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Effects of Web Height Reduction and Skew Angle Variation on Behavior of RC Inverted T-Beams

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Abstract: The use of precast inverted T-beams has been frequently used to minimize construction activities and installation time. However, shipping and placement of large invert T-beams can become challenging tasks due to their weight. Decreasing the web height of the beam can be effective in reducing the beam weight. This paper considers inverted T-beams with two overhangs, negative moment regions, and one span, a positive moment region. The examined parameters were the web height and skew angle of the inverted T-beams. To avoid high costs of testing beams and to save time, the application of numerical modeling is, hence, inevitable. A calibrated 3D nonlinear numerical model, using ATENA software, was further used to numerically investigate the effects of reducing the weight, by decreasing the web height and varying the skew angle of inverted T-beams on their structural performance. The outcomes of this study indicated that reducing the web height of the beam was an effective tool to reduce the weight without jeopardizing the strength of the beams. Increasing the skew angle of the inverted T-beam also decreased their ductility.

Keywords: inverted T-beams; web height reduction; skew angle; numerical analysis

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1. Introduction

Reinforced concrete (RC) inverted T-beams are commonly constructed structural elements in buildings and bridges. They are typically used as support girders for the stringers and are aligned in the transverse direction to the traffic flow. As the stringers rest on the flange of the inverted T-beam, it allows a reduction in the overall bridge height and provides extra height clearance underneath the bridge to satisfy design code provisions. In addition, skewed bridges are required in practical applications to meet landscaping requirements.

For wide or skewed bridges, large sections of inverted T-beams could create a major problem in transport and erection due to their weight. To overcome this challenge, several solutions have been proposed. The Wisconsin Department of Transportation [1], The Washington Department of Transportation [2], and a Strategic Highway Research Program (SHRP) 2 report [3] recommend connecting several small precast segments to form a single cap beam and have provided standards detailing the cast-in-place closures. Another technique for linking neighboring precast cap beams is proposed by the Precast/Prestressed Concrete Institute [4]. The technique requires that the precast beam segments have extended bars to be spliced together by using mechanical couplers. The joints between adjacent segments would be filled with cast-in-place concrete to connect the precast segments together. Even though the solutions stated above offer an alternative to building long precast bent cap beams, they may not be ideal when the objective of using precast beams is driven by the need to minimize installation activities. Connecting joints in the above solutions require formwork for the cast-in-place concrete. In addition, long-term durability of the connecting joints has not been well investigated.

Another approach to address the challenge of shipping and construction of cap beams is to reduce the weight of the whole cap beam as one unit. Reducing the weight can be

achieved by using internal voids in the beam stems. Furthermore, precast box beams and inverted U-shaped beams can be utilized to reduce the weight. Utilizing stay-in-place polystyrene blocks to make voids in the beams is proposed by SHRP 2 [3]. A bent cap was installed as a precast box beam in a bridge project in Honduras [5]. Inverted U-shaped beams were constructed in the Edison Bridge overpassing the Caloosatchee River [4]. A precast, post-tensioned inverted-T bent cap with void in the stem was proposed by Billington et al. [6]. It was highlighted that the use of prestressing was an essential procedure to control the level of shear cracking. Birely et al. [7,8], Lee et al. [9], and McKee et al. [10,11] 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 also proposed based on zero tensile stresses due to dead loads to make sure that any generated cracks close up upon removal of live loads. Examples were provided to show that use of internal voids reduced the weight of the beams and saved construction time and cost. It was underlined that the pretensioned bent beams with voids were vulnerable to shear cracking under design loads and exhibited brittle failure modes. The studies concluded that voids may not be suitable for overhangs. Further investigation was recommended to better describe the shear behavior of cap beams having internal voids.

For RC skewed inverted T-beams, there are no design provisions or calculation guidelines given in the design codes. Larson et al. [12] examined the effect of the ledge depth, web depth, the web reinforcement ratio, and loading points on the strength and performance of inverted skewed T-beams. It was found the shear strength of the inverted T-beams increased as the web reinforcement ratio increased. Zhou et al. [13] numerically studied the effects of web reinforcement spacing and arrangement, skew angle, and load positions on the performance of inverted skewed T-beams. The behavior was not affected by the arrangement of web reinforcement and failure mode was significantly governed by the skew angle change. Roy et al. [14,15], Roy [16], Dhonde [17], and Wang et al. [18] experimentally examined the use of skewed shear reinforcement as a substitute to conventional shear reinforcement and the effect of skew angle on the performance of inverted T-beams. The arrangement of skew shear reinforcement provided better serviceability performance compared to a traditional reinforcement arrangement. Shear failure governed beams with a skew angle of 30° or 45° while beams with a skew angle of 60° were controlled by torsional failure. Several studies in the literature have reported the behavior of skewed bridges and examined the effect of skew angle on the stress distribution [19–23]. The collapse mechanism and damage levels of bridges subjected to collision by medium and heavy vehicles were investigated by Li et al. [24]. The verified FE model was used to numerically simulate an actual heavy vehicle collision accident resulting in bridge collapse, and the dynamic behaviors and collapse process of the colliding bridge were investigated. For the bridge under vehicular impact, a novel quantitative damage evaluation methodology was suggested. Mahboubi and Kioumars [25] reviewed and categorized the published studies on corroded RC bridges in the last decade. It was found that the cumulative impacts of cyclic loading during earthquakes, such material nonlinearities, stiffness deterioration, nonlinear deformation, and fatigue are key concerns that have been overlooked in previous studies. Operation modal analysis (OMA) and experimental modal analysis (EMA) were used by Marcheggiani et al. [26] to evaluate the load-bearing capacity of concrete structures. The outcomes of the study were used and compared with the numerical model. The comparison concluded that the dynamic load test can supplement the static load test for evaluating the load-bearing capacity of the structure. Lately, there have been proposed studies centering on structure-specific methods. Examples of these methods are the simplified displacement-based assessment (DBA) methods that were recently proposed, tested, and refined for multi-span continuous girder RC bridges by Perdomo and Monteiro [27].

Based on the literature review above, there is a scarcity of reliable conclusions for inverted skewed T-beams. This study aims to fill the gap in knowledge of the behavior of RC skewed inverted T-beams. This paper investigates the effect of two parameters (skew

angle and web depth) on the behavior of inverted T-beams with overhangs through 3D simulation using finite element (FE) modeling.

2. Experimental Test Data

In this study, two experiments documented by Roy et al. [14], ITBC-0-T-2M, and ITBC-30-S-2M, were selected as references for finite-element modeling. Both specimens were inverted T-beams. The experimental data of these two tests were utilized in this study to confirm the FE numerical model accuracy. The test specimens had two overhangs, negative moment regions, and one span, a positive moment region, and were designated as ITBC-0-T-2M and ITBC-30-S-2M as shown in Figure 1a. Specimen ITBC-0-T-2M had 0° skew and had traditionally aligned shear reinforcement, whereas specimen ITBC-30-S-2M was 30° skewed with skew transverse reinforcement as shown in Figure 1b,c, respectively. The test matrix and parameters are summarized in Table 1. As stated by Roy et al. [14], the test specimens of 0° and 30° skew were designed to ensure that the load carrying capacity was governed by the shear failure mode. Therefore, torsion was not a failure mode and the attention of their study was on the shear behavior of the inverted T-beam specimens with two different skew angle arrangements of web stirrup (0° and 30°). The details of steel reinforcement are presented in Figure 1b–d. The provided amount of transverse reinforcement was double the minimum reinforcement amount specified by AASHTO LRFD [28]. Four sizes of deformed mild steel bars were used; No. 10, 13, 19, and 22 of yield strengths of 455, 462, 480, and 505 MPa, respectively. The steel modulus of elasticity was 200 GPa for all steel bars. The concrete cylinder compressive strengths in specimens ITBC-0-T-2M and ITBC-30-S-2M were 44.8 and 50.3 MPa, respectively. The total length of the specimens was 5.486 m. The specimens rested on two supports (roller and hinge support) 2.438 m apart from each other. The shortest shear span-to-depth ratio of specimens was 1.30. Loading was applied on the mid-span and the cantilevers as shown in Figure 1a.

Table 1. Details of test specimens.

Specimen	Skew Angle	Detailing of Transverse Reinforcement	Amount of Transverse Reinforcement	f'_c (MPa)
ITBC-0-T-2M	0°	Traditional	2M	44.8
ITBC-30-S-2M	30°	Skew	2M	50.3

Note: 2M = double the specified minimum amount of transverse reinforcement by AASHTO LRFD. f'_c = cylinder compressive strength.

Load cells were placed at the supports under the beams to measure the reactions. The load was applied at the six pedestals as a displacement-controlled loading. The test reaction forces and the free displacements at the cantilever tip recorded by Roy et al. [14] were plotted in Figure 2. A bilinear response was observed in both specimens. The skewed inverted T-beam did not significantly behave differently than the non-skewed beam. The skewed beam showed a slight reduction in ductility and a slight increase in load. The maximum captured peak reaction force was 1503 and 1697 kN for ITBC-0-T-2M and ITBC-30-S-2M, respectively.

Figure 1. Details of the tested specimens by Roy et al. [14]: (a) Details of beam geometry (in mm); (b) Transverse reinforcement details for specimen ITBC-0-T-2M; (c) Transverse reinforcement details for specimen ITBC-30-S-2M; (d) Section A-A (in mm).

Figure 2. Experimental reaction force versus free end displacement relations.

3. Finite-Element Modeling of the Test Beams

To numerically simulate the test beams by Roy et al. [14], ATENA 3D v5.6 (Advanced Tool for Engineering Nonlinear Analysis 3D) software was utilized [29]. The software has a practical interface that makes the pre-processing step easy. The authors have utilized ATENA 3D in earlier works, see Mansour et al. [30] and El-Ariss and Elkholy [31], due to its high simulation capability. Moreover, the accuracy of numerical outcomes in this study confirmed the validity of this software. ATENA 3D is facilitated by sophisticated and different embedded material models that enable the software to simulate the behavior of complex concrete structures and provide detailed data on the behavior such as cracks, deformation, and strains in concrete and reinforcement. The mechanical properties of materials reported in the research paper by Roy et al. [14] were the primary inputs for the FE models. The nonlinear finite element software, ATENA, provides three material models for concrete. These models are the micro-plane material model, crack band model, and fracture-plastic model. The latter was the model that best simulated the test beams and was adopted in this study. Therefore, the concrete behavior was simulated using “3D Nonlinear Cementitious 2” concrete material model, which is the fracture-plastic model, which is also recommended in the software manual for concrete material. In this research, the concrete strength was the only input parameter used for the concrete material model. So, other concrete properties/parameters were set by the software. However, these parameters can be manually tuned and adjusted when needed to calibrate the model. The adopted concrete material model considers concrete behavior under compression (plastic) and tension (fracturing). The hardening/softening plasticity model is based on Mentrety-Willam failure surface [32]. However, the fracture model is founded on the conventional orthotropic smeared crack formulation and crack band model. The fracture model uses Rankine failure criterion. The combination of the two behavior models allows simulating concrete crushing under high confinement, cracking, and crack closure due to crushing in other directions. The stress–strain relationship of concrete under compression is mainly composed of ascending and descending branches. The law of the ascending branch is based on the strain, while the descending branch is based on displacement. The ascending branch begins by a linear relation with a slope equal to E_c up to a compressive stress value of f'_{co} which is equal to $2 \cdot f'_t$, where E_c = concrete modulus of elasticity and f'_t = uniaxial concrete tensile strength. Then, the curve is continued by a nonlinear elliptical segment until the stress reaches concrete cylinder compressive strength (f'_c). The function of the curve is given by Equation (1), where σ_c = compressive stress, f'_{co} = compressive stress at the onset of nonlinear compressive behavior, ϵ_p = plastic strain, and ϵ_{cp} = plastic strain at compressive strength. Figure 3a demonstrates the compressive hardening behavior. The descending part of the concrete compressive stress–strain curve is assumed to be linear. The stress is inversely proportional to the displacements (w_c) through the length scale (L_c). The displacement w_c is a function of the plastic strain (ϵ_p) as expressed in Equation (3), where ϵ_{cp} is plastic concrete strain at compressive strength and L_c corresponds to the projection of element size into the direction of minimal principal stresses as shown in Figure 3b. The stress reaches zero when the displacement is equal to w_d , where w_d is the plastic displacement which is equal to 0.5 mm for normal concrete [33].

$$\sigma_c = f_{co} + (f'_c - f_{co}) \sqrt{1 - \left(\frac{\epsilon_{cp} - \epsilon_p}{\epsilon_{cp}} \right)^2} \quad (1)$$

$$f'_{co} = 2 \cdot f'_t \quad (2)$$

$$w_c = (\epsilon_p - \epsilon_{cp}) \cdot L_c \quad (3)$$

Figure 3. Concrete compressive behavior: (a) Compressive hardening; (b) Compressive softening.

For the concrete stress–strain curve under tension, the curve begins with linear relationship with a slope equal to the concrete modulus of elasticity (E_c). The relationship stays linear until the tensile stress (σ_t) reaches the concrete tensile strength (f_t). Then, the stress–strain relationship turns into exponential decay based on the crack opening displacement (w_t) computed from the fracturing strain (ϵ_f) multiplied by crack band length (L_t) as in Equation (4). L_t is assumed to be equal to the size of the element projected into the crack direction as shown in Figure 4. The fracture energy of the concrete needed to create a unit area of stress-free crack (G_f) determines the value of crack opening at the complete release of stress (w_{tc}).

$$w_t = \epsilon_f \cdot L_t \quad (4)$$

Figure 4. Concrete tensile softening.

The material constitutive model for longitudinal and transverse reinforcements was a bilinear stress–strain relationship as presented in Figure 5. The stress increases with strain linearly with a slope equal to Young’s modulus of steel (E_s) until yielding. Then, the stress was assumed constant and equal to the steel yield strength (f_y). The bond between concrete and reinforcements was assumed to be perfect and irrelevant to shear stress on the contact surfaces.

The concrete beam and steel plates were modeled as solid 3D macro-elements. The steel reinforcements were modeled as discrete reinforcement embedded in the concrete beam. This means that the reinforcements are active in one direction only. Boundary conditions were configured to ensure the simulation of the real experimental testing setup. A restriction of vertical displacement was applied on the supporting plates. A push down displacement-controlled applied load was set at the loading plates in the FE analysis at a rate of 0.1 mm per step to trace the beam performance after the ultimate load is reached. Tetrahedral mesh type was generated. ATENA software recommends to have a minimum of 4–6 elements in the shortest dimension of the member to warrant solution convergence

while minimizing the computational time. To determine the best model mesh, several mesh element sizes based on the recommendation above were tested before selecting the mesh layout. The best suitable mesh size for the analysis was found to be 25 mm. The mesh and beam geometry configuration are shown in Figure 6. The adopted solution method in the numerical modeling was the standard Newton–Raphson iterative solution method. Geometrical imperfections were not considered in this study since no geometrical imperfections were reported in the experimental research by Roy et al. [14].

Figure 5. Bilinear stress–strain response of steel bars.

Figure 6. 3D models of inverted T-beam: (a) Mesh configuration; (b) Geometry and reinforcements.

4. Verification of the Finite Element Simulation

In this section, the numerical behavior of specimens ITBC-0-T-2M and ITBC-30-S-2M predicted by the FE model were compared for validation with the test data described by Roy et al. [14]. The specimen details and test results are provided in Table 1 and Figures 1 and 2 above.

The experimental and predicted numerical support reaction force versus displacement at the tip of the cantilever of specimen ITBC-0-T-2M is depicted in Figure 7a. The figure shows that the numerical model fairly accurately predicted the experimental response of the test beam. The beam numerical stiffness in the pre- and post-cracking stages was identical to the experimental stiffness. The beam numerical and experimental stiffness

decreased at almost the same load of 490 kN due to flexure crack development and at a force of almost 845 kN due to shear crack evolution. The test specimen failed at a force of 1503 kN and corresponding vertical displacement of 11.2 mm, whereas the beam failed numerically at a force of 1480 kN and corresponding displacement of 11.0 mm. Therefore, the beam numerical modeling predicted a failure force and corresponding displacement within 2% difference in comparison with their test result counterparts. Roy et al. [14] reported that the specimen failure mode was shear failure initiated by yielding of the cantilever shear reinforcement. The numerical model was also capable of predicting the yielding in the shear reinforcement at multiple locations in the cantilevers and the beam span as well as the yielding in the flange longitudinal reinforcement, as shown in Figure 7b. In addition, the numerical simulation of the crack pattern shown in Figure 7c clearly shows the shear and flexure crack patterns in the beam at failure.

Figure 7. Experimental and numerical responses of specimen ITBC-0-T-2M (0° skew): (a) Experimental and numerical force-displacement curves; (b) Yielded reinforcements; (c) Crack patterns; (d) Test crack pattern [14].

The numerical model was further validated with test results of the 30° skewed specimen ITBC-30-S-2M. The experimental and numerically predicted force-displacement behavior of specimen ITBC-30-S-2M are presented in Figure 8a and it can be seen that they are in good agreement. The stiffness of the numerical model in the pre-cracking stage was softer than the stiffness of the test specimen; however, the beam was numerically stiffer than the test specimen in the post-cracking stage. This behavior is in agreement with similar conclusions reported by Zhou et al. [13]. In terms of failure force and ductility, the specimen ITBC-30-S-2M failed at a force of 1697 kN and corresponding vertical displacement of 9.8 mm, whereas the beam failed numerically at a force of 1665 kN, 2% less than the test data, and displacement of 9.2 mm, 6.5% less than the test data. Figure 8b shows the predicted yielding in the shear and longitudinal reinforcements at numerous locations in the beam. The numerical simulation of the crack pattern shown in Figure 8c displays the shear and flexure crack patterns in the beam at failure.

Figure 8. Experimental and numerical responses of specimen ITBC-30-S-2M (30° skew): (a) Experimental and numerical force-displacement curves; (b) Experimental; (c) Crack patterns; (d) Test crack pattern [14].

The comparison between the test and FE analysis outcomes illustrated in Figures 7 and 8 verified the accuracy of the developed 3D nonlinear FE model in predicting the behavior of the inverted T-beam specimens tested by Roy et al. [14]. Therefore, it can be concluded that the developed model was calibrated, validated, and can be further utilized to numerically perform a parametric study on the behavior of the inverted T-beam test specimens, with varying skew angle and web height, in lieu of carrying out costly and time-consuming testing.

5. Parametric Study of Inverted T-Beams

The study parameters in this section are the skew angle and web height of the inverted T-beam specimens. It is worth mentioning that throughout this parametric study the specimen concrete compressive strength was kept constant and equal to 50.3 MPa, unlike the test specimens by Zhou et al. [13] where the specimen with 0° skew had concrete strength of 44.8 MPa and the specimen with 30° skew had concrete strength of 50.3 MPa (see Table 1 above).

5.1. Effect of Skew Angle

To examine the effect of the skew angle on the behavior of inverted T-beams, the test specimens with 0° and 30° skew were further modeled with 45° and 60° skew angles. The calibrated 3D nonlinear numerical model, using ATENA software, was further used in this extended investigation to numerically study the effects of changing the skew angle on the behavior of such beams. The beam cross-sectional dimensions shown in Figure 1b–d above remained unchanged. The beam length, longitudinal and transverse reinforcements, and loading locations were kept unchanged as well.

In Figure 9, the reaction force versus free end displacement curves for the beams with the different skew angles were plotted together. It can be seen that the behavior of beams with 0°, 30°, and 45° was almost similar. The beam seems to get slightly stiffer in the post-cracking stage as the skew angle increased from 0° to 45°. The value of ultimate reaction force and ductility of the beams were insignificantly affected by the skew angle of up to 45°. The specimen with 30° skew demonstrated 2.3% lower peak reaction force than the specimen with 0° skew. Likewise, the specimen with 45° skew demonstrated 3.8% and 1.5% lower peak reaction force than specimens with 0° and 30° skew, respectively. On the other hand, the 30° skewed specimen exhibited 7.0% lesser displacement at peak reaction force than specimen with 0° skew. The 45° skewed specimen demonstrated 9% and 2% less displacement at peak reaction force than specimens with 0° and 30° skew, respectively. As for the beam with 60° skew angle, the behavior was stiffer in the pre- and post-cracking stages than all other beams and, therefore, it was less ductile. It had an 11.3%, 9%, and 7.5% lower peak reaction force than specimens with 0°, 30°, and 45° skew angles, respectively. It also showed a 37%, 30%, and 28% less displacement at peak reaction force than specimens with 0°, 30°, and 45° skew angles, respectively. The increase in the beam stiffness could be attributed to wider beam section on the skew.

Figure 9 reveals that varying the skew angle from 0° to 45° did not have a major impact on the inverted T-beam behavior. Minor reductions in the beam reaction force and ductility were observed. However, the beam with 60° skew angle demonstrated more controlled deformation by substantially reducing the vertical displacement associated with a relatively moderate reduction in the reaction force. This could be credited to the increase in the beam stiffness at high skew angle.

Figure 9. Comparison of force-displacement response of inverted T-beams with different skew angles.

5.2. Effect of Web Height Reduction

For wide or skewed bridges, large sections of inverted T-beams could create a major problem in transport and erection due to their weight. To overcome this challenge, this study proposed reducing the web height of the beam, as shown in Figure 10.

Figure 10. Beam varying web height (in mm).

Four different web heights/depths were considered: 406 mm (the web full depth, see Figure 10), 305 mm (three quarters of the web full depth), 200 mm (half of the web full depth), and 100 mm (one quarter of the full depth). In order to examine the effect of reducing the web height/depth on the behavior of inverted T-beams, the validated 3D nonlinear numerical model was further utilized. The effect of varying the web height/depth on the behavior of the beam was examined numerically for each of the considered skew angles: 0°, 30°, 45°, and 60°.

In Figure 11, the numerical reaction force versus free end displacement behavior of the beam with the four different web heights/depths (full depth 406 mm, 305 mm, 200 mm, and 100 mm) were plotted together for each skew angle. The figure reveals that as the beam web height reduced, a corresponding increasing displacement (ductility) associated with a relatively moderate reduction in the reaction force were observed. This behavior pattern was the same in all beams regardless of their skew angle value as demonstrated in Figures 11 and 12.

(a)

(b)

(c)

Figure 11. Cont.

(d)

Figure 11. Force-displacement response of inverted T-beams with different web heights/depths: (a) Non-skewed (0°); (b) 30° skewed; (c) 45° skewed; (d) 60° skewed.

(a)

(b)

Figure 12. Effect of varying the beam web height and skew angle on the reaction force: (a) Effect of web height on the reaction force; (b) Effect of skew angle on the reaction force.

On the other hand, it is worth noting that Figures 11 and 12 uncovered a remarkable conclusion indicating that when reducing the web heights of beams with 30° and 45° skew angles, the ultimate reaction force was either equal or slightly more than their counterparts of beam with 0° skew angle. This concludes that reducing the web height of the beam is an effective tool to reduce the weight without jeopardizing the strength of the beams. To better highlight and clarify this remarkable conclusion, the numerical findings in Figures 11 and 12b were tabulated in Tables 2 and 3 below.

Table 2. Effect of varying beam web height.

Web Depth	Ultimate Reaction Force (kN)				Ratio		
	F_{u0} (0°)	F_{u30} (30°)	F_{u45} (45°)	F_{u60} (60°)	F_{u30}/F_{u0}	F_{u45}/F_{u0}	F_{u60}/F_{u0}
406 mm (full depth)	1714	1661	1638	1526	97%	96%	89%
305 mm	1576	1586	1571	1516	101%	100%	96%
200 mm	1537	1558	1551	1430	101%	101%	93%
100 mm	1448	1490	1386	1386	103%	96%	96%

F_{u0} = Ultimate reaction force for inverted T-beam with 0° skew angle. F_{u30} = Ultimate reaction force for inverted T-beam with 30° skew angle. F_{u45} = Ultimate reaction force for inverted T-beam with 45° skew angle. F_{u60} = Ultimate reaction force for inverted T-beam with 60° skew angle.

Table 3. Effect of varying skew angle.

Skew Angle	Ultimate Reaction Force (kN)				Ratio		
	F_{full}	F_{305}	F_{200}	F_{100}	F_{305}/F_{full}	F_{200}/F_{full}	F_{100}/F_{full}
0°	1714	1576	1537	1448	92%	90%	84%
30°	1661	1586	1558	1490	95%	94%	90%
45°	1638	1571	1551	1386	96%	95%	85%
60°	1526	1516	1430	1386	92%	90%	84%

F_{full} = Ultimate reaction force for inverted T-beam with full web depth (406 mm). F_{305} = Ultimate reaction force for inverted T-beam with 305 mm web depth (three-quarters of full web height). F_{200} = Ultimate reaction force for inverted T-beam with 200 mm web depth (one-half of full web height). F_{100} = Ultimate reaction force for inverted T-beam with 100 mm web depth (one-quarter of full web height).

Table 2 shows the values of the ultimate reaction forces for the four different web heights of the non-skewed and skewed beams. It also shows the values of the ratios between the ultimate reaction forces of the skewed beam and their counterparts of the non-skewed beam. The table clearly indicates that for non-skewed and skewed beams, the ultimate reaction force systematically decreased as the beam height decreased. However, the ratios demonstrate that as the web height decreased the ultimate reaction forces of the 30° and 45° skewed beams and their 0° skewed counterpart beams were the same in one case and differed within −4% to +3% in other cases, as shown in the table. The 60° skewed beam had a reduction in the ultimate reaction force within 4% to 11% when compared to its counterpart non-skewed beam as the beam web height decreased. This behavior can be attributed to the simultaneous changes in the load path as the load tries to find its way across the beam shortest two points, which are at the opposite obtuse angles, and the in the beam stiffness due to the web height decrease. As the beam skew angle increased to 45°, the load path across the opposite obtuse angle got shorter resulting in more load-carrying capacity, and decreasing the beam web height lead to softer stiffness.

As a supplement to Table 2, the ultimate reaction force of beams with full web height (406 mm) and with any skew angle was the highest and steadily decreased as the skew angle increased. However, for beams with lesser web height, the force magnitude fluctuated with the increase in the skew angle. The ratios in the table clearly demonstrate that reducing the web height to three-quarters (305 mm) and one-half (200 mm) resulted in just 4% to 10% reduction in the ultimate reaction force, as the skew angle increased, when compared with its counterpart of full height (406 mm). Reducing the web height to one-quarter (100 mm) resulted in 10% to 16% reduction in the ultimate reaction, which is a relatively moderate reduction given the substantial decrease in the web height to one-quarter.

The weight of the beam with the different web height is shown in Table 4. A substantial reduction in the weight of the beam can be achieved by decreasing the beam web height. When comparing the substantial reduction in the beam weight with the corresponding ultimate reaction forces in Tables 2 and 3, it would be safe to conclude that reducing the web height of the non-skewed and skewed beams is an effective means to reduce the beam weight without jeopardizing its strength.

Table 4. Reduction in beam weight.

Beam with Different Web Heights	Volume (m ³)	Weight * (kN)	Reduction in Weight
Full depth (406 mm)	3.035	74.4	-
305 mm web depth	2.761	67.6	9%
200 mm web depth	2.476	60.7	18%
100 mm web depth	2.204	54.0	27%

* Concrete unit weight = 24.5 kN/m³.

5.3. Crack Patterns, Crack Widths, and Tensile Strains

Figures 13–16 display the crack patterns, crack widths, and tensile strains in the inverted T-beams.

Figure 13. Cont.

(c)

Figure 13. Crack patterns, crack width, and principal tensile strain of 0° skewed beam: (a) Crack pattern (0° skew); (b) Crack width (0° skew); (c) Principal tensile strain (0° skew).

For the non-skewed beams, flexural shear crack patterns were developed throughout the beam length regardless of the beam web height as shown in Figure 13a. The main failure cracks were the diagonal cracks and cracks developed at the interface of the beam ledge and web between the support reactions, as depicted in Figure 13b,c. The development of these main cracks was attributed to yielding of the web reinforcement.

For the skewed beams, additional diagonal cracks appeared in the web and ledge at the end face of the beams; however, when the beam web height decreased, these cracks seemed to disappear, as demonstrated in Figures 14a, 15a and 16a. Furthermore, the flexural shear crack patterns gradually transformed to flexural crack patterns when the beam web height was reduced, as shown in Figures 14b,c, 15b,c and 16b,c. This can be credited to the change in the load path that connects the shortest distance between the obtuse angles and to the beam behaving more as a plate than as beam when the web height was reduced.

(a)

Figure 14. Cont.

Figure 14. Crack patterns, crack width, and principal tensile strain of 30° skewed beam: (a) Crack pattern (30° skew); (b) Crack width (30° skew); (c) Principal tensile strain (30° skew).

Figure 15. Crack patterns, crack width, and principal tensile strain of 45° skewed beam: (a) Crack pattern (45° skew); (b) Crack width (45° skew); (c) Principal tensile strain (45° skew).

Figure 16. Crack patterns, crack width, and principal tensile strain of 60° skewed beam: (a) Crack pattern (60° skew); (b) Crack width (60° skew); (c) Principal tensile strain (60° skew).

6. Conclusions

This paper addresses the challenging tasks of shipping and placement of large skewed invert T-beams with two overhangs and one span by reducing their weight. Numerical outcomes were presented of an investigation into the effects of reducing the weight, by decreasing the web height, and varying the skew angle of inverted T-beams on their structural performance using a calibrated 3D nonlinear numerical model.

Varying the skew angle from 0° to 45° had insignificant effects on the behavior of inverted T-beams with constant web height. The specimen with 30° skew demonstrated 2.3% lower load-carrying capacity than the specimen with 0° skew. Likewise, the specimen with 45° skew demonstrated 3.8% and 1.5% lower capacity than specimens with 0° and 30° skew, respectively. On the other hand, the 30° skewed specimen exhibited 7.0% less displacement at peak load than specimen with 0° skew. The 45° skewed specimen demonstrated 9% and 2% less displacement at peak load than specimens with 0° and 30° skew, respectively. As for the beam with 60° skew angle, the behavior was stiffer in the pre- and post-cracking stages than all other beams and, therefore, it was less ductile. It had an 11.3%, 9%, and 7.5% lower load-carrying capacity than specimens with 0° , 30° , and 45° skew angles, respectively. It also showed a 37%, 30%, and 28% less displacement at peak load than specimens with 0° , 30° , and 45° skew angles, respectively. It can be concluded that minor reductions in the beam load-carrying capacity and ductility were observed. However, beam with 60° skew angle demonstrated more controlled deformations by substantially reducing the vertical displacement associated with a relatively moderate reduction in the load-carrying capacity. This could be credited to the increase in the beam stiffness due to wider beam section at higher skew angles. In addition, the numerical findings also revealed that as the beam web height reduced, a corresponding increasing displacement (ductility) associated with a fairly sensible reduction in the beam load-carrying capacity were observed. This behavior pattern was the same in all beams regardless of their skew angle value. However, reducing the web height to three-quarters (305 mm) and one-half (200 mm) resulted in just 4% to 10% reduction in the load-carrying, as the skew angle increased, when compared with its counterpart of beams with full web height (406 mm). It is worth noting that reducing the web height to 305 mm and 200 mm decreased the beam weight by 9% and 18%, respectively. Reducing the web height to one-quarter (100 mm) resulted in 10% to 16% reduction in the load-carrying, which is rather a reasonable reduction given the substantial decrease in the beam web height to one-quarter that resulted in 27% reduction in the beam weight. This behavior can be attributed to the simultaneous changes in the load path as the load tries to find its shortest path through the opposite obtuse angles as the skew angle increased, and in the beam stiffness due to the web height reduction. Increasing the beam skew angle resulted in a shorter load path across the opposite obtuse angles leading to more load-carrying capacity, and decreasing the beam web height led to softer beam stiffness.

This study concludes that reducing the web height is an effective tool to reduce the weight of non-skewed and skewed inverted T-beams without jeopardizing their load-carrying capacity and ductility.

The numerical results obtained in this study are recommended to be utilized in a future study to suggest analytical calculation methods for RC skewed inverted T-beams.

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