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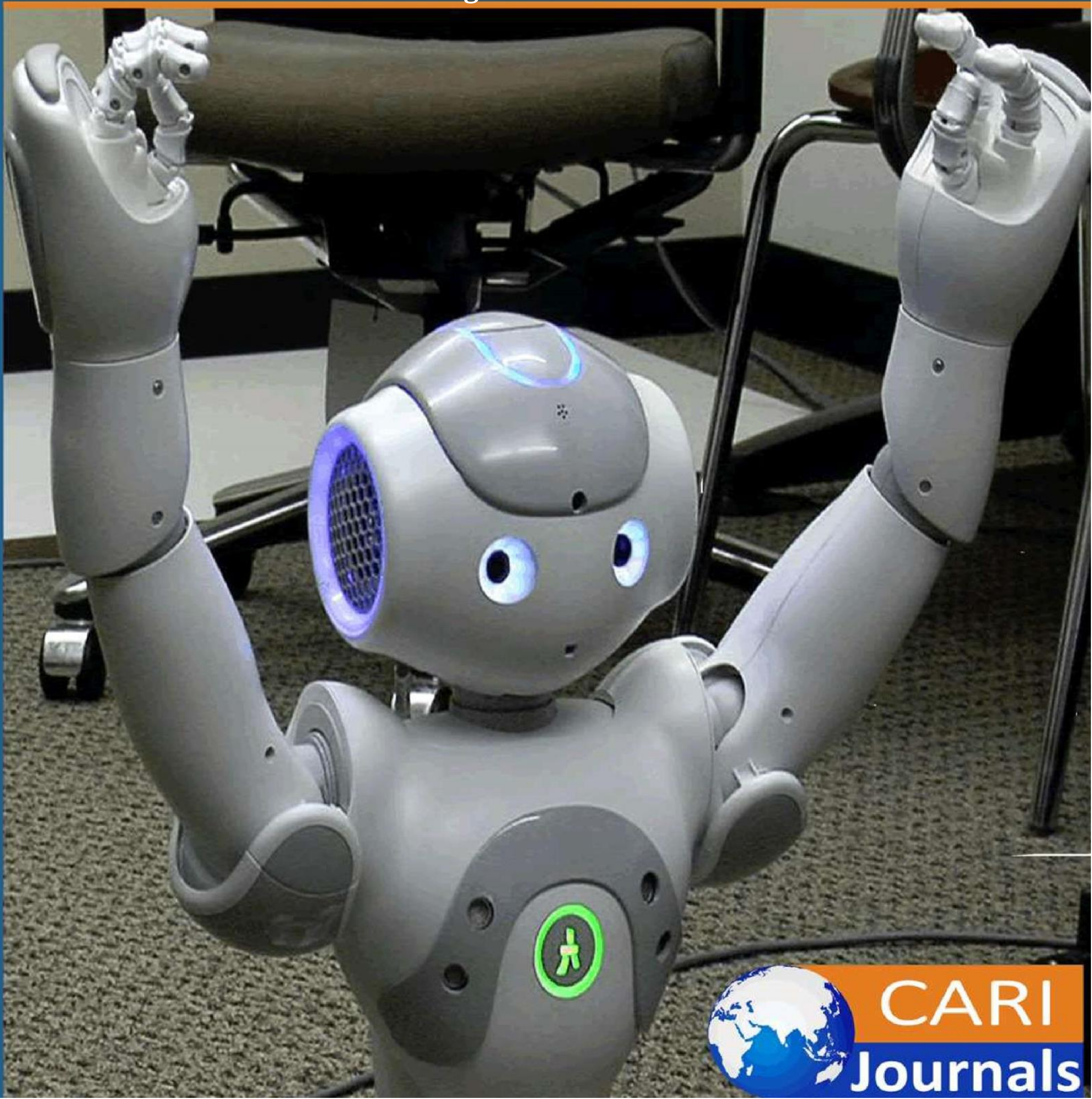

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Finite Element Analysis of Bellows Expansion Joint Under Large Deformation

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Abstract

Purpose: A bellows expansion joint is a flexible connector made from a series of convolutions, also known as bellows, that can accommodate movements in a piping system. The movements can include axial compression and extension, lateral deflection, and angular rotation.

Methodology: Bellows expansion joints are used to absorb thermal expansion, reduce vibration, and compensate for misalignments in piping systems. They help to absorb tensile or compressive forces arising from expansions or contractions in the system. In this study, Finite Element Analysis (FEA) is performed on a bellows expansion joint within a piping system subjected to large deformations due to axial compression, axial tension, cyclic loading and bending loading. The deformation behaviour and stress distribution of the joint under the different loading scenarios is thoroughly investigated.

Findings: The analysis results provide significant insights into the deformation patterns, stress distribution, and strain energy within the bellows expansion joint under loading. The result of the Finite Element Analysis is validated by comparison with experimental data from literature.

Unique contribution to theory, policy and practice: A detailed 3D model of the multi-convolution bellows expansion joint is developed, and appropriate material properties assigned using Abaqus. The material model parameters are calibrated using data from literature. Non-linear static analysis is then conducted to simulate the joint's response under load.

Keywords: *Bellows Expansion Joint, Convolution, Axial Compression, Lateral Deflection, Angular Rotation, Large Deformation, Axial Tension, Cyclic Loading, Bending Loading, Non-linear Static Analysis*

INTRODUCTION

PROBLEM DESCRIPTION

Bellows expansion joints are vital components in fluid and gas transfer systems, designed to accommodate thermal expansion, absorb vibrations, and counteract system misalignments. To ensure their effective functioning and longevity, it is essential to analyse the stress distribution, deformation, and fatigue life under various loading conditions prior to manufacture.

Finite Element Analysis (FEA) is a powerful tool that can be used to analyse the behaviour of bellows expansion joints under different operating conditions, with focus on evaluating the structural integrity and identifying potential failure modes, for improved performance and durability.

OBJECTIVE

The objective of our study is to investigate the deformation behaviour and stress distribution of a 4-convolution bellows expansion joint under different loading scenarios; tension, compression, bending and cyclic loading. We shall achieve this by doing the following:

a) Develop an Accurate Geometric Model: Create a detailed 3D model of the bellows expansion joint, considering the complex geometrical features and material properties.
b) Generate an Appropriate Mesh: Select and create an appropriate mesh for the FEA model that ensures the accuracy of the results while optimizing computation time.
c) Apply Boundary Conditions and Loading: Define relevant boundary conditions and loading scenarios.
d) Perform Stress and Deformation Analysis: Conduct stress and deformation analysis under various operating conditions to identify critical areas that might experience high stress concentrations or excessive deformation.
e) Validate the Model: Compare the FEA results with available experimental data available from literature to validate the accuracy and reliability of the model.

LITERATURE REVIEW

INTRODUCTION

Bellows expansion joints are used in piping systems to absorb vibration and shock [1]. They have the advantage of reducing the noise caused by misalignment in piping systems whilst compensating for the misalignment.

Bellows expansion joints are usually made from metal or rubber. Metal expansion joints are mostly used in thermal expansion applications. If the temperature of the pipe increases, the bellows compresses to compensate for the movement and alleviate stress from the pipe. There are a variety of material choices for metallic bellows, including stainless steel and nickel alloys. Rubber expansion joints are made from elastomers with metallic reinforcement and can absorb vibration and shocks extremely well. They are also effective in reducing noise.

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Fig. 1.1 (a) Metallic and (b) rubber bellows expansion joint [1].

There are three basic types of bellows joint: axial, angular, and lateral. Axial bellows joints absorb movement in an axial direction and are usually fitted with a guiding tube inside the metal bellows. This reduces flow resistance and prevents damage caused by direct contact with the flowing medium. Bellows joints are connected to the main piping system to absorb expansions or contractions through standard connectors (welded ends, fixed flanges, and loose flanges).

The schematic diagram of a bellows joint in practice is shown in Fig. 1.2. The geometric parameters are shown in Fig. 1.3: nominal diameter D_0; wall thickness t; pitch q, distance between the corresponding points of any two adjacent convolutions; convolution height h; convolution radius R; the length of the straight-line segment h_0 and convolutions number n [2].

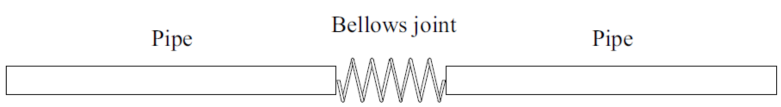

Fig. 1.2. Schematic diagram of a bellows joint [2].

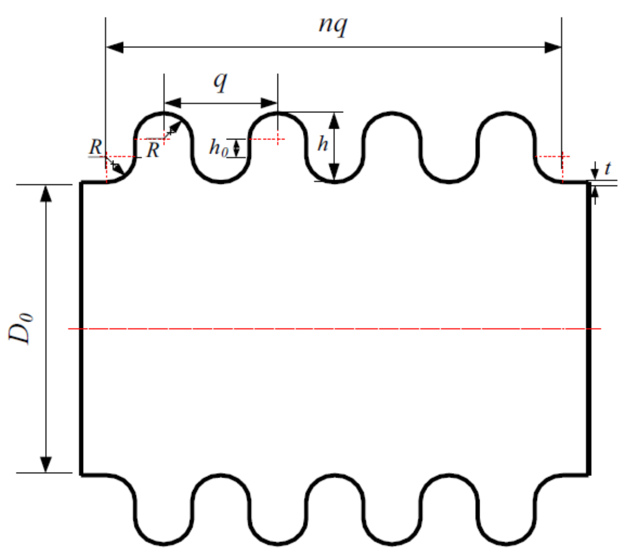

Fig. 1.3. Geometric parameters of a bellows joint [2].

Bellows expansion joints are often subject to cyclic loading, which can lead to fatigue failure over time. The cyclic flexing of the bellows can cause the development of cracks, which may eventually lead to failure.

APPLICATIONS

Bellows expansion joints have a wide range of applications across various industries due to their ability to accommodate thermal expansion, absorb vibrations, and manage system misalignments. Some of the key applications include:

1. Piping Systems
2. HVAC Systems
3. Power Generation
4. Shipbuilding
5. Water and Wastewater Treatment
6. Railway Systems
7. Building Structures
8. Aerospace Industry
9. Automotive Industry
10. Test Equipment

TYPES

There are several types of bellows expansion joints, each designed based on the specific application and requirements for which it is intended [1]:

S/N	TYPE	COMMON APPLICATION
1	Axial Bellows Expansion Joints	Designed to accommodate axial movement, i.e., movement parallel to the axis of the pipeline
2	Lateral Bellows Expansion Joints	Designed to absorb lateral movement, i.e., movement which is perpendicular to the axis of the pipeline
3	Angular Bellows Expansion Joints	Designed to accommodate angular movement, i.e., movement which involves rotation around a fixed point
4	Universal Bellows Expansion Joints	Designed to accommodate both axial and lateral movements
5	Gimbal Bellows Expansion Joints	Designed to accommodate both lateral and angular movements
6	Hinged Bellows Expansion Joints	Designed to accommodate angular movement and limited axial movement
7	Pressure Balanced Bellows Expansion Joints	Designed to absorb movement without exerting pressure thrust on the piping system. Pressure balanced bellows expansion joints can be axial, lateral, or universal

Each type of bellows expansion joint is designed to handle specific types of movements and loading conditions. Selection of the appropriate type depends on the specific requirements of the application, including the type and magnitude of movement, operating conditions of the expansion joint, and design parameters.

MATERIAL SELECTION

Material selection is a critical aspect of bellows joint design as it significantly impacts the performance, durability, and overall lifespan of the component. The choice of material affects key attributes, including the joint's ability to resist fatigue, withstand environmental conditions, and maintain its structural integrity.

Common materials used for bellows joints include stainless steel (e.g., 304, 316, 321), nickel alloys (e.g., Inconel), high-temperature alloys (e.g., Hastelloy) and rubber [1]. Each material has its strengths and weaknesses, so the choice depends on the specific requirements of the application.

USE OF FINITE ELEMENT ANALYSIS IN DESIGN

Finite Element Analysis (FEA) is a powerful computational tool that can be used in various aspects of the design and analysis of bellows expansion joints.

FEA can be used to analyse the structural behaviour of the joints under different loading conditions, such as internal pressure, external forces, and thermal expansion. This includes determining stress distributions, identifying stress concentrations, and evaluating the deformation of the joint.

Bellows joints are often subjected to cyclic loading, and FEA can be used to predict the fatigue life of the joint. This involves simulating the cyclic loading conditions and evaluating the damage accumulation over time to estimate the number of cycles to failure.

FEA can be used to optimize bellows joint design, including the geometry, material selection, and other design parameters. This involves evaluating different design options and identifying the configuration that best meets the performance requirements while minimizing stress concentrations and maximizing fatigue life.

Overall, FEA is a versatile and powerful tool that can be used in various aspects of the design and analysis of bellows expansion joints, providing valuable insights into their behaviour and performance under different conditions.

PREVIOUS FEA STUDIES

Underground pipeline systems often suffer from severe damage under the action of earth-moving forces like earthquake. Strong ground motion may cause rupture of an underground pipeline leading to leakage, waste of resources and environmental pollution.

Data from Michoacan earthquake (Mexico, 1985) and Kobe earthquake (Japan, 1995) showed that underground pipeline systems, such as gas, water supply and sewage system, were heavily damaged [3][4]. Analysis showed that about 75% of the damages were attributable to axial tension, which occurred mostly at the connecting joints.

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The seismic response of pipeline joints has attracted the attention of many researchers. Earthquake response analysis of a buried pipeline was performed using non-linear time-history analysis [5]. Compression performance of steel pipelines with welded slip joints was obtained by experimental measurements and FEM calculations [6].

Li et al. investigated the formulae for the maximum meridional stress of the longitudinal line per convolution when a bellows joint is subjected to an axial movement, lateral deflection, and angular rotation [7]. The low-cycle fatigue life of bellows using elastic-plastic analysis was predicted by Hamada and Tanaka [8]. Xiang et al. conducted experimental study on the load capacity, deformation capacity, and energy absorption of the bellows joint [2].

FINITE ELEMENT MODEL

In this study, we create a geometrical model of the bellows expansion joint using ABAQUS and mesh it. It is then subjected to compression, tension and bending loading, followed by compression-tension cyclic loading. One end of the expansion joint is fully fixed (encastre boundary condition) to prevent any form of translation or rotation, for ease of analysis.

GEOMETRY

The schematic diagram of the bellows expansion joint is shown in Fig. 1.3. The following geometric parameters were used in generating the model for our case study.

Nominal diameter, D_0 = 250 mm

Wall thickness, t = 5 mm

Number of Convolutions, n = 4

Convolution radius, R = 20 mm

Length of the straight-line segment, h_0 = 15 mm

Pitch, q = 4R = 80 mm

Convolution height, $h = 2R + h_0$ = 55 mm

ABAQUS geometry editing software "Sketcher" is used to design the bellows joint. The model is defined as a 3D shell deformable element.

Using symmetry, one section of the geometry is plotted and revolved through 360° to obtain the complete model. The wall thickness is specified during the section assignment.

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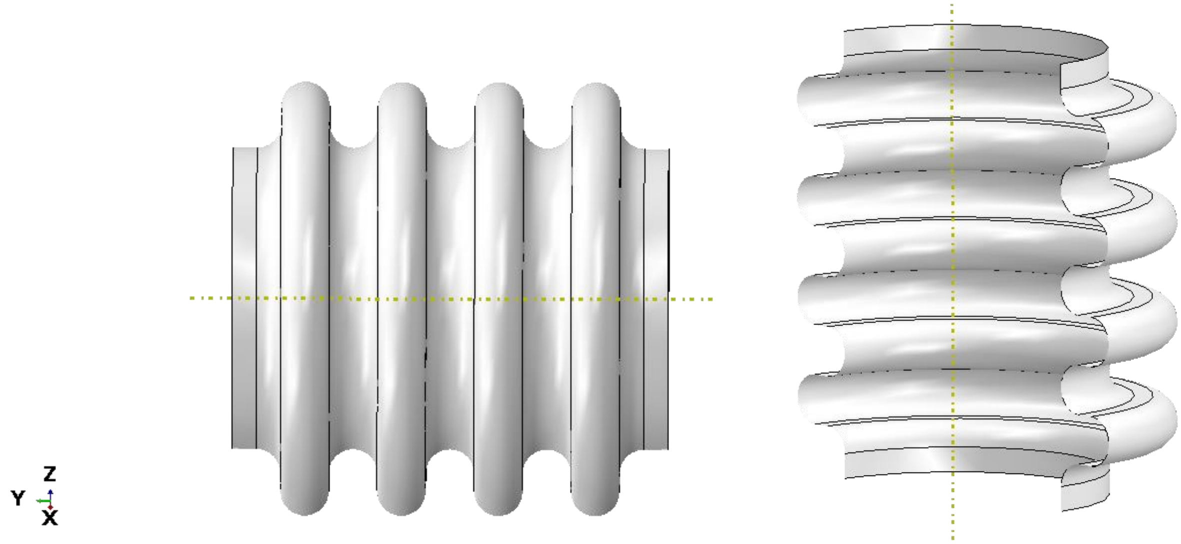

Fig. 2.1. FE Model of bellows expansion joint.

MATERIAL PROPERTIES

The material used for the bellows joint is 304 Stainless Steel. A simplified bilinear stress-strain relationship with strain hardening was assumed, and the material was defined as a kinematic hardening material. The material properties are provided below.

Material Property	Magnitude
Yield Stress (σ)	205 MPa
Poisson's Ratio (ν)	0.3
Young Modulus (E)	195 GPa
Plastic Tangent Modulus (E_p)	975 MPa
Failure Strain	0.8

Elastic and plastic material properties were specified for the material model.

LOADS, BOUNDARY CONDITIONS AND TIME STEPS

The boundary condition specified was full fixing of one end of the bellows joint. This was achieved by checking encastre (all three translational and rotational degrees of freedom).

$$U_1 = U_2 = U_3 = 0$$

$$UR_1 = UR_2 = UR_3 = 0$$

At the other end, compression and tension loads were imposed by specifying displacements in the axial direction of the bellows, while bending load was imposed by specifying displacement in the tangential direction. Single compression, tension or bending time steps were also defined for each of these cases with increment size of 0.05 and automatic stabilization.

Compression

	U_1	U_2	U_3	UR_1	UR_2	UR_3
Case 1	0	64.68	0	0	0	0
Case 2	0	129.36	0	0	0	0

Tension

	U_1	U_2	U_3	UR_1	UR_2	UR_3
Case 1	0	-6.468	0	0	0	0
Case 2	0	-43.12	0	0	0	0

Bending

	U_1	U_2	U_3	UR_1	UR_2	UR_3
Case 1	25.4	0	0	0	0	0
Case 2	64.68	0	0	0	0	0

A four-step cyclic loading was defined by alternately specifying compression and tension displacement loads. Alternate compression and tension time steps were also defined with the encastre boundary condition propagated to all the time steps.

Cyclic

	U_1	U_2	U_3	UR_1	UR_2	UR_3
Initial	0	0	0	0	0	0
Compression 1	0	64.68	0	0	0	0
Tension 1	0	-64.68	0	0	0	0
Compression 2	0	64.68	0	0	0	0
Tension 2	0	-64.68	0	0	0	0
Final	0	0	0	0	0	0

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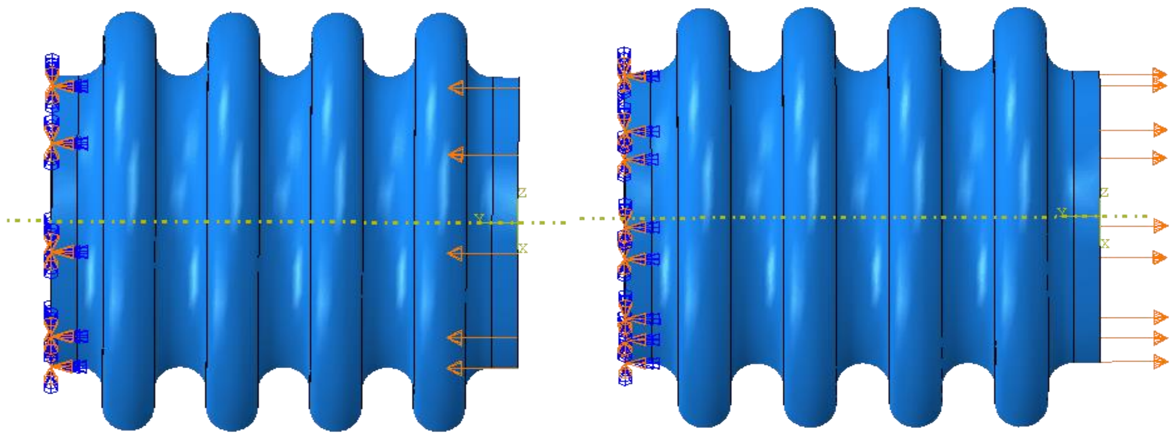

Fig 2.2: (a) Compression and (b) Tension loading cases

MESHING AND INTERACTIONS

Fully integrated standard linear shell element type was used for meshing. The mesh size was set at 6 mm and the number of through-shell-thickness integration points was set at 5.

Quadrilateral element shape was specified with sweep technique. A total of 16,390 linear quadrilateral elements of type S4 were generated in the model.

General contact was used for the contact treatment under large deformation. Friction penalty was defined for all contacts with a friction coefficient of 0.1.

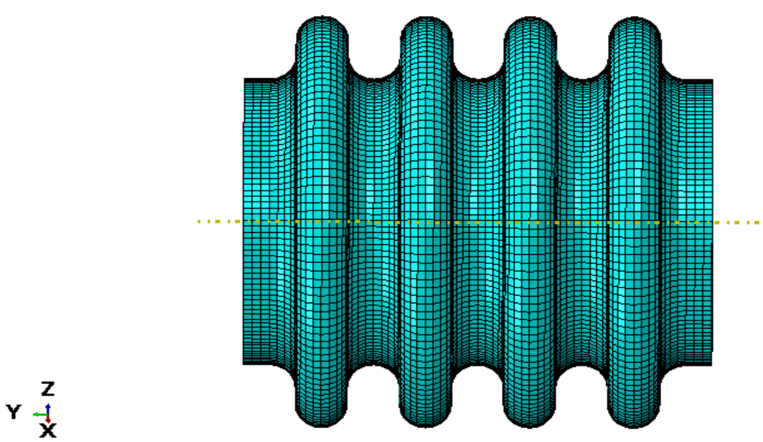

Fig 2.3: Meshing of Bellows Expansion Joint

RESULTS AND DISCUSSIONS

AXIAL COMPRESSION

When the bellows expansion joint was subjected to initial compressive displacement loading of 64.68 mm, the convolutions did not deform uniformly. It was observed that the middle two convolutions were compressed first. With additional load increases, the convolution at the loading end began to be compressed, followed by the convolution at the fixed end. When the displacement was further increased to 129.36 mm, the deformation was distributed uniformly on each convolution.

The contours of Von Mises stress and effective plastic strain are shown below.

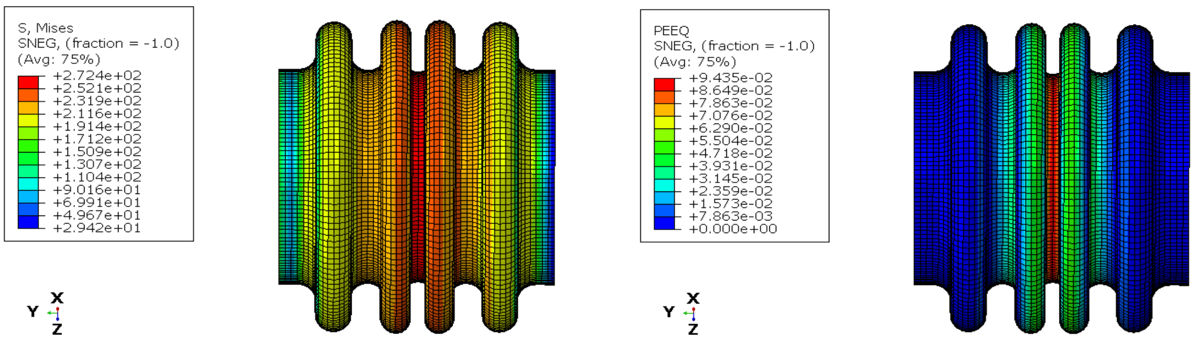

Fig 3.1: Contours of Von Mises stress and effective plastic strain for 64.68mm compressive displacement loading

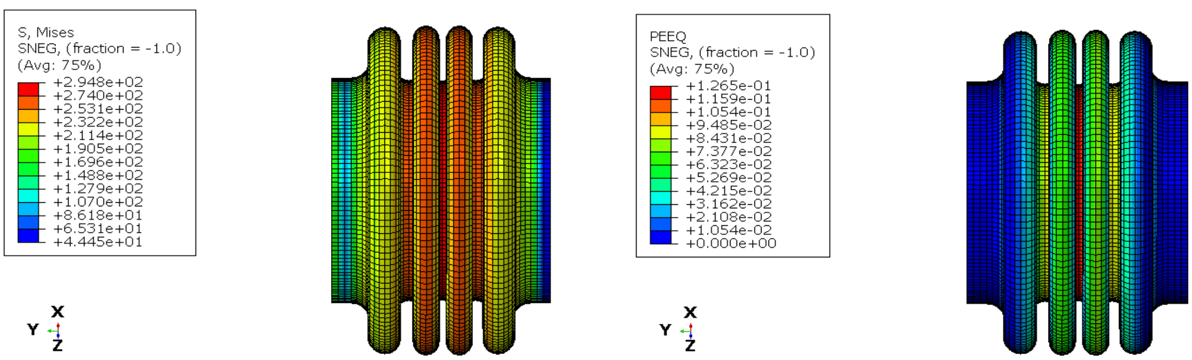

Fig 3.2: Contours of Von Mises stress and effective plastic strain for 129.36mm compressive displacement loading

AXIAL TENSION

When the bellows expansion joint was subjected to tensile displacement loading, it was found that the plastic strain travels through the bellows from the loading end to the fixed end for small displacement. When the displacement is large, the deformation is distributed uniformly on each convolution.

The contours of Von Mises stress and effective plastic strain are shown below.

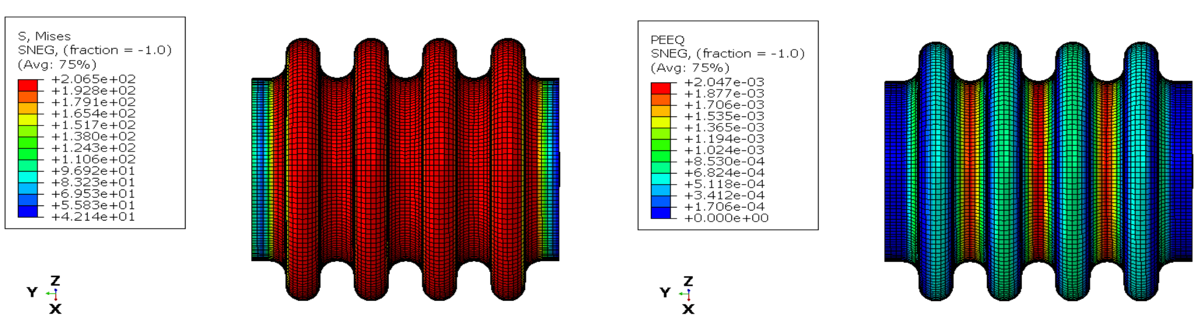

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Fig 3.3: Contours of Von Mises stress and effective plastic strain for 6.468mm tensile displacement loading

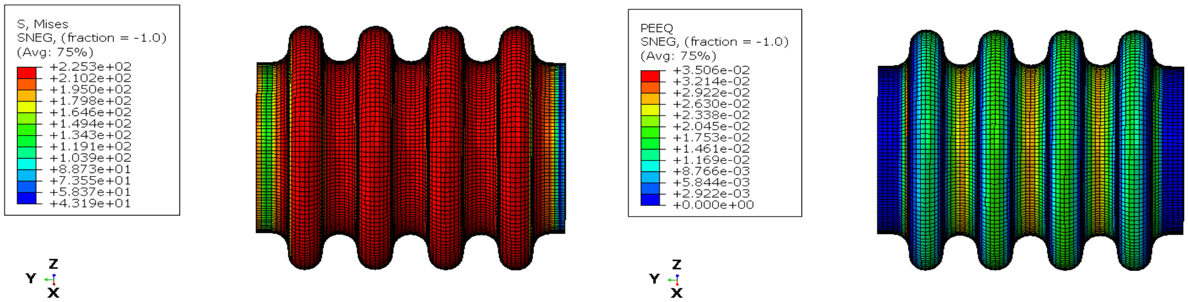

Fig 3.4: Contours of Von Mises stress and effective plastic strain for 43.12mm tensile displacement loading

BENDING

When the bellows expansion joint was subjected to bending displacement loading, the deformation travelled through the bellows from the loading end to the fixed end at the early deformation stage and was unevenly distributed on each convolution of the bellows joint. The maximum effective plastic strain occurred at the root near the loading end. When the angular displacement becomes large, the cross section of the loading end began to be irregular, indicating that the maximum angular displacement had been exceeded.

The contours of Von Mises stress and effective plastic strain are shown below.

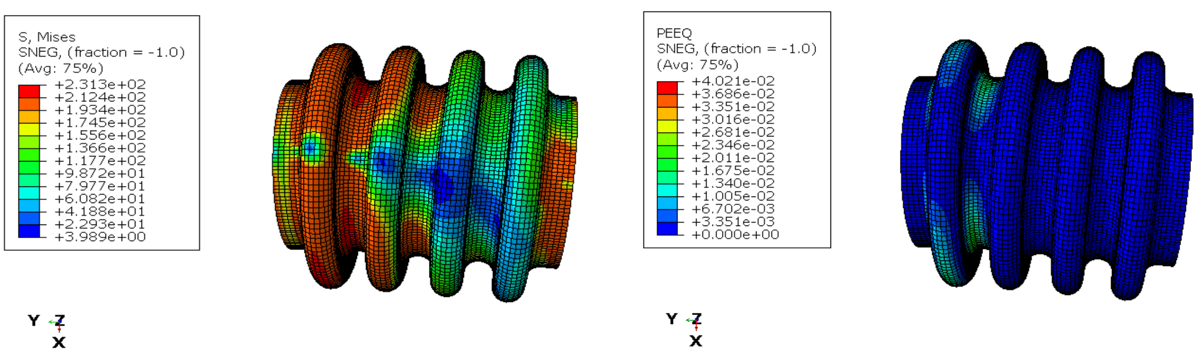

Fig 3.5: Contours of Von Mises stress and effective plastic strain for 25.4mm bending displacement loading

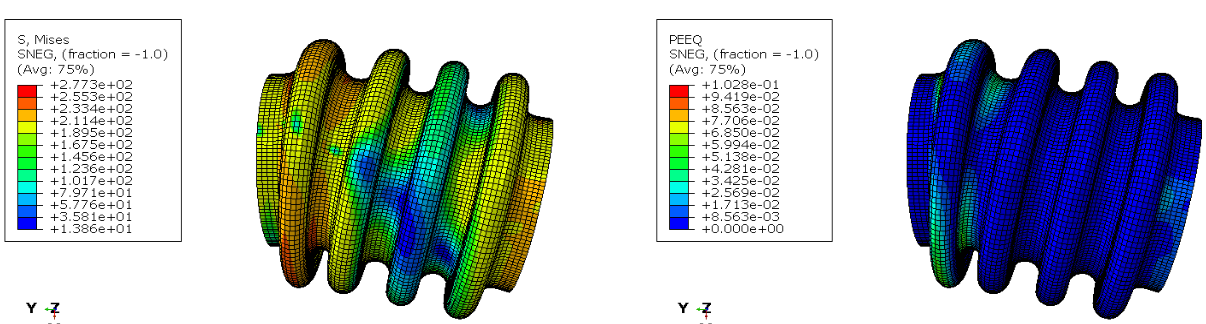

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Fig 3.6: Contours of Von Mises stress and effective plastic strain for 64.68mm bending displacement loading

CYCLIC LOADING

When the multi-bellows joint was subjected to a cyclic loading, the deformation was complicated. In the first compression cycle, the convolutions deformed with the two middle ones having the larger deformation. However, during the second compression cycle, the convolutions at the fixed end had the larger deformation. In the tension cycles, all the convolutions deformed uniformly.

The contours of effective plastic strain for the four deformation cycles, as well as the final state of the bellows upon return to initial installed conditions are shown below.

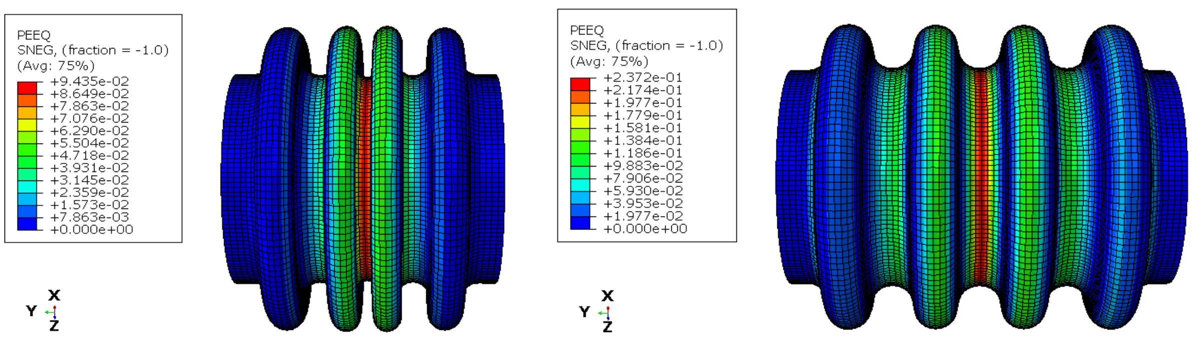

Fig 3.7: Effective plastic strain for (a) first compressive and (b) first tensile cyclic loading

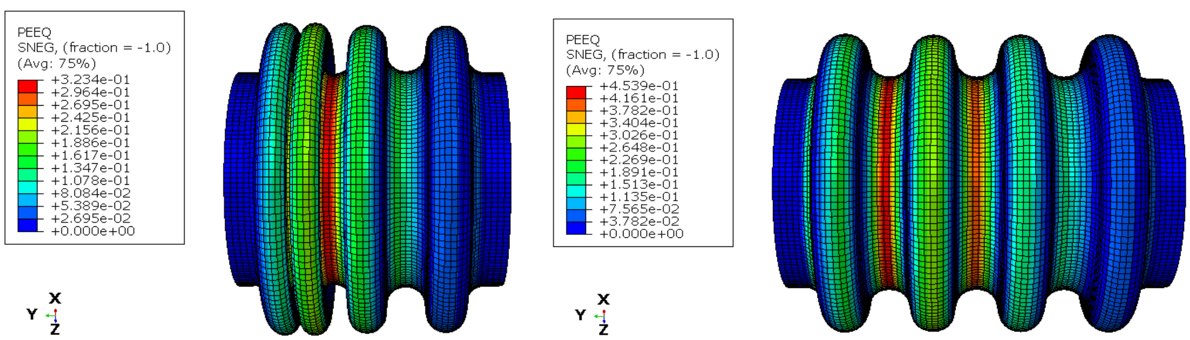

Fig 3.8: Effective plastic strain for (a) second compressive and (b) second tensile cyclic loading

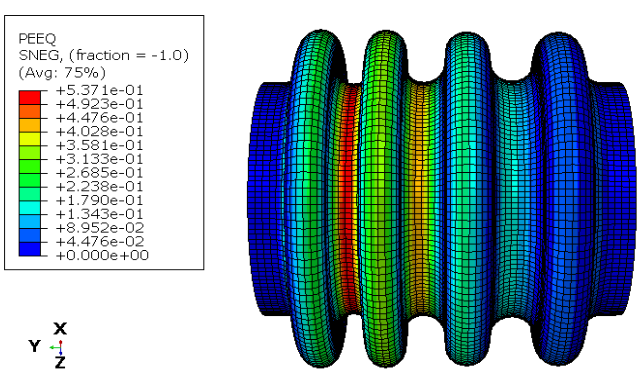

Fig 3.9: Effective plastic strain on return of bellows joint to initial state

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We observe that the bellows joint suffered severe plastic deformation from the cyclic loading, with the deformation gradually increasing from the loading end towards the fixed end.

The Force-Displacement curve for the cyclic loading case is shown in fig. 3.10. The reference point is taken at the loading end of the bellows joint.

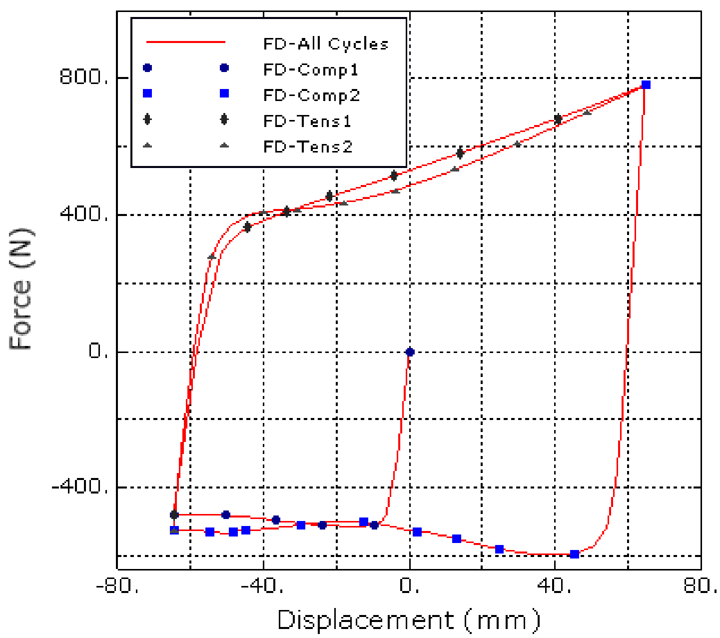


Fig 3.10: Force-Displacement curve for cyclic loading case

Elastic deformation occurs during the first compression cycle after the bellows is subjected to an axial displacement load of 3.234 mm. Plastic deformation occurs thereafter at an axial displacement load of 6.468 mm.

The maximum force of 780.88 kN experienced by the bellows occurs during the tension cycle. This occurs at the maximum axial displacement load of 64.68 mm used for the loading.

We observe that the maximum force for subsequent steps of the cyclic loading increased. This is due to strain hardening of the material property.

The maximum plastic strain occurs between the two convolutions near the fixed end of the model. Analysis of the evolution of plastic strain was carried out on the node with the highest PEEQ value.

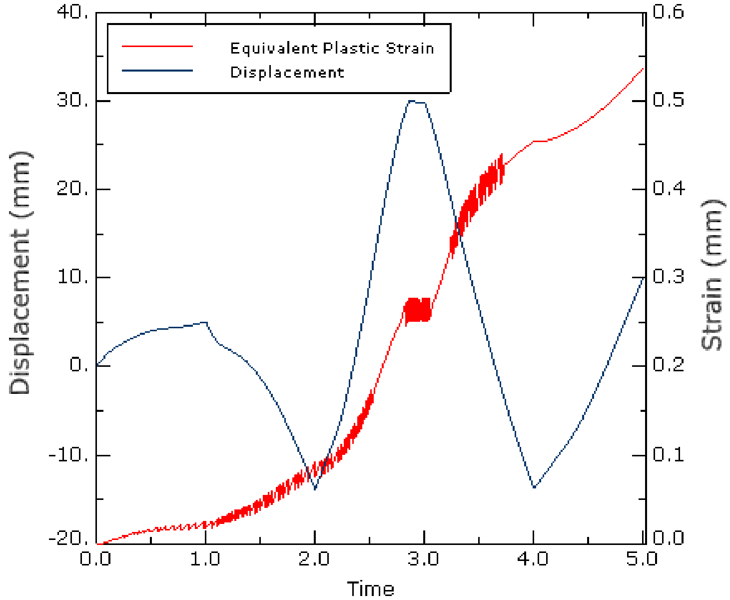
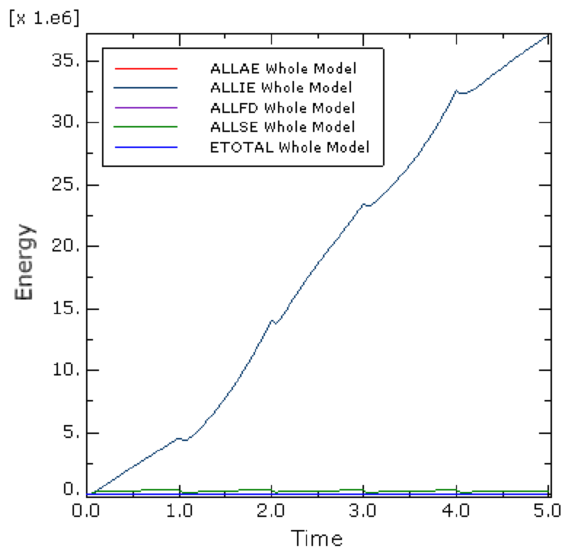


Fig 3.11: Evolution of plastic deformation during cyclic loading

We observe that the plastic deformation rises more rapidly during tension loading than during compression. The deformation is also cumulative over the loading cycles. This indicates that cyclic loading over extended periods of time will eventually lead to plastic failure.



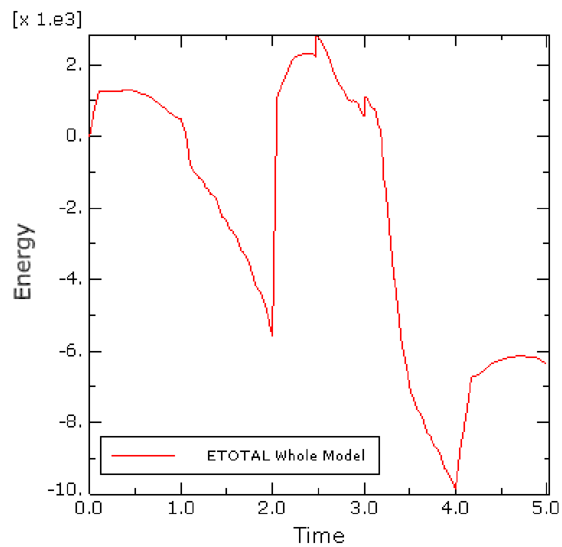


Fig 3.12: Energy plots for whole model

Finally, we observe that the Artificial Energy (ALLAE) of the whole model is very small compared to the Internal Energy (ALLIE), hence, hourglassing is not an issue in the analysis. Also, energy balance is satisfied (conservation of energy) because the total energy remains constant at almost zero.

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VALIDATION OF FEA MODEL

X.M. Xiang, G. Lu, Z.X. Li, and Y. Lv (2017) conducted experimental study on a 4-convolution bellows joint with similar material properties as our model, to determine the deformation characteristics. The test was conducted using an MTS hydraulic servo loading system, with the bellows joint fixed at one end, whilst loading was applied at the other end [2].

During the experiment, when the amplitude of the displacement exceeded 5 mm, bending deformation occurred indicating the onset of plastic deformation. The Force-Displacement curves were obtained for displacement amplitudes below 5 mm. The maximum force, F_{max}, under different displacement amplitudes was found to be approximately proportional to the thickness, t, of the specimen as follows:

$$F_{max} \propto t^{1.5}$$

To validate our model, considering that the maximum force is experienced during tension, sensitivity is conducted on the axial displacement load using two different model wall thicknesses, to establish a relationship between maximum force and wall thickness.

Wall thicknesses of 4 mm and 5 mm respectively, and axial displacement loads of 2 mm, 3 mm 4 mm and 5 mm were imposed on the model.

The results were used to establish a logarithmic relationship between the maximum force and wall thickness for each axial displacement loading as follows:

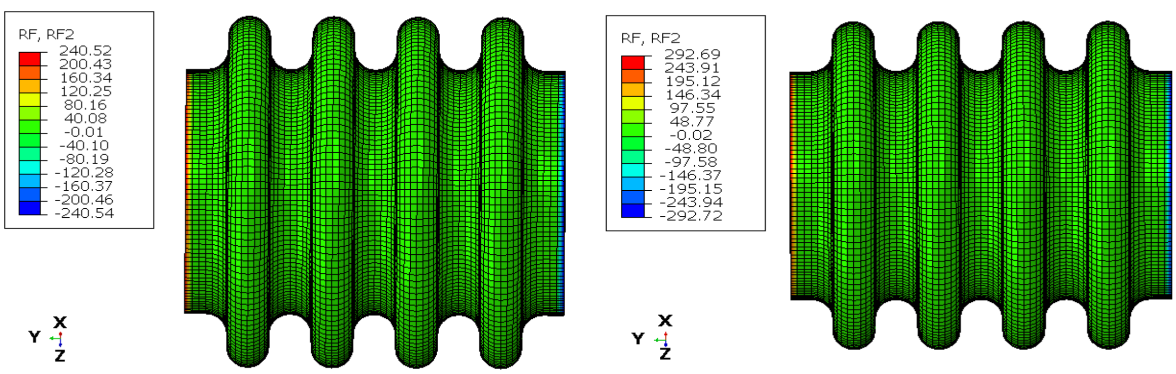

Fig 3.13: Maximum Force at 4mm and 5mm load cases for the 4mm wall thickness model

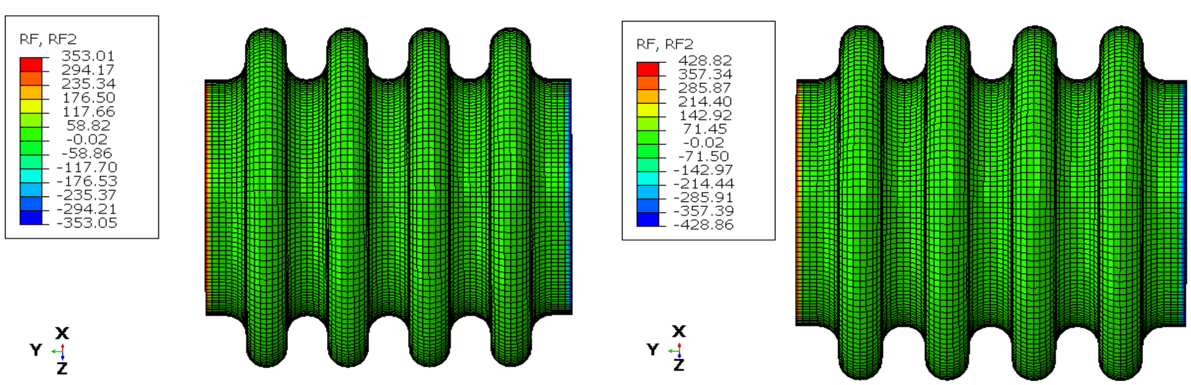

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Fig 3.14: Maximum Force at 4mm and 5mm load cases for the 5mm wall thickness model

	Displacement Load – (2 mm)	**Displacement Load – (3 mm)**	**Displacement Load – (4 mm)**	**Displacement Load – (5 mm)**
$F_{1\,max}$ (kN) – (t=4mm)	121.18	181.09	240.54	292.72
$F_{2\,max}$ (kN) – (t=5mm)	176.84	266.56	353.05	428.86
In (F_2/F_1)/In (t_2/t_1)	1.69	1.73	1.72	1.71

Thus, the maximum force is found to be proportional to the wall thickness with the approximate relationship:

$$F_{max} \propto t^{1.7}$$

The wall thickness exponent in the above relationship, obtained from our FEA is close to the value obtained from experiment, hence, the model is validated.

Also, from our studies, the axial displacement load that resulted in the onset of plastic deformation was determined to be 6.468 mm, (see figure 3.10). This is also similar to the amplitude of displacement that resulted in bending deformation from the experimental studies, indicating the onset of plastic deformation.

CONCLUSION

This study conducted a comprehensive finite element analysis of a bellows expansion joint under large deformation, revealing critical insights into their structural behaviour under various loading scenarios. The analysis highlighted the complex interaction between geometry, material properties, and boundary conditions, demonstrating that large deformation significantly influences stress distribution and the overall performance of the bellows. The finite element model successfully captured the nonlinearities associated with large deformations, providing accurate predictions that aligned well with experimental data and established analytical solutions.

The findings of this study underscore the necessity of incorporating large deformation effects into the design and evaluation processes of bellows expansion joints. Neglecting these factors can lead to underestimations of stress concentrations, particularly in the convolutions, which are prone to failure. This research offers a robust framework for optimizing bellows expansion joint design, ensuring reliability and durability in applications subjected to high stress and strain conditions.

RECOMMENDATION

It is recommended that the results of this FE analysis be further improved on by taking the effect of the weld joint between the bellows expansion joint and the parent material into consideration. This is because weld joints usually have a higher strength than the parent material, and with the heat-affected zone, the strength, ductility, and hardness become non-uniform, affecting the plastic deformation behaviour. Future studies should also expand on this work by evaluating the performance of different bellows configurations and materials to further enhance their applicability across various industries.

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