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Tests of Composite Beams with Web Openings

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Abstract

The aim of this study is to investigate experimentally the structural behavior of simply supported composite beams, in which a concrete slab is connected together with a steel I-beam by means of headed stud shear connectors under the presence of web openings. Six composite beams with constant degree of interaction were tested under central concentrated static load. One of the beams is constructed without web opening while the others contain various number, location and shape of openings. Deflection at midspan and at the ends of each opening were observed versus load. The experimental results show that the web openings decrease the strength of composite beams in the range of 19% to 24% for the tested specimens. Distinctive effects for the location, number and shape of openings took place after initiation of section yielding. Different patterns of cracks at concrete slab were observed.

Keywords: Composite beam, web opening, moment to shear ratio.

فحوصات عتبات مركبه حاويه على فتحات في ساق العتب

الخلاصه

تهدف الدراسة الحالية إلى التحري المختبري للتصرف الإنشائي للعتبات المركبة بسيطة الإسناد والتي ترتبط فيها البلاطة الخرسانية مع العتب الفولاذي ذو مقطع (I) بواسطة روابط قصيه ذات رؤوس بوجود فتحات في ساق العتب .تم فحص ستة عتبات مركبة ذات درجة تداخل ثابتة بواسطة حمل مركز نقطي ساكن. تم إنشاء عتبة واحدة خالية من الفتحات بينما احتوت باقي العتبات على أعداد مختلفه من الفتحات ذوات مواقع وأشكال مختلفة. تم رصد الانحراف مقابل الحمل عند منتصف الفضاء للعتبه و عند نهايتي كل فتحة.أظهرت نتائج الفحص أن الفتحات في الساق تقلل من مقاومة العتبات المركبة بحدود 19% إلى 24%. ظهر تأثير واضح لموقع وعدد و شكل الفتحات بعد حصول خضوع المقطع. لوحظت أشكال مختلفة من التشققات في البلاطه الخرسانة.

1. Introduction

Height limitations are often imposed on multistory buildings based on zoning regulations, economic requirement, and aesthetic considerations, including the need to match the floor heights of existing buildings. Web openings can be used to pass utilities through beams and thus, help to minimize story height. A decrease in building height reduces both the exterior surface and the interior volume of a building, which lowers the operational and

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maintenance cost. On the negative side, web openings can significantly reduce the shear and bending capacity of steel or composite beams.

Clawson and Darwin [1] presented an experimental investigation to study composite beams with concentric rectangular web openings. Redwood and Wong [2] described the effects of large web openings on the behavior of composite steel – concrete beams. Redwood and Poumbouras [3] described tests of two composite beams comprising a concrete slab supported on a steel deck and a steel wide flange shape containing large rectangular web openings. Donahey and Darwin [4] performed fifteen tests to failure on full scale composite beams with concentric web openings. The beams had ribbed slab with formed steel deck. The effects of moment shear ratio, quantity and placement of shear connectors, deck orientation and deck thickness were studied. Lawson et al [5] summarized the results of three load tests on composite beams of 10m span. Cho and Redwood [6] described nine full scale tests in which composite beams containing web holes are studied in an attempt to understand the mechanisms by means of which the slab participates in carrying vertical shearing forces.

In order to have more understanding for the behavior of composite beams with web openings, six composite beams with different number, location and shape of web openings were tested in the present work. Based on the experimental work the load-deflection curves, the failure loads and failure behavior were investigated and discussed.

2. Experimental Study

Six composite beams of steel I–section and concrete slab connected together by headed shear studs welded to the top flange of steel section, were tested. Each one had an overall length of 2.1 m and a clear span of 2.0 m . The steel section was IPEAA-160 and the concrete slab had 0.06 m depth and 0.5 m width. The effective width was specified according to the AISC Load and Resistance Factor Design Specifications (LRFD) [7]. The slab reinforcement was following the ACI Building Code requirements [8].The steel ratio was greater than that required for temperature and shrinkage for both longitudinal and transverse directions. In each direction, one layer of 5 mm diameter deformed bars was located at center of slab cross section with 100 mm center to center spacing. The provided concrete cover was not less than 25 mm.

The total depth of IPEAA-160 steel I-section was 160 mm. The flanges had 82 mm width and 5 mm thickness, while the web had 150 mm depth and 4 mm thickness. The shear connectors were distributed in two rows at 150 mm center to center distance in the longitudinal direction. The degree of composite action of 82% was constant for all beams . Figure (1) shows the typical cross section of the composite beams.

The openings in the composite beams had different numbers and locations in order to have a clear picture on the effect of multiple web openings and the effect of moment to shear ratio. The web openings are located as shown in Figure (2). The rectangular openings had a fixed size of 0.1 m depth and length twice the opening depth, 0.2 m.

This means that the opening depth equals to 62.5% of the steel beam depth and its length is 10% of the beam clear span. The square opening has the same depth of the rectangular opening, 0.1 m, then its length will equal to 5% of the beam clear span.

3. Steel Section Fabrication

Firstly, the locations of openings in the web of steel section were determined for all beams. A hole of 12 mm diameter was drilled at each corner of the openings to reduce the stress concentration. Then, the openings were cutout using an oxy-acetylene torch. Little cosmetic work was done and grinding of the flame cut surfaces was made for the opening sides. The shear connector studs with 45 mm length were well hand welded in two rows at top flange with uniform spacing.

4. Concrete Mix, Casting and Curing

Concrete mix used through the whole investigation was the same. It was designed to have an average cylinder compressive strength of 21 N/mm^2 at 28 days and to simulate the properties of normal strength structural concrete. The mix proportions by weight were one part of Portland cement, one and half parts of sand with maximum particle size 5 mm, and three parts of crushed coarse aggregate. The water to cement ratio was 0.5.

After lubricating of the inside faces of the framework, concrete mix was placed and well compacted using Poker vibrator for 2 minutes. The top surface of the concrete slab was finished level and smooth. During casting of each beam, three 300x150 mm diameter cylinders were made. The specimens were compacted by means of Poker vibrator also. Beam and cylinders were cured for 14 days by keeping them continuously moist by spraying water several times a day and covering them by damp canvas.

5. Instrumentation and Loading

Prior to testing, the beams were painted with white color in order to provide a better surface for crack marking. Each tested beam was placed on simple supports at 5 cm from each end and loaded with a single concentrated load at midspan. Dial gauges of sensitivity 0.01 mm, were used to measure vertical deflection at midspan of the tested beam, and at the centerline and the two ends of each opening, Figure (3).

The beams were loaded with a single concentrated load at the center of the beam midspan, using hydraulic loading system with maximum capacity of 2000 kN. The load was distributed across the entire width of the concrete slab by a steel rod with a cross section of (25 x 25) mm which was placed on the top of the concrete slab at the load point.

6. Behavior and Failure of Composite Beams

The behavior of the tested six composite beams is explained and shown in the following. For each test the transverse and longitudinal cracking in the concrete slab was observed, as well as the relative deflection between the opening ends and the mode of failure of the composite beam. The load-deflection curves for all tested specimens are shown in figure (12). The ultimate loads and other details are given in Table (1).

Beam CB0

Beam CB0 was fabricated without web opening. The point load (P) (line load across the slab width) was applied in increments. As the load increased, to (105) kN, transverse cracks occurred at the center of the bottom face of the slab. The crack continued to widen as the load increased. A longitudinal crack at the center of the upper surface of the slab began to develop as the applied load had reached (120) kN (96 % of the ultimate load of the beam). The crack propagated towards the ends of the slab up to failure.

The test indicated linear load – deflection relation up to (64 %) of the ultimate load followed by ductile failure. At failure, excessive deflection occurred due to yielding of the steel beam at midspan which was followed, as a result, by crushing of concrete slab at center, Figure(4).The ultimate load was 124.6 kN.

Beam CB1

Beam CB1 is constructed with one central rectangular opening RH1, 0.1 m depth and 0.2 m length. The cracking in the slab of this beam occurred when the applied load was (80) kN (83 % of the ultimate load). The initial crack of the concrete was transverse to the beam and at the center, where the M/V ratio is the highest. When the applied load was (90) kN, a longitudinal crack near the central section of the beam appeared and propagated longitudinally until failure. Initiation of longitudinal crack occurred at (93 %) of the ultimate load.

The load – deflection curve indicates linear relation up to first yielding of steel section, which took place after applying (80) kN (83 % of the failure load). However, yielding may have occurred firstly at the bottom tee of the web opening due to tensile stresses. The top tee yielding occurred due to compressive stresses after crushing of concrete slab at midspan which indicated the failure of the specimen. A close view for the opening RH1 at failure is shown in Figure (5).

Beam CB2

Beam CB2 has the opening RH2 which was centered at 0.6 m from nearest support, which means that the moment to shear (M/V) ratio is (0.6).

During loading, first cracking in the slab occurred at load level (65) kN (66 % of the ultimate load). The initial cracks of concrete slab were transverse to the beam near the low moment end of the hole. When the load was (80) kN (81 % of the failure load), a longitudinal crack at the top of slab and on the beam centerline, started from the high moment end of the opening and subsequently propagated towards the beam midspan. Transverse and longitudinal cracks are shown in Figure(6).

The most significant cracking began at about (95 %) of the ultimate load, near the center of the openings RH2 on the bottom face of the slab. The slab separated slightly from the steel flange, and cracks propagated at about 45 degrees across the bottom surface of the slab, moving toward the high moment end of the opening. At failure, these cracks extended to the edge and propagated diagonally to the top of the slab, Figure (7). This shear type failure appeared to be due to the prying action caused by the large relative displacement between the two ends of the opening at this stage of loading.

The relations of load-midspan deflection, load-high moment end (HME) deflection and load-low moment end (LME) deflection of opening RH2 are shown in Figure (8). In this figure, the first yielding occurred at about (66 %) of the ultimate load. Near failure, both midspan and HME of the opening showed excessive deflections, when LME of the opening had much lower deflection. The ultimate load for the composite beam CB2 was 98.4 kN.

Beam CB3

Beam CB3 contained two web openings, RH3 and RH4. Each one was located approximately at the third point. Cracking first occurred at the top face of the concrete slab over the hole RH4 when the load was (55) kN (about 54 % of the ultimate load carrying capacity). These cracks initiated near the low moment end of the opening and propagated transversely toward the edges. The same cracks appeared and propagated at hole RH3 approximately at load of (60) kN. At slightly higher load, longitudinal cracking began to develop along the center of the slab which initiated at midspan and propagated toward the two holes then, crossed the transverse cracks that had occurred at the openings.

Due to the increase in the relative displacement between the two ends of the opening RH4 with increasing applied load, inclined cracks occurred at the slab near the high moment end of the opening. These cracks began from the bottom face of the slab and propagated toward the upper face. Loading was stopped when the relative deflection of the hole RH4 increased significantly which caused a clear widening in the inclined crack and separation of concrete slab from steel beam had begun. Variation of deflection at the high moment ends of openings RH3 and RH4 during the test are plotted in Figure (9).

Beam CB4

The first crack occurred at the upper face of the slab near the low moment end of the opening RH7. At this stage, the load was (55) kN (56 % of the ultimate strength). This crack propagated transversely toward the slab edges. At the next load increment, the same thing occurred at opening RH5.

After a few load increments, longitudinal cracks appeared at the center of the slab and propagated toward the slab ends but it stopped at the transverse cracks that occurred at the openings.

With increasing load, a crack in the steel bottom tee near the low moment end of opening RH7 appeared at (85) kN. This was attributed to the concentration of tensile shear stresses at the opening corner. The crack softened the steel in the region and propagated excessively, that caused a rapid increase in the relative deflection between the hole ends. Due to this state of deformations, an inclined crack appeared at the bottom face of the slab over the low moment end of the hole. The crack propagated upward over the opening and appeared at the top face of the slab near the high moment end of the opening. Separation of concrete slab from steel beam began when the beam reached the ultimate load, 95.2 kN. Failure of opening RH7 is shown in Figure (10).

The opening RH7 exhibited more deflection than RH5 at early levels of loading. The difference in deflection increased as the load increased and finally led to the failure of the beam. Figure (11) shows the variation of relative deflection of the two ends of openings RH5 and RH7.

Beam CB5

Beam CB5 was modeled to have three square openings, 0.1 m length and width, RH8, RH9 and RH10 located at the quarter points of the beam span. This beam indicated behavior similar to that of beam CB0. Only one transverse crack and one longitudinal crack occurred. The transverse one took place at bottom face of slab midspan after applying a load of(60) kN (63 % of the beam failure load). The longitudinal crack started at midspan when the applied load was (75) kN and propagated toward the slab ends.

Loading was stopped at (98.3) kN when the beam exhibited no resistance to load increasing, at which crushing of concrete slab at midspan and yielding of top and bottom tees of hole RH9 occurred.

The load – deflection curves of all beams are shown in Figure (12). Also test results are summarized in Table (1).

7.Conclusions

1. Investigations demonstrate the significant effect of the web openings on the behavior of composite steel I-section-concrete beams. Generally, openings decrease the strength of composite beams. According to the position of the opening, its size and number, the reduction in the composite beam strength ranges between 19 % to 24 %.
2. The behavior of composite beams is highly effected by the location of opening within the beam span. Location of the opening may be represented by moment to shear ratio (M/V).Thus, a composite beam with opening having a high moment to shear ratios fails by general yielding in the steel below the neutral axis and crushing in the concrete above the neutral axis. A beam with opening having a medium to low moment to shear ratio fails by the formation of plastic hinges at corners in the bottom tee, accompanied by a diagonal tension failure in the concrete slab within the opening location.
3. Generally, deflections increased due to the presence of web opening. Yielding of steel at opening section, with low M/V ratio, significantly increases the relative deflections between the two ends of the opening. Slab separation may then occur.
4. Increasing the number of web openings with the same size decreases the load capacity. Also, more opening length means more relative deflection and then less beam strength.
5. The initial yielding of composite beam with central web opening is 83 % of the ultimate load of the beam. The initial yielding of composite beam containing web opening with low M/V ratio, varies between 64 % to 68 % of the ultimate load of the beam.
6. The transverse and longitudinal cracks in the slab of composite beams take place. Additional cracks appear at the location of opening , with low M/V ratio, and move diagonally towards the top face of the slab and the center of the beam.

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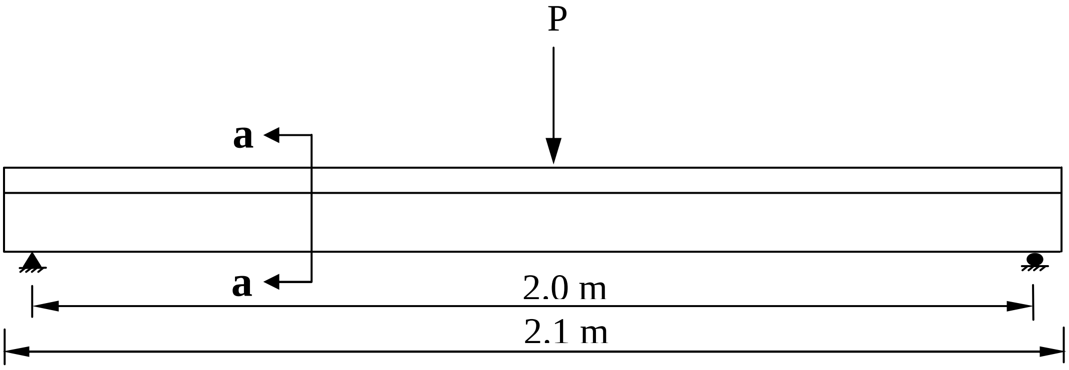
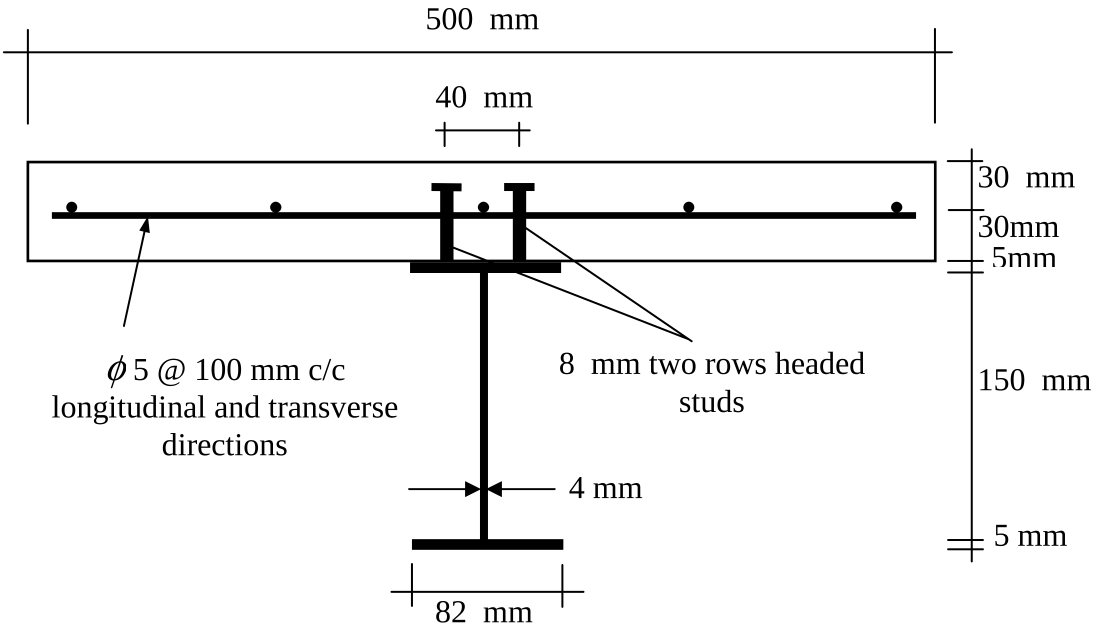
Table (1): Test Results

Beam	Ultimate load (kN)	Decrease in ultimate load (% of CB0)	Initial cracking load (% of ultimate load)		Initial yielding of composite beam (% of ultimate)
			Transverse	Longitudinal	
CB0	124.6	0	84	96	64
CB1	96.7	22	83	93	83
CB2	98.4	21	66	81	66
CB3	101.0	19	56	64	64
CB4	95.2	24	56	71	66
CB5	98.3	21	63	79	68



a) Typical dimensions of the composite beams



b) Section a-a

Figure (1): Typical Dimensions and Cross Section of the Composite Beams

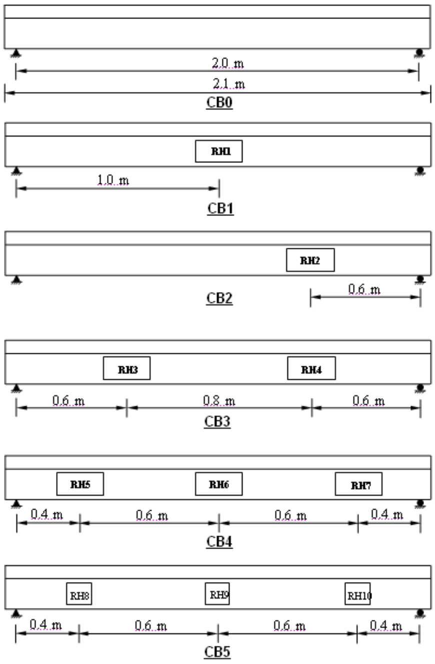


Figure (2): Configurations and Locations of the Web Openings

Figure (3): Typical Setting for Composite Beams before Testing

Figure (4): Beam CB0 at Failure

Figure (5): Opening RH1 of Beam CB1 at Failure

Figure (6): Cracking of concrete at Beam CB2

Figure (7): Diagonal Cracking at Hole RH2 of Beam CB2

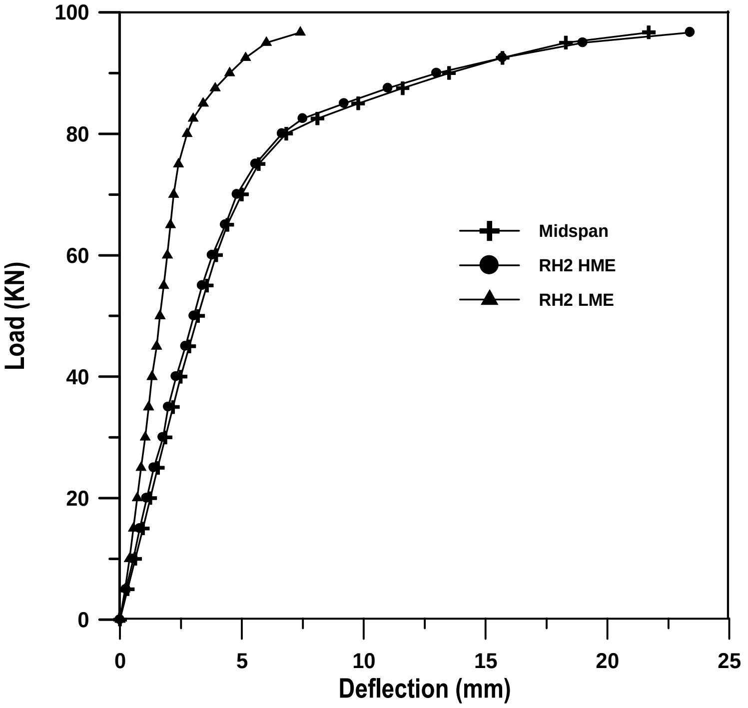


Figure (8): Load – Deflection Curves of Beam CB2

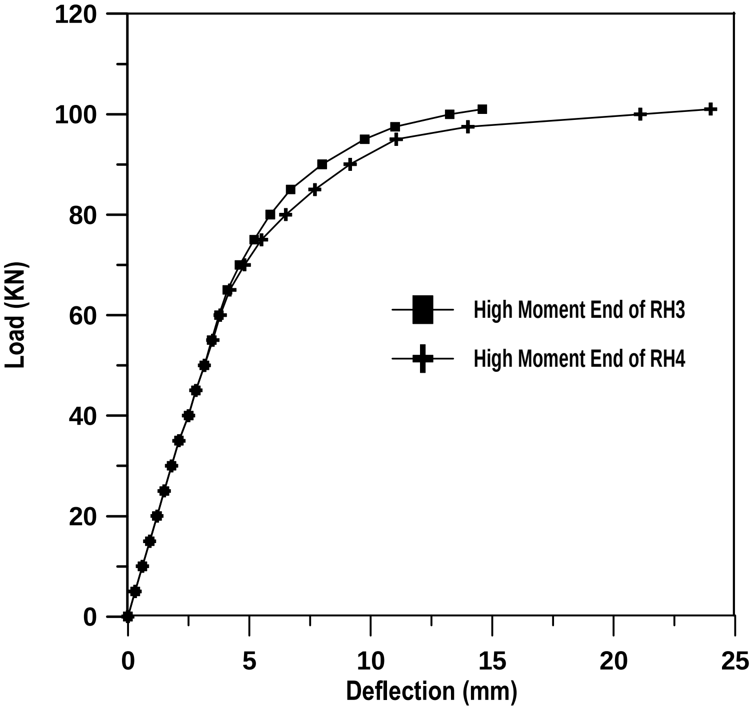


Figure (9): Deflection of High Moment Ends of Openings RH3 and RH4

Figure (10): Failure at Opening RH7 of Beam CB4

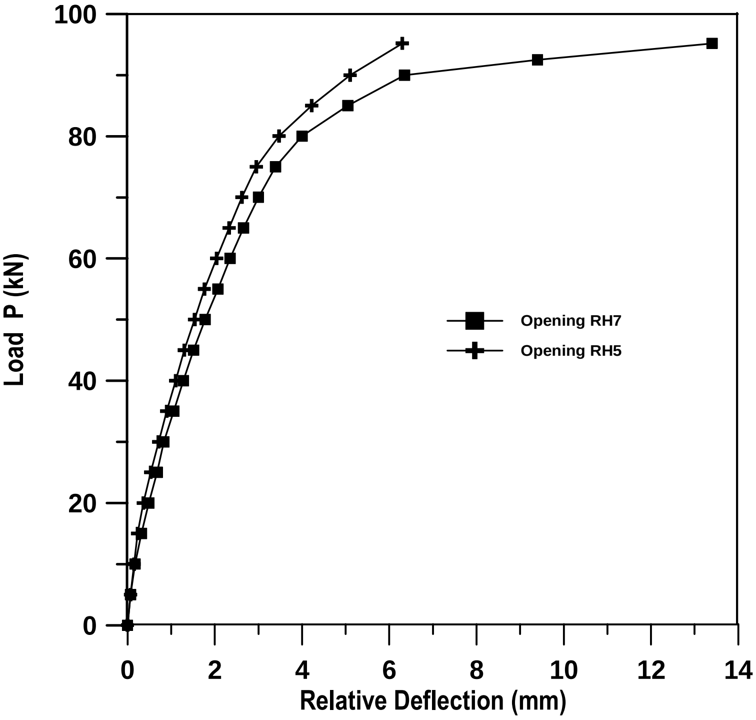


Figure (11): Relative Deflections through Openings RH5 and RH7

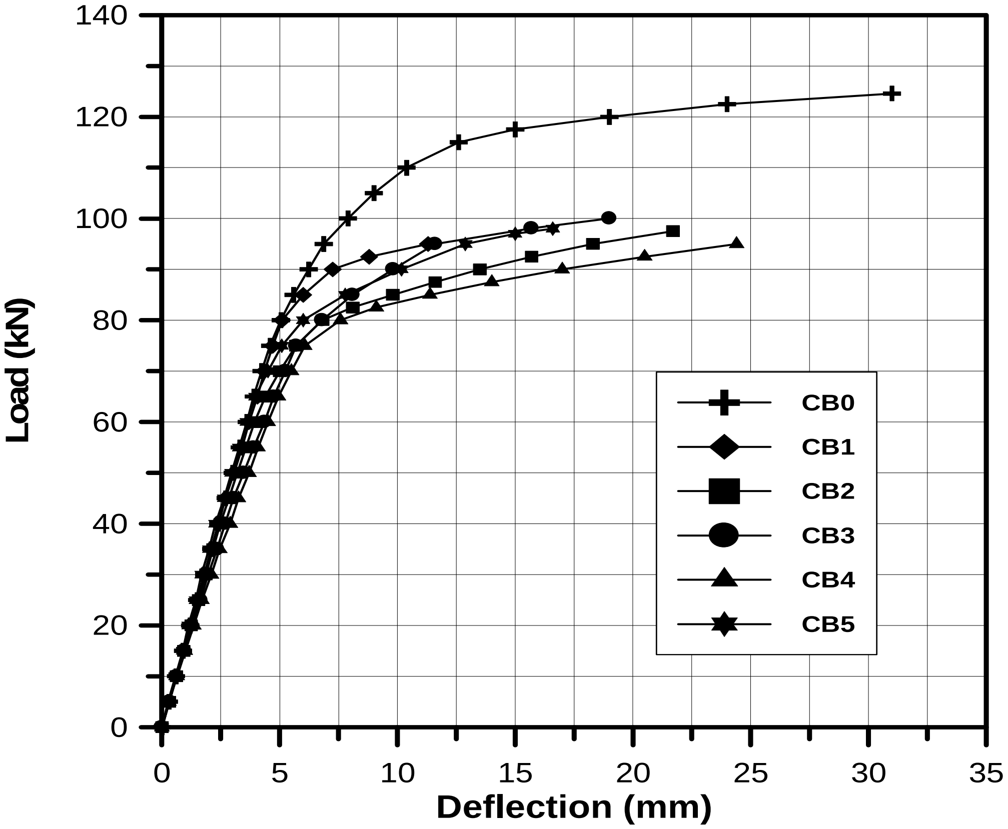


Figure (12): Load – Midspan Deflection Curves