80×80, and 100×100 mm). The third group included three hollow composite beams containing a hollow steel box with different shapes (square, rectangular, and circular). The fourth group included six hollow composite beams for determining the best location for the steel box among all its shapes. The fifth group included three hollow composite beams containing a hollow steel box in the tensile zone of the section in four different shapes (square, vertical rectangular, horizontal rectangular, and circular). Table 1 shows a summary of the groups of specimen variables. All beams had the same cross-section with a dimension of 220×150×1500 mm and a span length of 1400 mm. The hollow steel box was connected to the concrete by welding shear studs on its four sides and 11 studs on each side along the beam (44 studs) for each steel hollow with 8m diameter. The flexural behavior of all the beams was studied. Thus, they were equipped with horizontal reinforcement ($\phi$10@60 mm) to prevent shear failure. The longitudinal reinforcement was (2$\phi$12). The stirrups were fixed using (2$\phi$6). Figures 2 and 3. Shows the geometry of the solid beam (control beam).

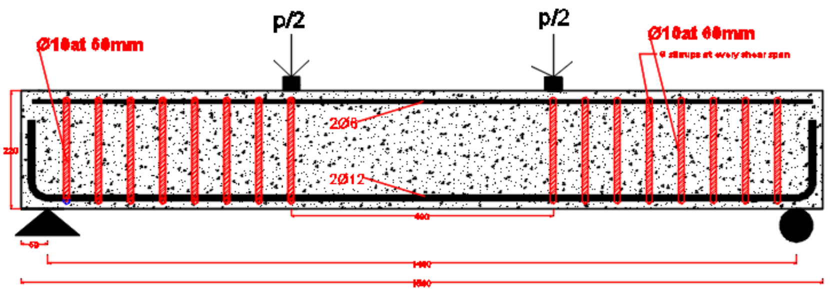



**Figure 3. The geometry of the solid beam (control beam)**

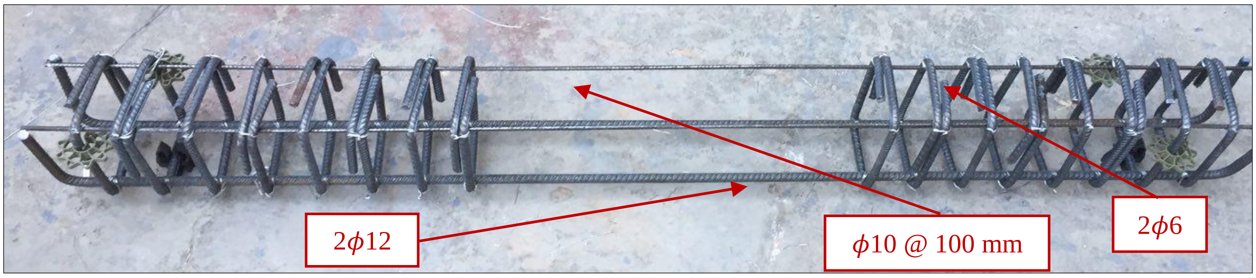
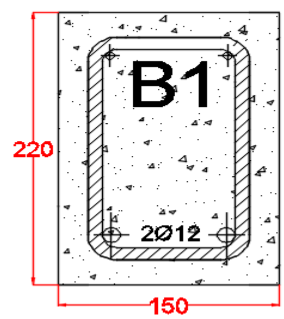
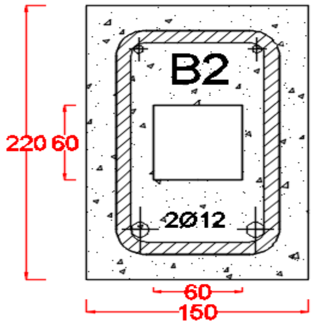
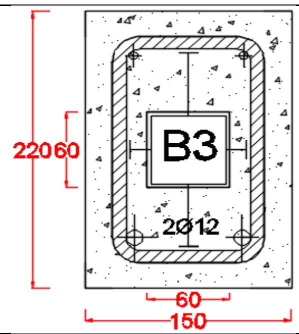
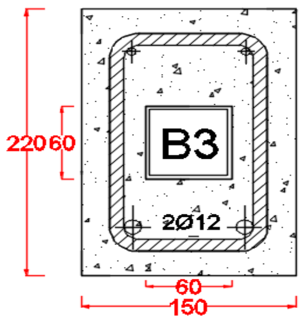
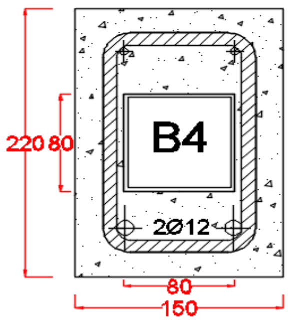
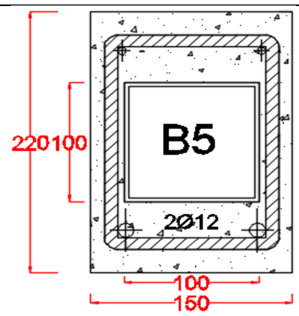
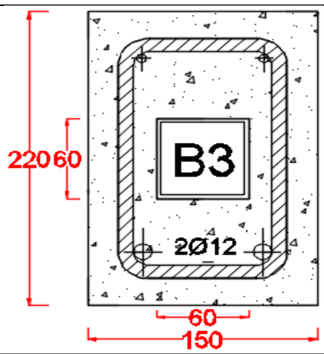
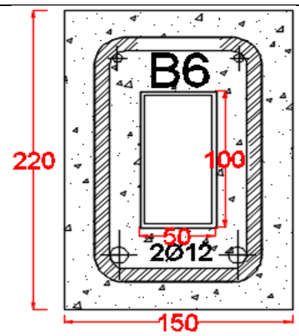
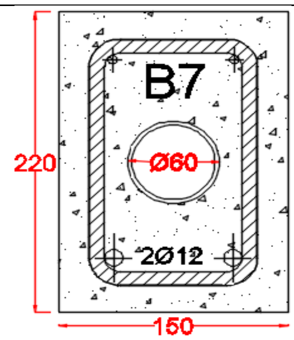


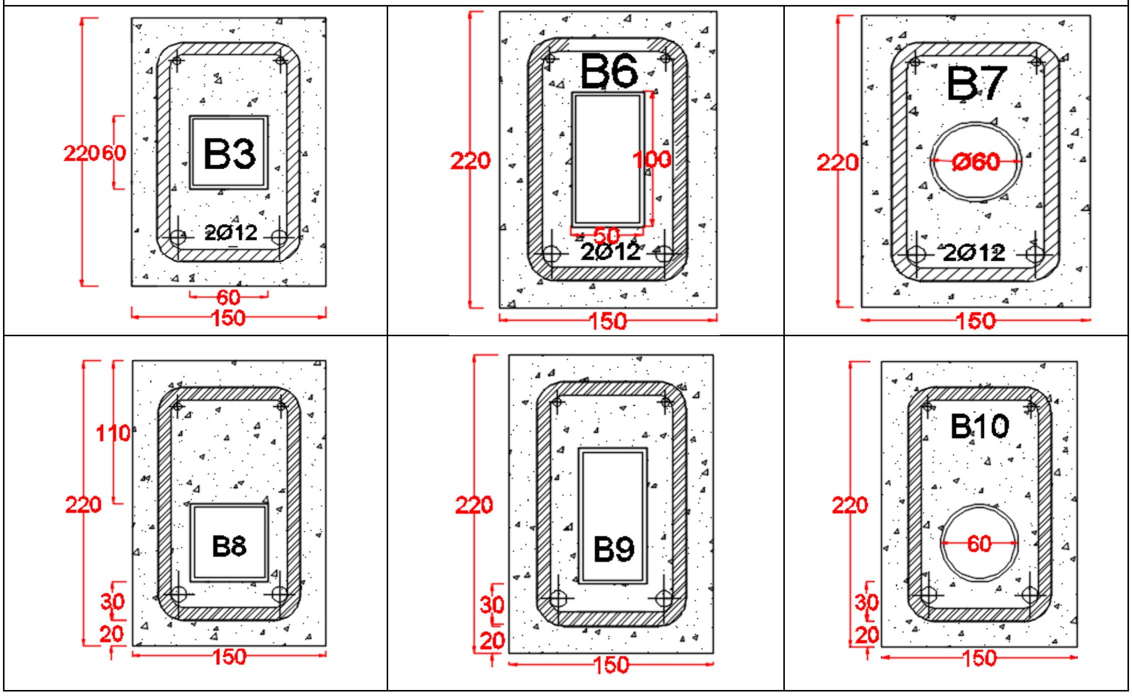

**Figure 3. Reinforcement details**

**Table 1. Groups of beam tested with details**

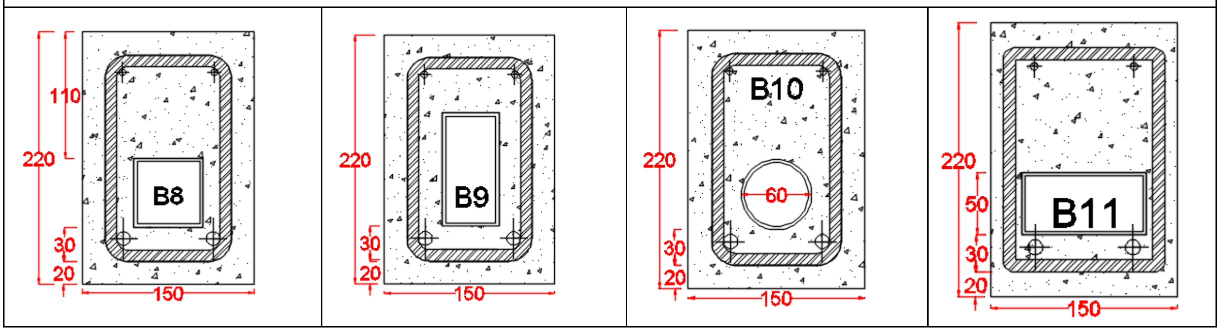
| **Group No. 1. Comparison between the solid and hollow beam and composite hollow beam** | | |
|---|---|---|
|   |   |   |
| **Group No. 2. Changing thickness of a concrete flange** | | |
|   |   |   |

| **Group No. 3. Changing the shape of the steel box** | | |
|---|---|---|
|   |   |   |

**Group No. 4. Changing the locations of steel box**




**Group No. 5. Put the steel box in the bottom part (tension zone)**




## 2.2. Materials

### 2.2.1. Steel Materials

- **Steel Hollow Sections**

Several steel sections were used in different shapes and dimensions as shown in Figure 4. square hollow box with three different dimensions 60×60, 80×80 and 100×100 mm². A steel rectangular hollow section with dimensions of 50×100 mm². Steel circular hollow section with 60 mm diameter. All sections have the same thickness 2.8 mm. All the steel sections were tested according to ASTM A370-10 [15].

- **Steel Reinforcement**

In this research, a four size of steel reinforcement was used ($\phi$ 6, $\phi$10, $\phi$12 and $\phi$16). All of the steel reinforcement tested in University of Technology using the testing machine SANS 1000 kN according to ASTM C78-02 [16].

- **Shear Connectors**

In order to obtain composite interaction between hollow steel box and the concrete surrounding it. Shear connectors (head studs) were used to a prevented separation between them by resisting the opposite shear forces between them during the loading. Figure 4 shows the welding process of the shear connectors.

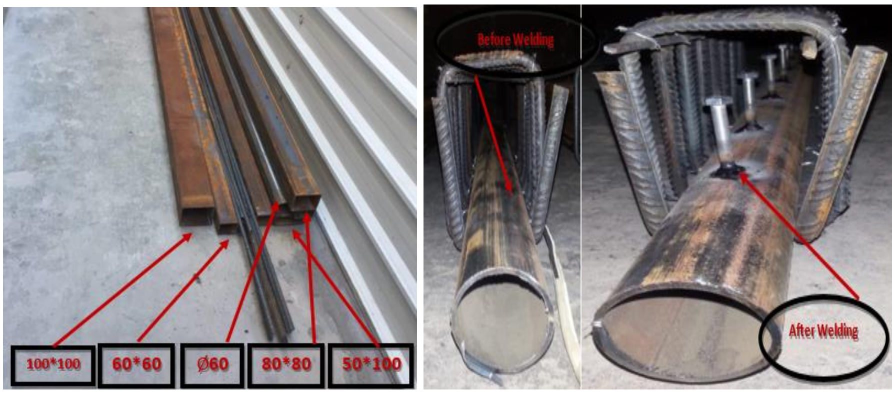



**Figure 4. The welding of the shear connectors and dimensions of hollow steel sections**

### 2.2.2. Materials Used in the UHPC

The materials used for UHPC production are relatively expensive because several of them are not readily available in local markets. The mixture in this study consisted of cement, fine sand, silica fume, steel fiber, HRWRA (High-Range Water-Reducing Admixture), and water. The cement used was Portland cement (type I), which is produced by Lafarge and conforms to the Iraqi Specification No. 5/1984 [17]. The fine sand used was imported from DCP Company; its granular gradient conforms to the B.S. specification No. 882/1992 [18], and the maximum size of its granule is 600 µm. Micro silica is one of the necessary materials used in this mixture; it is called commercial silica fume. Its granules are less than 0.1 microns, and it is chemical composition conforms to ASTM C 1240-04 [19]. Steel fibers imported from China were used in this mixture. Superplasticizer type PC 260 was also utilized in this work. It was imported from DCP Construction Chemicals Company and conformed to ASTM C494-99 [20] type A&G.

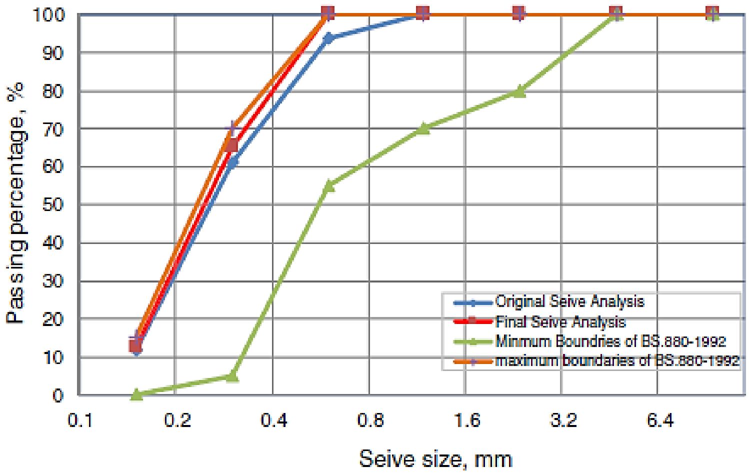



**Figure 5. Grading curve for the fine sand**

## 2.3. The Mixing Proportion of UHPC

After making several trial mixtures, we found that the trial mixture that contained the highest ratio of fine materials (cement + silica fume) and lowest w/c ratios had the highest characteristic. Thus, this trial mixture was used as the reference mixture for the structural member (beams). The proportions of this mixture are shown in Figure 5. The mechanical properties of the concrete were used to produce beam specimens. Cubes with 100 mm and three cylinders with 100×200 mm dimensions were tested for compressive strength (fcu and f'c), three cylinders were tested for splitting tensile strength (f't), and three prisms with a dimension of 100×100×500 were tested for modulus of rupture (f'r). All results are shown in Figure 6.

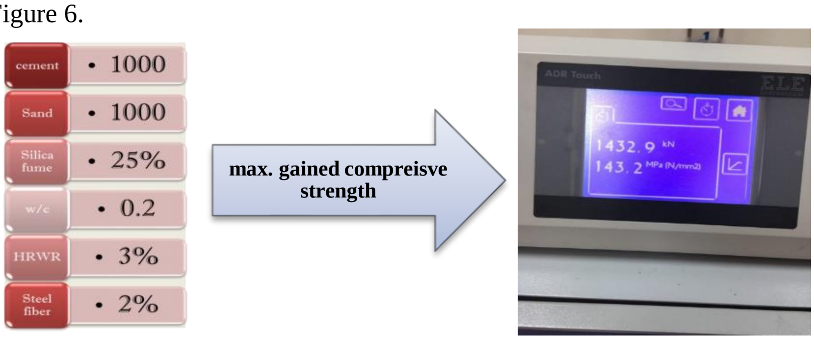



**Figure 6. Mix proportions, result of the target compressive strength (fcu)**

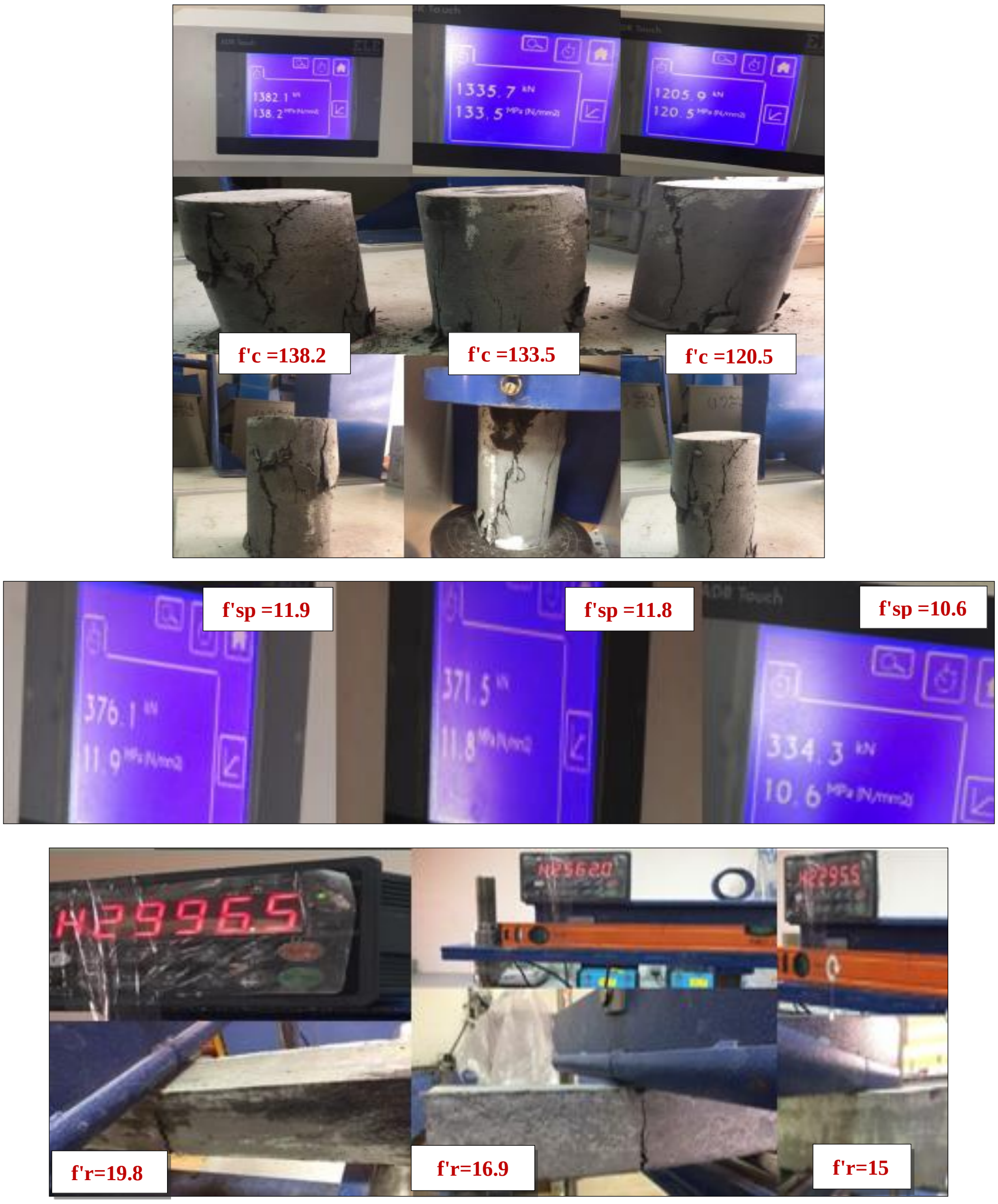
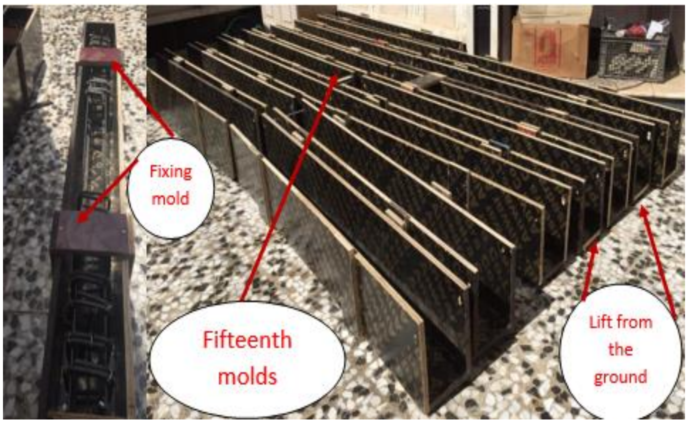



**Figure 7. Test results of mechanical properties**

## 2.4. The Longitudinal Opening Fabrication Process in the Molds

Eleven plywood molds were used to cast the solid, hollow, and composite hollow beams. Beams with a longitudinal opening (hollow core) were made for pipe services by using a hollow steel box or compressed cork, which must be operated from both sides and along the beam. Therefore, a length of 10 cm of the steel box or compressed cork was left from each side, as shown in Figure 7, to fix them and ensure that the steel box or compressed cork does not move during the casting process.



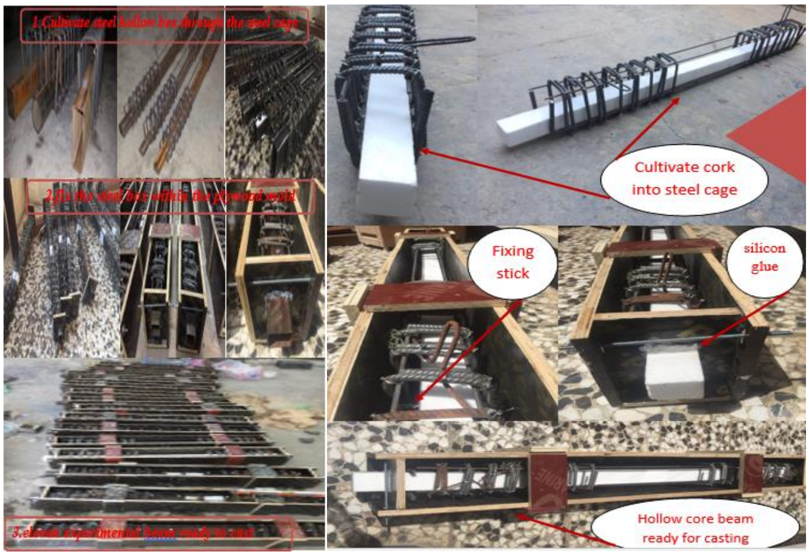



**Figure 8. Prepare molds before casting**

## 3. Experimental Results

### 3.1. Test Setup and Instrumentation

The beam specimens were tested under a two-point load to determine their flexural behavior at the pure moment zone. The loads were applied using a hydraulic jack, as shown in Figure 8, and the hydraulic jack was previously calibrated to provide the required load. The testing set up machine consists of two essential parts, two points loads and supports. The distance between the two points loads was 466 mm. The loads are applied in successive increments of (5 kN) until reaching the failure load. A dial gauge was used to measure the central deflection, and it was installed at the center of the beam specimens. The dial gauges were INSIZE type with a maximum measuring of 30 mm and precision of 0.01 mm.

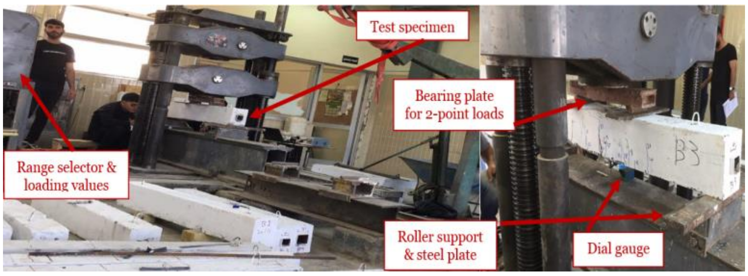


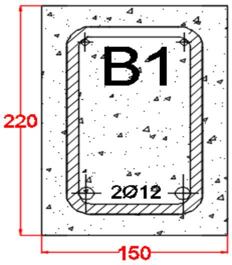
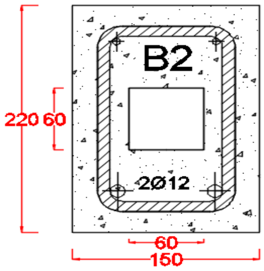
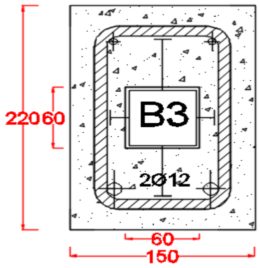
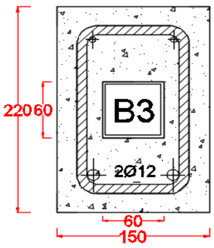
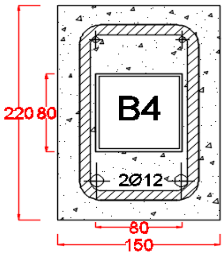
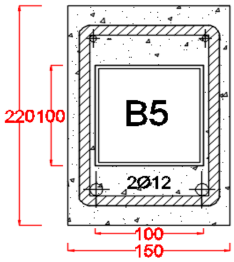
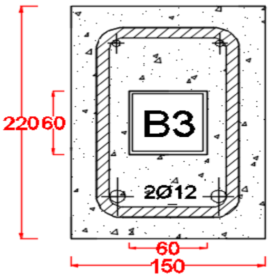
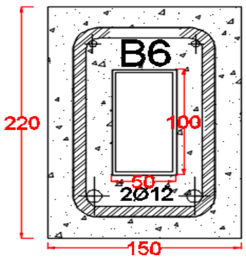
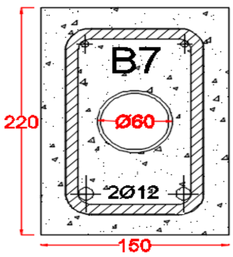

**Figure 9. Test setup of the experimental study**

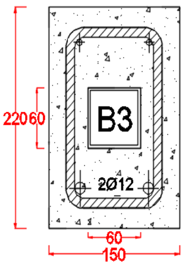
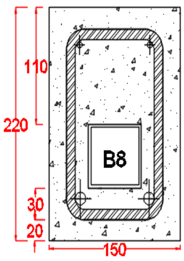
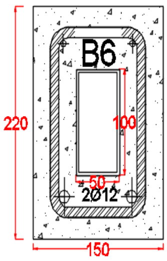
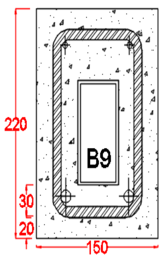
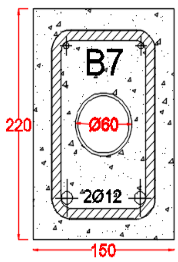
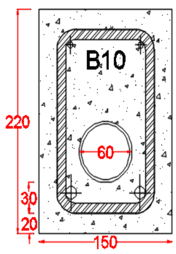
### 3.2. Ultimate Load and Moment Capacity

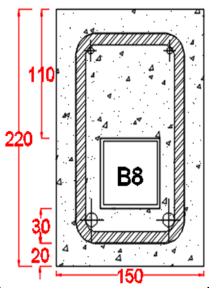
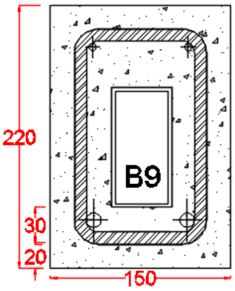
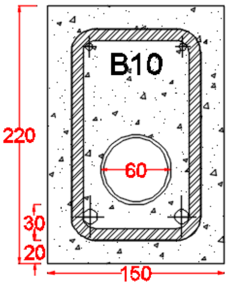
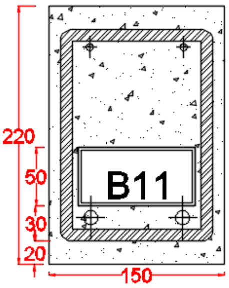
The ultimate load capacities of the tested beams are given in Table 2. The flexural capacity of the composite hollow beams was generally higher than that of the corresponding solid and non-composite beams. The increase in capacity was due to the embedded steel hollow sections in the concrete. For specimens in Group 1, compared with the solid beam (B1) as the control beam, the ultimate load and moment capacity decreased by 4.76% and 4.91%, respectively, when the hollow core was fabricated with the cork in the non-composite hollow beam (B2), the explanation for this decrease may be due to the reduction of the moment of inertia of the section when the core was performed by cork. However, the load and moment capacity increased by 109% compared with the solid beam (B1) when the hollow steel box was embedded in the composite hollow beam (B3), The explanation for this increase may be due to the increase in the strength of the tensile force or the compressive force when encasing the steel hollow box in the middle of the section. For specimens in Group 2, compared with the composite hollow beam (B3) which has a steel hollow section area of 60×60 mm², the load and moment capacity increased by 4.3% when the area of the hollow section of steel was increased from 60×60 mm² to 80×80 mm²; it increased by 26% when the area of the hollow section of steel was increased from 60×60 mm² to 100×100 mm², this indicates that the ratio between the strength of the section and the area of the embedded steel box is proportional. This may be because increasing the area of the embedded steel section leads to an increase in the moment of the inertia of the section.

For specimens in Group 3, compared with the composite hollow beam (B3) which has a square steel hollow box, the load and moment capacity increased by 3.9% when the shape of the hollow section of steel changed from square to vertical. This increase is due to the increase in the moment of inertia of the section when the shape of the hollow steel section is changed from square to rectangle. The load and moment capacities decreased by 15% when the shape of the hollow section of steel changed from square to circular. For specimens in Group 4, compared with the steel section located in the middle of the concrete section, the load and moment capacities increased by 4.3% for square, 2.5% for rectangular, and 20% for circular sections when the location of the hollow sections of steel was changed to the tensile zone of the concrete section, the increase may be explained that when the steel box is pushed down, will increase the tensile strength of the section because of the completion of the steel section in addition to reinforcing steel in increasing the bearing section. For Group 5, compared with the composite hollow beam (B8) which contains a square steel hollow box in the tension zone, the load and moment capacities increased by 2% when the shape of the hollow steel box within the tension zone was changed from square to vertical rectangular. The load and moment capacities increased by 4% when the shape of the steel box within the tension zone was changed from square to horizontal rectangular. However, no significant difference was found when the shape of the box was changed from square to circular within the tension zone of the section.

**Table 2. Ultimate load and Moment capacity of the tested beams**

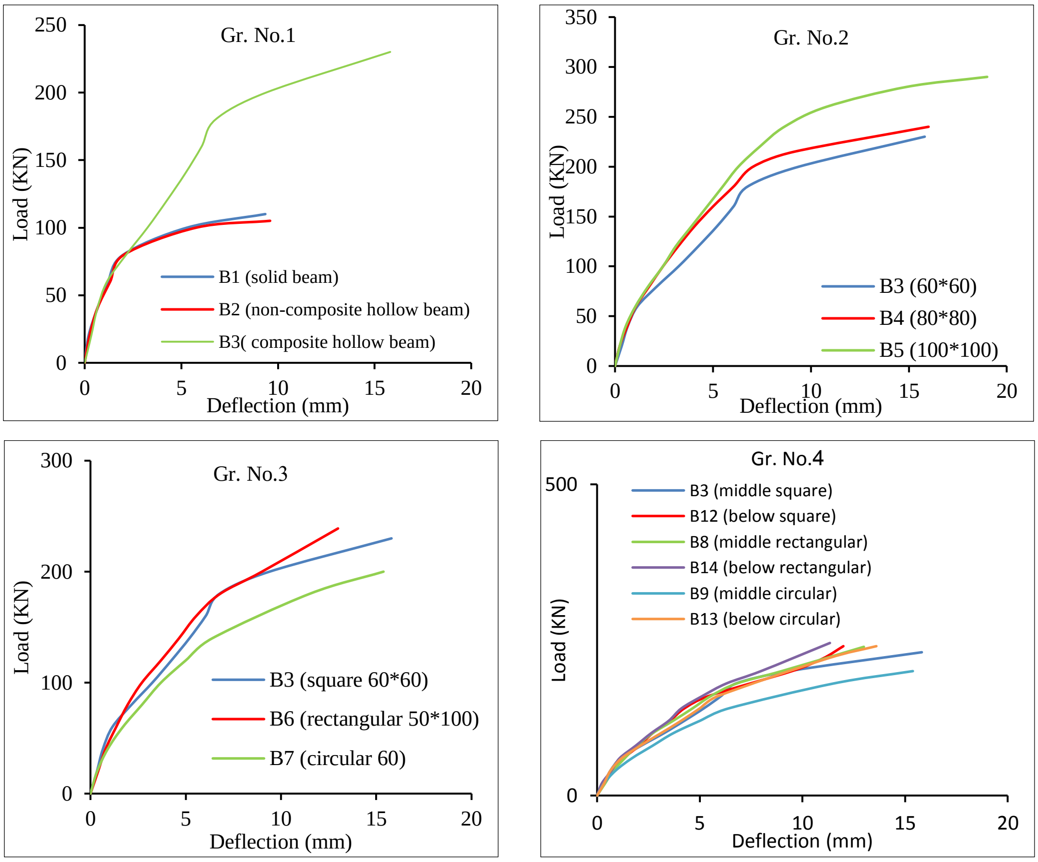
| **Name of group** | **Group No. 1. Comparison between the solid and hollow beam and composite hollow beam** | | |
|---|---|---|---|
| Cross-section |  |  |  |
| Load capacity | 110 kN | 105 kN | 230 kN |
| Moment capacity | 25.6 Kn.m | 24.4 Kn.m | 53.6 Kn.m |
| **Name of group** | **Group No. 2. Changing thickness of the concrete flange** | | |
| Cross-section |  |  |  |
| Load capacity | 230 kN | 240 kN | 290 kN |
| Moment capacity | 53.6 kN.m | 55.9 kN.m | 67.6 kN.m |
| **Name of group** | **Group No. 3. Changing the shape of the steel box** | | |
| Cross-section |  |  |  |
| Load capacity | 230 kN | 239 kN | 200 kN |
| Moment capacity | 53.6 Kn.m | 55.7 kN.m | 46.6 kN.m |

| **Name of group** | **Group No. 4. Changing the locations of steel box** | | | | | |
|---|---|---|---|---|---|---|
| Cross-section |  |  |  |  |  |  |
| Load capacity | 230 kN | 240 kN | 239 kN | 245 kN | 200 kN | 240 kN |
| Moment capacity | 53.6 Kn.m | 55.9 kN.m | 55.7 kN.m | 57.1kN.m | 46.6 kN.m | 55.9 kN.m |

| Name of group | Group No. 5. Changing the shape of the steel box in the tension zone | | | |
|---|---|---|---|---|
| Cross-section |  |  |  |  |
| Load capacity | 240 kN | 245 kN | 240 kN | 250 kN |
| Moment capacity | 55.9 kN.m | 57.1 kN.m | 55.9 kN.m | 58.3 kN.m |

## 3.3. Load – deflection Relationship

The load-deflection curves for the five parameter groups of all tested beams are shown in Figure 9. The curves show that all tested beams had similar load-deflection curve patterns in the early stages of loading. For specimens in Group 1, the non-composite hollow beam (B2) obtained higher deflection than the solid beam (B1) because of the decrease in the moment of inertia capacity of the section due to the existence of the hollow core. However, when the hollow steel box was fabricated in the composite hollow beam (B3), the deflections for specific loads decreased compared with the non-composite beams (B1) and (B2). For specimens in Group 2, the composite hollow beam (B5) with a high steel box area had higher ultimate load and higher ductility resistance than (B3) and (B4). For specimens in Group 3, the composite hollow beam (B6) with a rectangular steel box had higher ultimate load and higher ductility resistance than the composite hollow beams with square and circular steel boxes (B3) and (B7). These results indicate the apparent effect of the increasing moment of inertia of the section and its effect on bending stresses given that the rectangular section has a moment of inertia higher than the other sections and considering that all other factors are the same. For specimens in Group 4, lowering the hollow steel sections increased the ultimate loads and decreased the deflections, this means that the contribution given by the steel box is higher than the contribution that was given by the same amount of UHPC in the tensile zone. In Group 5, the horizontal rectangle section (B11) provided the highest carrying forces and least deflections compared with the remaining sections. The horizontal rectangle can explain this finding within the tensile area that provided an additional quantity of reinforced steel for longitudinal reinforcement and enabled the section to become more efficient in resisting deflections and resulting cracks.



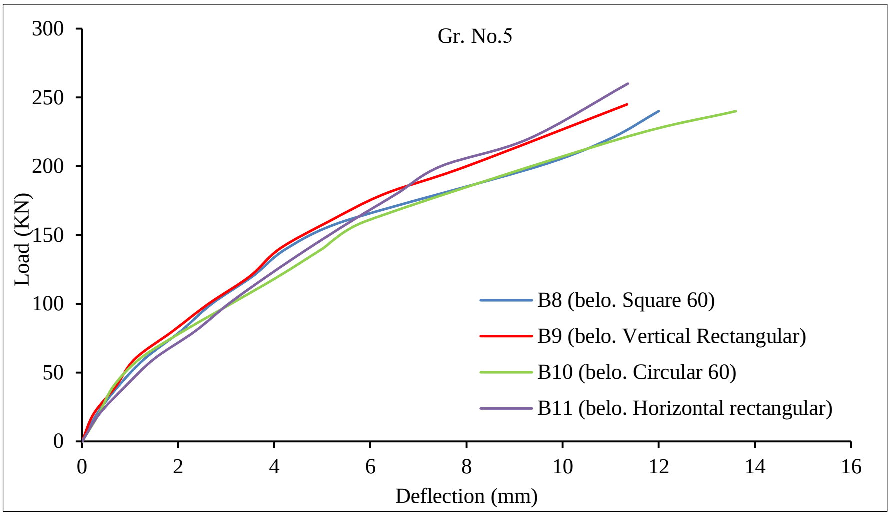
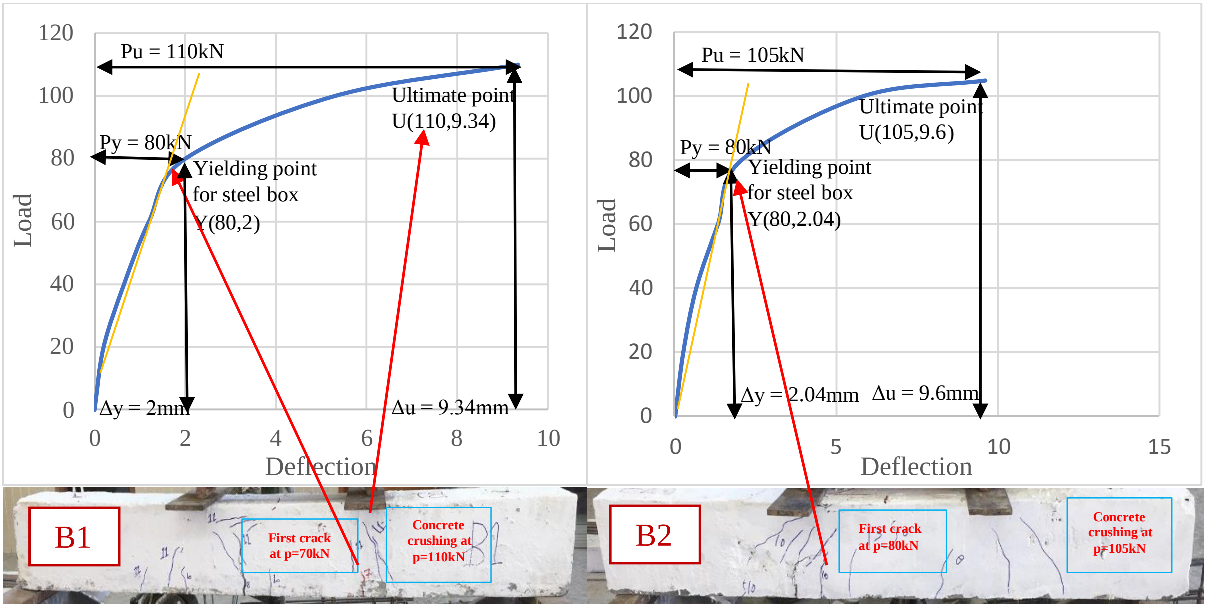


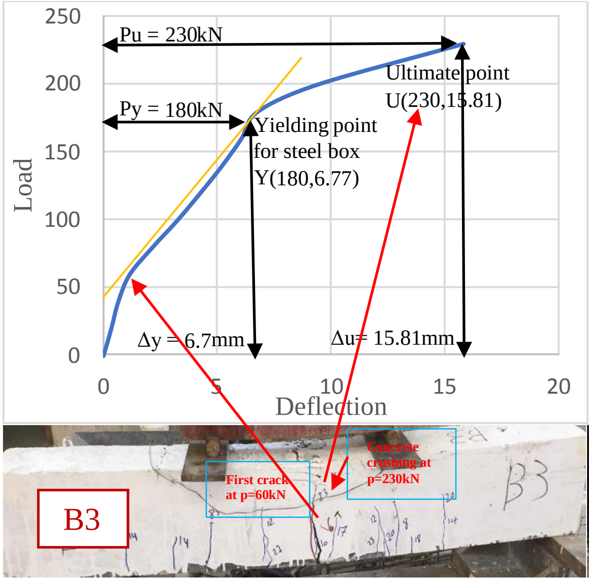

**Figure 10. Comparison of load-deflection behavior for the tested beams in five groups**

## 3.4. Failure mode and Crack Patterns Determination with Load – Deflection Curve

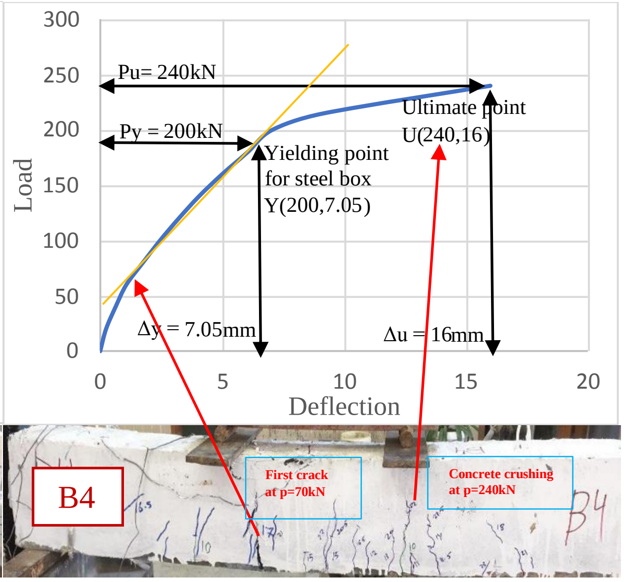
The general experimental behavior of the composite hollow beams observed during the test can be summarized as follows. When the applied load was increased, the first crack occurred in the tension zone, indicating that the concrete lost its tensile strength. The applied loads increased until a sudden non-linear increase in the dial gauge reading, indicating that the steel section had yielded. The applied loads increased further until the concrete was crushed at the compression fiber. When the loads further increased, the upper flange of the hollow section of steel buckled. At the end of the curing period, the beams were painted in white to facilitate the resulting cracks. During the testing of each beam, each crack was marked with its load to determine at which load the beam reached its yield or failure stage. Then, the results were compared with the load-deflection curve, as shown in Figure 10.



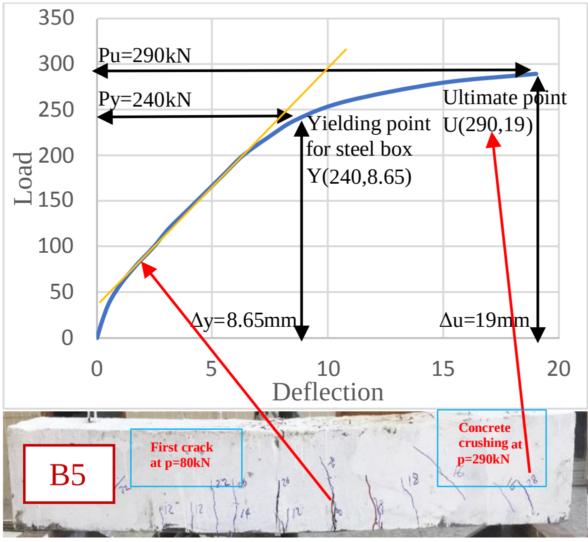

**"a" load-deflection & failure mode for B1** **"b" load-deflection & failure mode for B2**



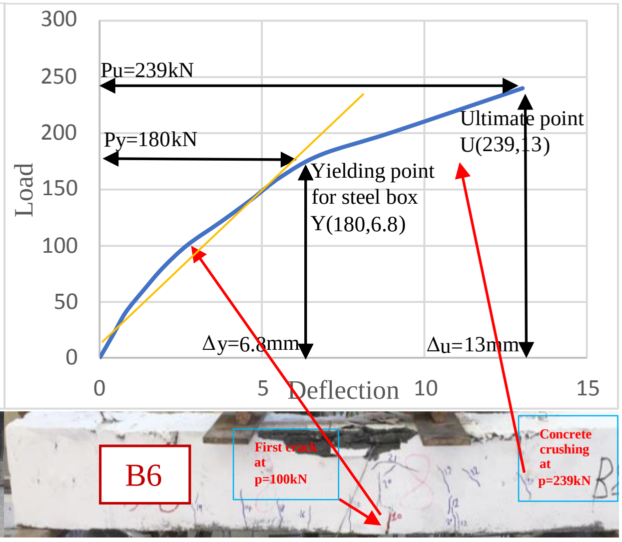

**"c" load-deflection & failure mode for B3**



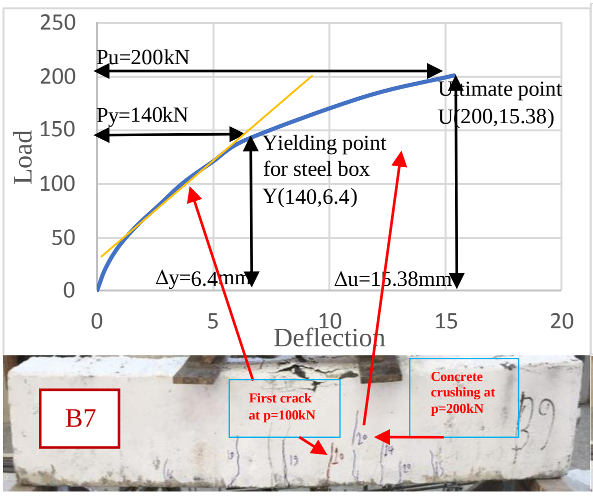

**"d" load-deflection & failure mode for B4**



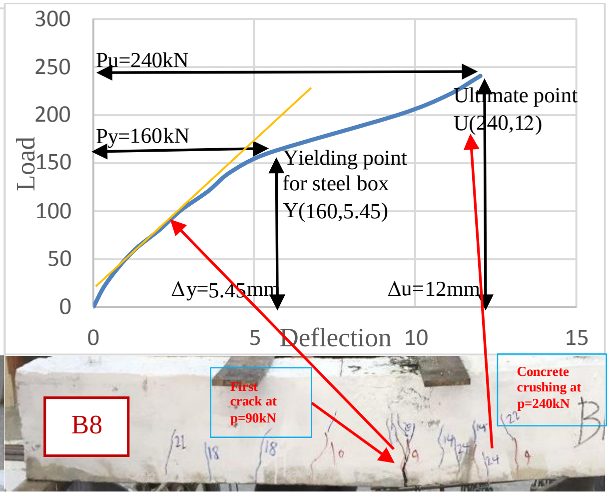

**"e" load-deflection & failure mode for B5**



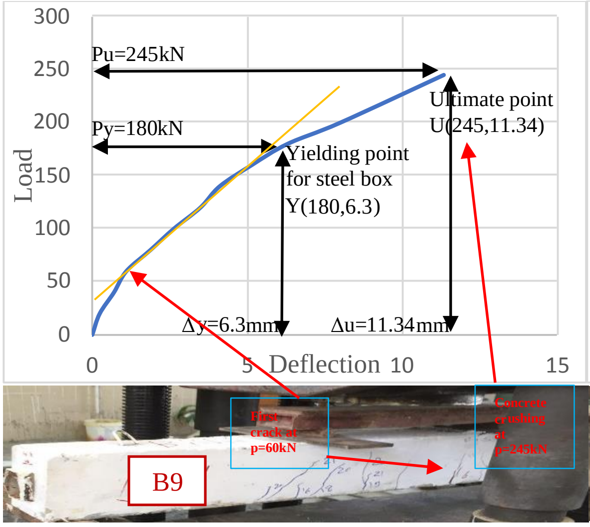

**"f" load-deflection & failure mode for B6**



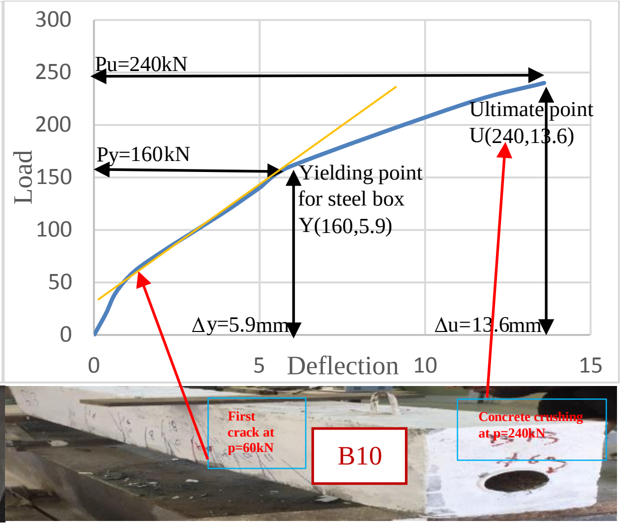

**"g" load-deflection & failure mode for B7**



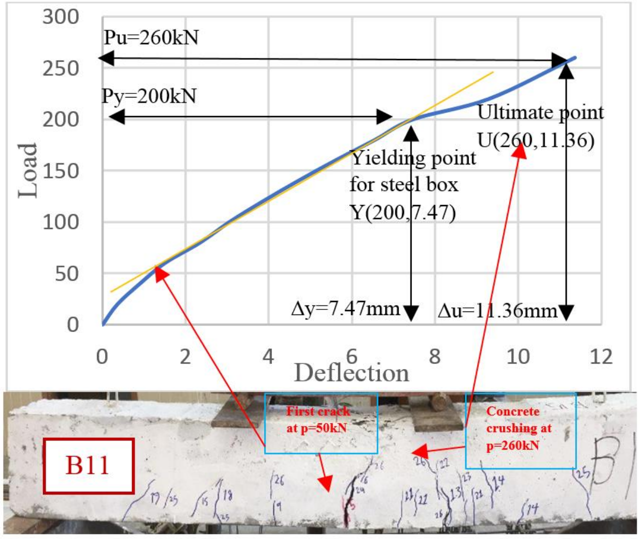

**"h" load-deflection & failure mode for B8**




**"i" load-deflection & failure mode for B9**




**"j" load-deflection & failure mode for B10**




**"k" load-deflection & failure mode for B11**

**Figure 11. Load-deflection & failure modes of all tested beams**

## 3.5. Stiffness Comparisons of the Tested Beams

Efficient structures have large stiffness-to-weight ratios, which can be achieved by using high strength materials or rearranging a section with a certain geometry. Stiffness is the required load for causing one unit of deflection. The value of stiffness can be calculated by dividing the ultimate load by the maximum deflection in the tested beam. Thus, a beam with a higher ultimate load and less deflection has a higher stiffness value. The stiffness values of the tested beams at ultimate loads are presented in Figure 11. Figure 11. shows that in the first group, the stiffness of the composite hollow beam (B3) was higher than that of the non-composite hollow beam (B2) by 33% and higher than that of the solid beam (B1) by 23.5%, thereby indicating that when the hollow section of steel is encased in concrete, the stiffness of the section can be increased by increasing the ultimate load of the beam. In the second group shown in Figure 13, the composite hollow beam (B5) with an encased steel box section with geometric properties of {[A=(100×100) mm²] and steel section ratio of [A box=4.73%×Ac]} had higher stiffness than the composite hollow beam (B4), which has geometric properties of {[A=(80×80) mm²] and steel section ratio of [A box=3.25%×Ac]}. The stiffness value is also higher than that of (B3), which has geometric properties of {[A=(60×60) mm²] and steel section ratio of [A box=2.17% ×Ac]}. Consequently, the composite hollow beams with a steel section ratio of 4.73% had a stiffness value higher than those with a steel section ratio of 3.27% and 2.17%. Therefore, the stiffness of the composite hollow beams increased as the steel section ratio of the encased steel section increased. In the third group shown in Figure 13, the composite hollow beam (B6) with an encased steel section with geometric properties of [A=(50×100) mm², A box=2.88%×Ac, box shape=rectangular, I box=416.6 $cm^4$, I box=3.23%×Ic] had stiffness (26.3%) higher than that of (B3), which has geometric properties of [A=(60×60) mm², A box=2.17%×Ac, box shape=square, I box=108 $cm^4$, I box=0.81%*Ic]. Moreover, it is 41.38% higher than that of B7, which has geometric properties of [A=($\pi \times 6024$) mm², A box=1.66%×Ac, box shape=circular, I box=63.61 $cm^4$, I box=0.48%×Ic]. Consequently, the composite hollow beams with encased steel section moment of inertia ratio of 3.23% have stiffness higher than those having encased steel section ratios of 0.81% and 0.48%. This finding indicates that the stiffness of the composite hollow beams increased as the steel ratio of the encased steel section increased. In the fourth group shown in Figure 13, when the square steel box was lowered toward the tension zone in the composite hollow beam (B8), its stiffness increased by 37.4% higher than that of the composite hollow beam (B3). Also, when the rectangular steel box in (B9) was lowered, the stiffness increased by 18% greater than that of (B6). Furthermore, lowering the circular steel box in (B10) increased stiffness by 35% compared with that of (B9). This result indicates that the stiffness of the hollow composite beams increased as the location of the hollow section of steel lowered toward the tensile zone of the section. In the fifth group shown in Figure 13), the composite hollow beams (B11) with a horizontal rectangular steel box within the tensile zone had a greater stiffness than (B10), which had a vertical steel box. This increase is due to the increase in the ultimate load and the decrease in the maximum deflection of (B11) and because the presence of the horizontal rectangle within the tensile area provided an additional quantity of reinforced steel to the longitudinal reinforcement, thereby making the section more efficient in resisting the deflections and resulting cracks. The figure also shows that a composite hollow beam (B10) with a rectangular steel box has higher stiffness by 22.3% than (B9), which has a circular steel box. It is also higher by 8% than (B8), which has a square steel box.

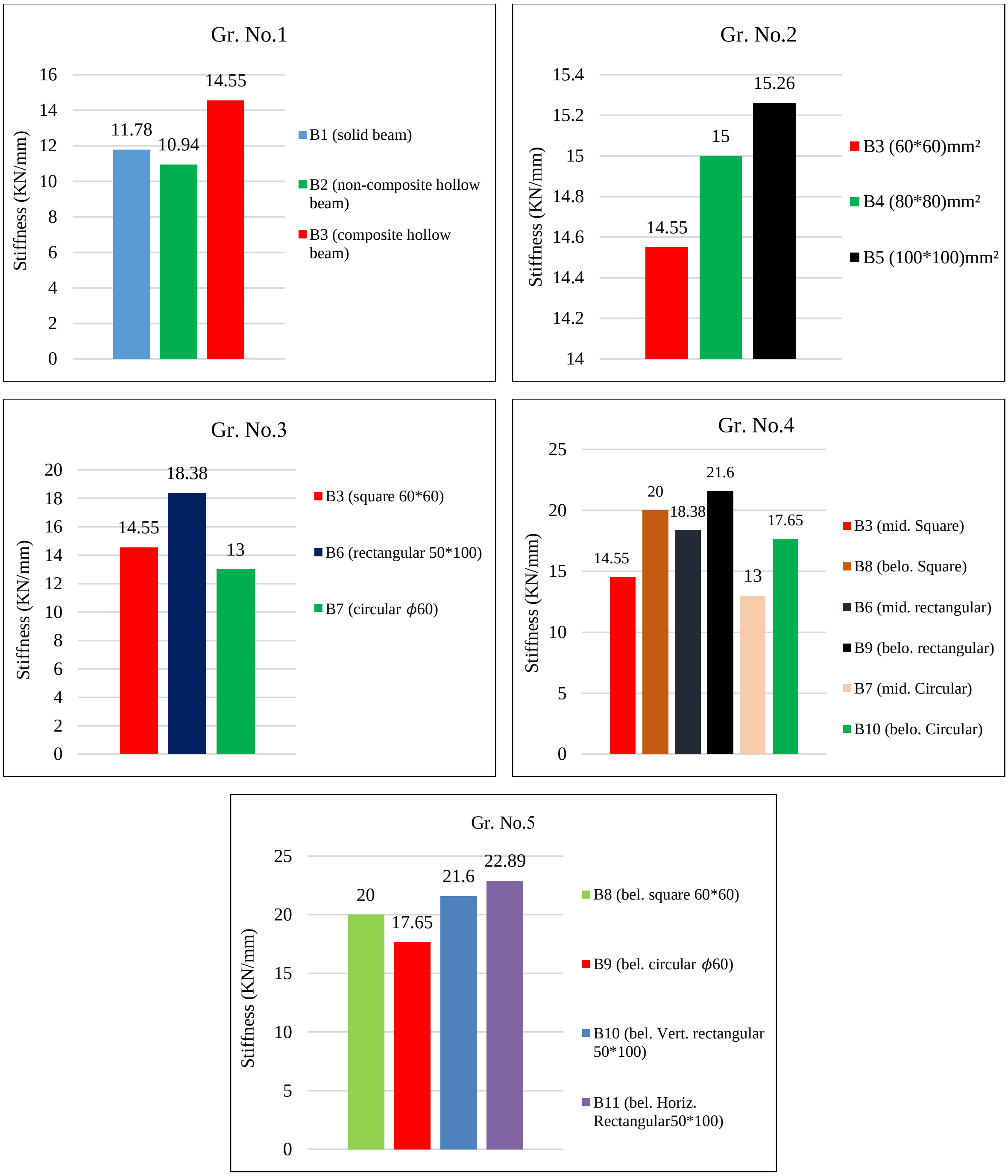



**Figure 12. Stiffness values of the tested composite beams**

## 4. Conclusions

The following can be concluded from the results obtained during this study.

- The ultimate load capacity decreased by 4.76% when a hollow core was made in the concrete section using a cork material. However, the ultimate load capacity increased significantly by 109% when the hollow core was fabricated using a hollow steel section material. These results show that the composite hollow beams had greater load and moment capacity than the non-composite beams. The presence of a hollow core in the concrete section decreased the section's capacity to resist deflections because it reduced its moment of inertia. However, using the hollow steel box increased the capacity of the section to resist deflections.
- The ultimate load capacity and stiffness of the hollow composite beam increased when the cross-section area of steel hollow section increased.
- In this new type of structural elements, the moment of inertia of the hollow section of steel plays an essential role as a direct indicator of the moment capacity of the section. When a rectangular steel hollow section of 50×100 $mm^2$ with I=416,6666 mm4 was used, the resulting load capacity was higher than when a square hollow section of 60×60 $mm^2$ with I=108,0000 $mm^4$ was used. It is also higher than the circular steel hollow sections with a diameter of Ø60 mm and I=63,6172 $mm^4$.
- The ultimate load and moment capacity of the composite hollow sections increased when the location of the hollow section of steel was lowered to the tension zone of the beam cross-section. However, the rapid emergence of initial cracks in the tension zone may occur as a result of the weakness of the tensile capacity of concrete below the section due to the presence of the hollow core. This research confirms that the hollow core or longitudinal openings should be located within the middle zone of the concrete section.
- The stiffness values of the composite hollow beam containing a steel box of 60×60 $mm^2$ were higher than those of the solid beam and non-composite hollow beam by 23.5% and 32.9%, respectively. The stiffness of the composite hollow beam increased when the area of the encased steel hollow sections increased. It also increased when the encased steel hollow section had a high moment of inertia. Moreover, encasing the steel box at the bottom of the concrete section provided higher efficiency in terms of final stiffness but accelerated the emergence of initial cracks because the hollow core weakened the concrete in the tension zone.

## 5. Conflicts of Interest

The authors declare no conflict of interest.

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