EVALUATION OF CONTINUOUS SYSTEM ECONOMY OF PRECAST COMPOSITE SLAB SPAN SYSTEMS

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ABSTRACT

The Minnesota Department of Transportation (MnDOT) has developed a precast composite slab span system (PCSSS) to be used in accelerated construction for bridges that span 20 to 60 ft. between supports. The system consists of shallow, precast, inverted-tee sections placed between supports with cast-in-place (CIP) concrete placed on top, forming a composite slab span system. The effects of restraint moments need to be considered if the PCSSS is made continuous across the piers. If the PCSSS were designed as a series of simple spans with no continuity, positive restraint moments would not develop. A parametric study of PCSSS designs was conducted to determine the economic benefit of continuous system design. In particular, design implications of time-dependent and thermal gradient restraint moments and their affects on continuity were studied.

Eight bridges covering the feasible range of span configurations were designed as both simple and continuous systems. Flexural design was performed for each case, resulting in optimized precast sections within practical design constraints. The continuous and simple-span design configurations were compared to evaluate economic benefit. Overall, continuous PCSSS design was found to be comparable or less economical than simple-span design. Spans less than 30 feet had a slight economic benefit with continuous design because large restraint moments did not develop. However, spans greater than 30 feet developed large restraint moments in continuous design, particularly due to thermal gradient effects. In addition, the restraint moments greatly reduced continuity, effectively negating the benefit to live-load capacity. It was recommended that PCSSS be designed as a simple-span system.

Keywords: Accelerated Construction, Creative/Innovative Solutions and Structures, Research

INTRODUCTION

Many highway bridges in the United States are in need of replacement due to aging infrastructure and increased traffic. Replacement projects are particularly detrimental to local traffic, with inconvenient and hazardous detours. New accelerated construction methods incorporating precast elements are increasingly popular to reduce construction time, safety hazards, environmental impact, and quality control problems. In response to these demands, the Minnesota Department of Transportation (MnDOT) has developed a design for a precast composite slab span system (PCSSS). The system was based on the French Poutre Dalle system following the 2004 FHWA International Scanning Tour of Prefabricated Bridge Elements and Systems[1]. A steady number of PCSSS bridges have been built in Minnesota to date, with three under construction in summer 2011.

PCSSS bridges are typically two or three spans, each 20 to 60 ft. in length, particularly suited for rural highways. The PCSSS superstructure consists of shallow, inverted-tee precast beam elements that are made composite with a cast-in-place (CIP) concrete deck to form a composite slab system. Figure 1 shows the typical PCSSS cross section. The six foot wide precast, prestressed inverted tee elements are placed adjacent between the bridge piers, with typically 7 to 13 sections across the width of the bridge per span. The precast elements are joined transversely by hooks extending from the precast webs. Drop-in reinforcement cages are placed in the trough regions above the precast flanges, providing crack control in

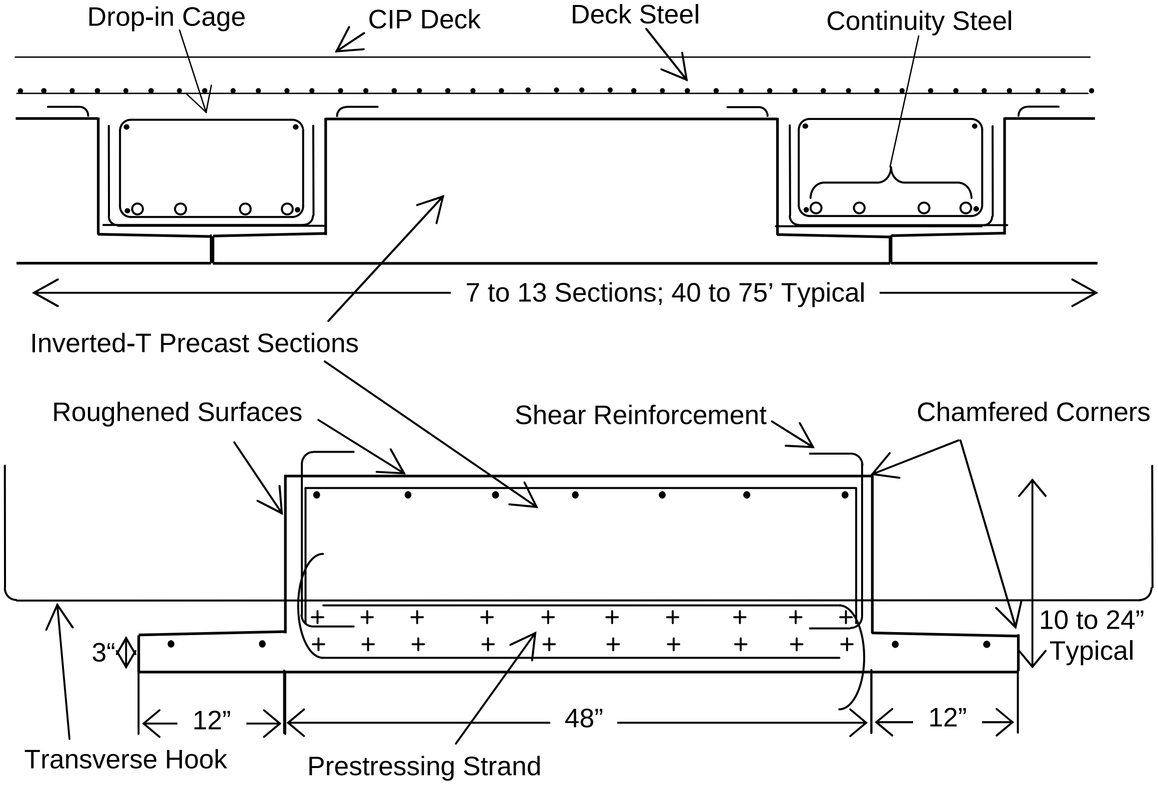

Fig. 1: Typical cross section for MnDOT PCSSS.

Fig. 2: Photograph of PCSSS construction showing inverted-tee precast beams and drop-in cage reinforcement prior to CIP placement

conjunction with the transverse hooks. Figure 2 shows a photograph of a PCSSS bridge in construction, with the precast beams and cage reinforcement visible prior to CIP placement. The precast elements are considered beams prior to continuity with the CIP concrete, at which point the system is considered a composite slab span.

Among other options, PCSSS is an alternative to slab-span construction. The precast elements in PCSSS eliminate the need for formwork for the CIP deck like voided slabs or adjacent box girders. The lack of formwork makes construction significantly less labor intensive than construction of a traditional slab-span bridge. PCSSS has several advantages over voided slabs and adjacent box girders as well. No post-tensioning is required in PCSSS construction. In addition, the CIP deck and cage reinforcement function to control cracking between adjacent beams.

When originally conceived, MnDOT designed the PCSSS bridges as continuous for live load, with the thought that it would be the most economical configuration. Continuity reinforcement in the trough region and the CIP deck steel carry the positive and negative moment over the piers, respectively. For the continuous system design, time-dependent and thermal gradient restraint moment effects should be considered[2]. Accounting for these effects has been design-intensive. While AASHTO allows restraint moments to be neglected if beams are 90 days old at continuity, manufacturers of PCSSS beams cannot hold beams this long. It has been unclear how much benefit a continuous system design could provide versus simple-span design. As a result, a parametric study was conducted to evaluate the design economy of continuous system PCSSS and to provide a recommendation for the design of future PCSSS bridges.

In order to provide a reasonable design recommendation, the design assumptions and methods for the parametric study followed current PCSSS design practices. The PCSSS bridges for the parametric study were designed according to the 2010 AASHTO LRFD Bridge Design Specifications (AASHTO)[2]. Design live loads were defined by the HL-93 load specification in AASHTO. Prestress losses were calculated using the Refined Method from Article 5.9.5.4 because the high volume-to-surface ratio of the inverted-tee precluded the Approximate Method. All of the designs were controlled by service limit states. In particular, the tensile stress limits in AASHTO Table 5.9.4.2.2-1 controlled the designs under the Service III load combination for tension cracking of prestressed members.

RESTRAINT MOMENT

Restraint moments are caused by restrained deflections of bridges made continuous from simple-span precast beams. The continuity connection at the piers restrains the deformation, causing moment to develop along the spans. Figure 3 shows the effect of both positive and negative restraint moment on a three-span system. Both the time-dependent effects of creep and shrinkage and the effect of thermal gradient can cause deformations that create restraint moments. Because continuous PCSSS bridges are fabricated from simple precast beams made continuous, the continuous system designs in the parametric study were subject to restraint moments.

Positive restraint moments are critical in the design of PCSSS because they add to the stress of the Service III load combination. Magnitude and direction of time-dependent restraint moments depend on the age of the precast beam at the time of continuity. Young age precast (less than 90 days) results in positive restraint moments due to prestressing creep, while old age precast (more than 90 days) results in negative restraint moments due to the deck shrinkage. Because PCSSS beams cannot be aged to 90 days by manufacturers, positive restraint moments must be dealt with in design.

Previous research has determined that time-dependent restraint moments for PCSSS are best modeled by the Peterman method (P-method)[3,4]. The P-method calculates the restraint

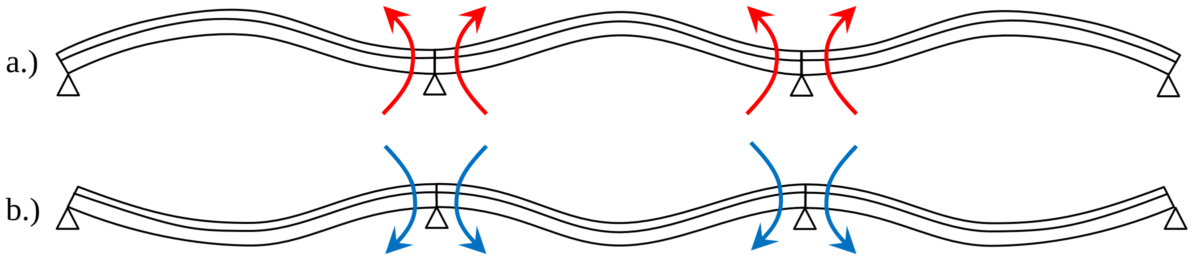

Fig. 3: Deflections and restraint moments for simple beams made continuous: a.) positive and b.) negative restraint moments.

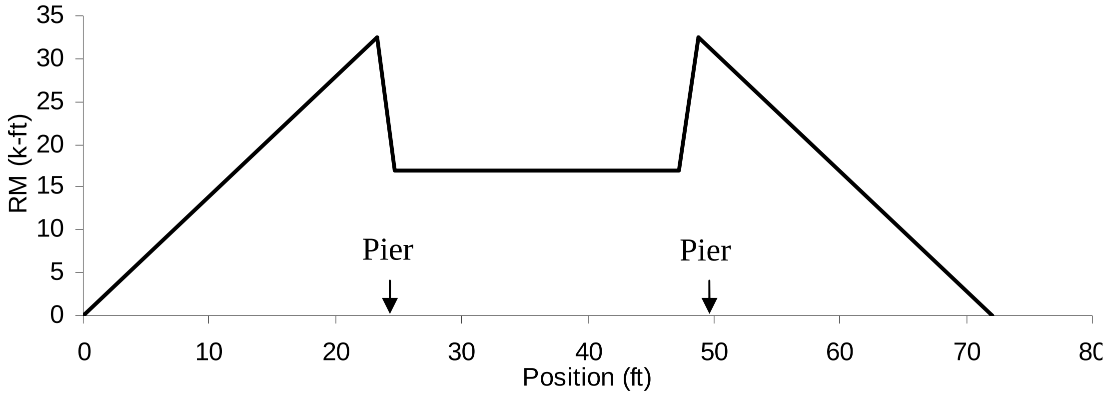

Fig. 4: Typical time-dependent restraint moment for PCSSS design using the P-method. The differences in moment at the piers (22 ft. and 44 ft.) are due to the effective diaphragm stiffness.

moment due to prestressing creep, dead load creep, and differential shrinkage between the precast and CIP deck. The restraint moment is then distributed using stiffness methods, accounting for the stiffness of the diaphragm at the pier. Figure 4 shows a typical positive restraint moment distribution using the P-method for a three-span bridge. The 2010 AASHTO creep and shrinkage models were used in calculating the P-method restraint moments.

The thermal gradient restraint moments were calculated according to AASHTO Section 4.6.6. Three thermal gradient components are specified in this section: axial expansion, flexural deformation, and internal stress. The flexural deformation component is associated with restraint moment. The thermal gradient restraint moment was distributed similarly to the time-dependent restraint moment, using stiffness methods.

PARTIAL CONTINUITY

The continuity connections of a PCSSS must be effective in order to transfer load through the continuous system. AASHTO Section 5.14.1.4.5 states that a diaphragm connection is only considered fully effective if the stress combination of post-continuity dead load, restraint moment, 50% live load, and 50% thermal gradient results in net compression on the bottom of the section at the pier. If there is net tension under these loads, cracks at the pier are assumed to be open, and the full section is not engaged in continuity action. Partial continuity must be used to calculate live load moments in this case.

Continuity action is most beneficial for reducing the center span, midspan live-load positive moment. The truck position that creates maximum midspan moment will put negative moment at the bridge piers. This negative moment causes compressive stress at the bottom of the section at the pier, improving the continuity check. If 50% of the stress caused by the truck position for maximum midspan moment was enough to satisfy the continuity check, then the connection was assumed to be fully continuous and the continuous live load envelope was used. If the check was not satisfied, the connection was assumed to be partially continuous and the live load envelope was modified.

A linear approximation was used to evaluate partial continuity for ease of design. AASHTO suggests in the commentary that a portion of the dead loads and live loads be applied to a simple span. It is assumed that it will take some load to first close a potential positive restraint moment crack at the pier to enable the generation of a compressive resultant force necessary for the development of the negative moment. This portion should cause zero tension at the bottom of the diaphragm, or enough to pass the continuity check. Then the remaining live load should be applied to the continuous span. In reality, calculating the effect of partial continuity is a non-linear problem that is not efficient for real world design. The linear approximation described in this paper is a rational and conservative simplification.

To determine how much live load needed to be applied to the simple span, the total compressive stress possible at the pier due to the midspan truck was calculated, as opposed to 50% originally. If the total stress was still not enough to pass the continuity check, then the system would not become continuous in the critical case, and the simply-supported live load envelope was used. If the total stress was enough to pass the continuity check, then the percentage required to bring the tension at the bottom of the diaphragm to zero was calculated. This percentage of the simple-span envelope was then added to the remainder of the continuous envelope to get the final live load envelope. For example, if 65% of the total stress was required to pass the continuity check, then 65% of the simple-span envelope was superimposed on 35% of the continuous envelope, resulting in the partially continuous live load envelope.

PARAMETRIC STUDY

The parametric study compared simple-span and continuous system designs for eight sample bridges with varied span configurations. These configurations covered the range of feasible PCSSS bridges in order to provide a general recommendation. Table 1 shows the span length configurations for the eight sample bridges. Sixteen designs in all (simple and continuous for each of the eight sample bridges) were used to compare design economy. The simple-span designs were completed before the continuous system designs. Simple-span designs did not require considerations for restraint moment or partial continuity as described previously because these are continuous system effects. The simple-span designs were used as starting points for the corresponding continuous system designs.

Table 1: Span configurations for the parametric study covering the range of feasible designs

Two Spans	Three Equal Spans	Three Unequal Spans
22’-22’	24’-24’-24’	22’-27’-22’
62’-62’	34’-34’-34’	20’-30’-20’
	50’-50’-50’	45’-62’-45’

A specific design methodology was developed for the flexural capacity of the precast sections in order to compare different configurations. Three primary design parameters were identified for the flexural design of the precast sections: beam depth, concrete strength, and number of strand. These parameters were used to evaluate the economy of a particular precast section, as well as to optimize the sections within design constraints. Each design started with precast concrete strengths of f'_c = 6.0 ksi and f'_{ci} = 4.0 ksi and typical precast beam depths. Beam depth and concrete strengths were consistent for all spans in the bridge, while strand pattern could change between middle and end spans. The middle span was designed first for the three-span configurations, because the depth of the longer center span controlled the depth of the precast sections overall. CIP concrete strength was 4.0 ksi and prestressing strand was 0.5 in., low-relaxation, Grade 270. At continuity, the precast beams were assumed to be 14 days old. This was a reasonable age in construction and resulted in worst-case positive restraint moments.

For each span, the primary design parameters were modified sequentially. First, the strand pattern design was optimized for the Service III limit state at midspan. The strand design was limited to two rows, one at 2 in. and one at 4 in. from the bottom of precast. Following common practice, each row had either an equal number of strand or two additional strands in the bottom row. This kept the center of gravity of prestressing around 3 in. from the bottom. If Service III could not be reasonably satisfied with strand design alone, concrete strength was increased up to 10 ksi. Finally, if the increased concrete strength up to 10 ksi did not satisfy the Service III limit state, the beam depth was increased by 2 inches and the sequence was repeated. Once the Service III limit state was satisfied, concrete strengths were adjusted to satisfy any strength limit states for Service I compression that had been exceeded by increasing prestressing force. Secondary design, such as positive moment connection design, was done after flexural design optimization.

RESULTS

Corresponding simple-span and continuous system designs were compared to evaluate economy. Table 2 shows the results of the optimized designs in terms of the primary design parameters. Because labor and construction costs vary from state to state, the comparison for economic benefit was made considering the optimized strand number as well as the design effort required. The number of strand placed has an associated material and labor cost and was an indication of the economy of the precast section. Continuous system design took significantly more design effort than a simple-span design because restraint moments did not need to be considered. A general cost analysis was not performed because of the differences in costs from state to state. Life cycle costs were not considered because the deck surface and joint conditions of the simple-span and continuous system are similar in PCSSS design. In both cases, the deck is continuous over the piers, preventing corrosive materials from reaching the pier caps. The only concern for the simple-span joints is cracking from the bottom, which should not propagate to the surface. Overall, a continuous system design needed to have a significant savings in strand number to account for the added design effort.

Table 2: Optimized simple span and continuous system PCSSS designs.

	Simple-Span				Continuous System			
Span Configuration	Strand No.*	f'_{ci} (ksi)	f'_c (ksi)	Section Depth (in.)	Strand No.*	f'_{ci} (ksi)	f'_c (ksi)	Section Depth (in.)
22'-22'	12	4.0	6.0	10	12	4.0	6.0	10
62'-62'	44	6.0	7.0	24	46	6.0	7.0	24
24'-24'-24'	14	4.0	6.0	10	16, 14	4.0	6.0	10
34'-34'-34'	20	4.0	6.0	14	22, 20	4.0	6.0	14
50'-50'-50'	34	6.0	7.0	18	36, 34	6.0	7.0	18
20'-30'-20'	10, 18	4.0	6.0	12	8, 16	4.0	6.0	12
22'-27'-22'	12, 20	4.0	6.0	10	10, 16	4.0	6.0	10
45'-62'-45'	22, 48	6.0	7.0	22	24, 50	6.0	7.4	22

* Where two strand numbers are given, the first is for the end spans and the second is for the middle span.

Two of the configurations showed some small economic benefit with continuity: the 20-30-20 continuous design used 2 fewer strand per precast element and the 22-27-22 continuous design used 8 fewer strand per precast element than the respective simple designs. These configurations had short spans that did not develop large restraint moments and maintained full continuity. The effect of the larger middle span was to reduce the end span restraint moment. The two-span 22-22 continuous design showed no economic benefit over the simply-supported design even though it was also fully continuous. With only two spans to provide continuity action, the restraint moment developed in this system was enough to counteract the benefit of continuity.

The continuous designs of the remaining configurations were all less economical than the corresponding simply-supported designs. These configurations were all effectively simply supported because they failed to pass the continuity check. With no continuity, the added restraint moments were large enough to control the design and require additional strand. All three span configurations with equal end and center span lengths (i.e., 24'-24'-24', 34'-34'-34', and 50'-50'-50') show similar optimized design behavior. The center spans are all equivalent to the simply-supported designs, while the end spans each required two additional strands. Restraint moments that developed in the end spans were at a maximum at the pier and decreased linearly to zero at the abutment. The controlling section was still at midspan where the restraint moment stress superimposed with the live load envelope required additional capacity.

CONCLUSIONS

Based on the results of the parametric study, a continuous system design for PCSSS is not always more economic than a simply-supported design due to the development of time-dependent and thermal gradient restraint moments.

One simplified design solution that has been considered is to design PCSSS as a series of simply supported spans and then add positive moment steel for redundancy. These results show that this is not a conservative design choice. The positive moment steel will develop restraint moments that could exceed the capacity of the simply-supported designs, particularly in long spans and three-span configurations with equal span lengths. The observed case where this design approach would be conservative, albeit less economical, is for a three-span system with shorter end spans, where the center span is not longer than 30 feet. No other PCSSS configurations should be designed with this method.

It may be possible to maintain continuity if time-dependent restraint moments did not develop by letting the continuity time reach 90 days. In this case, time-dependent restraint moments are ignored since creep and shrinkage are assumed to have finished, and only thermal gradient causes tension in the bottom of the section over the pier. This would most likely result in at least partial continuity for most configurations, changing the design economy considerably.

Overall, PCSSS should be designed as a series of simple spans instead of as a continuous system. The benefits of continuous design to some span configurations do not make up for the added design complexity for restraint moments and partial continuity. For most bridges, the simple-span design is more economical.

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