DEVELOPMENT OF MINNESOTA'S LONG SPAN PRESTRESSED "MW" GIRDERS

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ABSTRACT

In 2011, the Minnesota Department of Transportation developed standard plan details for 82 inch and 96 inch deep prestressed "I" shape concrete beams. The goal of the project was to produce high quality, low maintenance beams that are economical for the 150 to 200 foot span range. The development process included investigation of similar beams used by other agencies as well as collaboration with fabricators, contractors, and shipping companies to ensure serviceability, maintenance and delivery of the beams. Issues considered included flange widths for stability, top flange thicknesses for minimizing future damage during deck removal, bottom flange thickness for maximizing strand capacity, and updating associated details considering design, fabrication, and construction concerns. Fabricator and shipping limitations were determined with industry input. To best meet the needs of all involved parties, some constraints were put on the design of the beams, and fabricators made upgrades to equipment as a long term investment. In the future, additional details will be developed to allow the beams to be spliced and post-tensioned for greater span lengths.

Keywords: Creative/Innovative Solutions and Structures

INTRODUCTION

The Minnesota Department of Transportation (MnDOT) has been designing and building bridges using precast, prestressed beams since the late 1950s. Currently, prestressed beams make up 70 to 80 percent of the state's new bridges. Over that time, MnDOT has worked with the fabricators that produce beams in Minnesota to continue to improve the quality and efficiency of the beams that are used. Part of the process has been developing new standard shapes that allow for longer spans or fewer beams for a given beam depth. This paper will discuss the development of the beams designed to span 150 to 200 feet known as the "MW" shapes. Two standards were developed, a 96 inch deep beam (96MW) and an 82 inch deep beam (82MW).

The development process included investigation of similar beams used by other agencies as well as collaboration with fabricators, contractors, and shipping companies to ensure serviceability, maintenance and delivery of the beams. MnDOT bridge design, bridge construction, bridge rating, and materials personnel were involved in the development of the sections. The process followed was similar to that described in Bardow et. al[3] regarding the development of the New England Bulb-Tee Girder and in Seguirant[4] regarding the Washington State Department of Transportation (WSDOT) deep standard beam sections.

Prior to the development of the new "MW" beams, MnDOT had two standard beam shapes in use. The "M" sections ranged in depth from 27 inches to 81 inches. The "MN" sections ranged in depth from 45 inches to 63 inches[1]. The "MN" series sections are more efficient than the "M" series at a given depth due to wider top and bottom flanges, an additional half inch in web thickness, and the capability to add 10 additional straight strands.

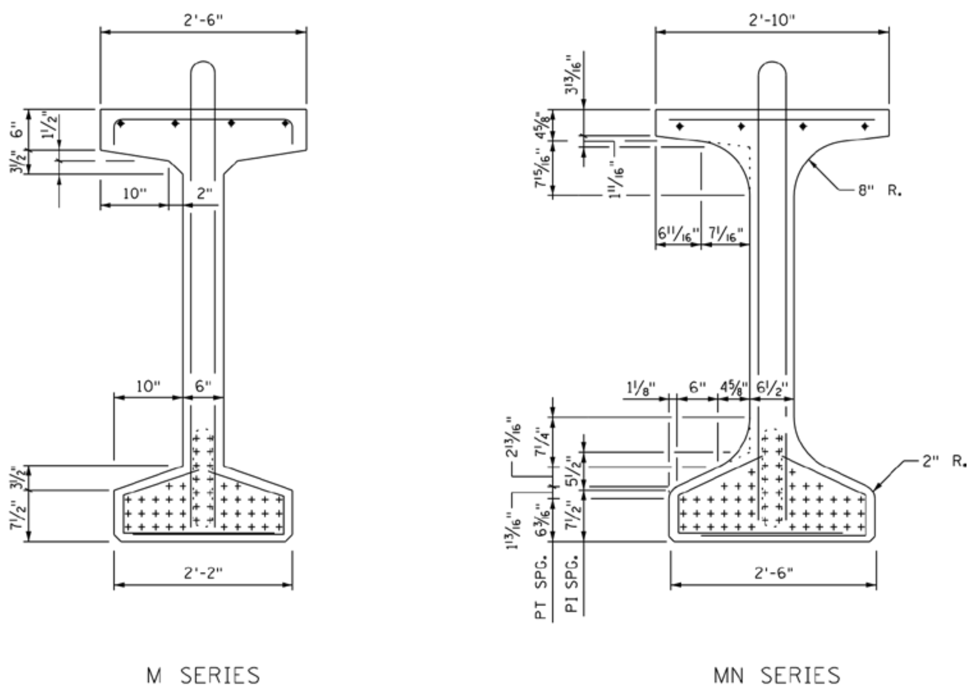


Fig. 1 "M" and "MN" Standard Prestress Girder Shapes[2]

SECTION DEVELOPMENT

REFERENCE MATERIALS

As a starting point, MnDOT investigated several deep prestressed beams which have been standardized by other states. These include the Nebraska NU2400[5], the Northeast Bulb-Tee NEBT 2200[6], the Utah 2400[7], and the Washington WF95G girders. In addition, the existing MN series of beams was used to help generate the new shapes. After comparing the features of each, three beam shapes were chosen to review for design capacity and efficiency. The first was the Utah beam shape utilized in their design-build program. The other two were based on the existing MN series, and were referred to as the Minnesota (1) and Minnesota (2).

GEOMETRY

Based on an immediate project demand and the standards developed by other states, MnDOT started an investigation of a 96 inch deep beam (96MW). In addition to the 96MW, MnDOT wanted to design a more efficient beam as a replacement for the 81M. Using a 14 inch step between beam sizes led to the development of an 82 inch deep beam (82MW) and the long range plan for a 110 inch beam (110MWPT) that was to be spliced and post-tensioned. The new beams are an inch deeper than the 81Ms they are intended to replace. Although at first there was concern about the ability to replace an 81M with an 82MW in the case of damage to the beam, the committee was comfortable making up the difference in potential haunch height, rather than requiring the new beam to be 81 inches deep. The 96MW and the 82MW have identical flanges. The only difference in the shapes is the depth of the web. Web thickness was constant across all of the preliminary sections under consideration with a 6½" thick web. The hold-down points for the preliminary designs were taken at the four-tenths and six-tenths points. The primary variables were the top and bottom flanges.

A relatively wide top flange was preferable to increase the lateral stability of the beams, especially during the fabrication, shipping, and erection stages. Based on a review of the four beam sections from other states that had been successfully utilized, a minimum 48 inch wide top flange was chosen. To reduce the risk of top flange damage during construction or rehabilitation, MnDOT wanted a moderately thick top flange. Damage to the top flange would cause a change to the beam and composite section properties. Previous experience has shown that flange damage is time consuming to repair and at times has required beam replacement. For example, the NU girder's 2½ inch flange tip dimension, while potentially more efficient due to a reduction in beam weight, was considered too thin to withstand damage during a potential deck replacement. The Utah girder used a 50 inch wide, 3 inch thick flange with fillet transitions to the web, while the two Minnesota shapes used a 48 inch wide, 3½ inch thick top flange with radiused transitions. The two Minnesota shapes were developed by continuing the slope of the bottom of the top flange using the existing "MN" series of beam to a total flange width of 48 inches. The Minnesota (1) kept the dimension of $2^{9}/_{16}$" based on the slope from the tip of the flange to the theoretical intersection point between the sloped bottom of the flange and the web. The Minnesota (2) rounded the dimension to 2½”.

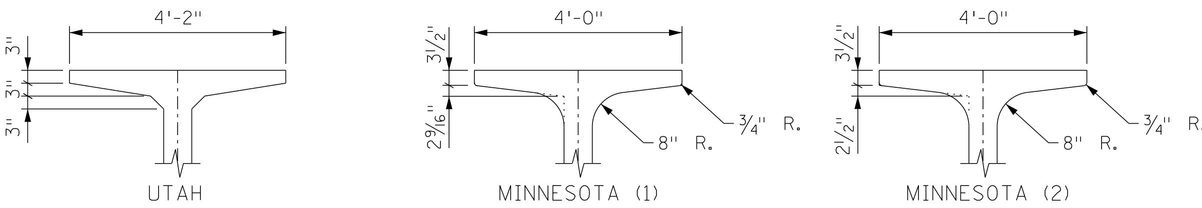


Fig. 2: Top Flanges of Preliminary Shapes

The bottom flange from the Utah shape was 40 inches wide and a slender 5 inches thick. The two Minnesota shapes used a 39 inch bottom flange width. Although a 38 inch width had been considered, the extra inch of width allowed for additional cover for the reinforcement without having to reduce the number of strands in the bottom flange. The primary difference between the Minnesota (1) and the Minnesota (2) was in the thickness of the bottom flange. The Minnesota (1) used a thicker 5½ inch bottom flange, which allowed for more strands, while the Minnesota (2) used a 5¼ inch flange, which made for a lighter section.

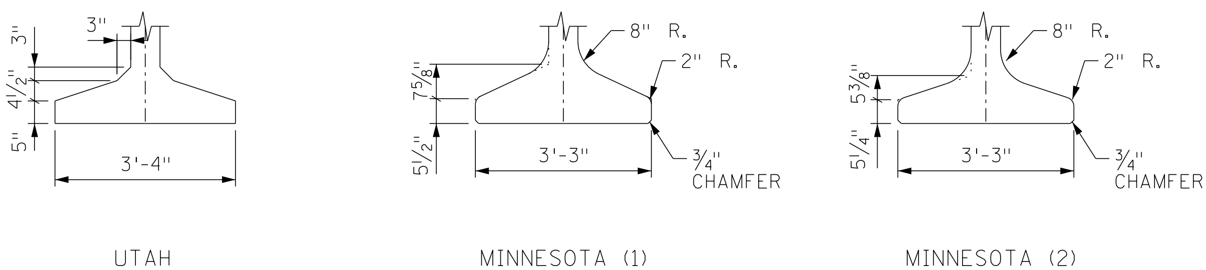


Fig. 3: Bottom Flanges of Preliminary Shapes

Table 1 shows a comparison of the section properties for all three of the preliminary shapes for the 96 inch beam. Although there was some early concern that the additional weight of the Minnesota (1) might lead to an inefficient design, the additional section modulus was determined to be a benefit.

Table 1: Section Properties of Preliminary Shapes

	Utah	**Minnesota (1)**	**Minnesota (2)**
Depth [in]	96	96	96
Area [in^2]	1,103	1,153	1,111
Centroid to Bottom [in]	46.25	45.02	46.29
Moment of Inertia [in^4]	1,427,550	1,486,510	1,431,730
Section Modulus (Top) [in^3]	28,694	29,159	28,802
Section Modulus (Bottom) [in^3]	30,866	33,019	30,930
Weight [lb/ft]	1,187	1,241	1,196

The Minnesota (1) is 4.5% and 3.8% heavier than the Utah and Minnesota (2) sections, respectively. However, the additional 7.0% and 6.8% bottom section modulus, along with the additional strand area proved to be beneficial in the effectiveness of the section.

MnDOT uses a 2 inch grid for strands in the bottom flange starting at two inches above the bottom of the beam. Draped strands must start at a minimum 3 inches from the bottom at the hold-downs and a minimum 3 inches from the top at the end of the beam. All three of the preliminary shapes used the same basic grid, shown in Fig. 4.

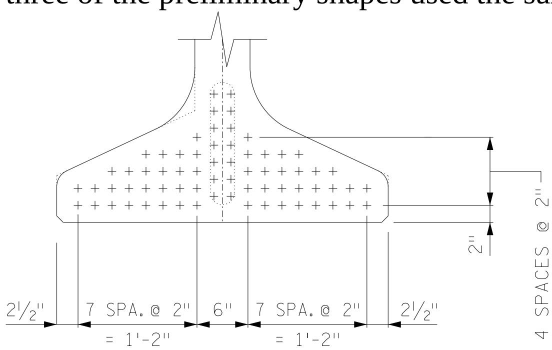


Fig. 4: Typical Strand Layout

The beam flange shown is the Minnesota (1). Fig. 5 and Table 2 show the layouts for each of the preliminary shapes. The thinner flanges of the Utah and Minnesota (2) beams had fewer spaces in the bottom flange to accommodate strands. All three sections had the capacity to fit 14 draped strands.

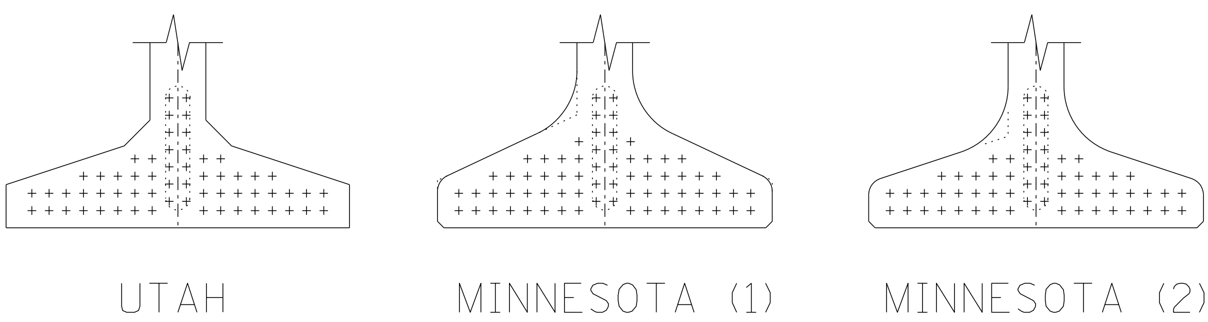


Fig. 5: Strand Layout of Preliminary Sections

Table 2: Available Strands in Preliminary Beams

	Utah	**Minnesota (1)**	**Minnesota (2)**
Straight	46	54	46
Draped	14	14	14
Total	**60**	**68**	**60**

DESIGN CRITERIA

Material Properties

Although the shape of the beams is new, MnDOT's existing policy for concrete strengths and strand diameters has not changed substantially. Concrete strength at release is limited to 7.5 ksi, with 7.0 ksi preferred. Preliminary design charts were done using 9 ksi concrete final beam strength. Based on the typical strengths found in the concrete being used by the fabricators, designers are permitted to design for final strengths of 10 ksi with special authorization. Deck concrete has a compressive strength of 4 ksi. Concrete weight is assumed to be 0.155 kcf for beam concrete and 0.150 kcf for all other concrete. Strands are 0.6" diameter low-relaxation 7-wire, as in the current standards for "M" and "MN" series beams. The mild reinforcement used in the beams is epoxy coated Grade 60 rebar. Welded-wire reinforcement is not used in the standards.

Additional Design Criteria

The design criteria used to develop the preliminary span capability envelopes are as follows:

1. 2010 AASHTO LRFD Bridge Design Specifications[8]
2. HL-93 Vehicular Live Load, including 33% dynamic load allowance applied on truck loading
3. 9 inch deck thickness with ½" loss for wear in determining section properties
4. 1½" haunch height for section properties; 2½" haunch height for dead load
5. 20 psf future wearing surface allowance
6. Girder spacing between 5 feet and 13 feet
7. Losses computed by the approximate method specified in AASHTO Article 5.9.5.3.

DESIGN METHOD

A series of designs was done at 5 foot, 9 foot, and 13 foot spacing to determine the maximum span lengths each beam could achieve. At all investigated spacings, the Minnesota (1) was the most efficient shape, allowing for the longest spans, making it the obvious choice to become the 96MW. The same flange shape and strand pattern used in the 96MW are also used in the 82MW.

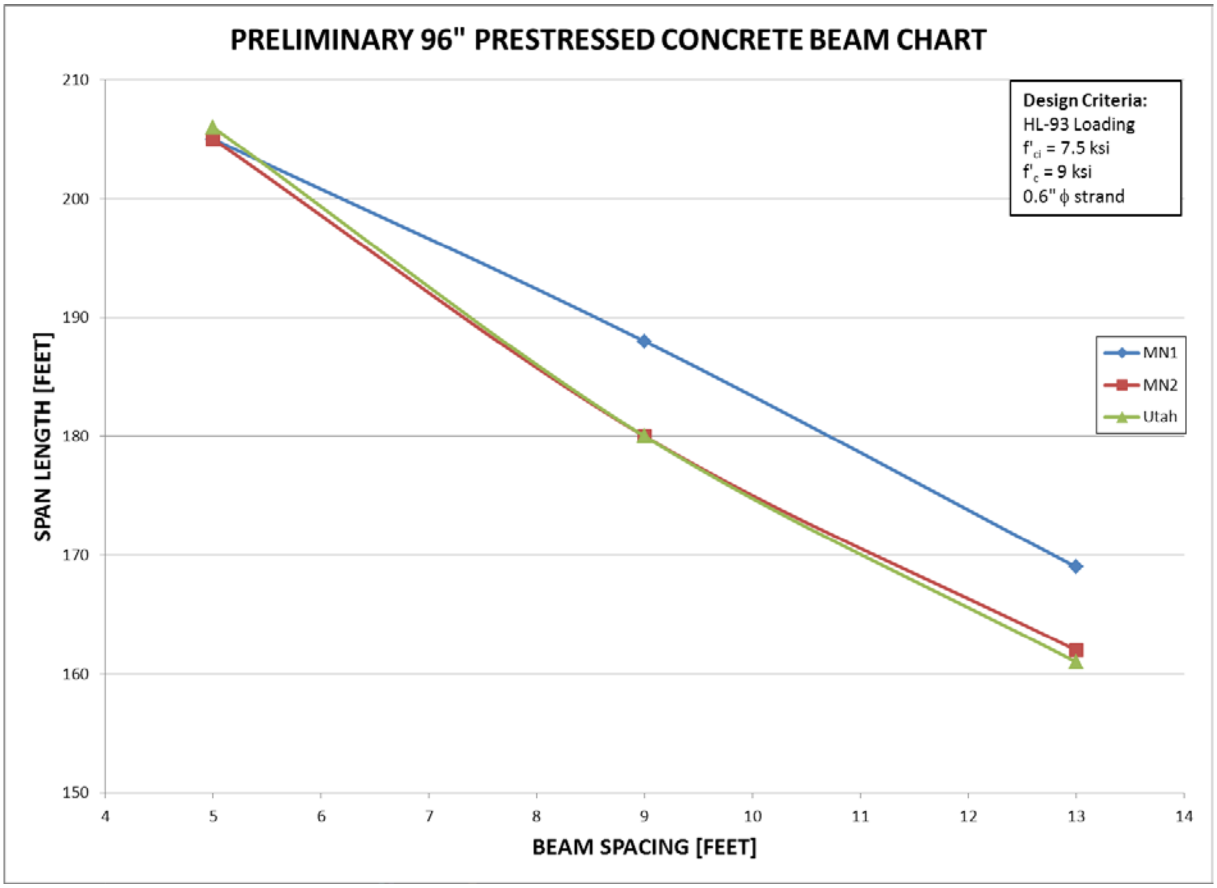


Fig. 6: Preliminary Beam Spacing vs. Span Length

Once the shape of the 96MW was finalized, designs were run in one foot increments for spacing. The beams are less effective at very tight spacing, because the design becomes compression controlled. The small effective flange area in compression requires the neutral axis to be deep in the web to balance out the prestressing force. Although technically the beams could be used at spacings as tight 5 feet, but given the 4 foot wide top flange, this spacing was seen as impractical. The guidance issued to designers limits the spacing to 6 feet, as this was deemed the tightest spacing that is both reasonable economically as well as constructible.

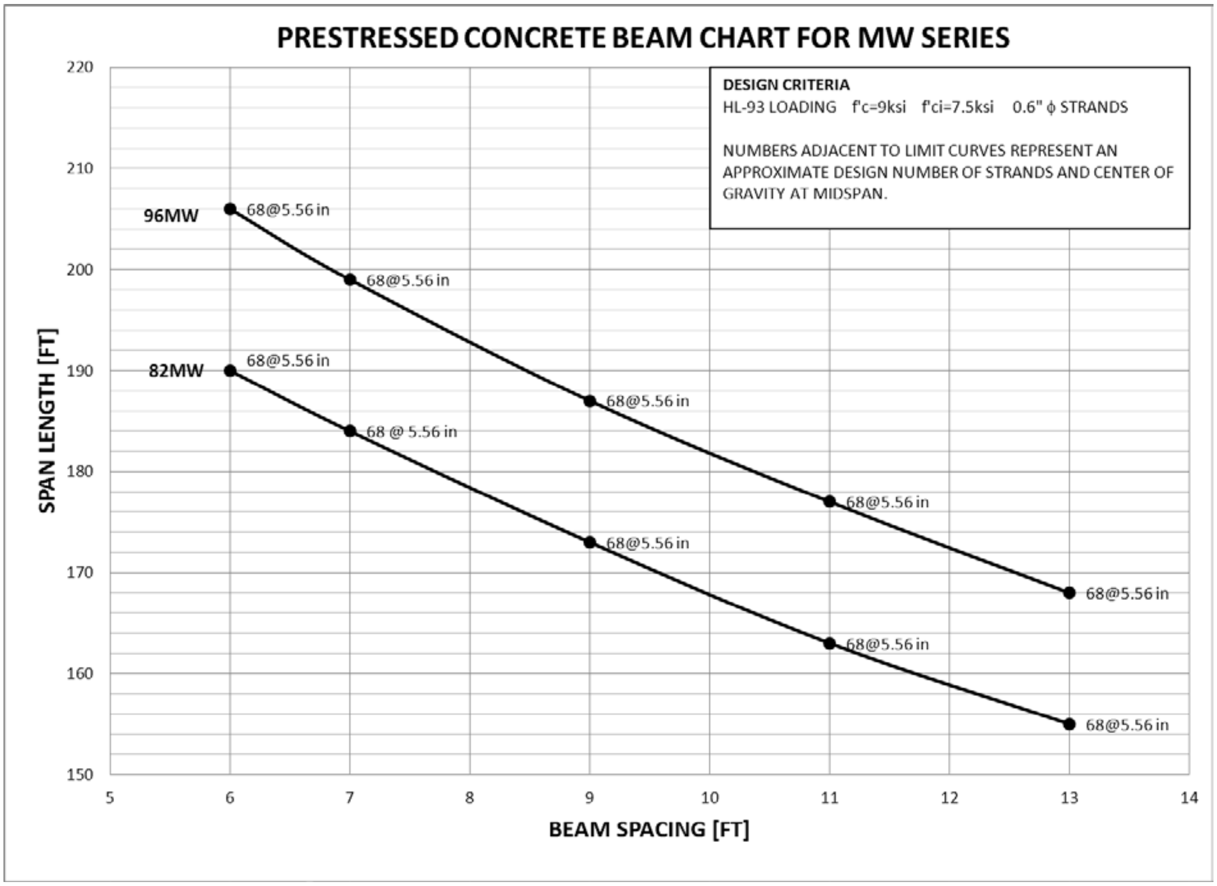


Fig. 7: Final MW Shape Beam Spacing vs. Span Length

FABRICATOR CONCERNS

In addition to the design process, throughout the development of the "MW" shapes, the decision considered concerns and input from fabricators. With a maximum of 68 strands, fabricators needed to have the capacity to pull 2,988 kips. All of the fabricators indicated that their capacity is at or above 3,000 kips, so the number of strands used was acceptable to them.

The next issue that was investigated was the ability of the precasters to handle the beams in their facilities. One of the fabricators expressed concern about exceeding the 100 ton crane capacity available at their facility. Limiting the weight of the beams to 100 tons would have limited the total beam length for the 96MW to approximately 161 feet. This would not allow the full potential of this new shape. MnDOT sees prestressed beams as the high quality, low maintenance, and least cost option for bridges. In order to also be an economical option in the 150 to 200 foot span range, fabricators agreed to upgrade equipment as necessary.

Delivery of the beams was a concern raised by MnDOT and the fabricators. The precasters agreed to coordinate with their shipping companies to determine if the additional weight and length could be accommodated. The shipping companies agreed that given the weights and lengths that were under consideration, they expected to be able to deliver the beams to projects around the state. Shipping routes and permits still need to be scrutinized with each project to ensure that the site-specific conditions do not prevent successful delivery.

Lateral stability issues can occur during the handling and transportation of very long beams. If there is too much lateral movement, lateral bending and possibly cracking in the top flange may occur. For MnDOT projects, the responsibility of successful delivery of the long span beams is entirely on the contractor and fabricator. To aid the fabricators, the "MW" standards allow for two of the longitudinal reinforcing bars in the top flange to be replaced by two ½ inch diameter straight strands pulled to a tension of up to 5 kips. Three inch diameter sleeves through the web to accommodate hauling chain connections are also part of the standard drawings. The locations of these holes are left to the discretion of the contractor, provided minimum distances from the edge of the beam and strand locations are met. This flexibility allows fabricators to meet the needs required by both the design and delivery processes.

DETAILING CONSIDERATIONS

All of the "M" and "MN" shape beams use #4 (#13) bars as confinement steel in the bottom flange, as shown in Fig. 8. In order to provide space for 54 straight strands without having to further increase the width of the bottom flange, the detail was changed to #3 (#10) bars. This allowed more room in the corners for strands and did not encroach on the bottom cover, while still meeting the requirements in AASHTO Article 5.10.10.2. Additionally, by extending the legs on the #3 (#10) confinement steel, the #5 (#16) ties that were originally included to enclose the strands were able to be removed. These changes not only allowed for additional strand area in the bottom flange, but the fabricators were pleased that the bar placement would be simplified.

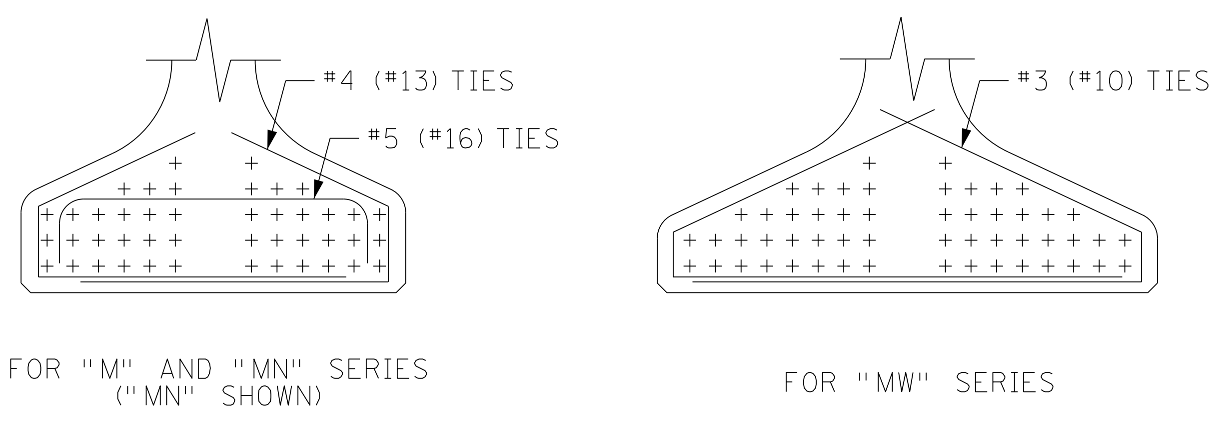


Fig. 8: Confinement Reinforcement

The shear stirrup spacing was adjusted to match the confinement steel. Where 6 inch maximum spacing for confinement was not necessary, shear stirrup maximum spacing was defined to meet the interface shear requirements per AASHTO Equation 5.8.4.4-1.

In addition to changing the interface shear requirements, increasing the top flange width from 2'-10" in the "MN" series of beams to 4'-0" in the "MW" beams necessitated adding additional longitudinal reinforcement to the top flange. In order to keep a similar spacing, two additional #8 (#25) bars were added to the top flange. MnDOT allowed two of the bars to be replaced with ½ inch strand that has been pretensioned to up to 5 kips for transportation stability and facilitation of stirrup placement.

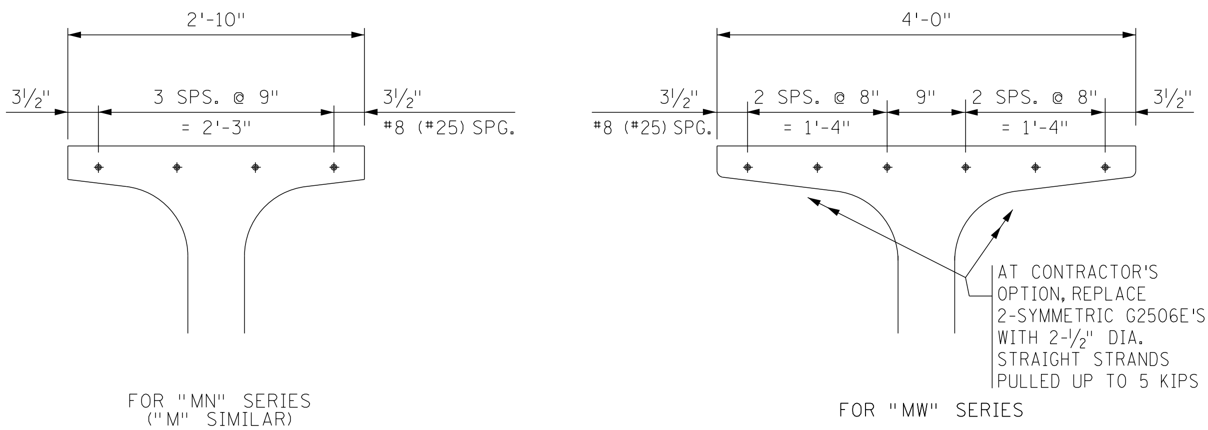


Fig. 9: Top Flange Longitudinal Reinforcement

MnDOT construction staff was concerned that on future redecking projects, the flanges of the beams would not be able to withstand the removal of the deck without suffering damage, even with very careful and labor intensive hand removal. The change was to apply a smooth trowel finish and a debonding agent on the outer 6 inches of each edge of the top flange to facilitate future deck removal. The goal of the debonding is to prevent the deck from adhering to the top flange, so deck removal can be done without impact to the thinnest part of the flange. Tests of materials demonstrated that the best debonding agent to use for this location is a waterproof sealant.

MODIFICATIONS TO OTHER STANDARD DETAILS

In addition to developing standard plan sheets for the beams, MnDOT set out to make all of the necessary changes to other standard plans and details that were related to the new beam size. Diaphragms, construction tolerance accommodation, and bearing design were all considered as part of the development of the new standards.

Intermediate diaphragm size and location was determined by meeting the diaphragm requirements of AASHTO Article 6.7.4. The purpose of the intermediate diaphragms is to transfer wind loads and provide stability to the beams prior to the hardening of the deck. Two checks were done on the compression members of the diaphragms: slenderness checks to meet AASHTO Article 6.9.3 and lateral torsional buckling stability requirements during deck placement[9].

Prior to the development of the "MW" shapes, MnDOT guidance for intermediate diaphragms stated that for spans under 45 feet no diaphragms were needed, one was needed at midspan for span lengths between 45 feet and 90 feet, and two evenly spaced diaphragms were necessary for spans exceeding 90 feet. Until the development of the new long span beams, there were very few cases where the span lengths so greatly exceeded 90 feet that an additional diaphragm would be warranted. In light of the new longer span possibilities, the guidance was changed to require an additional diaphragm for every additional 45 foot increment in span length rather than capping the requirement at two diaphragms and 90 foot spans. For spans under 135 feet, nothing has changed due to the development of the new beam standards.

Through investigation of the wind loads for beam spacings up to 13 feet, the angle sizes that had been used in the bolted diaphragm detail was increased from L6x4x5/16 and L6x6x3/8 to L6x6x1/2. The bent plates that connect the angles to the beams were also checked for adequate capacity at spacings up to 13 feet. For beam spacings exceeding 13 feet, a comprehensive design would need to be done to determine if the diaphragms as shown in the standard details was adequate.

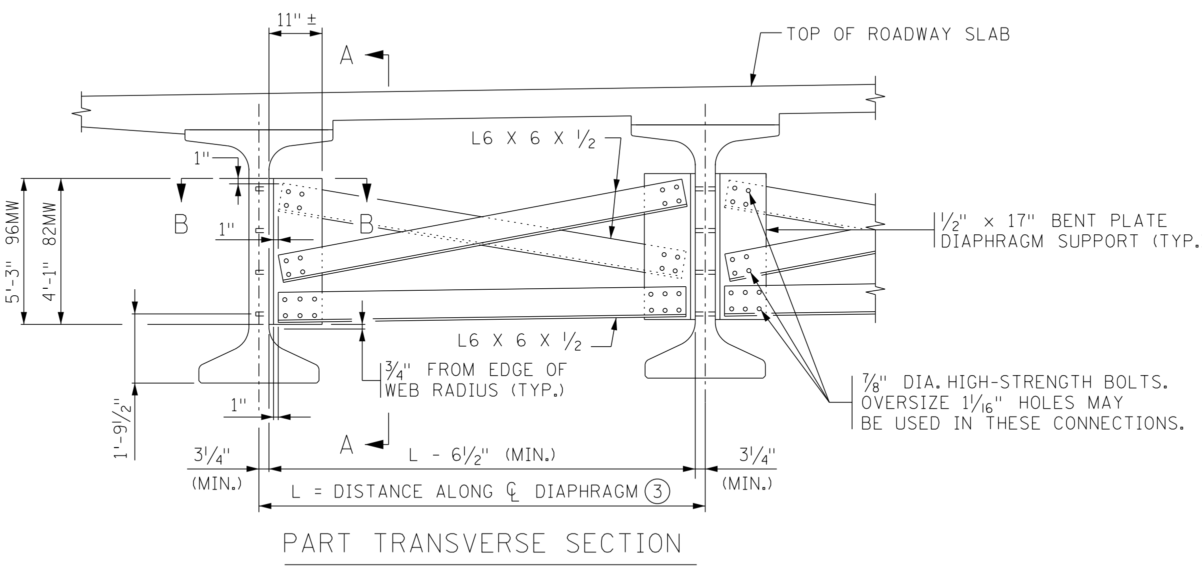
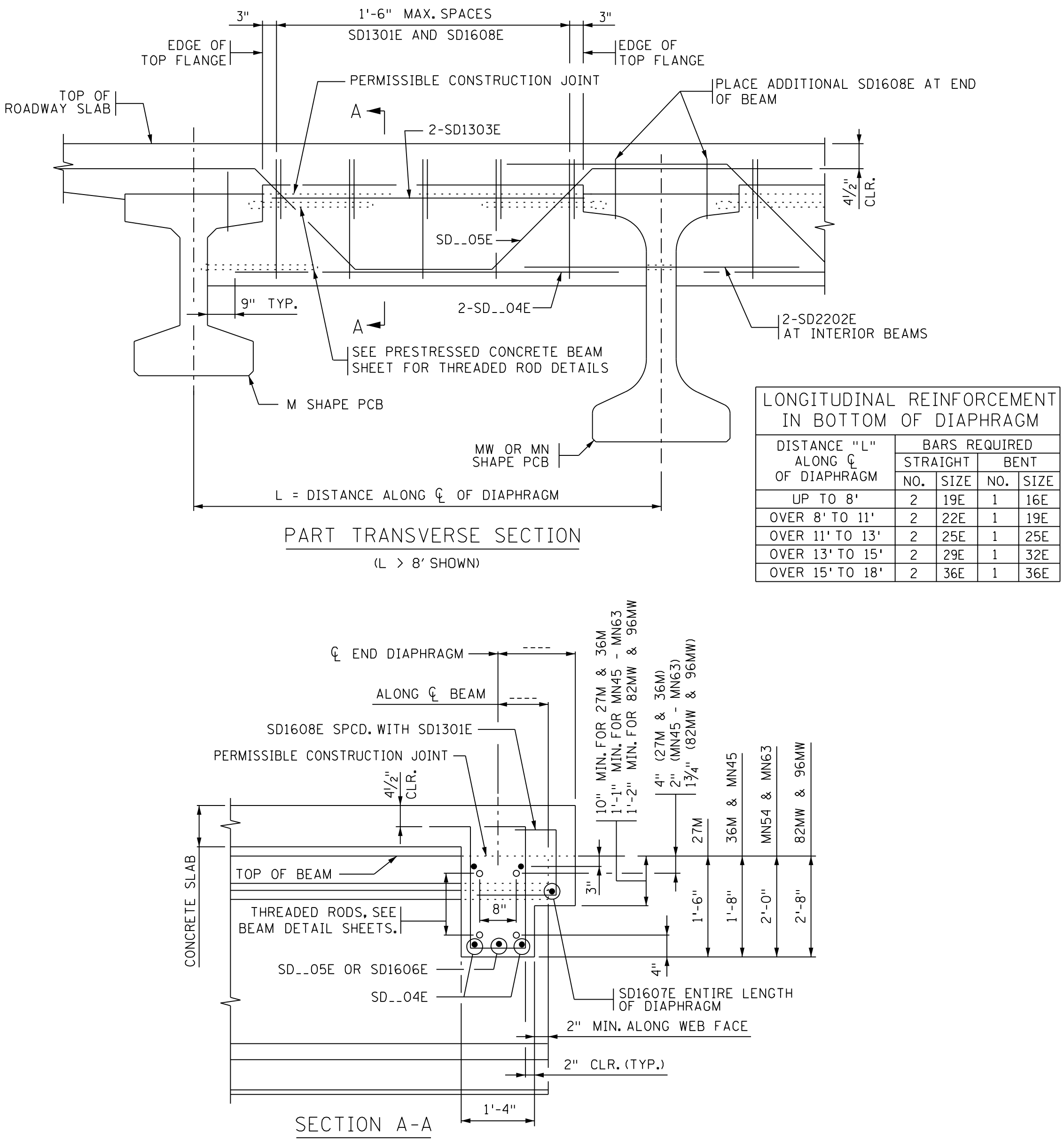


Fig. 10: Intermediate Diaphragms

The "MN" shapes have four connection points between the bent plate diaphragm support and the web of the beam. For the "MW" beams, the required strength was governed by the pullout of the strength of the fascia beam connection, and the spacing had to be adjusted due to the increased web height; the number of connections remained at four.

In addition to the steel intermediate diaphragms, the concrete end diaphragm standard needed to be considered. This detail is used for parapet style abutments, when the beams are not cast integrally with the deck. The previously existing detail is designed to transfer wheel loads of beam spacing distances up to 18 feet along the skew of the abutment. For a 13 foot spacing, this allows a skew up to 43 degrees, which was deemed sufficient. No change to the design was needed. However, for stiffness and stability, the total depth was increased to 2'-8" from 2'-0 due to the additional height of the beam.



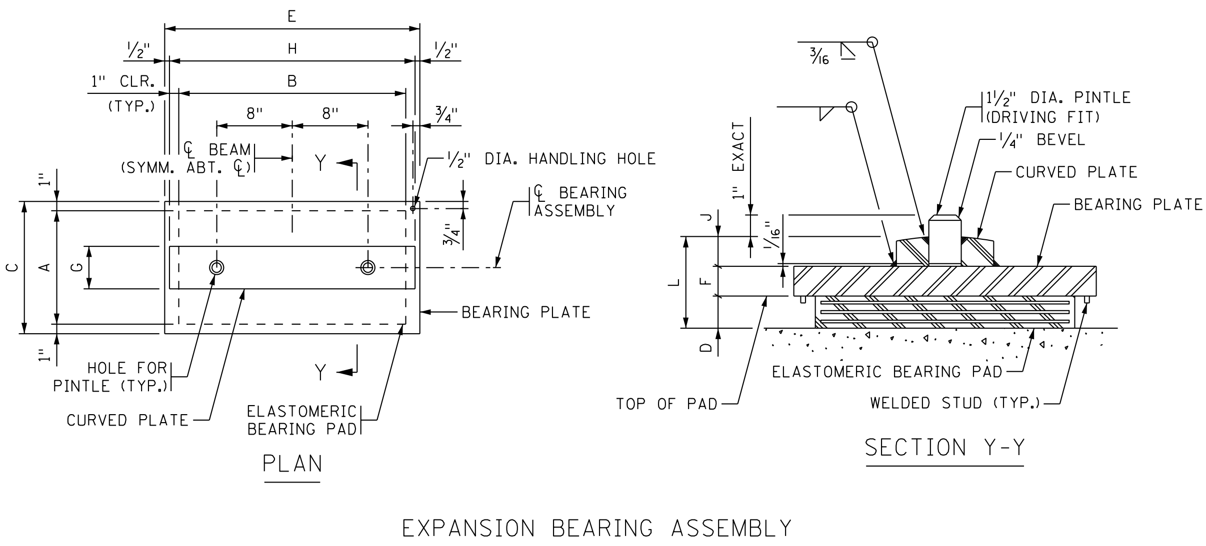
LONGITUDINAL REINFORCEMENT IN BOTTOM OF DIAPHRAGM

DISTANCE "L" ALONG ℄ OF DIAPHRAGM	BARS REQUIRED			
	STRAIGHT		BENT	
	NO.	SIZE	NO.	SIZE
UP TO 8'	2	19E	1	16E
OVER 8' TO 11'	2	22E	1	19E
OVER 11' TO 13'	2	25E	1	25E
OVER 13' TO 15'	2	29E	1	32E
OVER 15' TO 18'	2	36E	1	36E

Fig. 11: End Diaphragm

Making sure the beams fit at the substructures is another issue that had to be addressed as part of the standard development. To accommodate construction tolerance and beam rotation, a gap is left between the ends of the beams at the piers. MnDOT practice has been to leave a gap of 2 inches between the ends of the beams at the piers for bridges with two spans and a gap of 3 inches for bridges with three or more spans. The “MW” shapes, due to their longer lengths are more likely to encroach on the gap area than other smaller beams due to construction tolerance and the rotation of the beam due to camber. To prevent a conflict at the piers, particularly of the top flanges, MnDOT set the distance between ends of beams at piers to 4 inches for the “MW” series of beams. A similar situation must be addressed at abutments. It is imperative to check that there is adequate room from the end of the beam to the face of the back wall. Given the longer lengths, the sloped length versus the horizontal distance between substructures differences are more noticeable. On a 170 foot span, the sloped length is 7/8 inch longer than the horizontal distance with just a 3% slope.

Most of MnDOT’s prestressed beams sit on steel curved plate bearing assemblies. In an effort to minimize lead times and cost, standard sizes have been developed for the geometrics of “MN” and “MN” beams along with the typical loading that they transmit. The shape of the “MW” beams was enough of a departure from what has been done in the past that more significant investigation was necessary. The typical elastomeric bearing pad used with the smaller beams is a 12 inch by 24 inch elastomeric pad, with or without steel reinforcing. Stability of the beam was a concern with only a 24 inch wide elastomeric pad under a 39 inch wide bottom flange. In order to stay with the shape factors and aspect ratios that have worked well for MnDOT in the past, bearing pads are required to be sized so that the long side (“B”) does not exceed 2.5 times the short side (“A”). For a 36 inch wide bearing pad, a minimum 14.4 inch long bearing pad was required. The standards developed used a 16 inch by 36 inch elastomeric bearing pad as a minimum size, with provision for increasing dimensions by 2 inches in either direction as needed for loads and to maintain the aspect ratio. In addition to changing the size of the elastomeric bearing pad, the steel plates that are part of the assembly needed to be adjusted as well, because their dimensions are tied directly to the dimensions of the bearing pad. The bearing plate size for expansion bearings is 18 inches (“C”) by 39 inches (“E”); for fixed bearings, the dimensions are 18 inches (“C”) by 47 inches (“E”) to allow for placement of the anchor rods.



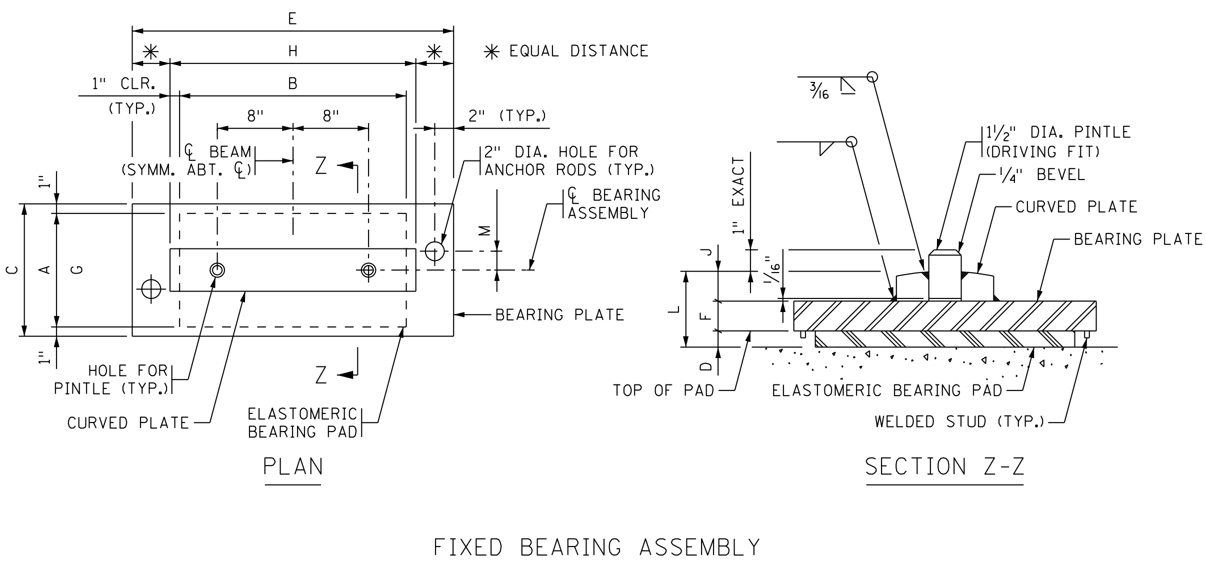


Fig. 12: Bearing Assembly Details

Typically, beams extend 7½ inches past the centerline of bearing for the "M" and "MN" shapes. However, with the bearing pad and bearing plate required for the large bottom flange 1½ inches of bearing plate would extend past the end of the beam. This amount of overhang created the potential for bearing assemblies to contact at the piers. To reduce the potential, the distance from the end of the beam to the centerline of bearing was increased to 8½ inches. The sole plate that is embedded into the beam was also lengthened. Although this still leaves ½ inch of bearing plate extending out past the end of the beam, that amount of overhang was considered acceptable. The increased size of the bearings made the earlier decision to require 4 inches between the ends of the beams even more prudent. With only a 2 inch gap on a two span bridge, the bearing plates would have been in contact

DEVELOPMENT TIMELINE

The initial discussions relating to the development of new deep beam standards began in July 2010. Fabricators were involved within the first month of the discussions to review draft shapes and contribute comments regarding their ability to form, fabricate, prestress, transport within the yard, and ship deeper and longer beams than had been done in Minnesota in the past. By late 2010, the beam cross-section was finalized to allow a current design build project fabricator to purchase forms. On July 29, 2011, a memo to designers was issued notifying all designers of the new beam shapes and the associated standards that were affected. The finalized standard plans were issued on September 22, 2011; only 14 months after the preliminary discussions began. The first beam was delivered to a project in October 2011.

ADDITIONAL INVESTIGATION

The development of the beams and adjustments to the standards are only the first step in long term success of the "MW" beams. A key element in constructability of a bridge using prestressed beams is an accurate camber prediction. For "M" and "MN" shapes, initial total camber is determined using multipliers of 1.50 for both prestress deflection and self-weight of the member. Although those multipliers have been adequate for the smaller beam shapes, MnDOT was uncertain whether new beams would behave similarly given the lack of historical data. All projects designed using the "MW" beams are required to use a refined analysis with an appropriate creep model. Estimated camber values are reported in tabular form varying with the age of the girder. Additional research, including the actual field measurements, will need to be done to monitor the behavior of the beams in use to determine what the best camber model is for this beam shape.

Another area of future investigation is extending the span of the beams through the use of the sections spliced together using post-tensioning. The post-tensioned "MWPT" beams would use the same forms as the "MW" beams, except the forms would be separated by an additional 1½ inches to create an 8 inch web. The additional web width is necessary to accommodate the post-tensioning ducts. Three depths of beam are planned for the post-tensioned shapes: an 82 inch, a 96 inch, and, in keeping with the 14 inch steps, a 110 inch deep beam. The 110 inch depth was not considered for the original portion of the standards development, because the span lengths and beam weights at which the beams would be efficient are too great to ship in a single piece.

EARLY USAGE

The first usage of the new "MW" beams was on a design-build project in Hastings, MN for the Highway 61 north approach spans to a Mississippi River crossing. There are 45 96MW beams with spans of approximately 137 to 173 feet long[9]. The total shipping distance from plant to site was approximately 62 miles. All of the beams were delivered successfully. The fabricator worked in collaboration with MnDOT to verify overload permit routes that could be used to get the beams to the site. Lateral stability was easily managed due to a combination of the wide top flange and the use of 10 foot wide trailers. One minor issue in the fabrication of the beams was requiring additional effort to restrain the forms from floating due to the hydrostatic pressure of 8 feet of wet concrete pushing on the top of the bottom flange form. This was resolved through an improved connection between the side and bottom forms.

Fig. 13: 96MW Beam at Hastings Bridge Site[11]

In order to determine cambers for the beams on this bridge, two camber models were investigated, the AASHTO LRFD model and the CEB-FIP model from 1990[11]. Based on NCHRP research, the final estimated cambers were computed using the AASHTO LRFD model. Expected camber values were listed for 14, 45, 90, 180, and 365 days after release. Actual performance will be evaluated as construction continues.

The second usage of the "MW" series beams in Minnesota will be on the approach spans to the I-90 Mississippi River crossing near Dresbach, MN. Those beams will be 82MWs with approximately 152 foot span lengths. The estimated erection of the beams is in late 2013 to early 2014.

CONCLUSIONS

MnDOT's new "MW" series beams have proven to be an efficient beam type for use in the 150 to 200 foot span range. The success would not have been possible without collaboration between MnDOT, fabricators, shipping companies, and contractors. A special thanks goes to Lunda Construction Company, Ames Construction, Inc., and Cretex Concrete Products for their assistance and encouragement developing the standard while working on the Hastings Bridge. The combination of experience of other agencies that have developed deep beams along with MnDOT's smaller beam past performance has allowed for another innovative option for use on longer spans. MnDOT continues to view prestressed concrete beams as a low maintenance and cost effective design option. The "MW" beams have added another tool to the toolbox.

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