Experimental Study on Composite Beams with Circular Web Openings

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ABSTRUCT

The behavior of composite beams with circular web openings is described. Four composite beams comprising one control beam were tested. The perforated beams have six circular openings with various locations. Opening size was fixed (66.7% of the steel section web depth) while number of openings in each composite beam was varied. Deflections at midspan and at openings were observed. Cracking of concrete slab and behavior of each opening were explained in detail. Tests indicated that circular web opening reduced the strength of composite beams. The behavior of composite beams relatively unaffected by the presence of circular web openings up to first yield. Less effect for the inclusion of circular web openings located out of midspan. The concrete slab has limited contribution to the strength of composite beams with circular web openings.

KEYWORDS: Composite beams, Web openings, Circular, Moment to shear ratio, Slab behavior.

الملخص

تم شرح تصرف العتبات المركبة الحاوية على فتحات دائرية في الساق. تم فحص أربعة عتبات مركبة بضمنها عتبة مركبة واحدة مرجعية. العتبات احتوت على ستة فتحات دائرية ذات مواقع مختلفة. تم تثبيت حجم الفتحة (٦٦.٧% من عمق وترة المقطع الحديدي) بينما تم تغيير عدد الفتحات في كل نموذج عتبة مركبة. تم قياس الهطول في منتصف كل عتبة وعند الفتحات. تم العرض لشرح تفصيلي عن تشققات السقوف وتصرف كل فتحة. أظهرت الفحوصات أن الفتحة الدائرية تقلل من مقاومة العتبة المركبة. تصرف العتبات المركبة لا يتأثر تقريبا بوجود فتحات حتى حصول الخضوع الأولي للمقطع الحديدي. تأثيراقل لوجود الفتحات الدائرية خارج

موقع منتصف طول فضاء االعتبة. السقف الخرساني له مشاركة محدودة في مقاومة العتبات المركبة ذات الفتحات الدائرية في ساق الوترة.

1. Introduction

Modern multistory buildings always have a stringent requirements on headroom. In order to accommodate building services within the constructional depth of a floor, it is common practice to provide web openings in structural floor beams for passing services such as air-conditioning pipeline, cables and ducts. Most openings may be rectangular or circular, and may be in the form of discrete openings, or a series of openings along the beam. Careful sizing and positioning of the openings in the beam web can minimize their adverse effects on shear and bending resistances of composite beams.

When a perforated steel beam is subjected to shear, the tee-sections above and below the web openings must carry the applied shear as well as the primary and secondary moments. The primary moment is the convectional bending moment and the secondary moment (Vierendeel moment), results from the action of shear force in the tee-sections over the horizontal length of the web opening. Therefore, the horizontal length of the web opening directly affects the secondary moment. In the absence of local or overall instability, perforated beams with standard web openings have two basic modes of collapse, which depend upon the geometry and the position of the web opening. They are as follows:

1. Plastic tension and compression stress blocks in the top and bottom tee-sections in regions of high overall buckling.
2. Parallelogram or Vierendeel action due to the formation of plastic hinges at the four corners or at specific angles around the web opening, in regions of high shear stress [1].

For composite beams, the composite action developed between the top-tee section and the concrete slab increases the resistance to Vierendeel action.

Circular web openings are structurally efficient, and also convenient for distribution of circular service ducts and water pipes [2]. The provision of multiple circular openings in the beams became a popular architectural feature of steel framed structures [3]. For a composite beam with a circular web opening, the effective length and effective depth may be taken less than the web diameter. Therefore, the Vierendeel bending effects are less critical [2].

Considerable amount of experimental research work on composite beams with rectangular web openings were done. Clawson and Darwin [4] conducted tests on six composite beams with one or two rectangular web openings with different moment-shear ratios. Redwood and Wong [5] described the effect of large rectangular web openings on five composite beams with ribbed slab. Only one of the beams contain two web openings. Redwood and Poumbouras [6] described tests of two composite beams with large rectangular web openings. Lawson et al [7] summarized the results of three load tests on composite beams of 10 m span, comprising one control composite beam, i.e. without opening and five rectangular openings of various sizes and locations. Cho and Redwood [8] describe nine tests in which composite beams containing one or two large rectangular web holes. Hamoodi and Hadi [9] conducted tests on six composite beams with rectangular and square openings. Various numbers and locations for openings were considered.

This study presents the results of an experimental investigation designed to provide information about composite beams with circular web openings. The key parameters in the current study were the number of openings and the moment to shear ratio (M/V) at the opening. The beams behavior was explained and the major observations were summarized.

2. Composite Beams Details

The study considered four composite beams of steel I–section and concrete slab which connected together by headed shear studs. One of the beams fabricated without web opening, while each of the others perforated with different number and locations of web openings; one central opening, two openings at third points, and three openings at quarter points. All openings have 100 mm diameter (66.7% of the steel section web depth) and centered at the mid-depth of the steel section. Information about beams and openings are listed in Table (1).

The steel section was IPEAA-160. Three tensile test specimens were cut out from top flange, bottom flange, and from web. The specimens were tested to get yield strength and modulus of elasticity of 337 N/mm^2 and 196x10^3 N/mm^2, respectively. The concrete slab thickness was 60 mm and the width was 500 mm reinforced with Ø5@100 mm steel deformed bars in both longitudinal and transverse directions at slab mid-depth. Tensile tests indicated that yield strength and modulus of elasticity of steel bars were 650 N/mm^2 and 198x10^3 N/mm^2, respectively. Based on characteristics of partial shear connection, shear connectors with 8 mm diameter were distributed in two rows at 150 mm center to center in the longitudinal direction. Also, three specimens of the shear connectors were tested to obtain the yielding strength and modulus of elasticity which was 256 N/mm^2 and 197x10^3 N/mm^2, respectively. The typical cross section of the composite beams is show in Figure (1).

3. Beam Fabrication and Casting

Firstly, the centers of openings in the web of steel section were determined for all beams. Then, the openings were cutout using an oxy-acetylene torch. The shear connector studs with 45 mm length were well hand welded at the top flange of steel section with uniform spacing.

Before casting, the steel framework of the concrete slab was lubricated and set level with top flange of steel section. The steel reinforcing mesh was kept at the mid-depth of slab. Concrete mix used through the whole investigation was the same. The mix proportions by weight were (1 : 1.5 : 3) of portland cement, fine aggregate, and crushed coarse aggregate, respectively. The water to cement ratio was 0.5. During casting of each beam, three (300 mm x 150 mm) diameter cylinders and three cubes of (150 mm x 150 mm) were made. All casted elements were well compacted using poker vibrator. The curing was done with same conditions. Results of cylinders and cubes at age of 28 days are listed in Table (2).

4. 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 simply supports and loaded with a single concentrated load at midspan using hydraulic loading system with maximum capacity of 2000 kN. Dial gauges of sensitivity 0.01 mm, were used to measure vertical deflection at midspan of the tested beam, and at the centerline of each opening, Figure (2).

At the start of each test, one cycle of 5 kN was applied to bed the beam on the supports. Load control with increments of 5 kN was used until a beam began to soften and deformed plastically. At this point deflection control was used. The dial gauges readings were recorded and cracks were marked after each load step. The test was stopped when excessive deflection happened with small load increments.

Cracks in the concrete slabs were marked and identified by load. After the beam had failed, the load system was removed, additional cracks were marked and additional photographs were taken.

5. Results

5.1 Load-deflection curves

The load-deflection curves for the composite beams during the tests are shown in Figure (3). The curves indicate approximately linear behavior up to (64 -79)% of the ultimate load followed by ductile failure. All beams have similar behavior before first yielding. When yielding began, two different behaviors can be noted. One for beams CB0 and CB2 and the other for beams CB1 and CB3. All beams had deflection about 30 mm at failure, except beam CB2 had about 20 mm.

The load-deflection relations show that the presence of circular web opening at midspn, the largest moment to shear ratio, controls the behavior of the composite beams. Beam CB2 which contains two openings each with 0.6 m M/V behaves as the imperforated beam CB0. Where beam CB3 which contains three openings one of them at midspan, behaves as beam CB1 which contains one opening at midspan. Since first yielding of steel section occurred at about 70% of ultimate load, it can be considered as a measure for the ultimate strength and the concrete slab contributes little to the ultimate strength. However, the compressive strength of concrete slab for beam CB2 was a little higher than those for other beams which results in a little more stiffness especially after first yield of steel section.

5.2 Slab behavior

In all beam specimens, transverse crack first formed at the bottom of concrete slab at midspan in the range of (73-84)% of the ultimate load. This crack was initially located adjacent to the steel flange edges and spread toward the edges of the slab. As load was increased the crack propagated toward the top of the slab with increasing in width. About 90% of the ultimate load, another transverse cracks started at the top of slab near the low moment ends of openings CH2 and CH6 (Figure (4)). Longitudinal cracks were occurred at applied load of the range (88-96)% of the ultimate load started at the center of the top surface of the slab. These cracks were at midspan and propagated toward the side edges up to failure load.

Longitudinal cracks occurred due to splitting of concrete at the region of shear connectors which were stressed at early stages of loading. . For beams CB0 and CB1 the longitudinal crack reached about the quarter of the span from each side

5.3 Ultimate load

Ultimate loads were governed by failure of the concrete at midspan. Tests indicated that there was a decrease in ultimate strength due to the inclusion of web openings. The failure load for beam CB0 was 125 kN. The other perforated beams; CB1, CB2 and CB3 failed at 102 kN, 116 kN and 100 kN, with reduction of 18.4, 7.2 and 20%, respectively. In spite of perforating beam CB2 with two holes each one with 0.6m M/V, its failure load was higher than that for beam CB1 which perforated with one hole at midspan. The results show that beam CB3 had little reduction in ultimate failure load by introducing two openings at M/V equal 0.4 m when compared with beam CB1.

5.4 Behavior at openings

The bottom tees of openings located at midspan were first position yielded in beams CB1 and CB3. Holes CH1 and CH5 yielded at 75% and 69% of the ultimate load, respectively. Yielding extended along the width of openings that indicates a flexure failure. Near failure, the top tees yielded also and the concrete slab over openings crushed. It can be noticed that there was a local buckling at the top tee of opening CH1.

Little increase in the deflection of opening CH2 with respect to CH3 (Beam CB2) and in CH6 with respect to CH4 (beam CB3) was observed near failure load, see Figure (5). This is due to the presence of concrete transverse cracks over openings CH2 and CH6. All openings shape at failure are shown in Figure (6).

5.5 Failure mode

Failure of the composite beams was quite ductile. The reaching of ultimate loads were preceded by major cracking in the concrete, yielding of the steel section and large deflections. Yielding of steel sections at midspan (in the presence of an opening or not) was observed at load level more than 64% of the ultimate load. Yielding occurred at the tension zone or the bottom tee of steel section at opening. As the load increased, longitudinal and transverse cracking occurred within the slabs. At collapse, the concrete around shear studs at midspan failed, and the slab may be lifted (bridged) from the steel beam. Typical failure mode for composite beams (beam CB3) is shown in Figure (7).

Ultimate loads and the levels of applied load at first cracks and at initial yielding of steel section corresponding its locations are summarized in Table (3).

6. Conclusions

Based on the experimental investigations conducted in this study, the following conclusions can be drawn:

1. Circular openings within the web of steel I-section reduce the strength of composite beams, especially when the opening is at the section of highest moment.
2. The behavior of composite beams is relatively unaffected by the presence of circular web openings up to first yield. For the stages after, no significant effect for the inclusion of opening located out of midspan.
3. Composite beams with circular web openings at midspan failed by flexure. Plastic hinges formed at the top and bottom tees of the opening. The bottom plastic hinge extended up to collapse.
4. The failure mode of composite beams with circular web openings is quite ductile. Failure is beginning by yielding of steel section, followed by major cracking of concrete, and then large deflection at midspan.
5. The first yield of steel section in the presence of opening gives a measure for the ultimate strength of the composite beam.

6. The concrete slab has limited contribution to the strength of composite beams with circular web openings.

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Table (1): Geometric Properties of Openings

Composite Beam	Opening	M / V at opening (m)	No. of Studs through Opening
CB0	-	-	-
CB1	CH1	1.0	2
CB2	CH2	0.6	2
	CH3	0.6	2
CB3	CH4	0.4	2
	CH5	1.0	2
	CH6	0.4	2

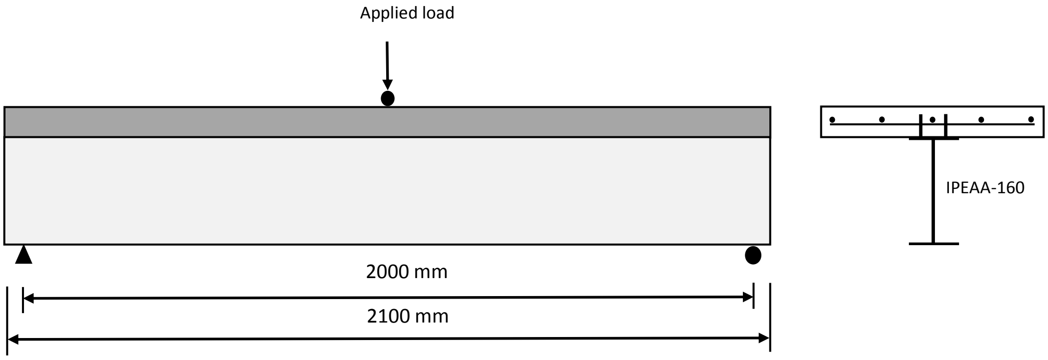

Figure (1): Composite beams details

Table (2): Concrete Properties

Beam	**Average Compressive strength at 28 day (N/mm^2)**		**Unit weight (kN/m^3)**
	Cylinder	Cube	
CB0	2٣.3	29.2	23.04
CB1	22.6	27.5	22.82
CB2	27.9	33.4	23.21
CB3	22.7	26.6	22.73

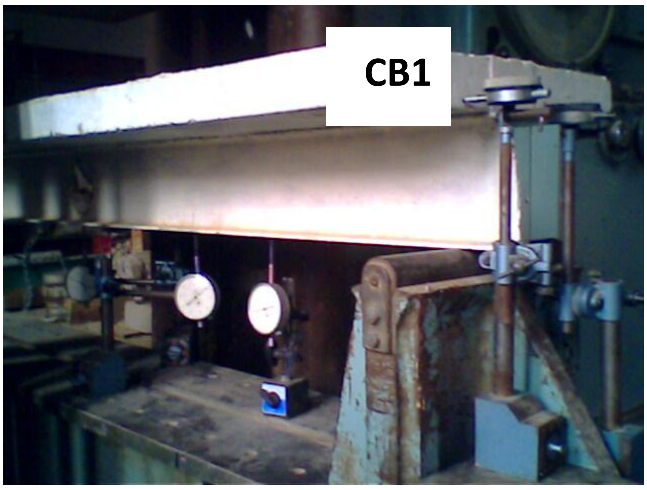

Figure (2): Beam setting

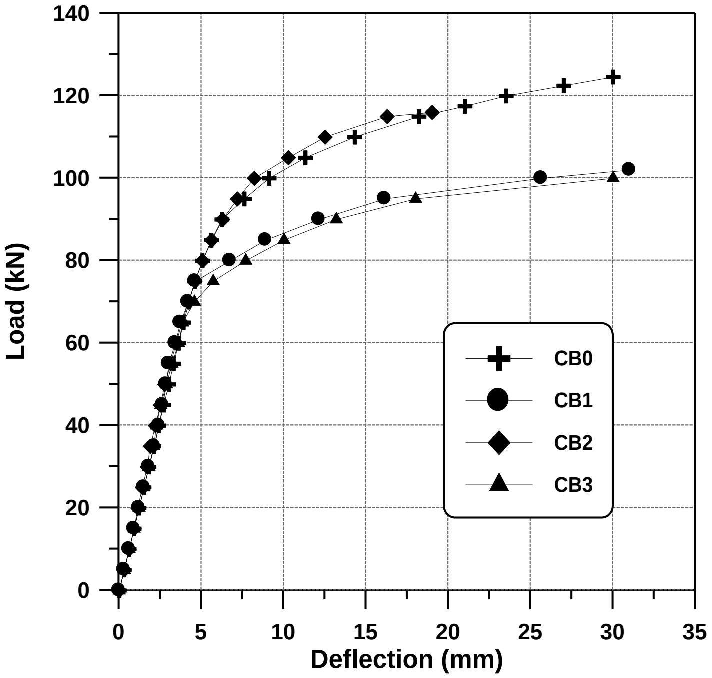

Figure (3): Load-deflection curves

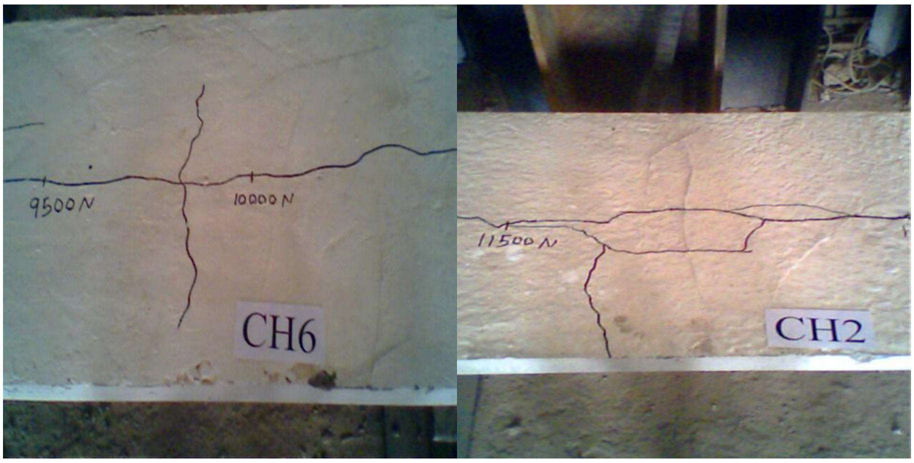

Figure (4): Concrete Cracking over openings

Figure (5): Openings at failure

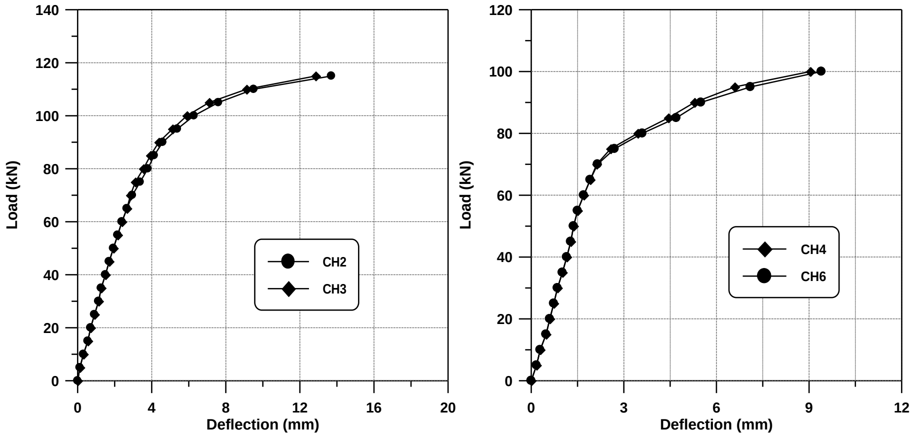

Figure (6): Deflection at Openings

Figure (7): Typical failure mode (Beam CB3)

Table (3): Test results

Composite Beam	Ultimate Load (kN)	Appearance of First Crack (% of ultimate load)		Initial Yielding of Steel Section (% of ultimate load)	
		Transverse	Longitudinal	Load (kN)	Location
CB0	125	84	96	64	bottom flange
CB1	102	78	88	75	bottom tee
CB2	116	73	95	79	bottom flange
CB3	100	80	91	69	bottom tee