CHAPTER 1 INTRODUCTION

The advent of bridges dates back as far as one can imagine. Whether it is a fallen tree lying across a flowing stream, a steel suspension bridge spanning from one side of a bay to the other, or possibly a drawbridge providing access to a medieval castle across a moat, bridges are evolving design elements.

Bridge design is a prime example of the successive technological improvements in engineering. The design process is based on fundamental principles of physics, but can become quite complex when a particular lay out is required. We rely on the designers and engineers who have guaranteed the structural viability of a bridge.

Due to a variety of reasons, geographic location, financial tolerance, aesthetics, etc., a particular type of bridge is usually needed. In areas that do not provide the necessary clearance above the waterway below for water traffic, a movable bridge is usually the only option. Several different types of movable bridges have been devised over the years, each using unique mechanisms of movement. One specific design is the bascule bridge. This design is believed to have originated from the medieval times, from the drawbridge lowered to cross a castle moat (Roland, 1990).

The basic design of modern bascule bridges consists of a leaf (or span), which is lifted by the rotation of a horizontal axis near one end of the span, along with the assistance of a counterweight. The rotation can be provided by a shaft, or trunnion, surrounded by a hub, which is inserted into the main girders of the leaf. This point of the system acts as the fulcrum. To keep the leaf in a state of equilibrium at all angles of motion, the center of gravity also coincides with the center of rotation (Roland, 1990). Since a single span can reach up to sixty meters in length, extra bracing is usually applied to the span for added rigidity (Roland, 1990). Due to this type of loading, the stress distribution in the bridge continuously changes during rotation. To provide a sufficient design, able to withstand the various stresses just described, a great deal of attention must be paid to all aspects of the bridge design process. One important area of concentration is the fabrication process, especially of the trunnion-hub-girder (THG) system. This three-part system is a critical one, due to the tolerances it must meet, the stresses it experiences, as well as the way it must act together.

As described above, bascule bridges use a trunnion-hub-girder assembly as the fulcrum to open and close. During the opening of the bridge, the fulcrum must resist torque, such as the torque due to the wind load and the dead weight of the bridge span. This can be achieved using shrink fitting of the trunnion and hub in an interference fit, as well as a slip critical joint fastened with bolts. There are two procedures commonly used to make this assembly. In the first procedure, the assembly is made by first shrinking the trunnion by placing it in a liquid nitrogen bath, and then slipping it into the hub. Then the trunnion-hub assembly is shrunk, and slipped into the girder of the bridge. In the second procedure, the hub is first shrink fitted to the girder and then the trunnion is shrink fitted to the hub-girder assembly. Each of the above methods has been used throughout the United States. However, using the first method has created failures (cracks) during the assembly process at three bridges in Florida – Miami Avenue Bridge, Christa McAuliffe Bridge, and the Brickell Avenue Bridge, according to the Florida Department of Transportation. As to which procedure is better is part of another study at the University of South Florida.

Shrink fitting is a technique used to create an interference fit between the inner and outer members of a system, for example the trunnion and hub, respectively. The inner member is cooled down to a temperature that will allow sufficient change in its outer diameter (if circular in shape), until it can slide into the outer member. The change in size can be calculated using the coefficient of thermal expansion of the material and the temperature change. Once the inner member has been cooled and inserted into the outer member, the system is allowed to reach steady state. As the system reaches steady state temperature, the inner member expands back to its original shape, and an interference fit is formed. This fit allows for a bond, in a friction joint, between the two members. However, in high-load situations, this fit is usually supplemented with another joint, for example, bolts. A bolted joint is slip-critical.

As mentioned, there have been problems in the fabrication technique of THG assemblies. In addition to construction delays, it costs more than 100,000 dollars to replace the assembly. So, the reason why such failures are taking place must be found. Shrink fitting subjects the materials used to a large temperature change, and correspondingly, high stress concentrations throughout the cross-section of the material. The members being shrink fitted have developed cracks in their surfaces, a sign of material failure. The reasons why these cracks develop are a matter of great debate, and much research must be done to find the origin of this problem and its solution.

As a step to work towards the solution of this problem, the bascule bridge design, fabrication, and operation must be analyzed and understood. To aid in this process four design tools have been developed. These design tools provide a general understanding of the physical (THG) system, and demonstrate how it reacts to various loading situations.

The first design tool simulates an actual bridge layout, and finds the actual torque necessary to raise the bridge leaf, given various parameters (for example, material properties and wind loading).

Due to the shrink fitting done to the system, and based on the type of standard fits at the interfaces of the trunnion-hub and hub-girder, interferences are created at the two interfaces. These interferences cause pressures at the interfaces and, correspondingly, develop hoop (also called circumferential and tangential), radial, and von Mises stresses in the THG assembly. The second design tool finds all of these stresses, as well as the radial displacements in each member (trunnion, hub, and girder). The results provide the design engineer with an idea of how the given diametrical interferences (from shrink fitting) affect the stresses in the various members of the THG assembly.

A third tool is developed to find all of the critical stresses (radial, hoop, and von Mises) in the THG assembly at steady state. The results from this tool are tabulated to show these stresses for various combinations of the material properties and geometric dimensions of the trunnion, hub, and girder. The design engineer can then use these as design parameters.

The fourth design tool is for developing the bolt pattern used to supplement the hub-girder interference fit. The amount of torque resisted by the hub-girder comes from two sources – hub-girder interference and the bolts. The torque resisted by the bolts is based on the number of bolts, diameter of bolt circles, bolt material and size, material and geometric dimensions of the hub and girder, etc. This design tool allows the user to test various bolt patterns. The designer then tabulates results for direct use.

These design tools, as well as all of the relevant technical information, will be described in the remainder of this report. There is also a section of tabulated results in the appendices from using the design tools.

CHAPTER 2 TECHNICAL INFORMATION

To understand the complexity of the four design tools used to analyze the trunnion-hub-girder (THG) assembly, an overview of their technical aspects is needed. Remember, the first design tool is used to simulate actual bridge design. It provides the user with an understanding of how much actual torque is created during the opening/closing of a bascule bridge. These torque calculations are explained in this section. The next design tool calculates the approximate steady state stresses and displacements in the THG assembly, given diametrical interferences, due to shrink fitting. This design tool also calculates and displays a stress profile along the radius of the entire THG assembly. The third design tool is intended to be used to find all of the critical stresses in the THG assembly. These stresses can vary with material properties, as well as with the dimensions of the trunnion, hub, and girder. This design tool allows the user to examine multiple design schemes involving the THG geometry and materials. In this technical analysis, approximate steady-state stress equations are developed for calculating the compressive radial stress at the trunnion-hub and hub-girder interfaces. These stresses determine the amount of torque the assembly can resist before slipping at the interfaces. Also calculated are the hoop and von Mises stresses, which determine the failure of the assembly. The fourth design tool assists in developing a bolt pattern, connecting the hub and girder. The bolts supplement the hub-girder interference fit. The bolt assembly is analyzed to calculate the amount of torque it can resist. The sum of these two torques, the torque due to interference and the torque resisted by the bolt assembly, gives the overall torque taking capability of the THG assembly.

Before an analysis of the design tools can be made, an understanding of the THG system geometry is necessary. The three main components of the THG assembly are shown in Figure 1. The outer diameter of the trunnion is secured to the inner diameter of the hub with an interference fit. Note the bolt pattern surrounding the hub, securing it to the girder. The hub also contains a system of gussets, which gives it additional rigidity.

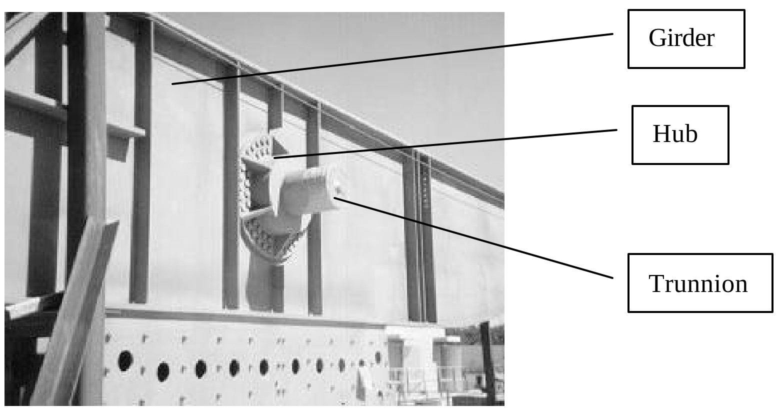

Figure 1. Trunnion-Hub-Girder Assembly of a Bascule Bridge

Torque Calculations for the THG Assembly

The THG assembly must resist sufficient torque to open and close. As previously mentioned, the trunnion acts as the fulcrum for the bridge movement. A schematic layout of a bascule bridge leaf is shown in Figure 2.

A counterweight on one side of the trunnion balances the dead weight of the leaf (girder span) on the other side. The leaf is usually comprised of concrete and steel, and when opened or closed can also be affected by a wind load. Forces such as these create torques that the

THG assembly must withstand. Hence, there are three main torques that make up the total torque resisted by the THG assembly. These are the torques due to wind load, friction loads at the bearing, and the moment caused by the unbalanced load of the leaf (girder span). The total torque (T_{THG}) that must be carried by the assembly then is the sum of these three torques:

$$T_{THG} = T_{wind} + T_{friction} + T_{unbalance}$$

where

T_{wind} = torque due to wind load,

$T_{friction}$ = starting friction torque on bearings of THG assembly, and

$T_{unbalance}$ = torque caused by the unbalanced load.

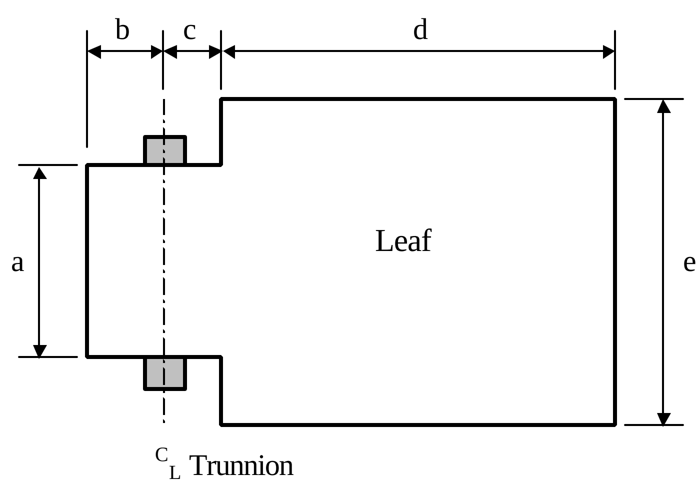

Figure 2. Schematic of a Bascule Bridge Leaf

The wind load acts on the surface area of the girder being opened or closed. For simplicity of calculation, the wind load, denoted σ_w, is assumed to be a pressure (stress) acting on the centroid of the section. The centroid for any given geometric section can be calculated using very general geometric formulas. For example, for the schematic section shown in Figure 2, the distance from the trunnion centerline to the centroid of the leaf is

$$X_c = \frac{(d\,e)\left(\frac{d}{2}+c\right)+(c\,a)\left(\frac{c}{2}\right)}{d\,e+c\,a}$$

As shown in Figure 3, the equivalent wind load, P_l, acts on the centroid (a distance of X_c from the trunnion centerline), while the bridge span is at an angle of θ_o from the horizontal. For the leaf shown above, P_l is given by

$$P_l = (d\,e+c\,a)\sigma_w \sin(\theta_o)$$

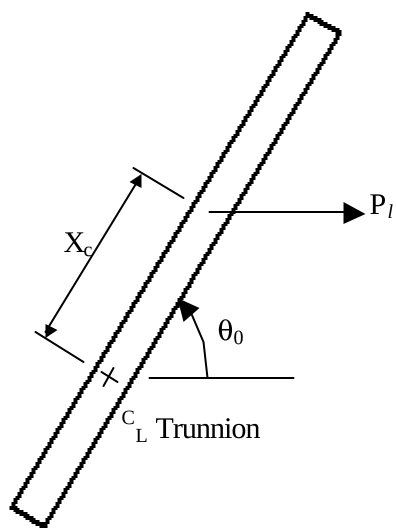

Figure 3. Schematic of Wind Load on a Bascule Bridge Leaf

The equivalent wind load acting on each girder (P_g) is half of the equivalent wind load acting on the leaf (P_l), given by

$$P_g = \frac{P_l}{2}$$

The torque due to wind, T_{wind}, acting on each girder can then be found using

$T_{wind} = P_g X_c \sin(\theta_o)$

The THG assembly must also resist the initial starting friction torque. The torque due to friction can be calculated using

$T_{friction} = \mu_{start} w_l d_b$

where,

μ_{start} = starting coefficient of friction of the roller bearing,

w_l = leaf dead load, and

d_b = bearing diameter.

The unbalanced load at the tip of the leaf also creates a torque that the THG assembly must withstand. This torque can be represented by

$T_{unbalance} = w_u x_e \cos(\theta_o)$

where,

w_u = unbalanced load at the tip of the leaf,

x_e = distance from the trunnion center to the tip of the leaf, and

Torque Resistance Due to Shrink-Fit

Due to the shrink-fit, compressive radial stresses are developed at the trunnion-hub and hub-girder interfaces. Such compressive radial stresses provide part of the torque taking ability needed during the opening and closing of a bascule bridge. The bolts between the hub and girder provide the remaining torque taking ability. In this section the formulas for calculating the compressive radial stresses at the two interfaces (trunnion-hub and hub-girder), based on the diametrical interferences at these two interfaces, are developed (Ugural and Fenster, 1995). The amount of torque taking ability from the interferences for the THG assembly is based on two types of standard interference fits – FN2 or FN3[1] (Shigley and Mischke, 1986). Also, calculated are the hoop and von Mises stresses in each of the three components – trunnion, hub, and girder. These determine whether the stresses created by interference fits are within tolerable limits.

A larger interference at the interface creates a larger compressive radial stress at the interface, for desirable larger torque taking capabilities. At the same time however, this creates larger hoop and von Mises stresses in the components. This may be undesirable, as these stresses may exceed failure limits, as determined by the yield strength of the component material and the factor of safety.

Since FN2 or FN3 fits can exist at either of the two interfaces, there are four possible combinations of fits, as given below in Table 1.

Table 1. Possible Combinations of Fits in Trunnion-Hub-Girder Assembly

Combination	Trunnion-Hub Fit	Hub-Girder Fit
1	FN2	FN2
2	FN2	FN3

[1] FN2 and FN3 fits are US standard based fits used in light and medium drive fits, respectively. According to Shigley and Mischke (1986), FN2 designation is for medium drive fits, given that "Medium-drive fits are suitable for ordinary steel parts or for shrink fits on light sections. They are about the tightest fits that can be used with high-grade cast-iron external members." FN3 designation is for heavy drive fits, given that "Heavy drive fits are suitable for heavier steel parts or for shrink fits in medium sections".

3	FN3	FN2
4	FN3	FN3

If cylinder 'B' is fit into cylinder 'A', there is an upper and lower limit by which the nominal (outer or inner, respectively) diameter of each cylinder varies. This limit, L, in thousands of an inch, is given by[2]

$$L = CD^{1/3}$$

where D (nominal diameter) is in inches and the coefficient C, based on the type of fit, is given in Table 2 (Shigley and Mischke, 1986).

Table 2. Coefficient (C) to Calculate Limits (L)

Class of fit	Cylinder A		Cylinder B	
	Lower	Upper	Lower	Upper
FN2	0	+0.907	2.717	+3.288
FN3[3]	0	+0.907	3.739	+4.310

Hence, for each interface there will be four possible extreme limits of diameter. For example, at the trunnion-hub interface there will be a lower and upper limit of the outer diameter

2 It is to be understood that limits, L, are only close approximation to the standards (Shigley and Mischke, 1986).

of the trunnion, and there will be an upper and lower limit of the inner diameter of the hub. For a typical nominal trunnion outer diameter and hub inner diameter of 4 in., using a FN2 fit, the four limits are calculated as follows.

$L = (0)\ (4)^{1/3} = 0.000$ in

$L = (0.907)\ (4)^{1/3} = 1.440\text{x}10^{-3}$ in

$L = (2.717)\ (4)^{1/3} = 4.313\text{x}10^{-3}$ in

$L = (3.288)\ (4)^{1/3} = 5.219\text{x}10^{-3}$ in

Hence, the outer diameter dimensions of the trunnion would be $4^{+0.005219}_{+0.004313}$ in., and the inner diameter of the hub would be $4^{+0.001440}_{+0.000000}$ in. These two pairs of extreme dimensions of the trunnion and hub diameters will produce four different possible values of diametrical interference, as shown in Table 3.

Table 3. Four Typical Extreme Values of Trunnion Outer Diameter and Hub Inner Diameter

Combination	Outer Diameter of Trunnion (in)	Inner Diameter of Hub (in)	Diametrical Interference (in)
1	4.004313	4.000000	0.004313
2	4.005219	4.000000	0.005219
3	4.004313	4.001440	0.002873

[3] Not for sizes under 0.95 inches

4	4.005219	4.001440	0.003779

Clearly from Table 3, any diameter of the trunnion and hub creates interference, but the level of the interference varies per combination.

Similar to the trunnion-hub assembly, there will be four limits for a particular fit between the hub and girder. Hence, there are sixteen possible extreme diameters of the trunnion, hub, and girder once the type of fit is selected for each interface. Now, the maximum compressive interfacial radial stress at each interface and the maximum hoop and von Mises stresses of the trunnion-hub-girder assembly can be calculated. These stresses (radial and hoop/von Mises) will determine the maximum torque that the assembly can take, and hence the safety of the assembly.

For calculating the approximate steady state stresses in the trunnion-hub-girder assembly, each of the components (trunnion, hub, and girder) is approximated by an axisymmetric circular cylinder (Figure 4) with the material and geometrical properties given in Table 4.

Table 4. Geometrical and Elastic Parameters of Three Cylinders

No.	Cylinder	Nominal Inner Radius	Nominal Outer Radius	Young's Modulus	Poisson's Ratio
1	Trunnion	r_i^1	r_o^1	E_1	ν_1
2	Hub	r_i^2	r_o^2	E_2	ν_2

3	Girder	r_i^3	r_o^3	E_3	ν_3

The nominal radii of the three cylinders have the following relationships:

$$r_i^2 = r_O^1$$

$$r_i^3 = r_O^2$$

The inner radius of the trunnion (Cylinder 1) can be zero if the cylinder is solid.

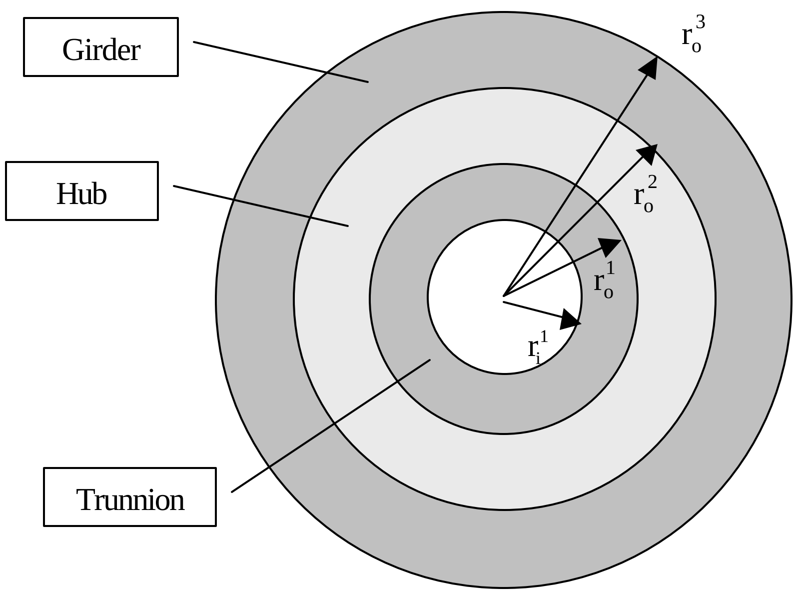

Figure 4. Axisymmetric cylinders representing the Trunnion-Hub-Girder Assembly

The interfaces at the trunnion-hub and the hub-girder have an interference of δ_1 and δ_2, respectively. After assembly, these interferences create interface, or contact, pressures at the interfaces. The interface pressure (p) at each interface (i = 1, 2) can be calculated using

$$p = \frac{E\,\delta_i}{r_o^{\,i}} \frac{\left((r_o^{\,i})^2 - (r_i^{\,i})^2\right)\left((r_o^{\,i+1})^2 - (r_o^{\,i})^2\right)}{2\,(r_o^{\,i})^2\left((r_o^{\,i+1})^2 - (r_i^{\,i})^2\right)}, \; i = 1,2.$$

The stresses (radial, hoop, and von Mises) and the radial displacements in each cylinder can then be found as follows[4].

For each cylinder 'i', the radial displacement (u_r) is of the form (Ugural and Fenster, 1995)

$$u_r^i = c_1^i r + \frac{c_2^i}{r}, \; i = 1,2,3$$

from which the radial stress is given as

$$\sigma_r^i = \frac{E_i}{1-\nu_i^2}\left[c_1^i(1+\nu_i) - c_2^i\left(\frac{1-\nu_i}{r^2}\right)\right]$$

The boundary conditions and the shrinking allowance give the following six simultaneous linear equations for finding the six unknown constants (c_1^i , c_2^i, i = 1,2,3).

Shrinking allowance (δ_1) on the radius at the trunnion-hub interface gives

$$u_r^2\left(r = r_O^1\right) - u_r^1\left(r = r_O^1\right) = \delta_1 \qquad (1)$$

Shrinking allowance (δ_2) on the radius at the hub-girder interface gives

$$u_r^3\left(r = r_O^2\right) - u_r^2\left(r = r_O^2\right) = \delta_2 \qquad (2)$$

Continuity of radial stress at the trunnion-hub and hub-girder interfaces, respectively, gives

[4] Plane stress conditions are assumed.

$$\sigma_r^1\left(r = r_O^1\right) = \sigma_r^2\left(r = r_O^1\right) \tag{3}$$

$$\sigma_r^2\left(r = r_O^2\right) = \sigma_r^3\left(r = r_O^2\right) \tag{4}$$

The radial stresses on the inside radius of the trunnion are zero, which gives

$$\sigma_r^1\left(r = r_O^1\right) = 0 \tag{5a}$$

If the trunnion is solid then the above equation is replaced by

$$c_2^1 = 0 \tag{5b}$$

The radial stresses on the outside radius of the girder (Cylinder 3) are zero, which gives

$$\sigma_r^3\left(r = r_O^3\right) = 0 \tag{6}$$

Solving the above six simultaneous linear equations (1), (2), (3), (4), (5a or 5b), and (6) gives the value of the six unknown constants, $c_1^i, c_2^i,\ i = 1,2,3$.

Now the radial displacement (u_r), and radial (σ_r), hoop (σ_θ), and von Mises (σ_e) stresses for each of the three members are given respectively by

$$u_r^i = c_1^i r + \frac{c_2^i}{r},\ i = 1,2,3b$$

$$\sigma_r^i = \frac{E_i}{1-\nu_i^2}\left[c_1^i\left(1+\nu_i\right) - c_2^i\left(\frac{1-\nu_i}{r^2}\right)\right], i = 1,2,3$$

$$\sigma_\theta^i = \frac{E_i}{1-\nu_i^2}\left[c_1^i\left(1+\nu_i\right) + c_2^i\frac{\left(1-\nu_i\right)}{r^2}\right], i = 1,2,3$$

$$\sigma_e^i = \left[\left(\sigma_r^i\right)^2 - \left(\sigma_r^i\right)\left(\sigma_\theta^i\right) + \left(\sigma_\theta^i\right)^2\right]^{1/2},\ i = 1,2,3$$

As mentioned earlier in the section, and shown in Table 3, there are four extreme interferences at each of the two interfaces. Hence, there are sixteen extreme combinations of the interference for the four combinations of fits given in Table 1. Then, the minimum and maximum hoop stress in each cylinder[5], the maximum von Mises stress in each cylinder, and the maximum and minimum radial stress at the two cylinder interfaces[6] can be calculated for each of these sixteen combinations.

The main component of the stress of interest is the minimum magnitude of compressive radial stress (σ_r^{min}) at each of the interfaces, since then the torque resistance (T_R) can be given by

$$T_R = \min\left[\, 2\pi\mu\left(r_o^1\right)^2 w_h\, \sigma_r^{min}\Big|_{r=r_0^1},\, 2\pi\mu\left(r_o^2\right)^2 w_g\, \sigma_r^{min}\Big|_{r=r_0^2} \,\right]$$

where

w_h = thickness of the hub at the interface,

w_g = thickness of the girder at the interface, and

μ = coefficient of friction.

Torque Resistance Due to Bolts

Bolts supplement the hub-girder interference fit so that the THG assembly can resist torque in addition to the torque resisted due to the interference fits. The aim of this analysis is to find the torque that can be resisted by the bolts based on number of bolts, number of bolt circles, bolt size, bolt material, joint materials and their thickness, etc. This torque determines the point at which the shear stress transfers from the interference fit to the bolts, while assuming that there is no fretting (that is, low level or zero interference fit) at the hub-girder interface.

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5 Maximum and minimum stresses do not imply magnitude but are calculated to show the maximum tensile (if any) and the maximum compressive (if any) stresses, respectively.

6 See previous footnote

Figure 5 depicts the problem schematic showing the trunnion-hub-girder assembly including the bolts and backing collar ring.

Bolted connections designed to resist shear and prevent slip may be either of the bearing type or the friction type. Bearing joints are when the fasteners, in effect, act as points to prevent joint slip. Friction joints are when fasteners create a significant clamping force on the joint and the resulting friction between joint members prevents joint slip. Only bolts can be used in a friction joint, whereas, bolts and rivets can be used in a bearing joint (Bickford, 1986). *Friction joints are also called slip-critical.*

According to Bickford and Mileck (1998), the Research Council of Structural Connections (RCSC) and the American Institute of Steel Construction (AISC) provide two versions of the specification for structural steel bolting based on different design philosophies. These are the Allowable Stress Design (ASD), and Load and Resistance Factor Design (LRFD). Both versions are supported by the same criteria for the strength and serviceability of fasteners and connected material, and both are extensively documented in research literature.

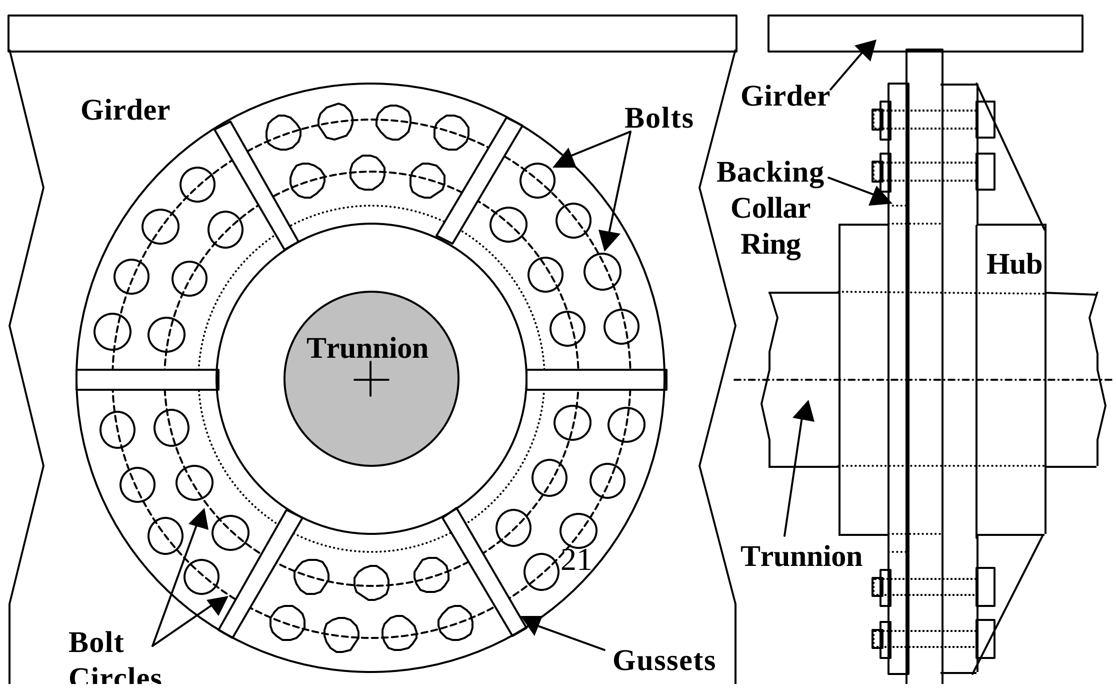

Figure 5. Problem Schematic of the Trunnion-Hub-Girder Assembly with Bolts

According to Bickford and Mileck (1998), the "Allowable Stress Design" (ASD) is "based on the more traditional approach of applying a global factor of safety", based on experience and judgement. This factor of safety must then provide for all of the uncertainties in strength of material, tolerances in the fabrication of fasteners and connected material, human error in fabrication and field installation, reliability of estimation of applied loads, reliability of engineering design formulas to predict actual connection performance, etc.

The "Load and Resistance Factor Design" (LRFD) separates the "load considerations from considerations of the resistance to the load of the fastener and connected material" (Bickford and Mileck, 1998). Theory and test develop the resistance factors (selected from the statistical study of the data) for the bolts and the connected material to different potential modes of failure.

The total torque (T) taken by the THG assembly with the bolts is given by

$$T = T_{BOLTS} + T_{FN2}$$

where

T_{FN2} = torque resisted due to the FN2 fit at the hub-girder interface, and

T_{BOLTS} = torque resisted due to the bolts in the hub-girder assembly.

The torque resisted by the bolts is given by

$$T_{BOLTS} = \frac{1}{2}\sum_{j=1}^{n}\left(N_{Bj}F_{Vj}D_j\right)$$

where

D_j = diameter of the j^{th} bolt circle,

N_{Bj} = number of bolts[7] in the j^{th} bolt circle,

F_{Vj} = shear force per bolt in the j^{th} bolt circle, and

T_{FN2} is due to the compressive radial stress between the hub and the girder assuming FN2 shrink fit, and is given by

$$T_{FN2} = \frac{\pi}{2}\sigma_r \mu D_{Gi}^2$$

where

σ_r = the radial stress between the hub and girder caused by the FN2 interference fit, and

D_{Gi} = nominal inner diameter of the bore in the girder.

In the preceding analysis it is assumed that the centroid of the bolt group is located at the center of the hub.

According to Bickford (1998) and LRFD (1995), the value of torque that the bolt assembly can take is based on twelve different criteria, as per AASHTO standards. The lowest

[7] Typical bolt diameters and wrench clearances are given in Table 10. Wrench clearance is the measure of clearance required between centers of bolts (in a bolt circle or between two adjacent bolt circles) to allow installation of bolts.

of these twelve values determines the torque that the THG assembly can resist due to the bolt assembly. These twelve criteria are:

1. Shear Stress in Bolts - Bearing Type Joints – ASD
2. Bearing Stresses on the Joint Member Hub – ASD
3. Bearing Stresses on the Joint Member Girder – ASD
4. Tear Out Stress in Hub – ASD
5. Tear Out Stress in Girder – ASD
6. Slip Resistance in Slip-Critical Connections – ASD
7. Shear Stress in Bolts - Bearing Type Joints – LRFD
8. Bearing Stress on the Joint Member Hub – LRFD
9. Bearing Stresses on the Joint Member – Girder – LRFD
10. Tear Out Stress in Hub – LRFD
11. Tear Out Stress in Girder – LRFD
12. Slip Resistance in Slip Critical Connections - LRFD

Criterion#1 - Shear Stress in Bolts - Bearing Type Joints - ASD

Joint slip is prevented when the bolt preload is high enough so that the friction forces between joint members (that is, the so-called faying surfaces) become high enough to prevent slip under design load. When this is not the case, joints are classified as the bearing type. To find the allowable torque due to the bolt assembly as per Criterion#1, the following steps are followed.

Step1: If bolts in a particular bolt circle, 'j', are failing due to shear, the force (F_{vj}) existing in the bolts in that circle is

$$F_{Vj} = S_{BSj} A_{Bj}$$

where

S_{BSj}	=	allowable shear stress in the bolts, and
A_{Bj}	=	cross-sectional area of each bolt that undergoes shear.

The allowable shear stress in the bolts, as per ASD is given in Table 5.

Table 5. Allowable Shear Stress in Bolts for ASD Design (Table 10.32.3B of AASHTO-SSHB-16)

Material	Allowable Shear Stress (psi)
A325 Bolts	19,000
A490 Bolts	24,000

If the shear plane passes through the unthreaded body of each bolt in the j^{th} bolt circle, the area of the bolt that undergoes shear is

$$A_{Bj} = \frac{\pi d_j^2}{4}$$

where

d_j = diameter of the bolts in the j^{th} bolt circle.

Step 2: Based on the assumption that the bolts fail in shear in the j^{th} bolt circle, the force existing in the bolts in the other (n-1) bolt circles can be found

$$F_{Vk} = \frac{D_k F_{Vj}}{D_j}, \ k = 1, 2, \ldots, n, \ k \neq j.$$

Step 3: Then the torque resisting capability due to bolts is given by

$$T_B = \frac{1}{2}\sum_{j=1}^{n}\left(N_{Bj}F_{Vj}D_j\right)$$

Step 4: The above process of Step 1 through Step 3 is repeated for each bolt circle, j=1,2, ….., n. The minimum of the 'n' such torques calculated is then the allowable torque due to the bolt assembly.

$T_{BOLTS} = \min(T_B)$; B=1,2, …,n,

where

T_B = torque due to bolts failing in the B^{th} bolt circle.

Criterion#2 - Bearing Stresses on the Joint Member Hub - ASD

If the bolts exert too great a load on the hub, the hub can be deformed (that is, bolt holes will elongate). To find the allowable torque due to the bolt assembly as per Criterion#2, the following steps are followed.

Step 1: The maximum possible shear force created in each bolt, if that is a limiting criterion[8], is

$$F_{Vj} = F_{Hu} d_j w_j$$

where

F_{Hu} = minimum specified tensile strength of the hub, and

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8 Table 10.32.3B of AASHTO-SSHB-16

w_j = width of hub flange in j^{th} bolt circle.

To find the allowable torque due to the bolt assembly, steps 2 to 4 are the same as in Criterion#1. Typical values of minimum specified tensile strength of some joint materials are given in Table 6.

Table 6. Minimum Specified Tensile Strength of Typical Joint Materials Used in Hub, Girder and Backing Collar (Table 10.32.1A of AASHTO-SSHB-16)

Material	Comment	Minimum Specified Tensile Strength (psi)
M270 Grade 36	Up to 4 in thickness of plates	58,000
M270 Grade 50	Up to 4 in thickness of plates	65,000
M270 Grade 50W	Up to 4 in thickness of plates	70,000
M270 Grade 70W	Up to 4 in thickness of plates	90,000
M270 Grades 100/100W	Up to 2.5 in. thickness of plates	110,870
M270 Grades100/100W	2.5 in. to 4 in thickness of plates	100,000

Criterion#3 - Bearing Stresses on the Joint Member Girder - ASD

If the bolts exert too great a load on the girder, it can be deformed (that is, bolt holes will elongate). To find the allowable torque due to the bolt assembly as per Criterion#3, the following steps are followed.

Step 1: The maximum possible shear force created in each bolt, if that is a limiting criterion, is

$$F_{Vj} = F_{Gu} d_j w_g$$

where

w_g = width of the girder, and

F_{Gu} = minimum specified tensile strength of the girder.

To find the allowable torque due to the bolt assembly, steps 2 to 4 are the same as in Criterion#1.

Criterion#4: Tear Out Stress in Hub - ASD

If the bolts exert too great a load on the hub, the bolts will tear out of the hub. To find the allowable torque due to the bolt assembly as per Criterion#4, the following steps are followed.

Step 1: To check the maximum possible shear in the bolts, if this is the mode of failure[9], then

$$F_{Vj} = 0.5\ L_c F_{Hu} w_j$$

where

L_c = clear distance between holes[10].

To find the allowable torque due to the bolt assembly, steps 2 to 4 are the same as in Criterion#1.

In the preceding analysis it is assumed that the backing collar ring simply slides and does not absorb any of the shear force.

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9 Table 10.32.3B of AASHTO-SSHB-16

10 Clear distance between holes is considered only along the circumference of the hub in this analysis.

Criterion#5 - Tear Out Stress in Girder - ASD

If the bolts exert too great a load on the girder, the bolts will tear out of it. To find the allowable torque due to the bolt assembly as per Criterion#5, the following steps are followed.

Step 1: To check the maximum possible shear in the bolts, if this is the mode of failure[11], then

$$F_{Vj} = 0.5\, L_c F_{Gu} w_g$$

To find the allowable torque due to the bolt assembly, steps 2 to 4 are the same as in Criterion#1.

In the preceding analysis it is assumed that the backing collar ring simply slides, and does not absorb any of the shear force.

Criterion#6 - Slip Resistance in Slip-Critical Connections - ASD

Bolted connections subjected to stress reversal, heavy impact loads, severe vibrations, and detrimental effects from joint slippage are designated as slip critical. In addition, bolted connections of tension members should be designed as slip critical. To compute the slip resistance of the joint under shear load, the slip resistance of a friction-type joint per "Allowable Stress Design" (ASD) is given by[12]

$$F_{Vj} = N_{Sj} N_{Bj} F_{Sj} A_{Bj}$$

where

N_{Sj} = number of slip planes in the j^{th} bolt circle, and

[11] Table 10.32.3B of AASHTO-SSHB-16
[12] Article 10.32.3.2.1 of ASSHTO-SSHB-16

F_{Sj} = nominal slip resistance per unit bolt area per bolt in the j^{th} bolt circle.

The value of the allowed load per unit area, F_{Sj}, is based on slip resistance. Slip resistance varies with surface condition of the joint, hole type, and direction of applied load. The values based on the above three conditions are tabulated for A325 and A490 bolts in Table 7.

Table 7. Allowable Slip Loads Per Unit of Bolt Area[13] for Slip Critical Connections as per ASD, F_s (psi) (Table 10.32.3C of AASHTO-SSHB-16)

Surface Condition of Joint Members	Hole Type And Direction of Applied Load							
	Any Direction				Transverse, Long Slots		Parallel, Long Slots	
	Standard		Oversize					
	A325	A490	A325	A490	A325	A490	A325	A490
Class A	15,000	19,000	13,000	16,000	11,000	13,000	9,000	11,000
Class B	23,000	29,000	19,000	24,000	16,000	20,000	14,000	17,000
Class C	15,000	19,000	13,000	16,000	11,000	13,000	9,000	11,000

Then, the torque resisting capability due to bolts is given by

$$T_{BOLTS} = \frac{1}{2} \sum_{j=1}^{n} \left(F_{Vj} D_j \right)$$

[13] For bolt diameters greater than 1.0 inch, multiply the values in Table 7 by 0.875.

Criterion#7 - Shear Stress in Bolts - Bearing Type Joints – LRFD

This criterion is the same as Criterion#1 for the ASD, except the allowable shear stresses in the bolts (S_{BSj}) are different, as given in Table 8.

Table 8. Allowable Shear Stress in Bolts for LRFD Design (Table 10.56A of AASHTO-SSHB-16)

Material	Allowable Shear Stress (psi)
A325 Bolts	35,000
A490 Bolts	43,000

Criterion#8 - Bearing Stress on the Joint Member Hub – LRFD

This criterion is the same as Criterion#2, except the equation to calculate the maximum possible shear force[14] in Step 1 is given by

$$F_{Vj} = 1.8\ F_{Hu} d_j w_j$$

Criterion#9 - Bearing Stresses on the Joint Member – Girder – LRFD

This criterion is the same as Criterion#3, except the equation to calculate the maximum possible shear force[15] in Step 1 is given by

$$F_{Vj} = 1.8\ F_{Gu} d_j w_j$$

[14] Article 10.56.1.3.2 of AASHTO-SSHB-16
[15] Equation (10-166b) of AASHTO-SSHB-16.

Criterion#10: Tear Out Stress in Hub - LRFD

This criterion is the same as Criterion#4, except the equation to calculate the maximum possible shear force[16] in Step 1 is given by

$$F_{Vj} = 0.9\ F_{Hu} L_c w_j$$

Criterion#11 - Tear Out Stress in Girder - LRFD

This criterion is the same as criterion#5, except the equation to calculate the maximum possible shear force[17] in Step 1 is given by

$$F_{Vj} = 0.9\ F_{Gu} L_c w_j$$

Criterion#12 - Slip Resistance in Slip Critical Connections - LRFD

To find the allowable torque due to the bolt assembly as per Criterion#12, the following steps are followed.

Step 1: Similar to Criterion#6 the slip resistance of each individual bolt can be interpreted as the shear force in each bolt, given by

$$F_{Vj} = N_{Sj} F_{Sj} A_{Bj}$$

Step 2: Then, the torque resisting capability due to bolts is given by

$$T_{BOLTS} = \frac{1}{2} \sum_{j=1}^{n} \left(N_{Bj} F_{Vj} D_j \right)$$

16 Equation (10-166b) of AASHTO-SSHB-16.

17 Equation (10-166b) of AASHTO-SSHB-16.

The values for the design slip resistance are based on slip coefficients, hole size parameters, and slip probability factors. The effect of these is included in the tabulated values for A325 and A490 bolts in Table 9.

Note that engineering specifications published by the AISC, and others, carefully define and limit the joint surface conditions that are permitted for structural steel work involving friction-type joints.

Table 9. Design Slip Loads Per Unit of Bolt Area for Slip Critical Connections as per LRFD, F_s (psi)[18] (Table 10.77A of AASHTO-SSHB-16)

Surface Condition of Joint Members	Hole Type And Direction of Applied Load							
	Any Direction				Transverse, Long Slots		Parallel, Long Slots	
	Standard		Oversize					
	A325	A490	A325	A490	A325	A490	A325	A490
Class A	21,000	26,000	18,000	22,000	15,000	18,000	13,000	16,000
Class B	32,000	40,000	27,000	34,000	22,000	28,000	19,000	24,000
Class C	21,000	26,000	18,000	22,000	15,000	18,000	13,000	16,000

[18] For bolt diameters greater than 1 inch, the design values given in Table 9 shall be multiplied by 0.875

CHAPTER 3 GRAPHICAL USER-INTERFACE MODEL

A user-friendly PC based design package is developed for the THG assembly design. As given in Chapter 2, torque-taking capability is calculated due to interference fits and due to the bolts in the hub-girder assembly. This program allows the user to simulate various designs of the THG assembly. The inputs to the program are explained step-by-step, and are related to the technical information given in Chapter 2. Then the outputs of the program are explained.

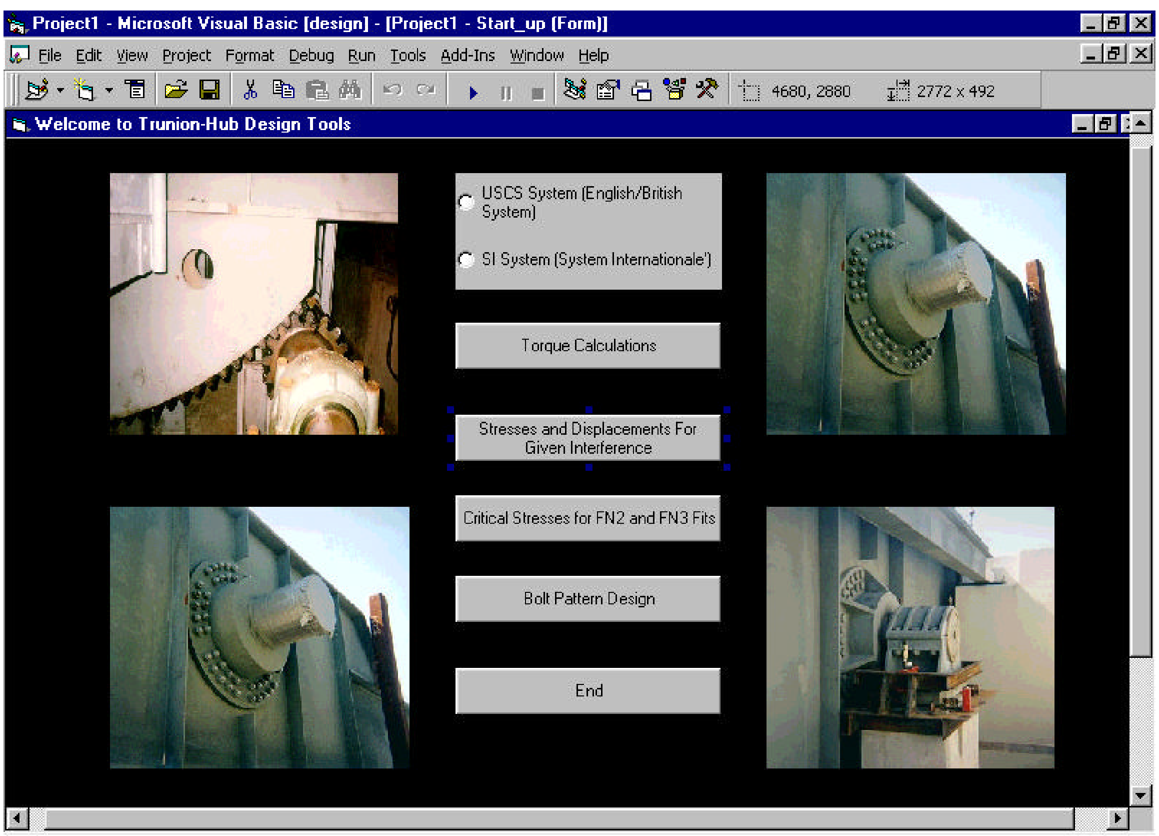

Figure 6. Main Menu of the THG-Assembly Program

THG-Assembly (see Figure 6) is a Graphical User Interface (GUI) designed to run on personal computers and takes advantages of their extensive number of programming tools, graphics packages, portability, and low cost.

THG assembly is comprised of four design tools. These are "Program 1 – Torque Calculations for THG assembly", "Program 2 – Stresses in the THG assembly with given interference", "Program 3 – Stresses in the THG assembly with given standard interference fits", and "Program 4 – Torque resisting capability of the THG assembly due to bolts and hub-girder FN2 fit."

Program 1 Torque Calculations for the THG Assembly.

The first design tool calculates the torque that the THG assembly is required to resist, given actual bascule bridge criteria entered by the user. The user is required to input the dimensions of a bascule leaf, as related to the diagram shown (Figure 2). The user must also input values such as the unbalanced load at the tip of the span, the dead weight load of the leaf, the wind load, the diameter of the trunnion, the starting coefficient of friction of the roller bearing, and the angle of opening of the bascule leaf. As discussed in Chapter 2, the design tool sums the three torques affecting the bearing (wind load, unbalanced load, and starting friction) to find the total torque that the assembly must resist. This design tool provides the user the torques that must be resisted by the bascule THG assembly.

Program 2 Stresses in the THG Assembly with Given Interference Fits.

The second design tool calculates the critical radial stresses at the trunnion-hub and hub-girder interfaces, and hoop and von Mises stress in the THG assembly for input diametrical interferences. This program gives the user a comprehension of how the stresses vary through the assembly radius, and is an academic tool for the designer to get a technical "feel" of the complexity of the problem due to the two interferences.

This program follows the equations given in Chapter 2, for a composite cylinder made of three cylinders with a diametrical interference at each of the two interfaces. The three cylinders approximate the trunnion, hub and girder. The inputs to the program are the elastic modulus of each cylinder, Poisson's ratio for each cylinder, the inner and outer radii of each cylinder, and the specified interference at each of the two interfaces. The program then outputs a radial profile of the radial, hoop, and von Mises and radial displacement across the entire THG assembly.

Program 3 Stresses in the THG Assembly with Given Standard Interference Fits.

The third design tool is very similar to Program 2, except now the user specifies the industry standard interference fit (FN2 or FN3) at each of the two interfaces. The critical stresses, as just discussed for Program 2, are then calculated. This program allows the designer to check what the approximate steady state stresses would be after assembly. In this program, the user can see if the hoop stresses (both compressive and tensile, if applicable) are more than the yield stresses, which may cause hoop cracks in that respective cylinder. The von Mises stress is also given to show how these stresses directly compare with the yield strength of the material.

Program 4 Torque Resisting Capability in the THG Assembly Due to Bolts and Hub-

Girder FN2 Fit.

The fourth design tool assists in designing a bolt pattern for the hub-girder assembly, used to supplement the hub-girder interference fit. The maximum allowable torque due to the presence of bolts is calculated based on the minimum torque value obtained through the twelve different criteria given in Chapter 2 – Technical Information. The allowable torque[19] due to the bolts is then added to allowable torque due to the FN2 fit between the hub and the girder. This gives the total allowable torque in the assembly.

To perform all of the calculations described in Chapter 2 for the twelve different design criteria, the user must supply the fourth design tool with various geometric and material properties for the three system components (trunnion, hub, and girder). The inputs to the program are briefly explained here so that their need and implication, as per the AASHTO standards, are understood.

1. Bolt Information

(a) Number of bolt circles, n. The maximum number of bolt circles allowed in the program is three. Generally on THG assemblies, only one or two bolt circles are found.

(b) Diameter of each bolt circle, D_j. The diameter of the bolt circle has to be between the inner and outer hub nominal diameter. The diameter of the bolt circle is further restricted by the wrench clearance, so that it does not extend outside the nominal girder inner diameter or

[19] Note that the influence of the trunnion-hub assembly is not accounted for in this program. It is expected that a FN2 or FN3 fit at the trunnion-hub interface shall create higher interfacial stresses at the hub-girder interface and hence, increase the overall torque taking capability of the THG assembly than only considering a FN2 fit between the hub and girder. Therefore, this approach is conservative in the measure of torque taking capability of the THG assembly due to interference fits.

outer hub diameter. Typical bolt diameters and wrench clearances are given in Table 10.

Table 10. Bolt Sizes and Wrench Clearance

Nominal Diameter (in)	Wrench Clearance (in)
0.500	1.810
0.625	2.100
0.750	2.440
0.875	2.800
1.000	3.100
1.125	3.380
1.250	3.640
1.375	3.880
1.500	4.120

Wrench clearance is the measure of clearance required between centers of bolts (in a bolt circle or between two adjacent bolt circles) to allow for installation of bolts. The difference between the diameters of two bolt circles is also restricted by the wrench clearance of the bolts in each circle. That is, the difference between the diameters of the bolt circles must be more than the sum of the wrench clearances for any two bolts. Also, the distance from the bolt circles to the hub edge is limited by AASHTO-SSHB-16 standards given in Article 10.24.7.

(c) Number of bolts in bolt circle, N_{Bj}. The maximum number of bolts in a bolt circle is determined by the size of the bolt hole chosen, and the wrench clearance (Table 10). Hence, the maximum number of bolts possible in a bolt circle is restricted by an equal-sided polygon with the largest number of sides that can be inscribed in a bolt circle, where each side is assumed equal to the wrench clearance diameter. The minimum spacing between bolts is restricted by Article 10.24.5 of AASHTO-SSHB-16 for spacing between fasteners.

(d) Diameter of bolts in bolts circle, d_j. The typical diameter of each bolt in a bolt circle is input. The bolt diameter used in each circle is the same for that circle, but can be different in another bolt circle. The choice of the bolt diameter (5/8" to 1 1/2") is made through a drop-down box in the program, and automatically dictates the needed clearance between bolts and bolt circles.

(e) Width of hub flange in bolt circle, w_j. This is the width of the hub-flange at each bolt circle. This width can vary along the radius of the hub. The width of the hub is used to calculate the maximum torque resistance due to the bolts. This is calculated using the bearing stress on the hub Criteria #2 (ASD) and #8 (LRFD), and tear-out stress on the hub Criteria #3 (ASD) and #9 (LRFD).

(f) Bolt material. The bolt material is chosen via the options given in a drop down box, in the design tool. The choices for the bolt material are as given in Table 5. When the bolt material is chosen, the shear strength, S_{BSj}, of each bolt is automatically chosen as given in Table 5 (ASD) or 8 (LRFD).

(g) Number of slip surfaces, N_{Sj}. The number of slip planes can be 1 or 2. This number is used in calculating the allowable torque due to bolts, as per slip resistance, in slip-critical connections, as per Criteria #6 (ASD) and #12 (LFRD).

(h) Hole type and direction of load. There are five choices, as given in Table 7 (ASD) or 9 (LFRD), for the hole type and direction of loading. These five types are standard, oversize any direction, short slot any direction, long slot transverse, and long slot parallel. Coupled with the class of surface and type of bolt, the allowable slip load per unit area is automatically chosen as given in Table 7 (ASD) or 9 (LFRD). The hole type determines the dimensions of the hole as given in Table 11. The hole dimensions affect the clear distance between holes, Lc, used in Criteria #4 (ASD), #5 (ASD), #10 (LRFD), and #11 (LRFD).

Table 11. Nominal Hole Dimensions (Table 10.24.2 of AASHTO-SSHB-16)

Bolt Diameter, d	Hole Dimensions			
	Standard (Dia.)	Oversize (Dia.)	Short Slot (Width × Length)	Long Slot (Width × Length)
5/8	11/16	13/16	11/16 × 7/8	11/16 × 1 9/16
3/4	13/16	15/16	13/16 × 1	13/16 × 1 7/8
7/8	15/16	1 1/16	15/16 × 1 1/8	15/16 × 2 3/16
1	1 1/16	1 ¼	1 1/16 × 1 5/16	1 1/16 × 2 ½
d ≥ 1 1/8	d + 1/16	d + 5/16	(d+1/16) × (d+3/8)	(d+1/16) × (2 ½ × d)

(i) Class of Surface. There are three types of surface classes. The allowable slip load per unit area is chosen (Table 7 or 9) based on the surface class. These two parameters are used in calculating the allowable torque due to bolts, Criteria #6 (ASD) and #12 (LFRD).

2. Hub Information

(a) Nominal hub inner diameter, D_{Hi}. The nominal inner diameter of the hub is used in calculating the stresses caused by the FN2 fit at the hub-girder interface.

(b) Nominal hub outer diameter, D_{Ho}. The nominal outer diameter of the hub, coupled with the bolt diameter and wrench edge clearance, restricts the diameter of the outermost bolt circle.

(c) Hub material. The hub material is chosen via the options given in a drop down box, as listed in Table 4. This determines the specified minimum tensile strength of the hub material used in Criteria #2 (ASD), #4 (ASD), #8 (LRFD) and #10 (LRFD).

3. Girder Information

(a) Nominal inner diameter of the bore in the girder, D_{Gi}. The nominal inner diameter of the girder is used in calculating the stresses caused by the FN2 fit at the hub-girder interface. Coupled with the bolt diameter and wrench edge clearance, it also restricts the dimension of the smallest diameter bolt circle.

(b) Nominal outer diameter of the bore in the girder, D_{Go}. The nominal outer diameter of the girder is used in calculating the stresses caused by the FN2 fit at the hub-girder interface.

(c) Width of girder, w_g. The width of the girder is used in Criteria #3 (ASD), #5 (ASD), #9 (LRFD), and #11 (LRFD).

(d) Girder material. The girder material is chosen via the options given in a drop down box, as listed in Table 4. This determines the specified minimum tensile strength of the girder, used in Criteria #3 (ASD), #5 (ASD), #9 (LRFD), and #11 (LRFD).

4. Collar Information

(a) The collar information such as its width and composition is not used in the program. However, the collar geometry may be used to address the number of slip surfaces and the minimum distance of bolt circles to the edge of the hub.

5. Miscellaneous Information

(a) Coefficient of friction between the girder and hub at the FN2 fit, μ. This value is used in calculating the allowable torque due to the FN2 interference fit.

The fourth design tool provides the user with helpful design information, such as:

(a) Radial stress between the hub and girder caused by the FN2 fit. This stress is calculated assuming a two-cylinder (hub and girder) problem. A two-cylinder problem can be solved as a three-cylinder problem by assuming the non-existent cylinder (trunnion) to be infinitely compliant (very low elastic modulus compared to other cylinders).

(b) Torque resisted by FN2 fit between hub and girder, $T_{FN2.}$ After the radial stress is calculated at the hub-girder interface, this torque can be calculated, as shown in Chapter 2.

(c) Torque resisted by the bolts for each of the failure modes. A torque is calculated for each of the twelve criteria.

(d) Torque that can be safely transmitted due to interference and bolts for each of the twelve possible failure modes. Among the twelve criteria, the allowable torque is calculated by finding the minimum of the twelve quantities.

CHAPTER 4 CONCLUSIONS

As mentioned in this report, cracks in the assemblies of some Florida bascule bridges have prompted the analysis of these bridges and their fabrication techniques. This report was compiled to provide insight to and an explanation of four computer-aided design tools that can be used in the design and analysis of trunnion-hub-girder assemblies of bascule bridges.

In summary, the first design tool simulates an actual bridge layout, and finds the actual torque necessary to raise the bridge leaf. The second design tool calculates radial, hoop, and von Mises stresses, as well as the radial displacements in each member (trunnion, hub, and girder). Design Tool 3, which is very similar to Tool 2, finds all of the critical stresses in the THG assembly at steady state. Finally, the fourth design tool is for developing the bolt pattern used to supplement the hub-girder interference fit

The primary benefit of the four design tools is that they make the design and analysis of THG assemblies less tedious for the user. The programs allow the user to operate in a user-friendly, visual basic interface, and provide feedback on input data when it is incomplete. The types of calculations that are done by the software are based on established methods of elasticity, bridge design, as well as the Allowable Stress Design and Load and Resistance Factor Design philosophies. The output of these four tools can be viewed in the appendices.

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APPENDICES

Appendix 1 Software Installation and System Requirements

The following are the minimum computer system requirements for the installation of Bascule Bridge Design Tool:

1. Personal computer running Microsoft Windows 95/98 or Windows NT
2. 32 MB RAM
3. Internet connection for downloading program
4. WinZip software to unzip the zipped file of the installation program - WinZip can be downloaded free for 30 days from http://www.winzip.com
5. Microsoft Mouse
6. Printer recommended
7. SVGA or higher resolution video adapter

Bascule Bridge Design Tool can be installed in the following manner:

1. Go to the WWW address of http://www.eng.usf.edu/~kaw/download/bascule.zip
2. Close all the applications except virus checkers.
3. Download the "bascule.zip" program to a temporary directory.
4. Unzip the program using a zip utility such as WinZip that can be downloaded free for 30 days from http://www.winzip.com.
5. Click on "setup.exe" file out of the unzipped files and follow the instructions.
6. Follow the instructions given on the screen. You can change the directory to anything you want.

Appendix 1 (Continued)

7. Once the installation is complete, the program "THG-Assembly" will be part of the Program in the Start Menu.

Appendix 2 Example Problem Design Tool 1

The following is an example problem using the first design tool, Torque Calculations for THG Assembly.

Example: Given for a typical South Florida bridge are the following parameters. These parameters correspond to those given in Figure 2 of the document.

a	=	48.75 ft
b	=	31.5 ft
c	=	18.75 ft
d	=	120 ft
e	=	66 ft
σ_w	=	20 psf (AASHTO Condition C)
μ_{start}	=	0.004
w_l	=	53.30×10^6 lbf
w_u	=	2696 lbf
d_b	=	3.281 ft
θ_o	=	57.5^o

Find the distance to the centroid from the trunnion centerline, the wind load affecting the leaf and each girder, and the torque that is generated by wind load, friction load, and unbalanced load. Then determine the total torque that the roller bearing assembly must resist.

Appendix 2 (Continued)

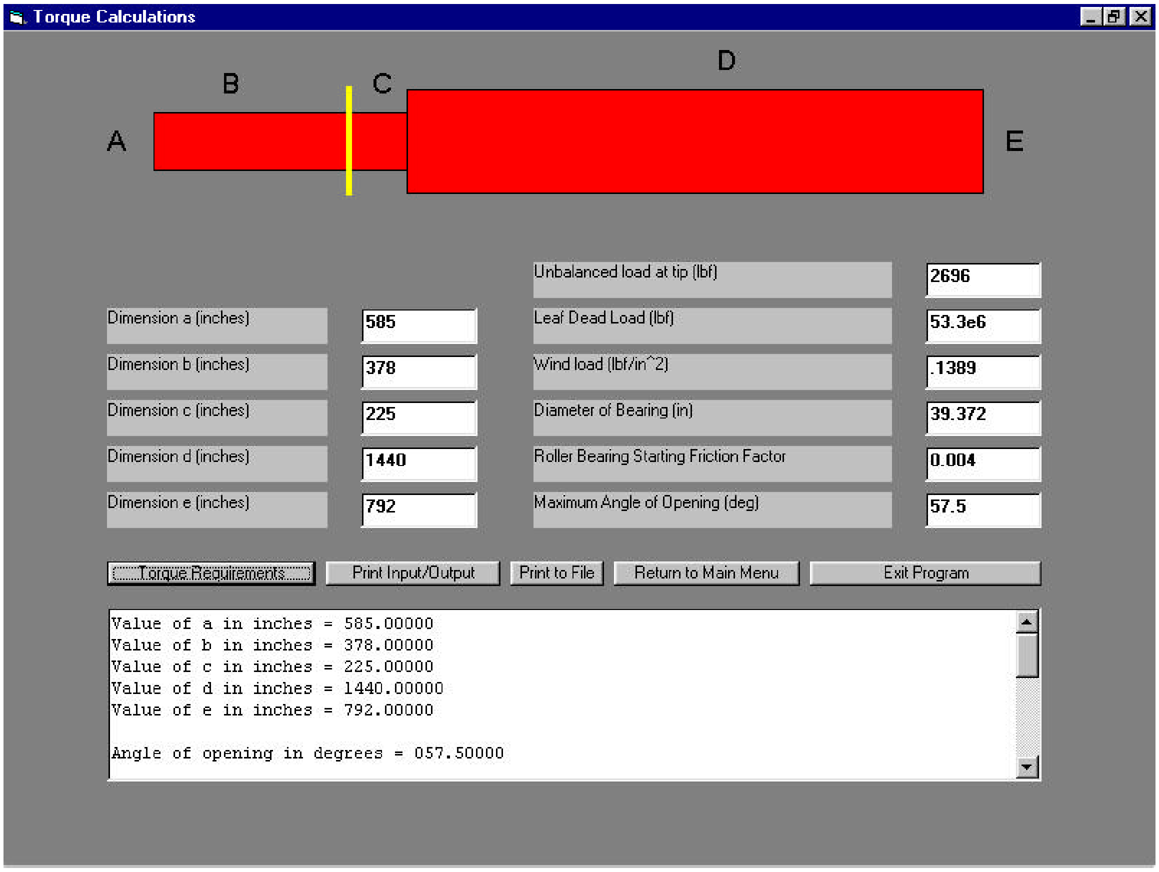

Figure A-1. Introductory Screen for the Torque Calculation Program

Solution: Substituting the above values into the Design Tool 1 interface, as shown in Figure A-1.

The program is run, and following data is output.

Value of a in inches = 585.00000

Value of b in inches = 378.00000

Value of c in inches = 225.00000

Value of d in inches = 1440.00000

Value of e in inches = 792.00000

Angle of opening in degrees = 057.50000

Wind load in pounds/sq in = 000.13890

Unbalanced Weight on Leaf Tip in lbs = 2696.00000

Leaf Dead Load in lbs = 53300000.00000

Diameter of Trunnion in inches = 039.3720

Centroid distance from Trunnion = 858.86103

Wind Load on Leaf in lbf = 149023.37580

Appendix 2 (Continued)

Wind Load on Each Girder in lbf = 74511.68790

Windmoment on girder in lb-in = 5.3973E+007 (0089.00%)

Unbalanced moment in lb-in = 2.4119E+006 (0003.00%)

Friction moment in lb-in = 4.1971E+006 (0006.00%)

Total moment on TGH assembly in lb-in = 6.0582E+007

Appendix 3 Example Problem Design Tool 2

The following is an example problem using the second design tool, Stresses in the THG Assembly with Given Interference Fits.

Example: A compound cylinder is made of three cylinders (with a solid inner shaft) as shown in Figure 4 with the radii given as $r_O^1 = 8.39$ in, $r_O^2 = 15.39$ in, and $r_O^3 = 36.5$ in. The Young's modulus and Poisson's ratio of all the cylinders is given as E = 30 Msi, ν=0.3, respectively. The diametrical interference at the interface of the Cylinder 1 and Cylinder 2 is given as δ_1=0.0080 in and δ_2=0.010 in, respectively. Find the pressure at the interfaces, and the maximum hoop and von Mises stresses in the compound cylinder.

Solution: The above data is input to the Design Tool 2 interface, as shown in Figure A-2.

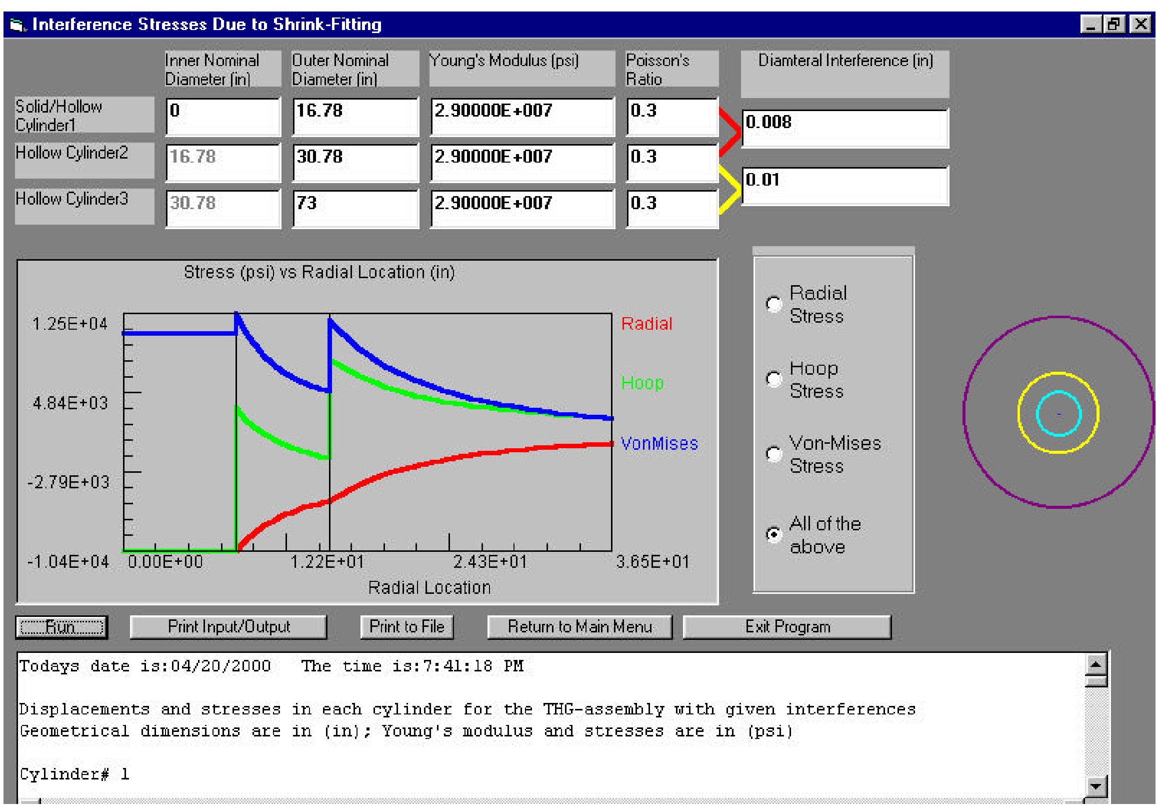

Figure A-2. Introductory Screen for the Steady-State Stress Analysis Program

Appendix 3 (Continued)

The program is run, and following data is output.

Todays date is:04/20/2000   The time is:7:41:18 PM

Displacements and stresses in each cylinder for the THG-assembly with given interferences

Geometrical dimensions are in (in); Young's modulus and stresses are in (psi)

Cylinder# 1

Nominal Inner Diameter = 0.00000E+000

Nominal Outer Diameter = 1.67800E+001

Young's Modulus = 2.90000E+007

Poisson's Ratio = 3.00000E-001

Cylinder# 2

Nominal Inner Diameter = 1.67800E+001

Nominal Outer Diameter = 3.07800E+001

Young's Modulus = 2.90000E+007

Poisson's Ratio = 3.00000E-001

Cylinder# 3

Nominal Inner Diameter = 3.07800E+001

Nominal Outer Diameter = 7.30000E+001

Young's Modulus = 2.90000E+007

Poisson's Ratio = 3.00000E-001

Diametrical Interference Between Cylinders#1 and #2 = 8.00000E-003

Interface Pressure Between Cylinders #1 and #2 = -1.04211E+004

Diametrical Interference Between Cylinders #2 and #3 = 1.00000E-002

Interface Pressure Between Cylinders #2 and #3 = -5.56261E+003

Displacements and stresses in each cylinder as a function of radial location

Note: Hoop, circumferential and tangential stresses are names for the same stress

Cylinder# 1

Radial Location	Radial Displacement	Radial Stress	Hoop Stress	von-Mises Stress
0.00000E+000	0.00000E+000	-1.04211E+004	-1.04211E+004	1.04211E+004
8.39000E-001	-2.11045E-004	-1.04211E+004	-1.04211E+004	1.04211E+004
1.67800E+000	-4.22089E-004	-1.04211E+004	-1.04211E+004	1.04211E+004
2.51700E+000	-6.33134E-004	-1.04211E+004	-1.04211E+004	1.04211E+004
3.35600E+000	-8.44178E-004	-1.04211E+004	-1.04211E+004	1.04211E+004
4.19500E+000	-1.05522E-003	-1.04211E+004	-1.04211E+004	1.04211E+004
5.03400E+000	-1.26627E-003	-1.04211E+004	-1.04211E+004	1.04211E+004
5.87300E+000	-1.47731E-003	-1.04211E+004	-1.04211E+004	1.04211E+004
6.71200E+000	-1.68836E-003	-1.04211E+004	-1.04211E+004	1.04211E+004
7.55100E+000	-1.89940E-003	-1.04211E+004	-1.04211E+004	1.04211E+004
8.39000E+000	-2.11045E-003	-1.04211E+004	-1.04211E+004	1.04211E+004

Appendix 3 (Continued)

Cylinder# 2

Radial Location	Radial Displacement	Radial Stress	Hoop Stress	von-Mises Stress
8.39000E+000	1.88955E-003	-1.04211E+004	3.40491E+003	1.24770E+004
9.09000E+000	1.63006E-003	-9.39736E+003	2.38120E+003	1.07869E+004
9.79000E+000	1.39920E-003	-8.58528E+003	1.56913E+003	9.46787E+003
1.04900E+001	1.19123E-003	-7.93028E+003	9.14128E+002	8.42463E+003
1.11900E+001	1.00188E-003	-7.39432E+003	3.78164E+002	7.59047E+003
1.18900E+001	8.27833E-004	-6.95020E+003	-6.59558E+001	6.91746E+003
1.25900E+001	6.66552E-004	-6.57808E+003	-4.38077E+002	6.37035E+003
1.32900E+001	5.16017E-004	-6.26319E+003	-7.52961E+002	5.92272E+003
1.39900E+001	3.74615E-004	-5.99438E+003	-1.02177E+003	5.55444E+003
1.46900E+001	2.41040E-004	-5.76308E+003	-1.25308E+003	5.24992E+003
1.53900E+001	1.14224E-004	-5.56261E+003	-1.45355E+003	4.99699E+003

Cylinder# 3

Radial Location	Radial Displacement	Radial Stress	Hoop Stress	von-Mises Stress

____

1.53900E+001	5.11422E-003	-5.56261E+003	7.96816E+003	1.17796E+004
1.75010E+001	4.61252E-003	-4.02894E+003	6.43449E+003	9.14107E+003
1.96120E+001	4.23201E-003	-2.96329E+003	5.36884E+003	7.31539E+003
2.17230E+001	3.93737E-003	-2.19293E+003	4.59848E+003	6.00326E+003
2.38340E+001	3.70578E-003	-1.61805E+003	4.02360E+003	5.03168E+003
2.59450E+001	3.52185E-003	-1.17769E+003	3.58324E+003	4.29494E+003
2.80560E+001	3.37482E-003	-8.32947E+002	3.23849E+003	3.72547E+003
3.01670E+001	3.25695E-003	-5.58007E+002	2.96355E+003	3.27837E+003
3.22780E+001	3.16251E-003	-3.35227E+002	2.74077E+003	2.92284E+003
3.43890E+001	3.08719E-003	-1.52199E+002	2.55775E+003	2.63714E+003
3.65000E+001	3.02767E-003	-2.15947E-013	2.40555E+003	2.40555E+003

____

From the above tables, the interference pressures at the two interfaces are –10.42 ksi and –5.563 ksi. The maximum tensile hoop stress in the assembly of 7.968 ksi exists in Cylinder 3 at the inside radius. The maximum von Mises stress of 12.48 ksi exists in Cylinder 2 at the inside radius.

Appendix 4 Example Problem Design Tool 3

The following is an example problem using the third design tool, Stresses in the THG assembly with given standard interference fits.

Example: A compound cylinder is made of three cylinders (with a solid inner shaft) as shown in Figure 4 with the radii given as $r_O^1 = 8.39$ in, $r_O^2 = 15.39$ in, and $r_O^3 = 36.5$ in. The Young's modulus and Poisson's ratio of all the cylinders is given as E = 29 Msi, ν=0.3, respectively. FN2 fits are assumed at each of the two interfaces. Find the critical stresses in the THG assembly.

Solution: The above data is input to the Design Tool 3 interface, as shown in Figure A-3.

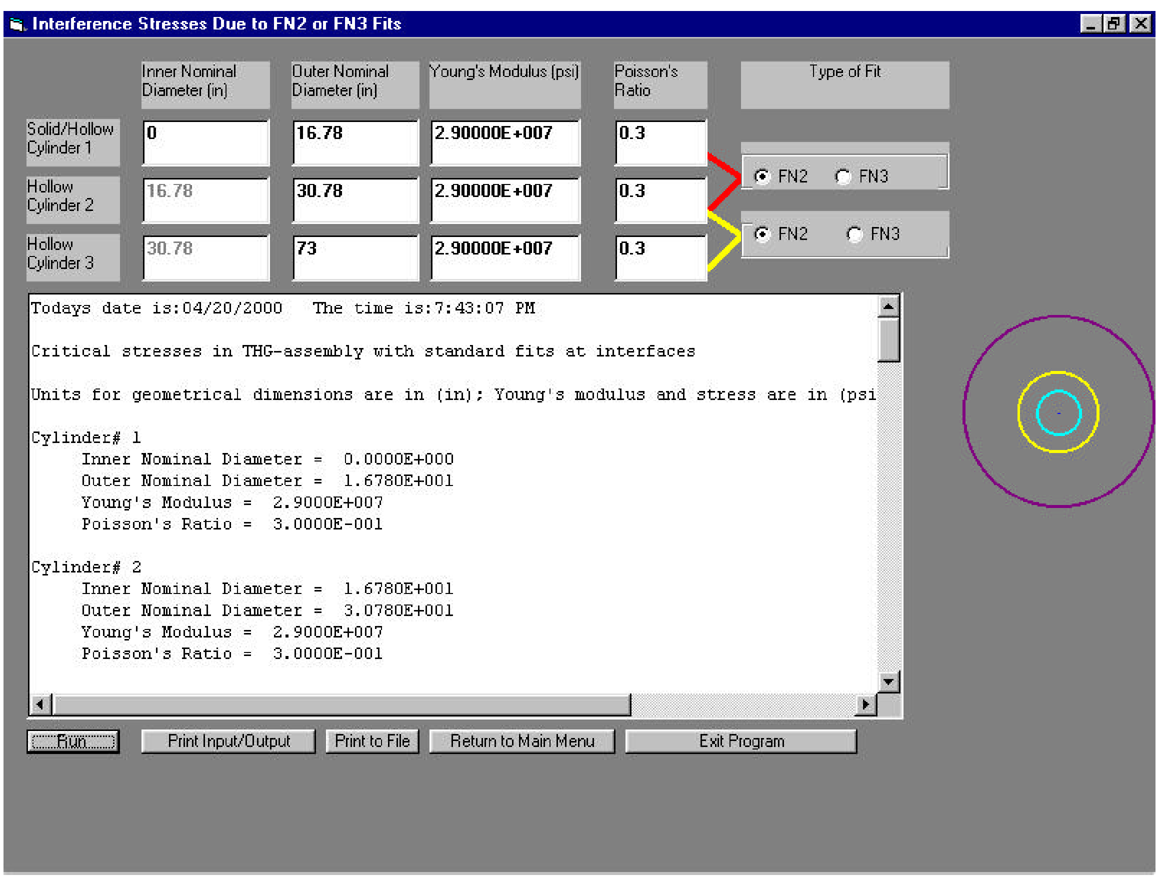

Figure A-3. Maximum and Minimum von Mises and Hoop Stresses in Trunnion-Hub Assemblies Based on FN2 and FN3 Fits.

Appendix 4 (Continued)

The program is run, and following data is output.

Todays date is:04/20/2000   The time is:7:54:48 PM

Critical stresses in THG-assembly with standard fits at interfaces

Units for geometrical dimensions are in (in); Young's modulus and stress are in (psi)

Cylinder# 1

Inner Nominal Diameter = 0.0000E+000

Outer Nominal Diameter = 1.6780E+001

Young's Modulus = 2.9000E+007

Poisson's Ratio = 3.0000E-001

Cylinder# 2

Inner Nominal Diameter = 1.6780E+001

Outer Nominal Diameter = 3.0780E+001

Young's Modulus = 2.9000E+007

Poisson's Ratio = 3.0000E-001

Cylinder# 3

Inner Nominal Diameter = 3.0780E+001

Outer Nominal Diameter = 7.3000E+001

Young's Modulus = 2.9000E+007

Poisson's Ratio = 3.0000E-001

Standard Fit Between Cylinder#1 and Cylinder#2 is FN2

Standard Fit Between Cylinder#2 and Cylinder#3 is FN2

Interface#	Cylinder#	Nominal Diameter	Lower Deviation	Upper Deviation	Lower Limit	Upper Limit
1	1	1.678E+01	6.955E-03	8.417E-03	1.679E+01	1.678E+01
1	2	1.678E+01	0.000E+00	2.322E-03	1.678E+01	1.678E+01
2	2	3.078E+01	8.514E-03	1.030E-02	3.078E+01	3.079E+01
2	3	3.078E+01	0.000E+00	2.842E-03	3.078E+01	3.078E+01

Maximum von-Mises stress in each cylinder

Cylinder#1 = 1.0881E+004 Cylinder#2 = 1.3105E+004 Cylinder#3 = 1.2216E+004

Maximum hoop stresses in each cylinder

Note: Hoop, circumferential and tangential stresses are names for the same stress

Cylinder#1 = -5.9898E+003

Cylinder#2 = 5.4612E+003

Cylinder#3 = 8.2634E+003

Minimum hoop stresses in each cylinder

Note: Hoop, circumferential and tangential stresses are names for the same stress

Cylinder#1 = -1.0881E+004

Cylinder#2 = -2.5896E+003

Cylinder#3 = 1.3733E+003

Appendix 4 (Continued)

Minimum radial stress in each cylinder interface

Cylinder Interface#1 = -1.0881E+004

Cylinder Interface#2 = -5.7687E+003

Maximum radial stresses at each cylinder interface

Cylinder Interface#1 = -5.9898E+003

Cylinder Interface#2 = -3.1756E+003

Diametrical Interference Limits at Trunnion & Hub (in)

4.6339E-003

8.4177E-003

6.9559E-003

6.0957E-003

Diametrical Interference Limits at Hub and Girder (in)

5.6724E-003

1.0304E-002

8.5149E-003

7.4619E-003

Diametrical Interference Trunnion-Hub (in)	Diametrical Interference Hub-Girder (in)	von Mises Stress Trunnion (psi)	von Mises Stress Hub (psi)	von Mises Stress Girder (psi)
4.634E-003	5.672E-003	5.990E+003	7.214E+003	6.725E+003
4.634E-003	1.030E-002	7.784E+003	7.899E+003	1.052E+004
4.634E-003	8.515E-003	7.091E+003	7.591E+003	9.056E+003
4.634E-003	7.462E-003	6.683E+003	7.435E+003	8.193E+003
8.418E-003	5.672E-003	9.087E+003	1.273E+004	8.417E+003
8.418E-003	1.030E-002	1.088E+004	1.311E+004	1.222E+004
8.418E-003	8.515E-003	1.019E+004	1.293E+004	1.075E+004
8.418E-003	7.462E-003	9.780E+003	1.285E+004	9.885E+003
6.956E-003	5.672E-003	7.890E+003	1.058E+004	7.763E+003
6.956E-003	1.030E-002	9.684E+003	1.104E+004	1.156E+004
6.956E-003	8.515E-003	8.991E+003	1.083E+004	1.009E+004
6.956E-003	7.462E-003	8.583E+003	1.072E+004	9.231E+003
6.096E-003	5.672E-003	7.186E+003	9.323E+003	7.378E+003

6.096E-003	1.030E-002	8.980E+003	9.850E+003	1.118E+004
6.096E-003	8.515E-003	8.287E+003	9.610E+003	9.710E+003
6.096E-003	7.462E-003	7.879E+003	9.490E+003	8.846E+003

Diametrical Interference Trunnion-Hub (in)	Diametrical Interference Hub-Girder (in)	Max Hoop Stress Trunnion (psi)	Max Hoop Stress Hub (psi)	Max Hoop Stress Girder (psi)
4.634E-003	5.672E-003	-5.990E+003	2.019E+003	4.549E+003
4.634E-003	1.030E-002	-7.784E+003	2.246E+002	7.119E+003
4.634E-003	8.515E-003	-7.091E+003	9.177E+002	6.126E+003
4.634E-003	7.462E-003	-6.683E+003	1.326E+003	5.542E+003
8.418E-003	5.672E-003	-9.087E+003	5.461E+003	5.693E+003

Appendix 4 (Continued)

8.418E-003	1.030E-002	-1.088E+004	3.667E+003	8.263E+003
8.418E-003	8.515E-003	-1.019E+004	4.360E+003	7.271E+003
8.418E-003	7.462E-003	-9.780E+003	4.768E+003	6.686E+003
6.956E-003	5.672E-003	-7.890E+003	4.131E+003	5.251E+003
6.956E-003	1.030E-002	-9.684E+003	2.337E+003	7.821E+003
6.956E-003	8.515E-003	-8.991E+003	3.030E+003	6.828E+003
6.956E-003	7.462E-003	-8.583E+003	3.438E+003	6.244E+003
6.096E-003	5.672E-003	-7.186E+003	3.349E+003	4.991E+003
6.096E-003	1.030E-002	-8.980E+003	1.555E+003	7.561E+003
6.096E-003	8.515E-003	-8.287E+003	2.248E+003	6.568E+003
6.096E-003	7.462E-003	-7.879E+003	2.656E+003	5.984E+003

Diametrical Interference Trunnion-Hub (in)	Diametrical Interference Hub-Girder (in)	Min Hoop Stress Trunnion (psi)	Min Hoop Stress Hub (psi)	Min Hoop Stress Girder (psi)
4.634E-003	5.672E-003	-5.990E+003	-7.955E+002	1.373E+003
4.634E-003	1.030E-002	-7.784E+003	-2.590E+003	2.149E+003
4.634E-003	8.515E-003	-7.091E+003	-1.896E+003	1.849E+003
4.634E-003	7.462E-003	-6.683E+003	-1.489E+003	1.673E+003
8.418E-003	5.672E-003	-9.087E+003	3.490E+002	1.719E+003
8.418E-003	1.030E-002	-1.088E+004	-1.445E+003	2.495E+003
8.418E-003	8.515E-003	-1.019E+004	-7.520E+002	2.195E+003
8.418E-003	7.462E-003	-9.780E+003	-3.441E+002	2.019E+003
6.956E-003	5.672E-003	-7.890E+003	-9.314E+001	1.585E+003
6.956E-003	1.030E-002	-9.684E+003	-1.887E+003	2.361E+003
6.956E-003	8.515E-003	-8.991E+003	-1.194E+003	2.061E+003
6.956E-003	7.462E-003	-8.583E+003	-7.863E+002	1.885E+003
6.096E-003	5.672E-003	-7.186E+003	-3.533E+002	1.507E+003
6.096E-003	1.030E-002	-8.980E+003	-2.147E+003	2.283E+003
6.096E-003	8.515E-003	-8.287E+003	-1.454E+003	1.983E+003
6.096E-003	7.462E-003	-7.879E+003	-1.046E+003	1.807E+003

From the above tables, the interference pressures at the two interfaces are –5.99 ksi and –3.18 ksi. The maximum tensile hoop stress in the assembly of 8.263 ksi exists in Cylinder 3. The maximum von Mises stress of 13.11 ksi exists in Cylinder 2.

Appendix 5 Example Problem Design Tool 4

The following is an example problem using the fourth design tool, Torque resisting capability in the THG assembly due to bolts and hub-girder FN2 fit.

Example: A hub-girder assembly made of A36 steel is approximated by two cylinders under plane stress conditions with the inner diameter of the hub 16.78 in and the inner diameter of the bore in the girder as 30.78 in. At the inner diameter of the bore in the girder an FN2 fit exists. The hub is further extended to a diameter of 49 in so bolts can be put in the hub-girder assembly. Two bolt circles of diameter 36 in and 45 in are on the hub. The first circle has 30 bolts and the second circle has 24 bolts. All bolts are of A325 low alloy steel bolts of diameter 1.25 in. Assume the standard hole type and a Class A surface. The outer diameter of the girder is 73 in. The coefficient of friction at the hub-girder interface is assumed to be 0.2. The number of slip surfaces is one, and the hub and girder thickness is 1.75 in and 1 in, respectively. The torque that must be taken by the assembly is 10,000 lb-in. Find the maximum torque taking ability of the hub-girder assembly with and without bolts, and the associated factor of safety.

Solution: The above data is input to the Design Tool 4 interface, as shown in Figure A-4.

The program is run, and following data is output.

Todays date is:04/20/2000 The time is:7:51:10 PM

Torque supported by bolts and FN2 fit according to twelve failure criteria

Young's modulus assumed is 29 Msi for all materials

Poisson's ratio assumed is 0.3 for all materials

Number of bolt circles = 2

BOLT CIRCLE # 1 DATA

Diameter of bolt circle (in) = 3.60000E+001

Number of bolts in circle = 30

Diameter of each bolt (in) = 1.25000E+000

Width of hub flange in circle (in) = 1.75000E+000

Appendix 5 (Continued)

Bolt material = A325

Number of slip surfaces = 1.00000E+000

Hole type and direction of Load = AnyD-Standard

Class of surface = Class A

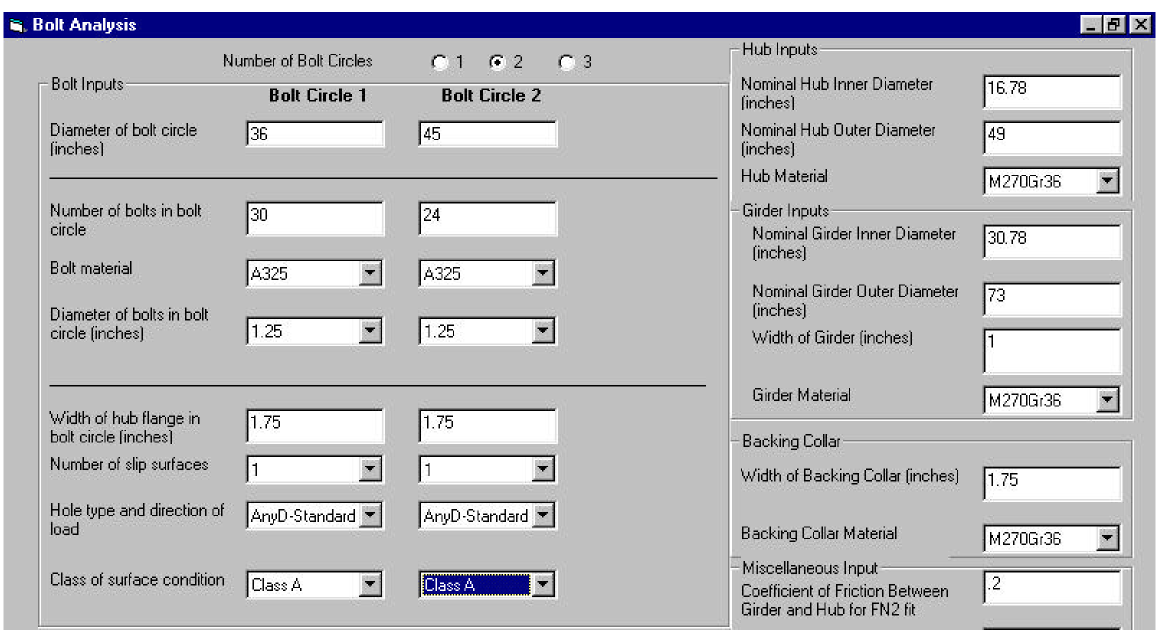

Figure A-4. Program for Torque Resisting Capability in the THG Assembly Due to Bolts and Hub-Girder FN2 Fit

BOLT CIRCLE # 2 DATA

Diameter of bolt circle (in) = 4.50000E+001

Number of bolts in circle = 24

Diameter of each bolt (in) = 1.25000E+000

Width of hub flange in circle (in) = 1.75000E+000

Bolt material = A325

Number of slip surfaces = 1.00000E+000

Hole type and direction of Load = AnyD-Standard

Class of surface = Class A

HUB DATA

Nominal hub inner diameter (in) = 1.67800E+001

Nominal hub outer diameter (in) = 4.90000E+001

Hub material = M270Gr36

GIRDER DATA

Nominal girder inner diameter (in) = 3.07800E+001

Appendix 5 (Continued)

Nominal girder outer diameter (in) = 7.30000E+001

Width of Girder (in) = 1.00000E+000

Girder material = M270Gr36

BACKING COLLAR DATA

Width of backing collar (in) = 1.75000E+000

Backing collar material = M270Gr36

Coefficient of friction = 2.00000E-001

Minimum Magnitude of Negative Radial Stress in Hub-Girder Interface (psi) =-2.96152E+003

Torque Transmitted by FN2 Fit Between Hub and Girder (lb-in) = 8.81459E+005

Criterion#1: SHEAR STRESS WITHIN BOLTS-ASD:

Torque supported by bolts (lb-in) = 1.98307E+007

Torque supported by FN2 fit (lb-in) = 8.81459E+005

Torque supported by bolts + FN2 (lb-in) = 2.07121E+007

Criterion#2: BEARING STRESS ON HUB-ASD:

Torque supported by bolts (lb-in) = 1.23323E+008

Torque supported by FN2 fit (lb-in) = 8.81459E+005

Torque supported by bolts + FN2 (lb-in) = 1.24204E+008

Criterion#3: BEARING STRESS ON GIRDER-ASD:

Torque supported by bolts (lb-in) = 7.04700E+007

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 7.13515E+007

Criterion#4: TEAR OUT STRESS ON HUB-ASD:

Torque supported by bolts (lb-in)= 1.51405E+008

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 1.52286E+008

Criterion#5: TEAR OUT STRESS IN GIRDER-ASD:

Torque supported by bolts (lb-in)= 8.65171E+007

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 8.73986E+007

Criterion#6: SLIP RESISTANCE IN SLIP-CRITICAL CONNECTIONS-ASD:

Torque supported by bolts (lb-in)= 1.73953E+007

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 1.82768E+007

Criterion#7: SHEAR STRESS WITHIN BOLTS-LRFD:

Torque supported by bolts (lb-in)= 3.65302E+007

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 3.74117E+007

Criterion#8: BEARING STRESS ON HUB-LRFD:

Torque supported by bolts (lb-in)= 2.21981E+008

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 2.22862E+008

Appendix 5 (Continued)

Criterion#9: BEARING STRESS ON GIRDER-LRFD:

Torque supported by bolts (lb-in)= 1.26846E+008

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 1.27727E+008

Criterion#10: TEAR OUT STRESS ON HUB-LRFD:

Torque supported by bolts (lb-in)= 2.72529E+008

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 2.73410E+008

Criterion#11: TEAR OUT STRESS IN GIRDER-LRFD:

Torque supported by bolts (lb-in)= 1.55731E+008

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 1.56612E+008

Criterion#12: SLIP RESISTANCE IN SLIP-CRITICAL CONNECTION-LRFD:

Torque supported by bolts (lb-in)= 2.43535E+007

Torque supported by FN2 fit (lb-in)= 8.81459E+005

Torque supported by bolts + FN2 (lb-in)= 2.52349E+007

Criterion	Bolt Torque	Bolt+FN2 Torque
SHEAR STRESS WITHIN BOLTS-ASD	1.98307E+007	2.07121E+007
BEARING STRESS ON HUB-ASD	1.23323E+008	1.24204E+008
BEARING STRESS ON GIRDER-ASD	7.04700E+007	7.13515E+007
TEAR OUT STRESS ON HUB-ASD	1.51405E+008	1.52286E+008
TEAR OUT STRESS IN GIRDER-ASD	8.65171E+007	8.73986E+007
SLIP RESISTANCE IN SLIP-CRITICAL CONN.-ASD	1.73953E+007	1.82768E+007
SHEAR STRESS WITHIN BOLTS-LRFD	3.65302E+007	3.74117E+007

BEARING STRESS ON HUB-LRFD	2.21981E+008	2.22862E+008
BEARING STRESS ON GIRDER-LRFD	1.26846E+008	1.27727E+008
TEAR OUT STRESS ON HUB-LRFD	2.72529E+008	2.73410E+008
TEAR OUT STRESS IN GIRDER-LRFD	1.55731E+008	1.56612E+008
SLIP RESISTANCE IN SLIP-CRITICAL CONN.-LRFD	2.43535E+007	2.52349E+007

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Maximum allowable torque using above 12 criteria	1.73953E+007	1.82768E+007

The critical criterion is: Criterion#6: SLIP RESISTANCE IN SLIP-CRITICAL CONNECTIONS-ASD:

The torque needed to be taken is = 1.00000E+004

Torque taken by bolts is = 1.73953E+007

Torque taken by FN2 fit is = 8.81459E+005

Torque taken by bolts+FN2 fit is = 1.82768E+007

Factor of Safety based on bolts only = 1.73953E+003

Factor of Safety based on FN2 only = 8.81459E+001

Factor of Safety based on bolts+FN2 = 1.82768E+003

Appendix 5 (Continued)

Figure A-5 shows the output diagrams from Design Tool 4.

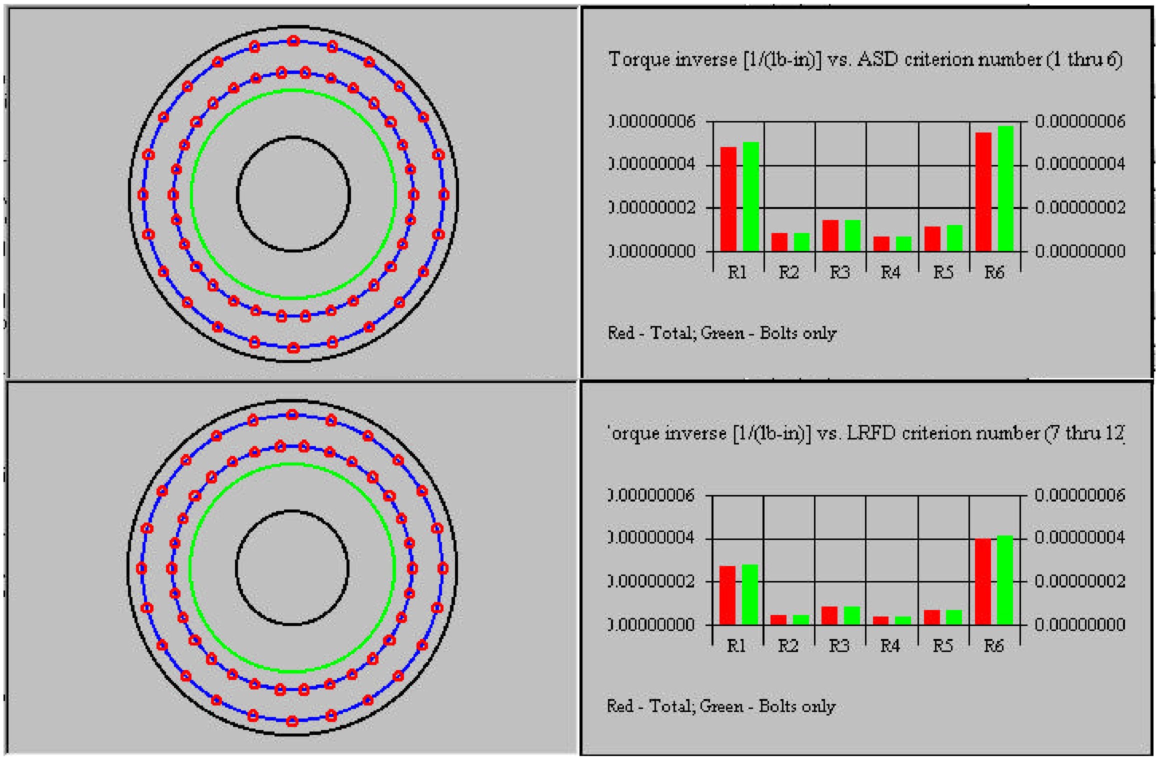

Figure A-5. Output for Torque Resisting Capability in the THG Assembly Due to Bolts and Hub-Girder FN2 Fit