HUB-GIRDER BOLT ASSEMBLY WITHOUT AN INTERFERENCE FIT IN BASCULE BRIDGES

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DISCLAIMER

PREFACE

The investigation reported in this document was funded by a contract awarded to the University of South Florida, Tampa by the Florida Department of Transportation (FDOT). Mr. Jack O. Evans was the Project Manager. It has been a pleasure to work with Jack and we would like to acknowledge his numerous contributions to this study.

This project could not have been successfully completed without enormous support and help from other members of the FDOT. We would like to especially acknowledge Mr. Siddhartha Kamath, Mr. Thomas A. Cherukara and Mr. Angel Rodriguez.

We wish to thank Mr. George Patton and Mr. Sergey Kupchenko of EC Driver & Associates in Tampa, FL for their assistance. Mr. George Patton's technical insights proved to be very valuable at early stages of the project. Also, we would like to acknowledge their assistance in providing information on some of the sample bridges analyzed in this project.

EXECUTIVE SUMMARY

Trunnion-hub-girder (THG) assemblies of bascule bridges are currently assembled using shrink fits. Failures during assembly of THG of the Miami Avenue Bridge and Brickell Avenue Bridge led to a study at the University of South Florida aimed at finding their causes. The study found that one of the two assembly procedures currently used results in high likelihood of hub cracking. One of the possible means to avoid such failures is to modify the assembly procedure by eliminating the shrink fit between the hub and the girder. This project presents the result of a study aimed at developing such hub-girder assemblies without shrink fits.

The proposed design scheme utilizes slip-critical bolted connection between the hub, girder and a backing ring. The bolted connection design utilizes turned bolts with locational clearance (LC) fit. Loads to be resisted by the connection are identified and computed individually and subsequently combined to arrive at the net required slip resistance. Using this value, the bolt size and number of bolts are determined using a spreadsheet developed for this purpose. In addition to slip resistance, the bolted connection is also checked for bolt shear strength and bearing stresses of the bolted members.

The design procedure presented here was refined using results from an axisymmetric finite element model. The model proved useful in highlighting the behavior of friction force resulting from the interference fit between the backing ring and the hub.

Six representative bridges were analyzed using this design scheme. The analysis revealed that the proposed design is unlikely to adversely impact practice since most THG assemblies utilize more bolts than required for achieving a slip-critical connection. This may be because hub flange dimension ratio to trunnion size are dictated by AASHTO and FDOT standards, and result in sufficient room on the hub flange to accommodate extra bolts.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The present study aimed at elimination of the shrink fit between the hub and the girder in a bascule bridge was initiated after several instances of failure during assembly in bridges utilizing an interference fit. Trunnion-Hub-Girder (THG) assemblies of bascule bridges were found to fail during assemblies of the Christa McAullife bridge and Brickell Avenue bridge in Florida. In addition, very minute surface cracks and shrink defects were observed in the hubs after the trunnion-hub assemblies were installed in the girders on the Miami Avenue Bridge. Such failures and associated delays can cost more than $100,000 and therefore need to be avoided.

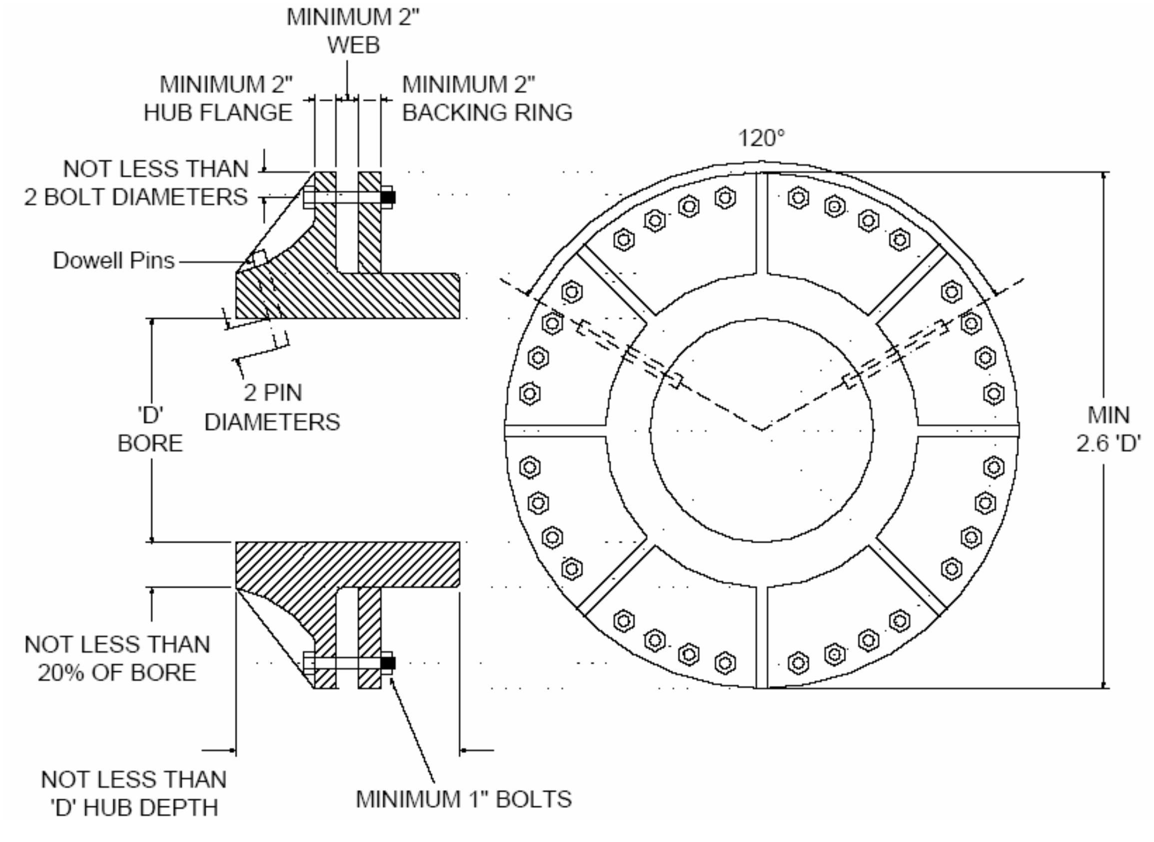


Figure 1.1 Trunnion Hub Design Guide [1].

Figure 1.1 shows a typical hub design currently used [1]. The web of the bridge girder is assembled between the hub and the backing ring. While current designs utilize an FN2 interference fit [2] between the radial interface of the girder and the hub, the design proposed here replaces this with a clearance between the hub and girder along with a slip-critical connection with high strength bolts at the hub flange to girder annular interface. The current practice of using FN2 interference fit between the backing ring and the hub is retained.

1.2 Current Design Practice

Current bascule bridge designs are governed by American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Movable Highway Bridge Design Specification [3], and utilize a FN2 interference fit between the hub and the girder. The FN2 fit is achieved by shrink fitting the trunnion-hub assembly into the girder. Recent analytical and theoretical study of the assembly process conducted at University of South Florida (USF) [4] showed that the probability of failure due to hub cracking is significantly increased due to the combination of large thermal stress in the assembly and the reduced critical crack length at the lower temperature encountered during the cooling of the trunnion-hub assembly.

In order to eliminate failure due to hub cracking during the shrink fitting assembly procedure, the present study proposes the use of a clearance fit between the girder and trunnion-hub assembly. The assembly design under consideration utilizes high-strength bolts to form a slip-critical connection between the girder and the hub. This connection transfers the girder loads to the trunnion through the hub, thereby eliminating the need for the FN2 interference fit. The bascule bridge designed by EC Driver & Associates for the 17th Street Causeway in Broward County utilizes such a design. Salient feature of the design are discussed in Chapter 2.

1.3 Literature Review

Literature review for the project primarily consisted of collection of information on design standards for bascule bridges and bolted connections [1-19]. References consulted for the current task are listed at the end of this report and referred to at the appropriate section in the report. In addition, preliminary calculations from the Bridge Development Report (BDR) and final design drawings of the 17th Street Causeway bascule bridge in Broward County were also reviewed [5 & 6].

1.4 Overview of Report

The remaining report consists of six additional chapters. Chapter 2 presents the general design scheme for the hub-girder assembly without an interference fit and discusses the design utilized for the 17th Street Causeway bascule bridge. Chapter 3 presents the procedure utilized for design of hub-girder connection without an interference fit. The design procedure is implemented using a spreadsheet, which is discussed in Chapter 4. Six existing representative bridges that were analyzed using the proposed procedure are presented in Chapter 5. Finite element models used to study some of the design issues are presented in Chapter 6. Finally, Chapter 7 presents the conclusions and recommendations from this study.

CHAPTER 2

DESIGN SCHEME

2.1 Introduction

Figure 2.1 shows the proposed scheme for the hub-girder assembly without an interference fit. It consists of a trunnion assembled to a hub with a FN2 fit. The hub is bolted to the girder with high strength bolts to form a slip-critical connection. A backing ring is utilized in the bolted connection to transfer the girder load to the hub through the bolts in double shear. The backing ring is assembled to the hub using a FN2 fit. Since the hub-girder connection utilizes a clearance fit, this scheme eliminates the need to shrink the previously assembled trunnion-hub assembly when being installed in the girder, thereby eliminating the risk of hub cracks associated with the shrinking process [4].

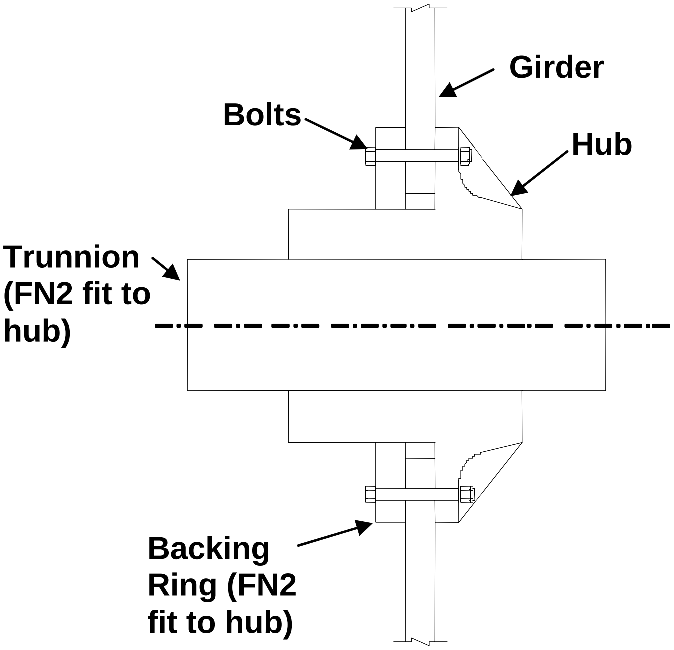


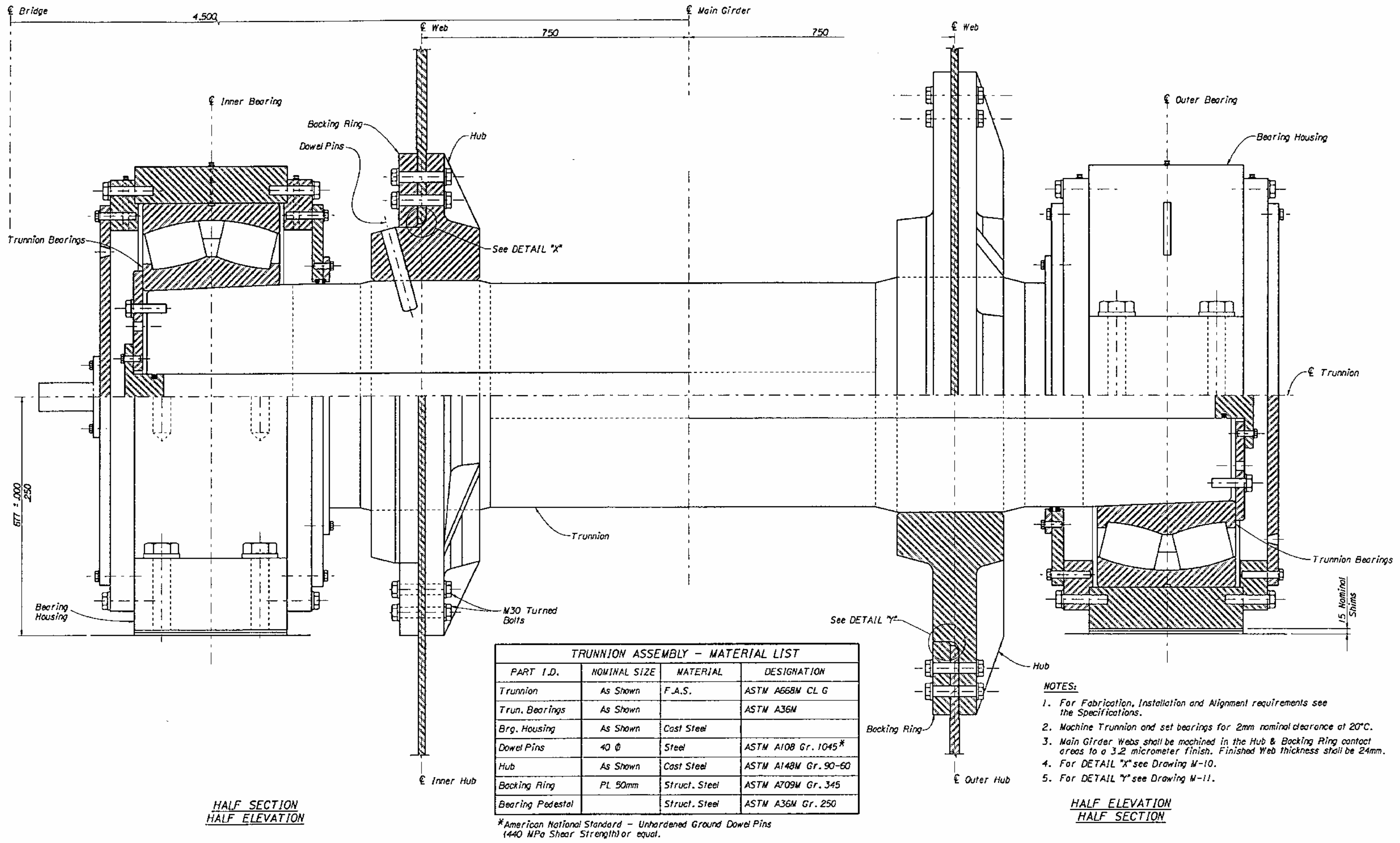
Figure 2.1 Hub-girder assembly without an interference fit.

The above scheme has been successfully utilized in the design of 17th Street Causeway bascule bridge in Broward County. The next section discusses some of the details of this design.

2.2 Review of 17th Street Causeway Bridge

The design of bascule bridge for the 17th Street Causeway, Broward County was reviewed since it did not utilize shrink fit between the hub and the girder. The final design plans [5] and preliminary calculations from the BDR [6] were made available to USF. The final design calculations for the bridge were unavailable. Preliminary calculations from BDR show the bolt being designed to take the dead load of the structure as a slip critical connection. However, the final design is significantly different from the scheme reflected in the preliminary calculations. Discussions with one of the design engineers revealed that the connections were designed with A449M bolts assuming equal distribution of load to all the bolts (i.e., shear lag was not explicitly considered).

The 17th Street Causeway bascule bridge design features dual hubs on a box girder as shown in Figure 2.2. The trunnion reactions used for the design are presented in Table 2.1. Additional loading required for design, such as the dead load dynamic allowance can be obtained as percentage of the reaction loads. The bridge was designed to operate in maintenance mode with one of the inner trunnion bearing removed for service. The inner hub flange has a inner diameter of 950 mm and outer diameter of 1360 mm. This is assembled to the girder with a 990 mm diameter opening. The outer hub flange has a inner diameter of 1385 mm and outer diameter of 1810 mm. This fits on to a girder with a 1420 mm diameter opening. Each hub is assembled to the girder with two bolt circles of M30 turned A449M bolts with a total of 54 bolts on each hub (see Figure 2.3). Backing rings with FN2 fit to the hub cylinder are used to transfer the load in double shear from the girder to the trunnion. Each trunnion therefore utilizes 108 M30 A449M turned bolts. It must be pointed out that A449M bolts are not generally approved for slip-critical connections [7] (possibly due to lack of test data). However, since the design required turned bolts machined down from stock with diameter larger than 1.5" (which are not available in A325) using A449M was considered to be acceptable.



TRUNNION ASSEMBLY – MATERIAL LIST			
PART I.D.	NOMINAL SIZE	MATERIAL	DESIGNATION
Trunnion	As Shown	F.A.S.	ASTM A668M CL G
Trun. Bearings	As Shown		ASTM A36M
Brg. Housing	As Shown	Cast Steel	
Dowel Pins	40 Ø	Steel	ASTM A108 Gr. 1045*
Hub	As Shown	Cast Steel	ASTM A148M Gr. 90-60
Backing Ring	PL 50mm	Struct. Steel	ASTM A709M Gr. 345
Bearing Pedestal		Struct. Steel	ASTM A36M Gr. 250

*American National Standard – Unhardened Ground Dowel Pins (440 MPa Shear Strength) or equal.

NOTES:

1. For Fabrication, Installation and Alignment requirements see the Specifications.
2. Machine Trunnion and set bearings for 2mm nominal clearance at 20°C.
3. Main Girder Webs shall be machined in the Hub & Backing Ring contact areas to a 3.2 micrometer finish. Finished Web thickness shall be 24mm.
4. For DETAIL "X" see Drawing M-10.
5. For DETAIL "Y" see Drawing M-11.

Figure 2.2 Trunnion-Hub-Girder Assembly of 17th Street Causeway Bascule Bridge [5].

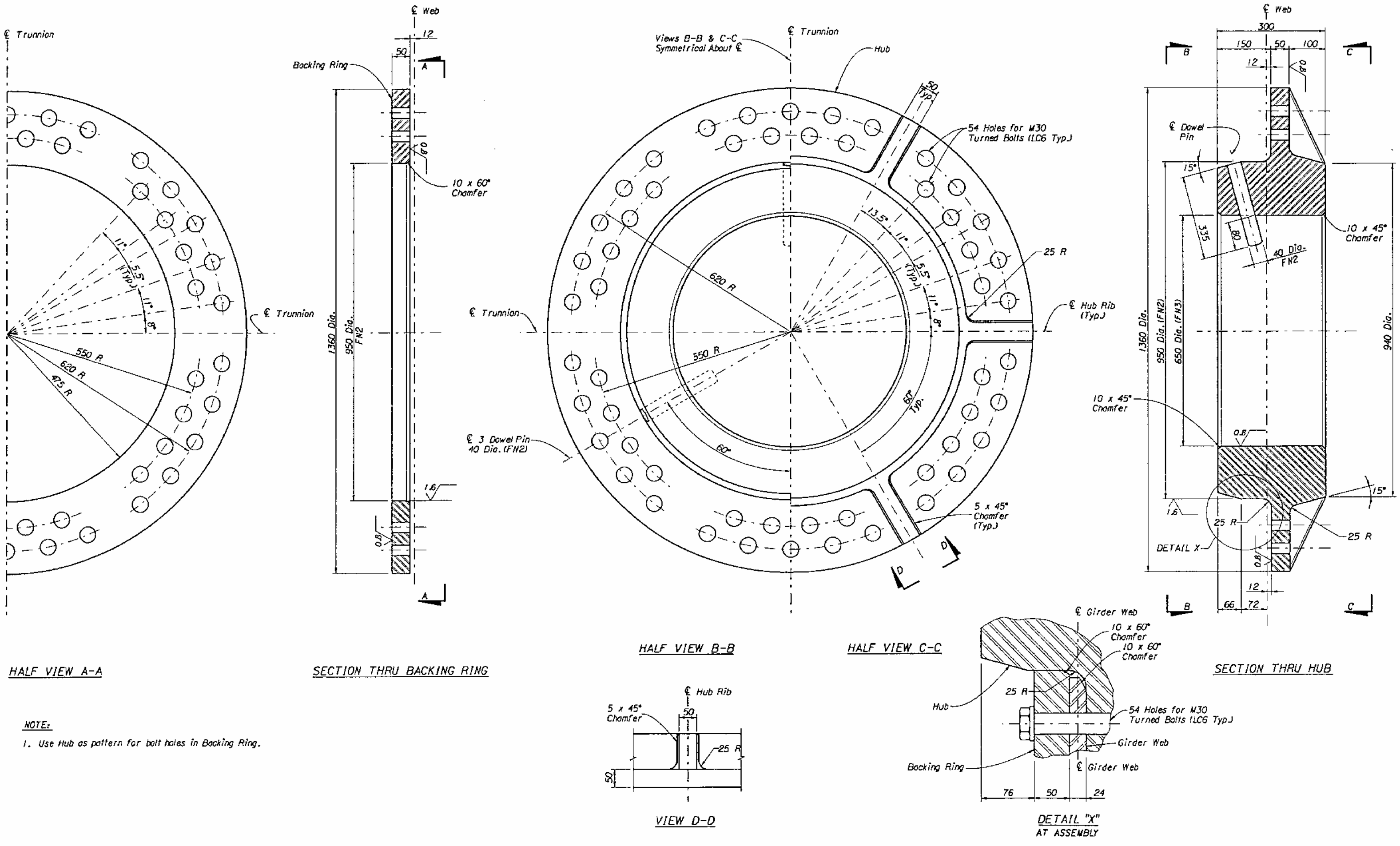


Figure 2.3 Trunnion-Hub-Girder Assembly Bolt-Pattern 17th Street Causeway Bascule Bridge [5].

Table 2.1 Trunnion reactions for 17th Street Causeway Bascule Bridge [5].

Loads	Span Closed		Span Full Open	
	Horiz. (kN)	Vert. (kN)	Horiz. (kN)	Vert. (kN)
Dead	-	5200	-	5200
Min. Live	-	-2230	-	
Impact	-	-670	-	
Max. Live	-	500	-	
Impact	-	150	-	
Wind	-	-	1970	320

2.3 Trunnion-Hub-Girder Assemblies

As discussed earlier, the proposed design scheme is similar to that being currently utilized in bascule bridges except that the interference fit between the girder and the hub is eliminated. Plans of existing bridges were reviewed to identify common bascule bridge designs used in Florida. Three different schemes were found. The most common among the older bridges is a Hopkins trunnion configuration (see Figure 2.4), which is essentially a cantilever arrangement with one end of the trunnion fixed to the main trunnion bearings and the other end (tapered) being supported at the trunnion girder. In such trunnion designs, the hub-girder assembly occurs on the main bascule girder. The Hopkins trunnion scheme utilizes one main bearing and one hub per main girder. The second scheme, which is commonly used in recent times, is referred to as a simple trunnion, and utilizes two main trunnion bearings and one hub for each main girder (see Figure 2.5). Since the current FDOT Structures Design Guidelines [1] recommends the use of simple trunnion, the current project primarily focuses on hub-girder connections in bascule bridges with simple trunnion. The final scheme, found in larger bascule bridge with box girders as the main girders, utilizes two hubs with two bearings for each of the main girders (see Figure 2.2).

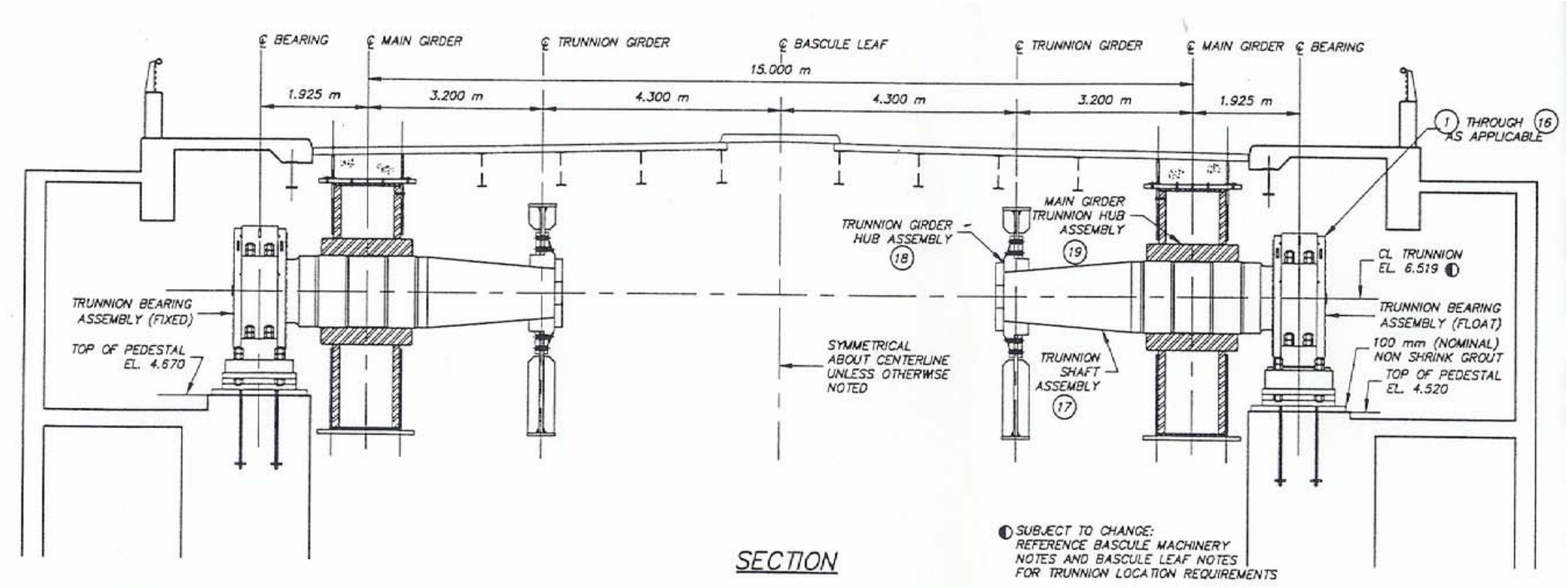


Figure 2.4 Bascule Bridge machinery with Hopkins Trunnion.

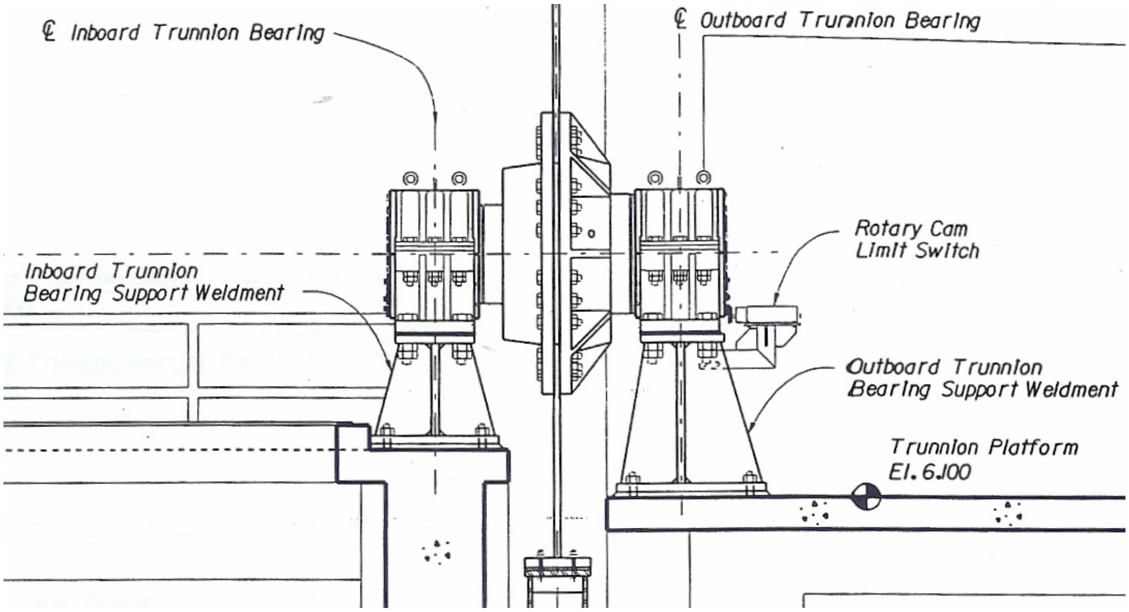


Figure 2.5 Bascule Bridge with a Simple Trunnion.

The hub-girder connection without an interference fit presented in Figure 2.1 can be used in any of the three types of trunnion-hub-girder assemblies discussed earlier, but Hopkins trunnion configuration may require additional analysis as indicated in later chapters. The procedure to design such assemblies is presented in the next chapter.

CHAPTER 3
DESIGN PROCEDURE

3.1 Introduction

The proposed design scheme for the hub-girder assembly without an interference fit was shown in Figure 2.1. Figure 3.1 shows current FDOT requirements on dimensions of various members of a typical trunnion-hub-girder assembly [1]. This chapter outlines the design process starting with identification of loads acting on the hub-girder assembly and leading to the final design of the bolted connection. The design method is based on the LRFD philosophy (see section 1.3, Ref. [8]).

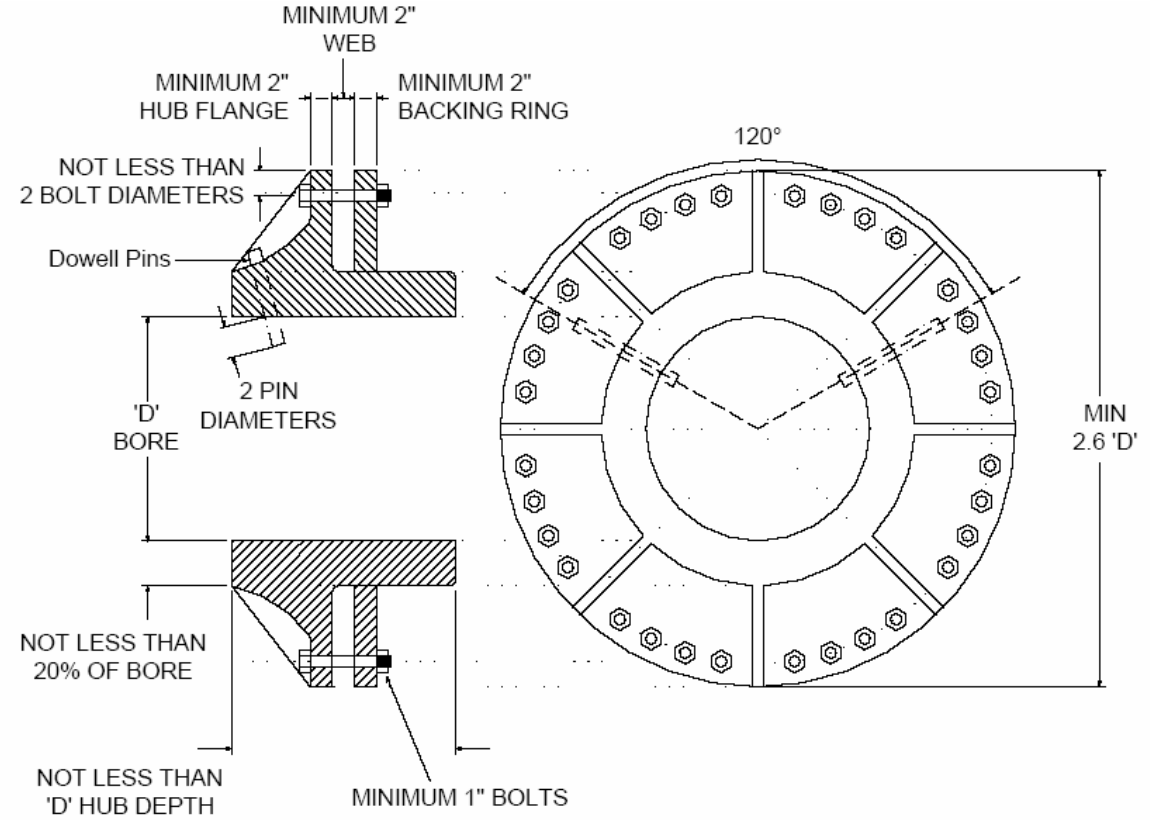


Figure 3.1 Trunnion Hub Design Guide [1].

3.2 Loads

General loading that influences the design (see Figure 3.2) are shear (V), torsion (T), axial load (P), and bending moment (M). In addition, the influence of friction force developed due to the interference fit between the hub and the backing ring is also considered. Details of these loads are discussed below.

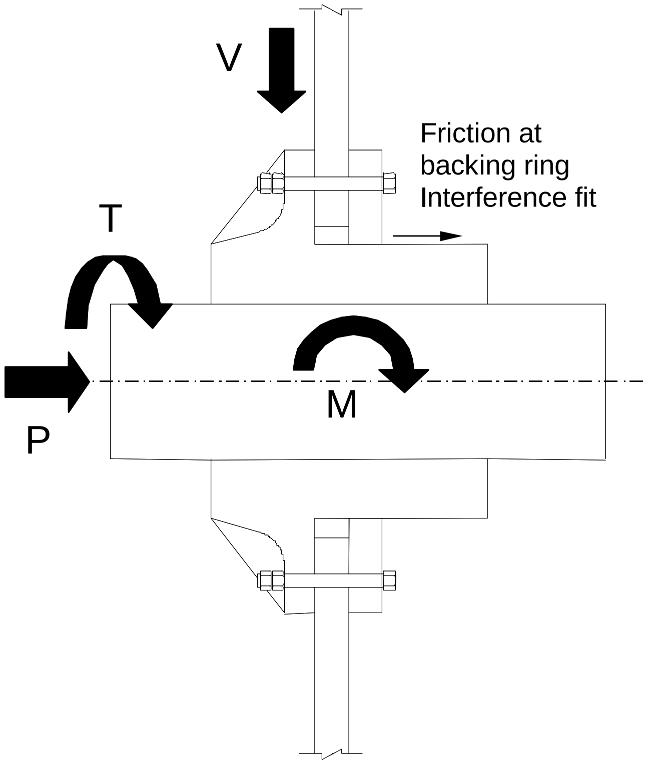


Figure 3.2 General loading on Hub-Girder Assembly.

3.2.1 Shear

The primary load resisted by the hub-girder connection is the load transferred from the girder to the trunnion bearings. This is obtained from determining the controlling limit state load case combinations of dead load, dead load dynamic allowance, live load, impact, wind etc. as specified by AASHTO (See Table 3.4.1-1 in Ref. [8], Section 2 in Ref. [3], Section 6.8.1.3.2 in Ref. [3]).

3.2.2 Torsion

Torsion that must be resisted by the hub-girder connections are a result of the friction at the trunnion bearings. Friction factors are specified as 18% for plain radial type bearing (see Section 5.8.2 in Ref. [3]) and 0.4% for roller bearings. Earlier AASHTO specifications [9] required the load acting at the circumference to be 1/5 the maximum radial load for bearings with bronze bushing and 1/100 the maximum radial load for anti-friction bearings (see Section 2.6.17 in Ref. [9]). In the analysis presented later, torsion loads are converted to equivalent forces on the bolted connection for the purpose of design. A torsion strength limit state is not explicitly considered in the connection design. In addition, since torsion loads are obtained as percentages of axial loads, influence of torsional impact loads is included when the corresponding axial loads are increased to account for dynamic effects.

3.2.3 Axial

The axial load acting on the connection is specified as 15% of the maximum bearing reaction per Section 6.8.1.3.2 in Ref. [3]. This may be ignored in design of the slip-critical double shear bolted connection such as the THG assembly shown Figure 3.1. This is because any increase or decrease in contact pressure at one of the outside members (say hub flange) due to the applied axial load is compensated by corresponding decrease or increase in pressure at the other outside member (backing ring). This means that there is no change in the net contact pressure between the faying surfaces due to small axial loads. Since the slip resistance of the bolted connection is a function of the net contact pressure, which is unaltered by axial loads, this may be ignored in connection design.

3.2.4 Bending Moment

The hub-girder assembly is subjected to small bending moment that is generally neglected in design. The bending moment is a function of the member stiffness, and in cases where the moment has been determined, for example using finite element models, it may be included in the analysis if desired. If the bending moment is found to be significant, for example in bridges with Hopkins trunnion, the bolted connection design must account for eccentric bolt loading and bolt fatigue. This case has not been addressed in this report.

3.3 Design Procedure

This section summarizes the design procedure for designing a hub-girder assembly without an interference fit by forming a slip-critical bolted connection between the hub and the girder. The objective of the design process is to determine the bolt diameter, grade, number of bolts and their placement on the hub to obtain a slip-critical connection between the girder and the hub. The design is checked for the following items -

a. Slip resistance of the connection
b. Shear strength of fastener (in bearing)
c. Tensile strength of fastener
d. Bearing strengths of members

Slip resistance of connections is designed based on Service II limit state (Table 3.4.1-1, Ref. [8]) while the remaining three items in the above list are designed based on strength limit states (section 6.13.2.1.1, Ref [8]). Strength limit states for bascule bridges design must consider those listed in AASHTO LRFD (Table 3.4.1-1, Ref. [8]) and also AASHTO LRFD Movable Highway Bridge Design Specifications (Table 2.4.2.3-1, Ref. [3]). Since load factors used for strength limit states are significantly higher than those for service limit states and corresponding resistance factors are lower for strength limit states than for service limit states, in some cases the strength limit state may determine the bolted connection design.

3.3.1 Design for Slip Resistance

The slip critical bolted connection must be designed for Service II limit state, which uses resistance factor, φ, equal to 1 (section 6.13.2.2, Ref. [8]). Loads specified above must be resisted by friction force developed between the hub, girder and the backing ring (see Figure 2.1) by the bolted connection. The resistance provided by a slip-critical connection is given by following (eqn. 6.13.2.8-1, Ref. [8]).

$$R_n = K_h\, K_s\, N_s\, P_t \qquad (3.1)$$

where

R_n = the nominal slip resistance

K_h = the hole size factor (1 for standard holes)

K_s = the surface condition factor (either 0.33 or 0.5)

N_s = the number of slip planes per bolt (two for hub-girder-backing ring assembly)
P_t = the minimum required bolt pretension
The design task is to determine P_t and specify the bolt size and grade to develop the bolt pretension.

The loads that act on the assembly and control the required tension were discussed earlier. In addition, the bolt pretension must overcome friction developed at the interference fit between the backing ring and the hub, which is assembled before the bolts are tightened (see Figure 2.1). The expression for P_t required is

$$P_t = (P_v + P_{tor} + P_a + P_{bm} + P_{brf}) \tag{3.2}$$

where

P_v = the bolt pretension required to resist shear load, V
P_{tor} = the bolt pretension required to resist the torsion, T
P_a = the bolt pretension required to resist the axial load, P
P_{bm} = the bolt pretension required to resist bending moment, M
P_{brf} = the bolt pretension required to overcome the friction forces due to interference fit between the backing ring and the hub.

Once the required amount of tension is determined, the minimum number of bolts required can be obtained by dividing the total tension requirement by 70% of the yield strength of a bolt (i.e., the bolt area times the yield stress of the bolt material) as specified in Table 6.13.2.8-1, Ref[8].

3.3.1.1 Shear

The bolt pretension required to resist shear, V, may be obtained by rearranging equation 1. Factored loads must be used to determine P_v as specified in the AASHTO LRFD code.

$$P_v = \frac{V}{K_h K_s N_s} \tag{3.3}$$

3.3.1.2 Torsion

Bolt pretension requirement to resist torsion can be estimated from the expression for frictional moment developed on an annular disk [10] to be

$$P_{tor} = \frac{3T(R_{out}^2 - R_{in}^2)}{2K_sK_hN_s(R_{out}^3 - R_{in}^3)} \tag{3.4}$$

where

R_{out} = hub outer radius

R_{in} = hub inner radius

This equation assumes a uniform distribution of the pressure due to bolt pretension $P_{tor.}$ In the actual assembly, the bolt pressures is located mainly on the outer parts of the hub, therefore the actual frictional resistance developed is more than predicted by the above equation (i.e., the above equation is conservative). The final design can be refined using the actual distribution of bolts using the equation below

$$T = \sum_{n=1}^{n_b} K_sK_hN_s\,P_{tn}r_{bn} \tag{3.5}$$

where

n_b = the number of bolts

P_{tn} = the part of bolt pretension for resisting torsion in bolt n

r_{bn} = the distance from hub center to center of bolt n

The direction of the force obtained by above analysis varies in a circular manner around tangential to the bolt circle. As a result the magnitude of the force acting on the bolts must be obtained by using vector addition of the shear force and the force from torsion. The maximum force on a bolt occurs when the direction of the force causing torsion coincides with the direction of other shear loads. For design purposes, all bolts are assumed to be subjected to the maximum load obtained by conservatively adding the component of force due to torsion to other shear forces.

3.3.1.3 Axial Load

This can generally be ignored, but if desired the bolt pretension required to resist axial loads can be obtained based on eq. 6.13.2.11.3 in Ref. [3] as

$$P_a = P \tag{3.6}$$

3.3.1.4 Bending Moments

Bending moments acting on the bolted assembly are generally not significant. If desired, it may be included in the analysis using the following expression (Section 7-11, Ref [11]).

$$P_{bm} = \frac{M}{r_m} \tag{3.7}$$

where:

M = the bending moment acting on the connection

r_m = the distance from the bending axis passing through the center of the trunnion to the location of resultant of bolt pretension in half the hub

If the bending moment acting on the connection is significant, bolts are subjected to fatigue loads as the bridge opens and closes due to load variations resulting from the eccentric loading caused by the bending moment. As a result, the bolted connection must be designed for combined shear and tension under fatigue loading (see Section 6.13.2.10 in Ref. [8]). It is important to note that examples presented in this report do not include this effect. In cases where the bending moment is significant, this effect is likely to govern the bolted connection design.

3.3.1.5 Friction at the Backing Collar

Based on current practice, the typical assembly process of the trunnion-hub to girder is expected to be similar to as shown in Figure 3.3. During assembly, the girder is laid horizontally (with the axis of the trunnion-hub vertical) on several supports. First, the backing ring is heated until sufficient clearance is obtained and supported below the girder. Next, the trunnion-hub assembly is lowered into the girder and the backing ring allowed to cool and form an interference fit between the hub and the backing ring. Note that only the dead load of the trunnion-hub-girder acts on the backing ring. Finally, bolt holes are drilled into this assembly and followed by bolt tensioning.

As a result of the above sequence of assembly, when the backing ring cools to form the interference fit with the hub, significant contact pressures are developed due to the shrink fit. The friction developed between the backing ring and the hub resists the bolt pretension, and therefore must be included as one of the loads that must be overcome to develop sufficient normal force between the faying surfaces of the hub-girder and girder-backing ring. Analytically, the friction force an be conservatively estimated using the following equation

$$P_{brf} = k_{br} \mu_{br} A_{brc} p_{br\,i} \tag{3.8}$$

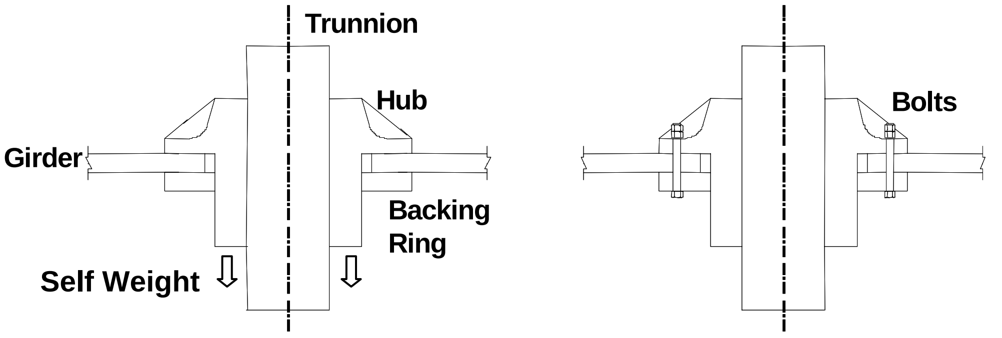
where

k_{br} = coefficient to account for bending action of the backing ring (0.2) (see Chapter 6 for details)

μ_{br} = the coefficient of friction between the backing ring and the hub

A_{brc} = the area of the backing ring in contact with hub

p_{bri} = the pressure due to interference fit between the backing ring and the hub given by the following equation based on axisymmetric analysis of thick cylinders [12].



STEP 1 - TRUNNION-HUB ASSEMBLY PLACED INTO GIRDER & SHRINK-FIT WITH BACKING RING

STEP 2 - BOLT HOLES DRILLED THROUGH HUB, GRIDER, BACKING RING & ASSEMBLY IS BOLTED.

Figure 3.3 Expected Assembly procedure of Trunnion-Hub to Girder.

$$p_{br\,i} = \frac{E\delta_{br}(r_{bro}^2 - r_h^2)}{2 r_h r_{bro}^2} \tag{3.9}$$

where

E = the modulus of elasticity of hub and backing ring material

δ_{br} = the interference between the backing ring and the hub

r_h= the hub outer radius (also inner radius of the backing ring)

r_{bro} = the backing ring outer radius

3.3.1.6 Friction between the Bolt and Bolt holes

The above case of frictional resistance to bolt pretension can also occur due to interference between the bolt and the bolt hole. This can be avoided by specifying the fit between the turned bolt and the hole to be a clearance fit. As discussed in section 3.4, an LC6 fit [2] is recommended for the turned bolts since this fit provides a small clearance but no interference. In spite of the specified tolerance, interference between bolt and bolt holes have been found to occur during assembly of the trunnion-hub assembly in to the girder. To account for such cases the required bolt pretension P_t must be increased by the total friction force developed due to all bolts with interference fits. The following equation may be used to estimate the friction force developed at any single bolt due to interference fit. The equation conservatively estimates the friction force developed due to the bolt to bolt hole interference.

$$P_{bhf} = \mu_{bh} A_{bhc} p_{bhi} \tag{3.10}$$

where

μ_{bh} = the coefficient of friction between the bolt and the bolt hole

A_{bhc} = the circumferential area of the bolt in contact with bolt hole

p_{bhi} = the pressure due to interference fit between the bolt and the bolt hole given by the following equation based on axisymmetric analysis of thick cylinders with large external cylinder[12].

$$p_{bh\,i} = \frac{E\delta_{bh}}{2d_b} \tag{3.11}$$

where

E = the modulus of elasticity of the hub and the bolt material

δ_{bh} = the interference between the bolt and the bolt hole

d_b= bolt diameter

3.3.2 Bolt Sizing

For a given set of loads and dimensions, the required bolt pretension, P_t can be determined using the above equations. Based on the P_t requirements size of standard bolts used for slip-critical connections may be determined. These are then placed in different number of bolt circles (generally one or two). The design can be refined using equation 3.5 and additional checks listed below can be performed to finalize the design. Minimum required bolt tension that must be developed for different size bolts in a slip critical connection is provided in Table 6.13.2.8.1, Ref. [8].

3.3.3 Additional Checks

Once the bolts are sized based on slip-critical connection, other checks must be undertaken to check the strength of the different members. These are as follows. As noted before, these checks are performed at strength limit states with factored loads (Table 3.4.1-1, Ref. [8]) and also AASHTO LRFD Movable Highway Bridge Design Specifications (Table 2.4.2.3-1, Ref. [3]) and factored resistances (see section 6.5.4.2, Ref. [8]).

3.3.3.1 Shear Strength of Fastener (in Bearing)

Considering the case where threads are excluded from shear plane, (Sections 6.13.2.7, Ref. [8]), the shear strength of a fastener is given by

$$R_n=0.48\ A_b\ F_{ub}\ N_s \qquad (3.12)$$

where

R_n = nominal resistance of the bolt

A_b = area of the bolt corresponding to nominal diameter

F_{ub} = specified minimum tensile strength of the bolt (see 6.4.3 in Ref. [8])

N_s = Number of slip planes.

The above equation accounts for shear lag in a simplified manner. Shear strength of a single bolt is experimentally found to be 0.6 times the specified minimum tensile strength. This is reduced by 20% to 0.48 in the above equation to include the effect of unequal load distribution in bolted connections with multiple bolts based on test results [13].

3.3.3.2 Tensile Strength of Fastener

For combined shear and tension from (Section 6.13.2.11, Ref [8]), the tensile strength of a fastener is given by

$$T_n=0.76\ A_bF_{ub} \qquad (3.13)$$

where:

T_n = nominal tensile resistance of bolt

As stated earlier, the above capacity is not applicable if the bolt is subjected to fatigue loading such as due to large bending moments.

3.3.3.3 Bearing Strengths of Members

Bolted members of the assembly (hub flange, girder and backing ring) are checked for bearing strength as follows (Section 6.13.2.9, Ref. [8])

$$R_n=2.4d\ t\ F_u \qquad (3.14)$$

where

d = nominal bolt diameter

t = thickness of connected material (i.e., hub flange, girder or backing ring)

F_u = tensile strength of the connected material

3.4 Detailing Considerations

Construction related details of the bolted connection, such as use of locking features, method of bolt pretensioning and the use of washers must conform to current AASHTO standards. In addition to current AASHTO requirements, the proposed elimination of the interference fit between the hub and girder requires the use of tighter tolerance between the turned bolts and the bolt holes as explained below.

Changes in the span configurations while opening and closing causes the loads to change and corresponding elastic deformations to change (see Figure 3.4). The change in elastic deformation at the faying surfaces alters the frictional resistances locally in bolted connection. In light of possibility of localized slip, it is recommended that the bolts used be turned bolts with small clearance fit between the bolt and the hole. The diameter of the threaded portion of a turned bolt is 1/16” less than the nominal bolt diameter at the shank (Section 6.7.15, Ref. [3]) and is accounted for in calculations presented later.

Another factor to consider during design is that turned bolts are obtained by machining stock which are oversized by 1/8" or more from the nominal turned bolt diameter. This affects the allowable bolt tensile strength, which is a function of the bolt diameter for A325 and A449 bolts.

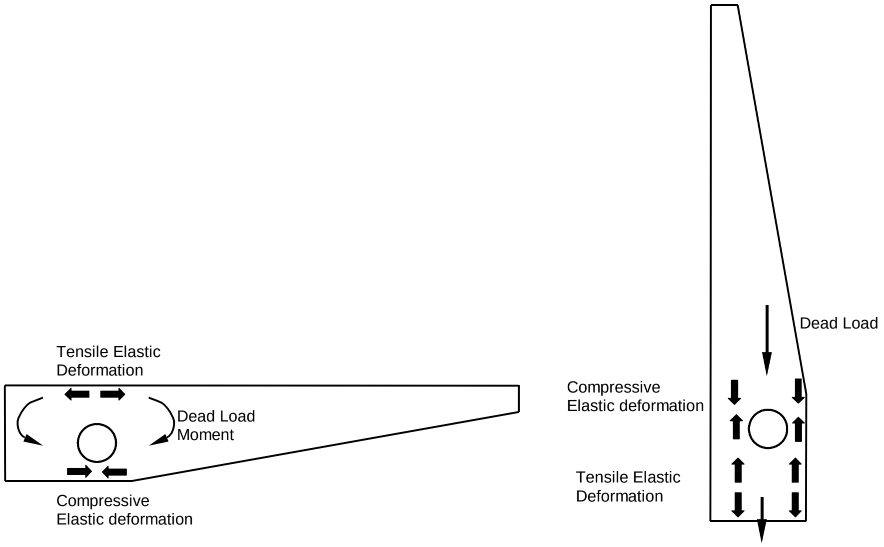


Figure 3.4 Change in elastic deformations due to span movement.

The 17th Street Causeway Bridge, which utilized a hub-girder assembly without an interference fit, used turned bolts with an LC6 locational clearance fit to minimize the amount of slip [5]. Other possible means to minimize slip is to use additional bolts, use dowels or using tighter fits for the bolts (transition fits instead of locational clearance).

CHAPTER 4

DESIGN TOOLS

4.1 Introduction

Based on the analysis of the hub-girder connection presented in Chapter 3, computer tools were developed to aid in the design of hub-girder connections. These tools require some basic inputs based on preliminary design of other aspects of the bridge (such as the trunnion diameter, the maximum expected trunnion reaction and choices of materials). These may be used to determine the number of bolts required, and subsequently analyze different bolt patterns based on AASHTO requirements of bolt clearances. These tools were developed as Microsoft Excel spreadsheets and utilize Visual Basic macros.

4.2 Design Tool

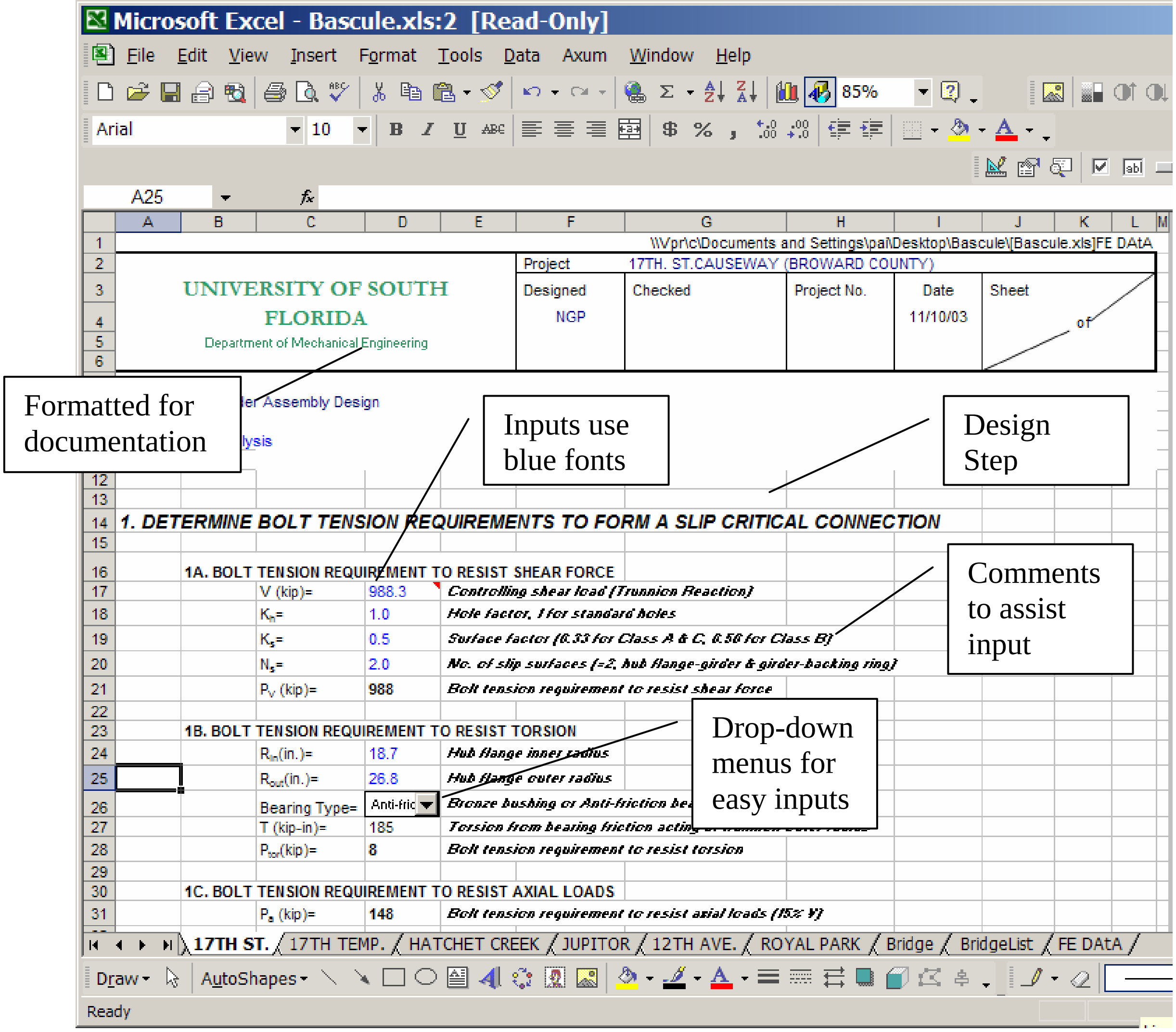
Given the loading, geometry and material of the hub, girder and backing ring, it is possible to arrive at the number of bolts required to resist the load for a given bolt diameter and the bolt material. One can obtain different designs by varying the bolt size, grade, etc.

The spreadsheet undertakes the following design checks

a. Slip resistance of the connection
b. Shear strength of fastener (in bearing)
c. Tensile strength of fastener
d. Bearing strengths of members

The spreadsheet essentially follows the same sequence of calculations as shown in Chapter 3.

Figure 4.1 shows a portion of the spreadsheet. All inputs are indicated by blue font and computed values are indicated by black font. The spreadsheet contains comments on the side to assist the user in selecting the appropriate values for the different inputs. Also, drop down menus are provided in cases where the options are limited to a few choices (such as the bearing type used). The spreadsheet shown utilizes customary US units.



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UNIVERSITY OF SOUTH FLORIDA
Department of Mechanical Engineering

Project	17TH. ST.CAUSEWAY (BROWARD COUNTY)			
Designed NGP	Checked	Project No.	Date 11/10/03	Sheet of

ler Assembly Design

lysis

1. DETERMINE BOLT TENSION REQUIREMENTS TO FORM A SLIP CRITICAL CONNECTION

1A. BOLT TENSION REQUIREMENT TO RESIST SHEAR FORCE

V (kip)=	988.3	*Controlling shear load (Trunnion Reaction)*
K_h=	1.0	*Hole factor, 1 for standard holes*
K_s=	0.5	*Surface factor (0.33 for Class A & C, 0.50 for Class B)*
N_s=	2.0	*No. of slip surfaces (=2, hub flange-girder & girder-backing ring)*
P_V (kip)=	988	*Bolt tension requirement to resist shear force*

1B. BOLT TENSION REQUIREMENT TO RESIST TORSION

R_{in}(in.)=	18.7	*Hub flange inner radius*
R_{out}(in.)=	26.8	*Hub flange outer radius*
Bearing Type=	Anti-fric	*Bronze bushing or Anti-friction be*
T (kip-in)=	185	*Torsion from bearing friction acting*
P_{tor}(kip)=	8	*Bolt tension requirement to resist torsion*

1C. BOLT TENSION REQUIREMENT TO RESIST AXIAL LOADS

P_a (kip)=	148	*Bolt tension requirement to resist axial loads (15% V)*

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Inputs use blue fonts

Design Step

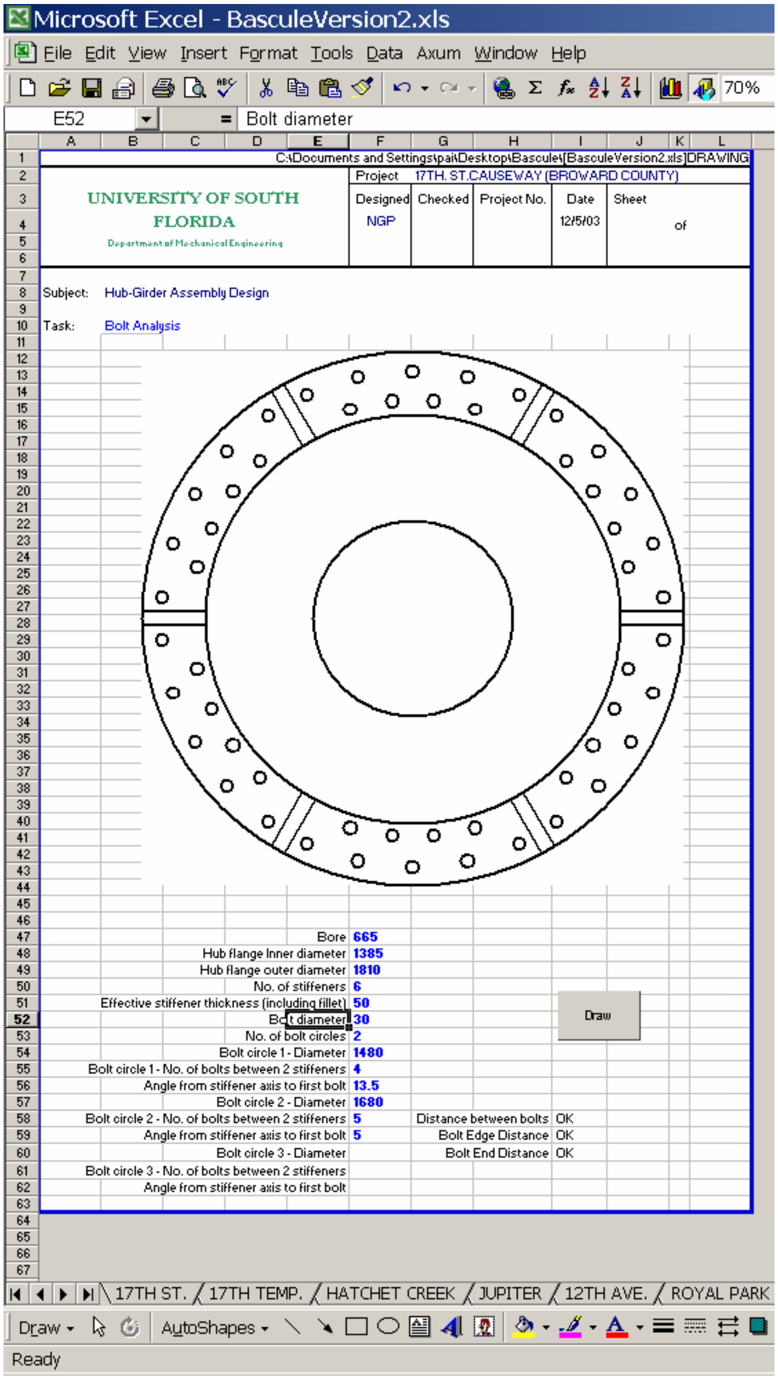
Comments to assist input

Drop-down menus for easy inputs

Figure 4.1 Excel Spreadsheet for design of hub-girder assembly.

4.3 Bolt Circle Analysis Tool

Once the number of bolts required are determined using the design tool, different bolt circle patterns can be generated and visualized using the bolt circle analysis tool (see Figure 4.2). This provides a quick way to evaluate different design options based on bolt spacing considerations provided in AASHTO LRFD (see section 6.13.2.6, Ref. [8]). The program checks for spacing requirements of distances between bolts, edge distance and end distances.



E52 = Bolt diameter

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UNIVERSITY OF SOUTH FLORIDA
Department of Mechanical Engineering

Project 17TH. ST.CAUSEWAY (BROWARD COUNTY)

Designed	Checked	Project No.	Date	Sheet
NGP			12/5/03	of

Subject: Hub-Girder Assembly Design

Task: Bolt Analysis

Bore	665		
Hub flange Inner diameter	1385		
Hub flange outer diameter	1810		
No. of stiffeners	6		
Effective stiffener thickness (including fillet)	50		
Bolt diameter	30		
No. of bolt circles	2		
Bolt circle 1 - Diameter	1480		
Bolt circle 1 - No. of bolts between 2 stiffeners	4		
Angle from stiffener axis to first bolt	13.5		
Bolt circle 2 - Diameter	1680		
Bolt circle 2 - No. of bolts between 2 stiffeners	5	Distance between bolts	OK
Angle from stiffener axis to first bolt	5	Bolt Edge Distance	OK
Bolt circle 3 - Diameter		Bolt End Distance	OK
Bolt circle 3 - No. of bolts between 2 stiffeners			
Angle from stiffener axis to first bolt			

Figure 4.2 Bolt circle visualization using design spreadsheet.

Several existing bridge were analyzed using these spreadsheets. These are discussed in the following chapter.

CHAPTER 5

ANALYSIS OF REPRESENTATIVE BRIDGES

5.1 Introduction

The computer tool described in the previous chapter was used to compare the bolting requirements for several bridges which utilized a hub-girder connection without an interference fit. Analysis of six bridges, two with Hopkins trunnion, two with simple trunnion and two with box-girder scheme are presented in the chapter.

5.2 Analysis Procedure

The objective of the analysis is to determine the impact the new design would have on current design practice by comparing the number of bolts currently being use to that required by the new procedure. Items required for this analysis were determined for the six bridges from design plans and calculations (where available). The six bridges and the key design items are listed in Table 5.1. Note that in most of these bridges the loads were estimated from plans and do not account for any special load cases such as those encountered during special maintenance operations with bearing removed.

All the relevant data is entered into the spreadsheet and the bolting requirements are determined for the bridges. Also, the relative contribution of the various factors, such as the shear, torsion and backing ring friction to the next pretension requirement is also obtained for each of the bridges.

5.3 Results

The analysis reveals that five of the six existing bridges utilize sufficient bolts to behave satisfactorily as slip-critical connection (see Table 5.2). The only exception was a bridge designed for temporary operations. This means that the new design will most likely not alter the current practice significantly. A possible explanation for the number of bolts found in existing designs is that the hub flange size is a function of the trunnion size, and with the current guidelines for the ratio of hub to trunnion dimension (see Figure 3.1), there is enough room on the hub to accommodate more bolts than actually required for forming a slip critical connection.

Table 5.1 Bridge data for bolted connection analysis.

BRIDGE	SHEAR	HUB FLANGE INNER DIA	HUB FLANGE OUTER DIA	BEARING	BACKING RING FIT	BACKING RING THICK.	NO. BOLT CIRCLES	BOLT DIA.	# OF BOLTS	BRIDGE TYPE
JUPITER 706 (PALM BEACH)	1813 kip (Total) (Add 20% impact)	40”	72”	Spher.	FN2	2”	2	1.50	78	Simple
N.W. 12 TH AVENUE (MIAMI-DADE)	1622 kip (normal) 2287 kip (maintenance mode)	37.5”	53.5”	Spher.	FN2	2”	2	1 1/8”	54	Box girder
HATCHET CREEK (SARASOTA)	3284 kN*	1062 mm	1652 mm	Bronze	FN2	75 mm	1	M38	24	Hopkins
17TH. ST.CAUSEWAY (BROWARD COUNTY)	Open 5520 kN vertical +1970 kN horizontal (per main girder)	950 mm	1360 mm	Spher.	FN2	50 mm	2	M30	54	Box girder
ROYAL PARK (PALM BEACH COUNTY)	Open 4649 kN vertical +1287 kN horizontal (per main girder)	1100 mm	1710 mm	Bronze	H7/s6	74 mm	1	M36	24	Simple
17TH ST. CAUSEWAY TEMP BRIDGE (BROWARD COUNTY)	2751kN*	850 mm	1140 mm	Bronze	FN2	20 mm	1	M22	36	Hopkins

* computed using the given bearing reaction and geometry of the Hopkins frame

Table 5.2 Comparison of bolts used to bolts required.

BRIDGE	# OF BOLTS USED	# OF BOLTS REQUIRED
JUPITER 706 (PALM BEACH)	78	46
N.W. 12 TH AVENUE (MIAMI-DADE)	54*	53**
HATCHET CREEK (SARASOTA)	24	21
17TH. ST.CAUSEWAY (BROWARD COUNTY)	54*	40**
ROYAL PARK (PALM BEACH COUNTY)	54	28
17TH ST. CAUSEWAY TEMP BRIDGE (BROWARD COUNTY)	24	36

* designed as slip-critical connections, remaining bridges designed as bearing connections

** number of bolts required is nearly 40% more using loads for maintenance mode operation

Table 5.3 Relative contributions of loads to bolt pretension requirement.

BRIDGE	Shear, P_V (%)=	Torsion, P_{tor}(%)=	Backing ring Friction, P_{brf}(%)=
JUPITOR 706 (PALM BEACH)	90	1	9
N.W. 12 TH AVENUE (MIAMI-DADE)	91	1	8
HATCHET CREEK (SARASOTA)	65	10	25
17TH. ST.CAUSEWAY (BROWARD COUNTY)	90	<1	10
ROYAL PARK (PALM BEACH COUNTY)	70	11	19
17TH ST. CAUSEWAY TEMP BRIDGE (BROWARD COUNTY)	80	14	6

Table 5.3 shows the relative contribution of different loads considered in Chapter 3 towards the bolt pretension requirement. As expected, shear is the most significant factor. The torsion due to bearings is significant only when using bearings with bronze bushing. It is seen that the backing ring friction can be a significant factor in determining the bolting requirement, especially as the ring thickness increases. The analysis used to arrive at the backing ring friction was based on elasticity equations for interference between two cylinders. The next chapter presents a finite element model used to estimate this value more accurately.

CHAPTER 6

FINITE ELEMENT ANALYSIS

6.1 Introduction

Results presented in the previous chapter indicate that backing ring friction is a significant factor in determining the bolt pretension requirements. The analysis used in the previous sections is based on elasticity solution of interference between two cylinders. This chapter presents results of simplified finite element analysis to study the factors that influence backing ring friction.

6.2 Finite element model

To estimate the magnitude of frictional resistance expected due to the above process, an axisymmetric finite element model of the trunnion-hub-girder-backing ring assembly was developed using ANSYS. The finite element mesh is shown in Figure 6.1. It utilized PLANE42, a four node element used for axisymmetric analysis [15]. The model consists of 740 nodes and 600 elements. To simplify the analysis, the gusset plates used to stiffen the hub are not modeled and the trunnion-hub assembly is modeled as a single entity since they are assembled prior to the hub-girder assembly. Other parts modeled are the girder and the backing ring. Contact elements are used to determine the contact pressures and friction forces developed during the assembly. The assembly is carried out in two steps. First, an interference fit is formed between the backing ring and the hub. During this stage a small vertical force is applied to simulate self weight of the members being assembled (see Figure 3.3). This is followed by application of equal and opposite forces at the location of the bolts on the outer surfaces of the hub and the backing ring to simulate compression resulting from the bolts. The part of the load resisted due to the friction force at the interference joint at the backing ring-hub interface is determined.

6.3 Results

Results of the finite element analysis for a representative bridge (Royal Park Bridge, [16]), indicate that this friction accounts for about 3% to 5% of the total bolt load applied.

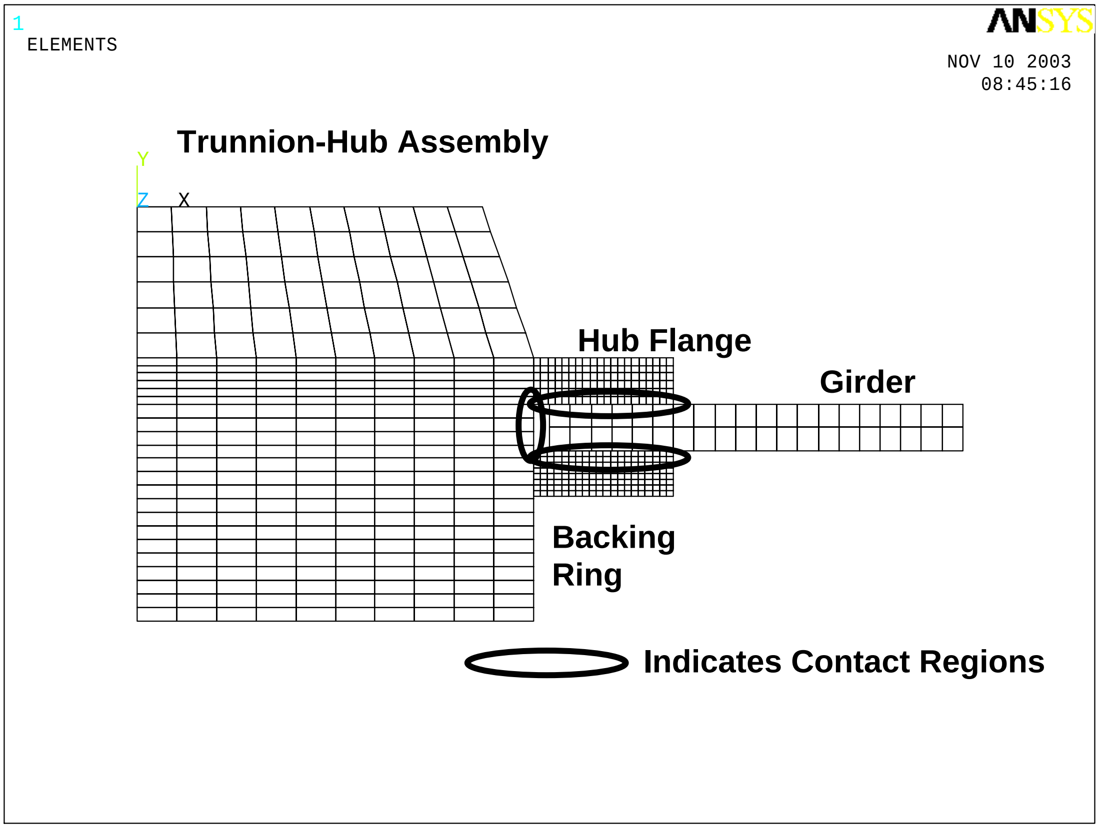

Figure 6.1 Finite element Mesh for Axisymmetric Hub-Girder Assembly.

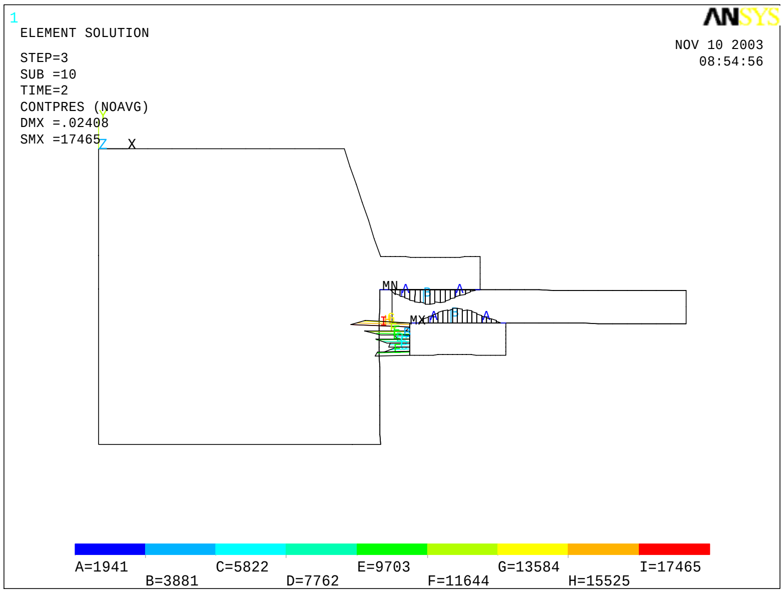

Figure 6.2 Contact pressures (psi) from finite element results.

Also, the backing ring friction influences the contact pressure distribution between the hub, girder and the backing ring, (see Figure 6.2), which in turn affects the resulting frictional torsion resistance since it is a function of the radius at which the friction force acts.

The magnitude of the backing ring pressure obtained from the finite element model was about 90% of the value obtained from equation 3.9. Refining the mesh further did not alter this ratio significantly. The difference is most likely a result of the fact that the actual hub geometry is not a cylinder of uniform radius as assumed by the equations in Chapter 3. The equation used for analysis in Chapter 3 is therefore conservative for current design purpose. Comparing the actual backing friction developed at the end of the bolting process, to the predicted value, it is found that the resistance obtained is between 7 to 11% of the predicted value. This is because the design assumes that the entire backing ring friction must be overcome to develop contact pressure between the faying surfaces of the parts. However, the finite element results indicate that the backing ring actually bends like a cantilever beam with the interference connection being the fixed end, and that the resulting deflection is sufficient to develop adequate contact pressure at the locations of the bolts. It seems therefore that the original estimate can be conservatively multiplied by a factor of 0.2 to obtain a more realistic measure of the influence of backing friction on the bolt pretension requirement.

One of the factors that influence the amount of backing ring friction force resisting the bolt pretension is the vertical load applied due to the self weight (see Figure 3.3) during the assembly process of shrink fitting the THG with the backing ring. A higher load results in better initial contact between the ring and the girder, therefore reduces the frictional resistance once the shrink fit is formed. This is shown in Figure 6.3, which shows the backing ring friction as a function of the initial load applied (mainly dead load) during the shrink fit process. Both quantities are normalized with respect to the bolt pretension used. It can be seen that increasing the load has beneficial effect to a limit as the resistance is dropped from about 4.5% of bolt pretension to below 3% by increasing the dead load used to press the parts together from 0.1% of the bolt pretension to above 4%.

6.4 Additional Studies

The finite element model was also used to study the effect of a temperature differential of 10^{o}F between the girder and other parts. It was thought that this may cause some local slippage as the part expands, however the results indicate no slip with this loading. Another study was conducted to study the effect of axial load (15% of V) acting on the girder. The results verified that axial loads can be ignored due to reasons stated in Chapter 3. Also, there was no slip observed due to resulting elastic deformation from girder bending.

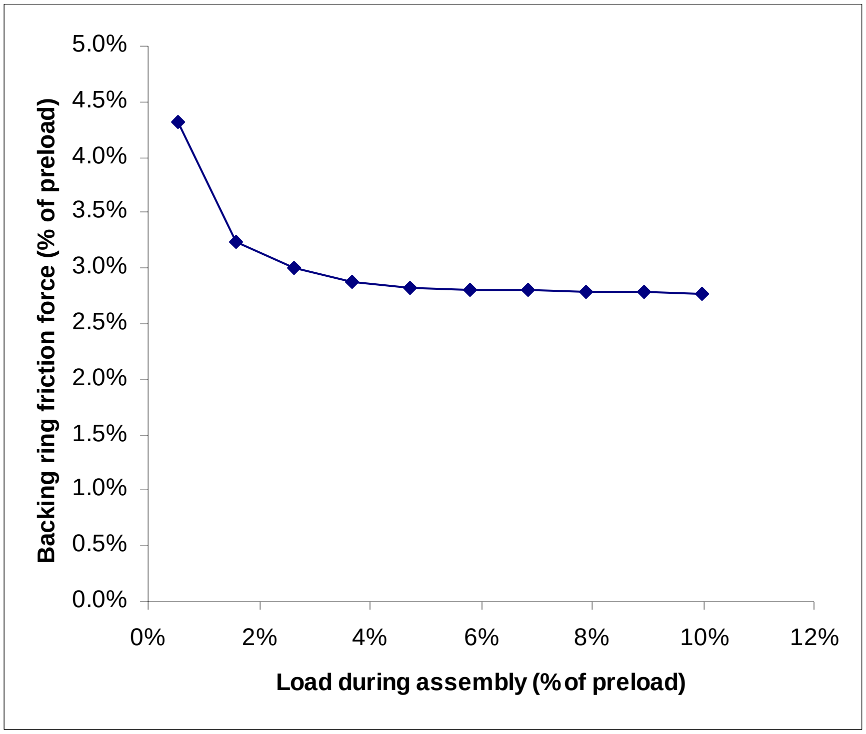

Figure 6.3 Influence of load applied during the shrink fit process on backing ring friction.

In conclusion, the simplified finite element model was useful in identifying that the backing ring friction is much lower than initial thought. Also, FE results indicate that applying vertical load to improve the contact between the hub flange and the backing ring during assembly might reduce the friction developed at the interference fit even further.

CHAPTER 7

CONCLUSIONS

The objective of the study was to develop design procedure for hub-girder connections in bascule bridges without using interference fit. A design methodology was developed based on the expected behavior of such an assembly without interference fit.

It was initially thought that the bolting requirements for a connection with slip-critical connection would be more than with the current practice of using interference fit. It is common practice to design the bolted connections in assemblies with interference fit to resist shear and torsion loads as bearing type connection. Typical ratios of allowable shear loads in comparison to the tensile strength of fasteners are 0.48 (where threads excluded from the shear plane) and 0.38 (when threads are included in the shear plane). In comparison, when using a slip-critical connection, using 0.33 as the surface factor, and 0.7 as the minimum tension required (which is 0.76 times the tensile strength computed with the nominal bolt area), each bolt provides resistance of approximately 0.18 times the bolt tensile strength. In addition, the friction at the interference fit between the backing ring and the hub further increases the bolt pretension demand. All these factors may lead one to conclude that that a slip-critical bolted connection would more than twice as many bolts as a connection that uses an interference fit between the hub and the girder. This in turn would require larger hub diameters and twice as many bolt circles as commonly found (typically two instead of one).

Analysis of existing bridges revealed that the above simplified view is not true and that most existing assemblies utilize sufficient bolts to form a slip-critical connection. One of the factors that contribute to this is that bearing type connections have to be designed for strength limit states, therefore utilize load factors as high as 1.55, while slip-critical connections are designed for service limit state and utilize load factors of 1 for major loads. But this alone does not explain the number of bolts found in existing bridges. A possible reason for the large number of bolts found in existing bridges is that the hub dimensions ratio to trunnion size are dictated by FDOT and AASHTO standards [1 & 3], and result in sufficient room on the hub flange to accommodate extra bolts.

An additional load that was considered for the new design was due to the friction force at the interference fit between the backing ring and the hub. However, this does not significantly alter the design since finite element results presented in Chapter 6 indicate that this is not as high as initially computed, and can be as low as 7% of the initially estimated value.

The above analysis indicate that most existing designs can resist the loads satisfactorily even without the hub-girder interference fit. As a result, the new design requirement is not likely to adversely affect current practice. While the elimination of the hub-girder interference fit is expected to slightly alter the assembly process of the THG, this is unlikely to significantly affect the connection performance.

Although the analysis in this report indicates that it may be possible to eliminate the interference fit between the girder and the hub, there are some situations that require additional considerations. For example, when the bolted connection is subjected to high bending moments (such as in some Hopkins trunnion configuration), the absence of the interference fit between the hub and the girder would lead to significant eccentric bolt loads due the bending moment and require connections to be designed based on fatigue performance of the bolts.

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