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Effects of Web Opening Size on the Behavior of Castellated Concrete Geopolymer Composite Beam

Dr. Waleed A. Waryosh[1], Ali S. Ali[2]
[1]*Assistant Prof., Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq*
[2]*M.Sc. Student, Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq*

Abstract: The functions of structural elements such as beam, slab, column and shear walls are to providing strength and resistance against loadings based on the material properties. Concrete, steel and composite structures are the main buildings around the worlds in recent years. In case of two or more different materials were connected with each other's by means of third components so that it working as unity. Castellated beams were used to passing too many services through it but in other way the presences of opening reducing the strength capacity of the steel or concrete beams. In present study ,Five simply supported composite castellated beams has been investigated, the effects of opening sizes on the behavior and strength of composite castellated geopolymer concrete beams are investigated under the static loadings with full interaction and partial interaction of (70%) from full . The opening shape of steel castellated beams is hexagon with different ratio on opening size from the web area as 35 and 70%. Full and partial interaction of (70% full)that related on the number of shear connectors is taking into accounts. Test results showed that the increase in opening percentage size lead to reduce in strength capacity of composite castellated beams. in case of same specimens but differ in partial and full interaction, the full interaction gave more strength capacity and less deflection and slip.
Keywords: Geopolymer Concrete, Castellated Beam, Opening size, Composite Beam, Slip, Partial and Full Integration.

Introduction

Composite structure specially concrete and steel section adopted in many countries around the world due to their advantages to resists applied loads, light weight and cost wise of this type of structural elements. Normal concrete become little use because giving less compressive strength so that many designer and researchers investigated the higher concrete compressive strength such as polymer concrete. The presences of openings in different shapes and locations were also investigated to check out the behavior and strength of castellated steel beams due to reduce in strength load capacity because the web perforations. In practical, the concrete slab when connected by steel joists there are friction at the interface and the shear connectors transmitting the shear flow so that there are slip at the surface of connection that lead there is no full unity even when provided shear enough connectors. Polymer concrete is a bonding material consists of the reaction of the raw material that has alumina silicate with alkaline solution. Different materials adapted to producing polymer concrete such as Fly ash, slag, metakaolin and rice husk ash. Different applications for polymer concrete in projects such as pavements, retaining walls, bridges, tanks and pipes. Toprac and Cooke, [1], investigated the behavior and strength of castellated steel beams under pure bending. Test results indicated that the main failure occur in both lower and upper of the web openings. Megharief, [2], explored the performances of steel castellated beams with different spans and different moment to shear ratio by numerical and experimental approaches. Based on the experimental test and analysis results that indicated the longer span gave more lateral torsional buckling of the compression flange. Gizejowski and Salah Khalil, [3], investigated the stability of the castellated composite beams under the effect of hogging bending. Based on test and numerical analysis, the researchers concluded that the slender structural steel sections. Xiuping and Boyd, [4], investigated the polymer concrete properties that contained fly ash. Test results showed that the ninety percent of fly ash gave the best quality and enhanced the properties of concrete. Raijiwala et al, [5], investigated the influences of the presence of alkaline activators on the behavior, strength and durability of the geopolymer concrete. Test results indicated that the temperature greater than 80 °C gave excellent behavior if the concrete properties. . Madheswaran et al., [6], explored different compressive strength and the presences of alkaline solutions that used in polymer concrete. Test results indicated that the mechanical properties of polymer concrete developed as increased in sodium hydroxide concentration. Nadjai et al., [7], investigated the full scale composite castellated.

Satalingappa et al., [11], compared the behavior and strength of polymer concrete slab under impact load with that casted by normal concrete. Polymer concrete slabs gave more resistance under impact loads than the normal concrete. Mahantesh et al, [12], examined the behavior and strength of reinforced concrete slab casted by polymer concrete by used fly ash under the effects of static loads. Different strengths but same behavior of polymer and normal concrete slabs that showed based on test results. Al-Saeedi, [13] investigated and evaluated self-compacted composite castellated beams under the effects of static and impact loads. Test and experimental results showed that the composite castellated beams with self-compacted concrete have higher strength capacity and lower deflections as compared with the normal concrete.

Aim and Significant of Research

Different tests for composite castellated steel beams with different opening size of web. Investigations of geopolymer reinforced concrete deck slab that casted above the castellated steel beams. The aims and objectives of present study are to investigate the effects of web opening size on the behavior of castellated concrete geopolymer composite beams under the effect of four point's static loadings. Different percentages of web opening such as 35 and 70% of web in case of full and partial composite interaction are adapted and the concrete slab type is polymer concrete in addition to the control beam without opening for comparisons. Composite beams capacity, deflections and slips for all tested specimens are recorded and discuses.

Experimental Works

The raw materials that used in present work are summarizes as follow

Geopolymer concrete: The geopolymer concrete prepared by replaced full the cement by geopolymer. Geopolymer concrete is made by reacting aluminate and silicate bearing materials with a caustic activator. The material that mixed to produced geopolymer concrete are"

Metakaolin: The methodology and processes to converting kaolinite to metakaolin relay on the applied temperature in which (100-200 Co) the most quantity of water will be loss and (500-700 Co) loss all water. Chemical, physical and the requirements based on the ASTM C618 [14]

Sodium silicate: The brand of sodium silicate adapted in present study manufactured in United Arab Emirate.

Sodium hydroxide: The sodium hydroxide is the most important item to prepare the geopolymer concrete. The sodium hydroxide prepared by dissolved caustic soda flakes in water. The chemical reaction between sodium hydroxide and water was an exothermic component after that the compositions cool in air for two hour. Table 5 lists the test results and compare with the requirements based on ASTM E 291-09 [15].

Prepared of alkaline solution by prepared from the (NaOH) and (Na_2SiO_3) by dissolve flaky high purity sodium hydroxide 98% in distilled water. One litter solution was prepared by mixed 560 g of (NaOH) with 826 ml. The Molarity for adopted mix was (14) and the weight of (NaOH) flakes is 404 g. Prepared of alkaline liquid by mixed one litter from (NaOH) with 3.5 litters from (Na_2SiO_3).

The mechanical properties of geopolymer such as compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity are explored; Table 1 lists the summary of mechanical properties

Table 1: Summary of mechanical properties - geopolymer concrete

Age (Days)	Compressive strength fc' (fcu) (MPa)	Splitting tensile strength (MPa)	Modulus of rupture (MPa)
28	32.60 (38.62)	4.55	4.46

Castellated beams and slab reinforcement

Layout and details of castellated composite beams is shown in Figure 1. Table 2 lists the mechanical properties of castellated cross section and Figure 2 show the specimen test setup. Reinforcement for concrete slab with one layer of BRC with ф6 mm and square spacing 150 mm was adapted based on the design of composite castellated beam that designed before tests. The reinforced concrete slab was connected to the castellated steel beams by means of smooth shear stud connector with diameter 8 mm and total height 40 mm and upper head diameter (13 mm) is adapted.

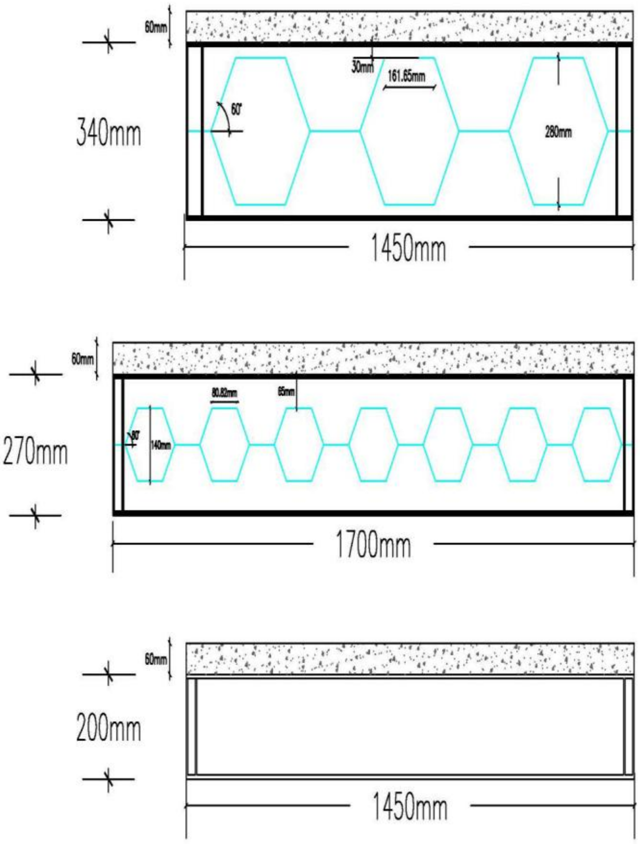

Figure 1: Layout and details of composite castellated beams

Table 2: Steel section geometry and mechanical properties

Flange (mm)		Web (mm)		Modulus of Elasticity (MPa)	Yield Strength *fy* (MPa)	Ultimate Strength fu (MPa)
Width	Thickness	Height	Thickness			
100	8	184	5	207000	376	517

Figure 2: Specimen setup

The specimens marks are classify and lists in Table 3.

Table 3: Specimens classifications

Specimen mark	% Opening size	Composition action
CRB	0	Full
CBF35	35	Full
CBP35	35	Partial
CBF70	70	Full
CBP70	70	Partial

C: Composite, R: Reference, B: Beam, F: Full, P: Partial, 35 and 70 is the opening percentages

Test Procedure

The boundary conditions of the Composite castellated beams CCB are simply supported that designed to out concentrated loads. The applied load incrementally in step initially (5 kN) up to (20%) from ultimate load and the deformations such as deflection, strain and slips are record. Load increments and record all values with step of (4 kN) up to (40%) and then the test continue with loads increments as (3 kN, 2 kN) up to (75% and 90%) respectively. All specimens are tested up to failure. The locations of dial gauges are in the mid and quarter bottom flange of steel beam to measure the mid and at quarter span deflection. Two dial gauges each at end of the specimen to record the slip at the ends. Three strains gauges at the bottom flange, mid web and at the center of concrete slab to measures the strain of steel section and slab with each incremental applied load.

Test Results

Table 4 lists the ultimate and first crack loads for all specimens and Table 5 lists the maximum deflection at quarter and mid span with maximum slip at the end span of all specimens. Based on the test results and test methodology, the load – deflection behavior for all specimens quarter, mid span are shown in Figures 3 and 4. Load –slip (average) at the end of the composite beams is shown in Figure 4. Composite castellated beams CCB classified based on composite action such as full and partial interaction and openings percentages (35 and 75%). The flexural behavior, ultimate capacity, deflection at quarter, mid span and slip at the end of castellated composite beams are investigated. First crack load and pattern cracks of the CCB specimens are discuses. The general behavior of the tested CCB at early stages of loading, cracks begin to initiated in the tension zone of concrete slab and with further applied loading, these cracks propagated upwards to the direction of applied loading and became wider.

Table 4: Ultimate and first crack loads for all specimens

Specimen mark	First crack load (kN)	Ultimate load (kN)	%(First crack load/ Ultimate load)
CRB	31.50	143.0	22
CBF35	74.00	262.5	28.20
CBP35	56.00	242.5	23.10
CBF70	44.00	212.5	20.70
CBP70	25.45	192.5	13.22

Table 5: Maximum deflection at quarter and mid span with maximum slip at the end span of all specime

Specimen mark	Maximum deflection at quarter (mm)	Maximum deflection at mid (mm)	Maximum slip (mm)
CRB	3.12	7.80	1.50
CBF35	1.86	9.65	1.34
CBP35	5.25	12.88	1.82
CBF70	2.88	9.36	1.48
CBP70	2.95	9.16	1.6

In general, all specimens were tested up to failure in which the failure occurred in concrete slab due to cracks propagations. The specimens behaved as linear started from zero up to load that caused first crack in concrete slab that rely on full or partial interaction and opening web of steel beam percentage. The behavior of the specimens after the point of inflection become nonlinear due to change in modulus of elasticity that influenced by increase in load that cause increase in strain that reflect in reduce on the magnitude of modulus of elasticity so that the specimen stiffness become less. Increases in load make the slop of the load - deflection less that indicate reduce in specimen stiffness due to increase in load and deflections. The deflection at the mid span gave the maximum value due to the curvature of the beam increase started from zero deflection at supports.

The reference specimen CRB solid web without openings casted by geopolymer concrete with number of stud shear connectors make the composite beam as full interaction, the ultimate load capacity is 143 kN and the corresponding deflection at mid span is 7.80 mm. The behavior of reference CRB start from zero up to 31.50 kN that represent the load caused first crack is linear.. Specimen CBF35 gave deflections at quarter and mid span at failure stage more than the reference specimen. The load strength capacity is greater than the reference specimen due to higher cross section. Specimen CBP35 recorded ultimate load 242.50 kN that reduce in capacity as compare with CBF35 because the number of stud shear connectors less so that it work as partial. Partial interaction reduces the strength specimen capacity due to presence of slips at the interface between top steel flange and bottom of concrete slab. The presence of slip leads to increase in deflection and reduce in ultimate strength capacity due to develop in horizontal displacements that lead to increase in curvature. Maximum deflection is 12.88 mm more than the specimen. The specimen CBF70, the load capacity is (212.50 kN) compared with the CBF35 there was reduced in strength and approximately same maximum deflection. The specimen CBP70 compare with CBF70, the strength capacity is less due to the effect of slip that reduce the resistance and increase the deflection.

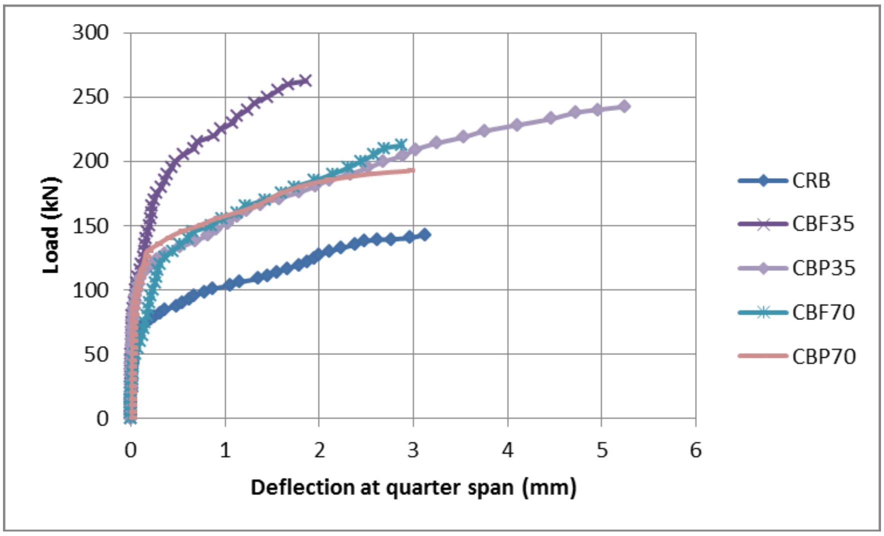

Figure 3: Load – deflection at quarter span for all specimens

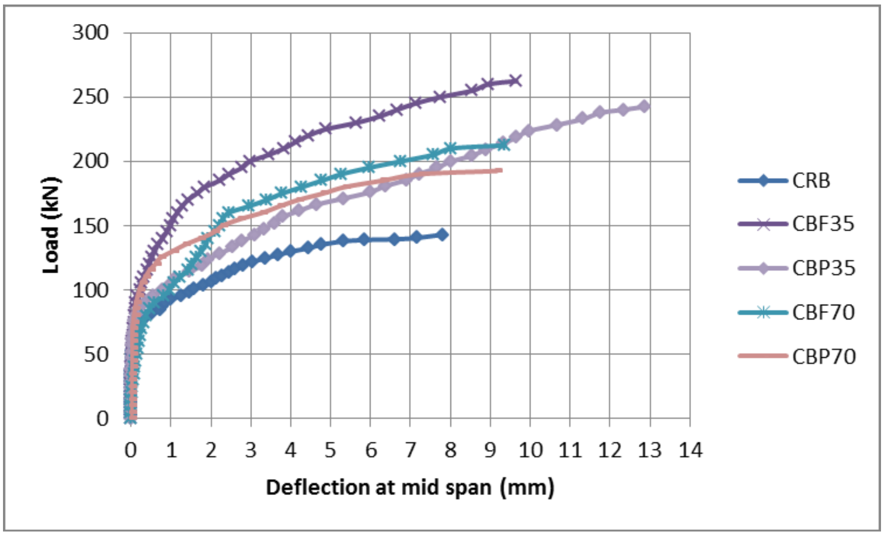

Figure 4: Load – deflection at mid span for all specimens

Even the number of shear stud connectors that provided to connect the two different materials as concrete and steel sufficient to working as unity, still there are slip developed at the interface surface. The behavior of slip for all specimens is shown in Figure 5 in which the slips distribution symmetric about the origin (mid span) with reversal in sign. The maximum slip values ranged between 1.34-1.82 mm rely on full or partial interaction. The load – slip behavior at mid span is zero due to the change in directions of shear flow (shear load) that developed due to applied load. The slips are very small at the early applied load and then increase at the load that caused more shear flow. In case of partial interaction, the slips are greater than that of full due to the magnitude of distributed shear flow more that caused slip at the interface in presence of friction that reduce the slip value because the frictional force direction in opposite direction of shear flow. The maximum slip is 1.82 mm occur in specimen CBP35.

The slip comparisons between the specimens as full and partial interaction CRB, CBF35 and CBF70, the specimen as full interaction gave less slip due to the sufficient number of stud shear connectors were provided so that the whole systems work as unity. In addition, the shear flow becomes less in case of presence of less opening percentages (35%).

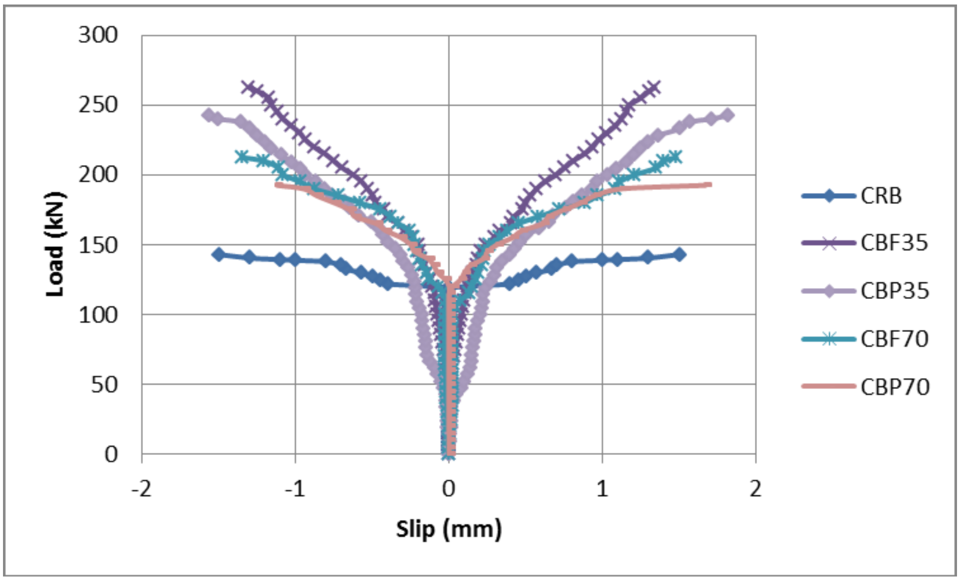

Figure 5: Load – slip at the end of span for all specimens

Strains were measured at the location at middle of bottom flange, mid web and mid reinforced concrete slab. The functions of measured strains that developed in steel section and concrete are to evaluate the strain behavior of the reinforced concrete composite castellated beams under the effects of static loadings and find out which material yield first. Figure 6 shows the load - strain behavior for all specimens. All behavior starts as linear with small increments in strain up to approximately (75%) from the ultimate load. the behavior of the models become nonlinear (curve) when the loads reach the ultimate load capacity. All recorded strain in the tension zone not reach the yielding strain (0.00175) so that the steel section not yield and still in the elastic zone.

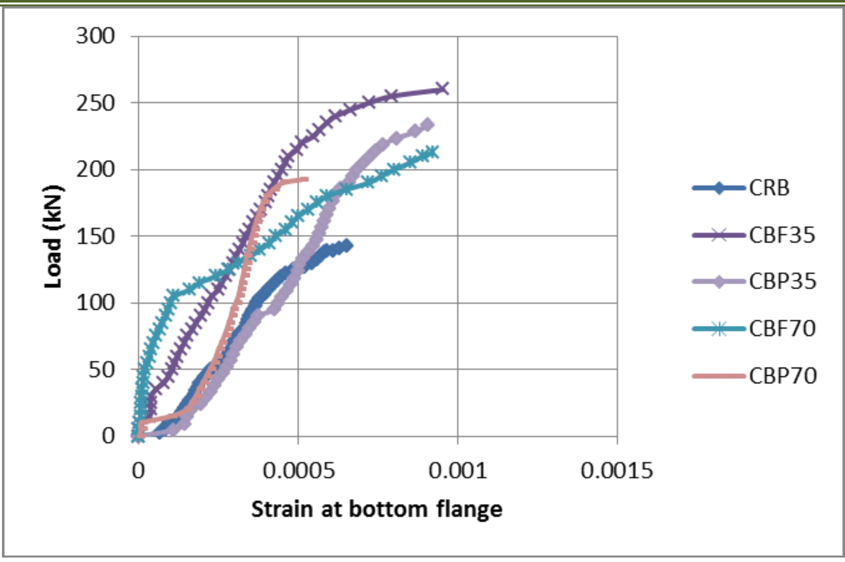

Figure 6: Load – strain at the bottom of steel flange for all specimens

Figure 7 represent the full behavior of the load – strain for all specimens that r4ecorded in the middle web of steel section. The midpoints of web lie in the tension zone of the composite castellated beam and all strains within the elastic range that not exceeded the yielding strain that mentioned above. All loads – strain behave as elastic up to ultimate load for each specimen.

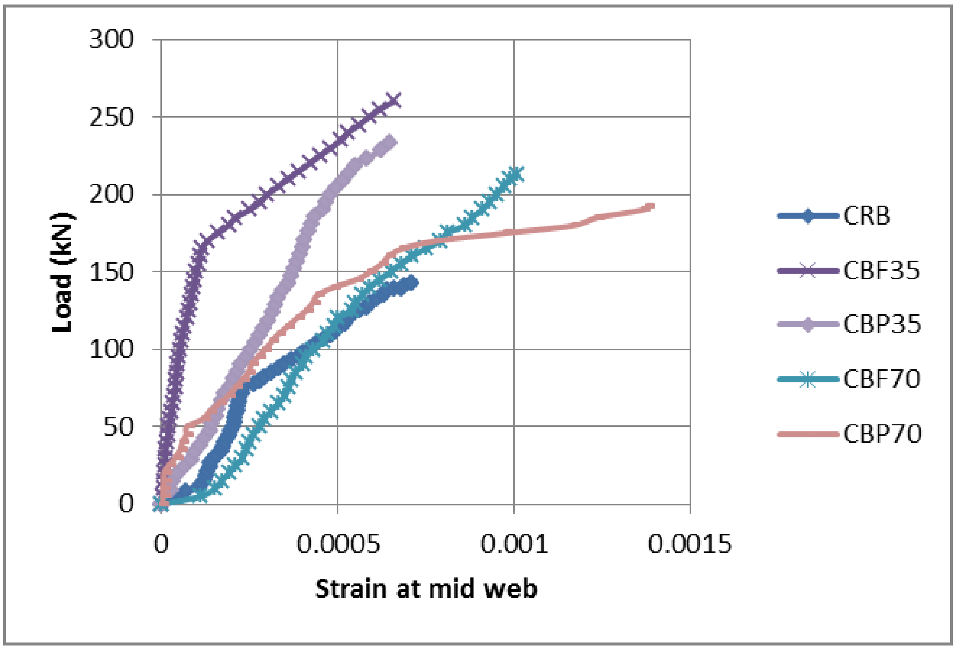

Figure 7: Load – strain at the mid of steel web for all specimens

Figure 8 shows the load – strain at the middle of the reinforced concrete slab for each specimen. The behavior of load – strain starts as linear up to nearly first crack that rely on the each specimen specification. After first cracks of each specimens, the behaviors become nonlinear but still in elastic range. All specimens not reach the maximum strain in concrete (0.003) based on ACI-318 – 2014 [16].

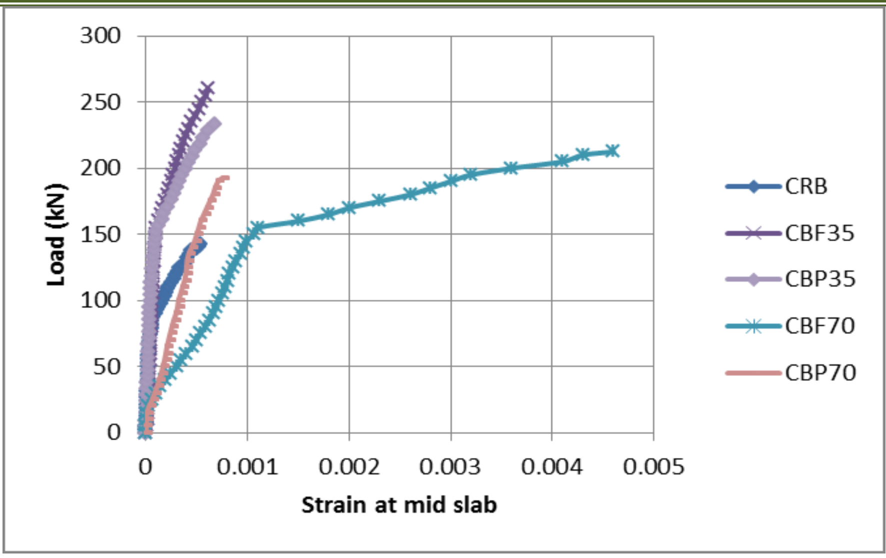

Figure 8: Load – strain at the reinforced concrete slab (mid) for all specimens

Crack Pattern and Mode of Failure

Concrete material such as geopolymer concrete classified as weak in tension resistance due to that the concrete is a brittle material. The cracks developed and progress when the load applied cause stress in tension zone more than the modulus of rupture in flexural test. When the applied load increased till reach to developed first crack that is mean the internal stress that inside the concrete in tension zone become near the value of modulus of rupture. The magnitude of first crack load relies on different parameters such as compressive concrete strength and geometry of concrete member. The enhancement in the concrete tensile strength due to increase in elastic deformation of the concrete in tension zone due to flexural that lead increase in strain of concrete so that become more ductile due to presence of steel section in tension zone. Also, in case of partial interaction the load caused first crack less than that in full interaction due to the presence of slip that increase the deflection and not make the concrete and steel section worked as unity so that the full stiffness of composite castellated beam reduce and make the internal stress in tension zone high to reach the limit of modulus of rupture of concrete.

A Figure 9 to 13 shows the cracks propagations and failure modes for all composite castellated beams. No pull – out of concrete slab failure and there are no cut of any headed stud shear connectors during test up to ultimate loads for each specimen. The specimen CRB in which the cracks at failure stage shows nearly vertical and parallel to slab thickness started from the locations of applied loads toward slab bottom. The whole CCB bend to the direction of applied load and the mode of failure is flexural due to concrete failure. The specimens CBF35, the cracks intensity at failure load are more than reference specimen. The cracks propagations of specimen CBP35 that the cracks lines more than CBF35 due to partial interaction between concrete slab and top flange of steel beam that produced slip that reflect on the cracks intensity. The vertical cracks of the specimen indicated that the fail is flexural. The specimen CBF70 has cracks at failure more than CBP35 and CBF35 due to increase in opening size. The CBP70 specimen carried out less ultimate load due to partial in connection and casted by geopolymer concrete. The amounts of cracks intensity with low failure load indicated in case of 70% opening specimens fail when the cracks in the slab growth more quickly due to weakness of the composite castellated beam due to large openings size.

Figure 9: Cracks pattern and mode of failure for CRB specimen

Figure 10: Cracks pattern and mode of failure for CBF35specimen

Figure 11: Cracks pattern and mode of failure for CBP35 specimen

Figure 12: Cracks pattern and mode of failure for CBF70 specimen

Figure 13: Cracks pattern and mode of failure for CBP70 specimen

Discusions

According to the experimental investigation followings are discussions due to observations and test results. The variations and comparisons of specimens CRB, CBF35 and CBF70 with each other's in three different test results deflection at quarter, at mid span and slips. Specimen CBF35 gave higher load strength capacity, less deflection at the same failure loads of other specimens CRB and CBF70 due to the percentage of opening is less that increase the stiffness of the specimen that lead to increase in load resistance and reduce deflection. The group CBP70 and CBP35, the CBP35 gave more load capacity because of reduce in opening percentages. Two percentages of openings size with respect to the web such as 35 and 70% are investigated. Increase ig percentage lead to reduce in strength load capacity and increase in deflection and slip due to reduce in moment of inertia that reflect on the beam stiffness. Table 6 lists the effects of opening size on ultimate load, deflection and slip of composite castellated beams.

Table 6: Effects of opening size on ultimate load, deflection and slip of composite castellated beams

Specimen mark	Ultimate load (kN)	Maximum deflection at quarter (mm)	% Increases in ultimate load	Maximum deflection at mid (mm)	% Decrease in deflection	Maximum slip (mm)	% Decrease in slip
CBF70	212.5	2.88	---	9.36	---	1.48	---
CBF35	262.5	1.86	23.53	3.83	59.08	0.78	47.30
CBP70	192.5	2.95	---	9.16	---	1.67	---
CBP35	242.5	5.25	25.97	7.49	18.23	0.94	43.71

Partial and full interaction theories are applied on the design of composite castellated beams to evaluate the full capacity, mid span deflection and slip. Table 7 lists the effects of composite action on ultimate load, deflection and slip of composite castellated beams. In case of full interaction between the reinforced concrete slab and the castellated steel section the whole system act as unity. In case of full interaction the number of shear stud connectors becomes more so that the shear flow transfer between the two contact surface distributed to the shear connectors less that lead to reduces slip and deflection and the composite beam capacity become more than partial system.

Table 7: Effects of composite action on ultimate load, deflection and slip of composite castellated beams

Specimen mark	Ultimate load (kN)	% Increases in ultimate load	Maximum deflection at mid (mm)	% Decrease in deflection	Maximum slip (mm)	% Decrease in slip
CBP35	242.5	---	12.88	---	1.82	---
CBF35	262.5	7.62	6.72	47.83	1.12	38.12
CBP70	192.5	---	9.16	---	1.67	---
CBF70	212.5	9.41	5.31	42.03	1.1	34.13

The presence of openings effects on the strength capacity of composite beams. Table 8 lists the effects of openings on ultimate load, deflection and slip of composite castellated beams. The control beam GFS00 is solid, other specimen's differed in castellated beam dimensions. Increase in steel depth (in case of presences openings) increase in load strength capacity and also reduce deflection due to increase in moment of inertia and so on beam stiffness.

Table (4.14): Effects of openings on ultimate load, deflection and slip of composite castellated beams

Specimen mark	Ultimate load (kN)	% Increases in ultimate load	Maximum deflection at mid (mm)	% Decrease in deflection
CRB	143.0	---	7.80	---
CBF35	262.5	83.57	0.95	87.82
CBF70	212.5	48.60	2.21	71.67

Conclusions

Based on the results from experimental tests, followings are the important conclusions points:

1. Increase in opening percentage lead to reduce in strength load capacity and increase in deflection and slip due to reduce in moment of inertia that reflect on the beam stiffness.
2. Full interaction between the two contact surface as top of steel castellated beam and reinforced concrete slab worked and act as unity. In case of full interaction the number of shear stud connectors becomes more so that the shear flow transfer between the two contact surfaces distributed to the shear connectors less that lead to reduce slip and deflection and the composite beam capacity become more than partial system.
3. Increase in steel depth increase in load strength capacity even in presences of openings and also reduce deflection due to increase in moment of inertia and so on beam stiffness.

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