MINNESOTA'S MH SHAPE: THE DEVELOPMENT OF EFFICIENT SHALLOW DEPTH PRESTRESSED BEAMS

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ABSTRACT

In 2018, the Minnesota Department of Transportation (MnDOT) developed standard plan details for 30, 35, and 40 inch deep prestressed "I" shape concrete beams. The goal of the project was to produce high quality, low maintenance beams that are shallow enough to compete with steel girders for bridges with a 75 to 105 foot span range without significantly impacting approach grades or vertical clearance envelopes. The development process included investigation of similar beams used by MnDOT and other state agencies as well as collaboration with fabricators to ensure constructability and delivery of the beams. Issues considered included flange widths, top flange thicknesses for balancing release stresses, bottom flange shape for maximizing strand capacity while still minimizing the weight of the overall section, and updating associated details considering design, fabrication, and construction concerns. Fabricator concerns were determined and resolved with industry input. To best meet the needs of all involved parties, beam use authorization was staggered to give fabricators time to procure forms, and fabricators made upgrades to equipment as a long term investment.

Keywords: Creative/Innovative Solutions, Structures

INTRODUCTION

The Minnesota Department of Transportation (MnDOT) has been designing and building bridges using precast, prestressed concrete beams since the late 1950s. Currently, they make up 70 to 80 percent of the state's new bridges annually. MnDOT has worked with local fabricators to continue improving the quality and efficiency of beams.

As new two-span bridges are proposed to replace existing four-span bridges with side piers, the preferred choices often include a grade raise of up to 18 inches with prestressed beams or constructing the bridge with shallow depth steel girders to accommodate vertical clearance requirements. Shallow concrete beams could be a more cost effective solution. An analysis of MnDOT owned bridges designed since 2001 and state funded local highway bridges designed between 2009 and 2016 showed a significant portion of bridges have spans of 75-105 feet with current beam depths between 27 and 45 inches. While typically the desire has been to develop deeper beams that can be used for longer spans, MnDOT identified efficiency gaps in the current shallow depth prestressed concrete beams that led to developing new 30, 35, and 40 inch deep "MH" shapes.

SECTION DEVELOPMENT

GEOMETRY

The study began by compiling other states' shallow depth prestressed concrete beam properties and comparing them against MnDOT's shallow depth prestressed concrete beams. A common depth of 36 inches was shared by a number of states, so this depth was chosen as the beginning depth for shape analysis (Table 1). MnDOT's standard MN shape (see Figure 2), which is used in the 45 to 63 inch depth range, was modified to a 36 inch depth to be included in the analysis. The modified depth was achieved by reducing the flat portion of the web between the top and bottom flanges.

Table 1 Summary of 36 inch prestressed concrete beam properties

State	Area (in^2)	I (in^4)	S_{bot} (in^3)
Ohio[6]	878	145,592	8,000
Louisiana[4]	792	125,051	7,479
Illinois 3838[3]	805	124,639	7,563
Illinois 2438[3]	728	100,433	6,832
Wisconsin[7]	632	99,980	6,012
Minnesota MN36	631	99,740	5,998
Minnesota 36M[5]	570	93,530	5,208
California[2]	432	63,000	3,684
AASHTO Type II[1]	369	50,979	3,221

Of the shapes reviewed, the Ohio shape (Figure 2) looked to be the most promising based on the section properties of the shape.

The typical MnDOT prestressed beam strand pattern is arranged in a 2 inch by 2 inch grid. MnDOT utilizes draped strands which typically begin at 3 inches from the bottom of the beam at the centerline of the span and end at a minimum of 3 inches from the top of the beam. See Figure 1 for the possible strand locations in the MnDOT 36 inch M shape.

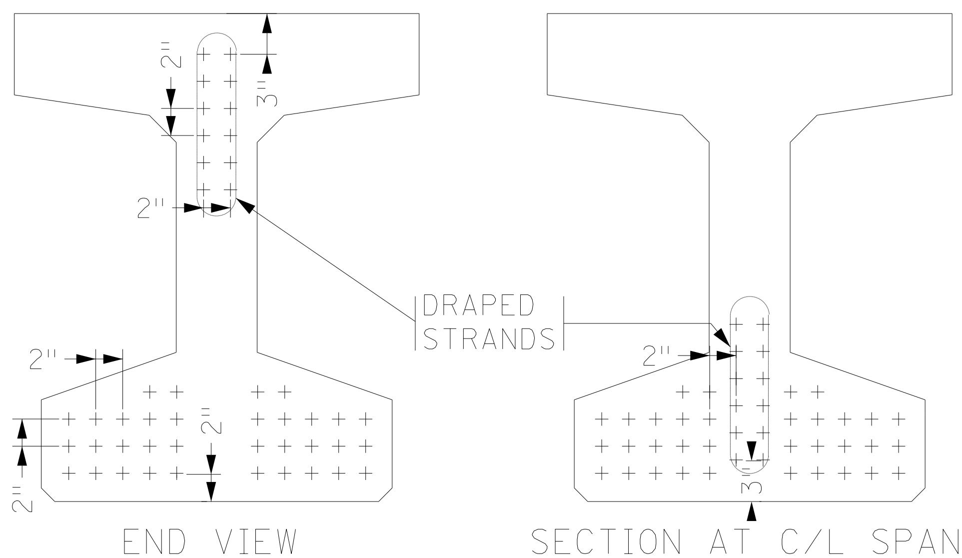


Fig. 1 MnDOT 36M possible strand locations

Beams were analyzed using the typical MnDOT strand pattern on the Ohio, M, MN, and a number of variations of a combined Minnesota-Ohio (MN/OH) shape. See Figure 2 for general beam shape information and Figure 3 for MN/OH. Ohio’s beam with MnDOT’s strand pattern spanned 12 feet farther than MnDOT’s 36M shape. Based on the increase in span MnDOT determined there was room for improvement in shape efficiency and attempted to see if the same span could be achieved with a smaller area. Table 2 illustrates a few iterations of beam shape and the resulting span length.

Table 2 Beam properties and maximum span for 7 foot beam spacing

State	y_{bot} (in)	Area (in^2)	I (in^4)	S_{bot} (in^3)	Span (ft)
Ohio	18.2	878	145,592	8,000	108
MN/OH36 - 5" top flange	15.9	741	117,945	7,418	107
MN/OH36 - 5" top flange 38" bottom width	16.3	714	115,186	7,067	106
MN/OH36	15.3	708	111,054	7,258	104
MN36 - 5" top flange	17.3	663	105,394	6,092	102
Minnesota MN36	16.6	631	99,740	5,998	
Minnesota 36M	18.0	570	93,530	5,208	96

The MN/OH shape with a 5 inch thick top flange and 38 inch bottom flange width was selected based on the low weight compared to the Ohio shape and the increased span length compared to the Minnesota 36M. The Ohio bottom flange shape is similar to the standard MnDOT MW bottom flange (see Figure 2), so a new MN/MW shape was analyzed utilizing the top flange of the MN shape and bottom flange of the MW shape. This revised shape spanned slightly further, 107 feet versus 106 feet, than the initially chosen MN/OH shape (see Table 3). After this investigation, MnDOT selected the following attributes for the MH shape:

- Top flange: 5 inch tip depth and 34 inch width to facilitate deck replacement and resist release stresses.
- Web: 6 ½ inch width to provide ample shear capacity and ability to place shear steel. This also matches the existing web width for Minnesota MN and MW beam shapes.
- Bottom flange: 39 inch width to match current fabricator bed width for MnDOT MW beams. The top slope of the bottom flange was also flattened compared to the MW shape bottom flange to minimize weight in areas where strands could not be practically placed.

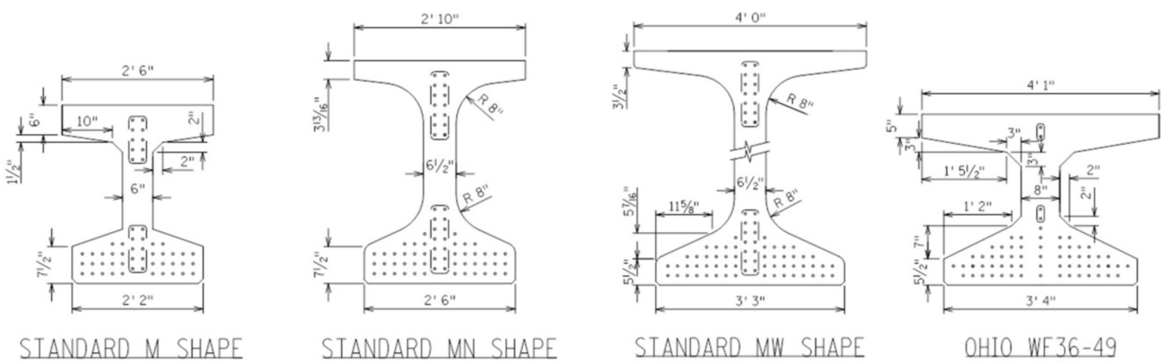


Fig. 2 Reference cross sections

Table 3 Results from MN/OH, MN/MW, and MH analysis at 7 foot beam spacing

Beam	**y_{bot} (in)**	**Area (in^2)**	**Area reduction from Ohio shape**	**I (in^4)**	**Span (ft)**	**Max span compared to Ohio shape**
MN/MW36	16.1	725	17%	116,300	107	99%
MN/OH36 - 5" top flange 38" bottom width	16.3	714	19%	115,186	106	98%
36MH	16.3	678	23%	113,399	106	98%

The MH cross-section also provides softened flange to web radius transitions to enhance form release and give aesthetic appeal. At a depth of 36 inches, the MH shape provides maximum span lengths within 2% of the Ohio shape and is 23% lighter per foot. Table 3 illustrates the progression in efficiency from the Ohio shape to the MH shape by reducing weight while maintaining span length. The final beam depths were chosen to fill gaps between existing MnDOT beam shapes and to provide beam depths that met the required vertical clearance for typical railroad crossings without significant grade raises. Based on the final chosen depths, the 35MH is 30% lighter and spans about 96% of the maximum span compared to the 36 inch deep Ohio shape. Figure 3 shows the progression of the cross-section geometry for the 40-inch depth. Table 4 shows the final cross-section geometry properties for the MH shape. Figure 4 shows possible strand locations for the MH shape. The strand locations for the MH shape differ from the typical MnDOT prestressed strand layout. While the 2 inch grid is still utilized, the location of the draped strands at the centerline of the span starts at 4 inches from the bottom of the beam as opposed to the typical 3 inches. This allows for 2 more straight strands to be placed in the bottom row increasing the strength capacity of the beam and allowing it to span farther. This also lowers the center of gravity of the strand pattern which increases the section's efficiency and could eliminate additional strands that may be required if the draped pattern were allowed to start 3 inches from the bottom of the section.

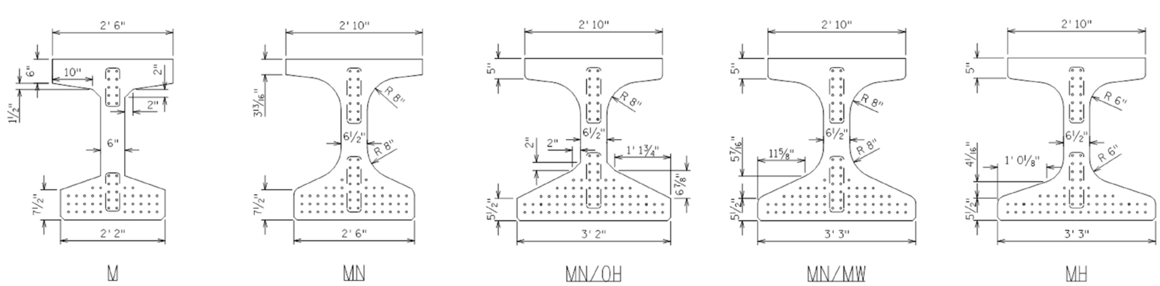


Fig. 3 Cross section geometry iterations at a 40 inch depth

Table 4 Final cross section properties for each beam depth

Beam	Depth (in)	Area (in^2)	Weight (lb/ft)	Centroid to Bottom (in)	Moment of Inertia (in^4)	Bottom Section Modulus (in^3)
30MH	30	639	688	13.66	70,416	5,155
35MH	35	672	723	15.85	105,570	6,661
40MH	40	704	758	18.07	149,002	8,246

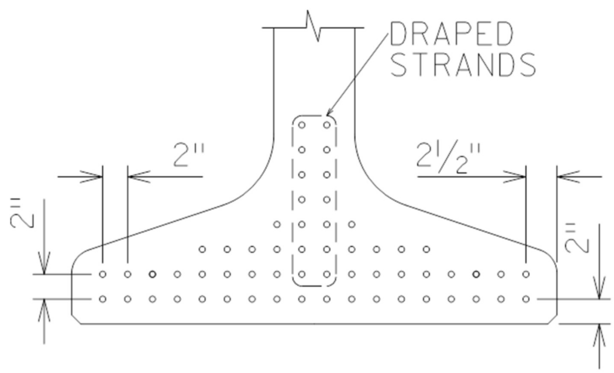


Fig. 4 Possible strand locations

DESIGN METHOD

Full design criteria can be found in the MnDOT LRFD Bridge Design Manual[5]. See Table 5 for a summary of design assumptions.

Table 5 MnDOT prestressed concrete beam design assumptions[5]

Design Specification(s)	2017 AASHTO LRFD Bridge Design Specifications, Eighth Edition 2005 High-Strength Concrete (ACI 363R), Vol. 228
Live Load	HL-93
Beam Concrete	$f'_c = 9.0$ ksi $f'_{ci} = 7.5$ ksi $w_{beam} = 0.155$ kcf $E_c = 1265\sqrt{f'_c} + 1000\text{ksi}$
Deck Concrete	$f'_c = 4.0$ ksi $E_c = 3987$ ksi $w_c = 0.145$ kcf for E_c computation $w_c = 0.150$ kcf for dead load computation
Prestressing Strands	0.6 in diameter low relaxation strands $E_s = 28{,}500$ ksi $f_{pu} = 270$ ksi with initial pull of $0.75f_{pu}$
Structural Layout	Simply supported span with six beams and deck without wearing course. Deck carries two 36" high MnDOT Type S Single Slope Barriers with no sidewalk or median (496 plf each). No skew. Effective deck thickness is total deck thickness minus ½ inch of wear.
Stool	1.5 inch stool height used for composite beam section properties. 2.5 inch average stool height used for dead load calculations.
Load Application	Barrier dead load applied equally to all beams. Dead load includes 20 psf future wearing surface.
Losses	Approximate long term losses are used per AASHTO LRFD Article 5.9.5.3

The MH and MN/OH shapes span farther than other shapes at the same depth (Figure 5). The MH shape was chosen based on a 6% weight reduction from the MN/OH section. The MH shape's efficiency is illustrated by either spanning farther than the existing and proposed modified MnDOT beam shapes or by providing comparable span lengths with a lighter section. For the beam selection chart published in the MnDOT LRFD Bridge Design Manual (Figure 6), maximum span length was determined at 5, 7, 9, 11, and 13 foot beam spacing.

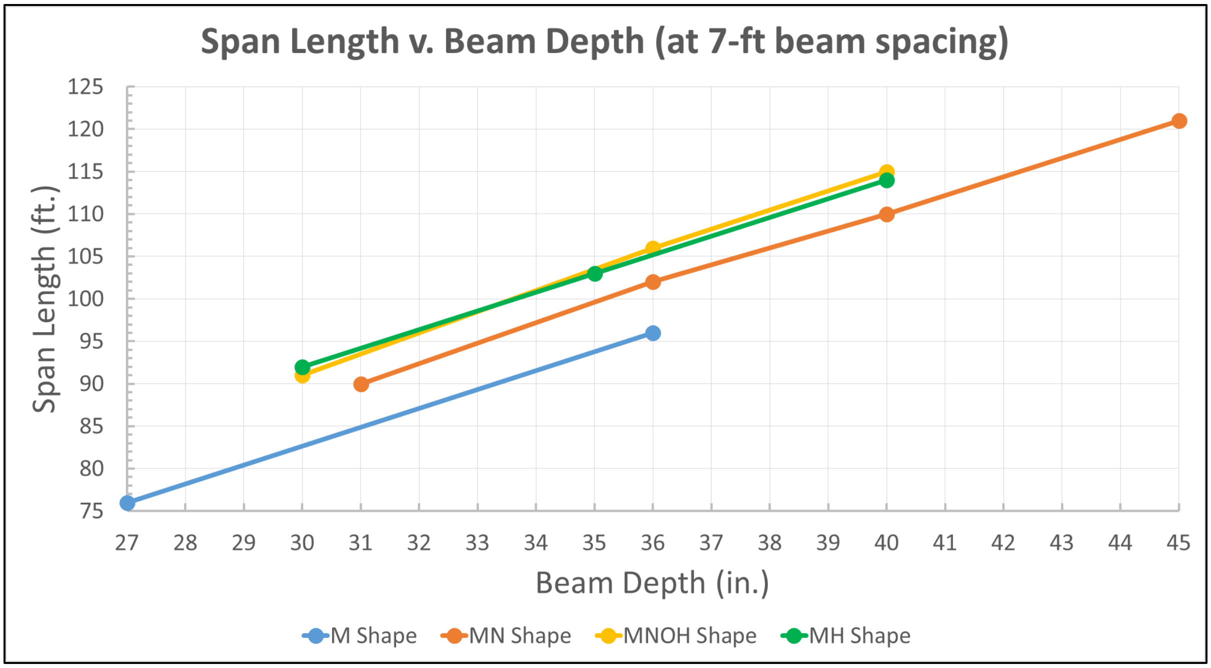


Fig. 5 Span length versus beam depth for different beam shapes

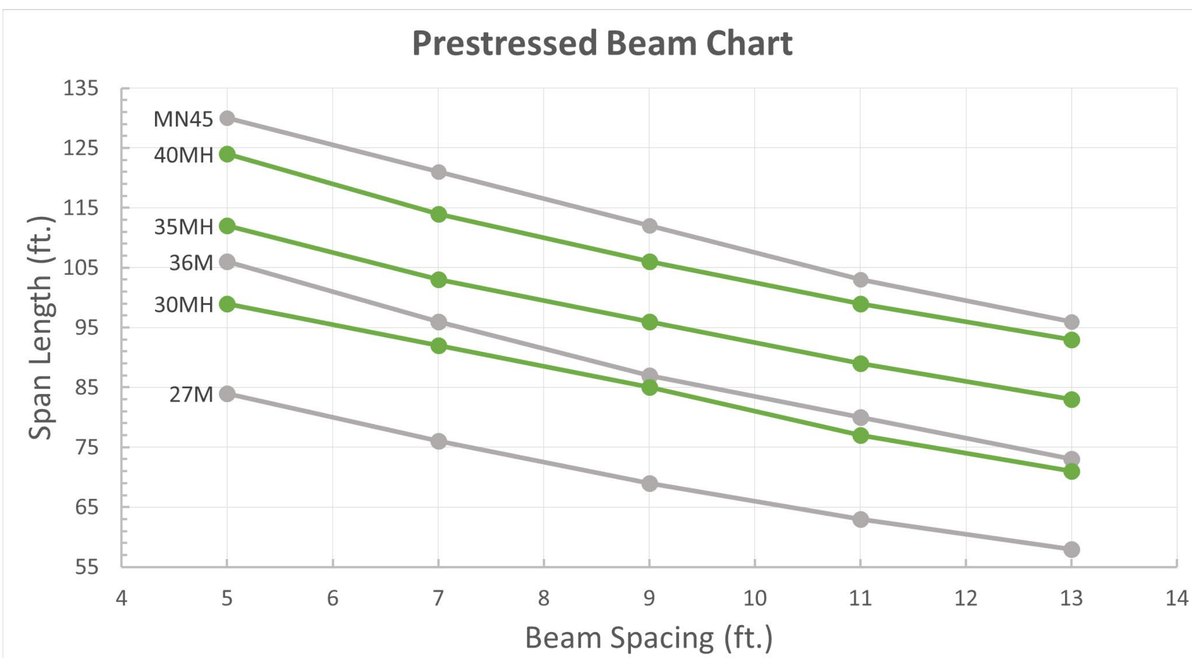


Fig. 6 Preliminary beam selection chart from Minnesota LRFD Bridge Design Manual

FABRICATOR CONCERNS

As part of the development process, MnDOT incorporated fabricator input on topics including constructability, form removal, and shipping. For hold down during transportation, the 30MH and 35MH will be strapped over the top flange, while the 40MH allows optional 2 inch sleeves through the web. For reinforcement to prevent end of beam splitting, MnDOT utilizes #5 stirrups at 2½ inch spacing for the M shapes and #6 stirrups at 3 inch spacing for the MN shapes. To ease fabrication and prevent cracking, #5 stirrups were chosen at 2 ½ inch spacing for the splitting reinforcement. Initially, the MH shape had web-to-flange chamfers with a 4 inch radius. These were changed to 6 inches to allow for better concrete flow and form removal. Additionally, by using a bottom flange that is the same width and thickness as the MnDOT MW shapes, fabricators are able to continue using their existing precasting beds.

DETAILING CONSIDERATIONS

Like all other MnDOT beam shapes, the MH beams are detailed with the outside 6 inches of the top flange troweled smooth, and an approved bond breaker is applied to this surface to facilitate future deck removal and replacement.

MODIFICATIONS TO OTHER MnDOT STANDARD DETAILS

MnDOT typically uses steel intermediate diaphragms. These are not required for the 30MH and 35MH. The flat portion of the web is too small to accommodate steel channel or bent plate diaphragms, and the bottom flange of these shapes is wider than the beams are tall, so lateral stability is not an issue. Like the existing 27M shape which also does not utilize permanent diaphragms, temporary bracing during construction is the responsibility of the contractor. The 40MH will follow intermediate diaphragm spacing guidelines consistent with other MnDOT beam shapes. Likewise, beam end dimensions, camber prediction, overhang criteria, and material properties will be consistent with other shallow to medium depth beams in the MnDOT library of standards. Standard bearing, intermediate diaphragm, and end diaphragm details were all modified to include the MH shape and modified as needed to include MH beam dimensional requirements. Figures 7 through 13 show changes made to MnDOT standard details to accommodate the MH series beams.

MnDOT uses a different practice for determining camber depending on beam series. M and MN beams use a standard 1.4 multiplier on the calculated camber at the time of prestress transfer to determine the expected camber at erection. This multiplier has been chosen based on research specific to MnDOT beams based on an expected time lapse of 30 to 180 days between prestress transfer and erection for deck placement. Camber for MW beams are calculated using an appropriate creep model and a refined time dependent analysis. For MH beams, given the shallow depth, the expectation is that the beam will behave in a manner similar to MnDOT’s other shallow beams. As these beams are utilized on projects, MnDOT will be collecting camber data at prestress transfer and at erection to determine if a revision to this policy is necessary.

Typical MnDOT expansion bearings are curved plate assemblies on steel laminated elastomeric pads, while fixed bearings are curved plate assemblies on cotton duck pads. For the M and MN series, the standard pad size is 12 inch by 24 inch; the MW series uses a 16 inch by 36 inch pad. Because the MH bottom flange is the same size as the MW series, the initial intention was to use the same standard pads. However, because the MW beams are used for much longer spans that the MH, pad design for the MH is governed by the minimum loads rather than the maximum loads. Ultimately, based on calculations for typical span configurations and past performance of this bearing type, MnDOT chose a 12 inch by 30 inch standard pad size for the MH series.

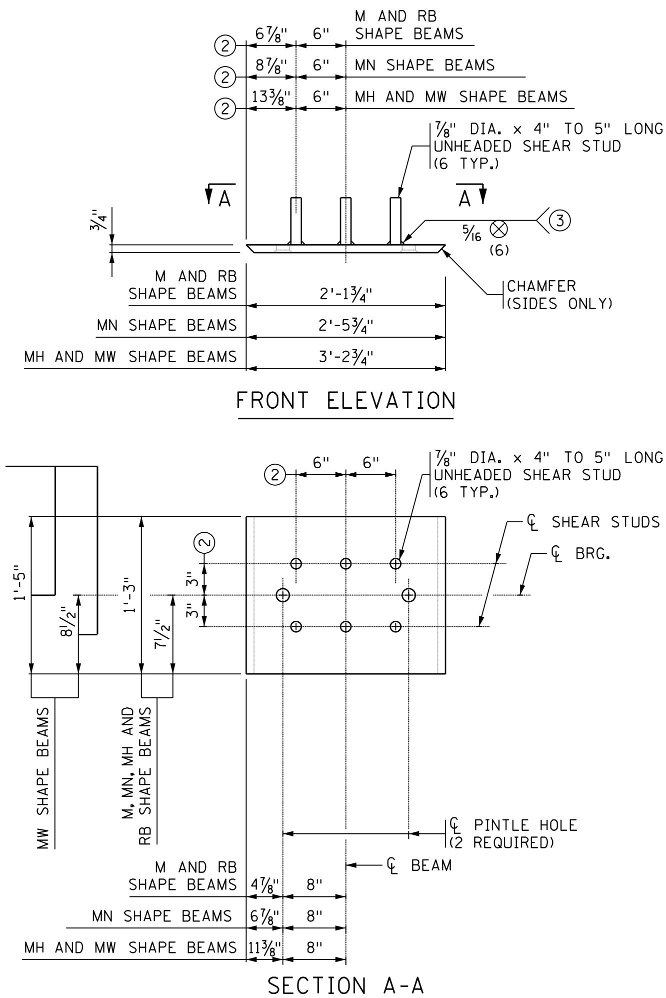


Fig. 7 Standard MnDOT detail B303 Sole Plate

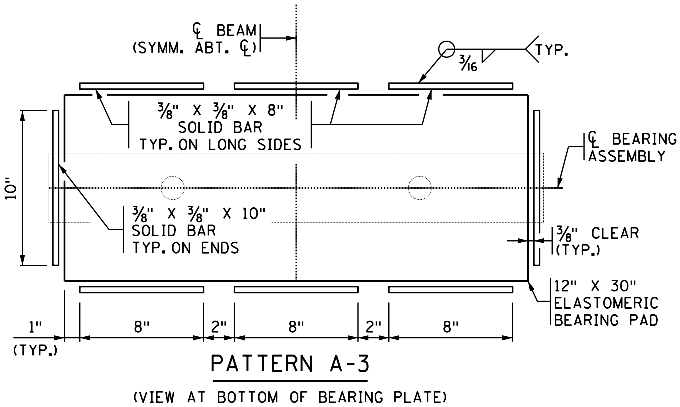
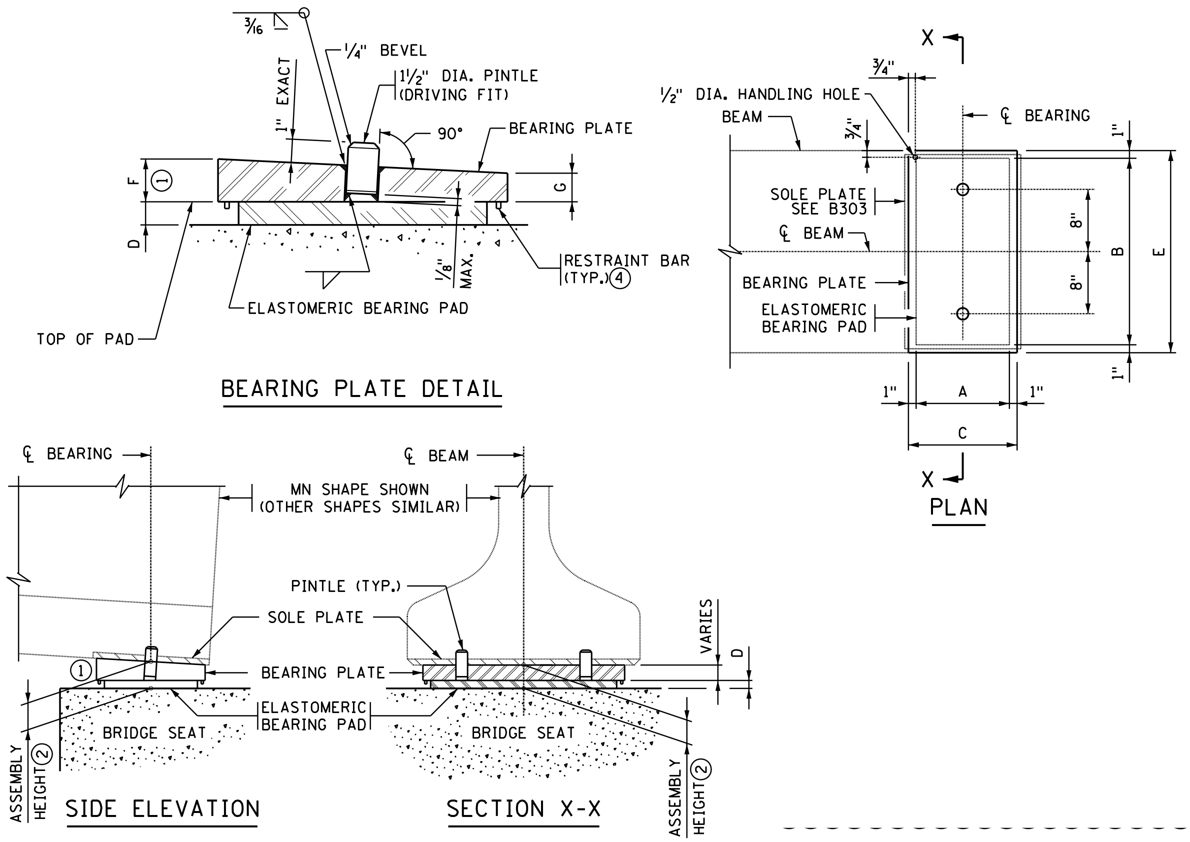


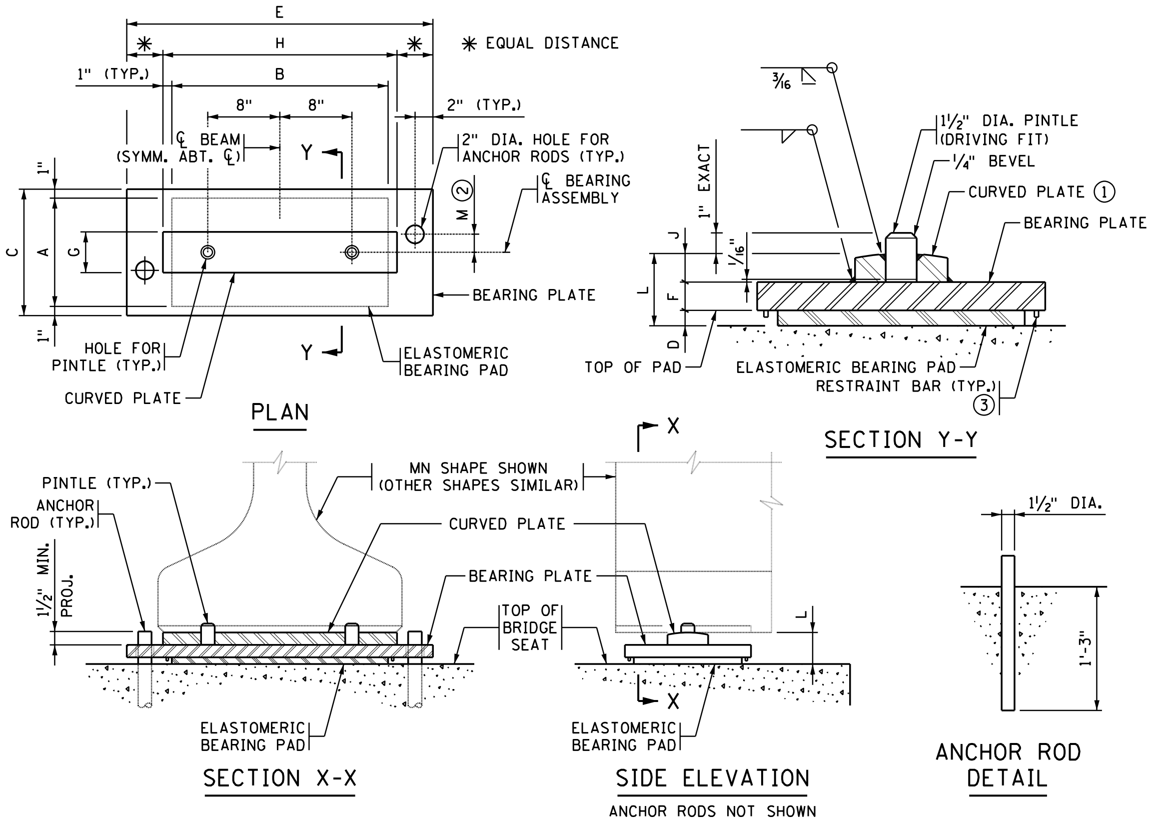
Fig. 8 Standard MnDOT detail B307 Bearing Pad Restraint



TABLE

ASSEMBLY TYPE	LOCATION	BEAM SIZE	BEARING PAD SIZE			SHAPE FACTOR	BEARING PLATE SIZE				ASSEMBLY HEIGHT	RESTRAINT PATTERN ④
			A	B	D ③		C	E	F	G	HT. ②	
		RB, M & MN	12	24	1⁄2	8.0	14"	26"				A-1
		MH	12	30	1⁄2	8.6	14"	32"				A-3

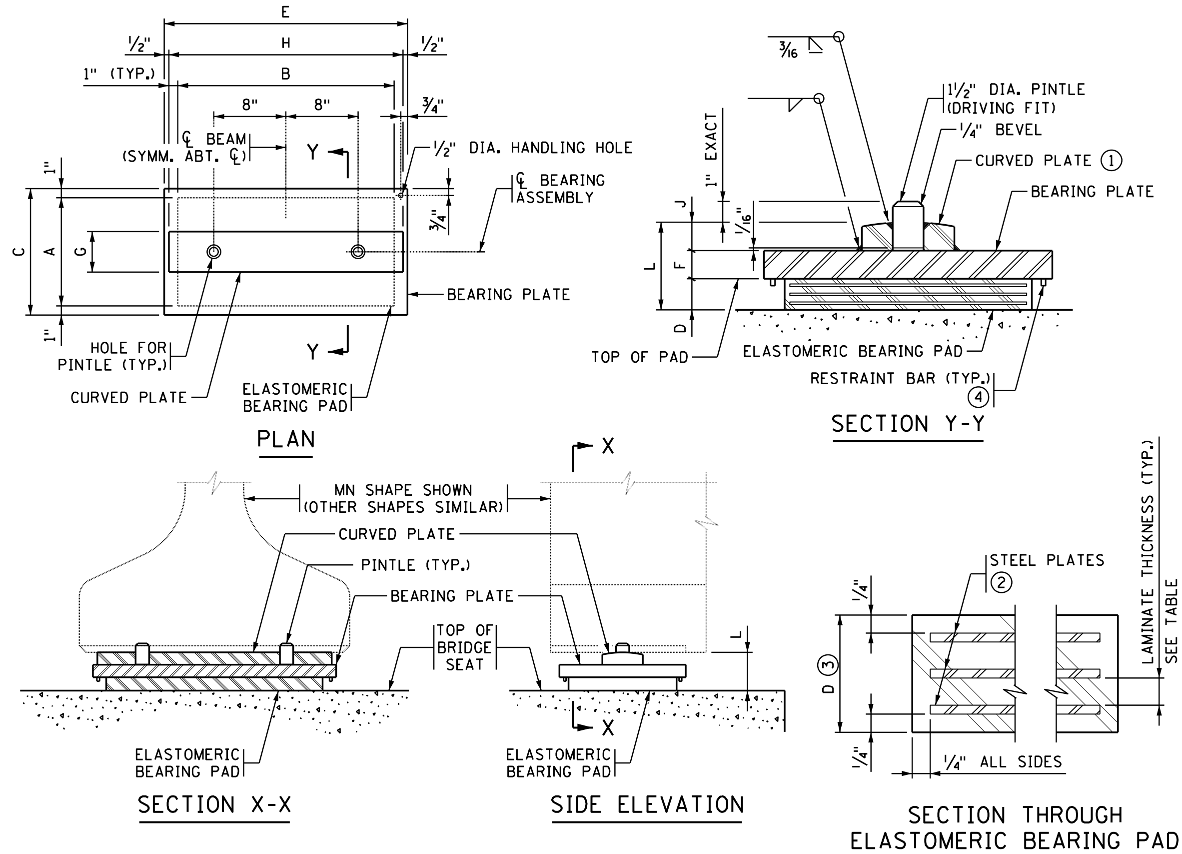
Fig. 9 Standard MnDOT detail B309 Tapered Bearing Plate Assembly



TABLE

ASSEMBLY TYPE	LOCATION	BEAM SIZE	BEARING PAD SIZE A	BEARING PAD SIZE B	BEARING PAD SIZE D	SHAPE FACTOR	BEARING PLATE SIZE C	BEARING PLATE SIZE E	BEARING PLATE SIZE F	CURVED PLATE SIZE G	CURVED PLATE SIZE H	CURVED PLATE SIZE J	CURVED PLATE SIZE R ①	ANCHOR ROD OFFSET +/- ②	ANCHOR ROD OFFSET M	ASSY. HEIGHT L	RESTRAINT PATTERN ③
		RB, M, & MN	12"	24"	1/2"	8.0	14"		1 1/2"	4 1/2"	26"	1 1/4"				3 1/4"	A-1
		MW	16"	36"	1/2"	11.1	18"	47"	1 1/2"	4 1/2"	38"	1 1/4"				3 1/4"	A-2
		MH	12"	30"	1/2"	8.6	14"	47"	1 1/2"	4 1/2"	32"	1 1/4"				3 1/4"	A-3

Fig. 10 Standard MnDOT detail B310 Curved Plate Bearing Assembly – Fixed



TABLE

ASSEMBLY TYPE	LOCATION	BEAM SIZE	BEARING PAD SIZE			STEEL PLATES		LAMINATES		SHAPE FACTOR	BEARING PLATE SIZE			CURVED PLATE SIZE				ASSY. HEIGHT	RESTRAINT PATTERN ④
			A	B	D	NO.	THICK.	NO.	THICK.		C	E	F	G	H	J	R ①	L	
		RB, M, & MN	12"	24"			1/8"		1/2"	8.0	14"	27"	1 1/2"	4 1/2"	26"	1 1/4"			A-1
		MW	16"	36"			1/8"		3/4"	7.4	18"	39"	1 1/2"	4 1/2"	38"	1 1/4"			A-2
		MH	12"	30"			1/8"		1/2"	8.6	14"	33"	1 1/2"	4 1/2"	32"	1 1/4"			A-3

Fig. 11 Standard MnDOT detail B311 Curved Plate Bearing Assembly – Expansion

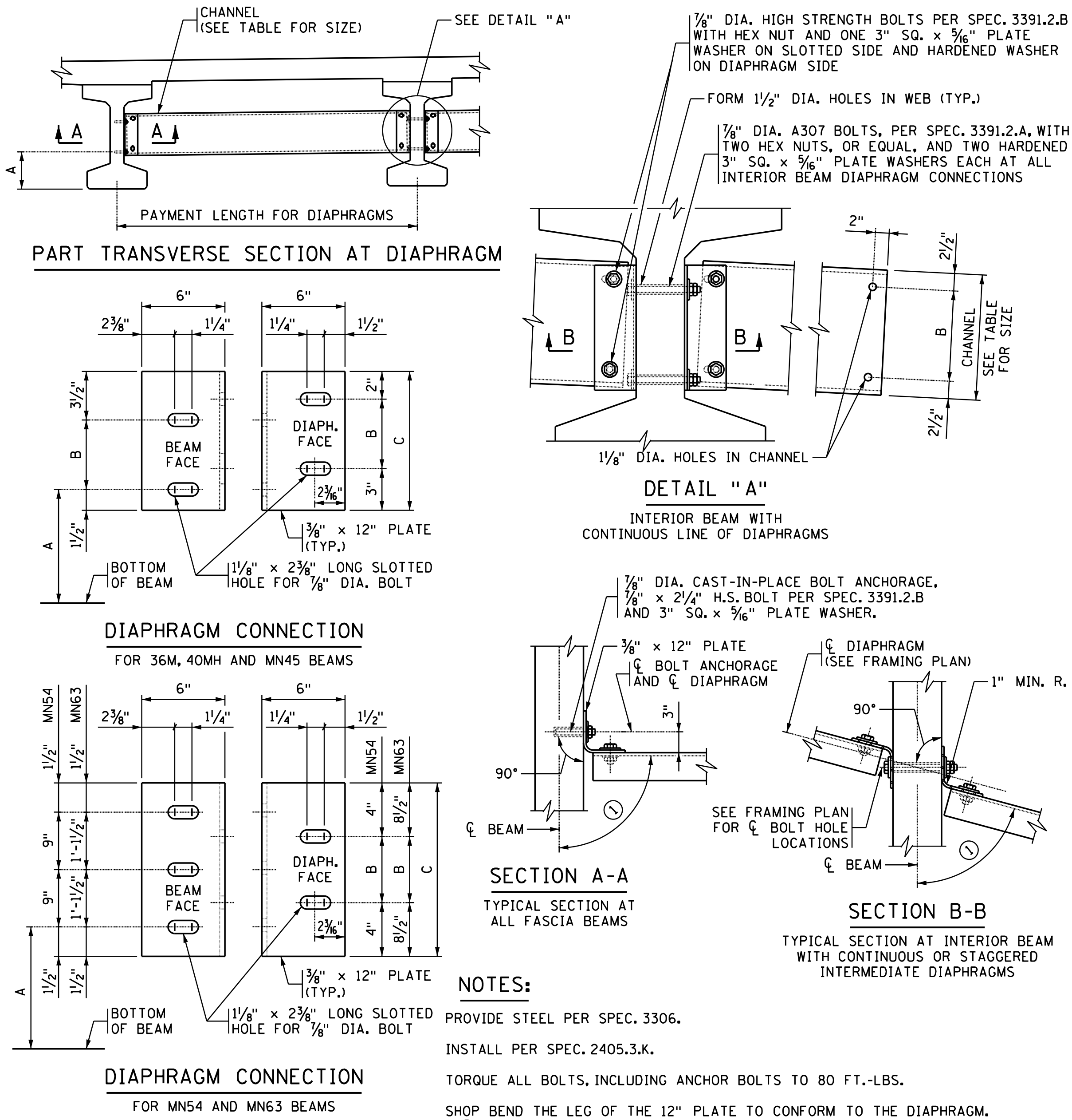


TABLE				
BEAM HEIGHT	DISTANCE			CHANNEL SIZE
	A	B	C	
36M	1'-3"	7"	1'-0"	C12×20.7
40MH	1'-5"	7"	1'-0"	C12×20.7
MN45	1'-7¾"	7"	1'-0"	C12×20.7
MN54	1'-7¾"	1'-1"	1'-9"	MC18×42.7
MN63	1'-7¾"	1'-1"	2'-6"	MC18×42.7

NOTES:

PROVIDE STEEL PER SPEC. 3306.

INSTALL PER SPEC. 2405.3.K.

TORQUE ALL BOLTS, INCLUDING ANCHOR BOLTS TO 80 FT.-LBS.

SHOP BEND THE LEG OF THE 12" PLATE TO CONFORM TO THE DIAPHRAGM. A ⅜" × 6" × 6" ANGLE MAY BE USED FOR DIAPHRAGMS PERPENDICULAR TO BEAMS.

INCLUDE ALL STRUCTURAL STEEL SHOWN ON THIS DETAIL, INCLUDING BOLTS AND WASHERS, IN UNIT PRICE BID FOR DIAPHRAGMS FOR PRESTRESSED BEAMS.

BENT PLATES MAY BE USED IN PLACE OF CHANNELS IF THE BENT PLATES HAVE THE SAME HEIGHT AS THE CHANNELS THEY REPLACE, ARE 5/16" IN THICKNESS, AND HAVE LEGS 5" LONG.

GALVANIZE STEEL PLATES AND SHAPES PER SPEC. 3394.

GALVANIZE BOLTS, NUTS AND WASHERS PER SPEC. 3392.

(1) FOR SKEW ANGLES UNDER 20°, USE 90° LESS THE SKEW ANGLE. FOR SKEW ANGLES OVER 20°, USE 90°.

Fig. 12 Standard MnDOT detail B403 Steel Intermediate Bolted Diaphragm

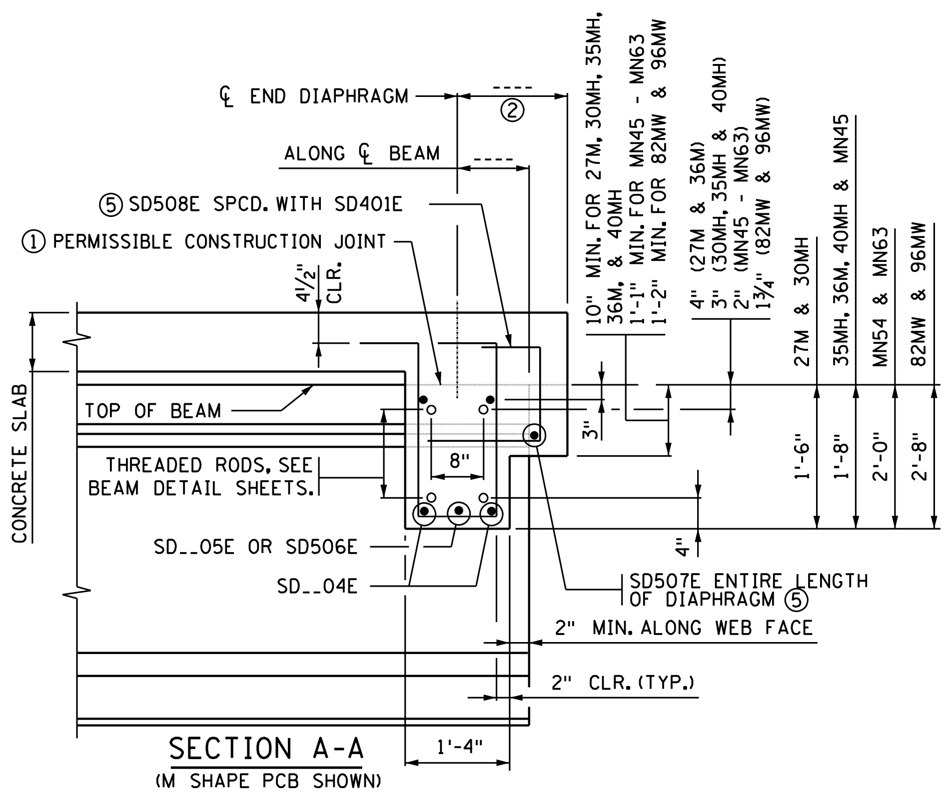


Fig. 13 Standard MnDOT detail B814 Concrete End Diaphragm – Parapet Abutment

AVAILABILITY TIMELINE

On December 20, 2018, MnDOT issued a Memo to Designers announcing the ability to use the new 30MH and 35MH for projects with a letting date on or after July 1, 2019. To allow fabricators adequate time to procure forms, the 40MH beams will be permitted for projects letting on or after November 1, 2019.

ADDITIONAL INVESTIGATION

These shapes are being utilized for upcoming MnDOT projects and on the state and local highway system. Cost savings involving the elimination of grade raises and potentially being able to drop beam lines, fabricator concerns, and contractor comments will be analyzed to determine if additional changes are needed. MnDOT has not typically utilized strand debonding but is utilizing both the MH and existing shapes with strand debonding in upcoming projects. The existing M series will continue to be permitted and will not be archived at this time. There are geometric configurations where the M beams are anticipated to be a more cost effective solution than MH beams. Additionally, MnDOT will consider whether developing MH shapes at additional depths would be cost effective based on information gleaned from upcoming projects that utilize the first set of MH beams.

CONCLUSIONS

MnDOT's new MH series beams should prove to be an efficient beam type for use in the 75 to 105 foot span range. The longer spans at shallower depths allow for project savings over the costs of grade raises or steel beams. Success developing the beams would not have been possible without collaboration between MnDOT and fabricators. The combination of experience of other agencies that have developed shallow beams along with MnDOT's smaller beam past performance has led to a more efficient option in the shallow beam category. MnDOT continues to view prestressed concrete beams as the preferred low maintenance and cost effective design option for typical bridges. The MH beams add another shape to the toolbox.

REFERENCES

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