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Original Research

Steel Sheets' Effects on The Structural Behavior of Interior Voided Slab-Column Connections Subjected to Unbalanced Moment: An Experimental Study

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ABSTRACT

The voided slabs are susceptible to punching failure, especially when subjected to unbalanced moments. Therefore, this paper aims to introduce a strengthening technique using steel plates. This paper investigated the structural performance of a voided slab when strengthened using a steel plate at the interior voided slab-column connections. Two specimens were made with slabs measuring 1100 × 1100 × 130 mm, featuring styropor voids distributed throughout their area. A square column with dimensions of 150×150 mm and a height of 250 mm was extruded from the top face of a slab center. To verify the unbalanced moment, the beam was constructed at 150 mm x 150 mm and extended 150 mm from the column face, with a total length of 300 mm. Four steel sheets were embedded in one specimen to strengthen it by placing two plates in each direction; the other specimen served as the control without a steel plate. These sheets were intersected orthogonally below the column stub. The two specimens had eight square voids with dimensions of 250 mm × 250 mm × 70 mm. They tested under an unbalanced moment until failure. The test findings indicated significant enhancements in the strength, ductility, and toughness of the voided slab with a steel plate compared to the control slab without sheets. However, the addition of steel sheets proved to be an excellent solution for enhancing the structural performance of the voided slab, where strength, ductility, and toughness increased to 15%, 73% and 35%, respectively .

Keywords: Voided slab, Unbalanced moment, Steel sheet, Punching failure, Slab-column connections

1. Introduction

The most common slab in modern reinforced concrete (RC) structures is a flat plate that rests directly on columns rather than beams. Because it doesn't need beams, this kind offers several benefits, such as shorter building heights, easier and faster formwork, and more flexibility when passing horizontal services [1]. This slab system typically features thick layers to meet deflection requirements and prevent failure due to punching shear [2]. However, this creates an uneconomical design, particularly for buildings with enormous spaces, because the self-weight rises. Consequently, lots of methods were expected to result in lightweight slabs. The voided slabs created in 1990 by Danish engineer Jørgen Breuning involve placing a void within the cross-section of the slab between the reinforcing meshes. Consequently, the considerable size of inactive concrete is eliminated, and the slab weight is drastically decreased, making them lighter than 30–35% of the solid slabs at the same flexural strength [3]. Polystyrene and plastic are common lightweight materials used for void formers [4]. Donuts, cubical, and spherical voids were utilized [5]. "Bubble deck" and "biaxial slab" occasionally describe empty slabs. In addition, voided slabs are considered environmentally beneficial structural elements because (1) they save building resources, which is essential because making one tonne of cement emits roughly 500 kg of CO_2 into the atmosphere [6], and (2) they are made from recycled materials. Lots of studies on voided slabs have been done in the past ten years. When compared to conventional slabs of the same depth, voided

slabs had flexural strengths that were almost identical. On the other hand, when contrasted with the traditional alternatives, the voided slabs showed somewhat reduced responses.
[7]. If the voids were placed within the concrete portion subjected to tensile strains, Corey[3] found that the flexural strength of the voided slabs was equivalent to that of the conventional slab of the same thickness. Voided slab stiffnesses were 10-20% lower than solid slab stiffnesses due to the reduced cross-sectional area. Ibrahim et al.[8] found that the flexural strength of voided slabs was somewhat lower, approximately 11% lower, compared to equivalent solid slabs. In another study, the ultimate load capacity of voided slabs was found to be 20% lower than that of the same solid slab [3]. Khouzani et al.[9] determined how much the reinforcing mesh helped to increase the flexural strength of the voided slabs. The improvement was noticeable, and the flexural strength was unaffected by the spacing of the voids or their position relative to the depth of the slabs. Mahdi and Mohammed [10] conducted tests on five fixed-edge voided slabs using equally distributed loads. They found that when the voids made up 15-18% of the slab volume, the flexural strengths of the voided slabs were 11.5-16% lower than those of the solid slabs. Conversely, it has been proven that the shear strength of the voided slab is significantly reduced. The one-way shear capacity was 27% lower in void slabs with rounded holes and 40% lower in doughnut formers compared to solid slabs [11]. In addition, researchers found that voided slabs with different previous profiles had a much lower punching shear strength. According to earlier research, the voided slab's shear strength is considerably affected by the form and distance of the voids from the edges of the columns. The cylinder voided slabs' punching strength was determined with a void ratio of 10%. Comparable RC solid slabs have a punching capability of around 70% [12]. Using donut voids decreased the punching strength loss to 13%. The critical failure region was found at locations ranging from half a slab depth (0.5 d) after the column boundaries to 2.5 times the adequate slab depth (d), as assessed by the number of voids in the slab section [13]. Both Oukaili and Husain found that slabs with spherical voids placed 2d and d from the column sides lower the slabs' punching strength to that of solid slabs by 29.4% and 18%, respectively [14]. According to this research, the voided slabs' critical failure perimeters lasted approximately 4.2- 41.7% longer than in the solid slabs. Plastic voids in the form of hexahedrons with round corners and solid cross-shaped components were the subjects of Valivonis et al.'s research. According to the study, the punching strength was reduced by 18% when using the second form of voids compared to the solid reference slab. However, a considerable loss of over 43% was seen with the first shape[15]. Sadadevan and Rao [16] used critical shear crack theory (CSCT) to find the biaxial voided slab's punching strength. In this literature, experimental data were available, including roughly 40 specimens, which formed the basis of their conclusions. Based on their findings, voided slabs exhibited the same load-rotation responses as conventional ones, except that the voids in the former were located within half a degree of the column margins. The researchers also found that the punching strength was similar to that of regular slabs when the voids were placed more than 2 d from the column. Using glass fiber-reinforced plastic (GFRP) and steel fibers, Al-Azzawi and Mtashar [17] increased the voided slab's punching strength. Various slab types, thicknesses, steel fiber ratios, and GFRP sheet counts were examined over eight slabs. Specimen testing revealed that the punching strength, as well as the strength and ductility of the slabs, was enhanced by including steel fibers and GFRP sheets. Although punching failure is the major problem with voided slabs, typically built as flat slabs, there is very little research on the subject. They were all primarily concerned with impacting the design of a solid zone around columns and changing the control limit for punching strength calculations in popular codes of such slabs. Nevertheless, a substantial increase in the number of workers or a delay in the building timeline might result from the extensive attention that is required to introduce a solid zone with a complicated shape. The economy and advantages of the voided slabs will be reduced. Moreover, prior research has failed to indicate that voided flat slabs have an improved punching shear strength or a different failure mechanism. The brittle punching failure mechanism was documented even when the solid area around the column took on complicated shapes. So, instead of adding a solid region surrounding the column, a novel method must be created to significantly increase the punching strength of voided slabs.

2. Study Significance

This work presents a novel, simple way to enhance the punching shear performance of voided slabs by utilizing steel plates. The voided slab included four embedded sheets, two oriented in each direction. The thickness of the sheet was 3 mm. To validate the effectiveness of the suggested approach, a voided slab empty of sheets was compared to the strengthened slab in an experimental study.

3. Testing Program

3.1. Specimens' description

The designed model represented a section of a voided flat plate located in the area of the negative moment around an internal column within the contra-flexure line. This area was determined with the help of the Auto Desk Robot program. The flat plate rested on 16 columns, distributed regularly in x directions and y directions, and the distance between columns center to center was 5 m in each direction. Then, the building was exposed to a uniformly distributed load. The analysis outcomes, showing the moment distribution in the x-direction, are displayed in Fig. 1. As shown, the saddle point when the negative moment transverse to the positive moment is located at a distance of 1.1 m from the face of the column. The studied samples were placed on a supporting border of 1000 mm × 1000 mm, extending down the lower face of the sample. The upper surface of the sample was subjected to a negative moment as a result of the applied vertical loads. This behavior completely contrasts with the true behavior of slab-column connections, where the bottom face is subjected to compression.

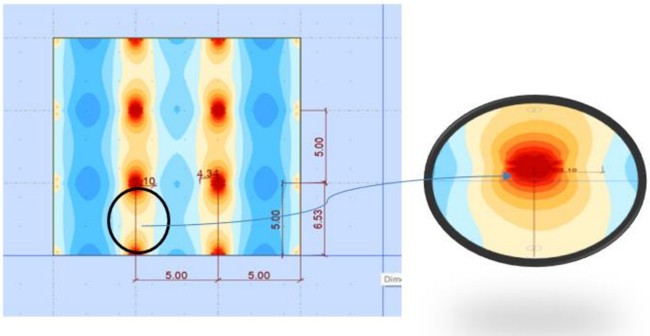


Figure 1. The specimen in the robot program

The two samples were cast using a self-compacting concrete (SCC) mixture, as listed in Table 1, which ensured the small holes between reinforcing bars were filled and prevented segregation. The specimens constructed on a half scale were used to achieve the purpose of this study. A central column inside the structure is depicted, which is coupled to a slab. The contra-flexure lines bound these slabs. The surfaces measured 1100×1100 mm on a plane with an entire depth of 130 mm. Fig. 1 shows that the middle column, which extended from the upper surface of the slab, was also square, measuring 150 mm × 150 mm and standing 250 mm in height. To verify the unbalanced moment, the beam was constructed in 150 × 150 mm and extended 150 mm from the face of the column, with a total length of 300 mm, as shown in Fig. 2.

Table 1. Proportion of the Mixed Materials.

Material	Quantity
Water/cement ratio	0.463
Water (kg/m^3)	185
Cement (kg/m^3)	400
Fine aggregate (kg/m^3)	1060
Coarse aggregate (kg/m^3)	586
Limestone Powder (kg/m^3)	70
Superplasticizer (kg/m^3)	12

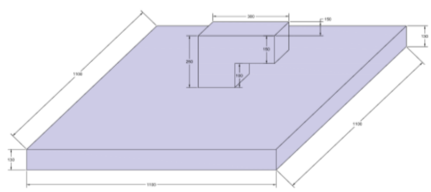


Figure 2. The dimension of the specimen

The reinforcement of all specimens was two layers of 8 mm steel bars spaced 100 mm from center to center in both directions. The two layers were positioned to provide an effective depth (*dav.*) of 108 mm. The longitudinal reinforcement of the columns consisted of 10Ø12 mm, and the transverse reinforcement consisted of five square ties made of 8 mm steel bars. While the longitudinal reinforcement of the beam was 3Ø12 at the top bar and 2Ø12 at the bottom, the transverse reinforcement consisted of two square stirrups made of an 8 mm steel bar. The ACI 318M-11 code specifies that the tension reinforcement in flat plates must extend for a distance of 0.3ln beyond the face of the supporting column. In this experimental study, the total distance between the sample's edge and the column's face was below the required value; hence, the ends of the used tension bar were hooked. The details of reinforcement are displayed in Fig. 3.

Figure 3. Reinforcement of the prepared sample.

For providing voids inside the slabs, eight styropor blocks with cross sections of 250×250 mm and a height of 70 mm were used. The styropor blocks were distributed uniformly in three lines. The clear distance between every two blocks was 50 mm. Fig. 4 shows the planning of the prepared voided slab.

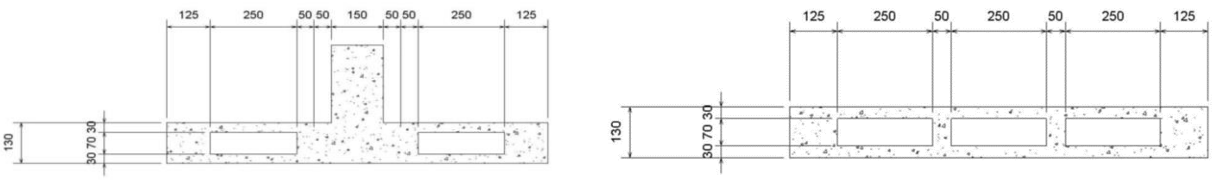


Figure 4. Arrangement of the voided slab

The designation of the prepared specimens is shown in Fig. 5. One slab was fabricated by spreading 8 square voids regularly inside it, which is represented as a control specimen that was without a steel plate, and the other one was a voided slab strengthened by steel sheets with a thickness of 3mm, see Fig. 5. Names for the voided slabs were given by adding the thickness of the steel strip to the letter (V). For example, a voided slab without strips would be V0, while a voided slab with 3 mm thick strips would be V3. To improve their punching strength, the voided slabs were reinforced with steel sheet strips.

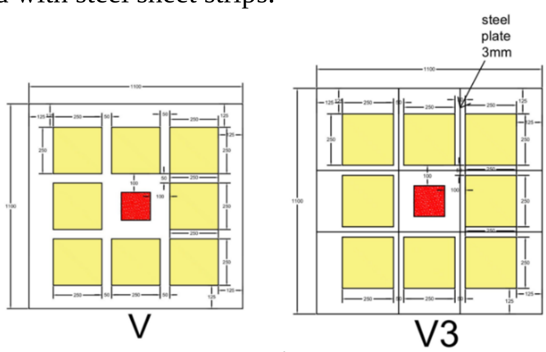


Figure 5. The designation of the prepared specimens and the arrangement of the steel thickness

Two stirrups in each transverse and longitudinal direction. In both directions, the two steel plate strips were located at the center of the two middle ribs, and the entire length of the 1000 mm specimen was extended to verify the demand development length. Furthermore, these four strips have been orthogonally linked around the column stub. Additionally, these strips have been positioned straight between the upper and lower reinforcement meshes, each 68 mm high and 3 mm thick. These sheets have a yield strength equal to an average of 310.33 MPa.
Sheets were punched with two lines of 15 mm holes to facilitate aggregate entrance into slabs. The holes were uniformly spaced throughout the strips in a staggered configuration with a space of 200 mm center-to-center and a 25 mm spacing between the two lines, see Fig. 6.

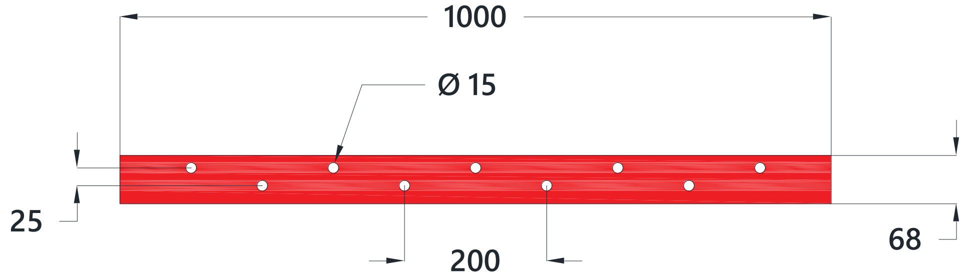


Figure 6. Details the steel sheets

The concept of tying up the sheets with holes has been proposed by Lameiras et al.[18]. They suggested that the diameter of the holes must exceed the size of the maximum aggregate and that the bond force improves with an increase in the number of holes. No guidance was provided on the spacing between holes. In this study, the diameter of the holes was chosen to be approximately 50% larger than the size of the maximum aggregate (10 mm), and this hole diameter appears appropriate (approximately 22% of the sheet's height) for minimizing the cut area from the sheets. Subsequently, to reinforce the slab, the assembly to the strips must be accurate, achieved by overlapping the slots. These overlapping joints should be welded, as shown in Fig.7, to ensure a strong connection between the four sections.

Figure 7. Details of the welding line in steel plates

Reaching concrete into tiny spaces in voided slabs is more challenging since they typically have more barriers than solid slabs. Consequently, those specimens were made using self-compacting concrete. The primary ingredients were Standard Portland cement, sand, finely crushed gravel, water, and an additive material. The size of the largest particle for crushed gravel was 10 mm, which was smaller than three-quarters of the clear cover. The rate of the compressive strength of cube concrete after 28 days of casting was 45.034 MPa.

3.2. Test configuration and instrumentation

As seen in Fig.8, all slabs were subjected to an unbalanced moment load test on the same day, 28 days after casting. The test was conducted using the beam-column area. A hydraulic jack capable of supporting 2000 kN was used to apply this force until the specimen collapsed progressively. The eccentric load was applied using the displacement-controlled technique at a 0.5 mm/min speed. The slab specimens were placed and supported by roller lines along the four corners of the testing frame, forming a perimeter with a 1000 mm clear span. As a result, during the test, the specimens' corners were free to uplift. The setup is enough to represent an interior slab-column connection limited by contra-flexure lines when the moment is zero.

Figure 8. Test setup

Since the 1950s, this setup has been implemented in most punching shear research [19]. A load cell was used to measure the exerted force by positioning it between the hydraulic jack piston and the column stub. Additionally, an LVDT, or linear variable differential transducer, was placed midway under the specimens, exactly below the center of the column, to quantify their central deflection. The tension bar strain was observed using strain gauges affixed to the center lower bars in both orientations, longitudinal and transverse. At last, all instruments utilized for monitoring the test outcomes were linked to a data logger, the Data Taker G85, which recorded measurements. Every second of the test occurrence, the readings were directly sent to a computer.

4. Test Results and Description

4.1. Cracking pattern and failure mode

The flexural cracks in the voided specimen (V0) were first noticed on the bottom face, which is the tension surface. The specimen's middle zone, which runs perpendicular to the steel bars' direction, was the first area where cracking began as little flexural fractures. The number of tangential and radial cracks that developed and spread to the specimen's edges increased directly with the applied stress. A series of diagonal cracks, radiating outward from the column corners and aligned with the specimen's exterior edges and corners, developed as the load was amplified. Upon collapse, the specimen displayed an abrupt and brittle failure by punching shear with diagonal cracks integrated (refer to Fig. 9a). The average distance from the column edges to the tension face, where the punching shear failure occurred, was 2d, or 216 mm.

The other specimen, V3, which had embedded steel sheets with thicknesses of 3 mm, showed similarly distributed cracks. This is entirely at odds with what was observed in the V0.0 specimen, where more diagonal cracks originated in the specimens' centers and extended toward their edges and corners. Due to the increasing applied stress, more diagonal cracks appeared, with the oldest ones reaching farther into the supporting lines and the column stub penetrating the specimens to a depth of almost half of the slab before they failed. Because of the steel sheets, the column stub could be supported, and its weight was distributed to other areas of the slab that could withstand even greater loads. Several irregularly shaped tangential fractures extended around the column just before it collapsed. Then, as shown in Fig. 9b, the specimen failed gradually and ductilely due to a combined punching-flexural failure mechanism. From what we could tell by looking at the spot where the concrete spalled off, the reinforced slabs did not exhibit any significant slippage between the sheet ductility and the concrete. Therefore, incorporating steel sheets proved a highly efficient method for enhancing the failure mode by moving it to ductile failure instead of the brittle failure that occurs in voided slabs, regardless of how far away the voids are from the column sides or the usage of shear bolts [13,20,21].

(a) (b)

Figure 9. Crack pattern at failure load; (a) V3, (b) V0

4.2. Load-deflection performance

4.2.1. General behavior

The response of the two experimental slab-column connections to load-central deflection is shown in Fig. 10. It has come to light that reinforcement-voided slabs with embedded steel plates caused these slabs' responses to differ significantly from those of other slabs (V0) that do not contain sheets. Two phases, pre-cracking and post-cracking, made up the V0.0 specimen's response. It all began with the pre-cracking stage, which was initiated at the start of the experiment until the first flexural cracking started to form.

Then, as expected, the second phase—the post-cracking stage—began and sustained till the final boundary condition, where the stiffness decreased due to cracking. As a final point, the load-carrying capacity was severely reduced due to the slab being punched by the column stub in a brittle way. The load-deflection responses for the specimen with steel sheets (V3) were completely different from what has been recently explained, and this is all because of the steel sheets. There were four distinct phases to these replies. Similar to the V0 specimens, the first two phases were also seen. In the third stage, the load-carrying capacity of the voided slab decreases as the loads go from ultimate to forces, which are around 50% of the peak loads. This behavior is caused by the concrete under the column stub entirely breaking and failing to withstand further loads. Additionally, the steel plates in the central zone, located under and around the column stub, also yielded.

On the other hand, these sheets reduced the column's sudden penetration of the slabs and transferred the applied force to the farther-off portions that could support greater loads. Next up is stage four. Discovered an area where the center deflection increased significantly without a corresponding change in the applied force. The plastic plateau zone describes the point at which the ductility of voided slabs is significantly enhanced due to the employment of steel sheets for punching shear failure reinforcement. As a result of a combined flexural punching failure, these three specimens exhibited a more ductile and progressive failure mechanism after the testing. Remarkably, the failure loads of the voided slabs strengthened by steel strips were around 50% of the comparable ultimate loads, indicating that the two loads were not similar.

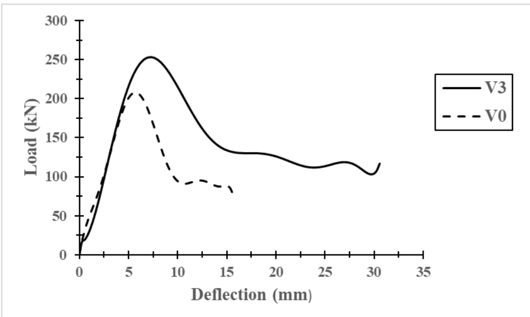


Figure 10. Force-central deflection curve of specimens.

4.2.2. Ultimate loads

Table 2 reviews the ultimate loads of the slab specimens. The results show that the V0 sample drops in the ultimate load by approximately 13% compared to the V3. In addition, the steel sheet reinforcement of the voided slabs increased their strength, successfully recovering and exceeding the strength missing due to the voids inserted across the slab-column joint. There are several possible explanations for this increase in strength. The first is that the steel sheets contained the concrete, which prevented the diagonal and flexural fractures from spreading further. The second factor stems from the significant vertical forces that these plates provided, which helped to withstand the punching power. The last consideration was the load-bearing capacity of these sheets, from the severely damaged region under and close to the column stub to the distant ones. The sheets also had four corners to support them, which allowed them to act as direct struts to a certain degree and transmit some of the applied load to the borders that provide support. In practice, the transfer of loads from the slab to the supporting column is the inverse of what happens in the test setting. Since the sheets are lying on the supporting columns, in the real situation, they can also give direct strutting. The voided slabs' flexural strength was significantly enhanced since the steel sheets acted as flexural reinforcement.

Table 2. Test outcomes of samples

Sample	Ultimate load, Pu, (kN)	Yield deflection, Δy, (mm)[a]	ultimate deflection, Δu, (mm)[b]	Ductility Index	Toughness kN mm
V0	232.45	5	15.76	3.15	883.6849
V3	267.77	6	30	5.45	1193.11

[a] founded by an equivalent elasto-plastic energy absorption method.
[b] founded by the fracture method.

4.2.3. Deflection

As seen in Figure 10, the difference in the deflection between the two specimens was particularly noticeable after the initial cracking.

Both specimens had nearly identical deflections before the cracking at the linear stage. Following that, slab V0 displayed a soft response to load deflection, while the voided slab with steel plates was the stiffest.

This point highlights that the voided slab-column connection stiffness was extremely degraded because of the quick extension and growth of cracks through these voids.

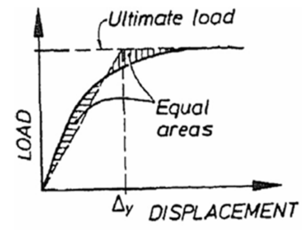
Also, Figure 10 indicates that the undesirable influence on the stiffness of the voided slabs was omitted by steel sheets that controlled the propagation and growth of both shear and flexural cracks. Additionally, these sheets functioned in conjunction with flexural and shear reinforcement, later enhancing the actual moment of inertia of the samples and resulting in a significant improvement in stiffness, which was reflected in decreasing the values of deflection.

4.2.4. Ductility

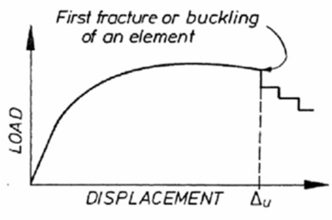
The concept of ductility describes a structural element's ability to undergo significant inelastic deformation before failure and is considered a crucial factor for buildings constructed in seismic zones [22]. The Ductility index presented the relation of ultimate deflection (Δu) to yield deflection (Δy).

Selecting the best approach for calculating yield and ultimate deflections is essential, particularly in seismic design, and there are several ways to do so in the literature [23]. As Park [24] stated, four techniques for estimating the yield displacement. One such group that determined the ductility of bubbling members was Hashemi et al. [23] using the equivalent elasto-plastic energy absorption approach.

This technique idealizes the experimental load-deflection curve into an elastic, perfectly plastic curve that absorbs the same amount of energy as the real System (Fig.11a). This definition is used here because it appears reasonable. Additionally, Park [24] detailed four processes for the final deflection. The method was selected after the work of Hashemi et al. [23]. It depends on the first element crack (Fig.11 b).



(a)



(b)

Figure 11. Park explanation for displacements, (a) Description of yield displacement dependent on equivalent elasto-plastic energy absorption, and (b) description of the ultimate deflection depended on the first fracture of an element [20].

The ductility index, yield, and ultimate deflections that were determined are listed in Table 2. A significant loss in ductility was observed due to the existence of voids in the slab-column connection.

Voided slabs have a limited capacity to absorb seismic energy. Therefore, more care must be taken while building such slabs in seismic zones. Nevertheless, it was discovered that reinforcing the voided slabs with steel plates may offset this decline in the ductility index. So, the suggested use of steel sheets is an excellent solution for voided slabs subjected to seismic loads. The ductility improvement for the V3 specimens was 73 % compared to the V0 slab.

4.2.5. Energy dissipation

The area enclosed by the load-displacement curve is equal to the energy absorption. It is the amount of energy that structural elements absorb just before they collapse [22,25]. Listed in Table 1 are the energy absorbance values for each sample. Energy absorption in concrete members is proportional to the concrete's crack and fracture resistance. The voided slabs contain a substantial quantity of concrete filled with space, so they could not absorb as much energy.

However, the energy absorption of the voided slab was improved significantly by using steel sheets for reinforcement. This was because the effectiveness of the sheet plate limited the propagation of fractures and delayed the concrete fracture.

5. Conclusions

Using steel plates inserted within the slabs, this study presented a novel and straightforward method for enhancing the punching strength and behavior of reinforced concrete voided slab column connections.

The experiment involved constructing and testing two specimens until they collapsed by applying an unbalanced moment through the column stub, which was connected to a beam. One slab was fabricated with a void,

Eight square voids are regularly spread inside it. The other one was reinforced with steel sheets of 3mm thickness. The following are crucial conclusions;

1. Extra ductile failure (mixed flexural and punching mode) was seen in the one that continued steel sheets, as opposed to the empty one, which collapsed abruptly and brittlely due to punching shear.
2. Using the steel sheets to overcome the loss in strength, the strengthened specimens achieved ultimate loads that were 15% more than those of the V0 slab.
3. Because of the voids that allowed cracking, the V0 showed a soft load-deflection response. However, because steel sheets may limit the development and expansion of cracks, strengthened slabs exhibited the stiffest response.
4. Inserting the steel plates considerably enhanced the ductility of the slab by about 73% compared with the reference slab without voids. However, the stiffness improvement was insignificant and did not exceed 0.6% due to the addition of steel plates
5. A notable increase in energy absorption in the V3 slab, about 35% higher than V0, occurred because the sheet plate effectively slowed the development of cracks and postponed the cracking of the concrete.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Author Contributions

All authors proposed the research problem. In addition to author Athmar M. Alazawiey and Sajjad H. Ali collected recent articles and organized them in simple shapes. Authors Athmar M. Alazawiey and Sajjad H. Ali verified the recommendation in the proposed work. Authors Athmar M. Alazawiey and Sajjad H. Ali designed and proposed work. Authors Thaar S. Al-Gasham is supervision. All the authors discussed the results and the final version of this paper.

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