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PARAMETRIC ANALYSIS AND ULTIMATE TESTING OF BASCULE TRUNNION ASSEMBLIES

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MACHINERY/MECHANISMS

Parametric Analysis and Ultimate Testing of Bascule Trunnion Assemblies

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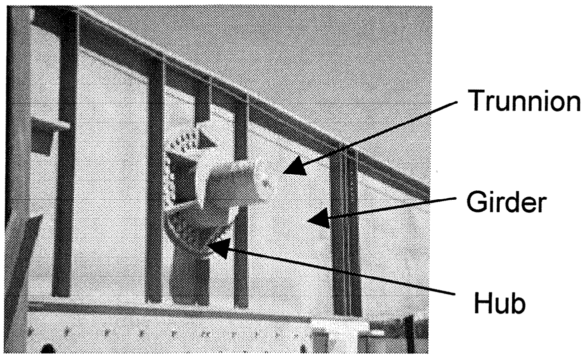
ABSTRACT

The paper presents an overview of the research on trunnion-hub-girder (THG) assemblies for bascule bridges conducted at the University of South Florida for the Florida Department of Transportation. A parametric model of the assembly was developed and temperatures, hoop stresses, Von-Mises stresses and critical crack lengths for the trunnion-hub-girder assembly were analyzed through the assembly process for transient and steady state conditions. The finite element analysis was followed by a full-scale ultimate testing of an assembly. This provided a comprehensive study and quantitative analysis of the thermo-mechanical behavior of the components and the system. The experimental observations of temperatures and stresses for transient and steady states closely matched the theoretical analyses.

The factor of safety for shrink-fitting the trunnion into the hub and the hub-trunnion into the girder utilizing liquid nitrogen cooling was doubled by first shrink-fitting hub into girder followed by trunnion into the hub-girder assembly. Cooling of the inner component in dry ice and alcohol and heating the outer component could easily avoid the undue risks associated with both these procedures. The heating of the outer component of the shrink fit assembly has significant advantages over the sub-cooling of the inner component. The parametric modeling identifies the maximum stress conditions for each procedure and analyzes the risks and economics of the assembly alternatives. Technical background on the assembly options is illustrated, along with the detailing aspects vital to the fabrication of the components and their assembly. The findings benefit engineers and contractors in designing and analyzing trunnion assemblies for bascule projects.

INTRODUCTION

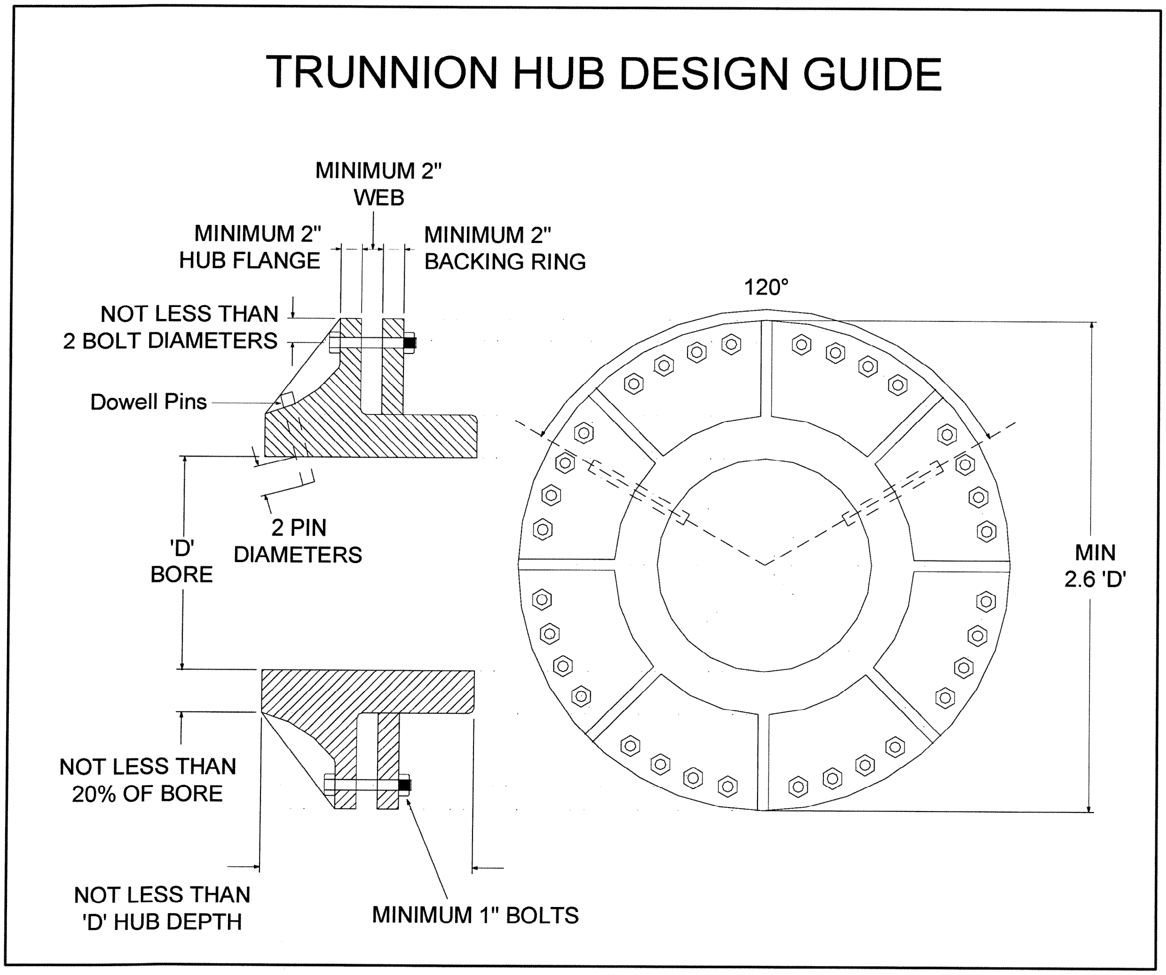
The 'Bascule' is the French word for "seesaw." It belongs to the first class of levers, where the fulcrum is located between the effort and the resistance. However, the bascule bridge belongs to the second or third class of levers depending on how the load is designated. Zooming in on the fulcrum of the bascule, the leaf seems to pivot on a fixed axis. The pivot assembly consists of a trunnion shaft attached to the leaf girder via a hub, and supported on bearings to permit rotation of the leaf. The Trunnion-Hub-Girder assembly forms the pivotal element of the bascule mechanism (Figure 1).



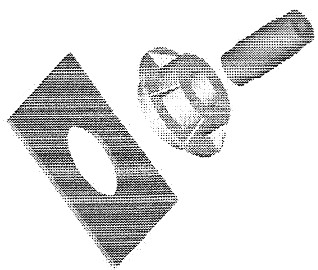
Assemblies of this type are generally constructed with interference fits between the trunnion and the hub, and between the hub and the girder. The interference fits allow the trunnion to form a rigid assembly with the leaf and permits the rotation of leaf through bearings. The two interference fits are supplemented by keys or dowel pins at the trunnion and by structural bolts at the girder. The recommended detail for hubs is shown in FDOT LRFD Design Guidelines 2002 (Figure 2).

Figure 1. Trunnion-Hib-Girder assembly

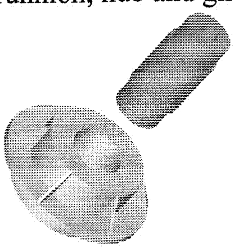
Figure 2. Hub Detail (FDOT LRFD Design Guidelines 2002)



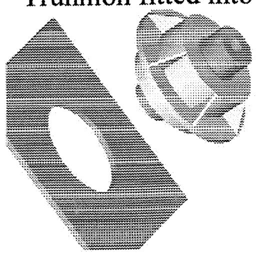
Basically two procedures are utilized in accomplishing the THG assembly. They are illustrated in sequential assembling order in Figure 3 and Figure 4. Assembly Procedure (AP) 1 involves cooling the trunnion and shrink-fitting it into the hub, and then cooling the trunnion-hub assembly to shrink-fit it into the girder. Assembly Procedure (AP) 2 involves shrink-fitting the hub into the girder, then cooling the trunnion and shrink-fitting it into the hub-girder assembly. Each procedure has its own limitations and merits. The FDOT commissioned a research project at the University of South Florida to study the transient and steady state thermo-mechanical behavior of the assemblies during the two procedures and to optimize the design and construction. The results of the finite element analysis of the assembly along with the full-scale tests are presented. Also FDOT experience over the years in the design and construction of THG assemblies are evaluated in light of the research findings, and several recommendations critical to the design, detailing, specification and construction of THG assemblies are presented under conclusions.



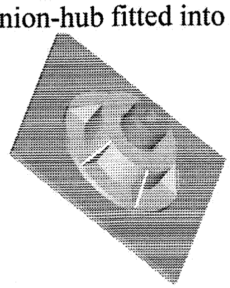
Trunnion, hub and girder



Trunnion fitted into hub

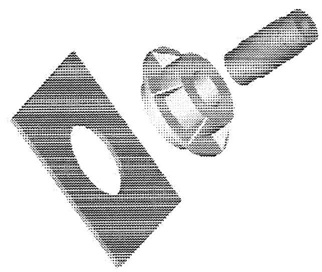


Trunnion-hub fitted into girder

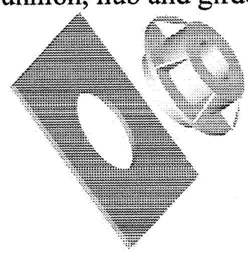


Completed THG assembly

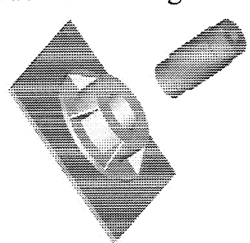
Figure 3. Assembly Procedure 1



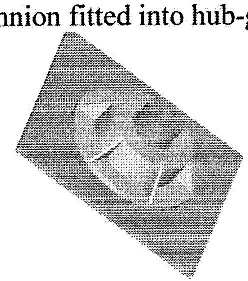
Trunnion, hub and girder



Hub fitted into girder



Trunnion fitted into hub-girder



Completed THG assembly

Figure 4. Assembly Procedure 2

THEORETICAL ANALYSIS

The following is a theoretical treatise on the physical metallurgy aspects, the mechanical properties and the thermal characteristics relevant to the shrink fitting of steel assemblies.

1. Crystal Structure

Materials with face-centered cubic (fcc) crystal structure such as Al, Cu, Ni and austenitic stainless steel are generally suited for low temperature processing and construction. The body-centered cubic (bcc) α ferritic steel and the body-centered tetragonal (bct) martensitic steel (low carbon steel and 400 series stainless steel) are undesirable for low temperature processing and applications. The hexagonal close-packed metals exhibit mechanical properties intermediate to those of the fcc and bcc metals.

2. Diametral Interferences and Clearances

To accomplish shrink fitting of assemblies, the inner component has to be cooled or the outer component heated to obtain the required temperature differential and the consequent dimensional clearances. The minimum diametral clearances required to accomplish the interference fit with a certain level of confidence, for typical trunnion-hubs are of the order of 0.02 in. Figure 5 shows FN2 diametral interferences in microinches per inch of shaft diameter, for sizes 20 through 50 inches nominal diameter, typical for trunnions and hubs. From the chart it is evident that throughout the range a diametral interference of 5×10^{-4} in/in of nominal diameter can be considered a mean value for analysis purposes. It is important to note that the minimum interference remains more or less constant at 4×10^{-4} inch per inch of nominal diameter for the entire range. Also, the maximum of the interference reduces as the diameter increases from 20 inches to 50 inches. The chart signifies an obvious advantage in the reduced amounts of required interference at higher diameters, while benefiting also from the larger amount of clearance attainable at the higher diameters.

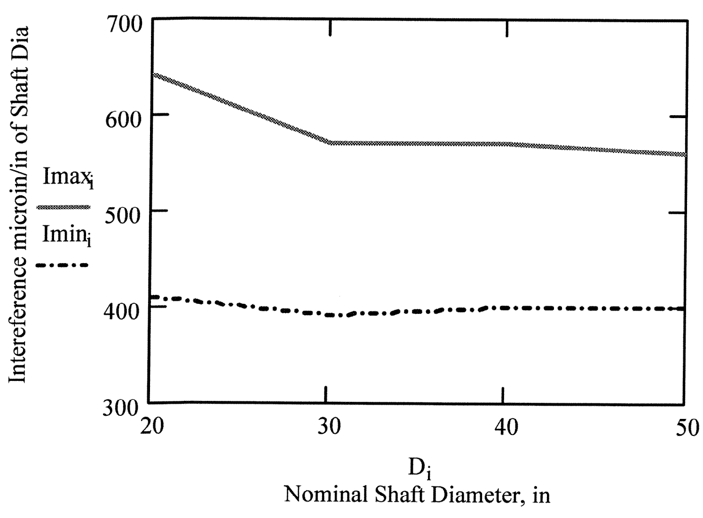


Figure 5. Diametral Interference vs. Shaft Diameter

3. Thermal Expansion Coefficient

The thermal coefficient of expansion of steel decreases exponentially by about 70 % between room temperature and liquid nitrogen temperature. The drop in the coefficient is very significant in the range of cooling from dry ice temperature to liquid nitrogen temperature as illustrated in Figure 6. The markers on the chart indicate dry ice temperature at –109° F and liquid nitrogen temperature at –321° F. The amount of clearance attainable by cooling from dry ice temperature to liquid nitrogen temperature is not very favorable from the thermal expansion coefficient point of view. However, even with this disadvantage, cooling in liquid nitrogen has the economic perspective of fast cooling to accomplish quantitatively favorable clearance levels due to the large temperature differential.

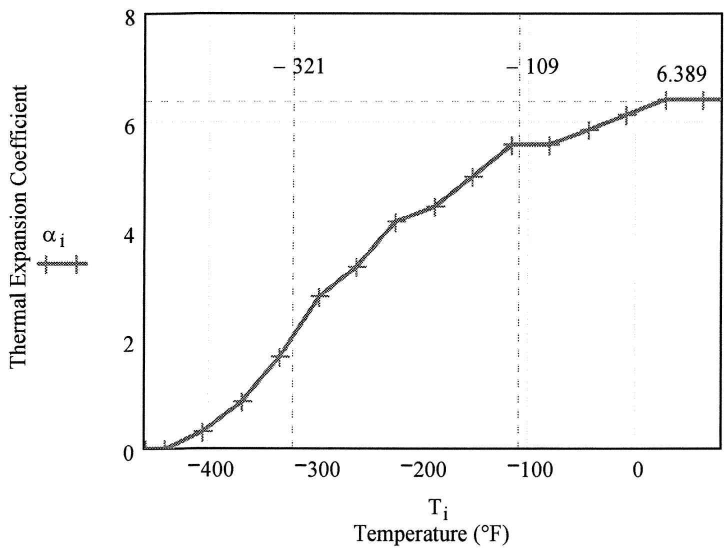


Figure 6. Coefficient of Thermal Expansion of Steel vs. Temperature

4. Total Elongation

The fcc metals such as aluminum and 6% nickel steel do not exhibit an abrupt change in ductility as the temperature is lowered. They do not have a pronounced ductility-transition temperature and hence are suitable for cryogenic processing and applications. Low carbon steels, on the other hand, have a marked ductility transition and are unsuitable for cryogenic processing. For example, even AISI 1020 steel with a low 0.2 % carbon content have a ductility transition temperature of –280° F which is above the –321° F liquid nitrogen temperature (Figure 7).

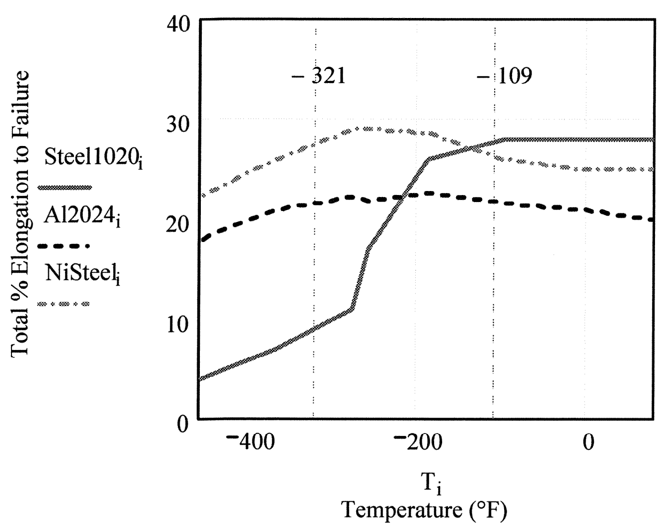


Figure 7. Total Percent Elongation to Failure vs. Temperature

5. Fracture Toughness and Critical Crack Length

Similar to the pronounced drop in ductility indicated by the percentage elongation, the toughness of steels also decreases with reducing temperature. Beyond that, the fracture toughness has a significant effect on any shrink-fitting process involving carbon steels.

A preexisting flaw or crack in a normally ductile material will propagate when its stress intensity factor (K_1) reaches the fracture toughness of the material (K_{1c}) and can result in brittle fracture. Subscript 1 represents crack opening mode 1 and indicates loading normal to the long axis of crack. The *plane strain fracture toughness* (K_{1c}) is a fundamental material property and is unique for a particular material. It is a function of temperature, crack size and location, and strain rate.

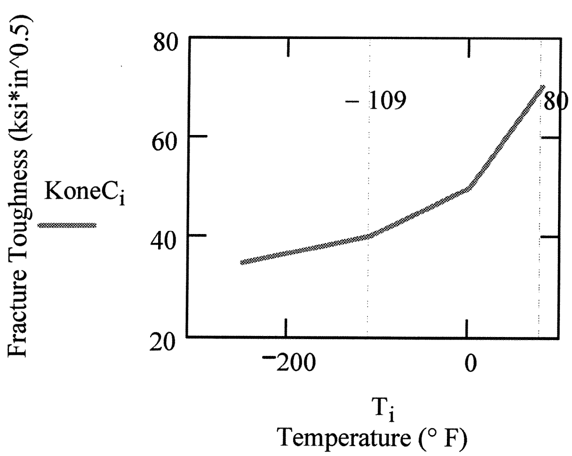


Figure 8a. Fracture Toughness vs. Temperature

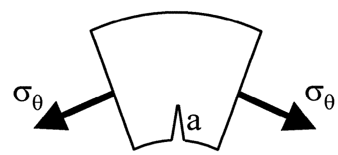


Figure 8b. Critical Crack Length

As indicated in Figure 8a, the fracture toughness decreases with decreasing temperature, while it also varies as the square root of the crack length (Figure 8b).

Critical crack length (a_c) required to cause failure in a material:

$$a_c := \frac{1}{\pi}\left(\frac{K_{1c}}{f_e \cdot \sigma_\theta}\right)^2$$

f_e = edge effect factor

σ_θ = hoop stress

Analysis indicated that the critical crack length for AP 1 is about half of that for AP 2. This means a crack or a flaw of only half the size will result in brittle fracture during AP 1, compared to AP 2. When AP 1 is used for assembly, more stringent inspection criteria must be used. If AP 2 can satisfactorily resist brittle failure in a particular assembly, the same components may fail due to the lower allowable crack length under AP 1.

6. Other Properties

Several other mechanical properties that affect the shrink-fit assembly are found to be temperature dependent. While some of these material behaviors at low temperatures are favorable for the assembly, others are unfavorable, and the extents to which they affect the assembly process also vary.

1. Both ultimate strength and yield strength of steel increase exponentially by about 40 to 80 % in cooling from room temperature to liquid nitrogen temperature. This is a favorable attribute from the assembly point of view. The range varies among different types of steels and is highly microstructure dependent.
2. Specific heat of steel decreases by a factor of 70 % between room temperature and liquid nitrogen temperature.
3. Thermal conductivity of steels also decreases exponentially by about 50 % within the cooling range.
4. Elastic modulus increases linearly by about 10 % within the cooling range.
5. Poisson's ratio decreases by about 10 %.

FINITE ELEMENT ANALYSIS

More than one hundred parameters were identified and utilized in the trunnion-hub-girder analysis. A finite element model of the assembly was developed and transient thermal-structural analyses were performed for different geometries of hubs and trunnions. The thermal response of the components was modeled after the conductive and convective modes of heat transfer coupled with contacts at the trunnion-hub and hub-girder interfaces. Figure 9 shows the temperature variations for the hub at the time of the highest hoop stress for the two assembly procedures.

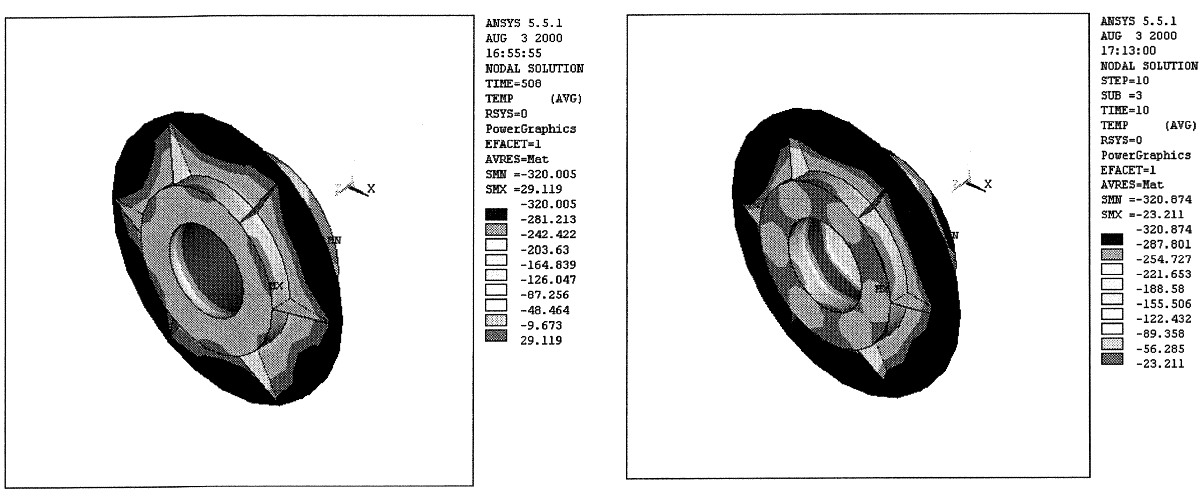


Figure 9. Temperature (°F) Plot at Highest Hoop Stress for AP 1 (left) and AP 2

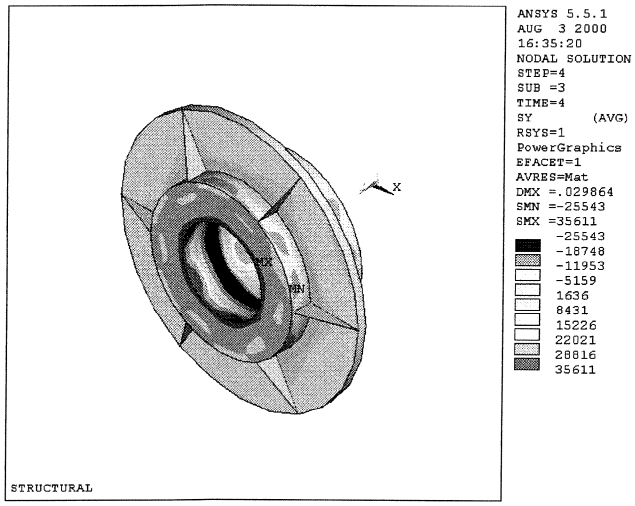


Figure 10. Highest Hoop Stress for AP 2

Complete analyses of the assemblies were performed to obtain temperatures, hoop stresses and Von Mises stresses and allowable crack lengths for the two procedures. Figure 10 is a plot of the highest hoop stress for Assembly Procedure 2. The Von Mises stresses were evaluated for the assembly processes to predict ductile failure based on the distortion energy theory. The critical and allowable crack lengths for the assemblies were evaluated to predict brittle failure based on the temperature dependent fracture toughness of the material and on hoop stress.

FULL SCALE TESTING

To validate the results of the finite element analysis, components fabricated to full size were assembled using the two assembly procedures. Strains and temperatures on each component were monitored through the assembly process using strain gauges and thermocouples. Figure 11 shows the locations of strain gages and thermocouples on the hub. The strains and temperatures at inner diameter of the hub were closely monitored, as this area is subject to relatively higher stress concentrations. A crack initiated or preexisting at this location is most critical to the assembly in either of the two assembly procedures. The attention was concentrated to this region, as such a crack can propagate and result in catastrophic failures in the assembly. To facilitate ultimate testing, liquid nitrogen was used as the cooling medium and the hub selected for the test had serious internal flaws. The defects verified by x-rays tests were considered detrimental to the assembly.

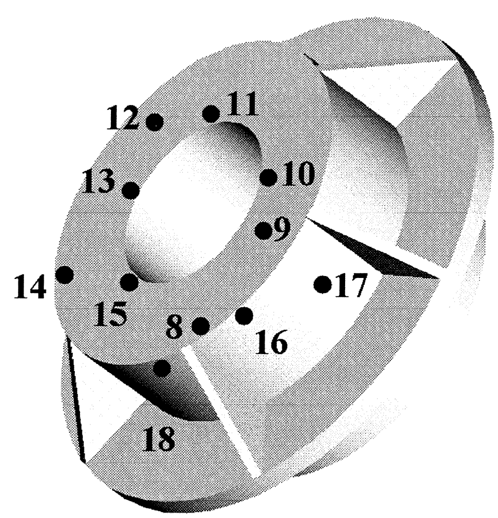


Figure 11. Gage Locations on Hub

Figures 12 and 13 provide comparisons of the hoop stresses and the Von Mises stresses through the assembly processes. The results of the experimental tests compared very closely with the finite element analysis. From Figure 12, the peak hoop stress of 25.7 ksi occurs at the cool down of trunnion-hub in liquid nitrogen during Assembly Procedure 1. Around the same time the Von Mises stress also reaches its maximum of 49 ksi as indicated in Figure 13. This is the most critical stage in AP 1. The peak Von Mises stress of 32 ksi for Assembly Procedure 2 occurs during the warm up of the trunnion in the hub-girder assembly and continues into the steady state. This value is significantly lower than that for Assembly Procedure 1, thereby clearly demonstrating its merit over the other procedure.

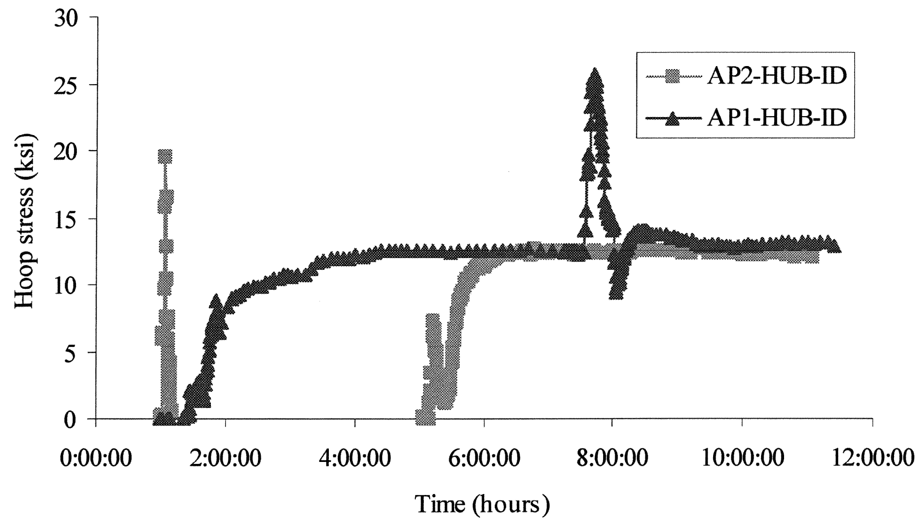


Figure 12. Hoop Stress During Assembly Procedures 1 and 2

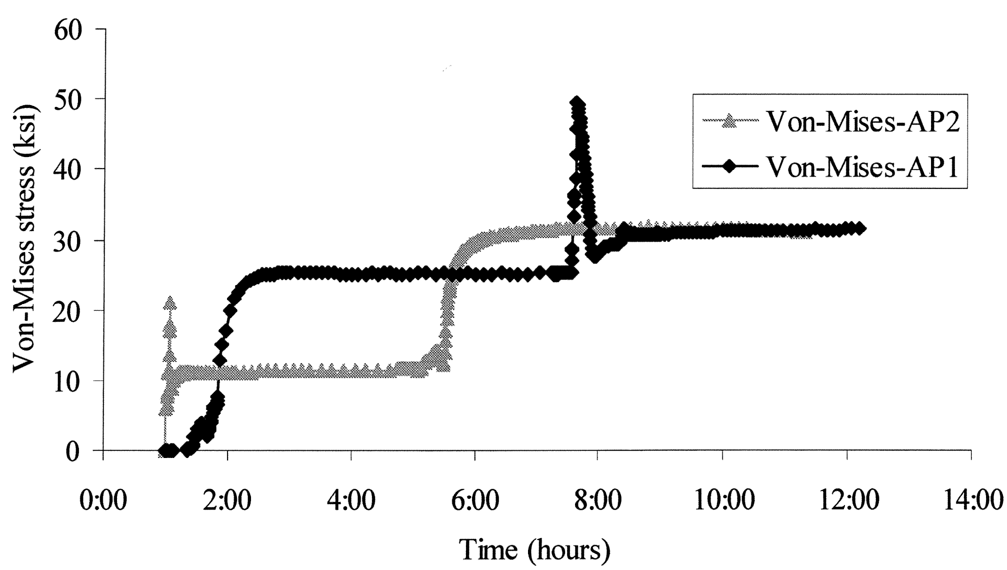


Figure 13. Von-Mises Stress for Assembly Procedures 1 and 2

Table 1 summarizes the results of the experimental data. Assembly Procedure 2 has an obvious advantage over the other. Both the maximum hoop stress and the Von Mises stress for AP 2 are significantly lower and the allowable crack length for the process is almost double that for AP 1. The finite element analysis verified by the full scale testing provided a quantification of the risks associated with Assembly Procedure 1 while demonstrating the reliability and merits of Assembly Procedure 2.

Table 1. Comparison of Assembly Procedures

	Assembly procedure	
	AP 1	**AP 2**
Temperature (^{0}F)	-278	-171
Fracture toughness (ksi-$\sqrt{in}$)	28	29
Yield strength (ksi)	96	65
Maximum hoop stress (ksi)	25.7	19.5
Maximum Von-Mises stress (ksi)	49.2	30.9
Allowable crack length (in)	0.2985	0.5562
Time during assembly	8th minute into trunnion-hub cool down	3rd minute into hub cool down

CONCLUSIONS

The following is a summary of the research findings and recommendations based on the review and analysis of trunnion assemblies on Florida bascules:

1. Use of liquid nitrogen as cooling medium for shrink-fitting of trunnion-hub assemblies poses the risks associated with cooling carbon steels below their ductility transition temperature. The components shall be evaluated for brittle fracture from a fracture toughness point of view.
2. The benefit from subcooling below the dry ice temperature is not noteworthy from the dimensional clearances obtainable per unit temperature drop. This is because the coefficient of thermal expansion decreases exponentially as temperatures drop below -109° F (Figure 6). Apart from the risks, and given that liquid nitrogen cooling is not the optimum means for accomplishing the shrink-fit assembly, it has the obvious advantage of fast subcooling to low temperatures that provides satisfactory assembly clearances.
3. The heating of the outer component has remarkable benefits in regard to the clearance attained per unit temperature differential. The coefficient of thermal expansion for steel at ambient temperature is significantly higher than that at temperatures below -109° F. The levels of clearances attainable by cooling from dry ice temperature to liquid nitrogen temperature can be safely accomplished by heating the outer component to a much smaller temperature differential. In heating, the material is subjected to lower thermal gradient and subsequent transient thermal stresses compared subcooling in liquid nitrogen.
4. A temperature of differential of 300° F could satisfactorily accomplish an interference fit for nominal trunnions-hub-girder assemblies. Cooling inner component in dry ice/alcohol and heating the outer component can easily accomplish temperature differentials of this order.

5. A survey of Florida bascules designed and built in the last decade indicated wide variations in radial hub thickness. The net radial hub thickness on State Route 44 Bascule is 1 inch, while that on the Hatchett Creek Bascule is 9.3 inches. Hub thicknesses of the order of 1 inch shall be avoided. Apart from the risks associated with brittle fracture and the poor thermal performance toward fabrication and assembly, this reduced thickness fails to take advantage of the reduced interference requirements at larger diameters and also the larger clearances achievable for larger sizes.
6. Hubs shall be designed for optimum thermal performance during the casting process as well as during the shrink-fitting processes. Hub thickness, flange thickness, flange diameter, hub outside and inside diameters, rib thickness and number of ribs shall be optimized toward thermal gradients and corresponding thermal stresses.
7. Gradual cooling in a refrigerated chamber is preferred over cooling in a media that subjects the components to large thermal gradients of the order of 300 to 400° F.
8. Specify tight machining tolerances and surface finishes for trunnion-hub and hub-girder interfaces. Design must indicate true position, perpendicularity and total run out tolerances to ensure relevant cylindricity or flatness as appropriate at the mating surfaces. This is particularly important in the case of assemblies involving box girders.
9. Specify and perform nondestructive evaluations to verify that castings are free of voids and cracks that can propagate at ductility transition temperature.
10. Proprietary cooling media that allow intermediate temperatures between that of dry ice and liquid nitrogen can be utilized to reduce the risks associated with liquid nitrogen cooling.

REFERENCES

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[2] Timmerhaus, K.D., and Flynn, T.M., Cryogenic Process Engineering, Plenum Press, New York, 1989.