© October 2025 | IJIRT | Volume 12 Issue 5 | ISSN: 2349-6002

Design, Comparison and Structural Analysis of Metallic Bellows

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***Abstract*—This research paper offers a comparative analysis of stress in cylinders and bellows, aiming to identify the more effective component for particular engineering applications. Through an in- depth evaluation of both components, we have established that bellows demonstrate enhanced performance attributes compared to cylinders. The analysis explores the detailed structural benefits and stress distribution characteristics of both bellows and cylinders. These fundamental traits position bellows as a more efficient and dependable option across various engineering contexts. The results of this study deliver important insights for engineers and designers in choosing the best components for applications requiring resilience, durability, and flexibility.**

I. INTRODUCTION

Metallic bellows are advanced components crafted from thin-walled metal tubes, usually made from resilient materials like stainless steel, brass, or Inconel. These tubes are skilfully shaped into a series of complex convolutions, resulting in a highly flexible structure. This design enables the bellows to experience significant expansion and contraction in response to changes in pressure or temperature, making them suitable for applications that require adaptability and movement. In addition to their flexibility, metallic bellows serve as strong hermetic seals, effectively preventing the escape of fluids or gases. This essential sealing function, along with their sensitivity to pressure variations, makes them vital in a wide array of industrial applications. These applications include precision pressure sensing and transmission systems, essential components for accommodating thermal expansion and contraction in complex piping systems, and the development of flexible connectors that not only facilitate movement but also absorb vibrations, thereby ensuring the integrity and reliability of critical systems. Metallic bellows serve as essential elements in various industrial sectors that demand flexibility, pressure sealing, and vibration isolation. Their applications extend to fields including aerospace, automotive, nuclear, chemical processing, and energy production. A considerable amount of research has been undertaken to explore the mechanical characteristics, design factors, material choices, and fatigue performance of metallic bellows, which has greatly enhanced their optimization for a wide range of uses.

Fig.1.Metallic Bellows

II. LITREATURE SURVEY

The design of metallic bellows has been the subject of considerable investigation, particularly concerning their structural performance under diverse loading scenarios. The configuration of the bellows, which includes factors such as the number of convolutions, the shape of the convolutions (for instance, helical or convoluted), and the thickness of the walls, is essential in influencing their flexibility, strength, and fatigue lifespan. Initial research conducted by Williams (1990) and Mench et al. (1993) introduced analytical models aimed at forecasting the deformation characteristics of bellows subjected to axial and radial forces. These models typically treated bellows as thin-walled cylindrical entities and employed classical elasticity and plasticity theories to articulate their mechanical behaviours. In more recent times, finite element analysis (FEA) has emerged as a key technique for examining the deformation and stress distribution within metallic bellows. Numerical investigations by Song et al. (2010) and Wang et al. (2015) have illustrated FEA's capability to anticipate stress concentrations, failure mechanisms, and deformation under intricate loading conditions. FEA has proven particularly useful in elucidating the impacts of different convolution shapes, material characteristics, and boundary conditions on the operational efficacy of bellows. Furthermore, these studies have underscored that the response of bellows to axial compression, pressure, and torsional loads is significantly non-linear, necessitating the use of more advanced computational methods. The selection of materials for metallic bellows is primarily influenced by the requirements for high strength, fatigue resistance, and corrosion resistance. Stainless steel, particularly the 300-series alloys, is widely utilized for general applications due to its favourable combination of mechanical properties and resistance to corrosion. In environments characterized by high temperatures and aggressive conditions, high-performance alloys such as Inconel, Monel, and titanium are often preferred for their capacity to retain strength and flexibility under severe circumstances. Research conducted by Song et al. (2007) investigated the fatigue characteristics of bellows constructed from various materials, revealing that while stainless steel demonstrated adequate performance, alloys like Inconel offered enhanced resistance to thermal aging and fatigue in high-temperature settings. Furthermore, the application of advanced coatings and surface treatments has been studied to enhance the corrosion resistance of bellows. For instance, a study by Matsuoka et al. (2014) analysed the impact of protective coatings, including nickel or chromium plating, on the functionality of bellows in challenging environments. These coatings significantly mitigate the effects of corrosion, thereby prolonging the lifespan of bellows, particularly in sectors such as chemical processing facilities or offshore platforms. Fatigue resistance is a crucial determinant of the performance and durability of metallic bellows. The cyclic deformation and repetitive loading associated with numerous applications result in a gradual buildup of damage, ultimately leading to failure over time. Initial research by Smith (1987) introduced analytical techniques for predicting the fatigue life of bellows, taking into account material characteristics, convolution geometry, and loading conditions. Subsequent studies by various researchers enhanced these models by integrating more intricate loading scenarios, such as the impacts of thermal cycling, pressure variations, and multi-axial loading. A considerable amount of research has been dedicated to understanding the influence of thermal cycling on the fatigue life of bellows. For example, Keane et al. (2018) illustrated that temperature variations induce additional stresses within the bellows' convolutions, thereby hastening the initiation and propagation of cracks. In high-temperature environments, such as those encountered in gas turbines or nuclear reactors, bellows experience extreme thermal expansion, which can markedly diminish their fatigue life. Fatigue testing conducted by these researchers validated that elevated temperatures can reduce the yield strength of bellows materials, leading to premature failure. Metallic bellows are employed across various sectors where flexibility and effective sealing are essential. In the aerospace industry, they are vital components in actuators and flexible couplings, facilitating movement while preserving pressure integrity. Within the nuclear and chemical sectors, these bellows are integral to piping systems, enabling the absorption of thermal expansion and accommodating vibrations, all while ensuring a leak-proof operation. Additionally, bellows are crucial in vibration isolation systems, as their capacity to absorb both axial and radial motion mitigates the transmission of undesirable vibrations to sensitive equipment. The performance of metallic bellows is significantly influenced by environmental factors such as pressure, temperature, and exposure to corrosive substances. Research indicates that bellows subjected to high-pressure or vacuum conditions may undergo alterations in their deformation characteristics, as the forces induced by pressure impact the convolution geometry and material properties. Investigations conducted by Matsuoka et al. (2014) revealed that exposure to harsh chemicals or moisture accelerates corrosion, thereby compromising the structural integrity of the bellows. In response to these challenges, researchers have concentrated on creating bellows with enhanced sealing properties and corrosion-resistant materials, including innovative hybrid designs that integrate both metallic and non-metallic layers. In recent years, the emergence of sophisticated manufacturing methods, particularly additive manufacturing (3D printing), has paved the way for innovative designs in metallic bellows. This technology facilitates the creation of bellows featuring intricate geometries and customized properties, which can enhance both performance and cost efficiency. Research conducted by Zhang et al. (2020) highlighted the capabilities of additive manufacturing in producing bellows with optimized convolution shapes and materials, resulting in improved fatigue resistance and increased customization for various applications. Furthermore, the incorporation of smart materials, such as shape-memory alloys (SMAs), into bellows design has been investigated. SMAs provide the opportunity to develop bellows that can adapt dynamically to fluctuating environmental factors, including temperature and pressure, thereby enhancing their versatility and performance in real-time scenarios.

III. EJMA STANDARD

Fig.2. EJMA Standard

EJMA= EXPANSION JOINT MANUFACTURING ASSOCIATION.

The Expansion Joint Manufacturers Association (EJMA) standard is a comprehensive set of guidelines and best practices for the design, manufacturing, and installation of expansion joints. EJMA, established in 1959, provides industry-standard specifications to ensure the efficient and safe performance of expansion joints across various sectors like construction, plumbing, and engineering.

The EJMA standard focuses on ensuring that expansion joints can effectively absorb movement due to thermal expansion, seismic forces, vibrations, and other stresses in systems such as piping, HVAC, and bridges. It covers material selection, design criteria, testing, and installation methods. The guidelines include calculations for stress, pressure, and movement limits, ensuring the joint maintains its function over time while reducing the risk of failure.

Key aspects of the EJMA standard include:

- Material Specifications: Materials like elastomers, metals, and composites are chosen for durability and flexibility.
- Design Criteria: Proper dimensions and allowances for axial, lateral, and angular movements.
- Performance Testing: Verification of the joint's ability to withstand pressure, temperature variations, and environmental factors.
- Installation Guidelines: Ensuring proper installation to maintain long-term reliability.

EJMA standards are widely used globally to ensure that expansion joints meet industry safety, performance, and quality benchmarks, making them crucial in minimizing risks and improving system longevity.

3.1 MOVEMENT CAPABILITIES:

i. Axial Compression: The shortening of the bellows length resulting from the expansion of the piping.

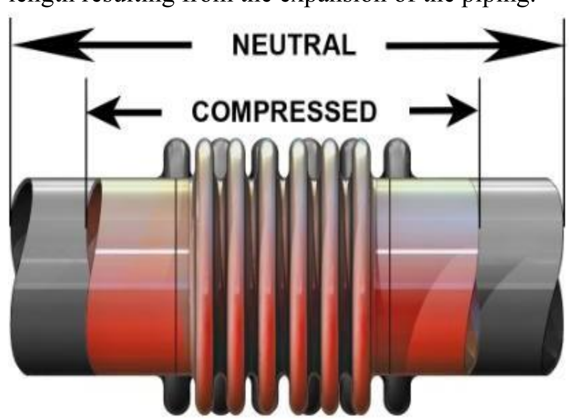


Fig.3. Axial Compression of bellows

ii. Angular Rotation: Bending about the longitudinal centre line of the expansion joint.

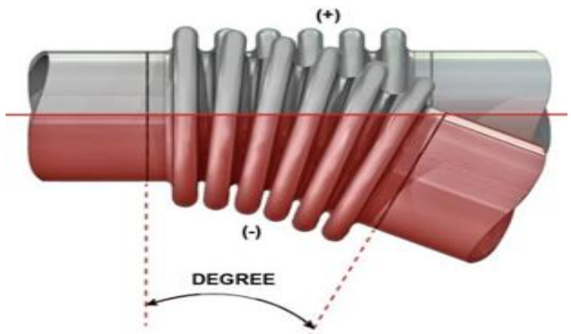


Fig.4. Angular Rotation of bellows

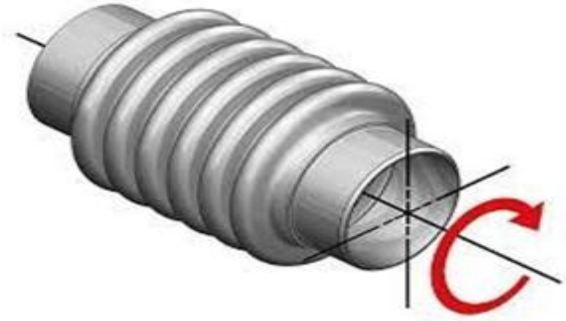


Fig.5. Torsional movement of bellows

iii. Torsion: Twisting about longitudinal axis of the expansion joint can reduce bellows life or cause expansion joint failure and should be avoided. Expansion joints should not be located at any point in a piping system that would impose torque to the expansion joint as a result of thermal change or settlement

iv. Axial Extension: Increase of the bellows length due to pipe contraction.

Fig.6. Axial Extension of bellows

v. Lateral Offset: Transverse motion which is perpendicular to the plane of the pipe with the expansion joint ends remaining parallel.

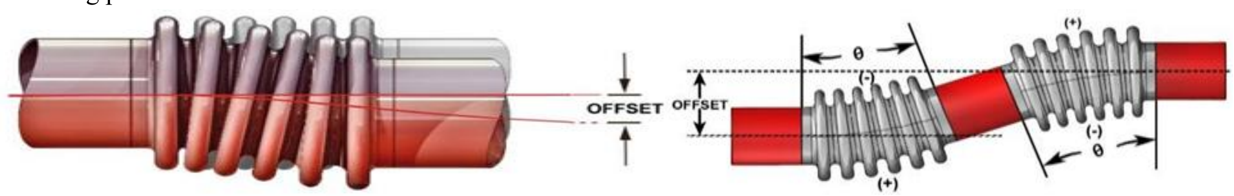


Fig.7. Lateral movement of bellows

IV. DESIGN OF A METALLIC BELLOWS

4.1. DIMENSIONAL REQUIREMENTS

Inner Diameter (ID): This is the diameter of the opening or the internal size of the bellows that allows for insertion into a pipe, tube, or other machinery component. The inner diameter must match the connection size of the system in which the bellows will be used.

Outer Diameter (OD): The external diameter of the bellows, which is particularly important when considering how much space the bellows will occupy in the assembly. The OD needs to be matched to the surrounding components to ensure the bellows are adequately supported and securely mounted.

Length: This refers to the overall length of the bellows when they are extended or compressed. The length is important to accommodate the required stroke, which is the range of motion the bellows need to absorb (i.e., the maximum expansion and contraction).

Stroke or Travel: The stroke is the amount of movement the bellows can undergo in both directions (compressed and expanded). This depends on the specific application’s needs, such as accommodating thermal expansion or absorbing mechanical movement.

Wall Thickness: The thickness of the bellows' material influences its strength, flexibility, and durability. Thicker walls generally provide more strength but less flexibility, while thinner walls allow for greater movement but are less resistant to high pressures.

Number of Folds and Pitch of Folds: The number of folds in the bellows affects its flexibility and the amount of movement it can absorb. A higher number of smaller folds increases flexibility, while fewer larger folds offer less flexibility but can handle greater stresses. The pitch (distance between the folds) influences both the bellow's flexibility and the amount of travel.

SPECIFCATION	TYPICAL RANGE	REMARKS
Material	Metal, rubber, plastic, Fabric	Depends on environment and application
Inner Diameter	10mm-1000mm	Customizable
Outer Diameter	20mm-1200mm	Customizable
Length	Varies with strokes	Depends on movement range
Pressure Rating	10 bar to 1000 bar	Depends on material
Temperature Rating	-40 degrees C to 1000 degrees C	Varies by material
Flexibility	Low to High	More fold= more flexibility
Fatigue	10^3-10^6 Cycles	Varies with pressure and material
End Fittings	Flanged, Clamped, Threaded	Depends on system convection

Table.1. Summary of key specifications

4.2 DIFFERENT TYPES OF CONVOLUTIONS

Convolution shapes	Waveform structure	Mechanical properties
U-shaped		Fatigue stresses in U-shaped bellows caused by repeated bending, leading to material fatigue and potential failure.
Semitoroidal		Bending stresses in semitoroidal bellows result due to its bending and flexing motion. These stresses can lead to material fatigue over time due to the cyclic nature of bending stresses.
S-shaped		Fatigue stresses in S-shaped bellows arise from cyclic loading, potentially causing material fatigue and failure. These stresses primarily affect the convolutions and the apex of the bellows.
V-shaped		V-shaped bellows experience significant bending stress along their convolutions and apex due to repeated flexing.
Welded disk		Fatigue stresses in welded disk bellows arise from cyclic loading and can lead to material fatigue and potential failure. These stresses are most significant at the welded convolution regions.

V. DESIGN OF BELLOWS

5.1. DIMENSIONS

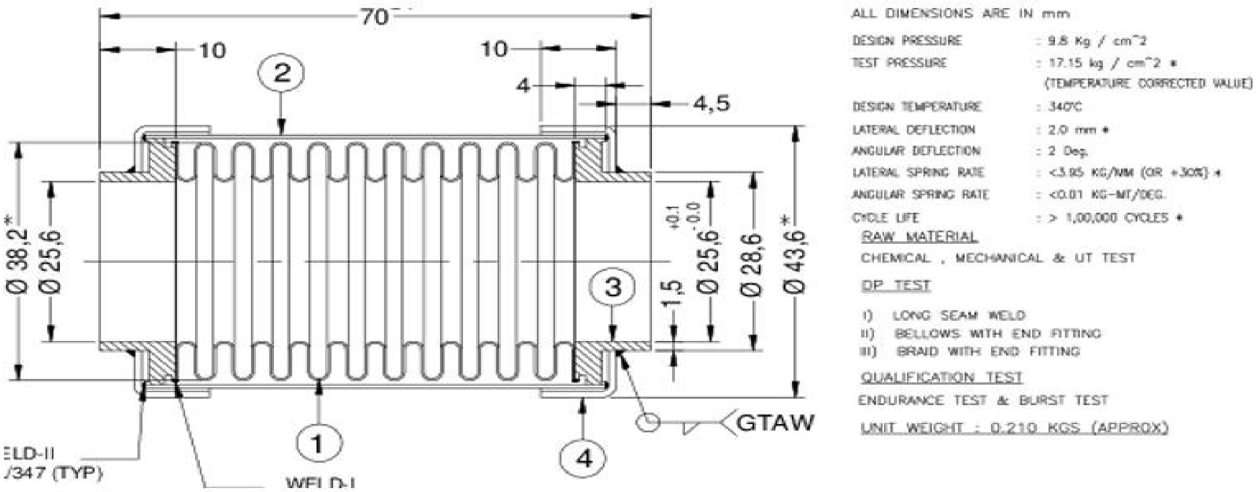


Fig.8. Dimensions of the designed bellow

The above bellow schematic was dimensioned based on the EJMA standard. Initially, the dimensions were set and further the same dimension were implemented on CAD software known as INVENTOR and the component was further designed using various commands like fillet, offset, extrude, revolve, etc for 3D modelling which resulted in the following CAD geometry.

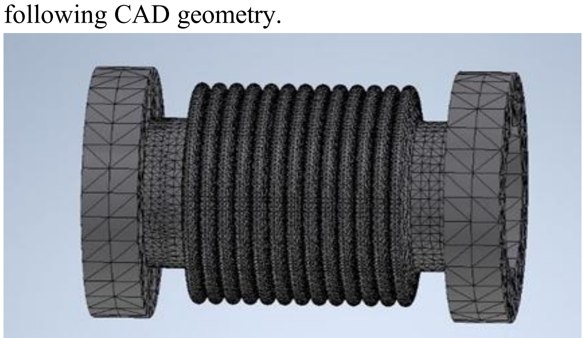


Fig.9. Assembled Bellow

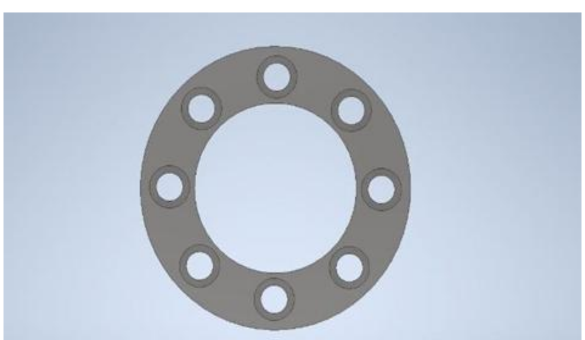


Fig.10. Flange Support

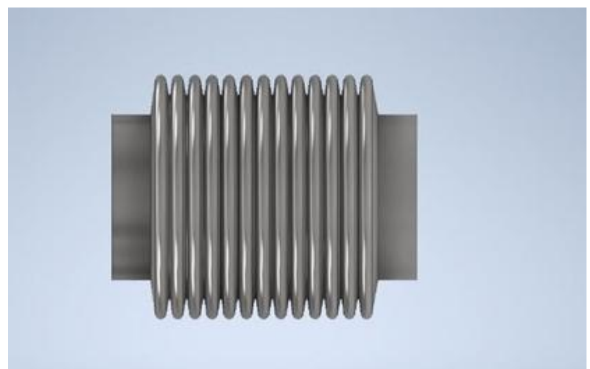


Fig.11. Designed Bellow

To analyse the advantage of a bellow another cylinder was designed with the same dimensions to understand the stress concentration on bellows and cylinders individually.

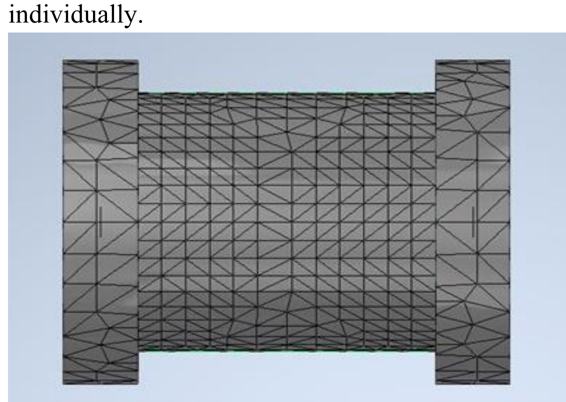


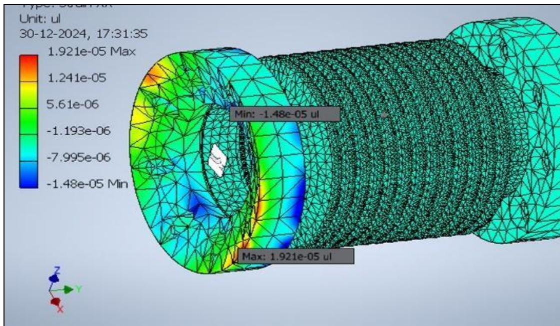
Fig.12.Designed Cylinder

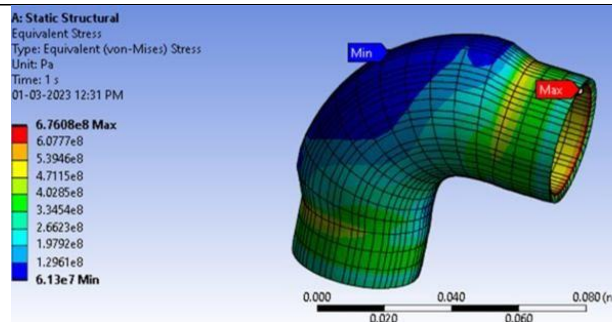
5.2 INPUT PARAMETERS

PARAMETER	MAGNITUDE	UNIT
Pressure	10	Bar
Temperature	10	Degree Celsius (°C)
Material	Stainless Steel	-

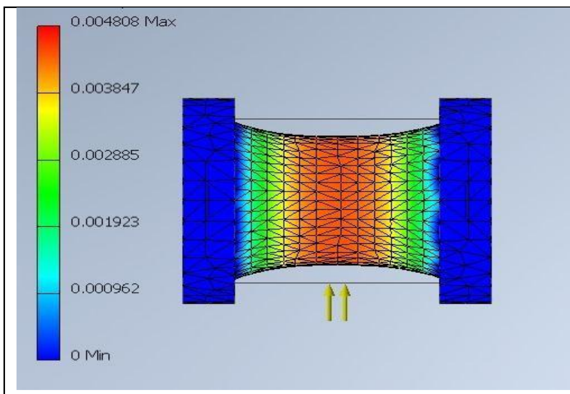
VI. VALIDATION

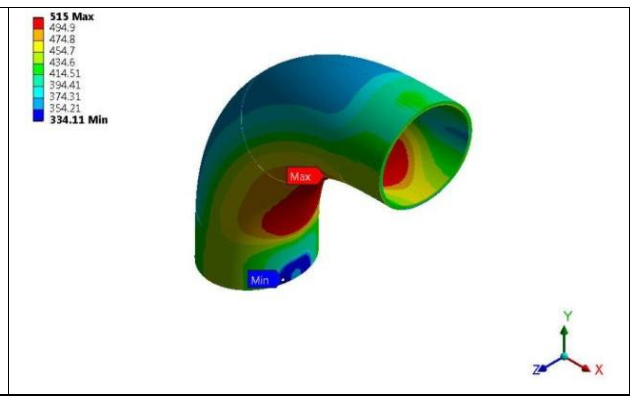
6.1 Stress acting on elbow joint with bellow:



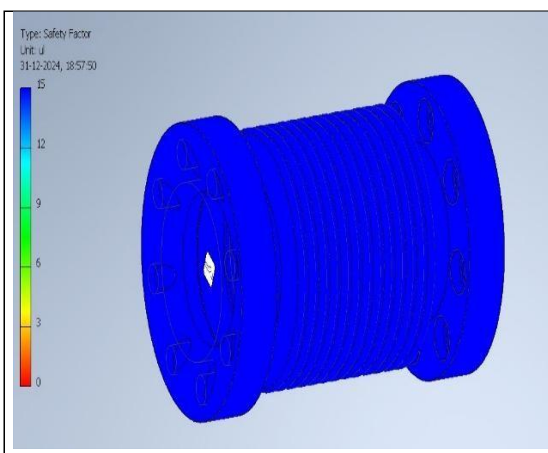


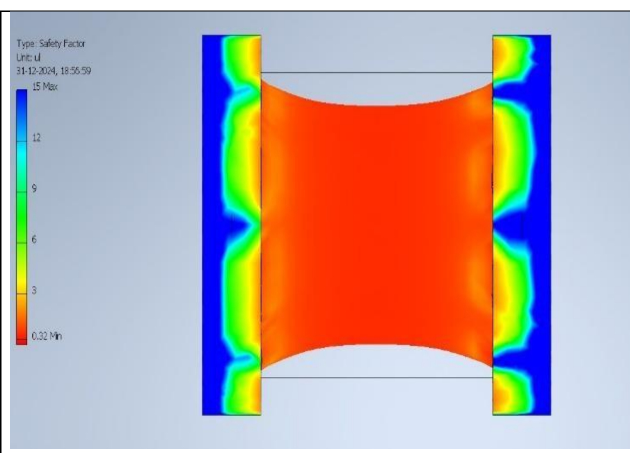
6.2 Stress Acting on elbow joint without bellow:





6.3 FACTOR OF SAFETY





VII. RESULT AND DISCUSSION

With the help of the above graphical colour maps it can be concluded that the stress concentration that is acting on the elbow joint is more when the elbow is attached to a cylinder. On the other hand, when the same cylinder geometry is attached to a bellow the stress acting on the elbow joint is very less. Hence, it can be concluded that the use of bellow makes the stress evenly distributed throughout the geometry.

Further, considering the case of cylinder the, it tends to deform from its original shape with the same input parameters as that of a bellow which again proves the use of bellows is much preferred. Considering the same of factor of safety the bellow is more superior in terms of safety. The reason being the cylinder tends to deform from its original position which might result in fracture which will further result in leaks. Hence, it can also be concluded that bellows also act as seal and prevent internal pressure leaks.

Bellows are flexible, hermetic seals commonly used in various industries. They are essentially thin-walled, convoluted metal tubes that expand and contract in response to pressure or temperature changes. This flexibility allows them to accommodate movement and vibration in piping systems. Bellows find applications in pressure sensors, expansion joints, and flexible

connectors. They offer a reliable seal while providing flexibility and accommodating thermal expansion and contraction.

REFERENCES

[1] Wankhede, S.D. and Gawande, S.H., 2023. Design and Analysis Aspect of Metal Expansion Bellows: A Review. Forces in Mechanics, p.100244.

[2] Xiang, X.M., Lu, G., Li, Z.X. and Lvhttps://www.document-center.com/standards/show/EJMA-STANDARDS/history/8TH%20EDITION, Y., 2017. Finite element analysis and experimental study on a bellows joint. Engineering Structures, 151, pp.584-598.

[3] Anderson, W.F., 1964. Analysis of stresses in bellows. part i. design criteria and test results (No. NAA-SR-4527 (Pt. 1)). Atomics International. Div. of North American Aviation, Inc., Canoga Park, Calif. US).

[4] Lin, J., Wang, X., Lei, Y., Ding, J., Li, K. and Guo, F., 2021. Residual stress analysis and measurement in multi-layer bellows. Journal of Manufacturing Processes, 72, pp.179-194.

[5] Krovvidi, S.K., Goyal, S. and Bhaduri, A.K., 2019. Design and analysis of formed bellows for nuclear applications-Case study. Procedia Structural Integrity, 14, pp.855-863.

[6] Becht, C., 2000. Behavior of bellows (Doctoral dissertation, Memorial University of Newfoundland).

[7] https://www.document-center.com/standards/show/EJMA-STANDARDS/history/8TH%20EDITION