Shear Punching Behavior for Flat Slabs with CFRP and Openings

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ABSTRACT

This study investigates the punching shear behavior of geopolymer flat slabs with transverse web openings reinforced with Carbon Fiber Reinforced Polymer (CFRP). Shear reinforcement plays a critical role in enhancing the slabs' resistance to punching shear failure, and the addition of transverse web openings allows for service apertures near the columns. In this study, three wooden molds were prepared to test 15 samples of geopolymer concrete under concentrated loading conditions. Each slab had dimensions of 70 cm × 70 cm × 7 cm, with 15 cm × 15 cm × 15 cm columns. The research models were divided into three groups: the first studied the effect of column location, the second examined the influence of openings near the columns, and the third evaluated the impact of CFRP reinforcement. The results showed that transverse web openings reduced the overall punching shear capacity of the slabs due to the loss of concrete in the geopolymer section. However, slabs reinforced with CFRP demonstrated superior performance, which was attributed to the excellent mechanical properties of the material. The full wrapping technique provided the most effective results among the various repair methods tested.

Keywords-CFRP; geopolymer flat slabs; opening

I. INTRODUCTION

Two-way concrete slabs with consistent depths are typical flat plates, which carry loads straight to auxiliary columns without the need for beams, capitals, or drop panels. Due to the ease with which formwork and reinforcing bars may be arranged for the assembly of flat plates, construction time can be minimized [1]. This kind of building is not only aesthetically pleasing but also has additional room. Because flat figures are less expensive to build, they are used extensively [2], resulting in a simpler arrangement of flexural reinforcement and are economical in their formwork. Reduced building story heights, which increase building useable space for a specific or constrained height, are another benefit of a flat figure. Flat figures also have many other benefits, such as lowering dead loads on the foundations and columns [3]. Punching shear, sometimes referred to as two-way action shear is a common cause of progressive failure in flat plate constructions. It happens at the point where the column and slab meet. As a result, caution must be used when designing such slabs to avoid an unforeseen failure scenario [4]. Obtaining reliable information about the structural behavior of reinforced geopolymer beams is crucial. Understanding the mechanical properties of geopolymer concrete is essential for evaluating its performance and for establishing a solid foundation for the proposed research program. This paper provides an overview of the structural behavior of reinforced geopolymer concrete slabs, highlighting their significance and potential applications.

II. DEFINITION AND STUDY OF GEOPOLYMER CONCRETE

A. Geopolymer Concrete

Cement production has grown significantly, increasing from around 1.5 billion tons in 1995 to 2.2 billion tons in 2010. However, the cement industry is a major contributor to CO_2 emissions, with each ton of Ordinary Portland Cement (OPC) produced releasing roughly one ton of CO_2 into the atmosphere. These emissions contribute to climate change and global warming, prompting the search for alternatives to traditional OPC. One approach involves incorporating supplementary materials like fly ash, silica fume, granulated blast furnace slag, and rice husk ash into cement production. Geopolymer concrete offers a promising solution to drastically reduce CO_2 emissions, helping to mitigate global warming [5]. The term "geopolymer," introduced in 1978, describes a broad class of materials composed of inorganic molecular chains or network structures that can replace OPC in concrete construction. The silica-to-alumina (Si: Al) ratio plays a critical role in determining the geopolymer's final structure, with typical Si: Al values ranging from 2 to 3.5 in most applications

[6, 7]. Geopolymer gels outperform conventional cement-based binding agents due to their superior mechanical strength, rapid strength development, excellent chemical resistance, sulfate attack resistance, and cost-effectiveness. These characteristics make geopolymer concrete a highly efficient and environmentally friendly alternative to traditional cement [8].

B. Studies on Geopolymer Concrete (GPC)

Low-calcium fly ash-based GPC was examined in [9]. Emphasis was given to the development of short-term characteristics and the impact of varying the mixture's component proportions. Because GPC samples have improved resistance to sulfur salt attack, decreased creep and shrinkage, and superior resistance to acidic media, their compressive strength is quite strong. Raising the mass ratio of Na_2SiO_3 to NaOH extending the curing temperature range from 30°C to 90°C, increases the molarity of the NaOH solution, and elevates the fly ash-based geopolymer. The concrete has a high compressive strength because of its 4- to 96-hour (4-day) cure period. This concrete works better and avoids fine fly ash agglomerations during mixing when a naphthalene-based superplasticizer is added to roughly 4% by weight of fly ash. To investigate the effects of apertures on punching shear strength, authors in [11] conducted experiments on 14 flat slab specimens, examining various factors including the number of openings (2 and 4), their shapes (circular, square, and rectangular), and their distances from the column face (1 and 4 times the slab thickness). Among the shapes studied, round openings had the least impact on punching capacity. Additionally, apertures positioned four times the slab thickness away from the column face showed a minimal reduction in punching capacity. However, increasing the openings from two to four significantly decreased the punching capacity. The punching capacities of all specimens were assessed using Eurocode 2 and ACI 318 design formulas, which demonstrated high accuracy based on the standard deviation and the mean ratio of analytical to experimental results [10]. Authors in [12] utilized a nonlinear layered Finite Element Method (FEM) to predict the impact of slab openings in slab-column connections reinforced with Shear Stud Reinforcement (SSR). They examined 21 models, varying parameters such as column aspect ratios, and the size and location of the openings. Empirical predictions, supported by the standards of the American Concrete Institute and the Australian Association, were included in the analysis. This study served as a crucial initial step in determining the optimal size and placement of openings in flat slab-column systems [11]. Authors in [12] tested four large slabs measuring 3000 mm × 3000 mm × 90 mm to evaluate the flexural behavior of two-way slabs reinforced with CFRP sheets. Two of the slabs were strengthened with CFRP sheets—one with prestressed CFRP and the other with non-prestressed CFRP—while the remaining two slabs included one unstrengthened slab for comparison. The slabs were simply supported at the center span and subjected to constant patch loads. Nonlinear three-dimensional (3D) FE modeling was performed using ANSYS 2004 software to predict the flexural responses of the tested slabs, assuming perfect material bonding. The results showed that the use of non-prestressed CFRP sheets increased flexural strength by up to 25%, while prestressed CFRP sheets improved it by up to 72% (compared to 32% and 80% predicted by the FEM, respectively). The control slab displayed a highly ductile failure mode, whereas the strengthened slabs exhibited a stepwise failure pattern due to the partial rupture or delamination of the CFRP sheets. The study confirmed the superior effectiveness of prestressed CFRP sheets in enhancing slab performance compared to their non-prestressed counterparts.

III. DEFINITION AND FAILURE ANALYSIS OF PUNCHING SHEAR

A. Punching Shear

Punching shear is a flat slab phenomenon where focused support reactions cause conical cleavage from the top of the slab. Although flexural failure often precedes punching shear failure, punch failure in structural concrete flat slab constructions is undesirable due to its brittle nature, it can lead gradually to a collapse [13]. Shear design approach with punching presumed that the slab experiences hogging moments above the column in both primary directions. Consequently, the slab could be either constant or the slab-column link could be momentarily resistive. Punching shear around the columns is crucial for shear in flat slab construction [14].

B. Punching Shear Failure Analysis

Because of the suddenness of brittleness, punching shear failure is recognized as a major concern for thin plate constructions [15]. Consequently, several researchers have examined useful modeling methods for determining shear forces and capabilities [16, 17]. When it comes to punching shear in plates, a recent parametric study confirmed that a nonlinear 3D FE model using "8-node brick components" can accurately estimate the shear capabilities [18]. It was discovered that increasing concrete strength, slab thickness, column size, or reinforcement ratios improves ability, albeit they can also lead to more delicate breakdowns. Moreover, studies like [19, 20] led to comparisons between various shear-reinforcing technologies and reinforcement techniques.

IV. MATERIALS

The materials used in the research are shown in Table I.

TABLE I. THE MATERIALS USED IN THE RESEARCH

Material	Description
Slag	Number of models: S95 Light grey Slag: Hot Final touch: 490 m^2/kg-510 m^2/kg Type: Powder
NaOH	The most common alkaline activator employed in polymerization was a combination of NaOH or KOH with either sodium silicate or potassium silicate [21, 22].
Na_2SO_4	Authors in [23] indicate that NaOH and sodium silicate solution as an alkaline activator enhance the reaction between the source material and the additive. The sodium silicate activator dissolved rapidly and began binding the base material's particles, according to [24, 25].
Sand	The fine aggregate can have a maximum size of 4.75 mm
Gravel	Crushed gravel no larger than 12.5 mm was used.
CFRP	CFRP rebar reinforcement offers good mechanical performance and a high specific strength [26].

V. REINFORCING BARS

The study used 8 mm distorted bars and the test results are shown in Table II. This study was conducted in the construction materials laboratory of the Civil Engineering Department at Mustansiryah University, according to [31].

TABLE II. TENSION TEST RESULTS FOR STEEL BARS WITHIN THIS STUDY

Nominal diameter (mm)	8
Normal diameter (mm)	7.9
Yield stress (MPa)	517
Yield strain (mm/mm)	0.00201
Ultimate strain (mm/mm)	0.167
Ultimate strength (MPa)	654
Elongation (%)	10

VI. MIXING PROCEDURE FOR GEOPOLYMER CONCRETE

The binder is the key factor that distinguishes GPC from OPC concrete. A geopolymer paste is formed by combining silica and aluminum oxide from Metakaolin with an alkaline solution (Na_2SiO_3 and NaOH). This paste is then mixed with additional components to produce GPC. The mixing process significantly influences the strength and workability of the concrete. Several researchers have stated that the traditional methods used for producing OPC concrete can also be applied to the production of GPC [27, 28]. The fine and recycled coarse concrete aggregates are first combined in a bucket mixer for 3 min in their dry form before being brought to the Saturated Surface Dry (SSD) condition. After the aggregates are mixed, metakaolin or cement is added and stirred for 2 min. The alkaline liquid, combined with 65% superplasticizer (and 35% water), is then added to the dry materials in the mixer tray. The superplasticizer is mixed with additional water for at least 2 min. Following this, iron filings and 35% more superplasticizer are added to the mixture and stirred for two minutes to incorporate the steel fibers. The compaction of the concrete is carried out using a vibrating table. Details and variables of the tested slabs are provided in Table III.

TABLE III. GENERAL DETAILS AND VARIABLES OF THE TESTED SLABS

Designation	Column location	Opening	CFRP
S11	Center	Without	-
S12	Center	Without	Punching shear area
S13	Center	Without	Around the column and in the punching shear area
S21	Center	With	-
S22	Center	With	Punching shear area
S23	Center	With	Around the column and in the punching shear area
S31	Ach	Without	-
S32	Ach	Without	Punching shear area
S33	Ach	Without	Around the column and in the punching shear area
S41	Ach	With	-
S42	Ach	With	Punching shear area
S51	Corner	Without	-
S52	Corner	With	-
S53	Corner	With	CFRP in the punching shear area

VII. RPC MIXTURES' MECHANICAL PROPERTIES

Control specimens were prepared and tested to measure the compressive and tensile strengths of the concrete. Three cubes with dimensions of 15 cm × 15 cm × 15 cm were tested under BS1881-116 to evaluate compressive strength [29]. Additionally, three prisms measuring 10 cm × 10 cm × 50 cm were tested as per [30] to determine the modulus of rupture. The average results from the three specimens were 90 MPa for compressive strength and 30 MPa for the modulus of rupture.

VIII. TESTING METHOD

Slab specimens were tested under monotonic loading using a universal testing machine (MFL system) to assess their behavior up to failure. Each slab was subjected to single-point loading with simple support. Testing was performed 28 days after casting. The centerline, supports, point load, and dial gauge were carefully positioned before loading to ensure accuracy. Stress was applied through a 40 mm × 40 mm loading plate and gradually increased at the central column. After each load increment, measurements were taken to record mid-span deflection and observe the development and propagation of cracks on the slab surface. Loading continued until the slabs reached their ultimate capacity, indicated by a rapid increase in deflection without a corresponding increase in the applied load. Crack patterns were marked on the slab surface using a pencil at each load increment to document their progression.

IX. RESULTS AND DISCUSSION

The test results of all 12 slabs including the first crack and ultimate load and failure mode are listed in Table IV.

TABLE IV. TEST RESULTS OF ALL SLABS

Group	Slab	First crack load (KN)	Ultimate load (KN)	Mid-span deflection at first crack (mm)	Mid-span deflection at ultimate load (mm)
G1	S11	20	135	1.75	5.8
	S12	30	140	0.56	4.81
	S13	35	155	0.75	4.35
G2	S21	45	130	0.64	3.96
	S22	35	230	0.82	3.95
	S23	35	255	0.6	4.19
G3	S31	10	125	0.12	8.95
	S32	30	130	0.68	12.26
	S33	25	135	0.68	6.8
G4	S41	20	50	0.27	2.48
	S42	35	65	1.4	2.87
G5	S51	40	70	0.31	2.28
	S52	15	135	0.19	0.3
	S53	30	145	0.16	0.53

A. *Cracking Loads*

Table IV presents the results of the crack load decrease with slab openings (S21, S41, S52) and notes the installation of CFRP in slabs (S12, S13, S22, S23, S32, S33, S42, S53). As for the location of the column, it is recalled that in the Ach Column, the fracture load is less than in the Center Column and less than in the Corner Column.

B. Load – Deflection

The behavior of Load-Deflection curves under the center of the loaded area for all tested slabs were set.

- The load deflection of Group 1 (S11, S12, S13) is shown in Figures 1-3.
- The load deflection of Group 2 (S21, S22, S23) is shown in Figures 4-6.

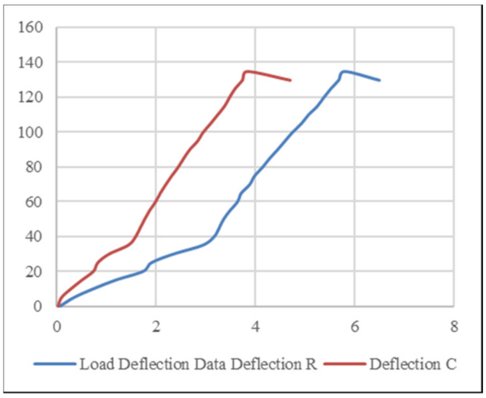

Fig. 1. Load- deflection for G1. S11.

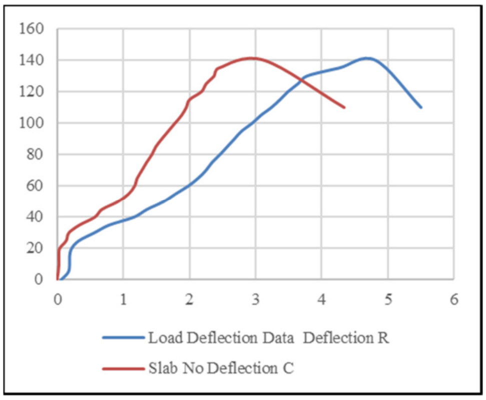

Fig. 2. Load- deflection for G1. S12.

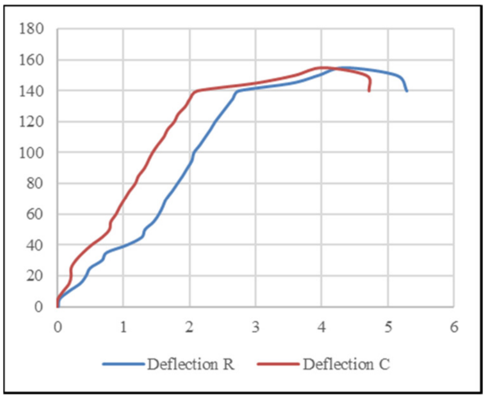

Fig. 3. Load- deflection for G1. S13.

- The load deflection of Group 3 (S31, S32, S33) is shown in Figures 7-9.
- The load deflection of Group 4 (S41, S42) is shown in Figures 10-11.
- The load deflection of Group 5 (S51, S52, S153) is shown in Figures 12-14.

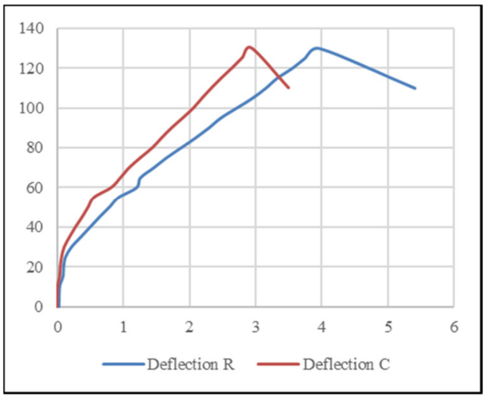

Fig. 4. Load-deflection for G2. S21.

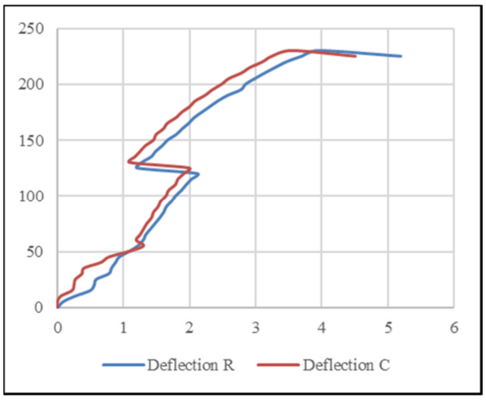

Fig. 5. Load-deflection for G2. S22.

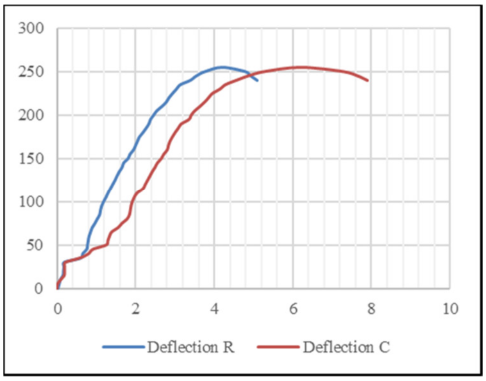

Fig. 6. Load-deflection for G2. S23.

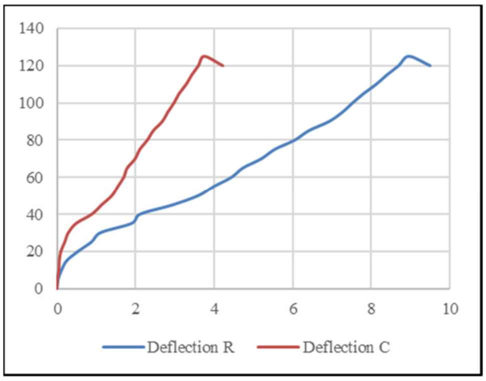

Fig. 7. Load- deflection for G3. S31.

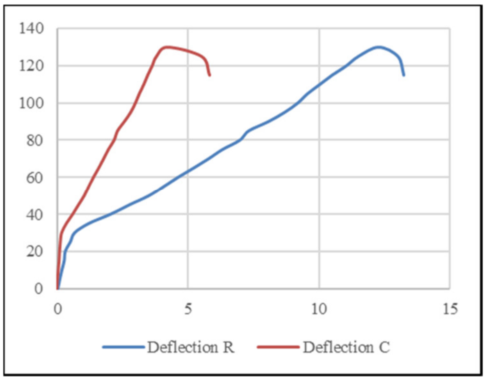

Fig. 8. Load- deflection for G3. S32.

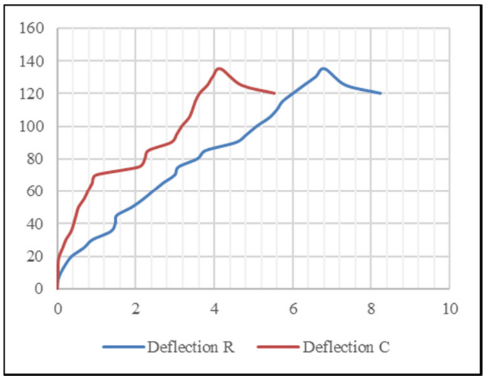

Fig. 9. Load- deflection for G3. S33.

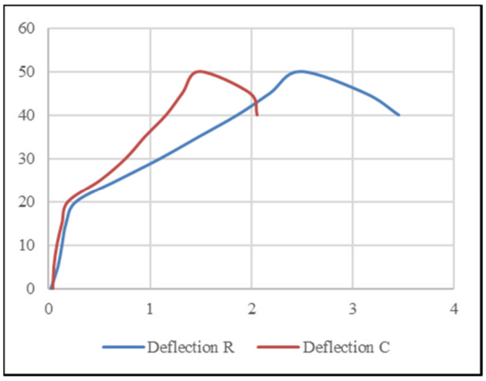

Fig. 10. Load- deflection for G4. S41.

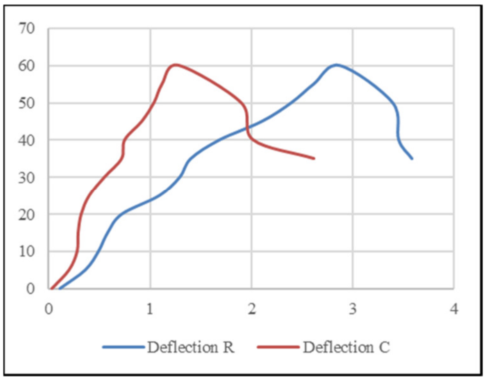

Fig. 11. Load- deflection for G4. S42.

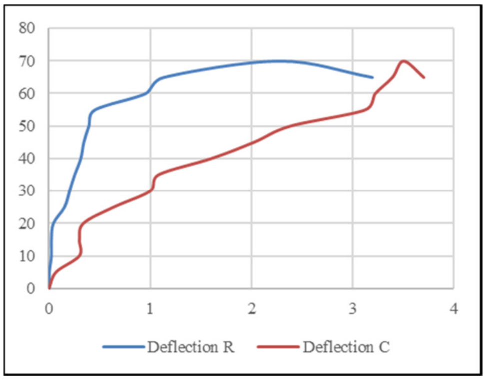

Fig. 12. Load- deflection for G5. S51.

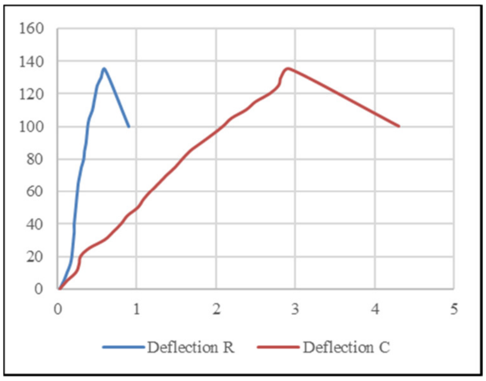

Fig. 13. Load- deflection for G5. S52.

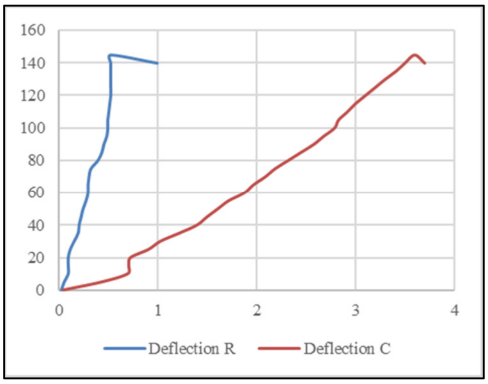

Fig. 14. Load- deflection for G5. S53.

X. CONCLUSIONS

International guidelines typically offer traditional methods for designing reinforced concrete slabs with service or architectural openings near columns. These methods are limited by factors such as the size and location of the openings, as well as the reinforcement strategies used to resist punching shear. This study investigates the use of CFRP in flat slabs with openings near columns, aiming to evaluate how these openings impact the slab's ability to resist punching shear. Based on the findings, the following conclusions can be drawn:

- As the drop percentage was 37%, the opening at the column's side suggests a lower ultimate load than in the reference model, which has no aperture.
- Compared to the reference model without an opening, an opening near the column reduces the first crack load by 55.5%.
- In comparison to the model with opening and no CFRP, the ultimate load rose by 76% when CFRP was utilized.
- The value of the first crack increased by 14% when CFRP was used.
- The punching shear behavior of slab geopolymer-reinforced concrete beams is negatively affected by transverse web holes, as these holes reduce the amount of concrete in the GC section.
- Due to their intrinsically low service load values, slab geopolymer-reinforced concrete slabs with a single transverse web aperture are less rigid than solid materials.
- When the number of CFRP strip rings is increased, the local buckling failure of the strengthened specimens decreases.
- The original structural behavior of the repaired geopolymer concrete slab can be restored by applying FRP sheets and adhering to the boundary conditions outlined in the current research.
- The primary factor contributing to the suggested techniques' effectiveness is the composite's significant strength, which is made up of epoxy and bonded FRP.
- The predominant failure mode in the tested geopolymer concrete flat plates was flexural.

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