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The Consequences of Expansion Joint Bellows Failure

by

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ABSTRACT

Expansion joint (EJ) bellows are thin walled, flexible components of a piping system. As such, they usually are the weakest structural link in the pressure boundary from a failure probability perspective. Previously, a 360°, circumferential rupture of a bellows was conservatively assumed to cause bellows collapse due to internal pressure resulting in a double-ended guillotine break (DEGB) and the associated, large leak rate. A finite element analysis was performed to determine the structural response of a ruptured bellows and its ability to resist large opening areas and hence, large leak rates.

The results show that a 360° break can lead to an opening width of up to 0.7 inch following an instantaneous rupture—provided the equalizing rings and tie rods remain intact. This would result in an initial leak rate reduction equal to 80% of the previously assumed DEGB flow. The reduced flow rate is less than the water removal system capacity—assuring that flooding will not occur.

INTRODUCTION

A flow rate analysis of a postulated 360° rupture of a piping system expansion joint bellows resulted in unacceptably large leak rates. Following rupture, the bellows was conservatively assumed to collapse, resulting in the leak rate associated with a double-ended guillotine break. An analysis was performed to determine the structural response of a ruptured bellows and a more realistic opening area and the associated leak rate. It is noted that there have been no sudden ruptures of an expansion joint over the history of the site. The several failures that have occurred were relatively small cracks. The analysis summarized in this paper applies to the unlikely event of a sudden rupture with no prior warning to allow operator action.

Expansion Joint Description

Table 1 lists the characteristics of the subject expansion joint (EJ) for this analysis.

TABLE 1. EXPANSION JOINT CHARACTISTICS

FEATURE	
Internal Flow Sleeve	no
Equalizing Rings	yes
# Convolutions	7
Bellows Ply Thickness	0.05"
Bellows Crest Cold Work	19 %
Bellows Material	SS304

Expansion Joint Features

Figure 1 depicts the geometry of the EJ bellows. This single ply bellows is made of SS304 and incorporates equalizing rings (not shown) for stability against internal pressure.

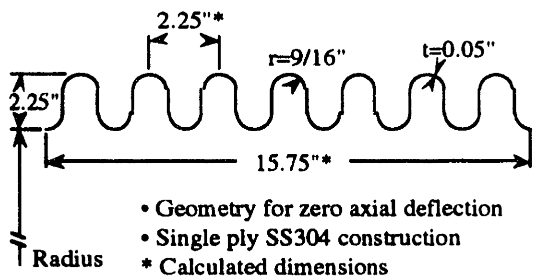


FIGURE 1. SCHEMATIC OF THE EJ BELLOWS

Material Properties

Because a cracked bellows will undergo plastic deformation, nonlinear properties are required for input to ABAQUS—the finite element code used for this analysis (HKS,1992). It has been found that the opening width and hence, leak rate of a cracked bellows is sensitive to the material response. This section summarizes the material model used for this analysis.

The Bellows Fabrication Process. A typical Savannah River Site EJ bellows is formed by placing a metal cylinder in a hydraulic press and pressurizing it internally until yielding occurs. The cylinder is supported on the outside by a convolution shape set of dies and the pressure is increased until the convolution is fully formed. If equalizing rings are to be used, they are typically incorporated into the die and remain on the bellows after formation is complete. The EJ bellows are installed in the as-formed condition. Solution anneal heat treatment of bellows is sometimes used but normally decreases the bellows fatigue life (EJMA, 1980).

Material Properties In ABAQUS. During the formation process, the crest of a convolution is cold-worked much more than the convolution root—approximately 19% in this case—primarily in the hoop direction. Bellows operational stresses are typically root/crest bending and normally cause yielding first in the root because of the increased yield strength due to cold-work in the crest. Cold-working was simulated in this analysis by assigning unique plastic material properties for each element. The degree of cold-work was assumed to follow the relationship in Equation (1) (EJMA, 1980).

$$W_c = \frac{r}{r_i} - 1 \qquad (1)$$

Where: W_c = the degree of cold-work
r = the distance of the element centroid to the bellows axis.
r_i = the inside radius of the bellows (root radius).

The initial yield stress for the finite elements was the stress corresponding to a strain of W_c on the base material (before bellows formation) stress-strain curve. For strains greater than W_c, the constitutive relationship was identical to the base material. Table 2 lists key base material properties used in the finite element analysis. These properties apply to a maximum operating temperature of about 75 ^oC. A constitutive relationship based on stress-strain test data (on specimens taken from a similar bellows) was incorporated in the analysis and is shown in Figure 2.

TABLE 2. BASE MATERIAL PROPERTIES

Property	Value
Elastic Modulus (psi)	28.3×10^6
Yield Strength (psi)	37.6×10^3
True Ultimate Strength (psi)	126.6×10^3
True Uniaxial Fracture Strain	0.53
Poisson's Ratio	0.3

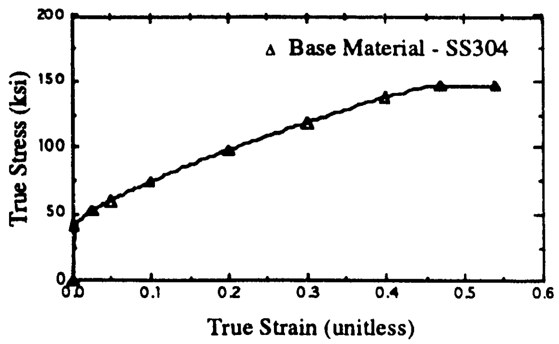


FIGURE 2. STRESS-STRAIN CURVE FOR ABAQUS BASED ON TEST DATA

Bellows formation also causes material thinning, especially near the crest. Equation (2) is the Expansion Joint Manufacturers Association (EJMA) equation for bellows thinning at the crest during the manufacturing process. As with the constitutive relationship in Equation (1), each bellows element is assigned an initial thickness according to Equation (2). The maximum thinning for this bellows was approximately 5% at the crest. A linear relationship between element centroid radius and bellows thickness was assumed.

$$t_p = t\sqrt{\frac{d}{d_p}} \qquad (2)$$

Where: t_p = the bellows crest thickness after forming
t = the nominal bellows thickness
d = the inner diameter of the bellows
d_p = the inner bellows diameter plus one convolution height

Figure 3 shows the thickness measurements taken from an EJ of similar design. The least-squares fit through the data shows the bellows thickness changes at a rate of -1.07e-4 inches per percent of prior strain. The EJMA equation for thinning, Equation (2), yields a comparable rate of -1.15e-4 inches per percent of prior strain.

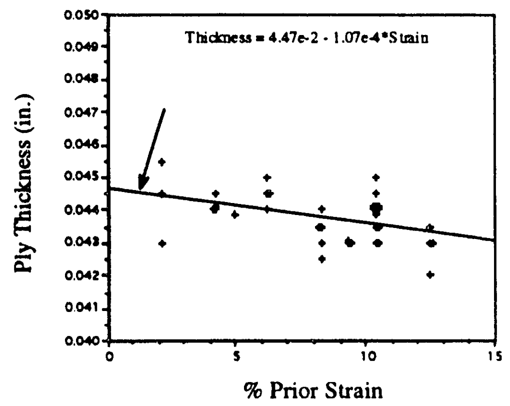
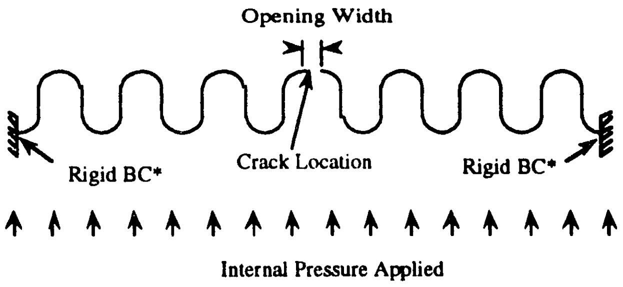


FIGURE 3. MEASURED BELLOWS THINNING DUE TO FORMATION

2D FINITE ELEMENT ANALYSIS

Both 2D and 3D finite element models were constructed of the bellows with the PATRAN mesh generator (PDA, 1990). 2D-axisymmetric models are applicable where the loading is restricted to uniform, internal pressure and uniform, axial loads. The effect of lateral loading and/or asymmetric geometry requires a full 3D model of the bellows.

Figure 4 represents one of several 2D models used in this analysis. All 2D models used ABAQUS SAX1 elements with 16 elements around the convolution crests and roots (HKS, 1992). SAX1 elements are two node, first order integration shells for optimal large plasticity behavior that allow transverse shear.



• ABAQUS SAX1 elements
•16 elements around root and crest
•Statically applied load
•Nonlinear material properties
•Equalizing rings simulated with rigid surfaces
* BC = boundary condition

FIGURE 4. 2D ABAQUS MODEL OF BELLOWS WITH A 360° CRACK

These particular EJs are installed with cast iron rings composed of two parts: equalizing and root rings. The function of root rings is to reinforce the bellows against internal pressure where the equalizing rings prevent unequal deflection between the convolutions (EJMA, 1980). The combination is referred to here as equalizing rings, which are located between each convolution fitting snugly in the root. For the purposes of this analysis they serve to stiffen the bellows against axial compression. This limits the total compression of the bellows in the case of a break provided they remain in place and intact. Equalizing rings were simulated with the use of interface elements between the bellows and root ring. Because the root rings are extremely rigid compared to the bellows, they were treated as rigid bodies in the analyses. Figure 5 shows the equalizing ring configuration.

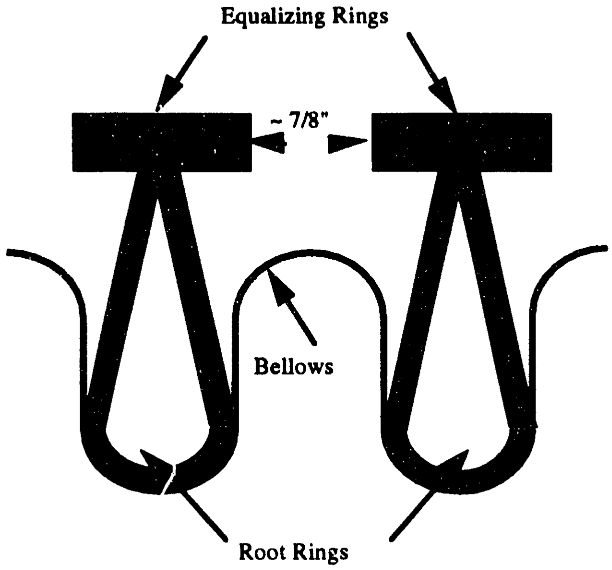


FIGURE 5. SCHEMATIC REPRESENTATION OF EQUALIZING RINGS

The most important parameter concerning the crack opening width is the stiffness of the bellows. Test data was available for a similar EJ that provided a load-displacement history. A finite element model was constructed using the same methodology described above. Figure 6 shows a comparison of the test data and the finite element results. The similar response of the finite element model compared to the test bellows validates the finite element modeling methodology used in this analysis.

The opening width is virtually independent of which convolution is cracked. Boundary effects change the results only slightly if the first or last convolution is cracked. For this reason, symmetry was used for the 2D analyses and the crack was assumed to occur at the midpoint. All numerical results refer to the full break width and pictorial representations are altered to show the full bellows for clarity .

The crack width was found to be dependent on the location of the 360° crack along a convolution. The most severe location for a 360° break in the EJ bellows is in the crest of any convolution. In this case an unbalanced pressure load on half of a convolution drives the bellows apart. Ideally, a 360° crack in the root of any convolution will not produce unbalanced pressure loads that drive the crack open. A large gap could occur in this case if the bellows were extended before rupture. Cracks were postulated in the convolution crests throughout the analysis to simulate the worst case crack.

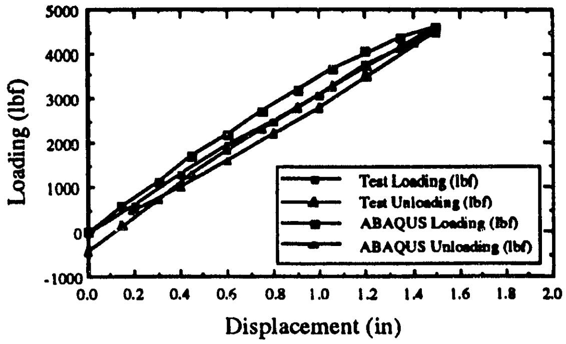
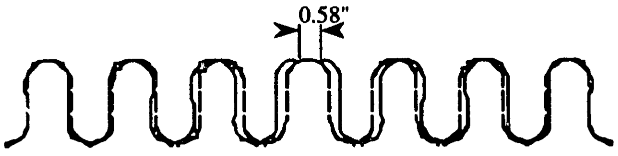


FIGURE 6. BELLOWS STIFFNESS COMPARISON - TEST DATA VS ABAQUS RESULTS

The normal operating pressure of 20 psi load causes an opening gap of 0.58 inches as shown in Figure 7. For this case no additional plastic straining occurs (above that of bellows cold-working) since the applied stress at each location remains below the local flow stress. The peak stress occurs on the sidewalls of the cracked convolution where the equalizing rings separate from the bellows. This is above the base material yield but slightly below the local cold-worked flow stress indicating that assuming base material properties throughout would overpredict the opening width.

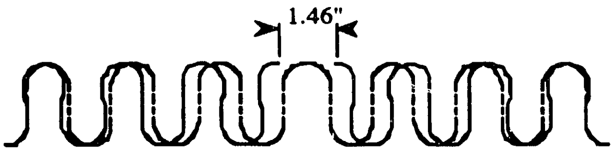


• 2υ r. internal pressure
• Original shape is the dashed line

FIGURE 7. 360° QUASI-STATIC CRACK OPENING WIDTH

The opening area is calculated by multiplying the minimum separation width by the bellows circumference at that location. If large rotation of the cracked convolution were to occur, the flow limiting orifice would be nearer the root than the convolution crest.

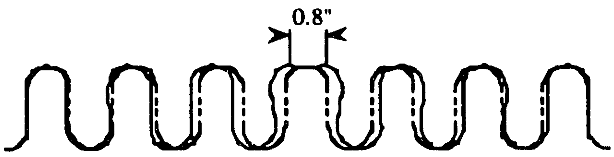
The worst case dynamic effect would occur if fracture occurred instantaneously because inertia effects would overshoot the equilibrium position causing plastic straining and resulting in a larger opening width. To simulate this event, an overpressure of twice the nominal pressure was applied statically (Harris, 1988). Figure 8 represents the conservative, bounding, transient opening width. Providing that bellows collapse does not occur, restoring forces on the bellows would reduce the opening from the transient maximum to the equilibrium point.



• 40 psi internal pressure
• Original shape is the dashed line

FIGURE 8. BOUNDING TRANSIENT OPENING WIDTH FOR DYNAMIC FRACTURE

By reducing the internal pressure to 20 psi, the steady-state opening gap for an instantaneous break is obtained. Figure 9 shows the bounding, constant pressure, maximum expected opening gap of 0.8 inches. Figure 9, simulating instantaneous break, shows that even after being exposed to an overpressure of twice the nominal pressure, the bellows does not collapse. This result is significant because bellows collapse would result in an opening larger than four inches and an unacceptably large leak rate.



• 20 psi internal pressure
• Original shape is the dashed line

FIGURE 9. BOUNDING STEADY-STATE OPENING WIDTH FOR DYNAMIC FRACTURE

A key assumption in this analysis is that the root rings fit tightly in the bellows root. If gaps exist between the root rings and the bellows or the equalizing rings were eliminated somehow, the reduced axial stiffness would result in a much larger opening width. This analysis unconservatively assumes that a perfectly rigid interface with zero clearance exists between the bellows and the root rings. A literature search and a conversation with an EJ manufacturer revealed that, due to the method of forming convolutions around equalizing rings, the root rings fit snugly in the bellows roots.

Because it is critical to the results, a parametric study was undertaken to determine the sensitivity of opening width to root ring/bellows gaps. The results were intended to reveal if very small gaps could lead to larger opening widths in the event of bellows rupture. Figure 10 is a normalized, parametric representation of the bellows stiffness sensitivity to gaps between the root ring and the bellows. Figure 10 shows the results of variable gaps that are zero inches at the bottom of the root and vary sinusoidally around the root ring representing a root ring with a tight fit at the convolution root and a finite separation at the sides. This is more realistic than a uniform gap between the root rings and the bellows. The data in Figure 10 is normalized to the static, 20 psi loading case with the "no gap" equalizing ring condition.

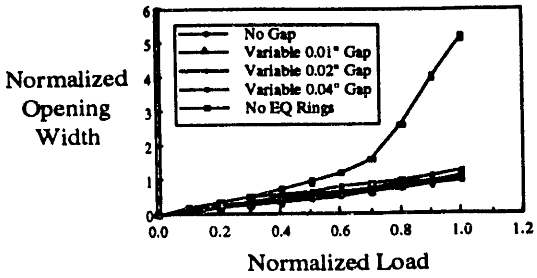


FIGURE 10. THE EFFECT OF A GAP BETWEEN THE BELLOWS AND THE EQUALIZING RING

The results show that the bellows stiffness is not sensitive to gaps between the root rings and the bellows as long as a snug fit exists at the bottom portion of the convolution as is the case with this bellows. The bounding cases show the difference between the EJ stiffness with tight root rings and without equalizing rings altogether. Without root rings, the opening gap resulting from bellows fracture would be over five times that of the case with tight equalizing rings. This analysis is based on quasi-static loading. Dynamic loads would increase that factor even more.

Assumptions used in the 2D analysis include:

- Uniform pressure loading on every element. A conservative assumption because of the pressure drop at the break location as a function of opening width.
- Ideal material and geometry throughout. A nonconservative assumption because material and geometry flaws reduce the bellows stiffness.
- Cold-worked material to a maximum of 19%. A potentially nonconservative assumption depending upon the amount of residual stress in the bellows.
- Bellows thinning corresponding to the EJMA Standards. A realistic assumption.
- No gaps exist between the root rings and the bellows. A somewhat nonconservative, though reasonable assumption.

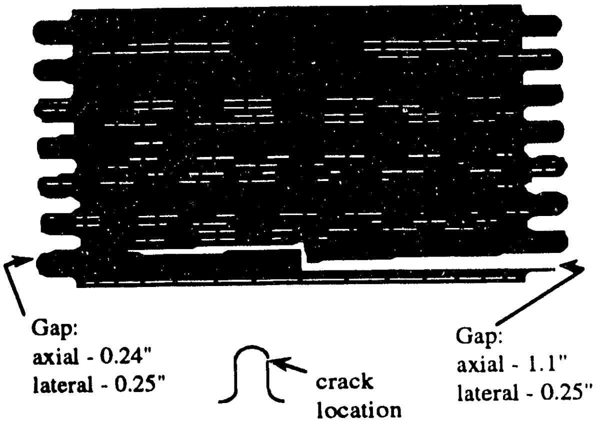
3D FINITE ELEMENT ANALYSIS

If the opening area determined by 2D analysis was found to be small, a slight lateral displacement would greatly increase the relative opening area. Additionally, the potential for the combination of lateral and axial loading to produce a structural instability in the bellows was addressed. Lateral loading was postulated to result from a nonsymmetric fracture. A 3D finite element model of the worst case, nonuniform crack was constructed. The worst case occurs where the crack path alternates from one side of a convolution to the other, at the intersection of the sidewall and the crest. No evidence is found in the literature of fatigue crack growth across convolutions, hence consideration of this configuration is considered conservative.

The highest stress gradients from bellows distortion is generally from bending in the root and crests. Finer meshing was used in the crest with eight elements around. The model does not simulate equalizing rings - making it a conservative representation. One plane of symmetry was used in this case. ABAQUS S4R shell elements were used in the 3D analysis. S4R elements are four noded, first order integration shell elements for improved large plasticity behavior.

Figure 11 shows the quasi-static distortion following the worst case asymmetric break. A moment is induced because of uneven geometry that causes the broken faces to rotate. Without including the stiffening effect of equalizing rings, the maximum, axial opening width is 1.1 inches and the minimum, axial opening width is 0.24 inch. The average, axial opening width is 0.67 inch. The lateral loads lead to a relative, lateral deflection of 0.25 inch. Dynamic effects are not included in this analysis. This result compares favorably with the 2-D quasi-static opening of 0.58 inches considering:

- the equalizing rings were not included in the 3-D case, reducing the stiffness and
- the 3-D case has a smaller surface area for the pressure to act against, reducing the net applied force.



- Average axial displacement - 0.67"
- Modeled conservatively without equalizing rings

FIGURE 11. DEFORMATION DUE TO AN ASYMMETRIC, 360° CRACK

Assumptions used in the 3D analysis include:

- Uniform pressure loading on every element. A conservative assumption because of the pressure drop at the break location as a function of opening width.
- Ideal material and geometry throughout. A nonconservative assumption because imperfections in the bellows can lead to a larger opening width.
- No accounting for dynamic loads. A nonconservative assumption because it underestimates the maximum displacement.
- Equalizing rings not modeled. A conservative assumption because the EQ rings serve to stiffen the bellows to axial compression.
- Annealed properties used throughout. A conservative assumption because plastic deformation occurs at lower stresses, reducing the overall stiffness.

SIMULATING VARIABLE PRESSURE

Flow calculations indicated that the internal pressure at the center of the EJ drops as a function of crack opening width. To incorporate this effect, and reduce the conservatism of assuming constant internal pressure, the internal pressure as a function of opening width was superimposed over the quasi-static load history of the bellows as shown in Figure 12. The equilibrium opening width occurs at the intersection of the linear-elastic unloading path and the variable pressure curve (Daugherty, 1992). This represents the crack width where axial "spring" forces in the bellows are in equilibrium with the variable pressure load acting on the cracked convolution halves. The bounding opening width for a 360° crack in the bellows is 0.7 inch. The leak rate is 20% of the previously assumed leak rate associated with a DEGB. The reduced leak rate is less than the water removal system capacity—assuring that flooding will not occur.

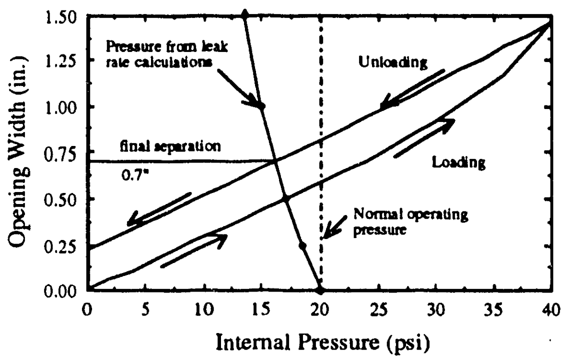


FIGURE 12. BOUNDING OPENING WIDTH WITH VARIABLE PRESSURE

CONCLUSIONS

Analysis has shown that the location of the postulated crack determines the crack width. If the crack occurs at the crest of any EJ convolution, the opening gap due to internal pressure creating a net force on the bellows portions will cause an opening width of up to 0.7 inches following dynamic fracture if all equalizing rings are active and tie rod failure does not occur. An opening width of 0.7 inches represents the maximum opening width following an instantaneous, 360° break, with a corresponding leak rate of 20% of the previously assumed DEGB flow rate. The reduced leak rate is within the water removal system capacity whereas a DEGB would cause rapid flooding. Bellows collapse will not occur although large opening widths are likely if equalizing ring failure occurs. Any initial compression or extension of the bellows due to installation will add or subtract directly from the reported values.

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