Research Article

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Efficiency of CFRP torsional strengthening technique for L-shaped spandrel reinforced concrete beams

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Abstract: The present study aims to get experimentally a deeper understanding of the efficiency of carbon fiber-reinforced polymer (CFRP) sheets applied to improve the torsional behavior of L-shaped reinforced concrete spandrel beams in which their ledges were loaded in two stages under monotonic loading. An experimental program was conducted on spandrel beams considering different key parameters including the cross-sectional aspect ratio (i.e., web height/web thickness), and the availability of the CFRP strengthening system. The ledge of the spandrel beams was exposed during testing to a very high eccentric load, which was transferred to the web of the spandrel beam causing high shear, torsion, and bending moments. Consequently, the applied load resulted in in-plane and out-of-plane deformations of the web accompanied by flexural and shear cracks. This article demonstrates the advantage of using CFRP sheets to strengthen the mentioned members. The applied CFRP sheets increased the failure torsional load by about 37% compared to the identical L-spandrels without strengthening. The outcomes indicate that using CFRP sheets show improvement in restricting the deflections and rotation of L-spandrels due to increasing spandrel stiffness. The reduction in the degree of rotation attained more than 33% in comparison to the spandrel beams without strengthening. The experimental program confirmed the applicability of the proposed strengthening technique for compacted and slender L-shaped spandrel-reinforced concrete beams.

Keywords: L-shaped spandrel beams, CFRP strengthening, shear and torsion stresses, load–rotation angle response

1 Introduction

L-shaped spandrel members are often subjected to a series of vertical eccentric loadings when used in parking structures and abutments of bridges to transfer heavy loads from double-tee decks to columns, see Figure 1 [1]. The mentioned loads developed torsion in these structural members at the end regions. Designs commonly require perpendicular closed stirrups terminated by 135° standard hooks ACI 318-19 [2]. The required reinforcement for spandrel members, as required by international codes [2,3] is generally designed according to a general procedure originally proposed by Zia and McGee [4] and later modified by Zia and Hsu [5].

Ali [6] investigated the influence of the amounts of longitudinal steel reinforcement, transverse steel reinforcement, and the concrete strength on 18 floor-spandrel beam assembly to determine the ultimate flexural load, torsional, and deformation capacities. The torsional resistance prior to cracking is affected by the ratio of bending moment to twisting moment, section geometry, and the concrete tensile strength. The ultimate torsional strength based on the skew bending theory is dependent on the concrete and steel stress–strain relationships, the ratio of the bending moment to twisting moment, section properties, and the amount of steel provided. When shear is present the torsional strength in addition to the above factors is also influenced by the shear to torsion ratio. Observations of spandrel members in the laboratory and the field by Raths [7], Klein [8], and Logan [9] detected that the failure planes of the compact and slender spandrels were the same, with out-of-plane bending causing web diagonal cracking growing upward from its end regions.
Salom et al. [10] studied both experimental and analytical programs of six L-shaped beams. Two beams were considered as control specimens, the other four specimens were strengthened with carbon fiber-reinforced polymer (CFRP) laminate. This study focused on the effect of strengthening on the torsional and shear capacity of beams when the ends of the specimen are exposed to pure twisting force. This study showed that the CFRP laminates could increase the torsional capacity of beams by more than 70%. A good agreement between experimental and analytical results was found. Hassan et al. [11] and Walter [12] investigated full-scale slender L-shaped spandrel precast concrete beams. Their study confirmed experimentally and numerically by finite element analysis that the open web stirrups could be used safely and effectively. Lucier et al. [1,13] developed rational design guidelines for L-shaped spandrel precast concrete beams depending on experimental testing and finite element analysis. These guidelines assumed the torque could be analyzed into two orthogonal components acting on an angle of 45° failure plane (Figure 2). The plate-bending component $T_{ob}$ causes the web of generic spandrel to bend about a diagonal line expanding upward from the support and the twisting component of torsion $T_{ut}$ influences on the cross-section of the web and causes twist about their axis perpendicular to the diagonal line. Nafadi et al. [14] tested long-span L-shaped spandrel beams and observed ledge behavior and punching-shear strength reduction due to global shear and tension in spandrel ledges. Hariharan et al. [15] examined the applicability of compact spandrel beams with alternative web reinforcement. This experimental study demonstrated suitable performance when compared to similar members with closed stirrups. Fadala and Abbas [16] presented a finite element model on the flexural behavior of the L-shaped reinforced concrete models and highlighted the influence of the web tension reinforcement distributed over an effective width of the flange. Numerical analysis was used to validate experimental study results that included simply supported scaled-down L-shaped specimens with the flange situated under the beam web, the wed uploaded to failure to simulate the slab-beam system in common structures. Results indicated that when the percentage of the web reinforcement was distributed in the flange of an L-shaped beam, the ultimate load decreased and the maximum deflection increased at failure and that the difference in the results increased as more rebars were shifted in a wider flange section.

Although several studies on L-shaped spandrel beams have been conducted in the past decades, studies on the spandrel beams strengthening loaded under two stages are uncommon. In terms of the influence of the externally bonded CFRP sheets on the torsional behavior of spandrel beams, no studies have been conducted yet. Therefore, this study aims to get experimentally a deeper understanding of the efficiency of CFRP sheets applied to improve the torsional behavior of L-shaped reinforced concrete spandrel beams in which their ledges were loaded in two stages under monotonic loading.

2 Experimental program

The experimental program consists of testing four simply supported L-shaped reinforced concrete beams under eccentric single load at ledge mid-span to study various limit state behaviors, including two stages of loadings. In stage 1, the load was applied up to the level corresponding to 60% of yielding stress in the vertical steel stirrup at the web mid-span section followed by an
unloading process up to zero level. In other words, the strengthening installation on already cracked and laterally deflected spandrel beams that are within the serviceability limits will be evaluated in this stage. In stage 2, the test specimen was exposed to reloading up to the failure level. Two beams were tested as control specimens without strengthening, while the others were retrofitted with CFRP sheets.

2.1 Test matrix of spandrel beams

The aspect ratio of the spandrel beam is defined as the ratio of the web height to web thickness \((h/t)\). In the present study, two aspect ratios were adopted to be investigated for the designed spandrel beams, mainly 4.3 and 3.0, which represent slender and compact sections, respectively. The identical cross-sections of the slender and compact beams had web dimensions of \(650 \text{ mm} \times 150 \text{ mm}\) and \(450 \text{ mm} \times 150 \text{ mm}\), respectively, with ledge dimensions of \(250 \text{ mm} \times 200 \text{ mm}\). All tested beams had a span of 1,500 mm. While the ledge was cut back for 150 mm on either end of the spandrel to simulate an idealistic field conditions detail that allows the typical web to be connected to supporting columns. Each side of the web was provided with two holes through the thickness to achieve connection with the vertical rigid frame assembly with high-strength threaded rods, as idealistic field conditions. The concrete strength of each spandrel was based on the average strength of three cylinders \((150 \text{ mm} \times 300 \text{ mm})\) tested in conformity with ASTM C39 [17]. Three samples of each steel bar with 500 mm length and diameters of \(\varnothing\ 10\), \(\varnothing\ 12\), and \(\varnothing\ 16\) mm were tested. The ASTM A370-19 [18] was used to evaluate the yield tensile strength and ultimate tensile strength of steel bars. Table 1 summarizes the properties of spandrel beams, while the results of reinforcing steel bars are listed in Table 2.

### Table 1: Properties of spandrel beams

<table>
<thead>
<tr>
<th>Group</th>
<th>Spandrels designation</th>
<th>Aspect ratio</th>
<th>Strengthening status</th>
<th>Cylinder concrete strength (MPa)</th>
<th>Cross-sectional configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>SB1-US-S</td>
<td>4.3</td>
<td>Unstrengthened</td>
<td>43.2</td>
<td><img src="image1" alt="Cross-sectional configuration" /></td>
</tr>
<tr>
<td></td>
<td>SB1-CS-S</td>
<td>4.3</td>
<td>Strengthened</td>
<td>44.0</td>
<td><img src="image2" alt="Cross-sectional configuration" /></td>
</tr>
<tr>
<td>II</td>
<td>SB2-US-S</td>
<td>3.0</td>
<td>Unstrengthened</td>
<td>45.0</td>
<td><img src="image3" alt="Cross-sectional configuration" /></td>
</tr>
<tr>
<td></td>
<td>SB2-CS-S</td>
<td>3.0</td>
<td>Strengthened</td>
<td>41.6</td>
<td><img src="image4" alt="Cross-sectional configuration" /></td>
</tr>
</tbody>
</table>

2.2 Reinforcement details

The modified design procedure remained unchanged in PCA Notes on ACI 318-11 [19]. It should be noted that there were no updates on the PCA notes for ACI 318-14 and ACI 318-19. Therefore, all spandrel beams in this study were fabricated according to PCA Notes on ACI 318-11 and the eighth edition of the PCI Design Handbook assuming that the outer branches of closed vertical stirrups are resisting torsion stress and acting as a hanger for the ledge. Thus, all spandrels were designed to resist shear–torsion distress, and twist loadings according to the latest revision of the ACI 318 code. In this investigation, to assure end-region failures, additional flexural and ledge reinforcement was provided. Also, the ledge punching shear (localized failures) must be considered.

### Table 2: Mechanical properties of steel reinforcement

<table>
<thead>
<tr>
<th>Nominal diameter (mm)</th>
<th>(f_y) (MPa)</th>
<th>(f_u) (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varnothing\ 10)</td>
<td>575.00</td>
<td>670.67</td>
<td>9.34</td>
</tr>
<tr>
<td>(\varnothing\ 12)</td>
<td>605.05</td>
<td>698.00</td>
<td>9.42</td>
</tr>
<tr>
<td>(\varnothing\ 16)</td>
<td>612.67</td>
<td>707.00</td>
<td>11.18</td>
</tr>
</tbody>
</table>
and prevented to transfer the load from the ledge to the spandrel web by using extra reinforcement. The spandrels had one configuration of shear and torsion reinforcement, which was available in the frontal and back web faces. Conventional deformed steel reinforcement was used to resist the bending, shear, and torsion combination that was induced in each spandrel. Figure 3 shows the reinforcement configurations used to test spandrels SB1-US-S and SB1-CS-S.

### 2.3 Test setup

The loading frame used to test both slender and compact spandrel beams was the same, which applied a single point loading at the mid-span section of the ledge with a distance of 150 mm from the frontal face of the web. The supporting system was designed to include specially built assemblies to transfer the spandrel beam end reactions to the loading frame and, consequently, to the rigid floor with minimal support yielding and to prevent spandrel overturning or sliding during testing. These spandrel beams were tested in a simply supported scheme at the ends over an effective span of 1,300 mm and were rested on steel plates of 100 mm × 150 mm dimensions, centered relative to the spandrel web, through which the vertical components of reactions were transferred.

Two load cells with a capacity of 500 kN were used to determine the vertical component of the reaction, one per end located at the center of the web. Two main advantages of these load cells, mainly were monitor and record the value of the reaction at the position of influence; and determine how the influence point of the reaction was shifted relative to the web of the spandrel during the process of testing. Each spandrel was supported laterally by the restraining of the web at both ends. Vertical rigid assemblies were provided at the back of the web using stiff steel channels attached to the back face of the spandrel’s web with two heavy threaded rods, at each end, inserted over through the created web holes that were accurately positioned during casting. The vertical rigid assembly was used to restrain the movement of the test specimen and to provide torsional restraint at the web ends. To capture the lateral forces in the threaded rod, other load cells were placed at the top of the web’s frontal face and the bottom of the web’s back face. Figure 4 shows a profile of the test setup while the photograph of the completed test setups is shown in Figure 5.

![Figure 3](image-url)  
**Figure 3:** Reinforcement details for tested spandrels of group I (all dimensions are in mm).
2.4 Loading sequence and strengthening implementation

The control spandrel beam (unstrengthened) was exposed to monotonic static loading in steps up to the level that achieved stress in the vertical steel stirrup at the web’s mid-span section of 60% $f_y$, then the spandrel was unloaded in one step. At each loading step, the corresponding linear and rotational displacement was recorded and the developed cracks were traced. After that, the spandrel was reloaded in steps up to failure, where the mentioned observations were monitored systematically.

The control spandrel beam tested was the same as for the control beam during stages 1 and 2 except that, before starting the reloading stage, the spandrel beam was strengthened with externally bonded CFRP sheets which were applied to the frontal and back faces of the web and on the soffit of the tested beams.

CFRP schemes were calculated according to the requirements of the ACI 440.2R-08 code [20]. Individual CFRP strips of 150 mm width were implemented which wrapped the beam cross-section and distributed along the beam span. The CFRP ‘wet lay-up’ system consisting of a primer, CFRP sheet, and resin used applied for strengthening in this study. The primer increases the bond between the composite and the concrete substrate and it consists of two parts.

The CFRP sheets are high-performance carbon fiber supplied in unidirectional tow sheets of 500 mm in width.

The fiber thickness was reported to be 0.167 mm and its dry density was 1.8 g/cm³ with 230 GPa modulus of elasticity in tension and dry fiber tensile strength of 4,900 MPa. The installation procedure includes the following steps: (i) sandblast the bonding surfaces to remove thin layers of cement laitance adhering to the concrete surface and expose coarse aggregates to improve the connection between the CFRP strips and the concrete substrate, (ii) apply primer to the exposed concrete substrate to fill cracks and pores, (iii) cut CFRP sheet strips to 150 mm wide and 1,950 mm long for SB1-CS-S or 1,550 mm for SB2-CS-S, (iv) impregnate CFRP sheet strips with resin and place them on top of the primer, and (v) leave specimens to cure at room temperature for 7 days. After completing the CFRP fabrication and epoxy resin curing, on the eighth day, the spandrel beam was reloaded in steps to failure. Figure 6 shows the application process of the CFRP fabric while Figure 7 illustrates the loading sequence for a typical test.

2.5 Instrumentation

Three types of instrumentation were used to monitor and record the applied load, reactions, strains, deflections, and rotations for all spandrels. Five load cells recorded the applied load, vertical reactions, and lateral reactions. Linear variable displacement transducers were used for recording vertical deflections and lateral deflections at various locations. Measurements of the vertical deflection were selected at the intersection line of the ledge and the web of spandrel at the mid-span section. Also, the deflections near the web ends were recorded to monitor support vertical settlement. Lateral deflections at the mid-span section were observed at the top and bottom centerline of the web’s back face to determine the rotation. Fourteen electrical resistance pre-wired strain gauges were used to measure strains in concrete, steel reinforcement, and
CFRP strips. Two strain gauges were glued on the top and bottom concrete fibers of the ledge at the mid-span section (SG-8 and SG-9) and four strain gauges on the concrete fibers of the ledge and web frontal (inner) face (SG-10 to SG-13). Seven strain gauges were used to measure steel reinforcement strains at different locations in the mid-span section and the section located at 300 mm from the left edge of the ledge on the main longitudinal bars (SG-6 and SG-7), skin longitudinal bars (SG-4 and SG-5), top horizontal leg of the transverse reinforcement of the ledge (SG-1), and on vertical legs of the transverse reinforcement of the web (SG-2 and SG-3). One strain gauge served to monitor strain in CFRP sheets (SG-14). All instrumentation was connected to a computerized (NI) data acquisition device to record data automatically. The strain gauge resistances were $120 \pm 0.5$, $118.5 \pm 0.5$, and $119.5 \pm 0.5 \Omega$ for concrete, rebar, and CFRP sheet, respectively. Strain gauges type (PL-60-11-3LJC-F) with base length 60 mm, type FLAB-6-11-3LJC-F with base length 6 mm, and type BFLAB-5-3-3LJC-F with base length 5 mm were used for concrete, steel rebars, and CFRP sheets, respectively. Figure 8 illustrates the strain gauge locations.

**Figure 6:** Strengthening procedure: (a) grinding of concrete, (b) application of CFRP and epoxy, (c) front face after application of CFRP, and (d) final form after the application of CFRP.

**Figure 7:** Typical loading sequence.
3 Results and discussion

Strengthening spandrel beams were reloaded to failure after CFRP installation and completing the curing time of the epoxy resin. Table 3 summarizes the applied load at the mid-span section, vertical reactions, lateral reactions, measured deflections at failure, and degrees of rotation.

3.1 Cracking pattern

During stage 1 of loading, all the tested spandrel beams showed cracks of different orientations. Commonly, light skewed cracks have appeared on the web’s frontal face of the spandrel beam while minimal flexural cracking appeared on the web’s back (outer) face near the mid-span section. Some of these cracks were closed during unloading. During stage 2 of loading, the cracking propagation was also investigated as the load increases to failure. The cracking pattern for all tested spandrels was similar.

It was noticed that the crack pattern was consistent for all specimens and agreed with what would typically be observed by Raths [7], Klein [8], and Logan [9]. The combination of shear and torsional stresses led to such a cracking pattern in a spandrel beam. It is important to note that the shear stresses and torsional distress act in

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Total applied load at mid-span (kN)</th>
<th>Increase of applied load (%)</th>
<th>Maximum vertical reactions (kN)</th>
<th>Maximum lateral reactions (kN)</th>
<th>Mid-span vertical deflection (mm)</th>
<th>Rotation (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>Right</td>
<td>Bottom left</td>
<td>Top right</td>
</tr>
<tr>
<td>SB1-US-S</td>
<td>190</td>
<td>Control</td>
<td>94.5</td>
<td>93.8</td>
<td>34.2</td>
<td>33.4</td>
</tr>
<tr>
<td>SB1-CS-S</td>
<td>260</td>
<td>37</td>
<td>127.3</td>
<td>125.5</td>
<td>46.1</td>
<td>45.6</td>
</tr>
<tr>
<td>SB2-US-S</td>
<td>200</td>
<td>Control</td>
<td>97.9</td>
<td>99.3</td>
<td>85.6</td>
<td>79.9</td>
</tr>
<tr>
<td>SB2-CS-S</td>
<td>276</td>
<td>38</td>
<td>135.3</td>
<td>130.5</td>
<td>123.5</td>
<td>119.3</td>
</tr>
</tbody>
</table>

Figure 8: Strain gauges location on (a) rebars, (b) concrete, and (c) CFRP sheet.
the same direction in the frontal face of the web, which led to making a high traditional diagonal tension in the web’s end regions. In the web’s back face, the interaction between the principal tensile shear and torsional distress tends to negate each other. Thus, the diagonal tension on the web’s back face was reduced and could even be opposite to that on the frontal face depending on the magnitudes of the shear and torsional stresses. Diagonal cracks on the frontal face of the web were initiated from the outer corners of the ledge and propagated upward with an initial angle of approximately 45°. Moving away from the spandrel ends to the mid-span section, the crack’s angle progressively decreased and the crack changed its orientation that became parallel to the line of interaction between the web and the ledge. Vertical flexural cracks were propagated with loading upward from the soffit of the ledge around the region of the mid-span section. At the failure stage, it was noticed that the crack width in the end regions of the control spandrels SB1-US-S and SB2-US-S was larger than that of the strengthened beams SB1-CS-S and SB2-CS-S, even though the strengthened spandrels were subjected to higher applied loading. Also, in all tested spandrels, some diagonal cracks excessively propagated on the web’s frontal face continuing their inclined growth and intersecting the top surface of the web forming skew cracks that reflected the torsion effect, see Figure 9.

Also, there was inclined severe cracking at 45° on the web’s inner face near the support, resulting from the out-of-plane bending induced by the end lateral couple force needed to prevent the spandrel from moving toward the applied load in response to eccentric vertical load.

The propagation of critical diagonal cracks and the cracks skewed across the top edge of the web depends on

Figure 9: Cracking pattern and failure mechanism of L-spandrel beams.
the implementation of the strengthening scheme. It was observed that the strengthened L-spandrels SB1-CS-S and SB2-CS-S had little skewed cracks across the top edge of the web in comparison to the unstrengthened L-spandrels SB1-US-S and SB2-US-S.

It was monitored that the vertical flexural cracks were dominant near the mid-span section of the L-spandrels, which initiated at the soffit of the ledge and propagated upward across the ledge's depth. These cracks were wrapped under the soffit of the web and also linked to the flexural cracks on the back (outer) face of the web (Figure 9). Between the ends of the L-spandrel and the mid-span section, many inclined cracks were observed, reflecting the shear effect in these regions. Increasing the applied load to higher levels, the symptoms of severe spiral cracking would become evident in the control spandrels SB1-US-S and SB2-US-S end regions of the web's faces accompanied by face–shell concrete spalling as their surfaces warp and deform under the effects of torsion distress. As would be expected, the L-spandrels SB1-CS-S and SB2-CS-S showed the efficiency of the CFRP strengthening system, especially at the ends of the
interaction line between the web and the ledge, which led to preventing the spalling of concrete and limiting the overall deformation.

3.2 Failure modes

Failure modes of end-regions are shown in Figure 9 for all tested L-spandrel beams. It is important to remember that spandrels were designed in such a way to prevent premature ledge localized failure or flexure failure by providing extra ledge reinforcement and web flexural reinforcement. All the four L-spandrels showed the same failure mode including moderate diagonal cracking on the web’s frontal face and moderate flexural cracking on the web’s back face at the first stage. At the failure stage, the spandrel’s failure modes began to differ depending on the availability of the CFRP strips.

As would be planned, localized failures did not occur during the testing of all spandrel beams. Both of the spandrels SB1-US-S and SB2-US-S failed in their end regions due to a global skew-bending mechanism in combination with vertical shear. These spandrels failed along an inclined-diagonal crack expanding upward from the bottom corners of the web and showed extensive diagonal cracking on their inner faces along with extensive flexural cracking on their outer faces with virtually identical modes at end regions. The skew-crack plane intersected the bottom edge of control spandrels and intersected the top edge of that spandrels. For the strengthened spandrels (SB1-CS-S and SB2-CS-S), the skewed failure plane not attained the extreme top concrete fibers of the web, also, the spandrel section was exposed to limited concrete spalling, see Figure 9.

3.3 Linear and rotational displacement of tested beams

The vertical and horizontal displacements were measured at the mid-span section. The deforming behavior of the four spandrels was almost identical in loading stage 1. It was observed that during loading, L-spandrel rotated toward the applied load achieving at mid-span section a bottom surface outward movement (i.e., away from the applied load) and a top surface inward movement (i.e., toward the applied load), more so the bottom surface moved more than the top surface. Figure 10 shows the load–vertical mid-span deflection curve, while Figure 11 illustrates the load–mid-span rotational displacement curves for all tested L-spandrel beams. These figures depicted the residual linear and rotational displacements that were attained by the end of the unloading process during stage 1. In comparison to unstrengthened beams, the strengthened L-spandrels showed stiffer performance due to the application of CFRP strips which achieved an efficient restrainer for the widening of the existing cracks and an active controller for limiting the creation of new ones. In addition, the maximum rotation values of spandrels SB1-US-S and SB2-US-S were exceeding the rotation values of spandrels SB1-CS-S and SB2-CS-S, see Table 3. CFRP strips around the web’s faces led to reducing the rotation in the strengthened spandrels due to the increase of the restraining effect induced by the CFRP strips attached externally to the structural member.

3.4 Strain of different reinforcing steel and CFRP strips

Different strain gauges were glued on longitudinal and transverse steel reinforcement and CFRP sheets to monitor the strain evolution during loading for each specimen. Among the 14 electrical resistance strain gauges which were used, four of them in this section were selected to demonstrate the load–strain response, mainly SG-2 (on the vertical leg of the transverse reinforcement of the web), SG-4 (on the web’s skin longitudinal bar), SG-7 (on the main longitudinal bar of the ledge), and SG-14 (on CFRP strip), see Figure 8.

The load–strain relationships are illustrated in Figure 12. As mentioned above, the tested spandrel beams were first exposed to incremental concentrated load up to the load that achieved a strain in the web’s vertical steel stirrup at the mid-span section of $1,725 \times 10^{-6}$ (i.e., a strain corresponding to 60% $f_y$ of the bar of 10 mm diameter). During this stage, it is important to note that before cracking, all spandrel beams showed an identical linear elastic behavior with various slopes. Whereas, after cracking, the slope of these curves incrementally decreased with different slope changes depending on the level of degradation that affected the tested specimen (i.e., the aspect ratio and the availability of the strengthening system).

The spandrel beams were unloaded in one step. On the other hand, at the unloading stage, the strain (SG-2) is gradually decreased where the residual value ranged between 503 and $630 \times 10^{-6}$ (i.e., 30% of the yielding strain).

Finally, at the second stage (i.e., the reloading stage) the strain in SG-2 was progressively increased in all specimens and exceeded the yielding strain of $2,875 \times 10^{-6}$. The tensile strain of longitudinal steel (SG-4 and SG-7) for each spandrel beam was monitored and recorded for each load.
Figure 10: Load–vertical deflection curve at mid-span section for tested spandrel beams.

Figure 11: Load–rotation curves at mid-span section for tested spandrel beams.
increment up to failure with the same observations being noticed.

It is interesting to note that the strain value in CFRP strips (SG-14) attained $1,600 \times 10^{-6}$ at failure load.

4 Conclusions

This article investigated the performance of a realistic strengthening that includes flexure, shear, and torsion capacities of spandrel beams under a one-point eccentric static load. The article focuses on monitoring the failure mode and recording the torsional capacity. Depending on the outcomes of this study, the following conclusions were drawn:

1. The behavior of all spandrel beams was similar at the load level corresponding to a stress level in the web’s transverse steel bars of 0.6 $f_y$ (i.e., stage 1), while the behavior of these tested spandrel beams had a different response and load magnitude at the failure stage (i.e., stage 2).

2. Diagonal shear cracks on the end regions of the web’s frontal face were initiated from the outer corners of the ledge and extended up with an initial angle of approximately 45°. The increasing eccentric vertical load caused the inclined cracks to change their orientation and became flattened out toward mid-span, which reflected the shear and torsion effect.

3. The propagation of critical diagonal cracks and the cracks skewed across the top surface of the web depends on the implementation of the strengthening scheme. The benefits provided by CFRP strips include minimizing the propagation of critical diagonal cracks and the cracks skewed across the top web surface. The strengthened L-spandrels SB1-CS-S and SB2-CS-S had little skewed cracks across the top surface of the web in comparison to the unstrengthened L-spandrels SB1-US-S and SB2-US-S.

4. The strengthened L-spandrels had control of crack widths with minimal spalling or crushing of concrete, which was attributed to the confinement effect provided by CFRP continuous strips. During the tests, debonding or rupture of CFRP was not apparent.
5. Eccentric vertical loads concentrated on spandrel ledge induced torsional distress and reduce a spandrel load-bearing capacity. Using CFRP strip wrapping is efficient in providing additional torsional capacity. In this experimental study, the torsional strength of the spandrel SB1-CS-S exceeded that of the traditional spandrel SB1-US-S by up to 37%, while the increase in SB2-CS-S was about 38% when compared to its counterpart spandrel SB2-US-S. These results confirmed that the performance of strengthening spandrels was satisfactory and will increase the torsional strength of reinforced concrete spandrel beams. Strengthening spandrels could avoid torsion brittle failure.

6. All four L-spandrels showed the same failure mode including moderate diagonal cracking on the web’s inner face and moderate flexural cracking on the web’s outer face at the stage 1 of loading. At the stage 2 of loading, the spandrel’s failure modes began to differ depending on the availability of the CFRP strips. The failure mode of the spandrel beams was combined shear and torsion along a skewed diagonal plane.

7. The results indicate that using CFRP strips show improvement in restricting the deflections and rotation of spandrel beams. The reduction in rotation degree of the spandrel SB1-CS-S when compared to the unstrengthened spandrel SB1-US-S was 33%, while the reduction in SB2-CS-S was about 36% when compared to its counterpart spandrel beam SB2-US-S, which indicates an increase in spandrels stiffness.

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