Development of a rational design methodology for precast L-shaped spandrel beams

G. Lucier, C. Walter, S. Rizkalla & P. Zia
North Carolina State University, Raleigh, NC, USA

G. Klein
Wiss, Janney, Elstner Associates, Inc., Northbrook, IL, USA

D. Logan
Stresscon Corporation, Colorado Springs, CO, USA

ABSTRACT: Precast concrete spandrel beams are commonly used in parking structures to transfer vertical loads from deck members to columns. These beams typically have slender, unsymmetrical cross-sections and are often subjected to heavy, eccentric loading. These factors produce a complex internal structural mechanism including significant out of plane behavior. Traditionally, slender spandrel beams have been reinforced using the torsion and shear provisions of ACI-318. These provisions assure torsional strength by requiring heavy closed reinforcement and well-distributed longitudinal steel to provide torsional resistance after face shell spalling. The need for such complex and expensive reinforcement in slender spandrel beams is questionable. From as early as 1961, extensive field observations and limited full-scale testing have documented a lack of face shell spalling and spiral cracking in slender spandrel beams. Rather, out of plane bending appears to dominate slender spandrel behavior. More recently, extensive full-scale testing has confirmed that the classically assumed mode of torsional distress is not realized in precast slender spandrels. This paper provides background information and argument for simplifying the reinforcement detailing requirements for slender spandrel beams. The paper presents an overview and selected results to date of research currently in progress to develop alternative, more efficient reinforcing schemes and a rational design approach.

1 INTRODUCTION

1.1 Background

Precast spandrel beams are commonly used in parking structures, serving the purpose of transferring vertical loads from deck members to columns. In many cases, a continuous ledge runs along one edge at the bottom of the beam, resulting in what is known as an L-shaped spandrel. In other cases, discrete haunches are used in place of the continuous ledge, creating what is known as a corbelled spandrel. The ledge or corbels provide a bearing surface for the deck members, and thus, the typical precast spandrel beam is subjected to a series of discrete eccentric loads.

Eccentrically loading the slender cross-section results in a complex structural behavior which, coupled with typically heavy loadings, often results in spandrel designs requiring conservative reinforcement details. Frequently, steel is heavily congested in critical zones such as the end regions where prestressing strands and reinforcing bars must weave through the numerous closely-spaced closed stirrups that are required by the ACI Code (318-05).

The eccentric location of the applied loads with respect to the unsymmetrical L-shaped spandrel cross-section causes vertical displacement in addition to significant lateral displacement and rotation. The maximum torsional and shear effects occur in the end regions. In resisting vertical loads, precast spandrel beams are simply supported at the columns. The ends of these beams are also connected to the columns to prevent out of plane rotation about the longitudinal axis. In addition, deck sections are often connected to the spandrel web at discrete locations, providing lateral restraint along the span.

Figure 1 depicts a typical L-shaped slender spandrel. Point loads from double tee deck sections are shown along the ledge, column reactions are shown at
1.2 Current practice

The current practice recommended by the American Concrete Institute (ACI 2005) for proportioning reinforcement to resist shear and torsion within a concrete member is based on a space truss analogy. Longitudinal steel and closed stirrups are provided to resist torsional stresses which are assumed to develop and spiral down the length of a member. Well distributed longitudinal steel and closed ties serve to maintain the integrity of the concrete core enclosed within the stirrups, allowing inclined compression struts to develop and to resist the applied forces.

The ACI approach assumes that later stage member response will be characterized by spalling of the concrete face shell outside the stirrups, and recommends detailing such as 135-degree stirrup hooks to maintain the integrity of the concrete core after spalling (Mitchell 1976). These detailing requirements often require tightly congested, interwoven reinforcement, especially in the end regions.

It is important to mention that within the torsion provisions of ACI-318-05, there is a stipulation allowing for alternative approaches to the torsion design of solid sections having an aspect ratio (height divided by web thickness) of three or greater. ACI-318 states “it shall be permitted to use another procedure, the adequacy of which has been shown by analysis and substantial agreement with results of comprehensive tests.”

For many years, the precast prestressed concrete industry has recommended an alternative procedure for torsion design developed by Zia and Hsu (1978). The procedure is outlined in the latest edition of the PCI Industry Handbook (PCI 2004), and, similar to the ACI approach, makes assumptions of face shell spalling and spiral cracking. Currently, this procedure is commonly used to proportion shear and torsion reinforcement in slender spandrel beams.

1.3 Challenges to current practice

The approaches to torsion design advocated by ACI and PCI are widely accepted, and are routinely applied to the design of both compact and slender members. While the appropriateness of these approaches is well documented for compact sections, many have challenged the validity of applying the same design methodology to slender precast members (Logan 2007). Decades of field observations (Raths 1984), limited experimental testing (Klein 1986), and observation of slender section behavior (Logan 2007) have supported the argument that design approaches relying on assumptions of spiral cracking and face shell spalling are inappropriate for application to slender members. If torsional distress is not generated by eccentric loading of slender precast members, then classical torsion design procedures and detailing requirements cannot be justified.

1.4 Skewed failure plane

It is well established that the failure mechanism for a slender reinforced concrete section subjected to combined flexure, shear, and torsion will be in the form of skew bending (Zia 1968, Hsu 1984). This skew may be idealized by four edges, each inclined at 45-degrees with respect to the next, forming a distorted surface. This skewed failure mechanism does not exhibit the characteristic spiral cracking and face shell spalling assumed as the basis of the current ACI and PCI approaches.

In compact, rectangular sections, this failure plane is crossed effectively on all four faces by closed ties. For slender sections, however, the value of the shorter legs of the ties is questionable because the projection of the failure plane crossing the narrow face of the member is often less than the longitudinal spacing of such ties.

Considering the slender spandrel as an example, the tie legs crossing the top or bottom edge of the web probably have minimal effect on the overall torsional
resistance of the member. Rather, it is the vertical legs of such closed ties which are providing the bulk of torsional resistance, since these legs cross the failure plane along the much longer inner and outer faces of the web.

For a slender spandrel beam with an assumed failure angle of 45 degrees, the short legs of any closed ties would effectively contribute to torsional resistance of the member only if tie spacing were maintained at one-half of the web thickness. Tie spacing greater than the web thickness creates a situation in which the top edge of the failure surface will likely pass between adjacent ties.

Thus, for a typical web thickness (200 mm) of a slender spandrel, the contribution of the short legs of stirrups spaced at more 100 mm is questionable. Such tight stirrup spacing is uncommon for long, slender members, and thus, the geometry of the skewed failure surface itself seems to indicate that the short legs of closed ties do not significantly contribute to torsional resistance in slender spandrels.

1.5 Field observations

Field observations of precast slender spandrel behavior have been discussed among precast producers and engineers for over six decades. However, the in-service behaviors of precast slender spandrel beams were not well documented until Raths reported on spandrel beam behavior and design in 1984. A substantial portion of his report describes field observations of structural failures and structural distress. This document, perhaps the most thorough account of precast spandrel behavior to date, contains no evidence of a precast slender spandrel developing internal torsional distress. Instead, extensive out of plane bending and web face cracking were observed to resist what Raths refers to as “beam end torsion,” the end couple acting to restrain the beam from rolling inward due to the eccentrically applied loads.

1.6 Previous testing and research

Informal load tests on precast L-shaped spandrel beams have been documented since the early 1960s. Informal testing of this nature was commonly carried out by precast producers to investigate design issues which had not been formally researched at the time. A test conducted in 1961 was unable to generate either torsional rotation or torsional distress in a precast L-shaped spandrel subjected to eccentric vertical loading. From this early stage, the necessity of providing complex torsion reinforcement in L-shaped precast members was called into question (Logan 2007).

Formal research into the behavior of slender spandrel beams was published in 1986. Research funded by the Precast/Prestressed Concrete Institute included full scale testing of L-shaped precast spandrel beams loaded eccentrically through the ledge. This research confirmed that neither spiral cracking nor face shell spalling occurred in any of the tested beams. Again, the need for complex reinforcement detailing was called into question for slender L-shaped members (Klein 1986).

More recently, a group of precast producers partnered with North Carolina State University to conduct preliminary research and failure testing on full-scale precast slender spandrel beams. Four beams were designed neglecting conventional torsion procedures. As such, closed stirrups were replaced by open web reinforcement proportioned to resist out of plane bending. For the purpose of the experiments, additional reinforcement was added to protect against potential failure modes outside of the end regions, allowing for observation of end region behavior at ultimate. The results from this study demonstrate the skew bending failure mode, and confirm the absence of classical torsional distress (Lucier et al. 2007).

The promising results of this preliminary research combined with a strong industry desire for simplified slender spandrel detailing requirements prompted the Precast/Prestressed Concrete Institute to embark on an extensive research project at North Carolina State University aimed to rationalize and simplify slender spandrel beam design. The ongoing research has extensive experimental and analytical components which are summarized below along with preliminary results and conclusions.

2 CURRENT RESEARCH

The objective of the ongoing research program is to develop a rational design methodology for precast slender spandrel beams loaded eccentrically along their bottom edge. It is intended that any underlying assumptions of the proposed methodology closely reflect the observed response and failure modes of slender spandrel members. In addition, the proposed design methodology should allow for simplified detailing of reinforcement when compared to current practice. The methodology itself must be straightforward enough to be used in everyday practice.

2.1 Experimental work

The research program includes extensive experimental work. Results from the experimental testing will facilitate characterization of slender spandrel behavior, and will allow for an investigation into parameters that influence this behavior. In all, 13 full-scale precast spandrel beams, each nearly 14 meters long, will be tested to failure in the laboratory. In addition, results from the preliminary research mentioned above will
be combined with the current work, creating a collection of 17 experimental tests. To date, 10 of these tests have been completed. The cross-sections under consideration have an aspect ratio (height divided by web thickness) of approximately 7.5. A web thickness of 200 mm has been chosen for the experimental tests, as this represents a lower bound of thicknesses actually used in production.

The experimental test matrix includes L-shaped spandrels along with spandrels having discrete haunches (or corbels) instead of a continuous ledge. In addition, prestressed and conventionally reinforced members are studied. While the majority of beams do not have any closed stirrups (instead having open web reinforcement), control beams reinforced with currently accepted design procedures are included. A variety of open-web reinforcement schemes are evaluated experimentally. In addition, tests using both slide bearings and typical bearing pads at ledge and column reactions are included. Out of plane behavior is a crucial element in spandrel response, and friction at bearing locations serves to restrain this behavior. Thus, slide bearings were included in most tests to evaluate member response under the worst case conditions.

2.2 Specimen design

All specimens were designed to resist typical dead, live, and snow loadings for parking structures. The design assumed that each 14 m spandrel supported half of an 18 m span continuous deck.

It is important to note that many of the beams included in the test matrix were constructed with special reinforcement details to prevent failures outside of the end regions. This extra detailing was provided to allow for study of the end regions at ultimate. For example, steel angles were embedded at ledge bearing locations to delay punching failure in the ledge. Care was taken to ensure that these additional measures did not influence end region behavior. For example, additional mild steel was provided at midspan to delay flexural failure, but this steel did not extend into the end regions. Spandrels without special detailing were included in the test matrix to eliminate concerns about unintentionally altered end-region response.

For specimens with open-web reinforcement, steel was provided to satisfy only the requirements of in-plane flexure, vertical shear, ledge or corbel hanger steel requirements, and out of plane web bending. All torsion design provisions found in ACI-318 and the PCI Industry Handbook were ignored. Web bending forces were determined from the eccentricity of the applied loads and the spacing of the web tie-back connections. A 45-degree failure plane originating from the lower connection was assumed for design.

Figure 2 compares closed and open reinforcement. The open reinforcement configuration shown was chosen for some of the tested specimens. The primary advantage in using open reinforcement over conventional closed reinforcement is a substantial savings in labor and material during production. Configurations of open reinforcement other than that shown are possible.

2.3 Test setup

Each spandrel specimen measures nearly 14 meters long. Spandrels were simply supported and attached at their ends to a steel testing frame. Specimens were loaded by hydraulic jacks through short double-tee deck sections to mimic field conditions.

Loading was quasi-static up to failure, and included a 24-hour holding period at the factored design load for each test. A variety of instrumentation was used to monitor loads, deflections, and strains. A profile view of the test setup is shown in Figure 3 while Figure 4 shows an overview photograph.

2.4 Analytical study

In addition to the experimental work, the research program includes significant analytical study.
The analytical program augments the experimental program by allowing for examination of parameters that may be impossible (or cost prohibitive) to test experimentally. Data from the experimental program are used to validate, refine, and calibrate the analytical models, providing confidence in the analytical methods. The most important task to be accomplished analytically is to identify and to define boundary conditions that limit the applicability of the proposed open reinforcement concept.

The analytical component of the research has two elements. The first is to develop and calibrate a three-dimensional nonlinear finite element model (FEM) to study various parameters influencing slender precast spandrel behavior. The second is to use the analytical results from the FEM along with the experimental results to develop a rational model describing the behavior of precast slender spandrel beams. This rational model will form the basis from which to propose a new design method.

The finite element code ANACAP is being used for analytical modeling. The code is known for advanced nonlinear capabilities of the concrete material model. Modeling half of a typical slender spandrel beam (symmetry at midspan) requires roughly 1500 20-node brick elements. Reinforcing bars are modeled individually as discrete sub-elements within the concrete elements. The stress and stiffness of the reinforcing sub-elements are superimposed on the concrete element in which the reinforcing bar resides. Applied loads are increased incrementally to failure. Details of the analytical FEM can be found elsewhere (Hassan et al. 2007).

In conducting the parametric study, several key factors are being examined. The first of these is the aspect ratio (web height divided by web thickness). The FEM is being used to generate results for a variety of aspect ratios within practical limits to examine the influence of aspect ratio on behavior and failure mode. This information will be used to define a key boundary condition, namely the limit of what can be considered a slender spandrel cross-section.

Another key factor being studied analytically is the influence of deck connections on spandrel behavior. The typical welded connections between the inner spandrel face and the deck sections tend to develop substantial forces which influence lateral motion in the upper portion of the spandrel. The effect of deck connections on spandrel behavior is being evaluated analytically.

The analytical model is also being used to evaluate friction forces which develop at the bearing reactions underneath each deck stem. Due to the large degree of lateral motion, bearing friction at these locations plays a major role in slender spandrel response. Evaluating the influence of friction has been done experimentally (by varying bearing pads), but more extensive study can be conducted analytically.

3 SELECTED RESULTS

To date, all specimens have been configured to study failure in the end regions. The end regions for each of these specimens were designed to resist required factored loads (dead, live, and snow). In every case, including those with completely open web reinforcement, the specimen resisted the sustained factored design load for a 24-hour period with no significant signs of distress. Ultimate loads ranged from approximately 1.25 times the factored load level to nearly twice the factored load level. The analytical models are able to closely predict the experimental failure loads.

As would be expected, end regions reinforced at higher ratios sustained higher loads than did those reinforced at lighter ratios. End regions reinforced with closed ties at a high ratio combined with additional longitudinal steel (the current code approach) were able to sustain approximately 25% more load than were end regions reinforced with entirely open reinforcement at significantly lower ratios. When an end region with closed ties is compared to an end region with open ties, both reinforced at the same ratio, the increase in load carrying capacity due to closed ties is approximately 10%.

Test results indicate that closed ties do enhance end region capacity. However, it is apparent that end region load carrying capacities are more than sufficiently conservative with appropriate open tie designs (at least 25% above factored design loads). It is important to put the differences in load carrying capacity into perspective by noting that fabrication of a typical experimental open tie design requires approximately 30% less steel and half the labor when compared to the closed reinforcement required by the currently accepted code approach.

3.1 Cracking pattern and failure mode

In all tests, the cracking pattern was observed as shown in Figure 5. The inner web face exhibits diagonal
cracking in the end regions which gradually flatten and arch towards the center of the beam. The outer web face exhibits vertical cracking extending upwards from the bottom of the beam. This outer face cracking is due to in plane and out of plane flexure. No spiral cracking is observed. As load is applied, the bottom of the spandrel moves down and away from the decks at midspan, while the top moves down and inward towards the decks. Resistance to this tendency to overturn is provided by the lateral column reactions, creating a warped deflected shape and significant out of plane bending demands along the diagonal cracks in the end regions.

The failure mode observed in most tests was that of skew-bending in the end regions along a primary crack angle of approximately 45-degrees. This failure mode is shown in Figure 6. Recall that the specimens tested to date have been specially configured to study end region behavior at ultimate. Thus, in upcoming tests of beams configured with the same end region reinforcement, but typical detailing elsewhere, it is anticipated that other failure modes will control long before end-region skew bending develops. The analytical model is able to accurately predict a skew bending failure.

3.2 Sample test data
Out of plane behavior dominates slender spandrel response. Measured lateral deflections often exceed vertical deflections at ultimate. Figure 7 presents experimental and analytical lateral deflections for a 14 m prestressed L-shaped spandrel beam. This figure highlights the opposing lateral motion at the top and bottom of the beam at midspan. Analytical predictions are shown for a range of assumed bearing pad friction coefficients.

4 CONCLUSIONS
The potential benefits of simplified detailing for precast slender spandrel beams are significant. Open reinforcement provides greatly enhanced constructability over traditional closed stirrups, and thus, the potential for increasing precast plant productivity is substantial. The research described here aims to make the concept of simplifying precast slender spandrel design a reality by developing a safe, simple, and rational design guideline for use by the precast prestressed concrete industry. The guideline will be based on the concept of providing open web reinforcement to resist the out of plane bending forces that develop as a result of interaction between flexure, shear, and torsion in a slender member. The challenge in creating such a design guideline is in evaluating the large number of relevant factors, both experimentally and analytically, and defining appropriate limitations for the new approach. The authors believe that, once completed, the significant research effort presented here will allow the industry to fully embrace the concept of using open reinforcement for slender precast spandrel beam construction.

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