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RC Flat Slab with Opening Strengthened Embedded Bearing Plate under Punching Shear

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ABSTRACT

Reinforced concrete slabs that contain service or architectural openings near the column are usually designed using traditional methods provided by international specifications. These methods are limited in terms of the location and size of the opening and the methods of reinforcement to resist punching shear. This research presents an experimental study of flat slabs that contain an opening near the column using a steel plate to demonstrate its effect on the behavior of the roof to resist punching shear. This research presents one of the ways to strengthen these openings using steel plate. Steel plate is considered one of the important solutions to increase the resistance of flat slabs to failure of perforating shear that contain service openings next to the columns. The results showed that the presence of openings near the column led to a decrease in the resistance to punching shear and a change in the behavior of the flat slab. The use of the steel plate leads to a further improvement of the behavior of the flat slab compared to the model that contains an opening and is not supported by the steel plate. The presence of the opening near the column led to a decrease in the maximum load by 58%, and the use of the steel plate and fixing it in different ways led to an increase in the maximum load (70-107%), depending on the fixation methods and the thickness of the steel plate.

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1. Introduction

Flat slabs are increasingly popular in developing countries due to their ease of deployment and several benefits. This type of slab is a structural component that carries longitudinal and transverse stresses, necessitating reinforcing steel in both directions. However, due to its low thickness and the presence of a column without a beam, it is vulnerable to penetration failure due to the distribution of shear stress in a circular shape around the column. This causes the column to enter the slab, causing partial failure [1, 2]. As noted by Wood [3], poor concrete quality and a lack of integrity reinforcement can cause a flat slab to erode and gradually collapse the structure. Flat slabs are built with apertures to support mechanical, structural, and electrical needs, including pipes, wires, and elevator equipment. In 1961, Moe [4] tested three 150-mm-thick slabs with 19-mm-thick steel plates placed over the column. Even with the slab's compression surface, the plates were supposed to boost the column's effective size. Punching shear failure at the intersection of the slab and column is one of the key difficulties with these slabs. This type of failure is frequently sudden and causes flat-plate structures to fail over time. As a result, attention must be paid when developing these slabs, and the unexpected failure condition must be avoided. The RC slab's design with opening is not clearly described in BS 8110(5). The American Concrete Institute (ACI 318) [6] provides more specifications for opening sizes in different places for flat slabs. Teng et al.'s research [7] focused on flat plate slabs with apertures in rectangular columns. The punching strengths of flat plate slabs were dramatically diminished in the presence of openings, according to their examination of 20 slab specimens under focused loads. Additionally, they recommended that construction be done along the column's long side if an aperture must be placed. Lib-Erati et al. [8] examined 12 reinforced concrete slabs without shear reinforcement under symmetrical pressure. Three groups of slabs were compared based on how many openings were near the column. As the number of perforations rose, it was found that the slabs' ability to disperse energy diminished. The purpose of this study is to evaluate the effects of two different steel plate thicknesses, installation strategies for the plate in the casting location, and rehabilitation on the punching shear capacity of flat slabs.

2. Methodology

2.1 Specimens Details

For this study, 6- medium-sized concrete flat plate slabs were cast using normal strength reinforced concrete. All specimen's slabs have the same dimension (1000 x 1000 mm), had a total thickness of 75 mm, and had monolithically cast (150 x 150 mm) square stub column at top and bottom face in the middle. As illustrated in Figure 1, the slab component of these models was strengthened with distorted wires of (ϕ6mm) dispersed across the section (75mm c/c). Concrete bottom cover (15 mm).

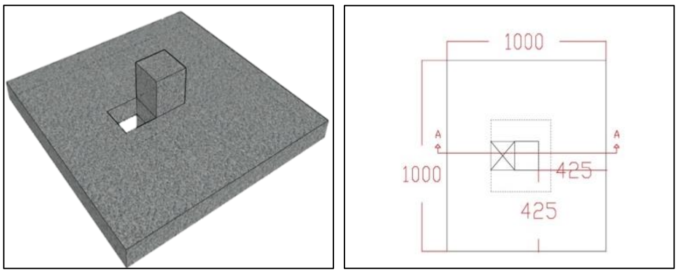


Figure 1. Geometry of slabs

2.2 Test Program

The experimental work is based on testing 6-specimens, divided into in to three group, Strengthening with plate in tension face with 375*375mm. The details of these groups labeling in the Table 1.

Table 1: Characteristic of the Tested Slabs

G	labeling	Opening	Strengthening with plate	NOTE
G	G1-1	Without	Without	Reference
one	G1-2	With	Without	Reference
G	G2-1	With	Plate 2mm	With shear stud
two	G2-2	With	Plate 3mm	With shear stud
G	G3-1	With	Plate 2mm	Without shear stud
three	G3-2	With	Plate 3mm	Without shear stud

2.3 Materials

One concrete mix was used NSC of fć (35) MPa compressive strength. Typically, chemical admixtures were used to achieve a low water-to-cement (w/c) ratio while maintaining appropriate workability. The distorted bars that used throughout the present study are of 6mm in diameter. The distorted bars are used for strengthening the reference slab samples throughout the present study. The tension test results of such bars are listed in Table 2 whereas Figure 2 shows the testing machine of that tests. The column was reinforced by (4Ø6mm) bars as shown in Figure 3 with 2Ø6@75mm tie to ensure the prevention of local failure in column before slab. The thickness of steel plates is (2,3 mm). The yield stress 380 MPa and the ultimate strength 504 MPa according to manufacture. The used steel bolt was of (50 mm) length and (10mm) diameter having, yield strength was (315 MPa), and the ultimate strength was (420 MPa).

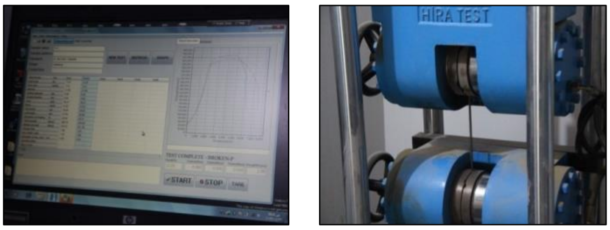


Figure 2. Test Setup for Steel Bar

2.4 MIX DESIGN CONCRET

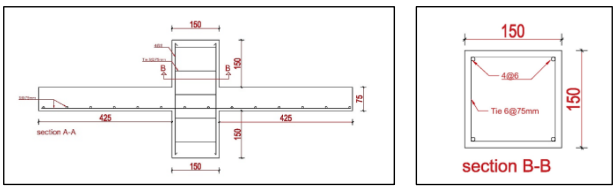


Figure 3. Column reinforcement**.**

Several test mixes were created, and the reference mixture was created to give 30 MPa strength at the end of 28 days. Cement, fine sand, and crushed aggregate create this normal-strength concrete mixture, which is used to cast both the NC slabs and the samples used for testing (cubes, prisms, and cylinders). The water/cement ratio of (0.45) was fit with the strength required. Table 3 shows details of the mix used through this part of experimental work.

Table 3. Properties of Concrete Mix (NSC)

Cement Wight kg/m^3	Gravel Wight kg/m^3	W/C	Sand Wight kg/m^3	Target Strength MPa (f'c)
350	1200	0.45	600	35

2.5 Casting and Curing Procedure

Before putting the concrete in the mold, steel reinforcement was put in the mold. Following the completion of the process of mixing, concrete was poured in molds (slabs, cubes, cylinders, and prisms) in 2 layers, and every one of the layers was shaken by vibrating for the removal of entrapped air from the mix. Following the completion of the casting, the column was then made into one slab at a time. Figure ٤ shows the details of reinforced concrete slab casting. 24h after the casting, the sample was put under polythene sheets samples and control samples (i.e. cylinder, cubes, and prism) were taken out of the molds and put in bowl that was full by the water till testing age of twenty-eight days. Figure ٤ indicates samples in curing.

Figure 4. NC slabs casting and curing

2.6 Mechanical Properties of the Hardened Concrete

2.6.1 Compressive Strength (f_{cu})

The cubical samples (150 x 150 x 150mm) were utilized for determining concrete's compressive strength. A compressive test was done according to BS (1881–116) (1983) [9] at The Multi-Disciplinary Consulting Bureau Thi-Qar University Laboratory, as can be seen in Figure 6, using an Automatic Concrete Compression Testing Machine with a capacity of 3000 kN. The average related to the six cubes was recorded. The values of compressive strength are listed in Table 4.

2.6.2 Splitting Tensile Strength (f_t)

This test was conducted based on ASTM C496-2011 [10], with the use of Automatic Concrete Compression Testing Machine. This test applied cylindrical samples which have the dimension (150x300mm). The average related to the three cylinders was noted. The arrangements of the test cylinder are shown in Plate ٦. Table 4 consists of details related to the tensile strength's values.

2.6.3 Modulus of rupture test (f_r)

The concrete's flexural strength had been estimated on (100x100x500mm) prism samples according to ASTM 293-79 [11]. Prisms were put through 2-point load with the use of Electromechanical Flexural-Compression Testing Machine with (100kN) capacity, average related to 3 samples was recorded.

Figure 6. Compression Strength Test for Cube and Splitting Tensile Strength Test for Cylinder Samples

The set-up of the test is indicated in Figure 7. Table 4 provide listing related to the values of modulus of rupture.

2.6.4 Modulus of Elasticity Test (E_C)

Uni-axial compressions test was applied for obtaining elastic modulus, chord modulus approach was utilized in accordance with the ASTM C469-2002 [12]. Test was conducted at age of twenty-eight days through the use of (150×300mm) cylinders, Figure 7 indicates the tests' arrangement.

Concrete	Compressive strength Cube (Mpa)	Rupture Modulus	Splitting tensile strength	Modulus of elasticity (GPa)
NC	36.5	3.23	3.68	28.3

Figure 7. Flexural Strength Test for Prism and Test of the Modulus of Elasticity

TABLE 4. Results of Concrete Properties

Concrete	Compressive strength Cube (Mpa)	Rupture Modulus	Splitting tensile strength	Modulus of elasticity (GPa)
NC	36.5	3.23	3.68	28.3

3.Results and discussion

3.1 Punching Load Test

All slab samples tested under punching shear load using hydraulic universal testing machine (MFL) with 3,000KN capacity which is available in the structural engineering Lab, college of engineering, Al-Mustansiriyah Univ. as can be seen in plate ٨. A 0.01mm (ELE type) dial gauge was placed below the center and right, lift of column with distance 15cm from face of column of each slab to measure the deflection.

Figure 8. Testing Machine

3.2 Cracking Load and Crack Pattern

In Table 5, we can see the results of tests for both the cracking and ultimate loads of the slab. Each slab's initial crack appears at a load of between 28 to 48 percent of its ultimate capacity. For the reference (G1-1) the cracking load is 48% of the U-load capacity. For the specimen with an opening and without a shear head (G1-2), The initial crack emerges near the perimeter around the column in the tension face and extends across the edges of the slab. The first crack appears at 39% of the ultimate load. However, for collar head Samples, cracks connect the edges of the opening on the tension face. Crack propagation continues with loading from the testing machine, and the cracks increase, delineating the cracking zone at the extending end of the support's ... wn

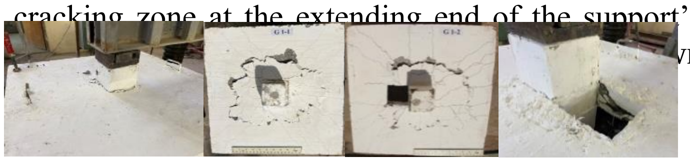


Figure 9. Compression and Tension Face for Slab G1-1,G1-2

Figure 10. Compression and Tension Face for Slab G2-1, G2-2

Figure 11. Compression and Tension Face for Slab G3-1, G3-2

G	Samples	(Pcr) First Crack Load KN	(Pu) Ultimate Load KN	Pcr /Pu %	Pcr/Pcr (G1-1) %	Pu/Pu (G1-1) %
G-	1-1	48	108	44	-	-
one	1-2	28	72	39	58	67
G-	2-1	44	104	42	92	96
two	2-2	48	116	41	100	107
G-	4-1	40	92	43	83	85
three	4-2	44	116	38	92	107

Table 5. Characteristics of Cracking also Maximum Force Applied to the Sampled Slabs

The discussions of the results of these Samples according to the presence and type of the steel plate as shear-reinforced are as follows:

➢ The first crack load value in the reference model G1-1 was 48 kN, and this value reduces to 58% in the specimen with apertures adjacent to the column (G1-2). Once we used steel plate 3mm with shear stud around column and the opening G2-2, this percentage increased to (107%) in comparison to its reference, and we used steel plate 2mm with shear stud around column and the openingG2-1, the percentage increased to 96%, in comparison to its reference. When we used steel plates without shear studs, this percentage decreased to 70% in the G3-2 model, and sample G3-1 reached 74% in comparison to the reference.

➢ The steel plate with shear stud had an increased first crack load value compared with G1-1. The first crack for the G2-1 and G2-2 models was 92% and 100%, respectively, from the first crack load for R.

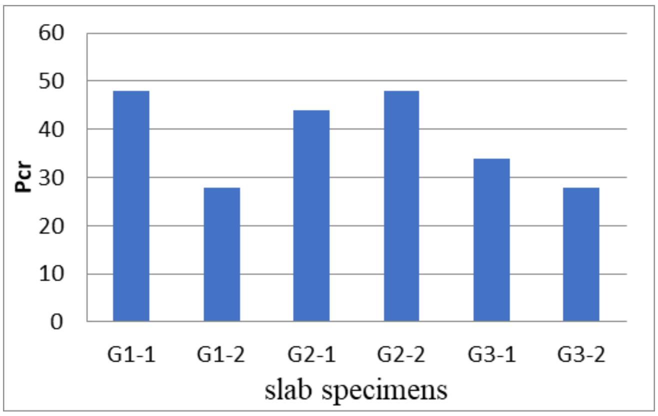


FIGURE 12. Cracking Load for Tested Samples

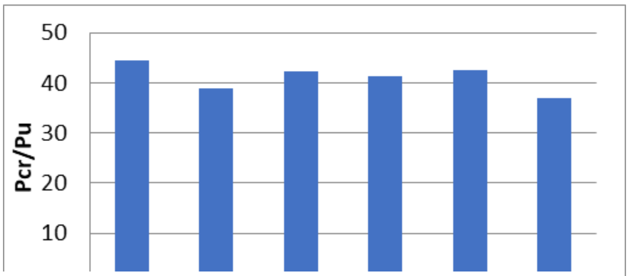


Figure 13: The Cracking Load / Ultimate Load for Tested Samples

From the above figure the test results showed:

➢ It was clear from the figure 13 that the largest percentages of cracking load to ultimate load capacity belong to the G٢-٢ specimen.

➢ It was obvious from figure ١٣ that the largest cracking load in the present work was (48 kN) , for Samples that were cast with an opening using a steel plate and shear stud. The lowest value achieved for the model with an opening without the use of a steel plate or a steel plate with a shear stud was (28 kN).

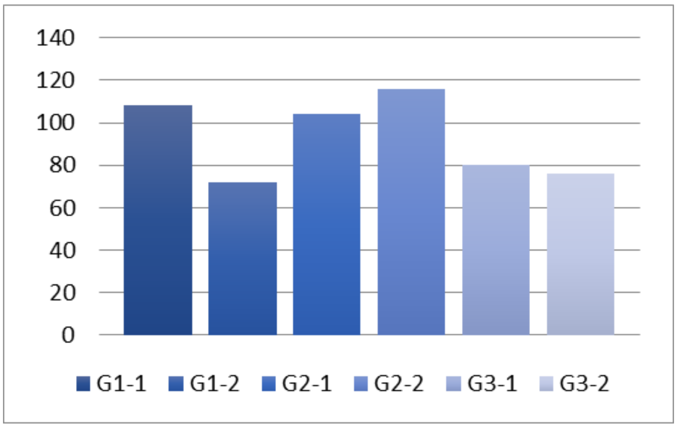
➢ On the other hand, by demonstrating the cracking appearance in the Samples it can be noticed that by existing the opening in slabs Samples lead to Accelerates their cracking load.

➢ All Samples with steel plate showed that value of the cracking load percentage to the ultimate load are greater than the value of the reference specimen(G1-2) that have an opening and does not have steel plate.

➢ From figure ١٤ can be noted that Samples (G2-2) attain 100% of its their reference cracking loads (48) kN , it resulted in the effective presence of this type of steel plate 3mm and shear stud to raise the cracking loads of Samples with apertures close to the column.

3.2Ultimate-Load Capacity

The primary goal of this research was to examine the effect of various steel plate designs and the existence of openings close to column on the maximum allowable load for Samples that have been strengthened for punching and shear, and then to compare these results to those obtained from the reference specimen (without opening and shear reinforcement). According to the data in Table 5, the maximum load that was for the G1-1 reference slabs of 108 KN. This value drops in G1-2 for other slabs because of the opening already there, which is set at (72 kN). The use of the steel plate increased the maximum load in G2-2 model by 107% compared to reference.



In general, from figure 15, can be noted:

1-The ultimate load capacity for all the Samples is between (116 – 72) kN. For all Samples, the G2-2 slab was strongest Samples compared with other slab, because it was used steel plate with shear stud.

2-The specimen G1-2 which have opening without steel plate achieved the least value of the ultimate load and this loss is due to the presence of an opening adjacent to the column.

3-In general, the use of steel plate with shear stud reduces the loss in the ultimate load, and this was observed through the results, where the Samples containing steel plate and shear stud achieved higher values of ultimate load than the Samples that contain an opening without the use of steel plate and Samples that contain steel plate without shear stud.

3.4Load-Deflection Behavior

The deflection profile is shown in Figures 16 and 17 where each curve represents a state of slab in each 4 kN increment. Deflection profile was measured using a dial gauge with a resolution of 0.001 millimeters, and measurements from this gauge were recorded for each load increment. Measurements were taken at the center of the slabs and right, lift of column with distance 2d from face of column. These data were used to illustrate the measured values of the deflection. As found in the table Table 6 below.

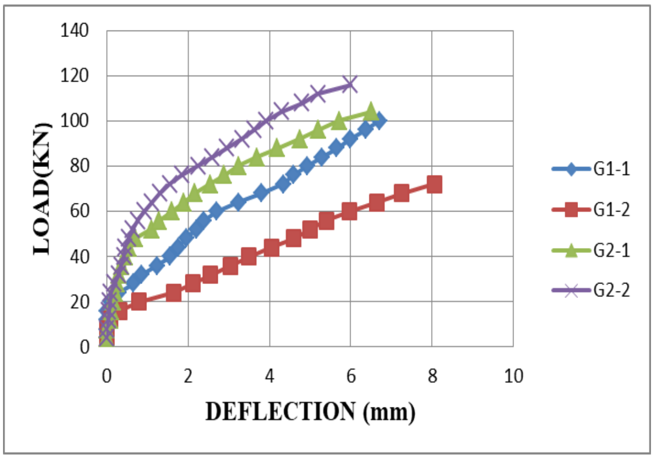


Figure 16. Central Deflection for G(one) , and G(two)

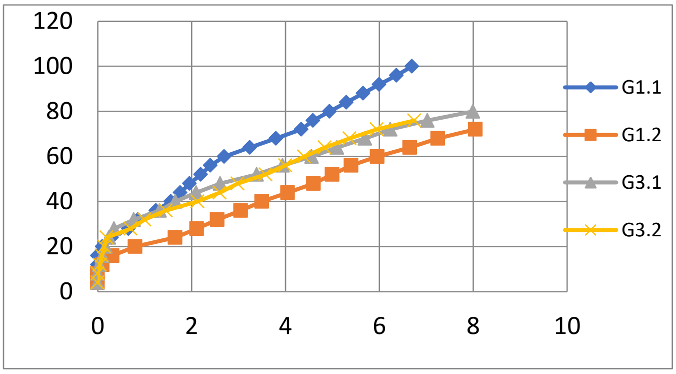


Figure 17. Central Deflection for G (one), and G (three)

Table 6. The Deflection of entirely Tested-Samples

Group	Samples	(Pu) Ultimate Load kN	Deflection at Pu (mm)		
			center	Right	Lift
G-one	1-1	108	7.4	5.4	5
	1-2	72	8.05	4.6	4.15
G-two	2-1	104	6.5	5.1	4.46
	2-2	116	6	4.08	3.52
G-four	4-1	92	6.7	3.75	5.32
	4-2	116	20.4	11.65	10.35

3.5Angle of Failure

Typically, the punching failure mode was formed like a conical pyramid, with the Samples' bottom faces at a (Ø) angle. The punching zone assumed to be circular, with a circular punching zone and a specified perimeter, the radius of the assumed circle can be determined using the circle area equation. Following that, AutoCAD was used to determine the angle of failure for all Samples as shown in table 7. The original position of the punching shear with shear angle was discovered after the test and slicing of the sample slab. The graphic representation of the slab sample after it was sliced along the axis of symmetry 2d from the face column is presented in Figure 18.

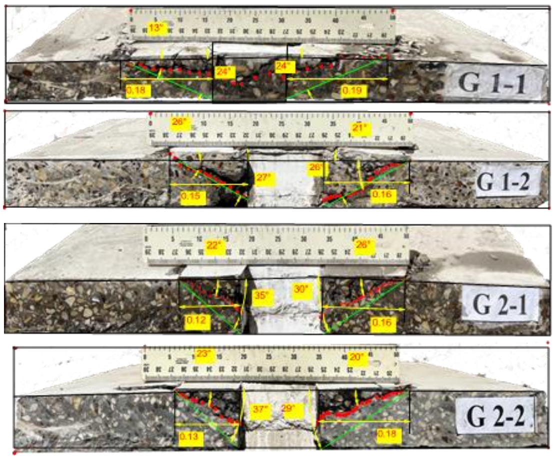


Figure 18. Angle of Failure for Slab

Table 7. Angle of Failure for all Samples

Samples	Measured Area (m^2) by Auto Cad	Radius (m)	Angle of Failure (θ°)
(1-1)	0.13	0.203	24.4°
(1-2)	0.24	0.276	21.68°
(2-1)	0.12	0.195	22.32°
(2-2)	0.14	0.211	23.89°
(3-1)	0.15	0.218	23.57°
(3-2)	0.19	0.245	25.15°

3.6Punching Shear Stress

The direct shear stress is added to the shear stress caused by moments to determine the overall stress. This calculation determines a maximum stress in compliance with ACI 318-19 [6] Section R8.4.4.2.3 by taking into account the geometric of the punched shear failure cone in addition to the induced shear and moment forces. This will invariably take place in one of the corner sites of the failure cone.

$$Vu = \frac{Vu}{Ac} + \frac{\gamma \times Mu \times c}{Jc} .... \qquad (1)$$

V_u: the direct shear's absolute value.
M_u: moment of imbalanced column.
A_c: Area of concrete in the assumed critical section.
γ: the fraction of the moment that shear transfers.
c: distance between the perimeter of the critical section and the centroid axis of the critical section in the direction of analysis.

J_c: the geometric characteristic of the critical section, which is comparable to the polar moment of inertia of the area forming segments Ac. In this study, Mu is neglected, so the second term of equations 1 will be equal to zero. The first critical shear failure plane is considered to be located at a distance of half of the depth from the face of the column, where d represents the effective depth of the section. The second critical shear failure plain is supposed to stand located at a distance of X/2, which was derived using the table 8.

The following expressions are offered for the AC of interior columns:

$$\text{Ac} = bo \times d \; .... \qquad (2)$$

Where bo is critical section permitter, and d is the effective depth.

Table 8. Shear stresses for the tested slabs

Samples	Load N	Ac at X/2 mm^2	Vu at X/2 N/mm^2
G1-1	108000	76380	1.41
G1-2	72000	78660	0.92
G2-1	104000	77520	1.34
G2-2	116000	68400	1.70
G3-1	80000	67260	1.19
G3-2	76000	80940	0.94

4. Conclusions

1- The presence of the opening at the side of the column indicates a decrease in ultimate load compared to the reference model, which does not have an opening, as the decrease percentage was 33%.

2- The presence of the opening at the side of the column indicates a decrease in the first crack load percentage compared to the reference model, which does not have an opening, as the decrease percentage was 58%.

3- The presence of the opening in the model led to a decrease in the value of shear stress at the critical section in this study, where the percentage of decrease was 65% compared to the reference model that did not have an opening.

4- The use of steel plate in the models had a positive effect on the ultimate load, as it increased it by a percentage ranging (05%-61%) compared to the model that has an opening and does not have steel plate.

5- The use of steel plate led to an increase in the value of the first crack compared to the model that contains an opening without a plate, as the percentage of increase ranged (0%-71%).

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