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Inverted T-Beams in Structures: A Review

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Abstract - Performance and analysis of inverted T-beams have not been extensively studied. In this paper, information on the use of inverted T-bent caps are gathered. Existing technologies, web design guidelines for shear, and strengthening techniques are analyzed. Drawing from the collected literature, the use of fiber reinforced polymers (FRP) materials in inverted T-beams are still in their infancy, and recommendations for future work in this area are furnished in this study.

***Keywords*:** Inverted T-Beams; Reinforcement ratio; Failure modes; Strengthening techniques; STM.

1. Introduction

Inverted-T (IT) beams are used as bent cap girders and provide an attractive alternative to rectangular bent caps in infrastructures. Rather than being loaded on the compression-chord, IT beams loads are mainly applied to the tension-chord (on the flanges at the bottom). Thus, the use of IT beams allows the overall reduction in the elevation, increase the available overhead beneath the structure, and provide an aesthetically pleasing design. Since the IT beams are loaded mainly on the flange, their performance and force transfer mechanism differ substantially from the rectangular bent caps. Additional types of reinforcement are required in IT beams compared to the typical reinforcement of rectangular beams. Loads applied on the ledges are transmitted through flange reinforcement to the stirrups in the web, these stirrups act as hangers to deliver vertical forces into the body of the web.

Skewed IT bent cap is a special type of IT beams with skew web and ledge reinforcement utilized when two roads are not perpendicularly aligned. Two transverse reinforcement configurations can be used in skewed beams: traditional, and skewed configurations. In traditional skew design, the end regions are characterized by the transition from straight bars to skew bars resulting in unequally spaced transverse reinforcement. While the skewed arrangement reinforcement are aligned parallel with even spacing along the length of the beam. This skew arrangement of the rebars could be used to facilitate the ease of construction of this type of beam. As a consequence of the unsymmetrical projection of the ledges and the location of the loading pads, skewed inverted-T bent caps (ITBC) are more susceptible to torsion.

In this paper, relevant information on the use of IT girders in structures are gathered. However, the use of fiber reinforced polymer materials in IT beams are still in their infancy, and recommendations for future work in this area include are described in this study.

2. Experimental studies on inverted-T beams

2.1. Web and Flange Reinforcement

Mirza et al. [1, 2] experimentally studied the effects of flange and web reinforcements on the strength and serviceability of IT girders. They recommended using additional bars in the flange in place of diagonal bars since diagonal bars are complex to construct, and to provide closed web stirrups within a distance equal to the beam effective depth centered at every concentrated load on the ledge, Figure 1. Closed stirrups or welded as in Figure 1(a) and (b) were preferred to avoid anchorage problems imposed by the short length of the flanges. They concluded from observations of their test specimens that having closed stirrups in the web with sufficient anchorage wrapped around the longitudinal reinforcement was critical to ensure adequate load transfer from the ledge to the upper portion of the web.

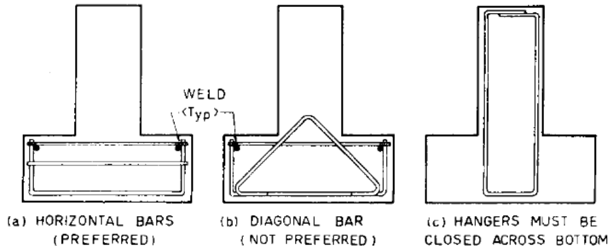


Figure 1: Suggested (a) (b) flange, and (c) web reinforcement[1]

Studies by Zhu et al. [3] focused on the cracking behavior of the interior regions of IT beams revealed that the diagonal and hanger steel were the most influential in controlling the diagonal crack width in the reentrant corners between the ledge and the web. However, the supplementary horizontal bars had no apparent effect.

Supplementary research by Zhu and Hsu [4] examined the effect of the length L_E from the load to the end face and the number of diagonal bars on the cracking behavior of the exterior cantilever of IT beams. In specimens with diagonal bars, horizontal cracks accompanied the shorter L_E while diagonal cracks were first to appear at larger L_E. For specimens with diagonal bars, however, no discernible trend could be established. Besides, specimens without diagonal bars were observed to fail in punching, whereas the diagonal bars seemed to increase the punching shear capacity and changed the failure mode to web shear, with the failure surface not intersecting these bars as presented by the thick line in Figure 2. Based on the experimental studies [4, 5], it was recommended to use more diagonal bars and increase the L_E to provide a better crack control.

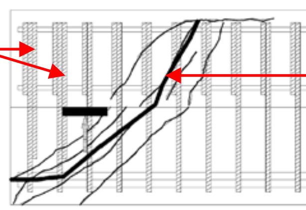


Figure 2: Web shear failure surface (specimen side view) [4]

2.2. Reinforcement ratio

Larson et al. [6] tested twenty-two simply supported IT beams to investigate the effect of web reinforcement on the strength of the beams. Doubling the web stirrup ratio from 0.3% to 0.6% improved the beam shear capacity. Similar conclusions were reported by Salman et al. [7] and Garber et al. [8]. The latter also reported that the web stirrups contributed to beam capacity to transfer the loads from the ledge to the upper portion of the web.

2.3. Ledge length

Larson et al. [6] experimentally investigated the three ledge lengths in Figure 3. Longer the length of the ledge, higher the capacity of the beam and higher the first diagonal crack load, although no appreciable effect on the crack width progression was observed. Cut-off ledges proved to have lesser levels of shear capacity than short and long ledges.

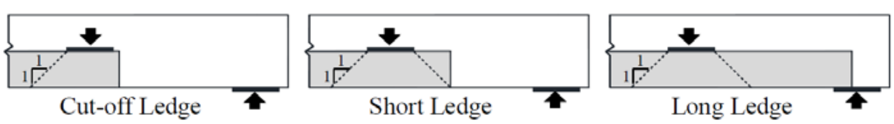


Figure 3: Ledge lengths studied by Larson et al. [6]

Garber et al. [8] experimentally examined IT beams with diversity in geometries that lead to different behaviors and ledge failures. The test results triggered an investigation of the different ledge failure modes, contribution of ledge and hanger reinforcements, load spread, and the applicability of existing design techniques to estimate the beam behavior.

2.4. Effect of other parameters

Larson et al. [6] studied the size effect and number of loading points on IT beams. Specimens had ledge depths of h/2 h/2 and h/3, where h is the overall height of the beam, as indicated in Figure 4 below, tested under 1-point and 3-point loads. loads.

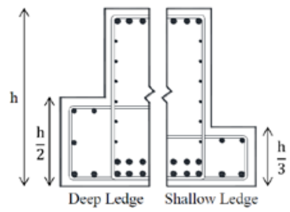


Figure 4: Ledge depths studied by Larson et al. [6]

Both the number of loading points and web and ledge depths had no appreciable impact on neither the strength nor the crack width, though deeper ledges slightly delayed the appearance of the first diagonal crack. Furthermore, the tension-chord loaded IT beams were compared to compression-loaded rectangular bent caps of similar dimensions from literature [9], the strength results did not seem to be affected, however, IT beams were found to crack at higher loads than of the R-beams, resulting in much narrower diagonal crack width. Finally, the decrease in span-to-depth ratio seemed to increase the normalized diagonal cracking load and the shear capacity of the specimens regardless of the other tested parameters.

2.5. Inverted-T beams subjected to combined forces/ Prestressing in inverted-T beams

Three half-scale IT beams were studied by Deifalla and Ghobarah [10] under combined shear and torsion. It was discovered that a low torque to shear ratio led to an increase in cracking and ultimate shear capacity and post-cracking torsional rigidity and a drop in the cracking and ultimate torque, spacing between diagonal crack and their angle of inclination, and strain developed in the transverse reinforcement.

Mirza and Furlong [11] experimentally examined the performance of 27 normal and prestressed inverted T-beam specimens under combined flexure and torsion effects. The prestressed specimens displayed better behavior than their normal counterparts.

Birely et al. [12, 13] and McKee et al. [14] assessed the use of interior voids in precast pretensioned bent caps with overhangs to reduce the weight and shorten the installation time. In these studies, a flexure design concept for pretensioned bent cap beams was proposed based on zero tensile stresses due to dead loads to ensure that any generated cracks close up upon the removal of live loads.

3. Skewed inverted-T beams

Roy et al. [15] investigated the structural behavior of one nonskewed and two kewed IT beams with traditional and skew transverse stirrups (Figure 5) for two different skew angles (0°, 30°). It was reported that the strength capacity between the traditional and skew transverse stirrup schemes was insignificant. Whereas the serviceability performance of skew reinforcement was relatively better than the traditional, as it showed a fewer number of cracks; which was accredited to the uniform distribution of web and ledge reinforcement. The former also exhibited lesser displacements at ultimate load.

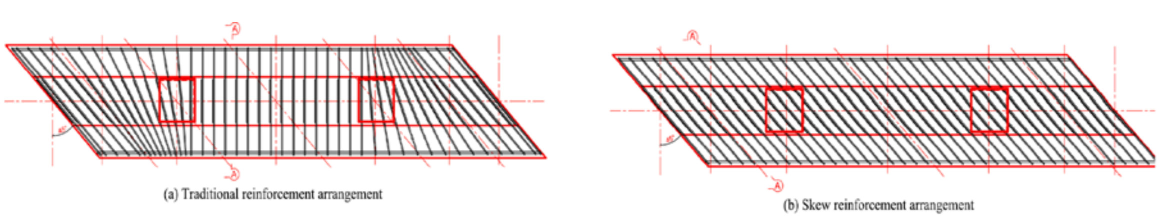


Figure 5: Skewed ITBC reinforcement arrangements (Plan view) [16]

Roy et al. [16] studied the effect of skew angle and reinforcement arrangement on the performance of six full-scale IT bent caps. The increase in the skew angle from 30° to 45° and 60° lowered the ultimate capacity of the ITBCs by 16% and 18%, respectively. Moreover, the torsional effect became more predominant with the increase in skew angles. Reinforcement arrangement at the end regions had no impact on the structural performance or the failure mechanisms of the beams. Specimens with skew arrangement exhibited a lesser number of cracks especially at the end regions, in addition to delayed yielding in transverse stirrups. Diagonal bars notably reduced the crack width, although were unable to fully eliminate the formation of diagonal cracks at the end face; while the extra web stirrups at the end face prevented horizontal cracking.

Zhou et al. [17] conducted experimental and parametric studies on the behavior of skewed IT beams. Tested parameters included the transverse reinforcement arrangement and spacing, loading location along the ledge, and skew angle. The outcomes were in agreement with earlier studies. The increase in the skew angle from 0° to 60° was accompanied by a drop in the cracking, yield, and ultimate capacities of the specimens regardless of the stirrups arrangement. The cracking, yield, and ultimate capacities decreased by 20%, 44%, and 37%, respectively, for the traditional rebars; while for the skewed arrangement the capacities dropped by 32%, 46%, and 30%, respectively.

Through a parametric finite element (FE) simulation, it was observed that as the load moved into the shaded region in Figure 6, the beam ultimate capacity and ductility were adversely affected; and the torsional effect magnified and the beam failed mainly in torsion. Similar effect on the capacity and ductility were achieved by doubling the reinforcement spacing. The length of this critical torsional region, L_{ext}, was recommended to be the maximum of $\frac{b}{2}\cot\theta$ and 305 mm, where b is the beam width and θ is the beam skew angle. Previous researches yielded comparable results [18, 19].

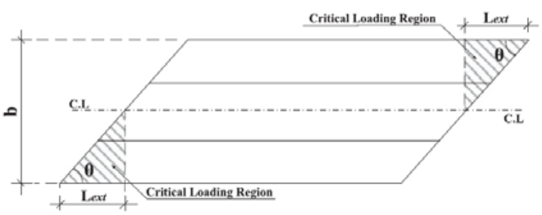


Figure 6: Critical torsional regions in skewed IT beams [17]

Wang et al. [20] selected three IT bent caps of a seven-span bridge, which were under construction in Texas, and developed their numerical models. Based on the developed numerical models, the maximum tensile stresses in the rebars were observed at the web-ledge interface at the end faces of the bent cap, as shown in Figure 7. Moreover, the maximum deformation in the bent cap always occurred at the acute angle skew at the end face, as indicated by the blue region in Figure 8, owing to the torsion generated by the unsymmetric loading on the ledges.

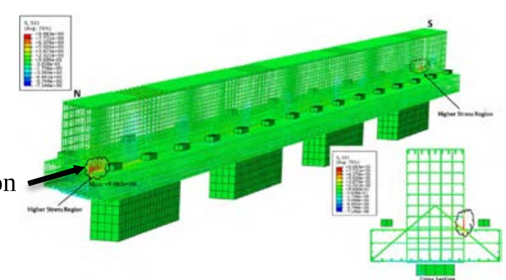
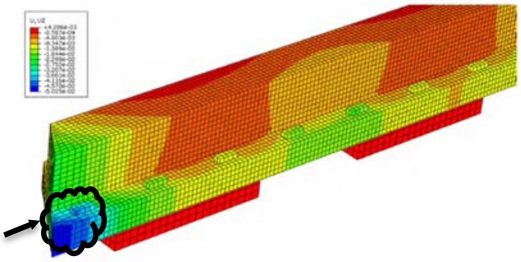


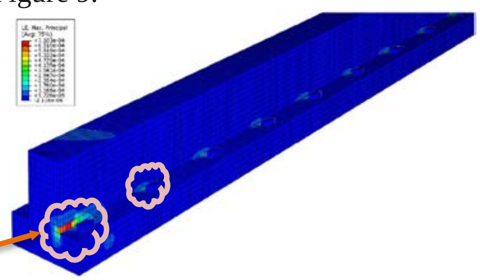
Figure 7: Tensile Stresses in Rebars [20]



Maximum deformation

Figure 8: Displacement at service load [20]

According to the principal tensile strain contour, there should not be many cracks observed in the bent caps; except for some microcracks localized near the loading pads and the re-entrant corners between ledge and web, which are characterized by their high tensile strains as indicated in Figure 9.



High tensile strain

Figure 9: Principal tensile strain of concrete [20]

To further investigate the performance of these beams a total of ninety-six full-scale FE models were developed from the models calibrated against the field test results; wherein the main parameters were the skew angle (43°, 33°), detailing of transverse reinforcement, end bars, amount of vertical web reinforcement (minimum, current design in AASHTO LRFD (2014), 20% more or 40% more than current design), size of diagonal bars (No. 3 to No. 7 bars), and concrete strength.

A considerable improvement in the beam stiffness and capacity followed the increase in the concrete compressive strength and the web reinforcement ratio. All types of end bars, however, had a negligible effect on the strength. As for the serviceability, a pronounced decrease in the crack width was achieved with mainly higher concrete strength and larger web reinforcement ratio, followed by the addition of end bars and increase in the diagonal bar area. AASHTO LRFD (2017) design recommendations for the web reinforcement and diagonal bars were adequate for structural safety and crack control. Regarding the cost, the diagonal bars had almost no effect on the cost while the web stirrups had a larger impact.

Based on the parametric results and the cost-benefit analysis, the skew arrangement reduced the number of cracks and restricted crack width compared to the traditional arrangement and notably reduced construction cost by around 11% to 16%. In apparent contradiction to previous studies, the rebar arrangement influenced the IT beam structural performance.

4. Strengthening of Inverted-T beams

Galal and Sekar [21, 22] experimentally proposed four new strengthening techniques of RC IT girders using externally bonded carbon fibre-reinforced polymer (CFRP) sheets. The use of 3 layers of CFRP sheets increased the capacity of the beams with hanger, web-shear, and punching deficiencies by around 20%, 10%, and 20% respectively; enhanced the displacement ductility capacity by up to 4, 1.8, and 4 respectively; and successfully eliminated the non-ductile failure mechanisms. Better performance of the retrofitting solution was achieved when the sheets were anchored using sandwiched (fan type) CFRP fibre anchors as in Figure 10.

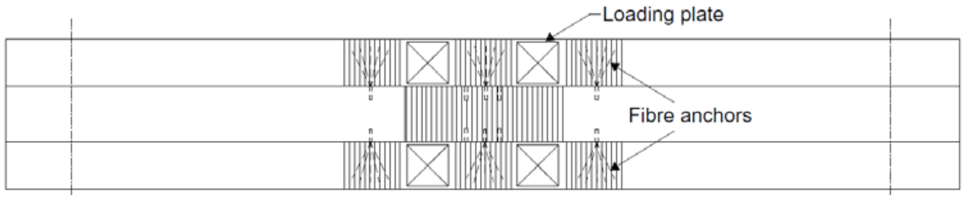


Figure 10: CFRP fibre anchors [22]

In a recent study, Hurlebaus et al. [23] experimentally evaluated the effectiveness of six new rehabilitation techniques in strengthening hanger- and ledge-deficient IT beams. Eighteen proposed retrofitting solutions were evaluated based on several criteria [24]: strength increase, total cost, constructability, clearance constraints, durability, and ease of monitoring. Based on these criteria, six solutions were selected and experimented; including end-region stiffener (Solution 3), clamped threadbar with channel (Solution 8), load-balancing post-tensioning [PT] (Solution 14), concrete infill with partial-depth (Solution 16), and full-depth (Solution 17) fiber-reinforced polymer [FRP] anchored by steel waling, and the use of large loading pads (Solution 18). All retrofit solutions successfully improved the capacity and significantly reduced damage to the specimens. Solutions 3, 8, 14, and 17 were tested on hanger-deficient specimens. For the exterior region, Solution 8 was the most effective in improving the capacity for both cracked and uncracked specimens, with an increase of 61 and 48%, respectively. The least increase in capacity was 18% by solution 3. The largest interior capacity increase of 23% was by Solution 17, which resulted in a shift in failure mode from hanger to ledge flexure.

The most significant exterior ledge capacity increase was 55% and 82% by Solution 16 and 17, respectively. While the smallest was provided by Solution 3 (33%). The interior ledge capacity increase was investigated by two solutions, with Solution 16 (21%) providing a greater increase in capacity than Solution 8 (16%). Solution 14 was implemented in hanger-deficient interior and exterior tests and the exterior of ledge-deficient specimens, it provided a substantial reduction in damage; however, it was not tested to failure. Finally, Solution 18 was observed to increase the punching shear capacity of the exterior by 14% with almost no effect on the interior portions.

It was concluded that AASHTO design equations accurately estimated the hanger capacity. However, it underestimated the ledge shear, flexure, and punching capacities. Based on the experimental results, modifications to AASHTO LRFD were introduced. It was proposed to use distribution widths of $c + S/2$ and $c + (W + 4a_v)/2$ for shear friction; and $c + S/2$ and $c + (W + 5a_f)/2$ for ledge flexure. Where c: distance from the centreline of bearing to the ledge end, S: centre-to-centre distance of bearing along the ledge, W: bearing pad width, a_v: distance from the centre of the bearing pad to the face of the web, a_f: distance from the centre of the bearing pad to the centre of the vertical reinforcement.

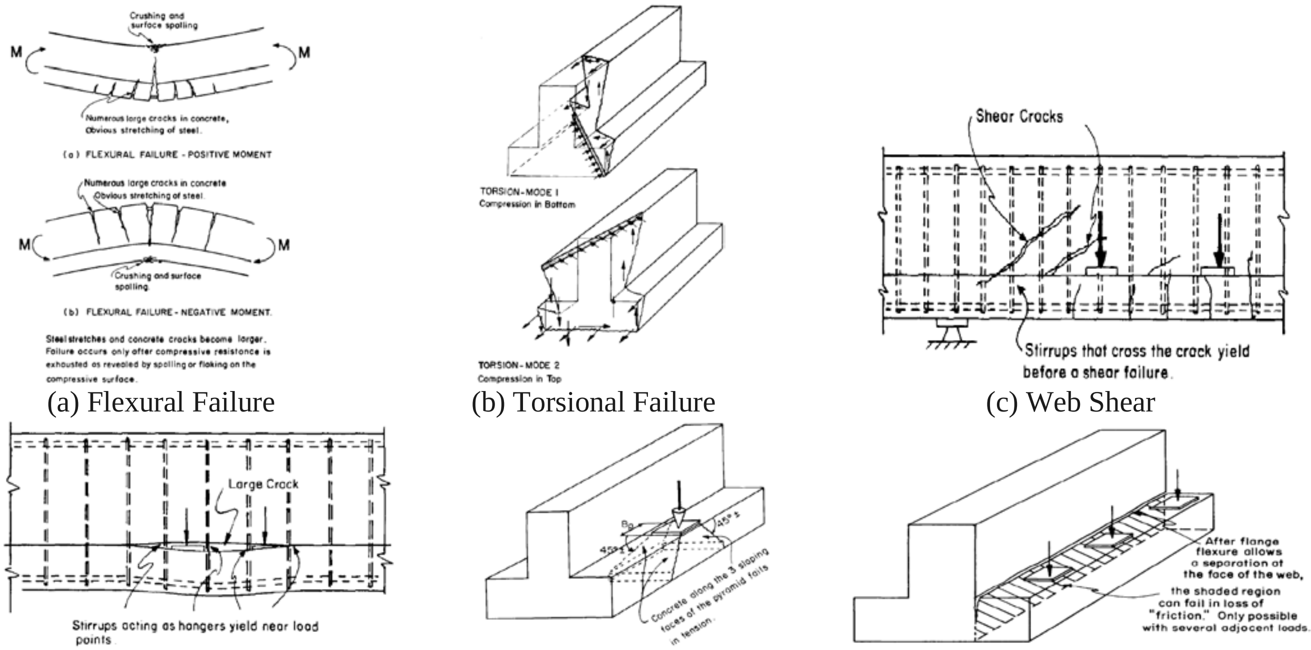
Punching shear cracks were observed to have an average of 35°, contrary to the estimated value of 45 in AASHTO LRFD. Accordingly, Article 5.13.2.5.4 in AASHTO LRFD (2014) were modified as in equations 1 and 2 below to account for these observations; where V_n: nominal shear resistance, f_c': compressive strength, W: width of loading pad, L: length of loading pad, c: is the distance from the centreline of bearing to the ledge end, and d_f: distance from top of the ledge to the bottom longitudinal reinforcement.

$$V_n = 0.125\sqrt{f_c'}\left(\frac{W}{2} + L + d_f \cot(35°) + c\right) d_f \quad (1)$$

$$V_n = 0.125\sqrt{f_c'}\left(W + 2L + 2d_f \cot(35°)\right) d_f \quad (2)$$

5. Failure Modes

Six possible failure modes can be expected for IT beams [11]: flexure, torsion, web shear, yielding of hanger reinforcement, punching shear in ledge, and shear friction in ledge failure, Figure 11.



(a) Flexural Failure (b) Torsional Failure (c) Web Shear

(d) Hanger failure (e) Punching Failure (f) Shear Friction Failure

Figure 11: Failure modes in IT beams [11]

6. Strut-and-Tie Model

Strut-and-tie models inherently consider all failure modes identified above. Garber et al. [8] compared ACI STM and the AASHTO LRFD empirical equations and deduced that the 3D STM, in Figure 12, was more accurate and conservative than AASHTO LRFD equations, with average tested/estimated capacity 1.2 and 2 respectively.

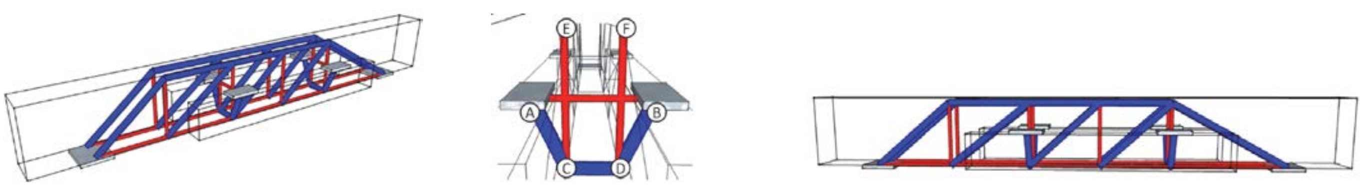


Figure 12: 3D STM for IT beam [8]

7. Conclusions

This study reviewed relevant literature of research work carried out by previous researchers on the performance and analysis of IT beams. There exist other literature works from past research on the subject that might have been missed. In addition, being a review paper, verification using experimental studies was not been performed. Existing technologies, web design guidelines for shear, and strengthening techniques were examined. This paper serves as a guide for future works and suggests the use of internal FRP reinforcing bars in IT beams to reduced corrosion-related problems and extend the lifespan of the structure, examining the applicability of STM to skewed IT girders, extending the use of strengthening schemes to prestressed specimens, studying the rehabilitation of girders with combined failure mechanism, analytically investigate the effect of different retrofitting solutions on IT beams, and studying the performance of tension-chord loaded IT beams with openings.

Acknowledgements

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