ABSTRACT

This paper demonstrates the use of research, typically performed by academics at universities, to provide valuable input for practical and safe design of structures and bridges and/or to solve problems identified by the industry. The examples used in this paper relate to the design of typical precast concrete parking structures using precast reinforced and prestressed concrete products. The paper describes research undertaken at North Carolina State University to address several issues and concerns raised by the industry related to the design and performance of these precast components and problems related to their connection details. Research objectives included developing rational design guidelines for precast slender spandrel beams and simplifying the reinforcement detailing using open reinforcement in lieu of traditional closed stirrups. Furthermore, the research extended to investigate the behavior and the capacity of the ledges of L-shaped beams, as the level of safety provided by the current design procedure has been called into question. Finally, research was undertaken to develop a rational design methodology for dapped ends of thin stemmed prestressed concrete beams and to identify the most effective reinforcement details for the dapped ends in term of serviceability, strength and constructability.

Keywords: Spandrel, L-shaped beams, Ledge, Punching shear, Dapped ends, Thin stemmed beams
INTRODUCTION

This paper demonstrates the use of research, typically performed by academics at universities, to provide valuable input for practical and safe design of structures and bridges and/or to solve problems identified by the industry. The examples used in this paper relate to the design of typical precast concrete parking structures with precast reinforced and prestressed concrete components. The research typically starts by performing comprehensive structural analysis to predict the behavior and to determine the most important parameters that could affect the behavior of the individual precast concrete products of the structure. The research is normally followed by performing an experimental program to study the effect of the important parameters identified by the analytical phase. Test results of the experimental program and the calibrated analysis are then used to propose a solution to the problem and/or to propose safe and practical design guidelines.

In the case of parking structures, slender spandrel precast concrete beams are typically used to transfer the vertical load from the deck sections to columns. Large double tees are often used as deck sections and generally span 40 to 65 feet (12.2 to 19.2 m). Typical slender beams are between 5 to 7 feet (1.5 and 2.1 m) deep with span ranging from 30 to 50 feet (9.1 to 15.2 m) therefore these beams have a large aspect ratio. In L-shaped spandrel beams, a continuous ledge runs along the bottom edge on one side to provide bearing for the deck, as shown in Figure 1(a), so the beam is subjected to series of discrete eccentric loading, as shown in Figure 1(b).

![Figure 1: Typical L-Shaped Slender Spandrel](image)

The beam is supported vertically on a simple span and secured laterally to a column at each end through two discrete web tie backs. One detail often used for double tee beams is the dapped end detail shown in Figure 1(a). The dapped end is created by notching the web of the beam at the bottom end corners; therefore, the beam relies on the reduced section to carry the reaction. The dapped end connection is especially...
useful at crossovers between spans in order to minimize the overall floor to floor height.

This paper describes the research undertaken at North Carolina State University to address several issues and concerns raised by the industry related to the design and performance of these precast components of the parking structures and problems related to their connection details.

The first concern was the design of the main L-shaped spandrel beam, which is subjected to combined flexure, shear and torsion due to the eccentric vertical loading and unsymmetrical cross section. The available design approach, before completion of the research, was based on an approach developed by Zia and Hsu which was formulated from testing rectangular specimens having aspect ratios of 3 or less [1]. The procedure was never intended for slender spandrel beams. Thus, the first objective of the research was to develop rational design guidelines for precast slender spandrel beams. The second objective of the research was to simplify the reinforcement detailing by investigating the use of open reinforcement in lieu of traditional closed stirrups to simplify fabrication and to reduce the cost of production.

If the applied concentrated loads are high, the ledge may fail in a localized punching shear mode. Therefore, a third objective was to investigate the behavior and the capacity of the ledge. The current ledge design equations recommended by the PCI Design Handbook can significantly overestimate the capacity of the ledge [2]. Thus, the current design procedure has been called into question and there is a need to develop a new design procedure.

A fourth objective was related to the design and performance of the dapped ends of typical single or double tee sections. Undesirable cracks are often observed even at service loading conditions. The fourth objective was to develop a rational design methodology for dapped ends of thin stemmed prestressed concrete beams. Cracks may be due to poor detailing or to inadequate web reinforcement. Therefore, a fifth objective was to identify the most effective reinforcement details for the dapped ends in term of serviceability, strength, and constructability.

The following sections of the paper describe three research projects undertaken to achieve these five objectives which were achieved through comprehensive experimental programs supported by analytical modeling using 3-D nonlinear finite element analysis. Each section will summarize the research undertaken for each member and the up-to-date research findings.
The main objective of the research was to:

a) Develop rational design guidelines of L-shaped spandrel beams
b) Investigate the use of open web reinforcement in lieu of closed stirrups

The experimental program was a larger part of the research effort, which also included analytical studies based on three-dimensional nonlinear finite element models and the development of a simple rational design procedure. A total of 16 precast spandrel beams were tested to failure at North Carolina State University. All of the specimens were full-scale beams, most spanning 45 feet (13.7 m). Two of the beams were tested at a 30 foot span (9.1 m). Each specimen was loaded through associated full-scale double-tee deck sections to mimic typical field conditions.

Two of the test specimens were designed and detailed with closed stirrups, according to the available design practice before the completion of the research, to serve as controls of the experimental program. The remaining specimens were designed with various configurations of open web reinforcement. The open transverse web reinforcement was proportioned in the test specimens using ACI procedures without considering torsion [3]. Additional transverse reinforcement was provided on the inner web face based on plate bending about a 45-degree inclined crack according to the rational design method developed in this research.

The parameters considered were:

a) Open versus Closed Reinforcement:
Thirteen of the 16 experimental specimens were designed and fabricated with open web reinforcement. Two of the 16 spandrels, the control specimens, were reinforced with traditional closed stirrups. Figure 2 shows sketches of a typical L-shaped spandrel cross-section with typical open and closed web reinforcement schemes. In addition, a sketch of the special partially closed reinforcement scheme is shown in the same figure. In this research program, ‘open’ reinforcement included flat sheets of welded wire reinforcement, conventional deformed reinforcing bars bent into L, C, or U shapes, and straight bars or tendons. An open web-reinforcement scheme utilized in several specimens was the combination of welded-wire reinforcement on the outer spandrel face and L-shaped bars on the inner spandrel face.
b) Production of Open versus Closed Reinforcement:
Observations made during the production of the experimental beams indicate that assembling an open reinforcing cage took 30% to 50% less time than assembling a traditional closed reinforcing cage. In producing the open cage (with the spandrel lying outer-face down on the form), the outer-face web reinforcement (often WWR) was placed in the empty form first. The strands were then pulled and stressed without obstructions, as shown in Figure 3(a). After stressing the strands, any required longitudinal steel bars, such as U-bars in the end regions, were simply placed in the form near their final locations.

In the case of the closed reinforcing cages, the stirrups (both web and ledge) had to be placed in the empty form. During this step, it was important to verify that the sequence of the stirrups corresponded to their final locations in the beam. With the stirrups in the form, the prestressing strands, along with any other required longitudinal steel, were threaded through the stirrups, taking care not to disrupt the stirrup order. The strands were then prestressed. A typical slender spandrel beam with a closed cage and longitudinal steel in place is shown in Figure 3(b), prior to stressing the strands. In addition to gains in production efficiency, the use of an open reinforcement cage offered a significant savings in steel compared to traditional designs using closed stirrups. In examining the test specimens in this program, an open reinforcement cage required up to 50% less shear and torsion steel than did a comparable closed cage.
c) Bearing Pads:
Two different types of bearing pads were used in the experimental tests: common Masticord pads and Teflon-coated Capralon pads. Bearing pads were located between each double-tee stem and the ledge.

The test setup used in the experimental program to test the L-shaped spandrel beams consisted of the components listed below.

1. A system of columns, beams, and stands designed to transfer the vertical and horizontal reactions of the spandrels to the strong floor.
2. A system of spreader beams, tie-down rods, and hydraulic jacks designed to produce required load and transfer to the appropriate points on the test specimens.
3. A system of concrete support blocks, steel channels, and tie-down rods which supported the end of the double-tee deck opposite the spandrel.
4. An array of load cells and other instrumentation was used to measure data loads, deformations, and strains.
5. A sketch of the testing configuration is shown in Figure 4 with a photograph of the actual test setup shown in Figure 5.
Figure 4: Profile of Test Setup

Figure 5: Photograph of Test Setup Profile
Test results indicate that the cracking patterns were similar for all spandrels, regardless of configuration, reinforcement, or aspect ratio. The inner face cracking pattern was the tied-arch type. The observed behavior of the slender spandrel beams also indicates that the effects of shear and torsion dominate in the disturbed end region. This end region is followed by a transition region where the effects of shear and torsion gradually reduce along with increasing effects of flexure. Beyond the transition region, flexural effects dominate slender spandrel behavior. The typical inner-face cracking pattern for all tests is shown in Figure 6 for a representative continuous L-shaped spandrel beam.

![Figure 6: Inner-face Cracking Pattern for a Representative L-shaped Spandrel](image)

Figure 7 shows the observed outer face cracking pattern for a typical beam. As with the inner-face cracking patterns, the outer face patterns were symmetrical about midspan. Initial cracks on the outer face were usually observed near midspan, where a region with only vertical cracks initiated from the bottom of the beam. Near the ends of a beam, cracks were observed extending downward from the top lateral reaction. The outer face cracking pattern seems to indicate that the disturbed end region extends for a distance equal to approximately 1.5 times the height of a spandrel.

![Figure 7: Outer-face Cracking Pattern for a Representative Spandrel](image)

Most of the tested slender spandrels failed at their end regions along a skewed diagonal crack plane, extending upwards from the support. Figure 8 shows two views of the inner web face of a typical beam with an end-region failure. The primary
diagonal crack initiates at the face of the support, and extends upwards at an angle of approximately 45-degrees.

Figure 8: Typical Skewed Diagonal Crack Plane with Decks in Place (left) and Removed (right)

Measured deflection data demonstrates the similar behavior of beams with open and closed reinforcement through the factored load. The measured load-deflection data at midspan are plotted in Figure 9. Plots of the load versus vertical deflection were nearly identical for both beams through the factored load level.

Figure 9: Measured Load - Vertical Deflection Response of Two Selected Spandrels

In conclusion, tests showed that spiral cracking and face-shell spalling did not develop as expected for rectangular beam with aspect ratio 3 or less, rather, slender spandrel beams develop a tied-arch cracking pattern. All beams failed along a skewed diagonal
crack extending upwards from the support. Conclusions drawn based on the results from this research project, are as follows:

1. The shear and torsional resistance of slender spandrel beams with traditional closed was almost twice the demand from the factored load.
2. Open web reinforcement can provide virtually the same performance as traditional closed web reinforcement.
3. Several ledge punching failures occurred at loads below those predicted by the PCI Design Handbook [2]. The following research project addresses the research findings related to the behavior and design of ledges of L-Shaped spandrel beams.

The proposed rational model for resisting the applied torsion was determined using equilibrium of forces shown in Figure 10 [4,5]. One component of the torque vector $T_u$ will act to bend the spandrel web out of plan about the diagonal crack. The second component of the torque vector act to twist the web about the axis perpendicular to that diagonal crack. Research finding proposed equation for the two components and define in detail the design procedure which is currently included in the PCI Design Handbook [2].

![Figure 10: Components of Applied Torque along a Diagonal Crack within the End Region (Note: The double-headed torque vectors indicate moments according to the right hand rule)](image)

**LEDGES OF L-SHAPED SPANDREL BEAMS**

The main objective of the research is to:

a) Define the failure surface of the ledge under the effect of concentrated loads
b) Investigate the effect of the different parameters on the ledge capacity
c) Propose a set of practical and reliable design guidelines for ledges of L-shaped beams
The research initiated with a comprehensive analytical phase based on 3-D non-linear finite element modeling to determine the effect of several parameters and identify the most significant parameters for the experimental program [6]. The parameters investigated in the analysis included parameters considered and others not considered by the current design approach. Based on the analytical phase, the experimental program was designed to study the effect of the following parameters:

1. Global stresses
2. Prestressing effect
3. Edge distance
4. Overlapping spacings
5. Concrete strength
6. Ledge height
7. Transverse steel
8. Longitudinal steel in the beam
9. Bearings length
10. Bearing type
11. Sustained load
12. Bearing width
13. Ledge projection
14. Eccentricity of the applied load

The experimental program consisted of 17 reinforced concrete short span L-shaped beams, each 16’-6” long, and 9 long span L-shaped beams, each 46’-6” long, including 7 prestressed concrete beams and 2 reinforced concrete beams. The short-span beams were intended to study the failure surface and the effect of 11 parameters on the ledge capacity without the influence of significant global stresses. Each beam was tested with a single load at the mid-span and near the two ends for a total of three tests per beam. The test beams were simply supported vertically using steel stands and were connected horizontally to columns of a testing frame at each end to maintain torsional equilibrium. The load was applied to the ledge by a steel beam which spanned between concrete blocks and the spandrel beam ledge. Hydraulic jacks were used to apply load to the steel beam, as shown in Figure 11.

Figure 11: Test setup for short span beams
Test results of the short span beams were used to finalize an ongoing testing program for the long span L-shaped beams; mainly to study the influence of the global stresses on the ledge capacity, in addition to the effect of the spacing between two adjacent loads at which one single overlapped punching shear failure would occur. The long span beams were tested in a manner similar to the short span tests; however, the tests were conducted with a sufficient number of extra loading assemblies placed along the length of the ledge to generate relatively high global stress levels (flexural and shear stresses). The applied ledge loads from these loading assemblies were held constant while load was slowly increased at the selected location up to failure. A typical setup used for the long beam tests is shown in Figure 12.

![Figure 12: Long-Span Full-Scale Test in Region of High Global Shear Stresses](image)

The observed failure mode for all the tests was punching shear in the ledge. Initially, a flexural crack at the ledge/web junction occurred. As the load was increased, the crack extended in length along the length of the ledge and propagated diagonally with an angle into the top face of the ledge. Prior to failure, additional cracks were observed to initiate at the back of the bearing plate and extended diagonally to the horizontal surface of the ledge. Failure occurred suddenly with diagonal tension cracks occurring on the front face of the ledge. The end failures exhibited similar behavior to the inner failures; however, the crack extended along the length of the spandrel until it reached the end of the ledge. The crack then extended on the side of the ledge until it reached the web. Figure 13(a) and Figure 13(b) show typical failure surfaces for both inner and end ledge failures respectively.
The percent increase or decrease of the measured ledge capacity with respect to the increase of selected parameters considered in the short beams study is shown in Figure 14. The results clearly indicate that four of the nine parameters have significant effect on the ledge capacity. These parameters include the ledge height, the concrete compressive strength, the load eccentricity and the edge distance of the applied load. The ledge height is found to be the most influential parameter on the punching shear capacity of the ledge. Test results indicated that increasing the edge distance of the applied load increases the ledge capacity. However, when the edge distance is increased more than twice the ledge height, the effect on the punching shear capacity of the ledge is negligible and the configuration of the failure surface is changed, as shown in Figure 15.
A typical failure surface is initiated by formation of cracks at the back of the bearing plate and extends horizontally on both sides at an angle of 27 degree, as shown in Figure 16(a). Then the cracks extend into the front face of the ledge with an angle that is dependent on the ledge height. If the edge distance of the applied load was less than twice the ledge height, the failure surface can be defined as an end failure, as shown in Figure 16(b). The cracked concrete was chipped off for several inner and end failures to measure the geometry of the failure surface [7]. Statistical analysis was performed to determine the most appropriate idealization of the failure surface with respect to the geometry of the observed failure surfaces. The idealized failure surface is based on a horizontal angle of 27 degrees and a vertical angle of 34 degrees, as shown in Figure 16(a) for a typical inner failure. The same procedure was used to define the end failure surface, as shown in Figure 16(b).

Figure 15: Effect of Edge Distance on Failure Surface

Figure 16: Idealized Failure Surfaces (a) Typical Inner Failure and (b) Typical End Failure
The corresponding shear strength to predict the ledge capacity is greatly influenced by the effect of the global stresses. The long span beams were used to study the effect of the global flexural and shear stresses on the punching shear capacity of the ledge by applying different loading configurations that represent different levels of global stresses. Both analytical and experimental results indicate that increasing the global flexure stresses reduces the punching shear capacity of the ledge at mid-span, as shown in Figure 17. Similar to the effect of the flexural global stresses, the ledge capacity at end region is also reduced significantly by increasing the global shear stresses, as shown in Figure 17.

![Figure 17: Effect of Global Flexural and Shear Stresses on Ledge Capacity](image)

**DETAILING AND DESIGN OF DAPPED ENDS**

While dapped reinforcement details have generally provided adequate strength, undesirable cracks are often observed even at service loading conditions, as shown in Figure 18, which could lead to extensive repairs when they exceed the limitation specified by the design codes. In many cases, the cracks may also be attributed to poor design and/or construction practices.

![Figure 18: Cracking in Dapped End Beams](image)
The main objectives of this research were to:

a) Identify the most effective reinforcement details for the dapped ends in terms of serviceability, strength and constructability

b) Develop a rational design methodology for dapped ends of prestressed concrete thin stemmed members

The experimental program was designed based on the results of extensive three-dimensional nonlinear finite element models. The testing program consisted of 40 foot long dapped ends prestressed concrete single tee beams, reinforced with different reinforcement schemes for the dapped ends. All beams had a cross section representing one half of a 30 inches deep and 12 ft. wide double tee beam. Each dapped end was tested to failure in a separate test. After testing one end of a beam, the test setup was rotated to test the other end. The experimental program examined the performance of six different reinforcement schemes. A horizontal load equal to 20 percent of the vertical beam reaction was applied to the beam end to account for superimposed horizontal forces as recommended in the PCI Design Handbook [2].

The six reinforcement schemes included in this experimental program are shown in Figure 19. Dapped end reinforcement for all six schemes was designed to have the same area of steel for hanger reinforcement and other dapped end reinforcing steel, allowing for comparison between the performances of the six schemes. For the vertical and inclined L schemes, the beams were prestressed using single column strand such that the hanger reinforcement bars are located on either side of the strand. For the other schemes, vertical Z shape, WWR, CZ scheme and vertical C scheme, the beams were prestressed using staggered arrangement of strands therefore the hanger bars or the WWR were inserted between the strands.

(a) Vertical L scheme (Specimen 1A)  
(b) Vertical Z scheme with corner angle (Specimen 2A)  
(c) Inclined L scheme (Specimen 3A)  
(d) Welded Wire Reinforcement (WWR) (Specimen 4A)
All tested dapped ends were supported by a pin-link system and were loaded separately to failure using hydraulic jacks close to the dapped end under consideration. An isometric view of the test setup used in this program is shown in Figure 20. The inclined link support was utilized at the tested end to resist vertical reaction, horizontal reaction as percentage of the vertical reaction and also allow full rotation. This horizontal reaction was resisted at the other end of the beam by a pin connection.
Four failure modes were observed in the tests.

a) Diagonal tension cracking in the web: failure was due to formation of diagonal tension crack within the web. This diagonal tension crack extended from or close to the bottom corner of the web up to the web flange junction with an angle of inclination of 30 to 35 degrees from the horizontal as shown in Figure 21(a).

b) Diagonal tension cracking within the nib: failure was due to diagonal tension cracking within the nib. The critical diagonal crack started from the inside edge of the bearing pin and extended upwards to the web-flange junction as shown in Figure 21(b).

c) Flexure-Shear after splitting and strand slip: failure was due to flexure-shear cracking at the bottom of the web in the region where the horizontal extension of the hanger steel terminated as shown in Figure 21(c).

d) Concrete crushing in the bottom corner: failure was due to a sudden diagonal compression crushing of the concrete at the bottom corner of the web as shown in Figure 21(d).

![Figure 21: Failure Modes for the Dapped Ends](image-url)
All six reinforcing schemes achieved ultimate capacities significantly higher than their factored design load and were sufficient to ensure that failure modes outside the dap end region would control. The measured load-deflection at the location of the applied load is plotted in Figure 22 for the six reinforcement schemes. The two reinforcing schemes with the best performance with respect to ultimate capacity were the vertical Z with corner angle and the inclined L-shape.

Figure 22: Measured Vertical Deflections for the Six Reinforcing Schemes

Observations of the crack patterns at service load for the six reinforcing schemes indicated that cracks were localized at the re-entrant corner and in the region of the full depth section adjacent to re-entrant corner. All reinforcement schemes had pre-existing re-entrant corner cracks prior to testing except for the vertical Z shape with corner angle and the inclined L shape schemes. A summary of maximum crack width at service load level for each reinforcing scheme is shown in Figure 23. Inspection of crack width versus the dap vertical reaction for the tested reinforcing schemes indicated that the vertical Z with corner angle and the inclined L shape showed the best performance in terms of crack control compared to all other schemes.
The superior performance of the vertical Z shape with corner angle can be attributed to the use of the corner angle which effectively reduced cracks at service load by resisting the cantilever bending of the nib section and providing rigid connection between the nib section and the full depth section at the re-entrant corner location. The inclined L shape scheme also showed satisfactory performance in regards of ultimate strength and crack control at service load.

Test results indicated that the most common failure mode was due to the formation of a diagonal tension crack within the full depth of the section. The projection of this crack extended to a distance twice the height of the member. This research identified load path regions in a typical dapped end prestressed thin-stemmed member by three regions: nib region, D-region which is twice the total height of the member and the B-region which is a typical behavior of a prestressed member. The research findings based on the nonlinear finite element analysis and the experimental results were used to develop design recommendations for the three regions. These recommendations address the strength, cracking behavior at service load and reinforcement details. The recommendations are tailored to be practical and seamless with the current design approach implemented in the PCI Design Handbook [2]. The influence of different parameters and the design recommendations developed in this study are described elsewhere [8]. Based on the research findings, the following conclusions and recommendations may be drawn:

1. Initiation of the first crack always occurred at the re-entrant corner of the dapped end due to high stress concentration at this location.
2. The extent of cracking at service load is highly influenced by the reinforcement arrangement at the dapped end.
3. Failure of a dapped end could be due to one of the following scenarios; (a) Formation of a sudden diagonal tension crack within the web of the full depth section of the beam (b) Formation of flexure shear cracking in the full depth
section of the beam precipitated by longitudinal splitting of the web and strand bond failure; (c) Crushing of the concrete of the diagonal strut at the bottom corner of the web and (d) formation of diagonal tension cracks within the nib.

4. All six reinforcement schemes are suitable for use in practice with ultimate capacities exceeding the factored design load by 35% to 74%.

5. The reinforcement schemes using inclined hanger reinforcement and vertical Z with corner angle performed better than other schemes in regards of strength and crack control.

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