ACCELERATING BRIDGE CONSTRUCTION USING THE PRECAST INVERTED T-BEAM CONCEPT

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ABSTRACT

Increasing traffic demands on bridge infrastructure present significant challenges for the departments of transportation within the framework of bridge construction and rehabilitation. It is essential to address these problems with minimal interference with the motoring public. The inverted T-beam system is a bridge system that provides accelerated bridge construction and replacement for short to medium span bridges. The system consists of precast inverted T-beams placed adjacent to one another finished with a cast-in-place concrete topping. This paper focuses on a comparison of cross-sectional shapes for the inverted T-beams and their connection in the transverse direction to address the issue of reflective cracking, which is a big problem associated with such composite systems. An analytical and experimental study was performed to investigate different ways to connect the inverted T-beams transversely and to optimize their cross-sectional shape. It is concluded that all tested specimens performed well and very similarly at service load levels. It is recommended that the detail which features an inverted T-beam with a tapered web cross-sectional shape and no mechanical connection with the adjacent inverted T-beams and cast-in-place topping be used in design.

Keywords: precast inverted T, transverse connections, cracking

INTRODUCTION

It is no secret that the supply of funds available to keep up with the demand for new bridge construction and rehabilitation is becoming scarce. The construction of new bridges and the rehabilitation of existing ones typically create detours or congestion in traffic, which in turn affect user's costs. Therefore, state departments of transportation are faced with the challenge of finding new and innovative ways to address infrastructure needs while minimizing traffic re-routing or congestion. The precast inverted T-beam system is a composite bridge system that eliminates the installation of formwork, which is one of the activities that prolong new bridge construction or rehabilitation. The precast inverted T-beam system consists of several precast inverted T-beams placed adjacent to one another. The contractor then installs the reinforcing steel for the cast-in-place concrete topping. Finally a jointless riding surface is provided by placing the concrete topping (Figure 1).

While similar bridge systems that consist of precast and cast-in-place components promote faster construction schedules, most problems associated with these systems are related to the performance of joints between adjacent members. Therefore, it is essential that these joints are detailed such that they do not compromise the advantages of the system. One of the causes of deterioration of such composite systems is reflective cracking, which is observed in bridge systems consisting of adjacent precast prestressed voided slabs and adjacent box girders. In both of these systems, usually a cast-in-place topping or an overlay is used to provide a continuous riding surface. Grouted shear keys are typically used at the joint between the precast members and they are intended to prevent the adjacent components from moving relative to one another. However, many times these grouted shear keys fail and monolithic action is lost, which gives rise to reflective cracking. Reflective cracking provides an avenue for water and deicing salts to penetrate the topping and corrode the reinforcing steel. In addition, once reflective cracking occurs the system is not as redundant as it was prior to cracking. This gives rise to narrower distribution of live loads and each precast component is be subject to higher live loads compared to a monolithic system. The precast inverted T-beam system is expected to address the issue of reflective cracking, since a thicker cast-in-place topping is provided over the joints and the profile is adjusted to reduce stress concentrations. In addition, some of the details that are investigated include a mechanical connection between the flanges of the precast inverted T-beams and the cast-in-place topping.

The precast inverted T-beam system will be used in the construction of a two-span continuous bridge in the Richmond area of the Commonwealth of Virginia. The research program described in this paper focused on a combination of different connections and cross-sectional shapes of precast inverted T-beams to investigate their performance under service loads and to determine the failure load and mode so that recommendations can be made accordingly for the design and construction of the bridge.

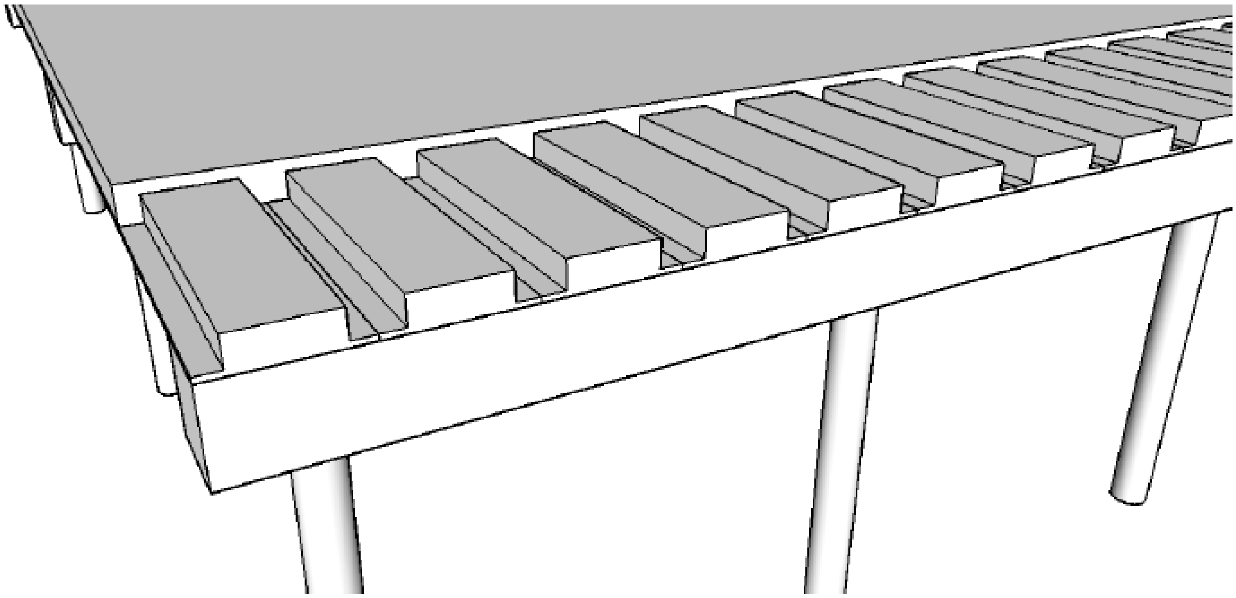


Fig. 1 Precast Inverted T-beam System

BACKGROUND

In 2004 the Federal Highway Administration sponsored a scanning tour in Europe and Japan to determine whether there were any accelerated bridge construction systems that could be adopted in the United States. The group of engineers and researchers presented their findings in a document titled "Prefabricated Bridge Elements and Systems in Japan and Europe"[1]. One of the systems that were selected as a potential system for implementation was the Poutre-Dalle System observed in France. Poutre-Dalle in French means Beam-Slab which describes the system in question. The State of Minnesota was the first state in US that implemented this system. Researchers at University of Minnesota and University of Tennessee (French et al. 2011[2,3,4]) did considerable research on the inverted T-beam system, including the investigation of the connection between the cast-in-place topping and the precast inverted T-beams. The precast inverted T-beam in the original French system is shown in Figure 2. Notice that there is reinforcing steel with 180 degree hooks protruding from the webs of the precast inverted T-beams. When the inverted T-beams are placed side by side, the reinforcing steel protruding from the webs overlaps and provides a connection with the cast-in-place concrete topping and adjacent inverted T-beams. The system investigated at the University of Minnesota and University of Tennessee is very similar to the French system with the exception that the bars extending from the webs have a 90 degree hook (Figure 3). The part of the investigation which relates to the transverse connection between the precast inverted T-beams consisted of seven tests and focused on the effects of size, spacing and placement of the transverse bars that protrude from the webs. In all of these tests the cross-sectional shape of the inverted T-beams consisted of a straight vertical web.

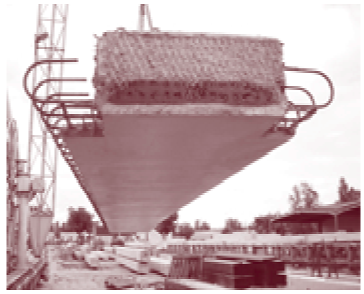


Fig. 2 Poutre-Dalle system observed in France during the 2004 Scanning Tour (Picture courtesy of Federal Highway Administration (FHWA)[1]

Fig. 3 Precast Inverted T-beam used by the Minnesota Department of Transportation (MnDOT) (Picture courtesy of MnDOT[5]). Picture on the left shows as a typical precast inverted T-beam while picture on the right shows the field installation of the precast inverted T-beams side by side.

The straight web cross-sectional shape in the precast inverted T-beams creates re-entrant corners with 90 degree angles, which are a source for crack initiation in the cast-in-place topping due to stress concentrations as a result of a radical change in the geometry of the component. To address this issue, two of the test specimens that are described in this paper include a tapered web cross-sectional shape. In addition, alternative ways of connecting the inverted T-beams transversely are investigated.

FUTURE IMPLEMENTATION OF THE INVERTED T-BEAM SYSTEM IN THE STATE OF VIRGINIA

The precast inverted T-beam system will be used in a two-span continuous bridge by the Virginia Department of Transportation in the Richmond area of the Commonwealth of Virginia. An aerial view of the construction site is shown in Figure 4. There are a total of four bridges which are planned for replacement at the site shown in Figure 4. One bridge is a single-span bridge, two are two-span continuous bridges and the fourth one is a multi-span bridge. One of the two-span continuous bridges will be built using the voided slab system and the other one will be built using the inverted T-beam system. In this manner the performance of the two different bridge systems can be observed over time. A preliminary plan view of the two-span continuous bridge, which will be built using the Inverted T-beam system, is shown in Figure 5 and an elevation of it is shown in Figure 6. Each span is 43 ft - 0 in. long and the depth of the superstructure consisting of the inverted T-beams and the cast-in-place topping is limited to 25 in. The bridge planned to be constructed using the inverted T-beam system is identified as B607 in Figure 4. There are three lanes in each direction and a median.

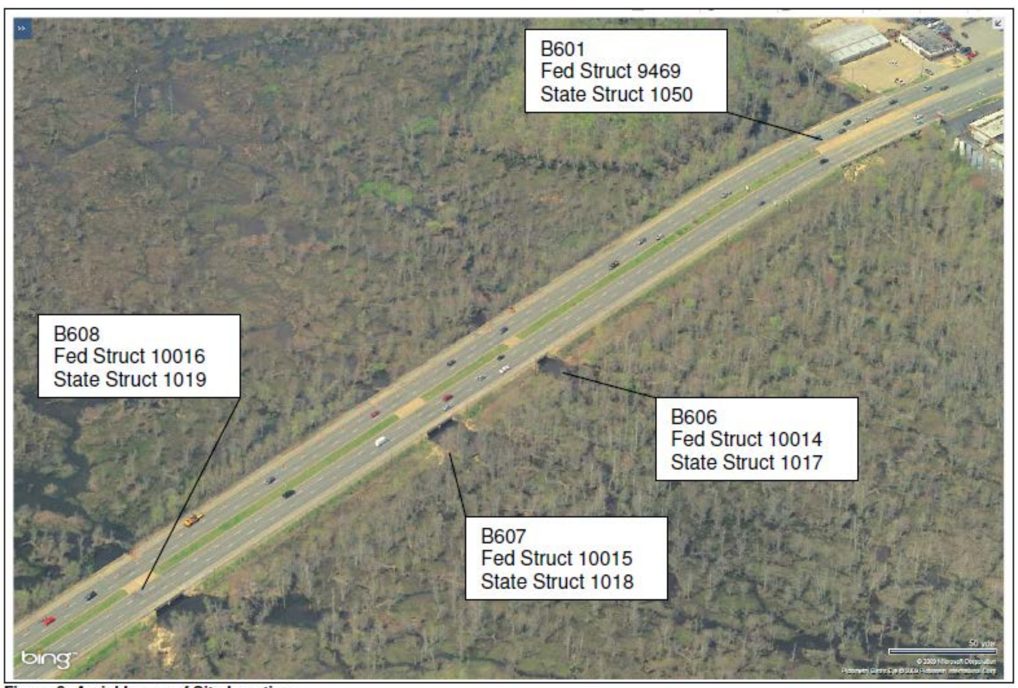


Figure 3: Aerial Image of Site Location

Fig. 4 Aerial view of the bridge replacement site on Route 360 over Chickahominy River[6]

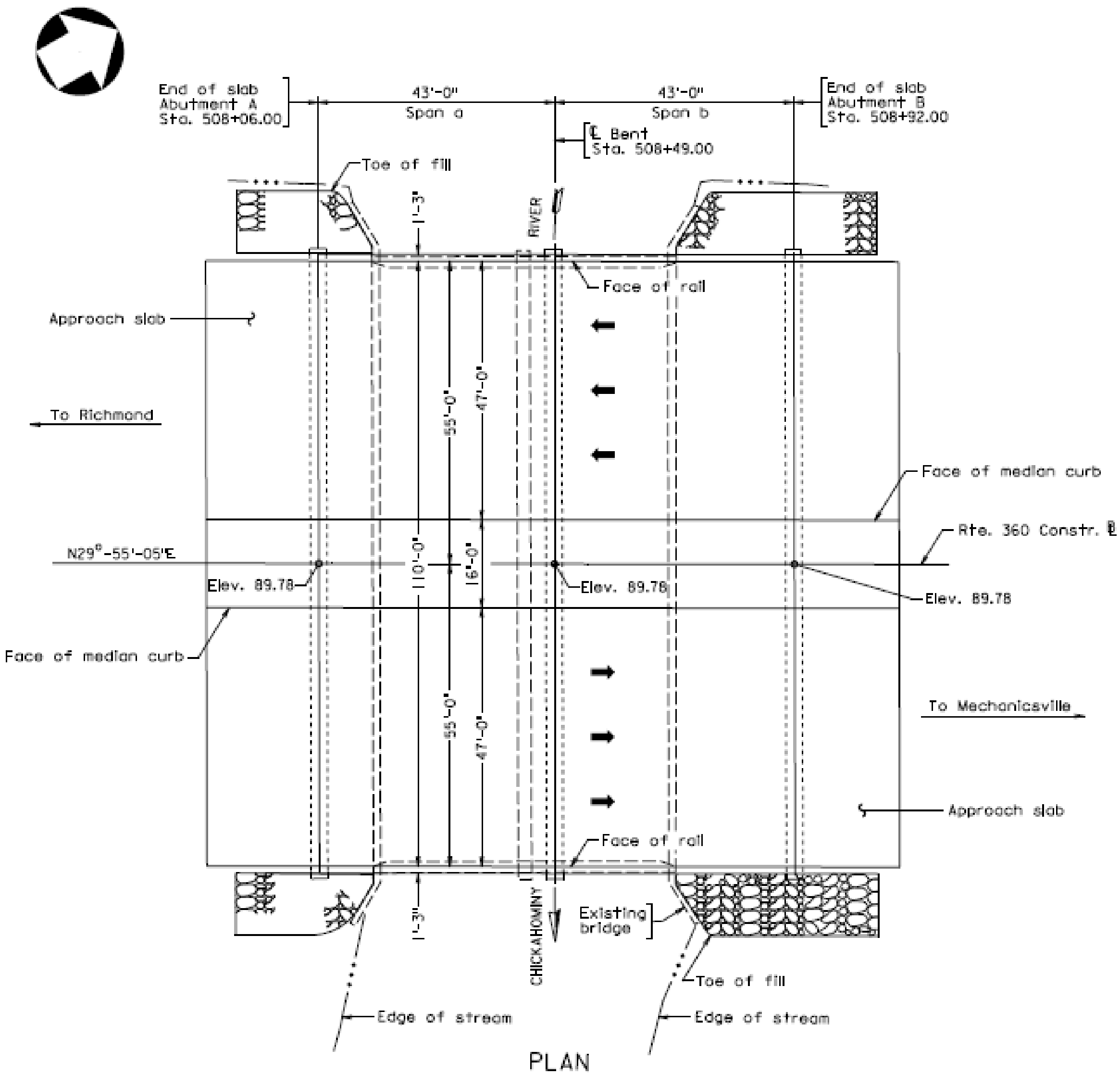


Fig. 5 Preliminary plan view of the soon to be replaced two-span continuous bridge on Route 360 over Chickahominy River (Courtesy of Virginia Department of Transportation[6])

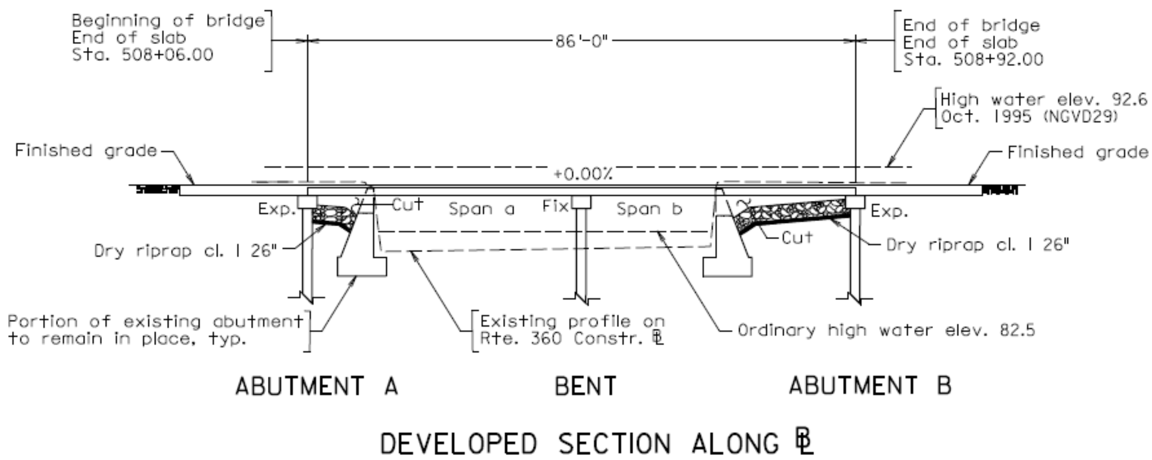


Fig. 6 Preliminary elevation of the soon to be replaced two-span continuous bridge on Route 360 over Chickahominy River (Courtesy of Virginia Department of Transportation[6])

ANALYTICAL INVESTIGATION

The beam-slab system consisting of inverted T-beams and cast-in place concrete topping is a one-way slab system (the beam-slab spans from abutment to pier and from pier to abutment). However, when this composite system is subject to concentrated loads, such as transient loads, a two-way plate bending action takes place. So, in addition to having bending in the direction of the span, which is expected, there is also bending in the transverse direction. The behavior of the system in the transverse direction is the focus of this paper. The incentive for investigating the behavior of the system in the transverse direction is that one of the reasons for reflective cracking in voided slab systems and adjacent box girder systems is the failure of the shear keys as a result of transverse bending which provides an opportunity for the adjacent box girders and voided slabs to move relative to one another. Another reason for reflective cracking is differential shrinkage however this issue will be dealt with separately in a future paper.

A finite element model of the two span continuous bridge, which will be built in the Richmond area of Virginia, was created in Abaqus[7] to determine the worst case transverse flexural stress in the CIP topping that is caused by the two-way plate bending action. This worst case transverse flexural stress was obtained by moving the live load (combination of truck and lane load or tandem and lane load) to different locations across the bridge to comply with the requirements of 2010 AASHTO LRFD Bridge Design Specifications 5th Edition[6]. Figures 7 and 8 show different views of the deformed shaped of the bridge under the influence of the live loads. Figure 9 shows a sectional cut in the transverse direction and the transverse flexural stress contours at the joints between the inverted T-beams. To obtain the desired stress a linear elastic analysis using 3D solid elements and un-cracked concrete was performed. The stresses created in the cast-in-place topping at any point in the bridge due to design live loads were smaller than the modulus of rupture.

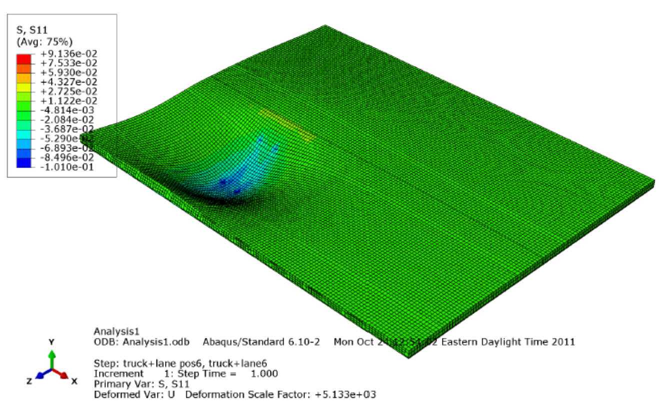


Fig. 7 An isometric view of the deformed shape due to live loads of the two span continuous bridge modeled with precast Inverted T beams and cast in place concrete topping (Finite Element Model created in Abaqus[7])

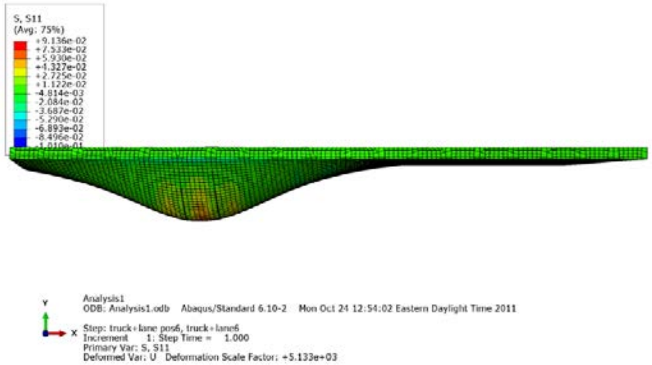


Fig. 8 Side view of the deformed shape due to live loads. Notice the effect of transverse bending on the joints between the inverted T-beams

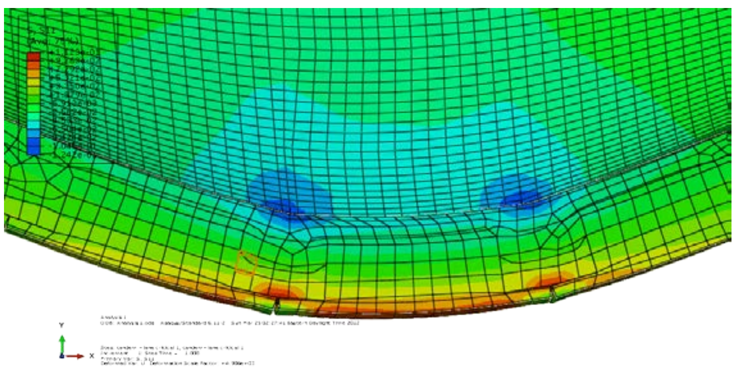


Fig. 9 A sectional cut in the transverse directions to illustrate maximum transverse flexural stresses above the joint between the precast inverted T-beams

EXPERIMENTAL INVESTIGATION

To simulate this transverse flexural stress at the joint between the inverted T-beams, a simply supported beam setup was designed as part of the experimental program. The rationale behind this test setup is illustrated in Figure 10 and is based on the logic that since we are interested in the transverse bending behavior of the inverted T-beam system, then this behavior can be reasonably approximated by a simply supported beam representing a section of the bridge in the transverse direction. While this test setup will not exactly represent the stress state in the real bridge at every point in the 12 ft - 0 in. section it will simulate the actual transverse flexural tensile stress in the region around the joint, which is believed to be one of the reasons for reflective cracking. A photograph of this setup is shown in Figure 11 and a schematic representation of it is shown in Figure 12. As can be seen from Figure 12 the setup consists of two adjacent inverted T-beams and the cast-in-place topping. At the supports the flange part of the inverted T-beams was eliminated and replaced with a full height web to get a better bearing condition. A total of four specimens were tested to investigate the influence of two main parameters:

- cross-sectional shape of the inverted T-beams and
- transverse connection between the inverted T-beams and cast-in-place topping

Figure 13 and 14 illustrate the two different cross-sectional shapes that were tested, which are the straight web cross-sectional shape (original French detail) and the cross-sectional shape with the tapered web. The depth of the specimens is 25 in. which matches the depth of the superstructure in the future bridge. The span length for the specimens was selected to be 12 ft - 0 in. such that it would capture two adjacent inverted T-beams each of which are 6 ft - 0 in. wide. The width of the specimens was selected to be 4 ft - 0 in., which is a multiple of the spacing of the embedded plate connectors with the welded rebars and the spacing of the extended bars from the webs of the inverted T-beams (this will be explained later in this paper). The spacing of the embedded plate connectors is 2 ft – 0 in., while the spacing of the extended bars from the webs of the inverted T-beams is 12 in. The reinforcing in these specimens was selected by designing the superstructure in the real bridge and extracting the amount of reinforcing that pertains to the portion of the composite system that is part of the test setup. The reinforcing details for all four test specimens are given in Figures 15 through 18. Since the transverse flexural stress at the joint between the inverted T-beams was the predominant stress component compared to the shear stress the four test specimens were loaded at quarter points to create a region of constant moment and zero shear. This loading condition also corresponds with the case when the truck wheel loads, which are 6 ft – 0 in. apart, are on each side of the joint.

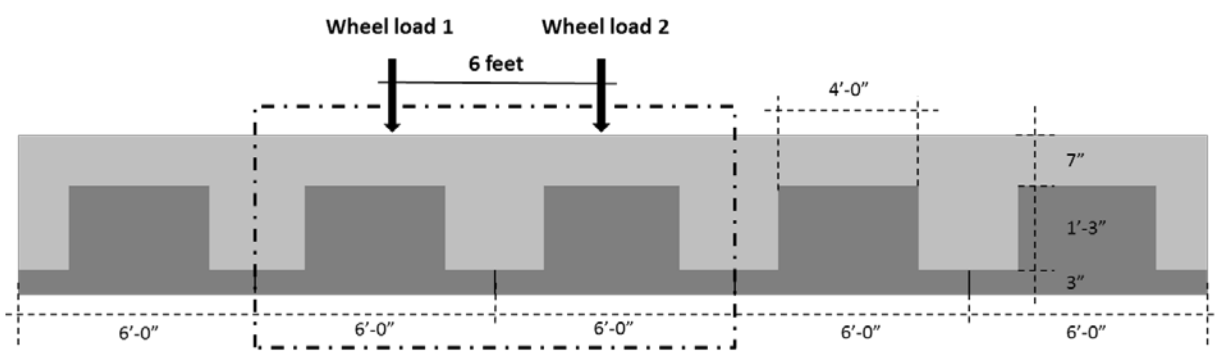


Fig. 10 This figure illustrates the rationale behind the selection of the geometry of the test specimens to investigate the performance of different connections and cross-sectional shapes when subject to bending in the transverse direction.

Fig. 11 Photograph of test setup showing the loading frame, load actuator, the spreader beam which loads the specimen at ¼ points and the two steel support beams which provide 6 in. bearing on each side.

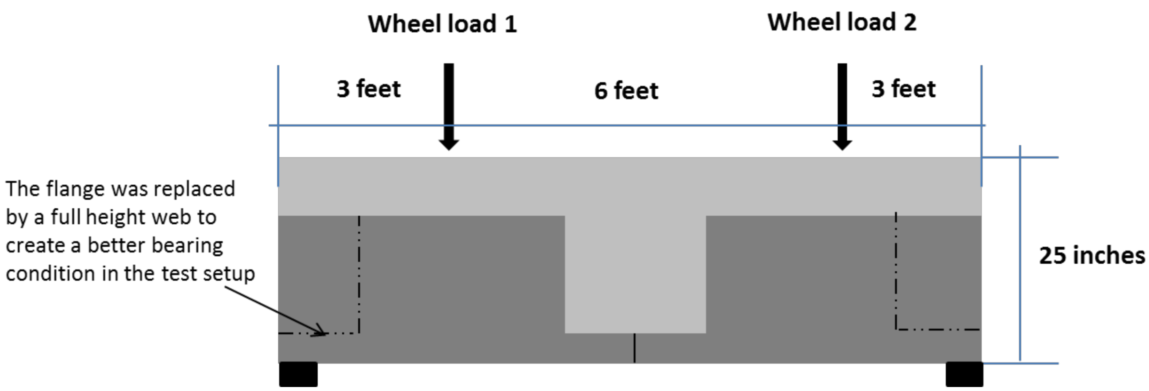


Fig. 12 Schematic representation of test setup

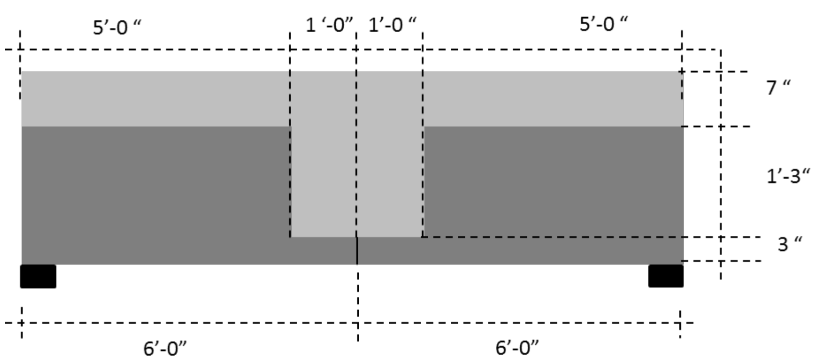


Fig. 13 Test specimen with a straight web profile. Width of the specimen is 4 ft - 0 in.

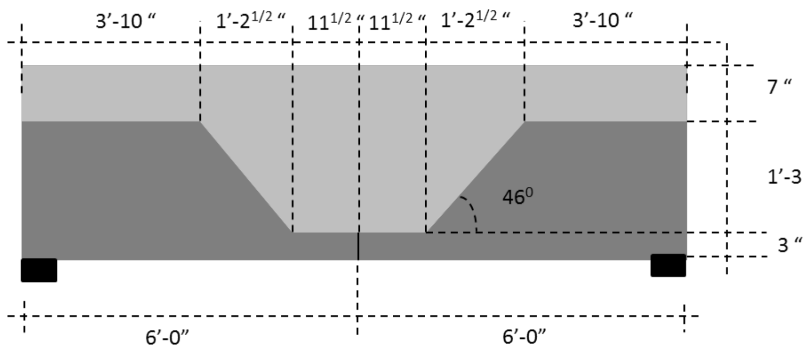


Fig. 14 Test specimen with a tapered web profile Width of the specimen is 4 ft- 0 in.

CAST-IN-PLACE TOPPING

The mix design for the cast-in-place concrete topping was selected based on an experimental study performed at Virginia Tech which investigated four different mix designs with a design compressive strength at 28 days of f'_c = 4000 psi to study their shrinkage and creep properties. The results of this study will be published in a separate paper. The goal of this study was to identify the mix with the lowest shrinkage and highest creep. Low shrinkage is desired to minimize cracking in the cast-in-place topping as a result of differential shrinkage between the precast component and cast-in-place component. High creep is sought to relax any stresses that might develop as a result of differential shrinkage. The selected mix design is provided in Table 1. Reinforcing for the cast-in-place topping was based primarily on minimum code requirements. One exception is the criteria for the bottom layer of transverse reinforcing in Specimen #4 which will be described under "Specimen #4 – Tapered Web no connection". Various material properties for this mix design were investigated such as compressive strength, splitting tensile strength, modulus of elasticity, unrestrained shrinkage and creep based on ASTM C39[9], C496[10], C469[11], C157[12], C512[13] respectively. In Table 3, however only the compressive strength, splitting tensile strength and modulus of elasticity are reported.

Since the material properties for the cast-in-place concrete topping used in each specimen are for the most part similar to one another, it is believed that any differences should not have a significant effect on the results. As can be seen in Table 3, the design compressive strength at 28 days was not achieved for the cast-in-place topping. While during the construction of a bridge such an event will be considered as a failure to meet the specifications, it provided the researchers with an opportunity to investigate the strength and performance of the specimens in the transverse direction of the bridge at lower than specified concrete compressive strengths. Since the inverted T-beam system is intended to provide accelerated bridge construction and rehabilitation, most of the time it would be desired to open the bridge to traffic in less than 28 days after the placement of cast-in-place concrete topping. This paper provides information on the load the caused the first crack and the one that failed each specimen for the indicated cast-in-place concrete compressive strengths at the day of testing. All reinforcing steel is ASTM A615, Grade 60, deformed bare steel.

Table 1. Mix design for cast-in-place topping

Mix design for cast-in-place topping (f'c = 4ksi)	
Ingredients	**Quantity for 1 yd^3**
#57 stone	1853 lbs
Nat Sand	1168 lbs
Cement	533 lbs
Fly Ash	133 lbs
Water reducer 161	34 ounces
Midrange water reducer	13 ounces
Water	30 gallons
w/cm ratio	0.38

PRECAST INVERTED T-BEAMS

The precast inverted T components were constructed using a concrete mix design with a design compressive strength at 28 days of f'c = 8000 psi. The ingredients of this mix design are presented in Table 2. The age of the specimens at the day of testing and the corresponding compressive strength, splitting tensile strength and modulus of elasticity are provided in Table 3. The selection of the prestressing strands in the longitudinal direction was taken from the design of the future bridge based on the requirements of 2010 ASSHTO LFRD Bridge Design Specifications for service and strength limit states. The prestressing strands in the test specimens were not prestressed since they do not have a significant influence on the behavior of the specimens in the transverse direction. The selection of the shear reinforcing was taken from the design of the future bridge based on the code requirements for vertical and horizontal shear. Other reinforcing selection criteria are described for each specimen later in this paper. As it can be seen from Table 3, the material properties for all for test specimens are similar to one another. All faces of the precast inverted T-beams with the exception of the bottom face and the side faces of the flanges were roughened to a ¼ in. amplitude to improve the bond with the cast-in-place topping. All mild reinforcing steel is ASTM A615, Grade 60, deformed bare steel. 4. Prestressing strands are ASTM A416, Grade 270, uncoated, low-relaxation strands.

Table 2. Mix design for precast inverted T-beams

Mix design for precast inverted T's (f'c = 8ksi)	
Ingredients	**Quantity for 1 yd^3**
#78 stone	1544 lbs
Nat Sand	1502 lbs
Cement	675 lbs
Microsilica	54 lbs
SIKA 2100	27 ounces
Retarder	24 ounces
Water	32 gallons
w/cm ratio	0.36

Table 3. Material Testing Data for the precast and cast-in-place components

	Cast-in-place Topping (f'c = 4ksi)				Precast Inverted T's (f'c = 8 ksi)			
	Age at testing (days)	f'c (ksi)	ft (ksi)	E (ksi)	Age at testing (days)	f'c (ksi)	ft (ksi)	E (ksi)
Specimen #1	28	3380	0.355	3110	54	8820	0.751	5510
Specimen #2	24	3680	0.418	3900	66	9390	0.815	5720
Specimen #3	28	3810	0.433	4190	70	9380	0.804	5730
Specimen #4	24	3400	0.341	3280	49	8990	0.741	5530

SPECIMEN #1 – STRAIGHT WEB WITH EXTENDED BARS

The specimen illustrated in Figure 15 is identified as "straight web with extended bars" and is very similar in concept to the modified French detail tested at the University of Minnesota. The specimen in this test consists of two adjacent precast inverted T-beams with a straight web, and with reinforcing steel bars protruding from the webs. The advantage of this system is that it accelerates new bridge construction and existing bridge rehabilitation by minimizing the amount of work done at the construction site, since the contractor can use the inverted T-beams as a working platform to place reinforcing steel for the cast in place topping and ultimately place concrete. In addition, the extended bars from the webs of the inverted T-beams provide a continuous tension tie in the transverse direction of the bridge.

The disadvantage of this detail is that it creates challenges for the precaster since the formwork for the webs of the precast inverted T-beams needs to be constructed such that it will accommodate the reinforcing steel protruding from the webs. The transverse bars in the flange of the inverted T-beams were sized to support the weight of the wet cast-in-place concrete topping during construction.

The criterion for selecting the extended hooked bars and the bars for the pre-tied cage which are described as No. 4 stirrups at 12 in. on center in Figure 15 is as follows. It is assumed that the entire cast-in-place topping over the joint between the precast inverted T-beams will be cracked under a stress equal to $6\sqrt{f'c}$ where f'_c is in psi. Since the top and bottom layer of topping steel were selected based on the AASHTO LRFD Specifications the summation of the area of the extended bars and the area of the pre-tied cage needed to make up for the deficit to provide a big enough force to resist $6\sqrt{f'c} * A_c$ where A_c is the area of the cast-in-place topping right over the joint in the longitudinal direction (parallel with the joint). This criterion is recommended by Frosch et al 2006[14] for sizing crack control reinforcing in bridge decks and was adopted by the researchers at the University of Minnesota and University of Tennessee for sizing the reinforcing in the cage and the bars protruding from the face of the webs of the inverted T-beams. This criterion is different from the one used to size reinforcing in the transverse direction to resist tensile stresses created by the bending action for Specimens #2, #3 and #4 which is explained later in this paper.

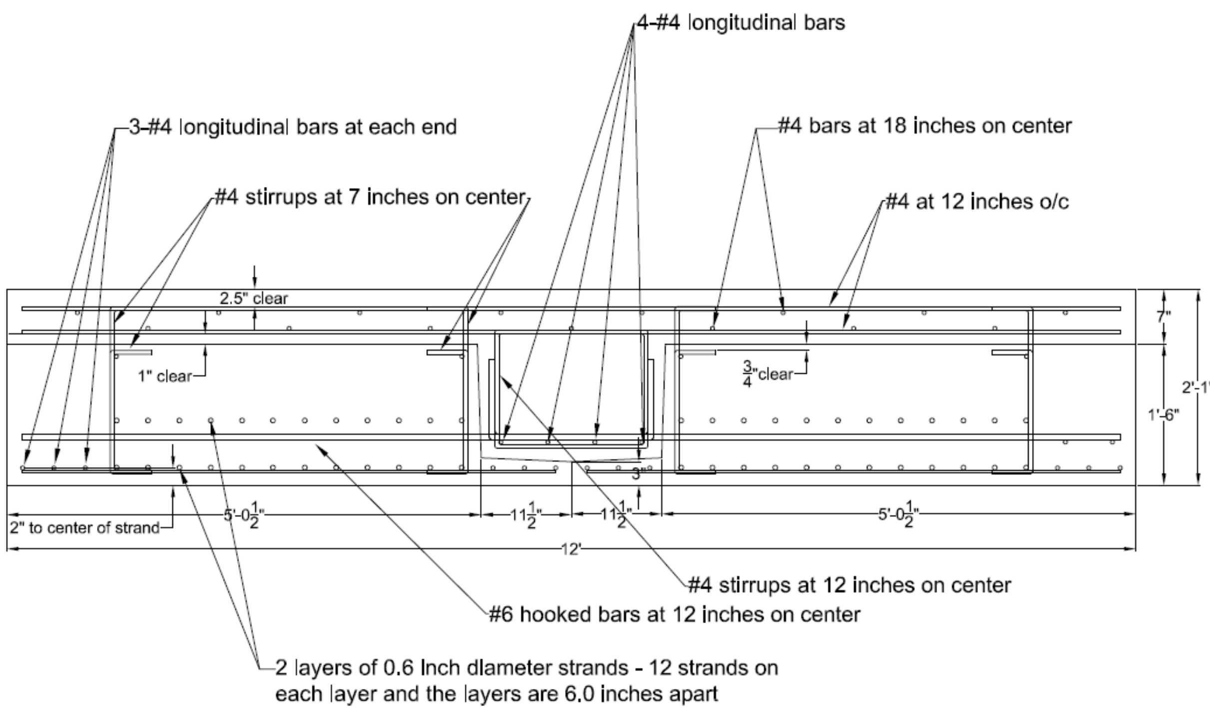


Fig. 15 Reinforcing Details for Test Specimen #1 – Straight web cross-sectional shape with extended bars

SPECIMEN #2 – STRAIGHT WEB WITH EMBEDDED PLATE CONNECTION

The specimen illustrated in Figure 16 is identified as “straight web with embedded plate connection” and has the same cross-sectional shape for the precast component. However, it does not have any reinforcing steel protruding from the webs of the precast inverted T-beams. Instead, the flanges of the inverted T-beams are connected by field welding a 6 in. long piece of reinforcing steel (ASTM A706) to an embedded steel plate (ASTM A36) 3 in. x 6 in. x 3/8 in. on the face of the flange which is slightly tapered to receive the “drop-in” piece of rebar. Each embedded steel plate on the face of the flange of the precast inverted T-beams is then welded to 2- No. 6 bars spaced 3 in. apart which run for the entire width of the precast inverted T and are welded to the embedded steel plate on the other side. A similar application of this detail can be found in precast parking garages between the flanges of double T’s. One advantage of this detail is the shift in location of the tension tie towards the bottom of the precast, where the tensile stresses as a result of transverse bending are maximum. So, instead of having a complete separation between the flanges of the precast inverted T-beams this detail connects them together and eliminates the joint.

Another advantage of this detail is the relative ease of forming the precast inverted T-beams when compared to the original French detail, in which the forms need to accommodate the protruding bars. One of the disadvantages of the system is the field welding, which goes against the concept of accelerating bridge construction since it adds an operation which needs to be done in the field. The welding process used has a great influence on the time required to perform the weld between the “drop-in” bar and the embedded steel plates on each face of the inverted T-beam flanges. The first welded connection was done using the Shielded Metal Arc Welding (SMAW) process and it took about 30 minutes to complete. The rest of the welded connections were done using the Gas Metal Arc Welding (GMAW) process and they took about 5 minutes per connection. Clearly the GMAW process is recommended for application in the field since it saves considerable time.

Another disadvantage of this detail is the fact that the bottom of the embedded steel plate is flush with the bottom of the precast inverted T-beam. Therefore, it is potentially exposed to atmospheric corrosion. However, this problem could be alleviated by using galvanized embedded steel plates and re-painting the field welded area with a galvanizing paint after the field welding is performed to repair the damage. Finally, the orientation of the embedded steel plate is inclined so that it can receive the “drop-in” bar as well as accommodate any differences in elevation due to construction tolerances between the precast inverted T-beams. The size of the transverse bars in the flange of the precast inverted T-beams was determined such that they would resist the entire tensile force created as a result of transverse bending. This tensile force was calculated as the volume under the triangular tensile prism which was obtained from the Finite Element Analysis.

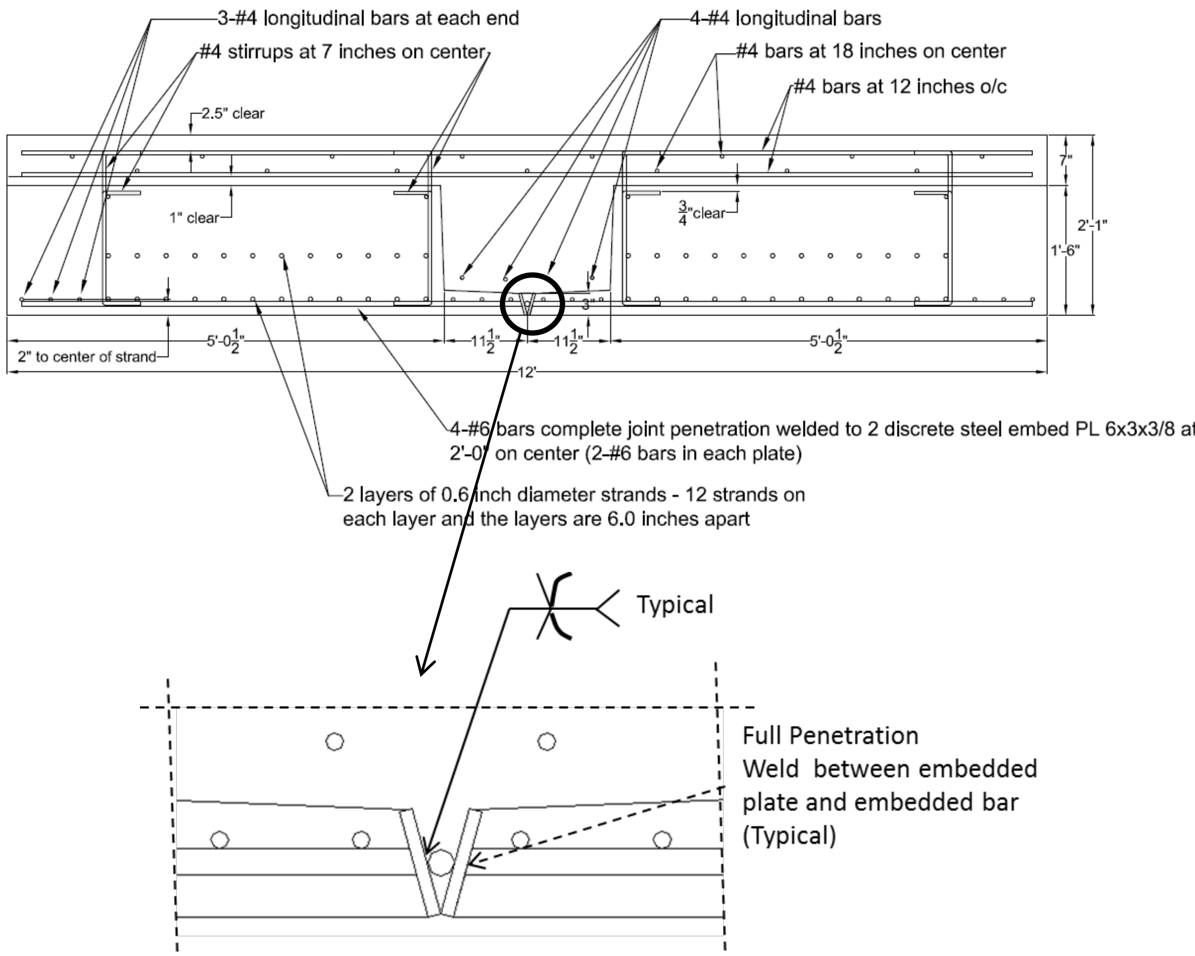


Fig. 16 Reinforcing Details for Test Specimen #2 – Straight web cross-sectional shape with embed plate connection

SPECIMEN #3 – TAPERED WEB WITH EMBEDDED PLATE CONNECTION

The specimen shown in Figure 17 is identified as “tapered web with embed plate connection”. The connection between the flanges of the inverted T-beams is identical to the one used in the specimen shown in Figure 16. The difference between these two specimens is the shape of the cross-section for the precast inverted T-beam. The specimen in Figure 17 has a tapered cross-sectional shape. Another difference is that the bottom layer of deck steel in this case is detailed such that it follows the shape of the cast-in-place topping as opposed to the specimen with the straight web and embedded steel plate connection where this layer was straight. The criterion for selecting the transverse reinforcing in the flange of the precast inverted T is the same with the one used in Specimen #2.

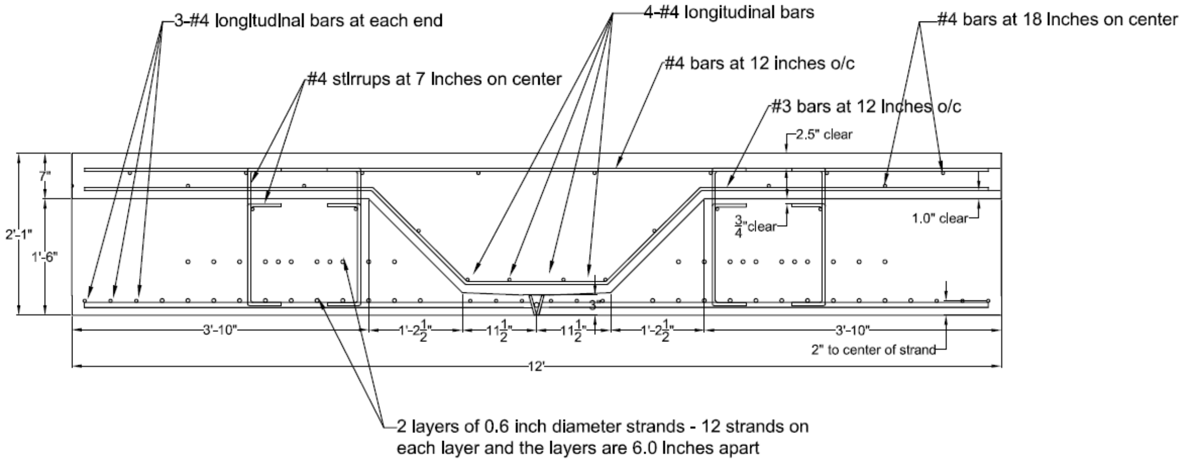


Fig. 17 Reinforcing Details for Test Specimen #3 – Tapered web cross-sectional shape with embed plate connection

SPECIMEN #4 – TAPERED WEB NO CONNECTION

Finally, the specimen shown in Figure 18 is identified as "tapered web no connection" and it differs from the other specimens since it has no mechanical connection between the inverted T-beams and the cast-in-place topping. So it is believed that composite action in the transverse direction, in the region above the joint, will be achieved due to the bond between the roughened surface in the precast inverted T and the cast-in-place topping. The selection of the bottom layer of reinforcing for the cast-in-place topping was based on the criteria that enough reinforcing should be provided to resists the tensile force created by transverse bending ignoring any contribution from the concrete. This is the same criterion used to size the transverse reinforcing in the flange of the precast inverted T-beams for Specimen #2 and #3. The transverse reinforcing in the flanges of the precast inverted T-beams, however, was only designed to resist the weight of the wet cast-in-place concrete topping and not to resist the tensile force created by the transverse bending action as it was the case in Specimen #2 and #3. So in this specimen, as one can see, a complete tension tie can be developed only if the tensile force resisted by the bottom layer of bars in the deepest portion of the cast-in-place topping (No. 6 at 12 in. on center) can be transferred via a non-contact splice to the transverse bars in the precast inverted T-beam (No. 3 at 18 in. on center). Clearly the weak link in this case is the flexural capacity of the composite section in the transverse direction provided primarily by the No. 3 at 18 in. on center.

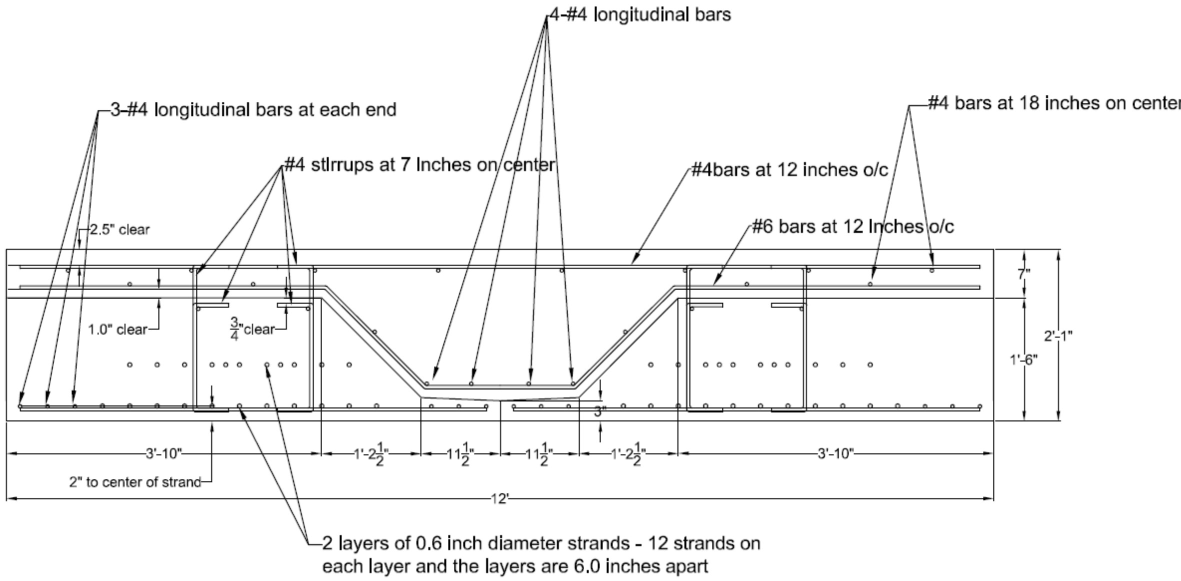


Fig. 18 Reinforcing Details for Test Specimen #4 – Tapered web cross-sectional shape with no connection

TEST PROTOCOL

Each specimen was loaded in increments of 5 kips up to 30 kips, which is approximately equal to the load that creates transverse flexural stresses over the joint of the simply supported beam setup that are similar to the ones created by the design live load in the future bridge . After that, the load increment was increased to 10 kips up to the first noticeable crack. The width of the first crack was recorded and the specimens were subjected to five cycles of loading with the maximum load being the load that caused the first crack. At the end of five cycles the crack width was re-measured with a microscope to determine whether there was any increase in the crack width. The crack length was also monitored to determine whether the crack propagated as a result of cyclic loading. Then the specimen was subject to three more cycles and the procedure was repeated. This was done for the 9th and 10th cycle as well, at the end of which the cyclic loading was terminated if it were determined that there was no increase in crack width or any crack propagation. If at the end of the 10th cycle the specimen showed signs of crack growth or propagation then the specimen was subjected to one additional cycle until crack stability was achieved. After the cyclic loading was terminated, the specimens were loaded up to failure or up until the capacity of the loading frame was reached. The capacity of the loading frame was 300 kips. The load step after the cyclic loading was 10 kips and at every load step the crack width was recorded and the crack pattern was marked on the specimens.

TEST RESULTS

The results of the four tests are summarized in Table 4. This table shows the first noticeable cracking load as well as the ratio of the first noticeable cracking moment to the moment creating the worst case transverse tensile stress in the bridge. The moment that creates the worst case transverse tensile stress in the bridge was calculated by first obtaining the worst case transverse tensile stress from the finite element model. This stress was then used to back calculate the corresponding moment. This moment will be referred to as the service level load. In addition the last column of Table 4 shows the ultimate load, which as explained earlier was either the load at which the specimen could not take anymore load or the capacity of the loading frame. In the case of the specimen with the tapered web and embedded plate connection the ultimate load could not be achieved because the capacity of the loading frame was reached before the specimen failed. Figure 19 shows the relationship between the load and the deflection at mid-span for all four specimens.

The results presented in Table 4 and Figure 19 can be interpreted from different perspectives. For example, if the ultimate load that each specimen was able to achieve and the corresponding stiffness (slope of the load-displacement curve) were considered, it can be concluded that the specimen with the straight web and the extended bars and the specimen with the tapered web and the embedded plate connection performed relatively better than the other two specimens, since they achieved higher ultimate loads. The specimen with the tapered web and embedded plate connection never achieved its ultimate load due to the capacity of the loading frame. However, such a relative comparison is not really useful or practical since the ultimate loads for these two specimens were at least six times the service level load.

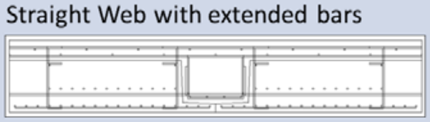
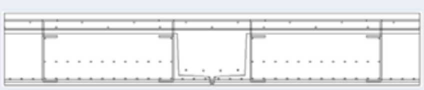
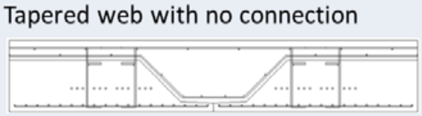
Alternatively, if the results were analyzed by considering the load displacement relationship up to the first crack, which is illustrated in Figure 20, then it can be seen that all specimens performed similarly.

Even the specimen which had a tapered web and no mechanical connection between the precast components and the cast-in-place topping had its first crack at a load that was 1.8 times the corresponding service level load. So, for all practical reasons the detail used in this specimen appears to be suitable for implementation since it is the least expensive one and the easiest to fabricate. This is due to the fact that it does not have any reinforcing steel protruding from the sides of the webs, which present a forming challenge to the precaster. It also does not have any mechanical connection between the precast members, which might take additional time in the field and work against the concept of accelerating bridge construction. In addition, the ultimate failure mode of this specimen was a large crack in the precast component at a load equal to 90 kips which is 2.5 times the equivalent service level load. This was due to the fact that the transverse reinforcing steel in the flanges of the precast component consisted only of No. 3 at 18 in. on center. Therefore this failure load is expected to increase by using bigger size bars and closer spacing.

From a durability standpoint the specimen with the straight web and extended bars, as well as the specimen with tapered web and no connection, have the advantage of not having any components subject to atmospheric corrosion, which is the case in both specimens with the embedded plate connection. However, this disadvantage may be overcome by galvanizing the steel plates. If the goal is to achieve the highest ultimate load then clearly the detail used in the specimen with the tapered web and the embedded plate connection is the one that will most likely fulfill that goal.

Another interesting aspect of these test results is the deflected shape of all four specimens. Wirepots were installed at the bottom of the specimens near the supports at quarter points and at mid-span to obtain the deflected shape of the specimens and to determine whether they would deflect as two rigid bodies hinged at mid-span, where there is a joint between the flanges of the inverted T-beams, or whether they would deflect as one monolithic body. The bearing condition at the supports consisted of neoprene bearing pads. Figures 21 through 24 illustrate the deformed shape of the four tested specimens based on the deflections recorded from the wirepots. As can be seen, these deformed shapes are closer to the behavior of a monolithic beam than that of two independent rigid bodies. This provides evidence that the inverted T-beam concept can deliver the advantages of jointless, monolithic, cast-in-place concrete construction while saving time in the field by eliminating the need for constructing formwork.

Table 4. Cracking loads and ultimate failure loads for all four test specimens and a comparison with the service level load.

Specimen Description	Cracking Load (kips)*	Ratio**	Ultimate Load (kips)
Straight Web with extended bars 	**90**	**2.5**	**260** Many cracks in all directions
Straight web with embedded plate connection 	**100**	**2.7**	**225** Fracture of weld at one location and rebar at another
Tapered web with embedded plate connection 	**110**	**3.0**	Test stopped at **300** due to capacity of the loading frame.
Tapered web with no connection 	**60**	**1.8**	**90** (Large Crack Through Precast Section)

* First noticeable crack
** Ratio of cracking moment to moment creating the maximum transverse tensile stress in the bridge

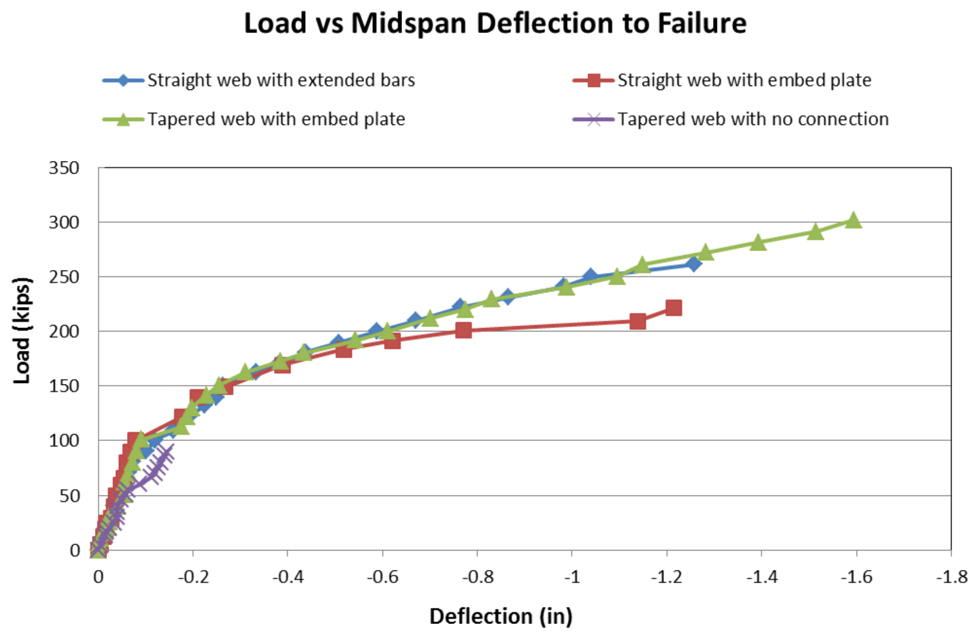


Fig. 19 Comparison of Load Deflection Curves for all four test specimens

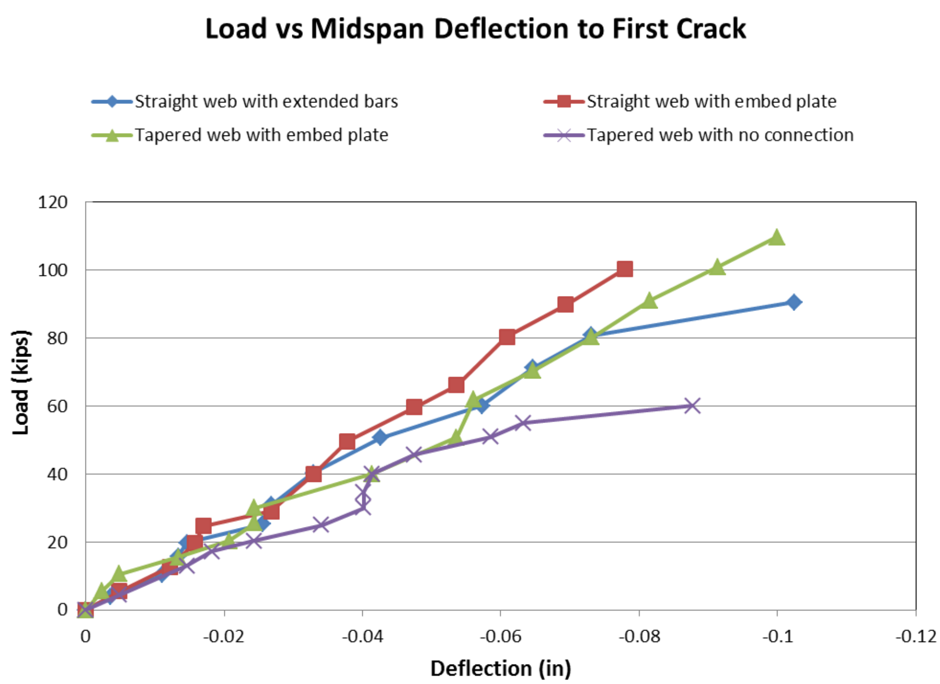


Fig. 20 Comparison of Load Deflection Curves for all four specimens up approximately first crack.

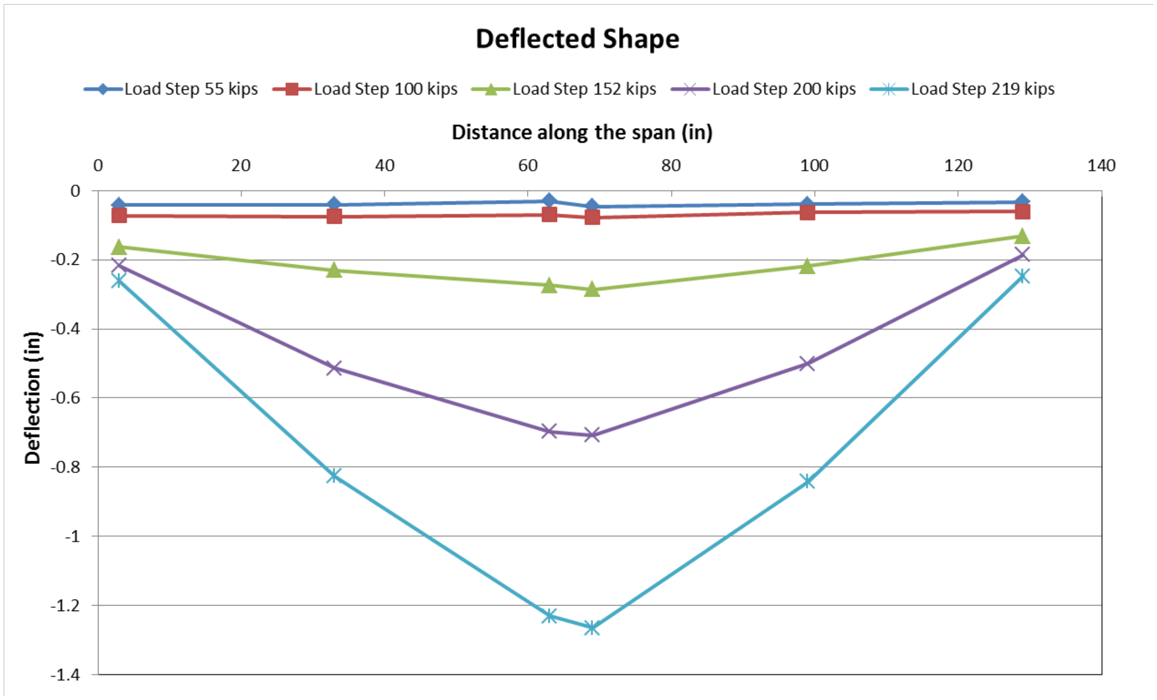


Fig. 21 Deflected shape for the specimen with the straight web and embedded plate connection for various load steps

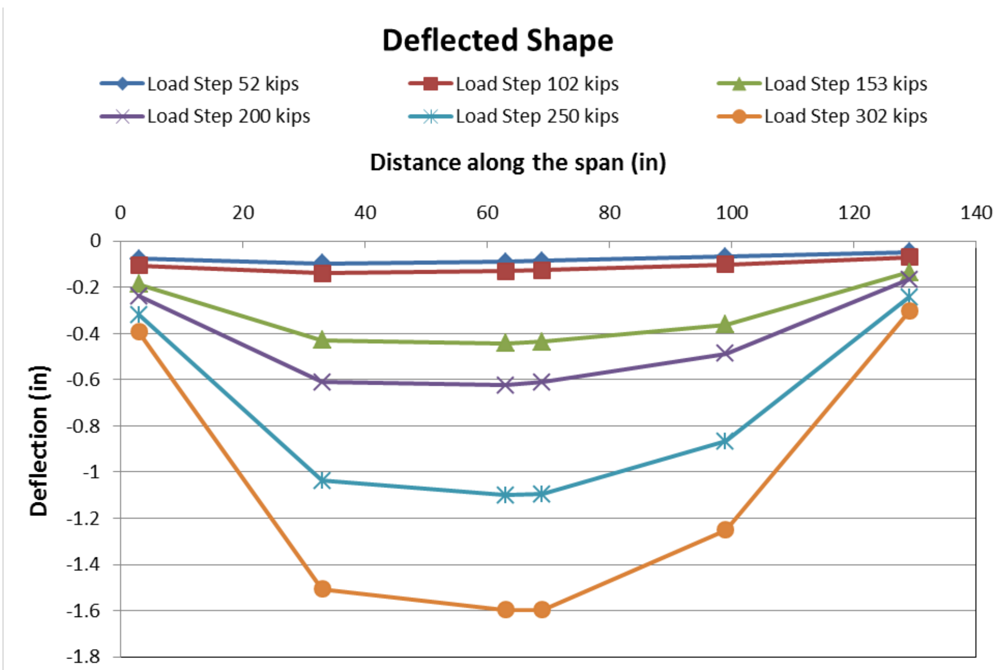


Fig. 22 Deflected shape of the specimen with tapered web and embedded plate connection for various load steps

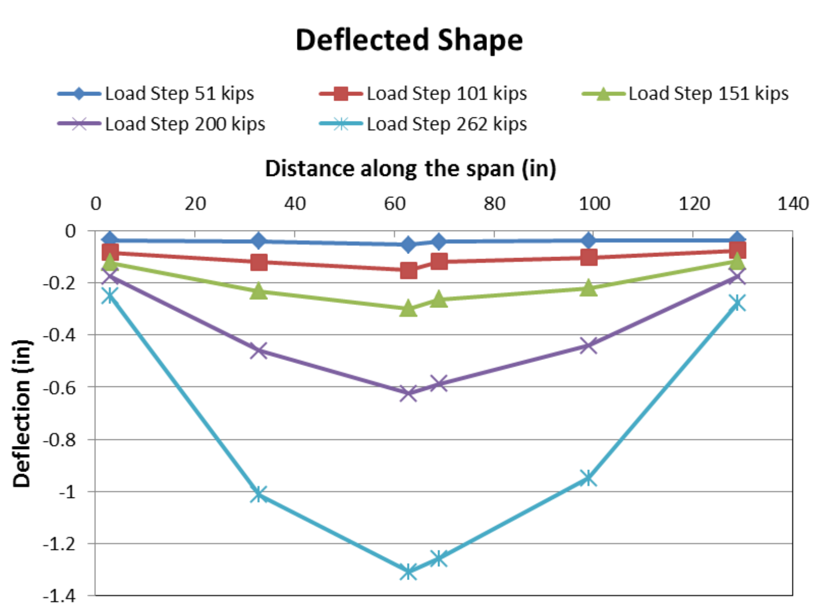


Fig. 23 Deflected shape of the specimen with straight web and extended bars for various load steps

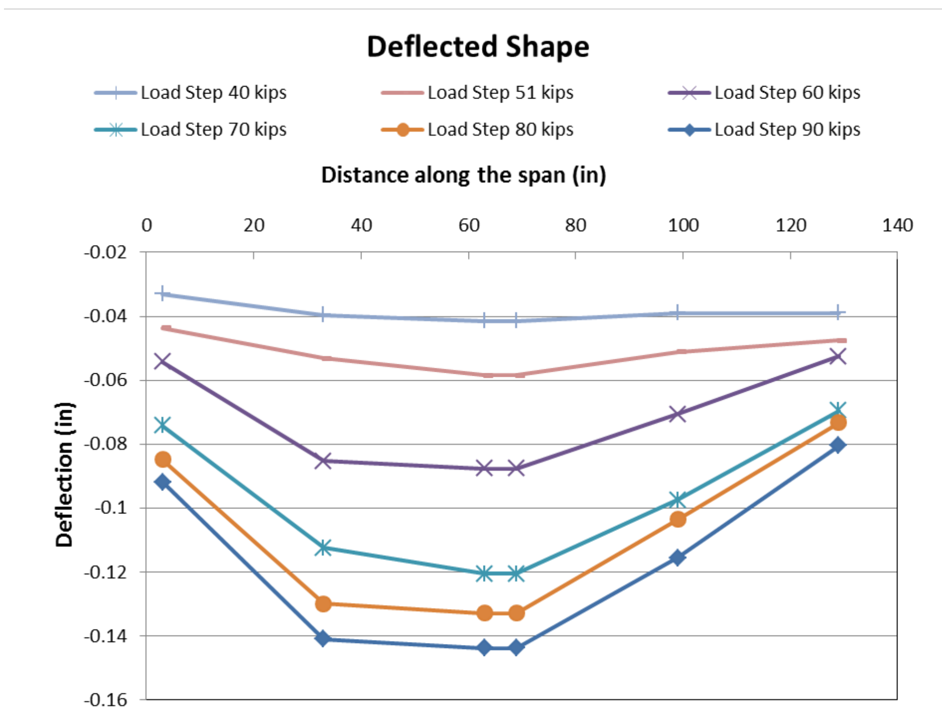


Fig. 24 Deflected shape of the specimen with the tapered web and no physical connection between the precast components and the cast-in-place topping for various load steps

CONCLUSIONS

The inverted T-beam concept is a useful and promising concept for short to medium span bridges which delivers the advantages of jointless, cast-in-place, concrete construction while eliminating the need for installing formwork. Tapering the webs of the inverted T-beams to reduce sharp angles at the re-entrant corners and placing them side-by-side appears to provide the necessary integrity to prevent cracking due to service level loads as a result of plate bending in the transverse direction. This detail is the least expensive one and the easiest to fabricate. This is due to the fact that it does not have any reinforcing steel protruding from the sides of the webs, which present a forming challenge to the precaster. It also does not have any mechanical connection between the precast members, which might take additional time in the field and work against the concept of accelerating bridge construction. Finally, the ultimate failure mode was a large crack in the precast component at a load equal to 90 kips which is 2.5 times the equivalent service level load. The ultimate capacity is expected to increase by using bigger size bars and closer spacing.

RECOMMENDATIONS FOR FUTURE RESEARCH

The detail in which the precast inverted T has a tapered web and no mechanical connection between the flanges of the precast inverted T-beams and the cast-in-place topping appears to provide adequate performance when subjected to design loads. It is believed that this detail can be further improved with minimal cost by increasing the size and reducing the spacing of the transverse reinforcing in the flanges of the precast inverted T-beams. To investigate this effect two more tests are scheduled for the summer of 2012. In addition, even though the magnitude of the vertical shear stresses in the transverse direction were minimal, another test, which will consist of a single point load, is scheduled to be conducted in the Summer of 2012 to determine whether the presence of shear will have any detrimental effect in the performance of the specimen. Other aspects of the inverted T-beam system include composite action in the longitudinal direction and overall system behavior which are planned to be investigated in the course of the following year.

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