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Behavior of Composite Geopolymer Reinforced Concrete Beams with Openings using an Underneath Steel Plate

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Abstract

Steel-composite-reinforced geopolymer concrete beams combine the strength of steel with the sustainability of geopolymers, offering a sturdy structural solution. This approach results in a composite material with excellent crack resistance and durability. The current research focuses on the impact of steel connectors on the flexural performance of composite-reinforced geopolymer concrete beams with transverse web openings, using experimental methods. The experimental program involves casting four geopolymer beams, with one being a traditional geopolymer-reinforced concrete beam (Control). The remaining three specimens are composite reinforced geopolymer concrete beams, each featuring a bottom 3 mm steel plate with six, twelve, and eighteen connectors near each support. The beams have dimensions, with a total length of 1600mm, a height of 250mm, and a width of 180mm. The results showed that increasing the number of connectors near supports increased the resulting flexural behavior of beams from about 7% to about 45% for different characterization parameters. Such connectors increased the first crack load from 6.67% to 42.22% while the service load increased from 16.22% to 36.20%. The load carrying capacity was also increased from 12.00% to 24.80%. Finally, the mode of failure was moved from traditional tension failure to concrete crushing.

Keywords: Bending; Composites; Connectors; Geopolymer Concrete; Steel Beam

1. Introduction

The collaboration between concrete and steel in composite construction brings about notable advantages. As indicated by several sources in the literature, the advantages of composite construction include rapid Steel Framework Erection; composite construction allows for a quick and efficient erection of the steel framework, saving time during the construction process. In addition, it enhances Structural Strength and Performance: The combination of concrete and steel results in structures with increased resilience and satisfactory performance during their service life. Furthermore, composite construction leads to a substantial decrease in the structure's weight and the overall materials cost, making it a cost-effective choice for construction projects [1].

Contemporary composite construction follows a specific sequence of actions. Initially, the steel framing elements are lifted into position, forming a robust structure capable of supporting various construction loads. Subsequently, the composite action takes place, where concrete or another material is introduced to provide resistance to external loads. Additionally, the stiffness and strength of the structure are significantly improved by the combined effort [2].

In modern engineering, serviceability requirements are crucial, and managing deflections and vibration response is just as crucial as guaranteeing load resistance. The main goal is to look at cutting-edge composite building technology that combines the use of in-situ concrete and steel sections cooperatively. In a range of building construction scenarios, this construction technique lowers material prices, expedites construction, permits bigger spans, and enhances overall efficiency [3]-[5].

Applying composite construction approaches wisely can unlock an array of benefits and optimize operational capabilities within the domain of service complexity [6]. Exploring the rich tapestry of conventional composite building reveals a story in which concrete slabs and steel beams perform together in perfect harmony to support applied loads on the structural frame. For composite slabs, steadfast guardians in the quest for increased structural integrity, adding more than just parts, acting as conduits for stiffness and strength, and creating an elaborate story within the architectural system [7].

However, in this delicate dance of materials, there is an inherent weakness that shows itself when the connection between the concrete slab and the steel beam is neglected. Imagine that loads are applied to the structure, and that the basic basis of structural stability is threatened by relative slippage in the absence of a strong connection. The grand symphony of performance is threatened by this possible slippage, a covert enemy that raises questions about the safety citadel and structural efficiency [8]–[9].

In the complex movement of structural harmony, preventing the potential danger of relative slippage becomes critical, requiring the coordination of a connection that is not only functional but also perfectly engineered and built.

Frequently appearing stud and shear connectors are essential techniques in structural engineering. They function like virtuosos, skillfully tying together steel beams and concrete slabs into a seamless, melodic ballet. When these components are linked, they become defenders of unity, transforming various parts into a single composite object. Witness the magic as concrete and steel come together, dancing to enhance the building's ability to bear weight and improve its overall structural performance. This process of alchemy is crucial for creating a robust and durable structure [9]-[11].

There are many advantages to composite construction, including increased stiffness, increased load-bearing capability, and better material use. As is frequently noted, the combined strength of steel and concrete regularly offers a dependable and economical structural solution in the construction of multi-story buildings and bridges [12],[13].

Other materials, such as pre-stressed concrete, aluminum, foam core, and timber, can be utilized in composite construction, depending on specific design requirements and application, although steel and concrete are the more prevalent choices for composite beams [14]-[16].

In fact, concrete is far stronger when compressed than when it is stretched. It has high compressive strength but relatively low tensile strength. On the other hand, steel is an excellent material for resisting tensile forces but can be susceptible to buckling under compression [17],[18].

Overall, composite beams provide a versatile solution to optimize the performance of different materials and create efficient and durable structural elements for various construction applications [18]-[21].

This study aims to make a substantial contribution to the research field by obtaining dependable findings on the performance of composite geopolymer concrete beams. Accurate experimental data are crucial for researchers trying to understand the relationship between the mechanical properties of geopolymer concrete and the structural performance of these beams.

2. Experimental Details

2.1 Mater2als

2.1.1 Fly 2sh

"EUROBUILD" high-low calcium fly ash is utilized as the source material for producing geopolymer concrete (GC).

2.1.2 Sand

The grading analysis was done in accordance with No.45/1984 (Iraqi specification) as shown in Fig 1.

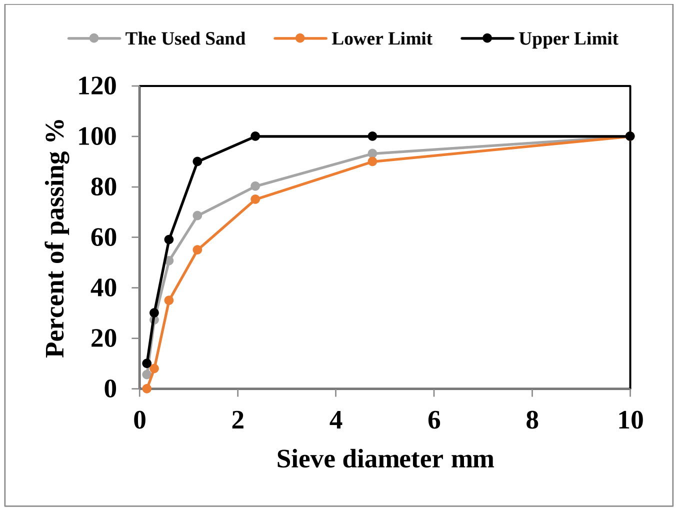

Figure 1. Sand grading curves

2.1.3 Gravel

Fig.2 illustrates the grading analyses of the gravel used in the present study in accordance with B.S 882/1992. The maximum size of this gravel is 10mm.

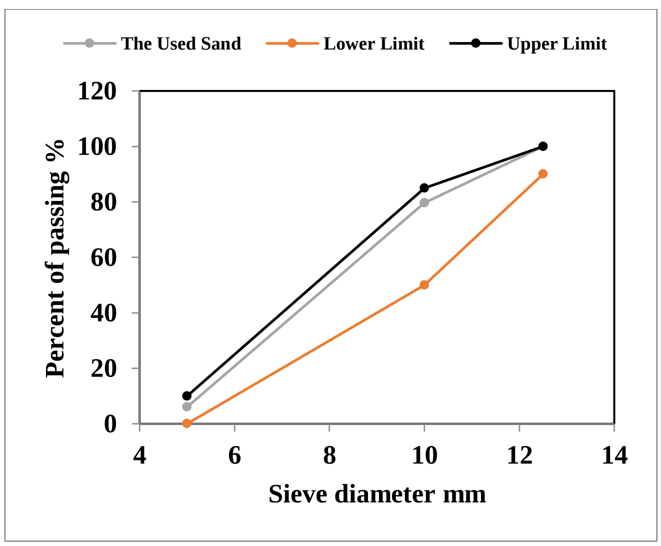

Figure. 2. Gravel grading curves.

2.1.4 Sodium Hydroxide NaOH

Sodium Hydroxide flakes were used to prepare a 10 M concentration to compound the alkali solution. The purity of such flakes is 98%.

2.1.5 Sodium Silicate Na_2SO_3

The water glass is compounded with NaOH to prepare the required alkali solution. According to the manufacturer, this sticky solution is about 55%.

2.1.6 Reinforcing Bars

The steel rebar diameters used in this study are 6mm and 8mm, respectively. Table 1. Shows the limitations of these rebars.

8mm and 12mm are the diameters used in this study. The bars were tested in accordance with American Testing Standard Measurements (ASTM) A615.

Table 1. Tension test results for steel bars within this study*

Nominal diameter mm	8	12
Normal diameter mm	7.89	11.983
Yield stress Mpa	517	705
Yield strain mm/mm	0.00201	0.00211
Ultimate strength Mpa	654	557
Ultimate strain mm/mm	0.167	0.171
Elongation %	10	9

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2.2 Mix Proportions

The concrete mix composition for the experimental program was determined based on the research by Abdul Aleem and Arumairaj (2012). The final mix proportions used for casting the specimens are detailed in Table 2.

Tables 2. The mixed proportions

Material	Sand	Gravel	Fly ash	10 Molar NaOH	Sodium Silicate
Quantity (kg/m^3)	571.2	1305.6	408	41	103

2.3 Specimens Details

Fig. 3 depicts the features of the tested beams in this experimental program. The stirrups, spaced at 120 mm, are of φ 8mm. The beam reinforcement includes 2 φ 8mm bars at the top and 2 φ 12mm bars at the bottom. The total section height is 250 mm, while the width is 180 mm. The total length is 1600 mm, while the center-to-center span is 1500 mm.

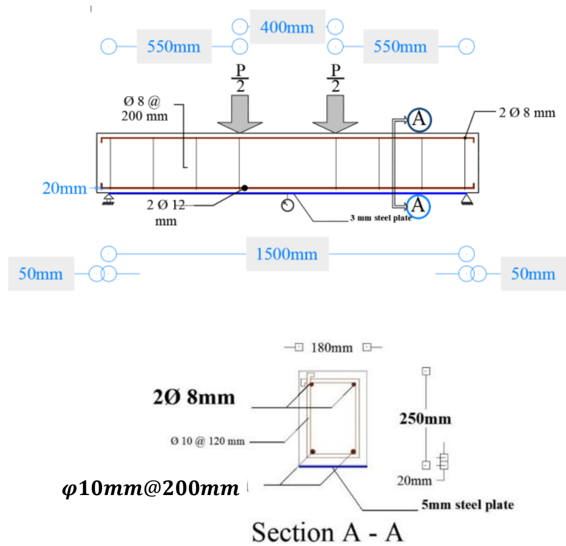
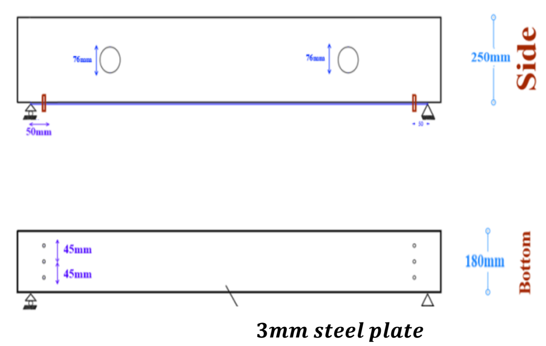
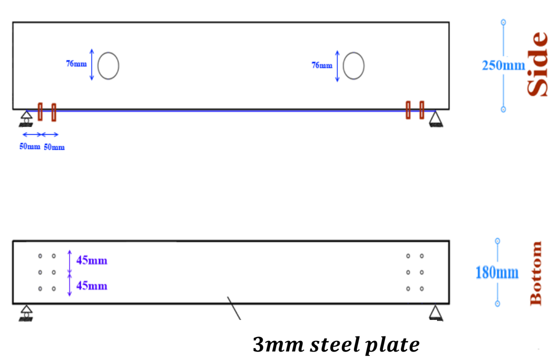


Figure 3. Specimen details of the present study

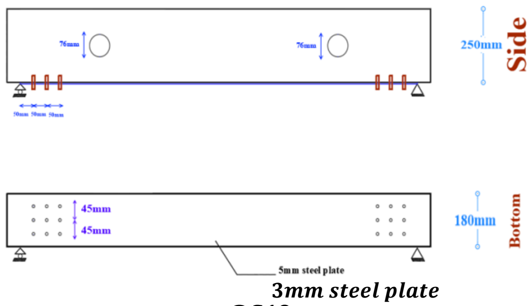
The first digit in is either (O), which refers to the existence of a transverse web opening. The second digit is (S), which means (Small transvers web opening). The last digit is a number that refers to the number of shear connectors. The initial sample is a solid geopolymer reinforced concrete composite beam with six bolts, three on the left and three on the right support. The second sample is a sturdy geopolymer reinforced concrete composite beam with twelve bolts, six on the left and six on the right support. The third sample is a robust geopolymer reinforced concrete composite beam with eighteen bolts, nine on the left and nine on the right, as shown in Fig 4.



OS6



OS12



OS18

Figure 4. Map of the current study

The map of the intended specimens is listed in Table 3.

Tables 3. Specimens designation

Specimen designation	Number of connectors
Reference	/
OS6	6
OS12	12
OS18	18

2.4 Molds

In the current experimental program, molds were created to cast specimens, and these molds were tailored to accommodate the required rebar. Their design allows for the easy adjustment of sides, ensuring precise dimensions for both the flange and web of the section. As shown earlier, the total section depth is 250mm and the width is 180mm. Commercial bolts were welded to the 5 mm plate at the specified location before installing the rebar mesh. For the second and third groups, the required transverse web opening was made by installing Poly Vinyl Chloride (PVC) pipes.

2.5 Mixing, Casting, and Curing Procedure

The blending process in this study program involved a series of carefully carried out processes to ensure perfect specimen preparation and casting. The following is a summary of the involved procedure:

2.5.1 Mixer Preparation

The rotary mixer was thoroughly cleaned before every mixing session to get rid of any residue from previous use. Maintaining the integrity of the ensuing mixes required this step. Such a mixer is shown in Fig.5.

Figure 5. The used mixer

2.5.2 Mold Preparation

After being cleaned, the casting molds were lubricated with an appropriate motor oil coating. This treatment enabled simple demolding and improved the cast specimens' overall quality.

2.5.3 Solution Preparation

Solutions of Na_2SiO_3 and NaOH were carefully produced at the necessary molar concentrations before the mixing process was started. The presence of consistent and precisely measured activators was guaranteed by this thorough preparation.

2.5.4 Material Mixing

Three materials were mixed together—sand, gravel, and fly ash—in the rotary mixer for sixty seconds. The uniform dispersion of aggregates and other elements was encouraged during this early mixing phase.

2.5.5 Addition of Activator Solution

The pre-made NaOH and Na_2SiO_3 solutions were fed into the rotary mixer, and the mixing process continued for 180 seconds. This period of time was chosen to ensure that the activators were thoroughly combined with the aggregate mixture.

2.5.6 Casting and Leveling

The well-mixed quantity was promptly cast into the prepared molds. A suitable trowel was employed to level the surface of the cast specimens, ensuring uniformity and precision in their form, as depicted in Fig. 6.

2.5.7 Curing Initiation

Following the casting process, the specimens were demolded after 24 hours within the laboratory conditions, marking the initiation of the curing phase. The specimens underwent curing under laboratory ambient conditions, setting the stage for subsequent testing.

Figure 6. Leveling the casted specimens

2.6 Beams Testing

To test all geopolymer concrete beam samples, the apparatus depicted in Fig 7. Was utilized. Prior to testing, the samples underwent brushing and were coated with white paint to enhance the visibility of any emerging cracks. Using a steel loading plate placed on a thin rubber strip for stability, two concentrated loads were applied to the samples. Initial readings from the strain gauge and dial gauge were obtained at the start of each experiment to set baseline values. The load was incrementally applied in each experiment, and readings of deflection, strain, and load were documented at each step to monitor the behavior of the samples. The load was gradually increased until failure occurred, enabling the observation and documentation of the progression of structural failure and associated changes in deflection, strain, and load.

Figure 7. Testing machine

3. Results and Discussion

3.1 P_{cr}, P_s and P_u

Table 4 shows the effect of connectors on such performance criteria for a composite geopolymer RC beam with a small transverse web opening.

When a small opening is evident, increasing the number of connectors from 6 to 12 and 18 increased PCR by 6.67%, 28.89%, and 42.22%, respectively. Additionally, such changes increased Ps by 12.45%, 17.28%, and 23.46%, respectively, for the same order above. For P_u and with the presence of a small transvers web opening, increasing the number of connectors from 6 to 12 and 18 increased this value by 12%, 16.8%, and 24.8%, respectively. P_{cr}, P_s, and Pu values are more than the reference despite the presence of transverse web openings, but due to the added moment of inertia.

However, understanding the impact of the subtracted concrete volume on the resulting Pcr, Ps, and Pu is a rich source for future research.

Table 4. P_{cr} P_s and P_u of the tested beams.

Specimen Designation	Reference	OS6	OS12	OS18
P_{cr} (kN)	22.5	24	29	32
P_{cr}%	/	6.67	28.89	42.22
P_s (kN)	103.6	116.5	121.5	127.9
P_s %	/	12.45	17.28	23.46
P_u (kN)	125	140	146	156
P_u %	/	12	16.8	24.8

3.2 Deflection at Service Loads, Deflection at Maximum Load Δm, and Load Deflection Paths

Table 5. shows the impact of connectors on Δm and Δs of composite geopolymer RC beam with small transversal web opening.

Table 5. Δ_s and Δ_m of composite geopolymer RC beams with small transverse web opening.

Specimen Designation	Δ_s (mm)	Δ_s %	Δ_m (mm)	Δ_m%
Reference	9.53	/	16.65	/
OS6	9.19	-3.57	15.97	-4.08
OS12	7.94	-16.68	15.17	-8.89
OS18	7.03	-26.23	14.55	-12.61

With the presence of a small transversal web opening, increasing the number of connectors from 6 to 12 and 18 decreased the relevant Δs by 3.57%, 16.68%, and 26.23%, respectively, while Δm levers were decreased by 4.08%, 8.89%, and 12.61%, respectively, for the same order.

Once again, it can be recognized that the gain in flexural rigidity results in a relevant gain in stiffness and a consequent decrease in Δs. But by comparing each specimen with the corresponding one in the first group, the values are less because of the differentiation in flexural rigidity, which is dictated by the existence of the small transverse web openings. Regarding Δm, the Δs values differentiation consequences were repeated because, as an expected result, in the load deflection response.

Fig. 8 illustrates the load deflection response of the Reference, OS6, OS12, and OS18, respectively. The same phases were repeated within the current group. This initial phase is characterized as elastic, extending until the beam reaches the first cracking limit. During this phase, the materials behave elastically, and no cracks are visible, but begin at their ends.

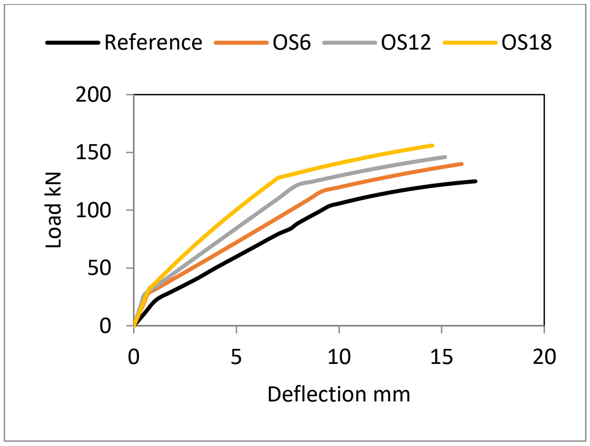


Figure 8. Load deflection diagram of composite geopolymer RC beams.

The transition to Phase II happens after reaching the first cracking load. In this phase, the number of cracks increases, and their width progressively expands until reaching the service load (Ps).

The final phase, Phase III, commences after reaching the service load (Ps). This phase is characterized by a further widening of the cracks and the final fracture of the beam at the end of its load-bearing capacity.

For the composite beams, the same phases were observed, including some observed differences. Cracking appeared at the extreme fiber of compression as a consequence of the redistribution of stresses that originally resulted from the strengthening in the tension zone.

For all specimens, the point of inflection between Phase I and Phase II is also obvious, and Ps is also clear, irrespective of the number of connectors.

3.3 Stiffness Ratio (k)

Throughout the present study, the stiffness behavior of composite geopolymer RC beams is characterized by the stiffness ratio (k):

$$k = \frac{P_s}{\Delta_s} \qquad (1)$$

Where:

k= Stiffness Ratio (kN/mm).

Ps= Service load (kN).

Δs= Service deflection (mm).

Table 6 shows the number of connectors affecting k of the composite geopolymer RC beam with a small transversal web opening. With the presence of small, increasing the number of connectors from 6 to 12 and 18 increased the relevant k by 16.61%, 40.76%, and 67.36%, respectively. Increasing the number of bolts increased the stiffness of the beam. This is usually understood due to the relevant levels of P_s and Δ_s. However, if each specimen is compared with its corresponding one, the values are lower as a consequence.

Research efforts should be devoted to understanding and quantifying the relation between the subtracted concrete volume and the relevant stiffness of composite beams.

Table 6. k \ for composite geopolymer RC beams without transversal web opening

Specimen Designation	Δ_s (mm)	P_s (kN)	*k* kN/mm	*k* %
Reference	9.53	103.6	10.87	/
OS6	9.19	116.5	12.68	16.61
OS12	7.94	121.5	15.30	40.76
OS18	7.03	127.9	18.191	67.36

3.4 Ductility Factor (d)

During this study, the ductility behavior of composite geopolymer RC beams is characterized by the ductility ratio (*d*):

$$d = \frac{\Delta_m}{\Delta_s} \qquad (2)$$

Where :

d= Ductility factor.

Δ_m= *Maximum deflection (mm).*

Δ_s= *Service deflection (mm).*

It can be drawn from Table 7 that increasing the number of connectors in the tested beams from 6 to 12 and 18 decreased relevant d by 0.54%, while it increased by 9.35% and 18.46%, respectively.

For 6 connectors, the loss in structural rigidity dictated that this number of bolts is not able to recover the referential reading of d, while increasing the number of bolts to 12 and 18 added would do the required recovery because the additional confinement role in the third phase of load–deflection response.

Another research program should be done to investigate the effect of the concrete subtracted volume on the composite ductility.

Table 7. *d* for composite geopolymer RC beams with small transversal web opening.

Specimen Designation	Δ_s (mm)	Δ_m (mm)	*d*	*D* %
Reference	9.53	16.65	1.75	/
OS6	9.19	15.97	1.74	-0.54
OS12	7.94	15.17	1.91	9.35
OS18	7.03	14.55	2.07	18.46

3.5 Failure Mode: Visual Observation

Fig. 9 shows the failure mode of the composite geopolymer RC beams with a small transverse web opening. For OS6, the type of failure is known as (Beam Shear Failure), where the cracks extend along the center line of the transverse web opening. In contrast, the OS12 is known as (Frame Shear Failure).

In OS18, the failure occurred outside the transverse web opening, and the cracks began to appear from the point load application and the connectors zone simultaneously. This has happened because of the excessive number of connectors and the relative discontinuities between steel and concrete. However, this circumstance didn't break the order of Pcr, Ps, and Pu because of the lateral component of strength of the resulting fragment. Finally, the last view of failure is the pull-out of the concrete cover and lateral separation.

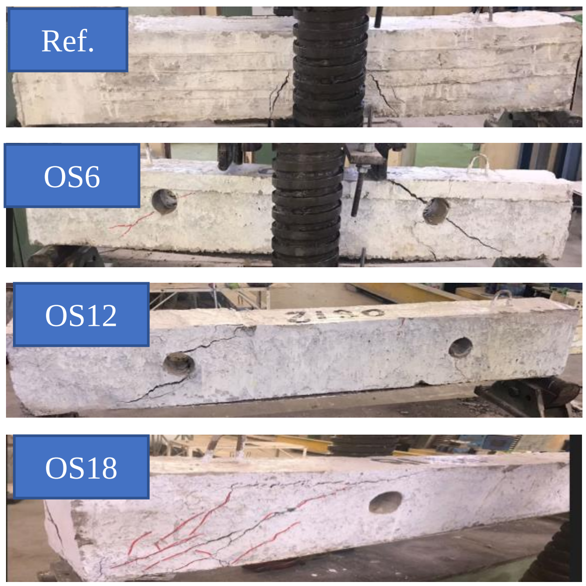


Figure 9. The failure modes.

4. Conclusions

During this study, it can be concluded that increasing the number of connectors results in an enhanced flexural performance for composite reinforced geopolymer beams that have transverse web openings. In addition, Cracking's load, the service load, and the load capacity were increased directly with the number of connectors. The stiffness and ductility factors of composite RC geopolymer beams were also increased with increasing such number according to the levels of service load, service deflection, and maximum deflection. Regarding the load deflection path, the same common three phases of RC beams were observed. However, further studies are required to explore the extent of correlation between the number of shear connectors and the resulting characterization parameters of structural behavior in specific boundary conditions of composite reinforced concrete beams. In addition, future studies should be extended to comprehend and measure the association between the number of connectors and the resulting stiffness of composite RC geopolymer beams.

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Conflict of interest

The authors assert that there are no conflicts of interest in connection with the publication of this manuscript.

Author Contribution Statement

Kafi Matloob collected and discussed the literature and did the experimental program.

Ali Sabah Al Amli proposed the research problem and discussed the results.

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