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# Development of Aluminum Diaphragms for Concrete Bridges

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**ABSTRACT**

Ordinary bridges are commonly designed and constructed using prestressed concrete superstructures. Prestressed concrete bridges normally use concrete diaphragms to provide stability during construction, distribute loads laterally, and maintain the cross sectional geometry of the superstructure. Over time, the concrete diaphragms tend to deteriorate and require costly repairs or replacement. Aluminum diaphragms can be considered as an innovative and economical alternative for replacing the concrete diaphragms. Aluminum diaphragms provide improved constructability over concrete diaphragms in situations where the need to maintain traffic is a concern. They are also significantly lighter than concrete, which will reduce the amount of dead load that the bridge members need to carry and in turn will increase the live load capacity of the bridge. This paper will describe the methodology of load and resistance factor design for aluminum diaphragms and their connections. The design procedure for aluminum diaphragms will be outlined. A design spreadsheet will be created to input diaphragm section properties and analyze member stresses. An illustrative design example will be included to provide clarification. The benefits (functionality, constructability and cost effectiveness) of using aluminum diaphragms instead of concrete diaphragms will be demonstrated. Relevant design recommendations will be proposed.

## 1. INTRODUCTION

Bridges with prestressed concrete girder superstructures use reinforced concrete intermediate diaphragms to laterally brace the girders within the span of the bridge and distribute loads. Over time the reinforced concrete intermediate diaphragms tend to deteriorate or fail, and require costly repairs or replacement. Aluminum diaphragms can be considered as an alternative for replacing the reinforced concrete diaphragms. Steel diaphragms are another viable option, but they are not as beneficial in terms of weight reduction and corrosion resistance as aluminum.

The aluminum diaphragms prove to have several advantages over conventional reinforced concrete diaphragms. Aluminum diaphragms will allow for higher live load capacity. They will also reduce the amount of time and cost for construction. The impact on traffic and the local economy will be decreased. While aluminum may have a relatively higher initial cost, lower stiffness, a lack of design codes and standards for bridge applications, and less familiarity in the bridge engineering community, it proves to be a useful structural material (Chevrotiere et al. 2012). Aluminum is becoming a more economical structural material. Design standards are now in place to allow engineers to develop innovative designs using aluminum.

Aluminum structural members have been used on several bridge projects around the world throughout the modern era of bridge construction. The first aluminum bridge deck was installed on the Smithfield Street Bridge in Pittsburgh in 1933 (Das et al. 2007). The first bridge constructed entirely of aluminum was the Grasse River Bridge in Massena, New York in 1946. Aluminum has been used extensively in bridge decks and pedestrian bridges. Primary structural members such as plate and box girders, arches, bascules and trusses can also be fabricated from aluminum (Chevrotiere et al. 2012). Aluminum diaphragms can be used as secondary structural members.
The primary objective of this study was to demonstrate the usefulness and advantages of aluminum diaphragms in prestressed concrete girder bridges. A literature review was conducted to learn about aluminum design standards

and material properties. A parametric study was conducted to create a database of possible diaphragm properties. Flowcharts were created to outline the diaphragm design procedure. Details of the AASHTO LRFD (AASHTO 2012) design methodology pertaining to aluminum and connections are presented in this paper, followed by benefits of aluminum diaphragms, conclusions and design recommendations. A design example is also presented in this paper to illustrate the detailed design process and utilization of aluminum diaphragms.

## 2. LITERATURE REVIEW

Research was conducted to assess the prevalence of aluminum use historically in bridge construction, structural aluminum material properties, and bridge diaphragm industry standards. The main focus of the literature review was the 2012 AASHTO LRFD Bridge Design Specifications (AASHTO 2012). Section 6 contains steel connection specifications which were used to design the bolted connections for the diaphragms. Section 7 contains aluminum structures specifications which were used to design the aluminum diaphragms.

The PennDOT Bridge Construction (BC) standards and Bridge Design (BD) standards were also utilized for state specific requirements. The concrete diaphragm section properties and reinforcement were extracted from BD-656M (Pub. 218M 2010). Reinforcement bar fabrication details were taken from BC-736M (Pub. 219M 2010). The standards were also used to aid in the PSLRFD input for the parametric study. The parameters for diaphragm placement locations and spacing within the bridge span were used.

Aluminum material properties were researched. Aluminum exhibits approximately one third of the density of steel, and it has a very high strength to weight ratio (Olive 2008). It is considered a durable, ductile and malleable metal (Aluminum 2013); however, aluminum can be susceptible to fatigue in certain situations. In such cases, structural elements must be designed for a finite life span. Aluminum melts at low temperatures compared to steel, and is sensitive to heat under certain circumstances. While it can be easily welded (Welding 2013), a portion of the aluminum material strength is lost during this process. The aluminum material strength can be increased by strain hardening, heat treatment or a combination of the two methods (Olive 2008). The thermal expansion coefficient of aluminum is approximately double that of concrete and steel, which means allowances must be made to account of additional thermal expansion and contraction due to ambient temperature changes (Chevrotiere et al. 2012). Aluminum structural shapes are generally non-compact. Therefore, all shapes must be checked for slenderness and lateral torsional buckling. Each individual element of the shape must be checked for compactness (Olive 2008).

Aluminum is resistant to corrosion. A layer of aluminum oxide forms when the metal is exposed to air, which prevents further oxidation (Aluminum 2013). Therefore, aluminum members do not require painting or maintenance. In most cases, aluminum is usually alloyed with another metal to improve its mechanical properties. Aluminum 6063-T6 is an alloy with magnesium and silicon (Olive 2008). It is recommended that 6XXX alloys be used for highway bridge applications due to their favorable strength properties and corrosion resistance (Chevrotiere et al. 2012). Aluminum production from bauxite ore requires a large amount of energy, which can be an environmental concern (Olive 2008). However, aluminum can be recycled easily using only a fraction of the original energy to create new structural members; therefore, it is considered safe for the environment.

Another advantage of aluminum is its excellent ability to be fabricated. In some applications, aluminum plate can be cut and welded more efficiently than steel. It is also easy to produce rolled members and aluminum extrusions of complex shapes. Aluminum structures and components are commonly pre-fabricated and quickly erected due to their light weight and ease of fabrication characteristics (Das et al. 2007).

The primary advantage of using aluminum in bridge applications is the reduction in long term life cycle costs (Chevrotiere et al. 2012). Aluminum materials tend to have a higher initial cost than traditional structural materials such as steel and reinforced concrete. This initial increase is usually counterbalanced to some extent with the long term cost savings.

## 3. PARAMETRIC STUDY

The purpose of performing a parametric study was to create a database containing all of the parameters that can influence the section properties of aluminum diaphragms. A database was created to encompass several different bridge superstructure layouts, and provide a variety of opportunities for unique diaphragm sizes and arrangements. The parametric study is necessary to determine the beam sizes, length and spacing. The concrete diaphragm cross section is a standard size, but the length and spacing are determined by the superstructure geometry. The three different superstructure types included in the parametric study were Spread Box beams, AASHTO I-beams, and PA Bulb-Tee beams. Single span and multiple span arrangements were considered in the study. A range of beam length and spacing configurations were investigated to determine the maximum beam size and spacing that would require the largest diaphragm section.

The beams were modeled using PennDOT's LRFD prestressed concrete girder design and rating program, version 2.4.0.0 (PSLRFD 2012). It was assumed that the bridge skew was within the program limitations. Standard shoulder and median widths were taken from PennDOT Design Manual Part 2, Table 1.3 (Pub. 13M 2009). Standard parapets were assumed for a separated dual bridge cross section. Each bridge was modeled to carry four lanes. The vertical clearance was assumed to be greater than 4.9 m. 1.3 cm diameter special strands were assumed. The compressive strength of concrete at the time of initial prestress, $f'_{ci}$, was assumed to be 55.2 MPa. The program input data was computed for a range of beam sizes and spacing, span lengths and lane configurations. Diaphragm spacing and configuration requirements were taken from BD-651M (Pub. 218M 2010). The maximum diaphragm spacing is traditionally 25 feet. The Pennsylvania standards are based on structural frame analysis and past design experience. The composite dead loads included concrete in the valleys of the stay-in-place forms, deck overhang and beam haunch. A standard barrier non-composite dead load was distributed to the fascia and first interior beams. A standard future wearing surface dead load was also applied. Seismic, centrifugal and wind loads were omitted from the study because they would not have a significant influence on the beam design. The live load used in the analysis included the PHL-93, P-82, ML-80 and TK527 vehicles. Based on a sample of previous bridge projects, the following maximum span lengths were set: 38.1 m for spread box beams, 51.2 m for bulb-tee beams, and 47.2 m for I-beams (Table 1).

The maximum span lengths were chosen to acquire the largest beam sections, which in turn require the largest diaphragms. The beam section properties were taken from BD-652M (Pub. 218M 2010). The larger reinforced concrete diaphragm sections cause the aluminum diaphragms to require a more conservative design. This allows for a uniform comparison of the types of diaphragms.

Table 1: Parametric Study Data

| BEAM TYPE | BEAM SIZE (cm) | TOP FLANGE WIDTH (m) | SPAN LENGTH (m) | # LANES | BRIDGE WIDTH (m) | BEAM SPACING (m) | # BEAMS | # INTERM. DIAPH. |
|---|---|---|---|---|---|---|---|---|
| Spread Box | 121.9x167.6 | 1.219 | 38.1 | 4 | 19.317 | 2.134 | 9 | 3 |
| PA Bulb-Tee | 83.8/237.5 | 1.219 | 51.206 | 4 | 19.317 | 2.159 | 9 | 2 |
| AASHTO I | 71.1/213.4 | 1.067 | 47.244 | 4 | 19.317 | 2.159 | 9 | 1 |

**4. DESIGN SPREADSHEET**

The main focus of the design was intermediate aluminum diaphragms, which are located between the beams within the span of the bridge. A Microsoft Excel spreadsheet was created to facilitate the designs for varying diaphragm section properties. A diaphragm design was created for each type of beam in the parametric study.

The design of aluminum diaphragms was developed using flowcharts to outline the procedure. The flowcharts help to visualize the aluminum diaphragm design process. Each aspect of the design was separated into its own flowchart. The different flowcharts included axial compression, flexure, shear, torsion and connections. The sequence of steps shows the decisions that must be made, and all of the design parameters that must be checked in order to arrive at the solution. The procedure was used to create the aluminum diaphragm design spreadsheet.

An I-shaped section was considered for the design of aluminum diaphragms. Alternative shapes and tubes were not investigated due to their less favorable section properties and constructability. Only single plate diaphragm members were considered. Multiple member k-brace and cross x-brace diaphragms provide reduced section area and weight, but were not investigated due to the complex geometry and connections. I-shaped sections are more favorable and provide sufficient weight reduction. ASTM B221 6063-T6 Aluminum material is proposed for the diaphragms. This alloy has a compressive yield strength of 172.4 MPa and a modulus of elasticity of 69637 MPa (AASHTO 2012). Using the "Aluminum Design Manual" (ADM 1994) it was determined that extruded and rolled aluminum beams are not available in large enough sections to meet the design requirements. Therefore, a built-up welded section is provided to achieve the necessary results.

A reduction in strength must be accounted for due to the built-up aluminum members being welded. A limiting stress, $F_{pw}$, must be used when greater than 15% of the section area is lying within 1" of a weld. Welding per ANSI/AWS D1.2 is required (AASHTO 2012). 6063-T6 is highly weldable using tungsten inert gas welding. Improved welding can be obtained using arc welds. Material can be re-heated or re-treated to restore a higher strength (Welding 2013). Another important design consideration is lateral torsional buckling, which can cause problems with the design of slender sections. Each individual component of the section must be checked for compactness. Diaphragms are considered secondary structural members. Therefore, if the section is compact, local buckling can be ignored.

The aluminum diaphragms are designed based on the allowable capacity of the reinforced concrete diaphragms. Among the structural design requirements, axial compression was found to be the controlling design parameter for the aluminum diaphragms treated as columns. Since the customary reinforced concrete diaphragms are primarily designed to resist wind loading and are strongest in compression, the proposed aluminum diaphragms must be designed to accommodate the required axial compressive stress. Rather than using structural analysis to determine the required strength of the aluminum diaphragms, this simplified approach was used to provide a more uniform comparison with the concrete diaphragms. Performing iterations of section properties determined that the required aluminum diaphragm dimensions exhibited relationships. As the depth of the section is increased, the axial compressive resistance increases. However, as the flange width to thickness ratio increases, the axial compressive resistance decreases (Figure 1). Similar relationships can be expected for flexure and shear. Flexure strength will increase as the depth of section increases. Shear strength will increase as the flange thickness increases.

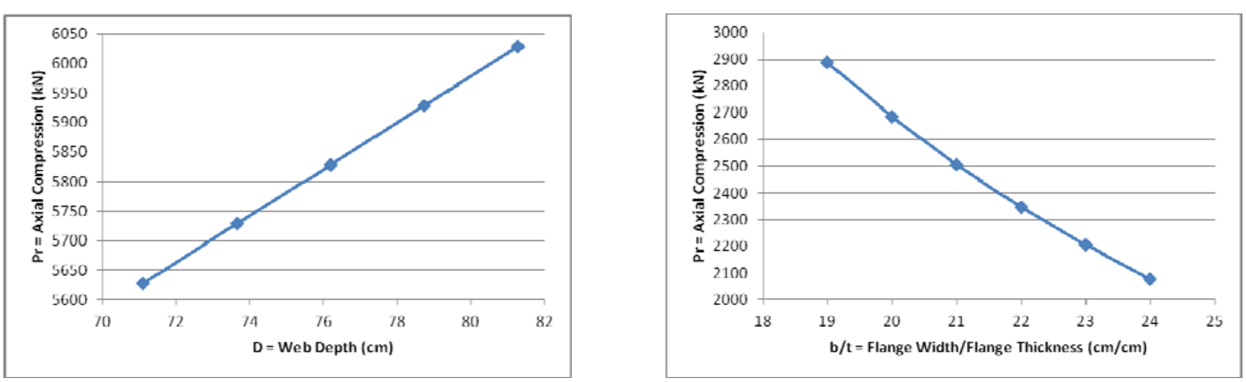


Figure 1. Aluminum Diaphragm Section Properties Influence on Axial Compressive Strength

The aluminum diaphragm design must be checked for flexure, shear and torsion. The fatigue design check is not required for the aluminum diaphragms as there is no apparent net tensile stress (AASHTO 2012).

The aluminum diaphragms are connected to steel WT section brackets with bolts. Welding of two dissimilar metals is considered unfavorable. Welding, especially overhead welding, in the field can be difficult and time consuming (AASHTO 2012). The steel brackets are bolted to the web of the prestressed concrete beams. ASTM A325 High Strength Steel bolts are used for the connections rather than aluminum bolts due to their availability, higher strength and lower cost. Stainless steel or galvanized steel could provide increased corrosion resistance for the connections, but these materials also require higher cost. The use of bolted connections is easier for construction, and saves time throughout the duration of maintenance and protection of traffic during a repair. This provides an economical savings for less labor in the field.

Designs were considered for each type of connection including aluminum diaphragm to steel T-shape, steel T-shape to aluminum diaphragm, and steel T-shape to prestressed concrete beam. The connection designs were checked for bearing, combined tension and shear, block shear rupture, and slip resistance. The bolt spacing and clearance was also evaluated.

## 5. DESIGN METHODOLOGY AND PROCEDURE

### 5.1 Axial Compressive Strength of Existing Reinforced Concrete Diaphragm (AASHTO 2012) (ACI 2008)

For concrete members with tie reinforcement (typically true for concrete diaphragms), the nominal axial compressive resistance, $P_n$ , is determined by:

[1] $P_n = 0.80\ [0.85f'_c\ (A_g - A_{st}) + f_y\ A_{st}]$

where $A_g$ is the gross area of section and $A_{st}$ = total area of longitudinal reinforcement. The required axial load, $P_u$ , is set to equal the factored axial resistance of existing concrete diaphragm, $P_r$ .

[2] $P_u = P_r = Ø_c\ P_n = 0.75P_n = 0.60\ [0.85f'_c\ (A_g - A_{st}) + f_y\ A_{st}]$

where $Ø_c$ is the resistance factor for axial compression.

### 5.2 Axial Compressive Strength of Proposed Aluminum Diaphragm (AASHTO 2012)

Rolled channels, solid plates, rectangular tube shapes or I-shapes may be selected as the aluminum diaphragms. Aluminum diaphragms must be designed to satisfy the code-specified axial compression, flexure, shear and lateral torsional buckling requirements. In general, the axial compression limit state will control for this design. Most available rolled aluminum shapes are considered slender for compression. Therefore, the design must be checked for compactness. After several design trials, it was determined that a built-up welded I-shaped section is required for this design. For aluminum members, the factored compressive resistance of the section as a whole and treated as a column shall not exceed:

If $\lambda \leq S_2$ , then:

[3] $F_r = Ø_c\,[B_c - D_{cc}\ \lambda] \leq Ø_s\ (F_{cy}/k_c)$

If not,

[4] $F_r = (Ø_c\ F_{cy})/\lambda^2$

where $\lambda$ is the column slenderness factor defined by:

[5] $\lambda = (KL/r)\ (1/\pi)\sqrt{F_{cy} / E}$

[6] $S_2 = (C_c/\pi)\ \sqrt{F_{cy} / E}$

[7] $D_{cc} = \pi D_c\sqrt{E / F_{cy}}$

where K is the column effective length factor (= 1.0 typically, assuming pinned ends), L is the unbraced length and r is the radius of gyration of the section shape. $Ø_c$ is the resistance factor for axial compression (= 0.90) and $Ø_s$ is the resistance factor for shear (= 0.90). $B_c$ , $C_c$ and $D_c$ are buckling parameters, and $k_c$ is a coefficient based on the aluminum designation, alloy and temper (ASTM B221, 6063-T6). $F_{cy}$ is compressive yield strength. If the area of a cross section lying within 2.54 cm (1 in.) of a weld, $A_w$, is greater than 15% of the net area, A, the limiting stress shall be:

[8] $F_{pw} = F_n - (A_w/A)(F_n - F_w)$

Check web plate compactness. The slenderness of plates shall satisfy:

[9] $b/t \leq k\sqrt{E/F_y}$

The factored compressive resistance of outstanding flanges for an I-shaped section shall be taken as:

If $(b/t) \leq S_2$ , then:

[10] $F_r = Ø_c [B_p – 5.1D_p (b/t)] \leq Ø_s (F_{cy}/k_c)$

[11] $S_2 = (C_p /5.1)$

If not,

[12] $Fr = (Ø_c \pi^2 E)/[5.1 (b/t)]^2$

where b and t are the width and thickness of the flange respectively, and $B_p$ , $C_p$ and $D_p$ are buckling parameters.

Check flange plate compactness. The slenderness of plates shall satisfy:

[13] $b/t \leq 0.64\sqrt{k_c E/F_y}$

$P_r$ must be at least equal to the required $P_u$ value calculated by equation [2], namely:

[14] $P_r \geq P_u = 0.60 [0.85f'_c (A_g – A_{st} ) + f_y A_{st}]$

For accommodating the connection bolts, the proposed aluminum diaphragm will likely be deeper than one third of the depth of the existing prestressed concrete beam. The selected aluminum diaphragm will then be checked against flexure, shear and lateral torsional buckling requirements, followed by connection designs.

### 5.3 Design of Bolted Connections (AASHTO 2012) (AISC 2005)

For field erection of the proposed aluminum diaphragms, bolted connections are desirable and high-strength bolts are typically used. For the ASTM A325SC high strength steel bolts connecting the proposed aluminum diaphragm and connection steel shape, structural tees with one row of holes is desirable. For the high strength steel bolts connecting the steel tees to the existing prestressed concrete beam, two rows of holes are preferred. For the connection from steel tee to aluminum diaphragm, the following bolt strengths must be assessed: shear, bearing, block shear, and slip resistance. For the connection from steel T-shape to prestressed concrete beam, the bolt shear, combined tension and shear, bearing, block shear, slip resistance, bolt spacing and edge distance parameters must be checked. First, propose a bolt pattern based on the shear requirement and then check all other relevant design requirements. The nominal shear resistance is determined by:

[15] $R_n = 0.38 A_b F_{ub} N_s$ (conservatively assuming threads to be through the shear planes)

where $A_b$ is the cross-sectional area of bolt, $F_{ub}$ is the specified minimum tensile strength of bolt and $N_s$ is the number of shear planes per bolt. Bolts should be arranged to meet the code-specified minimum clear distance and minimum edge distance requirements.

## 6. ILLUSTRATIVE DESIGN EXAMPLE

The illustrative design example represents a typical bridge studied, which possesses the following data:
Existing reinforced concrete diaphragm: 25.4 cm x 182.9 cm with two M19 reinforcement bars at the bottom, six M16 reinforcement bars on each face, and M13 stirrups spaced at 30.5 cm on center. All bars are epoxy coated. Concrete cover = 3.8 cm; $f'_c$ = 20.7 MPa; $f_y$ = 413.6 MPa. Existing prestressed concrete girder: 83.8 cm x 237.5 cm PA Bulb-Tee girder spaced at 215.9 cm on center. The structural aluminum assumed in this example is ASTM B221 6063-T6 Aluminum. The structural steel assumed in this example is AASHTO M270 or ASTM A709 Grade 50 (AASHTO 2012).

### 6.1 Select the Aluminum Diaphragm Size based on Axial Compression

$P_n = 0.60\,[0.85f'_c\,(A_g - A_{st}) + f_y\,A_{st}] = 0.60\,[0.85x20.7((25.4x182.9) - 29.5) + 413.6x29.5] = 5600$ kN

$S_2 = (C_c/\pi)\sqrt{F_{cy}/E} = (66/\pi)\sqrt{161.13/69637} = 1.0106$

$\lambda = (KL/r)\,(1/\pi)\sqrt{F_{cy}/E} = (1x195.6/34.01)\,(1/\pi)\sqrt{161.13/69637} = 0.0881 < 1.0106$

$F_r = \text{Ø}_c\,[B_c - D_{cc}\,\lambda] \le \text{Ø}_s\,(F_{cy}/k_c) = 0.9\,[204.25 - 1.106x0.0881] \le 0.9\,(161.13/1) = 178.1 \le 145$ MPa

Try 78.7 cm x 2.54 cm web; 50.8 cm x 2.54 cm flanges, A = 458.06 $cm^2$ (Figures 2-4).

$P_r = F_r\,A = 145x458.06 = 6642.65$ kN > 5600 kN, OK

Check web slenderness: $b/t \le k\sqrt{E/F_y} = 78.7/2.54 \le 1.49\sqrt{69637/161.13} = 31 \le 31$, COMPACT

Check flange slenderness: $b/t \le 0.64\sqrt{k_c E/F_y} = 50.8/2/2.54 \le 0.64\sqrt{0.7184x69637/161.13} = 10 < 11.2773$, COMPACT

### 6.2 Connection between the Steel T-shape and the Existing Prestressed Concrete Beam

Steel shape: WT180x50.5 (mmxkg/m) ($F_y$ = 345 MPa).

High strength bolts: 2.2 cm diameter ASTM A325SC bolts in oversize holes ($d_h$ = 2.7 cm).

*Bolt Shear*: $R_n = 0.38\,A_b\,F_{ub}\,N_s = 0.38x387x827.3x1 = 121.7$ kN/bolt

$R_r = K_h\,\text{Ø}_s\,R_n = 0.85x0.8x121.7 = 82.7$ kN/bolt

Required Number of bolts, $N_b = V_u/R_r = 758.2/82.7 = 10$ bolts (2 columns of 5 bolts through flange, Figure 4)

### 6.3 Connection between the Aluminum Diaphragm and Steel T-shape

Steel shape: WT180x50.5 (mmxkg/m). Aluminum Diaphragm: 78.7 cm x 2.54 cm web; 50.8 cm x 2.54 cm flanges

High strength bolts: 3.18 cm diameter ASTM A325SC bolts in short-slotted holes ($d_h$ = 3.33 cm along the tension plane and 4.13 cm along the shear plane).

*Bolt Shear*: $R_n = 0.38\ A_b\ F_{ub}\ N_s = 0.38 x 793.5 x 827.3 x 1 = 249.5$ kN/bolt

$R_r = K_h\ Ø_s\ R_n = 0.85 x 0.8 x 249.5 = 169.6$ kN/bolt

Required Number of bolts, $N_b = V_u/R_r = 758.2/169.6 = 4.5$ => Use 5 bolts (1 column through web, Figure 3)

*Bolt Bearing for Aluminum*: (Edge Distance)/(Bolt Diameter) ≤ 2.0 = 2.5/1.25 = 2.0

$F_r = Ø_y\ F_{by} = 0.9 x 275.8 = 248.2$ MPa < 325.7 MPa

$R_r = F_r\ d_b\ t_w = 248.2 x 31.75 x 25.4 = 200.16$ kN/bolt > $V_u = 758.2/5 = 151.6$ kN/bolt, OK

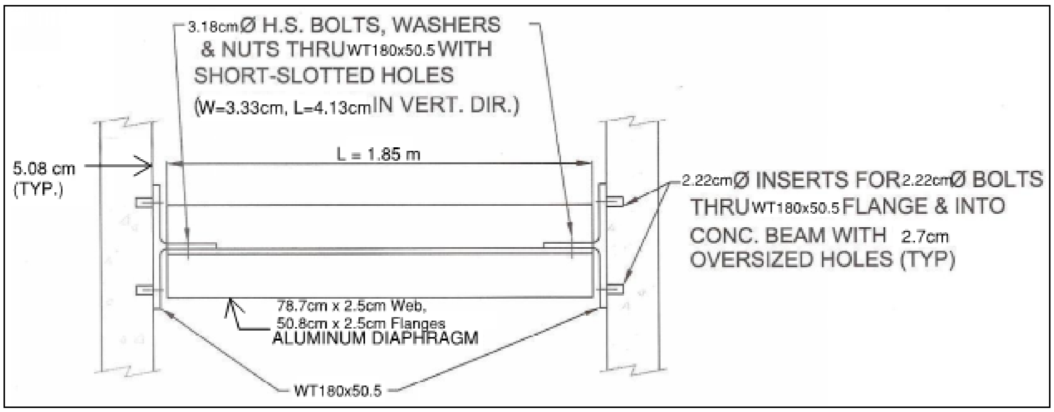


Figure 2. Aluminum Diaphragm Plan View

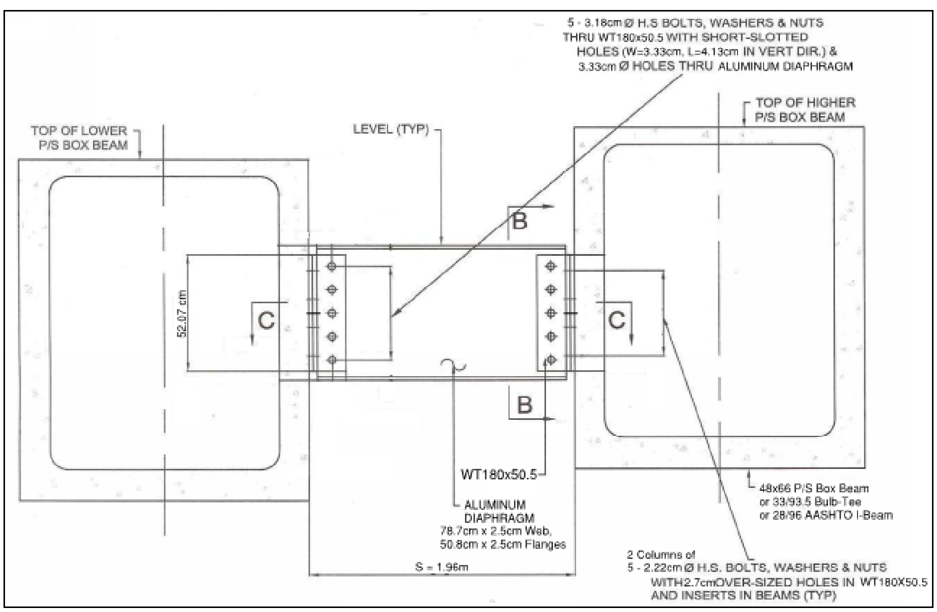


Figure 3. Aluminum Diaphragm Elevation View

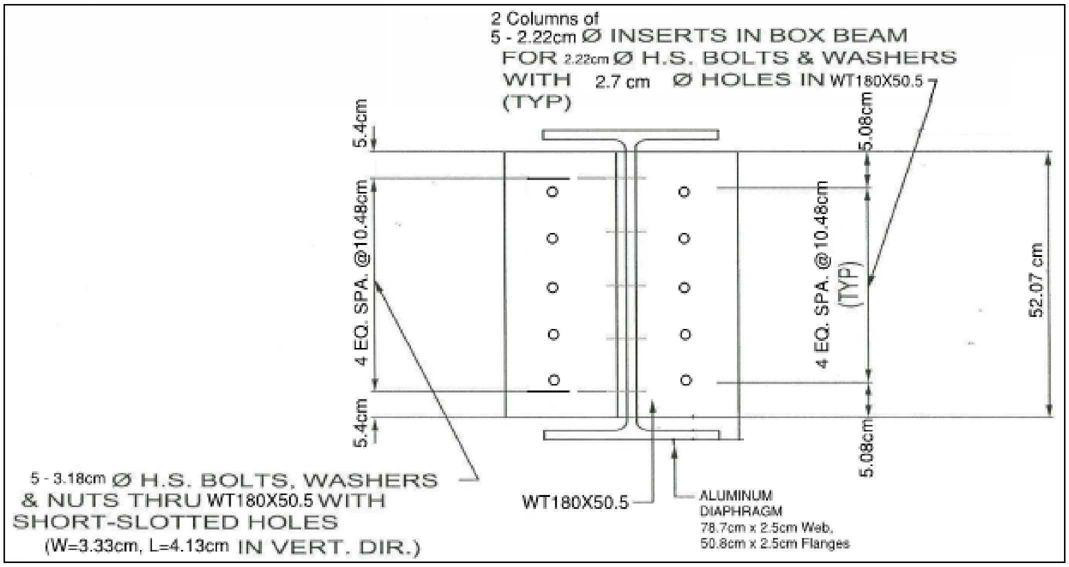


Figure 4. Aluminum Diaphragm Typical Section and Connection Detail

## 7. BENEFITS OF USING ALUMINUM DIAPHRAGMS

The benefits of using aluminum diaphragms instead of traditional reinforced concrete diaphragms include decreased dead load, reduced construction time and cost, and decreased maintenance cost.

### 7.1 Diaphragm Weight Comparison

Total number of diaphragms (N) = 8 bays x 2 per bay x 2 spans = 32

Existing reinforced concrete diaphragms: Weight = 21,406 N x 32 = 684,992 N

Proposed aluminum diaphragms: Weight = 2,251 N

Steel connection shape = 525 N

Bolts = 10 (3.18 cm Ø bolts); = 20 (2.22 cm Ø bolts); Weight = 178 N

Total Weight = (2,251 + 525 + 178) x 32 = 94,528 N

The proposed aluminum diaphragm weight is less than 14% of the reinforced concrete diaphragm weight. The savings of dead weight will result in higher live load capacity for the structure. Extra live load capacity can be a key benefit for existing structures that are weight restricted. Therefore, the load posting could be increased or removed entirely depending on the results of a revised load rating analysis, which incorporates the aluminum retrofits.

### 7.2 Diaphragm Quantities and Construction Cost Comparison

The estimated quantities and construction costs for the representative project are summarized in Table 2, in which the unit costs are based on the average costs in Pennsylvania for 2013 (ECMS 2013) (Gates 2013) (Steele 2013). For the estimate of construction days, two two-man construction crews were assumed to be earning regular labor wages for the central Pennsylvania region (Gates 2013). The aluminum diaphragms were assumed to be fabricated from 1” x 48” x 96” stock plates, which require programmed CNC machine cutting, and welded using 5/16” fillet welds . A unit cost of $263/cwt (hundredweight) was assumed for the stock plate aluminum (Steele 2013). As shown in Table 2, the material cost for aluminum diaphragms is about 60% higher than traditional reinforced concrete diaphragms for this particular two-span bridge. However, the installation savings by using aluminum diaphragms is about 62%, and the difference in total project cost for each alternative is only 23%. Additional savings can be expected for larger bridges. This estimate does not include maintenance costs; however, the aluminum diaphragms would prove to be a substantial cost savings since they would require no maintenance or painting. The concrete diaphragms would eventually require additional repairs, and ultimately replacement. The corrosion resistant aluminum diaphragms would most certainly outlast the rest of the structure. The aluminum diaphragms necessitate less construction time in the field because they are fabricated in the shop instead of on site. There is no concrete forming or curing time required. They also provide a shorter construction time because they can be quickly bolted into position during installation.

Table 2: Estimated Quantities and Construction Costs for the Representative Project

| OPTION | ITEM | UNIT | UNIT COST | QUANTITY | ITEM COST |
|---|---|---|---|---|---|
| Concrete Diaphragms | Installation of New Concrete Diaphragms | DAY | $3,128.00 | 8 | $25,024.00 |
| | 12” Dowel Holes | EACH | $30.00 | 896 | $26,880.00 |
| | Class AA Concrete | CY | $1,200.00 | 38 | $45,624.00 |
| | Epoxy-Coated Reinforcing Bars | LB | $1.60 | 6717 | $10,746.68 |
| | Total | | | | $108,274.68 |
| Aluminum Diaphragms | Installation of New Aluminum Diaphragms | DAY | $2,392.00 | 4 | $9,568.00 |
| | 6” Dowel Holes | EACH | $20.00 | 640 | $12,800.00 |
| | Fabricated Structural Aluminum | LB | $5.79 | 16171 | $93,660.14 |
| | Fabricated Structural Steel | LB | $6.00 | 3763 | $22,576.00 |
| | High-Strength Steel Bolts | EACH | $4.00 | 960 | $3,840.00 |
| | Total | | | | $142,444.14 |

1 inch (1” or 1 in.) = 25.4 mm; 1 foot (1’ or 1 ft.) = 0.3048 m; 1 $in^2$ = 645 $mm^2$; 1 cu. yd. (1 CY) = 0.76455 $m^3$; 1 lb (1 LB) = 4.448 N; 1 lb/ft (1 plf) = 0.0146 N/mm; 1 ksi (1 $kip/in^2$) = 6.894 MPa; 1 kip-ft = 1.355 kN-m; 1 kip-in = 0.113 kN-m; WT7x34 = WT180x50.5 (mmxkg/m)

## 8. CONCLUSIONS AND RECOMMENDATIONS

This paper describes the load and resistance factor design methodology and procedure as related to aluminum diaphragms in a prestressed concrete bridge, as well as an illustrative design example and applicable benefits. This study concludes that aluminum diaphragms provide improved constructability, and their use is both functional and economical.

The use of aluminum diaphragms in a typical prestressed concrete bridge will result in a significant reduction of dead load and a proportional increase in live load capacity. By improving the capacity of an existing bridge, it can remain functional for an extended period of time. Use of aluminum diaphragms will also yield savings of construction costs and maintenance costs.

Reinforcing steel and tendons must be avoided when drilling holes for dowels and inserts in the prestressed concrete beams. Due to the functionality, rapid construction, and economical benefits, aluminum diaphragms are recommended in rehabilitation projects and new construction for prestressed concrete bridges. Similar studies can be performed to further validate the advantages of using aluminum diaphragms using international design standards such as the German code DIN 4113 and the European code EN 1999. Alternative methods for designing equivalent aluminum diaphragms can be explored using structural analysis.

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