This paper presents the results of nonlinear finite element analyses conducted to model the behavior of L-shaped, precast, prestressed concrete spandrels constructed with open web reinforcement. The finite element model was calibrated using experimental results from recent tests of slender, L-shaped, precast, prestressed concrete spandrels. Detailed correlative studies between analytical and experimental results are presented, demonstrating the capability of the finite element program to describe the observed experimental behavior.

The feasibility of using open web reinforcement in compact, L-shaped, precast, prestressed concrete spandrels to achieve a more construction-friendly reinforcement scheme is also examined. Five different web reinforcement configurations for the compact spandrels were studied in order to evaluate the contribution of closed stirrups to the spandrels’ shear-torsion behavior.

The behavior, ultimate load-carrying capacity, and mode of failure of both the slender and compact L-shaped precast, prestressed concrete spandrels are presented. For loading values near the ultimate, the out-of-plane bending behavior of compact, L-shaped, precast, prestressed concrete spandrels is strongly influenced by the web-reinforcement configuration. Results from the analysis show that for long-span, compact spandrels, open web reinforcement can be used effectively to resist torsional forces throughout the member.
Despite past research, there still exists a need to study the behavior of L-shaped, precast, prestressed concrete spandrels when subjected to different combinations of torsional, flexural, and shear loads. Industry methods and published procedures vary significantly with respect to several fundamental aspects of the design and detailing of such members. Current U.S. and Canadian provisions for the design of members for compatibility torsion are simple to use and conservative for design, but they often result in areas of heavily congested reinforcement within a beam.

Significant potential exists for reducing the complexity of L-shaped, precast, prestressed concrete spandrel designs by removing closed ties from slender members. Limited tests on full-scale L-shaped spandrels revealed the possibility of reducing the transverse reinforcement at their end regions. Elastic theory (assuming an uncracked section) is a necessary tool for proportioning the member. However, an analysis of the post-elastic behavior—including stiffness, deformation, and cracking patterns—is essential for evaluating the complete response of the member to different loading conditions.

Knowledge of the complete response of an L-shaped spandrel to different loading conditions is critical for assessing the amount of the transverse reinforcement needed at the member ends. Test results have shown that the torsional stiffness of a member is greatly affected by cracking and by the interaction among torsional, flexural, and shear loads. Figure 1 shows a typical L-shaped spandrel that is used in parking structures.

A unified procedure for the design of prestressed concrete members for shear and torsion was originally developed by Zia and McGee in 1974. Their design procedures were derived from a comprehensive set of test data and were coordinated with existing design practice. Further refinement of these procedures was subsequently proposed by Zia and Hsu.

Although these procedures are commonly used, research data have never validated them for slender spandrels, which are typically used in practice. Recent efforts to classify spandrel behavior include a study by Rahal and Collins, which describes a procedure to calculate compatibility torsion in spandrels. Their procedure relies on modified compression field theory to calculate the cracked torsional and flexural stiffnesses for sections subjected to various combinations of stress resultants. Rahal and Collins’ procedure was capable of predicting the response of concrete members where the effect of compatibility torsion is dominant.

The American Concrete Institute’s ACI 318-05 requires closed stirrups to be placed throughout a concrete member subjected to combined shear and torsion. According to this document, closed stirrups are mandatory to avoid spalling of the concrete cover. Test results by several researchers showed that this type of behavior is unlikely to occur in deep spandrels.

Recently, the Precast/Prestressed Concrete Institute (PCI), and many PCI Producer Members, have questioned the need for closed stirrups along the entire length of a slender spandrel. It should be noted that in the precast concrete industry, common detailing practices for torsional reinforcement in deep spandrels do not usually follow the ACI requirements. Transverse reinforcement is often provided in L-shaped spandrels with pairs of lap-spliced, mild-steel, U-shaped stirrups. Unfortunately, widespread, full-scale experimental testing to examine the influence of various web reinforcement configurations in L-shaped spandrels is prohibitively expensive.

Therefore, the use of nonlinear finite element analysis coupled with limited experimental studies is a powerful tool for predicting the behavior and failure modes of L-shaped, precast, prestressed concrete spandrels. The complex combination of stress resultants that develop in the member due to bending, shear, and torsion, as well as the size effect of the L-shaped spandrel’s slender web, dictate the intricacy of such analyses.

This paper presents the results of nonlinear finite element analyses conducted to simulate the behavior of L-shaped, precast, prestressed concrete spandrels. The main objective of the current study was to develop reliable and computationally efficient finite element models (FEMs) to analyze L-shaped, precast, prestressed concrete spandrels subjected to combined bending, shear, and torsion. Results from previous testing were used to calibrate the FEM. Once a model was validated, it was used to investigate the response of compact, L-shaped, precast, prestressed concrete spandrels designed with open web reinforcement.

The behavior, ultimate load-carrying capacity, and failure mode of both slender and compact, L-shaped, precast, prestressed concrete spandrels are presented. The influence of the lateral deck ties and several different

![Figure 1. Typical spandrel used in parking structures](image-url)
Fig. 2. Reinforcement details of spandrels SP3 and SP4. Note: ' = ft; " = in.; 1 ft = 304.8 mm; 1 in. = 25.4 mm; 1 lb = 0.00448 kN; #4 = 12M; #5 = 16M; #6 = 19M.

Fig. 3. Mesh dimensions used in the finite element model. Note: ' = ft; " = in.; 1 ft = 304.8 mm; 1 in. = 25.4 mm.
web reinforcement configurations on the out-of-plane behavior of compact, L-shaped, precast, prestressed concrete spandrels is also discussed.

VALIDATION OF THE FEM

The first reinforced concrete FEM that included the effects of cracking was developed in 1967. Cracks were modeled by separating the nodal points of the finite-element mesh, thus creating a discrete crack model. With the change of topology and the redefinition of nodal points, the narrow bandwidth of the stiffness matrix was destroyed, resulting in increased computational effort. Moreover, the lack of generality in crack orientation has made the discrete crack model unpopular. The need for a crack model offering automatic generation of cracks and complete generality in crack orientation, without the need for redefining the finite element topology, has led the majority of investigators to adopt other crack models.

In the current study, the ANATECH Concrete Analysis Program (ANACAP) was used to model the behavior of the L-shaped, precast, prestressed concrete spandrels. The concrete material model in ANACAP has evolved over the past 30 years and is based on smeared cracking methodology for the treatment of concrete tensile cracking. Modeling of the compressive behavior of the concrete follows the generally accepted principles of computational plasticity, though these principles are modified for the unique and computationally demanding aspects of concrete response.

Cracks are assumed to form perpendicular to the directions of the largest tensile strains. Multiple cracks are allowed to form at each material point, but they are constrained to be mutually orthogonal. At the onset of cracking, the normal stress across the crack is reduced, and the distribution of stresses around the crack is recalculated through iteration of equilibrium equations. This recalculation allows stress redistribution and load transfer to the reinforcement. Once a crack forms in the model, the direction of the crack remains fixed and it can never heal. However, a crack may close to resist compression and then reopen.

The smeared-crack model represents an engineering approximation to the concrete’s actual behavior and permits the analysis of concrete structures up to and during failure. In the smeared-crack approach, the modulus and strength of the concrete in the direction normal to an open-crack surface is zero, but the shear modulus and shear strength remain intact. The shear modulus is gradually reduced, however, as crack widths increase. This gradually reducing shear resistance is critical to the continued load resistance of the structure.

Several attempts have been made in the past few years to model the behavior of L-shaped, precast, prestressed concrete spandrels using finite element analysis. Nevertheless, the complex behavior of these spandrels under combined bending, shear, and torsion limited the previous analyses to modeling only linear-elastic behavior.

Two L-shaped, precast, prestressed concrete spandrels, denoted spandrels SP3 and SP4, were selected from the literature to validate the

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Table 1. Materials Properties Used in Finite Element Analysis

<table>
<thead>
<tr>
<th>Property</th>
<th>SP3</th>
<th>SP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete compressive strength, psi</td>
<td>5790</td>
<td>7190</td>
</tr>
<tr>
<td>Modulus of rupture of concrete, psi</td>
<td>456</td>
<td>509</td>
</tr>
<tr>
<td>Yield strength of welded wire reinforcement, psi</td>
<td>98,000</td>
<td>98,000</td>
</tr>
<tr>
<td>Yield strength of conventional mild-steel reinforcing bars, psi</td>
<td>64,500</td>
<td>64,500</td>
</tr>
<tr>
<td>Yield strength of prestressing strands, psi</td>
<td>243,000</td>
<td>243,000</td>
</tr>
<tr>
<td>Prestressing losses, %</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Note: Modulus of elasticity of all conventional and prestressing steel is 29,000 ksi. 1 psi = 0.006895 MPa.; 1 ksi = 6.895 MPa.
FEM. The spandrels measured 45 ft 6 in. (13.87 m) long from end to end. Figure 2 shows cross-sectional dimensions and reinforcement details of both spandrels. A detailed description of the testing of these two specimens is reported in this issue of the PCI Journal and elsewhere.3

**Modeling the Concrete Spandrels**

Because geometry and loading of the members were symmetrical about their midspans, half of each spandrel was modeled using 20-node brick elements, each node having three translational degrees of freedom. The finite-element mesh was chosen so that elements would maintain acceptable aspect ratios while accurately representing geometry, loading conditions, and support conditions. Figure 3 shows the finite-element mesh dimensions used in the FEM.

**Modeling the Prestressing and Mild-Steel Reinforcement**

The prestressing force in each member was applied gradually to the spandrel ends in the model to replicate the transfer length of the strands. This was accomplished by splitting each strand into 10 small strands. Each small strand has one-tenth the area of the original strand, but all occupy virtually the same location in the spandrel.

The first of the 10 strands started at the spandrel end, and the 10th started at a distance equal to the transfer length. The remaining eight strands started at equal, incremental distances between the spandrel end and the transfer length, as shown in Fig. 4. The reinforcement was modeled as individual subelements within the concrete elements. The stress and stiffness of the mild-steel reinforcing bar subelements were superimposed on the concrete element in which the reinforcing bar resided. The analytical model accounted for every mild-steel reinforcing bar used in each of the spandrels.

**Simulation of the Applied Load**

Load was applied to the spandrel ledge at each double-tee stem as a uniform pressure acting over the stem bearing area. The analysis was conducted using an incremental-iterative solution procedure, in which the applied load was incrementally increased. The loading increment was set to 1 kip (4.448 kN) per step. Within each step, equilibrium was achieved and iteration was repeated until internal equilibrium conditions were sufficiently fulfilled and convergence was obtained. At the end of each step, the program adjusted the stiffness matrix to reflect any nonlinear changes in the spandrel’s stiffness.

The self-weight of the spandrel, loading jacks, and spreader beams, along with the weight of the double tees, were introduced at the first load-
Materials and Boundary Conditions

Table 1 summarizes the material properties used in the FEM for spandrels SP3 and SP4. The spandrel model employed the same boundary conditions as those implemented in the laboratory tests. In the model, the spandrel was restrained vertically throughout its width for the first 12 in. (305 mm) along both ends to simulate the bearing pads used at the laboratory spandrels’ ends. Lateral restraint was provided throughout the width of the spandrel, 6 in. (152 mm) from each end and 12 in. (305 mm) from the top and bottom of the spandrel. This lateral restraint simulates the tiebacks provided by the threaded rods during laboratory testing of the actual spandrels. A symmetry boundary condition was applied at midspan for each analysis because only half of each spandrel was modeled.

RESULTS AND DISCUSSION

Deflections

Figures 5 and 6 plot the predicted and measured vertical end reactions versus midspan deflections for spandrels SP3 and SP4, respectively. It should be noted that the load was held during testing for several relatively long periods of time, including a 24-hour period, causing a small amount of creep, which is reflected by the progressive increase in residual deflections upon each unloading cycle. This short-term creep behavior was not simulated in the ANACAP program and, thus, the increases in deflection at various load levels are not seen in the FEM-predicted behavior. It should also be noted that the end reactions plotted for both spandrels represent the externally applied loads and do not include the dead load of the system. Linear behavior was predicted for both specimens up to the initiation of the first crack at a load level of 95 kip (423 kN). Predictably, this initial behavior was followed by a nonlinear behavior up to failure. In general, the FEM-predicted behavior is in good agreement with the measured values, with the exception of the effect of creep as discussed previously.

From the figures, it is observed that the predicted post-cracking stiffness is slightly lower than the measured values, especially for spandrel SP4. A significant portion of this error can possibly be attributed to the instruments used to obtain the vertical deflection measurements. As the spandrel rotates and deflects vertically, a component of the lateral deflections is included in the vertical measurements. This error, inherent to obtaining vertical deflections, is a common issue in laboratory testing of structures.

Fig. 7. Cracking potential of spandrel SP3 with an end reaction of 60 kip (267 kN) (above) and 100 kip (445 kN) (below).

Fig. 8. Predicted crack pattern at different loading stages.
measurements from a rotating cross-section that is moving both vertically and laterally, is discussed elsewhere. Contributions of the double tees at greater load levels could also result in the higher spandrel stiffness values than the predicted values.

Crack Pattern

Cracking potential is defined as the ratio of the principal concrete tensile stress to the tensile strength of the concrete at any given point in the analysis (expressed in terms of percentage). Concrete cracking will occur when the cracking potential reaches a value of 100%. At this stage, the principal tensile stress at a given location is equal to the tensile strength of the concrete.

After cracking, the cracking potential will drop to zero in the vicinity of the crack. Figure 7 depicts the cracking potential for spandrel SP3 with an end reaction of 60 kip (267 kN). The figure clearly shows the tendency of the concrete to crack along a diagonal near the end of the spandrel. Figure 7 also shows the cracking potential of spandrel SP3 with an end reaction of 100 kip (445 kN). At an end reaction of 100 kip, the shear crack has already developed because the cracking potential in the marked area has been reduced to zero.

Although these figures are shown for spandrel SP3 only, spandrel SP4 had a nearly identical cracking pattern. Figure 8 shows the predicted cracking patterns for the spandrel at various loading stages. The FEM effectively captures the observed deflection behavior. In the model, the top of the spandrel rotates forward at midspan, the ledge rotates back, and the entire cross section deflects downward.

Rotation

Figures 9 and 10 show the predicted rotations of spandrels SP3 and SP4 at their quarter spans, respectively. FEM-predicted rotations compare well with the measured values up to failure. The figures clearly illustrate the capability of the FEM to reasonably predict the out-of-plane deflections of the spandrels.

Shear Stresses

Figure 11 illustrates the predicted shear stresses for spandrels SP3 and SP4 along the front face of the spandrels. High shear stresses were observed at the junction of the ledge and the spandrel web. Spandrel SP4 experienced slightly higher shear stresses than spandrel SP3 did at different loading stages. This increase could be attributed to the distribution of the web reinforcement at the ends of the spandrel. Spandrel SP4 had relatively uniform web reinforcement, whereas in spandrel SP3, the web reinforcement was more concentrated at the ends.

Failure Mode

In the laboratory, both spandrels SP3 and SP4 failed along a skewed-diagonal crack and experienced a horizontal separation across the diagonal crack extending across the top of the web. Compression shear failure at the end.
regions of the spandrels was the governing mode of failure for both specimens.³

Failure in the FEM ultimately occurred in both spandrels due to crushing of the concrete along the primary compressive strut, as shown in Fig. 12 for spandrel SP3 (spandrel SP4 was virtually identical). Analysis was terminated when the principal compressive strains along the compressive strut reached a value of 0.002, as recommended by modified compression field theory.⁷ The predicted failure loads for spandrels SP3 and SP4 are within 3% of the measured values. Table 2 summarizes the predicted ultimate loads and deflections for both specimens.

Influence of Deck Ties

Deck ties consisting of steel plates of dimensions 3 in. × 6 in. × % in. (76 mm × 152 mm × 0.5 mm) were used to connect the double tees to the spandrel webs in the actual specimens. To investigate the influence of the lateral restraint provided by deck ties on the predicted behavior of the spandrel, the FEM incorporated lateral springs at the spandrel front face at the center of these plates. The stiffness of the springs was set to 21,750 kip/in. (3809 kN/m), which is equivalent to $EA/L$ of a given steel plate, in which $E$ is the elastic modulus of the steel, $A$ is the cross-sectional area of the plate, and $L$ is the length of the plate.

It should be noted that using spring supports simulates an upper boundary condition for the lateral stiffness provided in the actual test. Figure 13 shows the predicted load-deflection behaviors with and without deck ties for spandrel SP3. The finite-element analysis demonstrated the lateral restraint provided by the deck ties had a minor effect on the stiffness of the spandrel.

This discrepancy could be attributed to the fact that the location of the deck ties within the spandrel web nearly coincides with the center of rotation of the web. Figure 14 shows the FEM-predicted lateral displacements at midspan at the bottom of spandrel SP3. The lateral restraint provided by the deck ties reduces the post-cracking

![Image](image_url)

**Table 2. Results of the Finite Element Analysis for Specimens SP3 and SP4**

<table>
<thead>
<tr>
<th></th>
<th>SP3</th>
<th>SP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_u$, kip</td>
<td>Experimental</td>
<td>174</td>
</tr>
<tr>
<td>$\Delta_{ver}$, in.</td>
<td>1.98</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Note: $R_u$ = the end reaction of the spandrel at ultimate; $\Delta_{ver}$ = the vertical deflection at midspan at ultimate; 1 kip = 4.448 kN; 1 in. = 25.4 mm.
lateral displacements 45% to 65%, depending on the load level.

The finite-element analysis indicates that the only significant effect of the deck ties is the restraint of lateral displacements induced by bending about the weak axis of the spandrel. As expected, the actual behavior of the spandrel falls between the two extreme cases considered in the analysis. Such a phenomenon indicates that the assumed spring stiffness was much higher than the actual stiffness provided by the deck ties.

### ALTERNATIVE CROSS-SECTIONAL DIMENSIONS

#### Compact Sections

While the previous analysis focused on slender, L-shaped spandrel cross sections (d/b of 7.5), the following analysis is related to compact, L-shaped cross sections (d/b of 1.75), in which d and b are the depth and the width of the spandrel web, respectively. This study relies on the validated analytical model discussed previously to investigate the influence of various shear and torsion reinforcement schemes on the behavior of compact spandrels.

Five different reinforcement schemes were considered. Because the researchers desired to compare the transverse reinforcing schemes in the slender and compact L-shaped spandrels to one another, the cross-sectional dimensions and prestressing levels were kept constant for all five cases. All analyses were conducted using a 45 ft (13.7 m) span.

The compact section geometry and reinforcement layouts were proposed, designed, and detailed by the PCI Producer Members sponsoring the study. Longitudinal reinforcement complied with ACI 318-05 requirements. Shear and torsion design of the first reinforce ment case (utilizing closed stirrups) followed the procedure recommended by Zia and Hsu.²

The remaining four reinforcement configurations are variations of the first. Figure 15 shows the reinforcement details of the proposed compact section. All details shown in the figure, with the exception of the web reinforcement, are common to all other spandrels evaluated in this study. Figure 16 shows the details of the transverse reinforcement used in all five cases.

Cases 1 and 2 are included to demonstrate the efficiency of open vertical stirrups with 90-degree hooks at the top and bottom. Case 1 also serves as a basis for comparison with the other four cases because it is the only case currently accepted in common practice. The influence of hooking the vertical web reinforcement at the front face of the spandrel is investigated by comparison of cases 3 and 4.

In these cases, welded-wire rein-
Vertical Deflections

Figure 18 shows the vertical-load-deflection behaviors of the five compact, L-shaped spandrels for the different reinforcement configurations. Identical precracking and postcracking stiffnesses were predicted, regardless of the web reinforcement configuration.

All five load-deflection curves demonstrate a typical flexural response for the respective precast, prestressed concrete spandrel. Linear behavior was predicted up to the initiation of the first flexural crack at an end reaction of 45 kip (200 kN), followed by a nonlinear behavior to failure. All five cases demonstrate substantial ductility prior to failure. While the deflection behavior of the spandrel certainly does not provide great insight into the effectiveness of a particular shear and torsion reinforcement configuration.
load, while cases 1, 2, and 5 sustained a slightly higher end reaction of 105 kip (467 kN). Ultimate vertical deflections for the five cases ranged from 5.5 in. to 6.8 in. (140 mm to 173 mm), with cases 1, 2, and 5 outperforming cases 3 and 4.

The analysis indicates that all five reinforcement cases were sufficient for preventing premature end-region failures.

Cases 3 and 4 sustained an ultimate applied end reaction of approximately 100 kip (445 kN), not including dead load, while cases 1, 2, and 5 sustained a slightly higher end reaction of 105 kip (467 kN). Ultimate vertical deflections for the five cases ranged from 5.5 in. to 6.8 in. (140 mm to 173 mm), with cases 1, 2, and 5 outperforming cases 3 and 4.

Lateral Displacements

When lateral displacements at mid-span at ultimate load are considered, the influence of the five reinforcement configurations becomes much more pronounced, as shown in Fig. 19.

In the FEM, lateral displacements are predicted at the bottom edge of the web on the back face of the spandrel. Displacements toward the ledge side are considered positive, while those away from the ledge side are negative. While the ultimate end reactions sustained by the five cases are all similar, the lateral displacements predicted for each case vary substantially.

Case 1 (using closed stirrups) demonstrates the least lateral displacement of all cases. The maximum predicted lateral displacement at midspan was about 0.8 in. (20 mm). Absence of the hooks on the front vertical web reinforcement (case 4) resulted in larger lateral deformations of the spandrel than in other cases. The maximum lateral displacement in this case was nearly three times that predicted using closed stirrups.

This behavior demonstrates that the lateral and torsional stiffness of the member is significantly influenced by the amount of reinforcement crossing the top and bottom faces of the web.
Interestingly, the lateral displacement results from case 5 are nearly identical to those from case 1. Therefore, the reinforcement crossing the top web face is more significant than that crossing the bottom web face. On the other hand, under service load, the lateral displacement of case 4 is about 0.4 in. (10 mm), almost twice that of the other four cases.

**Crack Pattern**

A similar crack pattern was predicted for all five cases, regardless of the web reinforcement configuration. Flexural cracks were initiated at an end reaction of 45 kip (200 kN), as shown in Fig. 20. These cracks were first initiated at the back face of the spandrel as a result of the out-of-plane bending behavior of the spandrel. The cracks started to propagate toward the ledge of the spandrel as the applied load was increased.

Localized cracks around the spring supports were also observed as the result of stress concentrations at these locations. Diagonal cracks at the spandrels’ ends started to appear shortly after the initiation of the flexural cracks at an end reaction of 55 kip (245 kN). As the load was increased, the cracks were further extended and diagonal tension cracks developed farther from the support.

In general, extensive diagonal and rainbow cracking was predicted by the FEMs along the front faces of the spandrels due to the combined torsional and shear stresses. The back faces of the spandrels showed rather evenly spaced vertical cracking, mostly due to the flexural effect (because the stresses due to torsion and shear counteracted each other). The vertical cracks were tallest toward the center and gradually decreased in height toward the end of the spandrel. Minor diagonal cracks were also predicted by the FEM at the back faces of the spandrels toward their ends.

**Shear Stresses**

Figure 21 shows the ultimate shear stress distributions at the ends of each spandrel for the different reinforcement configurations. The use of open vertical stirrups with 90-degree hooks at the top and bottom did not have any detrimental effect on the induced shear stresses in the spandrels (compared with the case with closed stirrups). The FEM predicted the same level of stress for both cases 1 and 2.

A direct comparison between cases 4 and 5 indicates that absence of the horizontal top web reinforcement increases the concrete shear stress 20%. It was also observed, by comparing the induced shear stresses in cases 3 and 4, that the presence of hooks enhances the
behavior and reduces the shear stresses 20%. Obviously, this is because the hooks provided more anchorage for the web reinforcement.

**Failure Mode**

Flexural failure due to crushing of the concrete at the midspan section of the spandrel was predicted by the FEM for all five cases. Failure loads were nearly identical for all specimens. Cases 1 and 4 exhibited the highest and lowest ultimate load-carrying capacity, respectively. Nevertheless, the variation of the ultimate load between these two extreme cases was less than 12 kip (54 kN), which corresponds to approximately 6% of the capacity of the spandrel. Finite-element analysis was terminated when the principal compressive strains exceeded 0.003 according to ACI 318-05.

It was observed that the principal compressive strains were much higher at the front face of the spandrel than at the back face due to out-of-plane bending behavior of the spandrel. Such behavior was highly pronounced for the spandrels analyzed without deck ties. At the onset of flexural failure, the maximum principal compressive strains along the diagonal compression strut were less than 0.002, which is recommended by other researchers for shear compression failure.7

**Forced Shear Failure Mode**

To further examine the influence of the different web reinforcement configurations on the shear-torsional

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**Table 3. Results of the Finite Element Analysis for Cases 1, 2, and 4 for Compact Sections**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Flexural Reinforcement</th>
<th>$R_{u}$ kip</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal</td>
<td>104</td>
<td>Flexural failure</td>
</tr>
<tr>
<td>1</td>
<td>Nine #11 bars were added at midspan</td>
<td>133</td>
<td>Shear-compression failure</td>
</tr>
<tr>
<td>2</td>
<td>Normal</td>
<td>104</td>
<td>Flexural</td>
</tr>
<tr>
<td>2</td>
<td>Nine #11 bars were added at midspan</td>
<td>123</td>
<td>Shear-compression failure</td>
</tr>
<tr>
<td>4</td>
<td>Normal</td>
<td>99</td>
<td>Flexural</td>
</tr>
<tr>
<td>4</td>
<td>Nine #11 bars were added at midspan</td>
<td>110</td>
<td>Shear-compression failure</td>
</tr>
</tbody>
</table>

Note: $R_{u}$ = the end reaction of the spandrel at ultimate; 1 kip = 4.448 kN.
strength of compact, L-shaped spandrels, additional top and bottom flexural reinforcement was provided at midspan. Placement of this additional reinforcement was limited to between the quarter points $L/4$ and the midpoint $L/2$ to eliminate the possibility of affecting the shear-torsion strength of the spandrels at their end regions ($L$ is the span of the spandrel).

It was intended that this additional reinforcement would prevent the flexural failure mode observed previously, allowing a mode governed by shear and torsion to develop. Cases 1, 2, and 4 were all reanalyzed with the additional flexural reinforcement, and Table 3 summarizes the results of the analysis. In all three of these cases, failures occurred in the end regions and were due to crushing of the concrete along the primary compressive strut, as shown in Fig. 22. Finite-element analysis was terminated when the principal compressive strains along the compressive strut reached a value of 0.002. Figure 23 shows the predicted lateral displacements at midspan. The maximum predicted end reaction for the case with closed stirrups (case 1) was 133 kip (592 kN), which did not include dead load.

Finite-element analysis indicated that using open vertical stirrups with 90-degree hooks instead of closed stirrups did not have a dramatic effect on the strength of L-shaped spandrels. For case 2, the FEM predicted a reduction of 8% in the ultimate load-carrying capacity of the spandrel. Using open, unhooked web reinforcement (case 4) reduced the shear capacity of the spandrel 17% compared with case 1. Based on these results, the analysis indicates that it is possible to use open web reinforcement effectively in compact L-shaped spandrels, provided that the designer accounts for reductions in the shear-torsion strength of the spandrel.

**CONCLUSIONS**

Based on the results of this investigation, the following conclusions are drawn:

- FEM is capable of accurately predicting the response, up to failure, of L-shaped, precast, prestressed concrete spandrels subjected to combined shear, bending, and torsion.
- For the compact, L-shaped spandrels spanning 45 ft (13.7 m), typically used by the precast/prestressed concrete industry, flexural failure controls design.
- In this case, web reinforcement configurations have a trivial effect on serviceability as well as on the spandrel’s ultimate load-carrying capacity.
- The out-of-plane bending behavior of compact, L-shaped spandrels is highly dependent...
on the configuration of the web reinforcement. The absence of hooks in the front vertical web reinforcement (as in case 4) may result in larger lateral deformations of the spandrel compared with spandrels using closed stirrups, without reductions in load-carrying capacity.

- Deck ties reduce the lateral displacements induced in L-shaped spandrels typically caused by bending about the weak axis of the spandrel. The presence of ties does not have any significant effect on a spandrel’s ultimate load-carrying capacity or its failure mode.

- The use of open vertical stirrups with 90-degree hooks at the top and bottom did not have any detrimental effect on the induced shear stresses at spandrel ends (compared with closed stirrups).

- The absence of horizontal top web reinforcement increases the shear stress in the spandrel 20%. Conversely, the presence of hooks in the web reinforcement at the front face enhanced the spandrel’s behavior and reduced its shear stresses 20%.

- Using additional reinforcement to prevent flexural failure led to compression shear failure at the end regions of the compact L-shaped spandrels. Finite-element analysis indicated that the use of open, unhooked web reinforcement reduces the spandrel’s shear strength 17% compared with a closed-stirrups configuration. The spandrel’s shear strength reduction is about half as much when open vertical stirrups with 90-degree hooks replace closed stirrups.

ACKNOWLEDGMENTS

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