Investigation of Stresses in U-Shaped Metal Bellow Using EJMA Standards

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Abstract: Metal Bellows finds wide application in expansion joints, which are used in aerospace, chemical plants, power system, heat exchangers, automotive vehicle parts, piping system, petrochemical plant, refineries, etc. During service they are subjected to various stresses and exposed to different environments, which leads to failure. Hence there is a need for proper design of metal bellow as per the application. The main objective of the paper is to evaluate the stresses generated in the metal bellow and the cycle life working at different working pressures. In this paper, the stresses are calculated using Expansion Joint Manufacturing Association (EJMA) standards and compared with the results obtained using ANYS software for two different materials namely Inconel 625 and Inconel 718 for the pressure values ranging from 20 to 40 bar.

Keywords: EJMA, Expansion joints, Metal bellow


Biographical notes: Kondapalli Siva Prasad obtained PhD from Andhra University, India in 2003. He is currently working as Associate Professor at the Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India. His current research interest includes Manufacturing and product design. Gudla Pavani is PG student of Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India.
1 INTRODUCTION

An expansion joint is an assembly designed to safely absorb the heat-induced expansion and contraction of construction materials, to absorb vibration, to hold parts together, or to allow movement due to ground settlement or earthquakes. Bellows is corrugated part of the expansion joint which is capable of compensating large amount of axial, lateral and angular movements as a single unit. It must be strong enough circumferentially to withstand the pressure and flexible enough longitudinally to accept the deflections for which it is designed, and as repetitively as necessary with a minimum resistance. This strength with flexibility is a unique design problem that is not often found in other components in industrial equipment. Based on the application the material of the bellow is selected. Its present requirement is for the aerospace applications at the bleed air outlet of aircraft engine.

In the field of expansion joints very limited literature is available. Only few technical books and hand books of piping includes about the expansion joints which are used in the piping. But these references are limited up to the working principle of expansion joints. No text or reference books include, design of expansion joints, as this is a specialized area. But all authors are mentioning the reference of standards developed by EJMA. Since major contribution in the design of bellows expansion joint is given by Expansion Joints Manufacturers’ Association (EJMA). EJMA has established the codes and guidelines for the design of bellows expansion joints. These codes are available based on membership of EJMA. Jayesh. B. Khunt and Rakesh. Prajapathi [1] studied different types of expansion joints used in industry.


In the above literature review most of the work is done on bellows made of various grade stainless steels which are subjected to different types of corrosion such as fatigue corrosion, liquid droplet erosion, and stress corrosion when used at high temperatures. Fatigue analysis of bellows is less concentrated. Based on these studies, there is a necessity that the materials used should possess great corrosion resistance at elevated temperatures. The fatigue life of the bellows is of great importance as they are subjected repeated loads. Therefore, these two high temperature nickel-chromium alloys Inconel 625 and Inconel 718 are used in our work. These materials have good oxidation resistance, excellent strength and are easily fabricated. As most of the bellows are used in corrosive environment use of these nickel chromium alloys will minimize the failure due to corrosion. So, these material properties are used to calculate the stresses produced in bellows. Hence this work focusses on selection of proper bellow material, design, calculation of stresses both analytically and numerically and finally comparing both with the allowable stress limits.

2 DESIGN OF BELLOW USING EJMA STANDARDS

The design of a bellow is complex and it involves an evaluation of pressure capacity, stresses due deflection and pressure, fatigue life, spring forces and instability. The bellow used in this joint will be tested for two high temperature materials. The design should be based on the actual bellow metal temperature expected during operation. The design values are considered based on conditions available at the bleed air outlet of aircraft engine. Detailed design calculations of bellow used in gimbal joint are shown below.

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Design considerations

Normal Working Pressure = 37 bar
Normal Working Temperature = 650°C
Angular Moment required = 17.5Nm
Maximum Permissible Deflection = ±6°

Equations used below are based on norms followed by Expansion Joint Manufacturer’s Association (EJMA) and accepted by ASME (American Society of Mechanical Engineers).

The following are the stresses

1. Bellows Tangent Circumferential Membrane stress due to pressure (S₁)
2. Primary Collar Circumferential Membrane stress due to pressure (S₁')
3. Circumferential Membrane stress is also induced in the convolutions (S₂)
4. Bellows Meridional Membrane stress due to pressure (S₃)
5. Bellows Meridional Bending stress due to pressure (S₄)
6. Bellows Meridional Membrane stress due to deflection (S₅)
7. Bellows Meridional Bending stress due to deflection (S₆)

For Inconel 625 Material

I. Bellonk 625 Material

\[
S_1 = \frac{P \times (D_h + n \times t)^2 \times L_t \times E_h \times k}{2 \times \{n \times t \times E_h \times L_t \times (D_h + n \times t) + t_c \times k \times E_c \times L_c \times D_c\}}
\]

E_b = E_c = 16700 kgf/mm²
Sₙ = 3.89 kgf/mm²
S₂ₐ = Ultimate tensile strength of Inconel 625 at design temperature (650°C) = 760 Mpa or 76 kgf/mm²
S₂ₐ = allowable material stress of Inconel 625 at design temperature = 76/2.5 = 30 kgf/mm²
Cₑ = Factor accounting for Welding joint efficiency = 0.7
Effective S₂ₐ = Cₑ × S₂ₐ = 21 kgf/mm²

From the above calculations, it is clear that S₁ < S₂ₐ. Hence design is safe.

II. Primary collar circumferential membrane stress due to pressure (S₁')

This is the circumference membrane stress induced in the collar directly due to pressure p

\[
S_1' = \frac{P \times D_c^2 \times L_t \times E_c \times k}{2 \times \{n \times t \times E_h \times L_t \times (D_h + n \times t) + t_c \times k \times E_c \times L_c \times D_c\}}
\]

S₁' = 4.25 Kgf/mm²
Effective S₂ₐ = 21 kgf/mm²
S₁' < S₂ₐ
Hence design is safe.

III. Circumferential membrane stress induced in the convolutions (S₂)

The main causes for the stresses in the bellows are pressure and initial deflection. Pressure and deflection causes circumferential and meridional stresses in the bellows. Stresses due to internal pressure remain largely unaffected by the number of piles except for the convolution meridional bending stress, which are reduced when the total bellows thickness increases. The deflection stresses are decreased due to thinner material per ply resulting in an increase in fatigue life. The equations used below are based on norms followed by Expansion Joint Manufacturer’s Association (EJMA) and accepted by ASME (American Society of Mechanical Engineers).
The stresses $S_5$ and $S_6$ are used in the evaluation of bellows fatigue life.

### 2.2 Column Squirm (Calculation of $P_{sc}$)

Column Squirm is defined as a gross lateral shift of the centre section of the bellows. It results in curvature of the bellows centre line. This condition is mostly associated with bellows which have a relatively large length to diameter ratio and is analogous to the buckling of a column under compressive load. The bellows have to be designed for either elastic or inelastic condition based on length to diameter ratio.

i.e.

For $L_b/D_b > = C_z$, the squirm pressure $P_{sc}$ is evaluated as

$$P_{sc} = \frac{0.34 \times \Pi \times C_y \times f_{ui}}{N^2 \times q}$$

For $L_b/D_b < C_z$, the squirm pressure $P_{sc}$ is evaluated as

$$P_{sc} = \frac{0.87 \times A_c \times S_y}{D_b \times q} \left(1 - \frac{0.73 \times L_b}{C_z \times D_b}\right)$$

$$C_z = \text{Transition point factor} = \sqrt{\frac{4.72 \times f_{ui} \times q^2}{S_y \times D_b \times A_c}}$$

This indicates the value of length to Diameter ratio where the critical instability pressure transitions to a maximum value at the length of one convolution which represents purely inelastic behavior.

Where

$S_y = \text{Yield Strength at room temperature of bellows}$

### For Inconel 625

$S_y = 49 \text{ kgf/mm}^2$ (at room temperature for Inconel 625)

$$f_{ui} = \frac{1.7 \times D_m \times E_b \times L_p \times n^3}{w^3 \times C_f} = 116.75 \text{ kg/mm per convolution}$$

$D_b = 42 \text{ mm}$

$A_c = \text{cross-sectional area of one bellows convolution} = \left(0.571 \times q + 2 \times w\right) L_p \times n = 16.88 \text{ mm}^2$

Substituting the values, $C_z = 0.776$

Since $L_b / D_b \geq C_z$
Fatigue life of a bellow is a function of the sum of the meridional pressure stresses range and the total meridional deflection stresses range. The equation for fatigue life is as follows:

\[ N_c = \left( \frac{c}{S_t - b} \right)^a \]

where a, b and c are material and manufacturing constants. These constants are derived from the graph of total stress range \( S_t \) versus number of cycles \( N_c \).

From EJMA standards, the values of a, b and c are as \(a = 3.4, b = 54,000, \ c = 1.86 \times 10^6\)

Total Stress \( S_t = 0.7 \ (S_3 + S_4) + (S_3 + S_6) \)

\( S_1 = 1.52 \text{ kgf/mm}^2, \ S_4 = 31.29 \text{ kgf/mm}^2 \)

**For Inconel 625**

\( S_5 = 0.351 \text{ kgf/mm}^2, \ S_6 = 29.84 \text{ kgf/mm}^2 \)

\( S_t = 53.158 \text{ kgf/mm}^2 = 77099.161 \text{ psi} \)

\( N_c \) (at design temperature) \( = 3.02 \times 10^6 \) cycles

### 3 NUMERICAL INVESTIGATION OF STRESSES

At first the bellow surface model is designed with the help of CATIA V5 software, which is one of the leading design software, and after that the surface model is saved in IGES format and the geometry is imported to ANSYS software. After importing the geometry, the material properties are given with a thickness of 1 mm. The bellow part is analyzed with the help of ANSYS WORKBENCH 15.0. Figure 2 shows the surface model and figure 3 shows the meshed ANSYS model with the thickness given. The loading conditions are given such that one edge of the bellow is fixed and internal surface is subjected to pressure varying from 20 bar to 40 bar for the materials Inconel 625 and Inconel 718. Figure 4 shows the loading conditions of bellow.
2 RESULTS & DISCUSSIONS

4.1 Theoretically calculated Values
Theoretical values of design stresses, squirm values and fatigue life values for the two materials at 4 different pressures are calculated using EJMA standards.

Table 5.1 Stresses developed at different pressures in Inconel 625

<table>
<thead>
<tr>
<th>At Pressure</th>
<th>20 Bar</th>
<th>30 Bar</th>
<th>37 Bar</th>
<th>40 Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$(kgf/mm$^2$)</td>
<td>2.10</td>
<td>3.152</td>
<td>3.89</td>
<td>4.202</td>
</tr>
<tr>
<td>$S_1'$(kgf/mm$^2$)</td>
<td>2.30</td>
<td>3.452</td>
<td>4.25</td>
<td>4.602</td>
</tr>
<tr>
<td>$S_2$(kgf/mm$^2$)</td>
<td>1.838</td>
<td>2.757</td>
<td>3.4</td>
<td>3.675</td>
</tr>
<tr>
<td>$S_3$(kgf/mm$^2$)</td>
<td>0.822</td>
<td>1.234</td>
<td>1.52</td>
<td>1.645</td>
</tr>
<tr>
<td>$S_4$(kgf/mm$^2$)</td>
<td>16.91</td>
<td>25.36</td>
<td>31.29</td>
<td>33.81</td>
</tr>
<tr>
<td>$S_5$(kgf/mm$^2$)</td>
<td>0.351</td>
<td>0.351</td>
<td>0.351</td>
<td>0.351</td>
</tr>
<tr>
<td>$S_6$(kgf/mm$^2$)</td>
<td>29.84</td>
<td>29.84</td>
<td>29.84</td>
<td>29.84</td>
</tr>
</tbody>
</table>

4.1.1 Design Stresses induced in Bellow
In the above tables 5.1, and 5.2, the stresses developed in two high temperature metals at four different pressures are calculated and it is observed that the stresses $S_1$, $S_1'$, $S_2$, $S_3$, $S_4$ are increasing within increase in pressure whereas the deflection stress $S_5$, $S_6$ are calculated by using room temperature material properties which does not have any significant change with the change in pressure and vary according to the material used. These stress values are checked with the allowable stress values and the design is found to be safe.

4.1.2 Column and In-plane Squirm
A factor of safety for limiting stress of 2.25 is used in the relation for $P_{sc}$ and $P_{si}$. As $P_{sc}P_{si} < 2.25$ times of working pressure, theoretically it is required to go for higher thickness but these bellows were tested for burst pressure of 125 bar and are found satisfactory.

Table 5.2 Stresses developed at different pressures in Inconel 718

<table>
<thead>
<tr>
<th>At Pressure</th>
<th>20 Bar</th>
<th>30 Bar</th>
<th>37 Bar</th>
<th>40 Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$(kgf/mm$^2$)</td>
<td>2.10</td>
<td>3.152</td>
<td>3.89</td>
<td>4.202</td>
</tr>
<tr>
<td>$S_1'$(kgf/mm$^2$)</td>
<td>2.30</td>
<td>3.452</td>
<td>4.25</td>
<td>4.602</td>
</tr>
<tr>
<td>$S_2$(kgf/mm$^2$)</td>
<td>1.838</td>
<td>2.757</td>
<td>3.4</td>
<td>3.675</td>
</tr>
<tr>
<td>$S_3$(kgf/mm$^2$)</td>
<td>0.822</td>
<td>1.234</td>
<td>1.52</td>
<td>1.645</td>
</tr>
<tr>
<td>$S_4$(kgf/mm$^2$)</td>
<td>16.91</td>
<td>25.36</td>
<td>31.29</td>
<td>33.81</td>
</tr>
<tr>
<td>$S_5$(kgf/mm$^2$)</td>
<td>0.337</td>
<td>0.337</td>
<td>0.337</td>
<td>0.337</td>
</tr>
<tr>
<td>$S_6$(kgf/mm$^2$)</td>
<td>28.692</td>
<td>28.692</td>
<td>28.692</td>
<td>28.692</td>
</tr>
</tbody>
</table>

4.1.3 Fatigue Life

Table 5.3 Squirm values for different materials

<table>
<thead>
<tr>
<th>INSTABILITY</th>
<th>Inconel 625</th>
<th>Inconel 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Squirm</td>
<td>$0.236$</td>
<td>$0.23$</td>
</tr>
<tr>
<td>Inplane Squirm $P_{si}$</td>
<td>$0.44$</td>
<td>$1.056$</td>
</tr>
</tbody>
</table>

Table 5.4 Fatigue life values (number of cycles $N_{cy}$)

<table>
<thead>
<tr>
<th>Pressure (Bar)</th>
<th>20</th>
<th>30</th>
<th>37</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 625</td>
<td>$1.2\times10^6$</td>
<td>$8.94\times10^6$</td>
<td>$3.022\times10^6$</td>
<td>$2.078\times10^6$</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>$2.78\times10^5$</td>
<td>$1.281\times10^7$</td>
<td>$3.908\times10^7$</td>
<td>$2.613\times10^7$</td>
</tr>
</tbody>
</table>
From theoretical calculations, it is observed that fatigue life values depend upon the working pressure as the pressure increases fatigue life values decreases. Inconel 718 has better fatigue life at all the pressures.

4.1 Comparison of Analytical and Numerical Stresses due to Internal Pressure for Inconel 625 and Inconel 718

The analytical stresses obtained from EJMA standards and numerical stresses obtained from FEA are compared and tabulated below.

4.2.1 For Inconel 625

<table>
<thead>
<tr>
<th>STRESS</th>
<th>SOURCE</th>
<th>20 Bar</th>
<th>30 Bar</th>
<th>37 Bar</th>
<th>40 Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁(kgf/mm²)</td>
<td>EJMA</td>
<td>2.10</td>
<td>3.152</td>
<td>3.887</td>
<td>4.20</td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>9.21</td>
<td>13.84</td>
<td>16.47</td>
<td>18.18</td>
</tr>
<tr>
<td>S₁(kgf/mm²)</td>
<td>EJMA</td>
<td>2.30</td>
<td>3.45</td>
<td>4.25</td>
<td>4.602</td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>8.41</td>
<td>13.54</td>
<td>15.72</td>
<td>17.14</td>
</tr>
<tr>
<td>S₂(kgf/mm²)</td>
<td>EJMA</td>
<td>2.76</td>
<td>3.4</td>
<td>3.675</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>17.29</td>
<td>20.942</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₃(kgf/mm²)</td>
<td>EJMA</td>
<td>0.822</td>
<td>1.23</td>
<td>1.52</td>
<td>1.644</td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>11.45</td>
<td>16.43</td>
<td>20.97</td>
<td>22.85</td>
</tr>
<tr>
<td>S₄(kgf/mm²)</td>
<td>EJMA</td>
<td>16.91</td>
<td>25.36</td>
<td>31.29</td>
<td>33.81</td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>13.94</td>
<td>20.42</td>
<td>25.35</td>
<td>28.38</td>
</tr>
</tbody>
</table>

From the table 5.5 it is observed for Inconel 625 that all the stresses obtained by both the approaches are within the allowable limit and are increasing with increase in the pressure. The difference in the stress profile is comparatively large and is due to variation of the approach methods.

Fig. 5  Circumferential stresses in bellow tangent (S₁) for Inconel 625:S₁ < Sₐ (21 kgf/mm²)

Fig. 6 Primary collar circumferential stress (S₁₁) for Inconel 625:S₁₁ < Sₐ (21 kgf/mm²)

Fig. 7 Circumferential membrane stress induced in convolution (S₂) for Inconel 625 S₂ < Sₐ (21 kgf/mm²)

Fig. 8 Meridional membrane stress (S₃) for Inconel 625

Fig. 9 Meridional bending stress (S₄) for Inconel 625 (S₃+S₄) < Cₘ×Sₐ (63 kgf/mm²)
The allowable stress value \(S_{ab}\) for circumferential stresses \(S_1, S_1, S_2\) is 21 kgf/mm\(^2\). Whereas for meridional stresses \((S_3 + S_4) < C_m \times S_{ab}\) i.e. 63 kgf/mm\(^2\) for the design to be safe. Figures 5 to 9 show the comparison graphs of the stresses in the bellow when subjected to internal pressure.

When compared to the meridional bending stress \(S_4\) all the other stresses have considerable variation, but as per design criteria they are within the allowable limit. The circumferential membrane stress induced in convolution \(S_2\) for the pressure 40 bar is slightly above the allowable stress which states that withstanding the pressure more than 40 bar there is a necessity to go for higher thickness of the bellow. Figures 10 to 13 show the stress distribution for Inconel 625 at different pressures. It is also incurred from the diagrams that the maximum and minimum values of stresses developed in bellow when compared to theoretically calculated stresses show a close match.

### 4.2.2 For Inconel 718

From the table 5.6 it is observed for Inconel 718 that all the stresses obtained by both the approaches are within the allowable limit and are increasing with increase in the pressure. The difference in the stress profile is comparatively large and is due to variation of the approach methods.

<table>
<thead>
<tr>
<th>STRESS SOURCE</th>
<th>20 Bar</th>
<th>30 Bar</th>
<th>37 Bar</th>
<th>40 Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_1) (kgf/mm(^2))</td>
<td>EJMA</td>
<td>2.10</td>
<td>3.152</td>
<td>3.89</td>
</tr>
<tr>
<td>FEA</td>
<td>9.77</td>
<td>15.06</td>
<td>18.63</td>
<td>20.18</td>
</tr>
<tr>
<td>(S_1) (kgf/mm(^2))</td>
<td>EJMA</td>
<td>2.301</td>
<td>3.452</td>
<td>4.25</td>
</tr>
<tr>
<td>FEA</td>
<td>8.39</td>
<td>14.76</td>
<td>17.58</td>
<td>19.51</td>
</tr>
<tr>
<td>(S_2) (kgf/mm(^2))</td>
<td>EJMA</td>
<td>16.907</td>
<td>25.361</td>
<td>31.29</td>
</tr>
<tr>
<td>FEA</td>
<td>15.12</td>
<td>22.58</td>
<td>29.06</td>
<td>31.37</td>
</tr>
</tbody>
</table>
Figures 14 to 18 show the comparison graphs of the stresses in the bellow when subjected to internal pressure in Inconel 718. When compared to the meridional bending stress ($S_4$), all the other stresses have considerable variation, but as per design criteria, they are within the allowable limit.

Fig. 14 Circumferential stresses in bellow tangent ($S_1$) for Inconel 718 $S_1 < S_{ab} (32.34 \text{ kgf/mm}^2)$

Fig. 15 Primary collar circumferential stress ($S_{11}$) for Inconel 718 $S_{11} < S_{ab} (32.34 \text{ kgf/mm}^2)$

Fig. 16 Circumferential membrane stress induced in convolution ($S_2$) for Inconel 718 $S_2 < S_{ab} (32.34 \text{ kgf/mm}^2)$

Fig. 17 Meridional membrane stress ($S_3$) for Inconel 718

Fig. 18 Meridional bending stress ($S_4$) for Inconel 718 $S_3 + S_4 < C_m \times S_{ab} (97.02 \text{ kgf/mm}^2)$

Figures 19 to 22 show the stress distribution for Inconel 718 at different pressures varying from 20 bar to 40 bar. It is also incurred from the diagrams that the maximum and minimum values of stresses developed in bellow at these pressures show a close match.

Fig. 19 Stress distribution at Pressure 20 Bar
In this paper the design of the metal bellow and theoretical evaluation of the stresses is done using EJMA standards and the numerical evaluation is done by using ANSYS WORKBENCH software. The results obtained are compared and there is slight variation in the stress values and is due to different approaches followed. From the theoretical calculations it can be said that the maximum stress value is Meridional bending stress and this value is checked with the allowable stress value so that the bellow does not fail.

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