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Research Article

Behavior of self-connected composite columns under eccentric load

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Abstract

This study presented a detailed structural evaluation of the behavior of composite columns under the effect of eccentric loads. The study focused on the impact of circular and square openings in the steel section. The study was carried out on 10 composite column specimens with different opening sizes and at three positions in the flanges and the web. The effect of these openings on the load-carrying capacity of the columns, as well as the slip behavior between the concrete and the steel section and their interaction, was studied. The study also aims to compare the effects of openings with those of shear studs and to explore the extent to which openings can replace shear studs to improve the structural efficiency of composite columns and simplify the construction process. The results of the study showed that the use of openings, especially those in the flanges, reduces slip and friction between the steel section and the concrete, thereby increasing the efficiency of force transfer between the concrete and the steel section and enabling them to act as a single element. Square openings reduced slip by 51.5%, while circular openings reduced it by 43.4%. Accordingly, this study represents an essential contribution to improving the design of composite columns, enhancing structural performance, and leveraging the mechanical properties of the section itself during self-connection with concrete to ensure load transfer, as well as the possibility of replacing shear studs with openings in future designs.

1. Introduction

Composite structural systems have been widely used in structural frameworks and bridges for several decades to minimize material use. The benefits of using composite elements include reducing construction time, decreasing the overall weight of the structure, and minimizing vertical floor space. This construction system may help provide cost-saving services to the community. The composite column with shear connectors is a well-known integrated structural element of composite structures, offering economic feasibility and excellent structural performance. Shear connectors are used to connect two structural elements at an interfacial stratum to prevent the upward separation of a slab from a steel girder and to provide smooth transmission of longitudinal shear forces [1]. Load-slip between steel and concrete and shear capacity are essential characteristics for the design of steel-concrete composite structures [2,3]. The shear connector is the component that ensures shear transfer between the steel profile and the reinforced concrete slab, enabling composite action in composite beams. Several different types of connectors have been studied, proposed, and used in the past. [4,5]. Numerous studies have investigated various types of shear connectors, including headed studs, channels, perforated plates, and innovative geometric designs. These investigations focus on parameters such as on-site installation, load-carrying capacity, failure modes (e.g., concrete crushing, steel yielding, or stud shearing), and

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allowable interface slip [6,7,8]. These studies vary according to design codes and the intended structural function, using different types of shear connectors compared with the most common type, namely the headed–stud shear connector [9-11]. Despite the many advantages of hybrid systems, more attention is needed to improve the bond between steel and concrete, aiming to maximize efficiency and reduce material consumption. From reviewing most of the studies, it was observed that they mainly focused on the use of connectors and on developing some of them to ensure bonding between the concrete and the steel section in composite structural members. Few studies, however, relied on openings in the steel section for bonding. This method was previously used in composite beams and was referred to as Self-connected. A self-connected, partly enclosed composite beam with a perforated steel section and concrete shear connectors was compared with conventional composite beams [12]. This type of bonding has not been previously used in composite columns, and the current study is the first to address its use.

2. Materials

The cement used in this study is Iraqi cement produced in Nineveh Governorate at the Badush Cement Plant, in accordance with Iraqi standard specifications [13], and it meets the requirements for ordinary Portland cement. Table 1 shows the chemical properties of the cement, and Table 2 outlines the physical properties of the cement used. All these tests were conducted in the laboratories of the University of Mosul. River gravel with a maximum particle size of 12.5 mm was selected for casting. Specific gravity 2.51 and density 1508 kg/m^3.

Table 1. Chemical analysis of cement and its compounds

NO	Oxides of cement components	Percentage(%)	Specification limits (%) [13]
1	Al_2O_3	5.4	3.0-8.0
2	SiO_2	23.4	17.0-25.0
3	Fe_2O_3	3.25	0.5-6.0
4	CaO	61.8	60.0-67.0
5	SO_3	2.25	Does not exceed 2.8%
6	MgO	3.5	Does not exceed 5.0%
	Main compounds of cement		
7	C_3S	38.53	31.03-41.05
8	C_2S	33.45	28.61-37.90
9	C_3A	11.99	11.96-12.30
10	C_4AF	7.92	7.72-8.02

A sieve analysis was carried out on the gravel to verify its conformity with the American standard specifications [14], as detailed in (Fig. 1). Sand sourced from the Knihesh area was utilized for casting molds. The sieve analysis confirmed that the sand meets the American standard specifications [14]. Specific gravity 2.41, the fineness modulus is 2.97, and the density is 1758 kg/m3. The clay content was measured at 2%, which is below the maximum permissible limit of 3% for clay materials, as indicated in (Fig. 2).

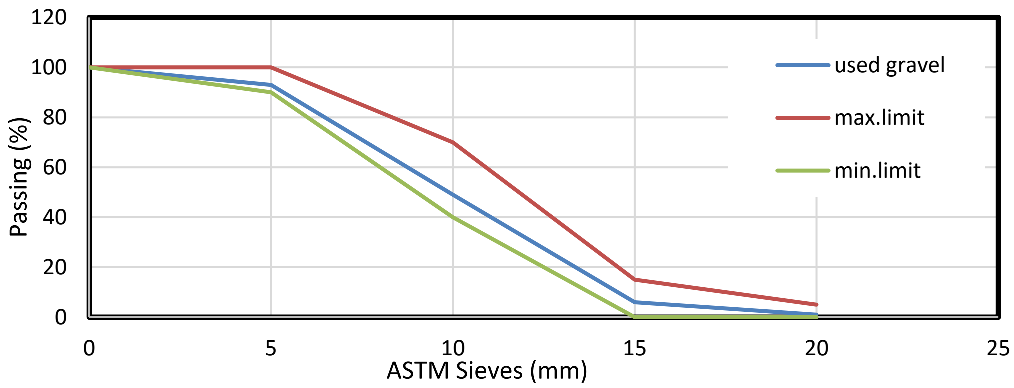


Fig. 1. Sieve analysis of coarse aggregate

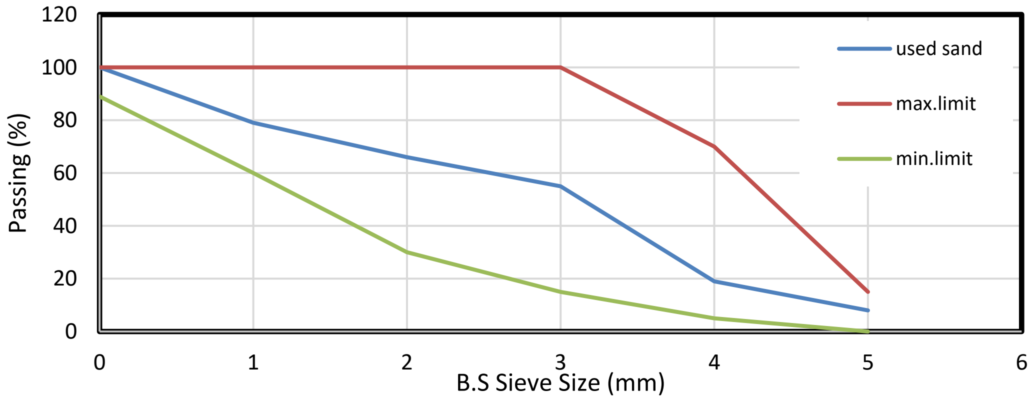


Fig. 2. Sieve analysis of fine aggregate

The water used in the concrete mix and for curing the concrete is potable. The composite concrete columns were reinforced with eight mm-diameter longitudinal bars and six mm-diameter hoops. Tensile tests on the reinforcement steel were conducted using a universal testing machine with a capacity of 600 kN; the test results are presented in Table 3. All the bars used comply with the ASTM Standard [15]. An H-Steel section was used in the composite concrete columns, with dimensions of 80 mm for the flange (6 mm thick) and 64 mm for the web (4 mm thick) (H80*80*8*6), and a length of 2800 mm. The tensile properties of the flange and web were verified through a coupon test [16]. The results indicated that the section complied with the ASTM specification [17], as presented in Table 4**.**

Table 2. Physical properties of the used cement

NO	Properties	Results	Specification limits (%) [13]
1	Fineness (percentage retained on sieve No. 170)	3%	Does not exceed 10%
	Setting Time		
1	Initial (minutes)	120	Not less than 45 minutes
2	Final (minutes)	225	Does not exceed 600 minutes
	Compressive Strength (MPa)		
1	3 Days	19.7	Not less than (16 MPa)
2	7 Days	24.8	Not less than (24 MPa)
	Tensile Strength (MPa)		
1	3 Days	1.77	Not less than (1.6 MPa)
2	7 Days	2.45	Not less than (2.4 MPa)

Table 3. Steel bar properties

Bar db	fy (MPa)	fu (MPa)	Elongation %	Standard Limits [15]%
6	378	458	16.4	≥ 9%
8	433	541	15.8	≥ 9%

Table 4. H steel section properties

H Steel section	Plate Thickness mm	fy (MPa)	Standard Limits for fy [17]	fu (MPa)	Standard Limits for fu [17]	Elongation %	Standard Limits Elongation% [17]
flange	8	278	>250	427	400-550	21	>20
web	6	261	>250	409	400-550	24	>20

3. Concrete Mix Design

The concrete mix was designed according to the American standard [18]. Several trial mixes were conducted to achieve a compressive strength of 30 MPa, as shown in Tables 5 and 6. Coarse aggregate with a maximum size of 12.5 mm was selected to ensure uniformity of the mix and ease of handling. The water-to-cement ratio was set at 0.48 to balance strength and durability requirements. The slump value was adjusted to range between 75-100 mm, ensuring an adequate level of workability and ease of pouring. The final concrete mix demonstrated high workability.

Table 5. Properties Of the Concrete Mix Used.

Materials	Quantity per 1m^3
Water/cement ratio	0.48
Water (Kg/m^3)	216
Cement (Kg/m^3)	450
Fine aggregate (Kg/m^3)	714
Coarse aggregate (Kg/m^3)	912

Table 6. Compressive strength test of cubes

Sample	Compressive Strength (MPa)
1	31.7
2	32.6
3	32.1
4	33.9
5	32.3
6	31.8
Average	32.4

4. Experimental Program

Ten composite columns 140x140x2800mm were fabricated using plywood forms. The H steel sections were placed and leveled in the molds with the 4 bars with 8mm diameter longitudinal reinforcement and stirrups of 6mm diameter each 150mm spacing, as shown in (Fig.3). Concrete with a compressive strength of 30 MPa was cast and used for the molds by employing a vibrator during casting. Six standard concrete cubes (150x150x150 mm) were used to test compressive strength, and six standard cylinders (150x300 mm) were used to test tensile strength. The concrete was cured by spraying potable water for 28 days, then transported to the laboratory for testing. Four strain gauges of type (FLAB-6-11-3LJC-F) of 6 mm length were used on each column, glued to the top and bottom flanges of the steel section. Another two gauges (PFL-30-11-3LJC-F with a length of 30 mm) were fixed on the concrete at the center of the column, as shown in (Fig.4). Two types of openings were used: a circular opening with two diameters of 15mm and 30mm, and square openings of 13.35 mm and 26.6 mm. The openings were placed in symmetrical positions at the top and bottom flanges and web, with a distance in the longitudinal direction of 150mm on centers, as shown in (Fig.5). Specimens made with 12.5mm diameter and 17.5mm length stud shear connectors were installed and welded at locations similar to the openings' locations, as shown in (Fig.6) and Table (7) shows the details of the specimens. The LVDT (Linear Variable Differential Transformer) with an accuracy of 0.001 was mounted to measure the slip between the concrete and steel sections. The eccentric loads were applied to the specimen through a thick steel plate (25mm) using a hydraulic jack having a capacity of 1000 kN with a load cell connected with all other measuring instruments (LVDT and Strain gauge) to the data logger used to record readings during the test as shown in (Fig.7). All test data were exported from the data logger to the computer in Excel format. The work conducted in the Civil engineering department's material laboratory, at university of Mosul, which has a certificate from the C.O.S.Q.C.IQ. (Iraqi Central Organization for Standardization and Quality Control) and Iraqi Accreditation System. The accuracy of the measurements and testing ensured by a qualified technician, double check all measurements and using a calibrated equipment.

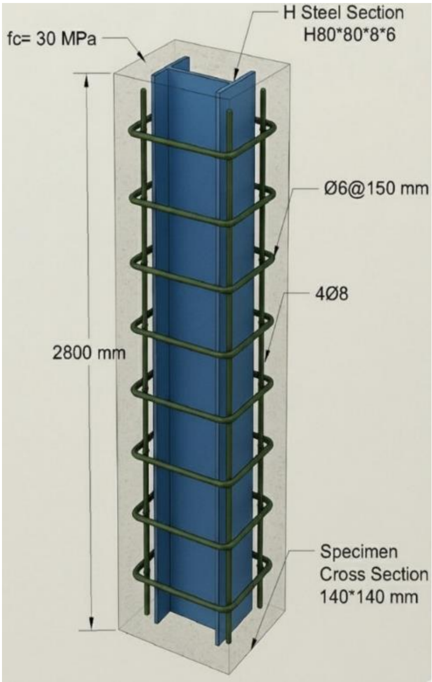
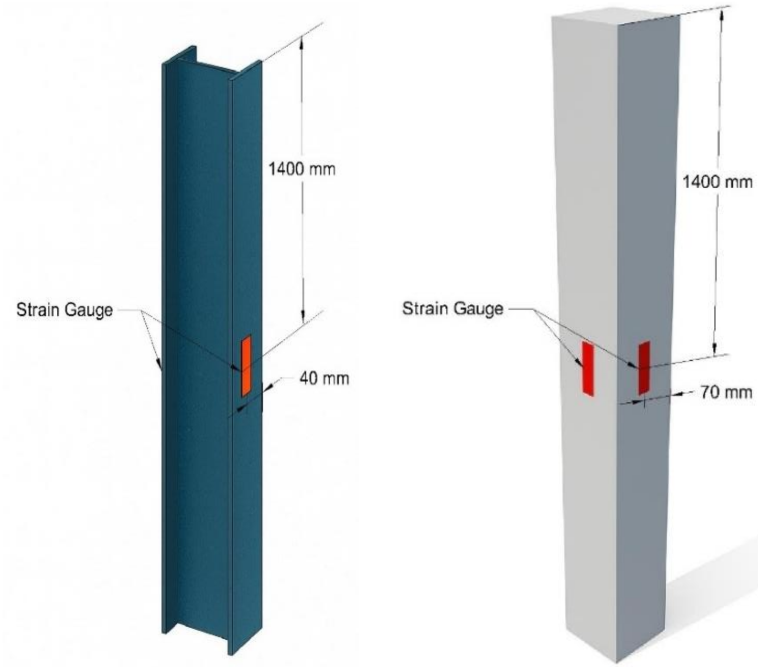


Fig. 3. Composite columns reinforcement



(a) (b)

Fig. 4. Strain gauge locations

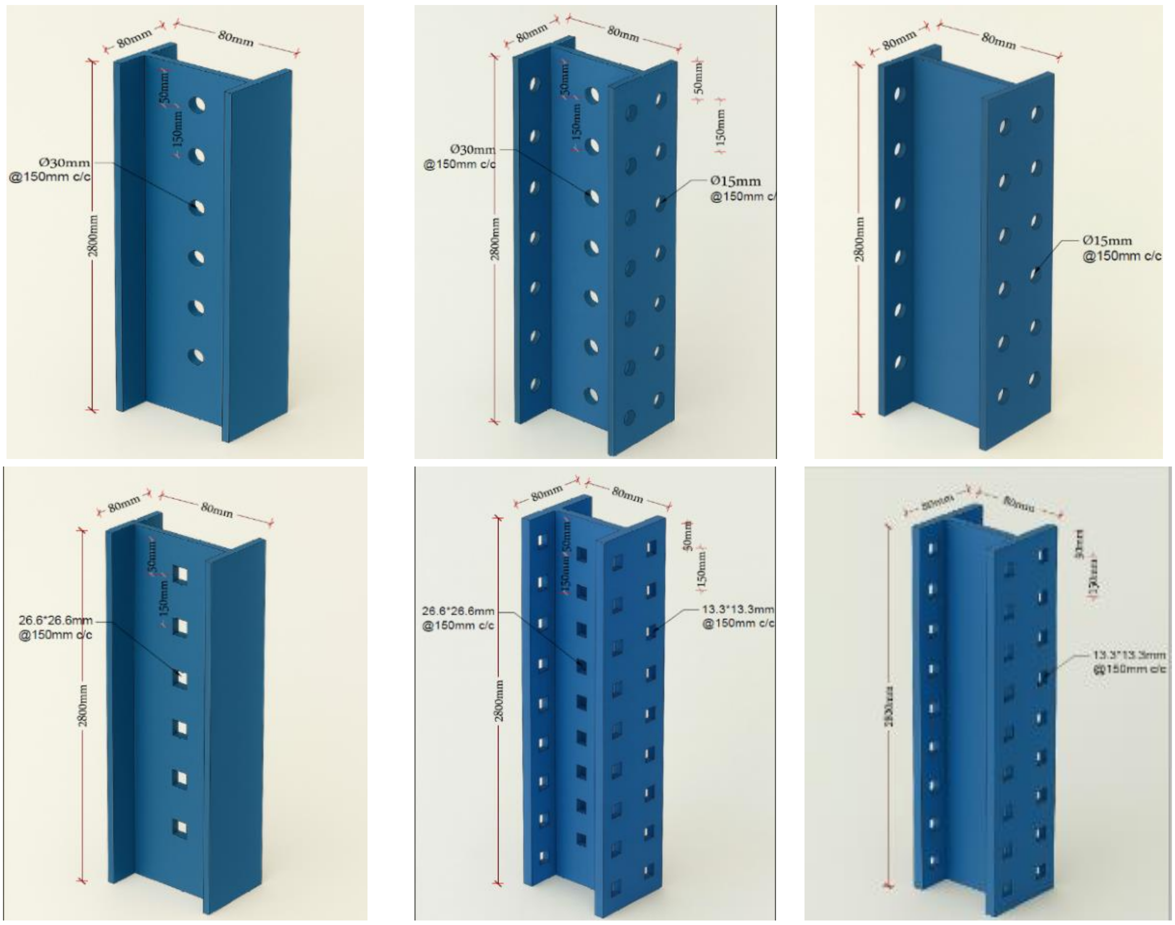


Fig. 5. Shape, details, and locations of the openings

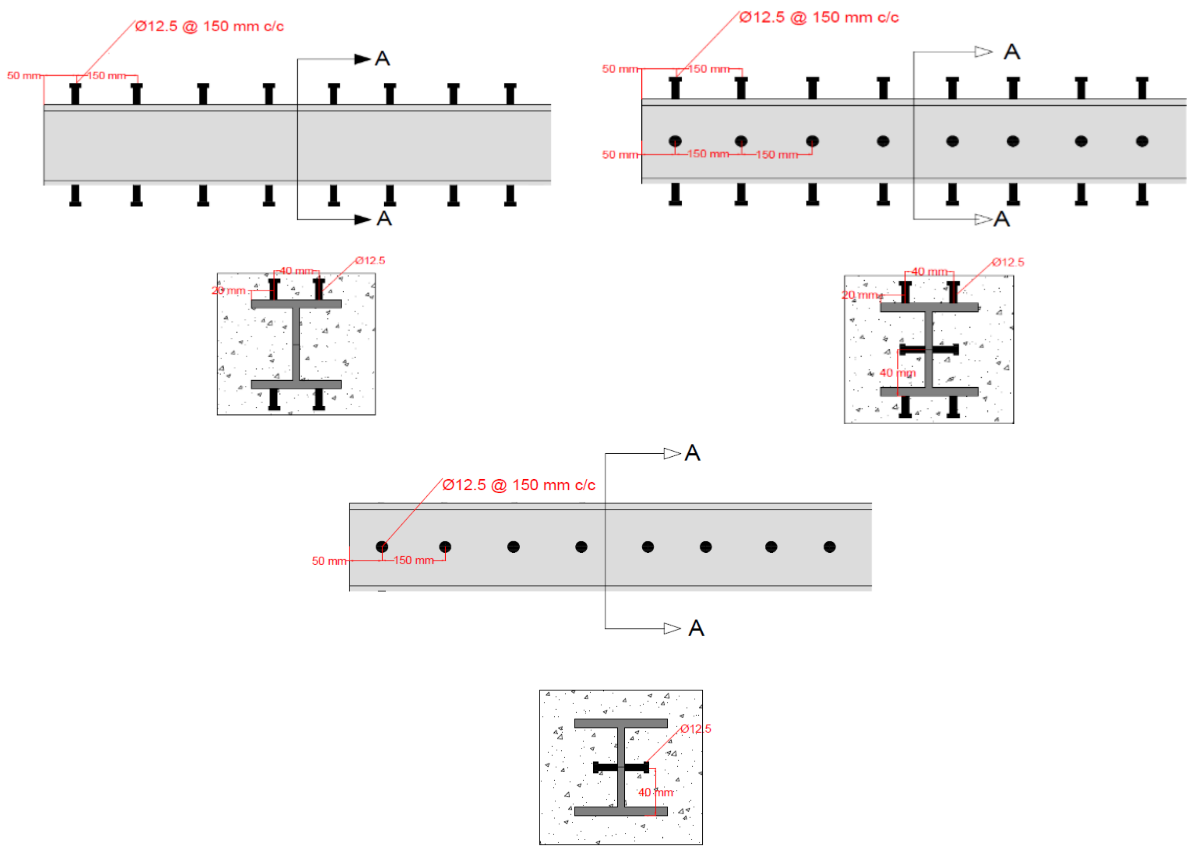


Fig. 6. Shape, details, and locations of the headed studs

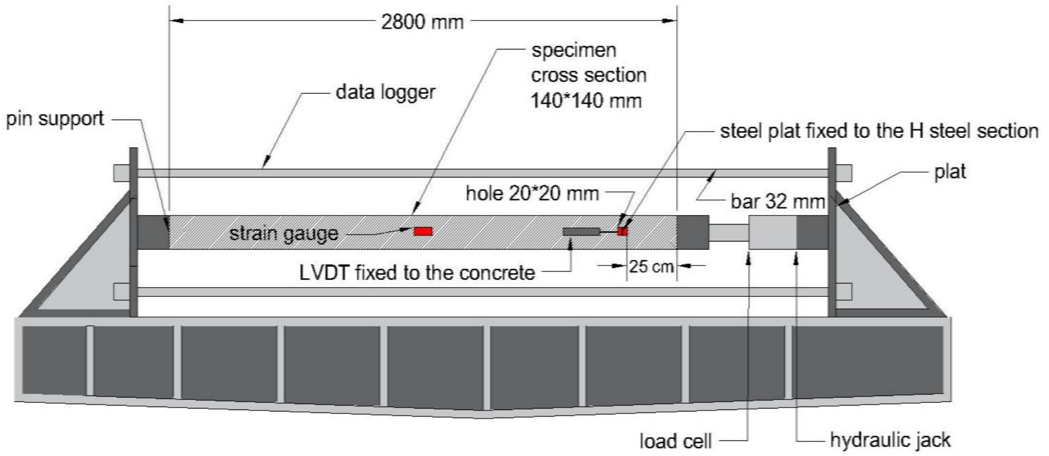


Fig. 7. Illustrates the preparation of the specimen for testing and the details of the main testing apparatus

Table 7. Specimen details

No.	Specimen	Hole Shape	Number of Holes	Cross-Section Area mm^2	Location of Parameter	Dimension of opening mm
1	CO2	no hole	No holes	1664	Non	nill
2	OFS2	square openings	72	1238.4	Flange	13.3*13.3
3	OWS2	square openings	18	1504.4	Web	26.6*26.6
4	OFWS2	square openings	90	1078.8	Flange and web	13.3*13.3 26.6*26.6
5	OFC2	circular openings	72	1184	Flange	Ø15
6	OWC2	circular openings	18	1484	Web	Ø30
7	OFWC2	circular openings	90	1064	Flange and web	Ø15 Ø30

No.	Specimen	Connector	Number of Conn-ector	Cross-Section Area mm²	Location of Parameter	Dimension of Connector mm
1	SF2	Headed shear studs	72	1664	Flange	Ø12.5
2	SW2	Headed shear studs	36	1664	Web	Ø12.5
3	SFW2	Headed shear studs	90	1664	Flange and web	Ø12.5 Ø12.5

5. Mechanism for Applying Loads to The Specimen

the eccentric load, applied from one direction at a distance of) e=35 mm (from the center of the applied load on the specimen, corresponding to a ratio of (e/h = 0.25) This ratio is commonly used in experimental studies as it represents a moderate eccentric loading condition, not too small not to affect the behavior, and not too large to cause an uncontrollable failure. This type of loading was designed to simulate realistic structural loading conditions, in which loads are often applied outside the section's centroid, thereby generating additional moments that influence the column's structural behavior. The specimens were supported during testing using a pin support, as illustrated in Fig.8, which details the loads and the mechanism of their application on the specimens.

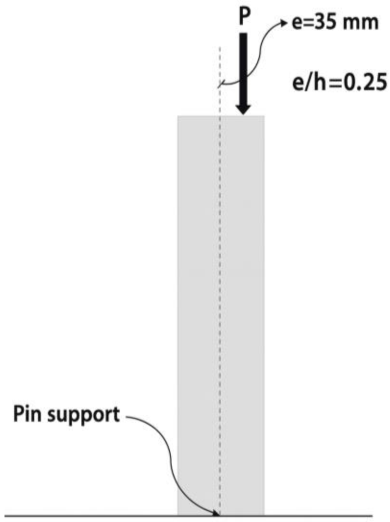


Fig. 8. Mechanism for applying loads

6. Test Results

6.1 Composite Columns Containing Circular Openings

This study evaluated the behavior and performance of three different models of composite columns featuring openings in the steel section subjected to eccentric loads (OFC2, OWC2, OFWC2) are shown in (Fig.9) (Fig.10). The analysis was directed towards several factors including the effect of the openings on the load-bearing capacity of the column as compared to hosts without openings. Also, the load-slip response between the steel and concrete parts was studied, and possible failure mechanisms were explored. During the load application process on the model (OFC2), cracks appeared in the concrete at the mid-height of the column. As the applied loads increased, the cracks continued to propagate from the middle towards both sides of the column. Additionally, the column exhibited buckling with cracks forming in the first third of the column in the direction of the applied load. These cracks continued to develop until final failure at the column head, where the concrete crushed in a layered manner, with one layer stacking over another .For model (OWC2), cracks initially appeared at mid-height of the column during load application and continued to increase as the column buckled, leading to final failure at the column center .In the last model (OFWC2), cracks appeared near the load application area and continued to propagate in a layered manner until final failure, when a fracture occurred in the steel section, resulting in the flange separating from the web. Minimum slip levels in the column with circular openings are attributed to several interlinked factors, compared to the reference column.

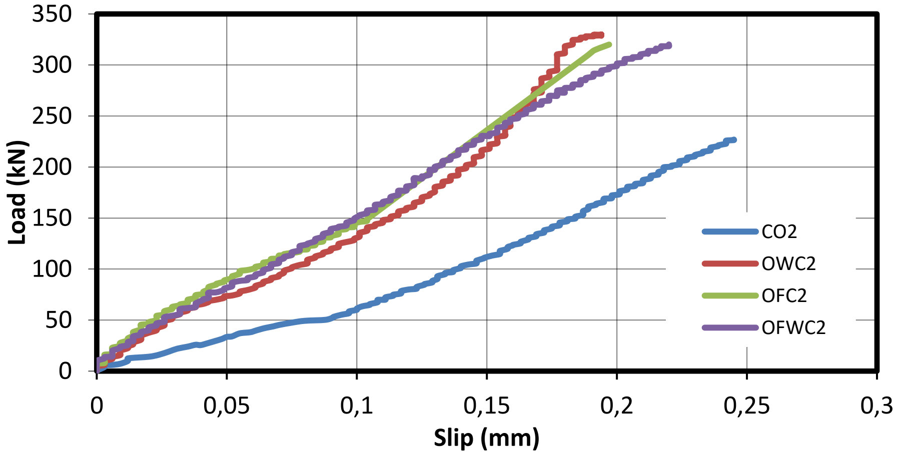


Fig. 9. Load-Slip for Specimen CO2, OFC2, OWC2 and OFWC2

(a)

(b)

(c)

Fig. 10. Failure mode of the specimen. (a) OFC2, (b) OWC2, and(c) OFWC2

Firstly, the openings assist in redistributing stresses in the Steel section, reducing the concentration of forces at specific points and thus minimizing slip. Furthermore, the steel's exposure area is reduced, leading to reduced direct frictional impact a significant cause of slip in the reference column. Besides this, the slots enhance the column's versatility, allowing it to better adjust to applied loads with no or minor slip. They also reduce stress concentration at the surface of the steel section, thereby decreasing the forces that cause slip. In addition, the openings change the failure mechanism. The column with openings depends more on composite action than on frictional resistance, unlike the reference column. The bearing stresses at the contact area of concrete inside the circular opening will increase the connections and enhance axial load resistance but the rotation depends only on the friction between the steel and concrete at the contact face. Meanwhile, the use of square opening will cause stress concentration at corners, which enhance the rotation resistance rather than the bearing stress. [18] Finally, the openings also increase the column's stiffness and allow it to accept loads more easily, with fewer slips than the reference column.

6.2 Composite Columns with Square Openings

To investigate the influence of eccentric loads on the behavior and performance of composite columns with square openings (OFS2, OWS2, OFWS2) in their steel sections, tests were carried out on three models of composite columns. These openings were used to assess their impact on the columns' load-carrying capacity, compared with results from models without openings. The interaction between the steel and concrete components was analyzed regarding load-slip behavior to identify potential modes of failure for each model. During the testing process of model (OFS2), cracks began to appear in the lower third of the column, accompanied by buckling. The concrete continued to fracture and buckle until reaching ultimate failure. As for model (OWS2), during loading, cracks formed in the upper third of the column, along with buckling towards the back and upward. These cracks continued to propagate along with the buckling until ultimate failure. In the last model (OFWS2), cracks initially appeared in the middle of the column, accompanied by upward buckling. The buckling continued to increase, along with the expansion of cracks, until the column reached ultimate failure.

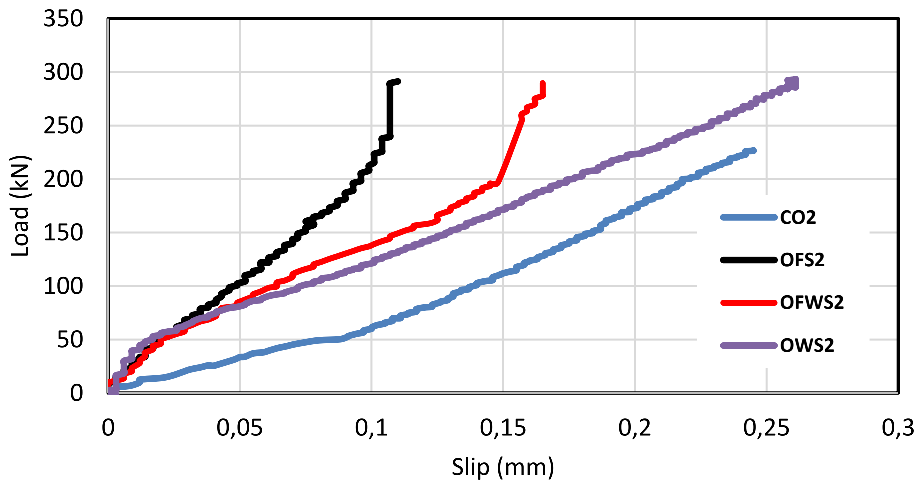


Fig. 11. Load-slip for specimen CO2, OFS2, OWS2 and OFWS2

The load-slip curves obtained from the tests are shown in (Fig.11) (Fig.12), illustrating the response of the specimen under the effect of eccentric load. The presence of openings leads to greater stress concentrations in the regions surrounding the openings; therefore, the columns typically fail at discrete locations around the opening(s) rather than, for example, gradually failing throughout the whole column along its length or width. Regarding the position of openings, flange openings significantly influence the slip response more than web openings. The flange is a critical transfer element for axial loads between steel and concrete. Thus, a few openings in the flange decrease the effective contact area and spread the stresses to other places, thereby minimizing slip.

(a)

(b)

(c)

Fig. 12. Failure mode of the specimen. (a) OFS2. (b) OWS2. (c) OFWS2

6.3 Composite Columns with Shear Studs

The study was carried out on composite columns with shear studs in the steel section (SF2, SW2, SFW2) under eccentric loading. The test was conducted on three composite column models. The bond behavior between the steel section and the concrete was studied. The load–slip curve was drawn separately for each model, providing a deeper understanding of the effect of vertical shear studs on the cohesion and bond between the steel section and the concrete, as well as the ultimate load capacity under eccentric loads. During testing of the model (SF2), the concrete began to fracture near the top of the column. It continued to break until ultimate failure, when the flange separated from the web at the load application area. The same failure pattern was observed in model (SW2). As for the last model (SFW2), the concrete also began to fracture at the top of the column and continued to deteriorate until reaching ultimate failure. The load-slip curves were plotted, as shown in (Fig.13), and the Failure mode of the specimens in (Fig.14), illustrating the response of the specimen under the effect of eccentric load. Shear studs improve the connection between steel and concrete, reducing slip. However, the effectiveness of the studs depends on their location. Since the flange primarily transfers loads between steel and concrete, shear studs placed in the flange are more effective in reducing slip. On the other hand, studs placed on the web are less effective at transferring forces than those in the flange, limiting their impact.

Regarding load-bearing capacity, the reference column has a higher capacity and exhibits more ductile failure. Stress is distributed more uniformly when loads are applied, resulting in better load-bearing capacity for the column than for columns with shear studs. Columns with shear studs show slightly lower load-bearing capacity and more brittle failure. This means that failure is not uniform throughout the column; rather, it is more severe in areas of localized stress around the studs.

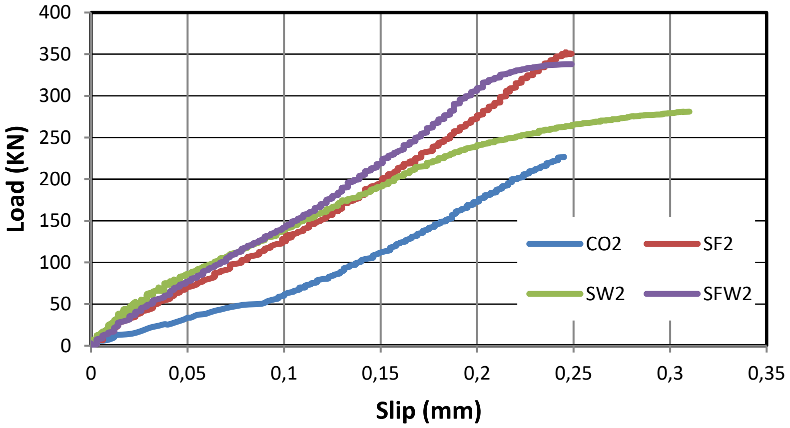


Fig. 13. Load-slip for Specimen CO2, SF2, SW2 and SFW2

(a)

(b)

(c)

Fig. 14. Failure Mode of The Specimen (a)SF2. (b)SW2. (c)SFW2

7. Effect of The Shape and Location of Openings

Six composite column models with various openings were tested to investigate the effects of openings under eccentric loads. There were three columns with circular openings (OFC2, OWC2, OFWC2) and three with square openings (OFS2, OWS2, OFWS2). The openings were placed at different locations in each model, and two opening shapes were used to study the effects of location and shape on slip behavior and load-bearing capacity. The models were tested under eccentric loads, and load–slip curves were drawn for each. The curves provided a deep understanding of the models' performance under the influence of eccentric loads. The curves also showed the effects of the shape and location of the openings on the mechanical properties of the composite columns. They allowed comparison of the structural performance of composite columns with openings. The load-slip curves indicate that the slip between the steel and concrete sections of a composite square column is lower than that of a composite column with a circular opening. There are several reasons for this effect; the first is that the square shape has sharp corners, which act as resistance factors, preventing the limited concrete in the steel section from transferring, reducing its tendency to rotate. These corners help to develop the mechanical bond between concrete and steel much better than the circular openings do.

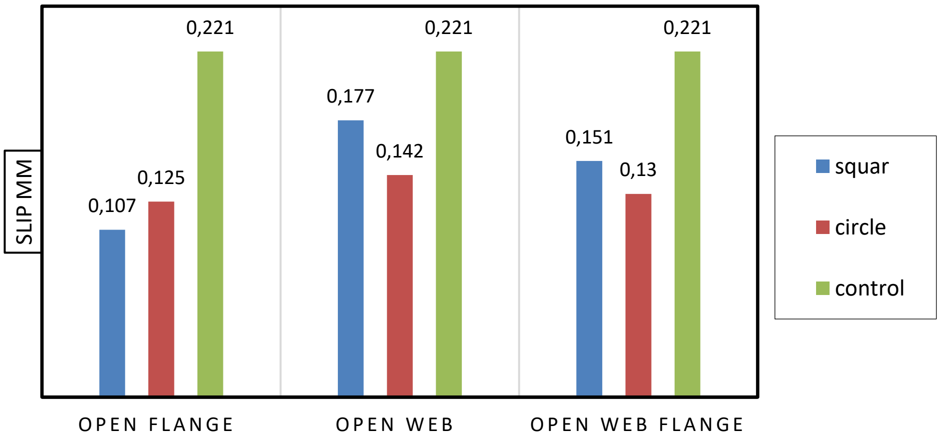


Fig. 15. Slip values at a load of 200 kN for columns with circular and square openings

Table 8. Slip at load 200 (kN)

Code	Slip (mm)	%Slip Decrease
CO2	0.221	reference
OFS2	0.107	51.5
OFC2	0.125	43.4
OWS2	0.177	20
OWC2	0.142	35.7
OFWS2	0.151	31.6
OFWC2	0.130	41

Shown in Figure 15 and Table 8 is the effect of the shape of the openings on reducing slip between the concrete and steel portions of the column under a load of 200 kN. Square edges allow for greater contact between materials because they have a larger internal surface area than circular edges. This increased contact helps improve friction resistance between the concrete and steel, lessening slip under axial loads. The additional friction from the larger contact area enhances the column's cohesion and load-bearing capacity. As a result, it can be concluded that the use of square openings improves bonding between concrete and steel.

Table 9. Summary results

Code	Load at yield (kN)	Slip at yield Load (mm)	Ultimate Load (kN)	Slip at ultimate Load (mm)	Load Increasing%	Ductility index
CO2	140	0.175	227	0.245	reference	1.3
OFC2	170	0.11	320	0.197	40.96	1.79
OFS2	150	0.09	300	0.168	32.15	1.87
OWC2	156	0.116	328	0.194	44.5	1.67
OWS2	180	0.157	285	0.261	25.55	1.66
OFWC2	173	0.118	320.1	0.22	40.97	1.86
OFWS2	140	0.133	287	0.23	26.43	1.73

The minimum slip gained from using opening in flanges can be attributed to the increasing in rotation resistance mainly depends on the coupling of tension and compression forces at both tension and compression zones. Moreover, the presence of openings increased the ductility index and the ultimate load capacity of composite columns with openings, as shown in Table 9. This improvement can be attributed to the fact that the presence of openings enhanced the columns' ability for plastic deformation and increased their capacity to absorb the applied loads.

8. Comparison Between Composite Columns with Shear Studs and Columns with Openings in the Steel Section Under Axial Load

The objective of this study is to investigate eccentric loaded behavior of composite columns with shear studs, without shear studs but possessing openings in the steel section, and to explore whether it is possible to remove shear studs and use openings instead. They included three with square openings, three with a circular opening, and three with shear studs. Load-slip curves were used as a diagnostic tool to examine each model's response to variations in cohesion and slip behavior under load. Results indicate that shear studs in those columns develop high levels of cohesion and minimize slip, whereas openings can affect the force transfer mechanisms and stress distributions. It was shown that the potential of using cohesion as an effective alternative in cases where columns with openings achieve safe and efficient designs that satisfy structural performance requirements and even exhibit behavior similar to that of columns with shear studs, which comply with the results obtained by Al-Darzi, 2007 [18]. The results also showed a close similarity in the behavior of columns with shear studs and those with openings, as the openings in the steel section significantly improve slip resistance between the steel section and the surrounding concrete., as shown in Table 10.

Table 10. Slip decreases at load 200 (kN)

Code	Slip (mm)	%Slip Decrease
CO2	0.221	reference
SF2	0.151	31.67
OFS1	0.107	51.5
OFC1	0.125	43.4
SW2	0.157	28.95
OWS1	0.177	20
OWC1	0.142	35.7
SFW2	0.139	37.1
OFWS1	0.151	31.6
OFWC1	0.130	41

Table 11. Slip decreases at load 200 (kN)

Code	Load at yield (kN)	Slip at yield Load (mm)	Ultimate Load (kN)	Slip at ultimate Load (mm)	Load Increasing%	Ductility index	Standard Deviation
CO2	140	0.175	227	0.245	reference	1.3	0.06725
OFC2	170	0.11	320	0.197	40.96	1.79	0.04078
OFS2	150	0.09	300	0.168	32.15	1.87	0.03761
SF2	150	0.119	350	0.247	54.18	2.08	0.07366
OWC2	156	0.116	328	0.194	44.5	1.67	0.06003
OWS2	180	0.157	285	0.261	25.55	1.66	0.08739
SW2	191	0.151	281	0.31	23.78	2.05	0.09717
OFWC2	173	0.118	320.1	0.22	40.97	1.86	0.06772
OFWS2	140	0.133	287	0.23	26.43	1.73	0.05500
SFW2	176	0.126	338	0.249	48.9	1.99	0.06886

Moreover, the presence of shear studs leads to an increase in the ductility index of the composite columns, in addition to an increase in the ultimate load capacity of the columns. Table 11 summarizes the results for all specimens tested. The standard deviation shown in Table 11 explained that the results deviate with no more than 9%.

9. Conclusions

In this study, the test results for self-connected composite columns were obtained. The effect of openings in the steel section on the slip behavior and ultimate load-bearing capacity of the composite columns was investigated through load–slip curves. The influence of the shape and location of the openings on the column behavior was also examined. Furthermore, these columns were compared with columns with vertical shear studs to assess the feasibility of replacing conventional shear studs with openings. Based on the experimental results, the main conclusions obtained within the limits of the present work were as follows:

- The use of headed stud connectors will increase the column ultimate load resistance with a ductile behavior having less slip compare with the control specimen.
- The composite column with opening gives larger resistance compare with control specimen and reduce the slip between the steel and concrete. The results showed that the composite columns containing openings exhibited an increase in ultimate load-bearing capacity. The increase in columns with square openings in the flange reached 32.15%, while the rise in columns with circular openings reached 40.96%.
- The composite column with opening gives lesser resistance compare with headed stud specimen, but reduce the slip between the steel and concrete.
- The shape of opening affects the behavior of the composite column. The composite columns with square openings in the flange give a larger slip reduction than those with circular openings. The slip reduction for columns with square openings was 51.5%, while it was 43.4% for columns with circular openings. It can be stated that the use of openings leads to better bonding between the concrete and the steel, thereby enhancing composite interaction within the column and making openings a more effective means of improving structural performance.
- The results show that the shape and location of the openings have a significant effect on slip in composite columns, as the results indicated that openings located in the flange area play an essential role in reducing slip. The web area plays a minor role in opposing slip compared to the flange, which governs the steel and concrete's load transfer and bond mechanism. These openings can create a mechanical bond between the steel section and the concrete by interlocking the concrete with the steel section.
- The composite columns containing openings exhibited a higher value of the ductility index, indicating that the presence of openings enhanced the columns' ability for plastic deformation and increased their capacity to absorb the applied loads.

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