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**FAILURE OF EXPANSION JOINT TIE RODS - IMPACT ON
BELLOWS INTEGRITY (U)**

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Failure of Expansion Joint Tie Rods - Impact on Bellows Integrity

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ABSTRACT

Expansion joints are used in piping systems to accommodate pipe deflections during service and to facilitate fitup. Often, tie rods are employed to limit the range of axial deflection. Additional restraint against excessive displacement can be provided by the surrounding pipe and associated supports. This paper presents a methodology that was employed to estimate the consequences of tie rod failure. Of particular interest is whether tie rod failure can lead to sufficient displacement as to cause bellows rupture.

Expansion joints with four tie rods are in use at the Savannah River Site. This provides sufficient redundancy against the isolated failure of a single tie rod. However, if two or more tie rods were to fail, the possibility exists for large rotation and extension of the bellows. Specific calculations have been made of the consequences of failure of three and four tie rods using the AUTOPIPE computer code to model the piping system. Failure of three tie rods leads to minor rotation only, less than 1 degree in magnitude. Failure of all four tie rods produces an additional axial extension of about 6.3 inches (16 cm) under normal operating loads.

The impact of these deflections on the expansion joint bellows has been evaluated. The ABAQUS computer code was used to construct both 2D and 3D finite element models of the bellows. These models were used to 1) confirm the AUTOPIPE-calculated displacements with all tie rods failed, and 2) estimate the bellows strain resulting from stretchout. The bellows strain from stretchout is combined with the fabrication strain to estimate the margin to failure that remains. In order for this comparison to be valid, the equivalent uniaxial strain for each step is calculated and compared to the failure strain from uniaxial tensile tests. Large margins to failure are calculated, indicating that bellows rupture will not result from tie rod failure.

BACKGROUND

Expansion joints are typically used in piping systems to accommodate pipe deflections under thermal loads and to facilitate fitup. Since the expansion joint is inherently very flexible, some provision such as the use of tie rods is often required to prevent hyperextension of the bellows. Expansion joints containing 4 tie rods are used in the K Reactor secondary cooling water system (CWS). Any one of these tie rods can fail without any adverse consequences on operation - the remaining three tie rods will prevent rotation or extension of the bellows past preset limits. However, in the event of failure of two or three tie rods, the possibility of bellows rotation exists, depending on the forces and moments imposed by the surrounding pipe structure. A single tie rod has sufficient strength to prevent excessive bellows extension. Therefore, hyperextension of the bellows will occur only in the unlikely event of failure of all four tie rods.

Figure 1 shows a schematic of the CWS expansion joint. Two expansion joint designs, from different vendors, are used in this CWS application. Both expansion joint designs have been analyzed, but results are presented in this paper for only one design, for simplicity. (Results are similar for the other design.) The presence of equalizing rings helps stiffen the bellows, reducing the extension under a given load. The consequences of tie rod failure are of importance in determining the potential for producing bellows rupture and subsequent core damage. In the event of tie rod failure, the possibility exists for the bellows to be stretched to the point of failure.

The tie rods are constructed of AISI C-1141, with 1.5 inch diameter. The axial thrust load on each tie rod from normal operating pressure produces an axial stress of 2.0 ksi. Even with three tie rods failed, the stress in the remaining tie rod is well below allowable values. The bellows is made of Type 304 austenitic stainless steel.

In the event of failure of two or more tie rods, the potential for bellows rotation or extension is determined by the stiffnesses of the bellows and the adjoining piping. In practice, the bellows response will be dominated by either the bellows or the surrounding piping, whichever provides greater resistance against the applied loads.

DISCUSSION

The expansion joints which were analyzed are located in a relatively flexible run of piping. Upstream is a solid anchor point. Downstream, the pipe changes direction and elevation several times, with relatively few supports. Therefore, the potential exists for relatively large displacements. Of the several lines containing expansion joints, the most flexible line (the line with the largest displacements with all tie rods intact) was selected for more detailed analysis as a bounding case with tie rods failed. The general layout of this line is shown in Figure 2.

Upon failure of three tie rods, the internal pressure load will produce an applied moment at the expansion joint flange due to the load path shifting from the joint centerline to the single remaining tie rod. With an internal pressure load of 10,763 pounds, and a moment arm from the expansion joint centerline to the tie rod of 18 inches, the moment applied to the pipe is 194,000 inch-pounds. With all four tie rods failed, the internal pressure load path does not shift, but the relatively elastic bellows must transmit the pressure load. The AUTOPIPE computer code was used to estimate the pipe response to these two load conditions.

Pipe Response Analysis

AUTOPIPE is an engineering analysis computer code for modeling and analyzing piping systems. In this application, AUTOPIPE was used to estimate pipe displacements under applied loads, including pressure, thermal, deadweight and seismic. Seismic loads were included in the base case (all tie rods active) for information. Since a single tie rod is sufficient to resist axial seismic design loads, failure of two or more tie rods during a seismic event is not considered credible. Rather, failure is postulated to occur during normal operation due to fatigue, corrosion, or some other mechanism. Inclusion of seismic loads in the model with one or more tie rods failed was not practical, based on the modelling techniques used and limitations of the computer code.

The internal expansion joint model was used, which includes features representing the bellows stiffness against axial, lateral and rotational movement, tie rod stiffness, and tie rod gap. The tie rod gap specifies the distance of bellows travel allowed before the tie rod nuts engage to take axial load, limiting total bellows compression or extension. Simulation of all four tie rods failed was accomplished by specifying a gap size larger than the resulting axial displacement. Comparing the results to the specified gap size confirmed that the selected gap size was appropriate.

Key input parameters are listed in Table 1. In the absence of vendor data, the bellows stiffness values derive from several sources. The bellows axial stiffness and lateral stiffness are derived from finite element computer models of the bellows. The ABAQUS computer code was used to analyze a 2-dimensional model for the axial stiffness, and a 3-dimensional model for the lateral stiffness. The 2-dimensional model used two-noded axisymmetric elements that allow transverse shear. The 3-dimensional model used four-noded doubly-curved shell elements.

The axial response curve, calculated from the 2-dimensional model, is shown in Figure 3. It is noted that for loads up to and exceeding the nominal pressure thrust load of 10,763 pounds, the spring rate (slope) is relatively constant, therefore an average stiffness value will give reasonable results for a wide range of loading conditions.

Parameter	Value
Bellows axial stiffness	2020 lb/inch
Bellows lateral stiffness	3750 lb/inch
Bellows bending stiffness	1200 inch-lb/degree
Bellows torsion stiffness	rigid
Tie rod stiffness	4.97×10^6 lb/inch
Tie rod gap	2 inches compression, 0 inch extension

Four cases were run to predict the bellows response to tie rod failure. A base case with all tie rods intact was subjected to deadweight, thermal, pressure and seismic loads. This is the only case that included seismic loads. The second case simulated all four tie rods inactive. The last two cases simulated failure of three tie rods, with the remaining tie rod located on the side or on the top. The results of these analyses are summarized in Table 2.

Applied Load	Displacement, inch			Rotation, degrees		
	dx	dy	dz	θx	θy	θz
<i>Base Case - All Tie Rods Active</i>						
Deadweight	0.02	-0.02	0	-0.04	-0.04	0
Thermal	-0.04	0.02	0	0.06	0.08	0
Pressure	0.01	0	0	0	-0.01	0
Seismic	+/- 0.53	+/- 0.06	0	+/- 0.12	+/- 1.01	0
Net (abs. value)	0.54	0.06	0	0.14	1.04	0
<i>4 Tie Rods Failed</i>						
Deadweight	0	-0.02	0.03	-0.04	0.01	0
Thermal	-0.02	0.02	0.30	0.06	0.03	0
Pressure	0.41	-0.01	5.92	-0.02	-0.78	0
Net	0.39	-0.01	6.25	0	-0.74	0
<i>3 Tie Rods Failed, Remaining Tie Rod on Side</i>						
Deadweight + Pressure Moment	NA	NA	NA	0.08	-0.03	NA
<i>3 Tie Rods Failed, Remaining Tie Rod on Top</i>						
Deadweight + Pressure Moment	NA	NA	NA	-0.09	0.71	NA
Notes:						
NA - This displacement was not analyzed.						

As might be expected, the major displacement in the case of all tie rods failed is axial, with 6.25 inches extension. This displacement results primarily from the applied pressure load. As a check on the modelling technique and results, the finite element bellows model was used to estimate the bellows extension under applied pressure load, ignoring the stiffness of the surrounding pipe. This gave an estimated extension under pressure alone of 5.3 inches, in good agreement with the AUTOPIPE result. This agreement may be deceptive, however, given the relative crudeness of the AUTOPIPE modelling and considering that the piping model including the stiffness of the downstream pipe gave a higher extension. Nevertheless, the comparison provides a measure of confidence that the results are reasonable. It also suggests that over this range of deflection the pipe offers relatively little resistance to bellows extension.

Since the modelling techniques did not allow inclusion of a single active tie rod, the pressure moment in the case of one tie rod active was applied to the downstream flange of the expansion joint and the stiffness of the bellows and remaining tie rod were conservatively ignored. Since this approach produced unrealistical displacement estimates, only rotations are shown in Table 2. The estimated rotations are conservative since the bellows stiffness is ignored.

Since an expansion joint can be installed in a number of orientations with regards to rotation about its axis of symmetry, the tie rods will not necessarily align with the horizontal and vertical axes. Therefore, a bounding estimate of the rotation resulting from failure of three tie rods is obtained from a square root of the sum of squares (SRSS) combination of the two cases with 1 active tie rod. Combination of the resulting horizontal and vertical components gives a maximum rotation of 0.72 degrees.

Bellows Integrity Following Tie Rod Failure

Estimates of bellows deflections following tie rod failure are only the intermediate step in this analysis. The primary issue is whether such postulated failure will lead to bellows rupture, compromising the system pressure boundary. Finite element models were employed to investigate the impact of postulated tie rod failure on the bellows integrity. Failure of the bellows is assumed to occur if the cumulative strain reaches a critical value - otherwise the bellows will not fail.

Bellows strain derives from two sources. Since the bellows is not solution annealed after fabrication, the strain accumulated during fabrication contributes to the total strain at failure. The second contribution is from the displacements due to postulated tie rod failure. Each of these processes produce strain under multiaxial stress states, with a different stress state for each process, and varying from one region of the bellows to another. As a result, direct comparison to simple failure criteria based on uniaxial tensile tests is not valid. In order to compare the analysis results to a simple failure criterion, the concept of a triaxiality factor is used. Such a factor has been discussed in the literature on several occasions [e.g. reference 1].

The triaxiality factor is defined as:

$$TF = (\sigma_h + \sigma_m + \sigma_r) / \sigma_e$$

where: TF = triaxiality factor

σ_h , σ_m , σ_r = hoop, meridional, and radial stresses

σ_e = equivalent (Mises) stress

The maximum principal strain at a given location is multiplied by the triaxiality factor based on the stresses at that location to give the equivalent uniaxial strain. Equivalent uniaxial strains from separate operations can be added linearly to get the total effective uniaxial strain, a value that can be compared to the failure strain from uniaxial tensile tests.

Both the fabrication process and the effect of bellows extension following tie rod failure have been separately modelled with the ABAQUS finite element computer code. Only one-half of a single convolute is modelled, invoking symmetry for the remainder of the bellows. Thirteen axisymmetric shell elements are used to represent the half-convolute. Annealed material properties are used in this model since the bellows material starts out in that state.

The maximum principal strain at any location within the bellows is the hoop strain. Finite element model results show that a good estimate of the hoop strain is given by the ratio of the convolute height to the bellows radius at the convolute root. The finite element model also provides estimates of the principal stresses needed to calculate a triaxiality factor. The maximum principal strain and the highest triaxiality factor both occur at the convolute crest. For this case, the true hoop strain at the crest is 17%, with a corresponding triaxiality factor of 1.32, giving a maximum equivalent uniaxial strain due to fabrication of 22.4%. The equivalent uniaxial strain drops to less than 1% at the convolute root.

For the strain due to bellows stretchout following tie rod failure, a 3-dimensional model was constructed. This model invokes two-fold symmetry between the two ends of the bellows and employs four-noded doubly-curved shell elements. Ideally, the 3-D model should reflect the variation in material properties from the convolute root to crest, since the fabrication process left the bellows with varying degrees of cold-work. However, assigning different material properties to each element is too complex computationally. Therefore, two runs were made, one using annealed properties throughout, and one using properties representative of the maximum cold work at the convolute crest. The results of the first run are reasonable for the lower portion of the convolute near the root, while the second run provides representative results for the convolute crest region. At locations in between an average of results from the two runs is used.

The displacements and rotations estimated for the postulated failure of all tie rods are input to the finite element model and the bellows response is calculated. The maximum true strain due to stretchout following tie rod failure is 2.6%. This strain occurs at the bottom of the flat sidewall region (near the root) on the first convolute. (By symmetry, this result applies to the last convolute also.) With a triaxiality factor of 1.75 at this location, the equivalent uniaxial strain is 4.5%.

The results of the finite element analyses of both bellows fabrication and stretchout are plotted in Figure 4. These results are specific to the first or last convolute and are bounding for the other convolutes. The maximum total equivalent uniaxial strain following bellows stretchout is about 25% and occurs at the convolute crest. This provides a large margin to failure compared to the uniaxial failure strain of 53%.

This result applies specifically to the bellows response immediately following the postulated failure of all four tie rods. The estimated large margin to failure, and the relatively small contribution to total strain that results from the stretchout itself, provide confidence that failure will not result even with the modelling approximations that were made. This result does not address the long-term bellows response, during which the piping system may place relatively large cyclic loads on the stretched-out bellows. If the degraded condition is not identified shortly after it occurs (short in terms of the frequency of plant evolutions that produce cyclic loading), fatigue failure of the bellows is considered likely. However, the condition of four failed tie rods and over-extended bellows should be easily spotted when personnel enter the area.

The bellows rotation estimated for postulated failure of three tie rods is less than that for the case of all tie rods failed. Since the latter case, including additional bellows displacements, is more severe, and large margins to failure were demonstrated, a separate finite element analysis of the case of three failed tie rods was not performed. Bellows rupture will not result from the failure of three tie rods.

SUMMARY

Analysis of the expansion joint response to postulated tie rod failure has been estimated. The bounding case of all four tie rods failed will not lead directly to bellows rupture. Failure of fewer tie rods has correspondingly less severe consequences.

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Figure 1. Expansion Joint Schematic

Figure 2. Piping layout schematic

Figure 3. Bellows response to applied axial load

Figure 4. Equivalent Uniaxial Strain for Bellows Stretchout

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