A Review on Application of Bellows Expansion Joints and Effect of Design Parameters on System Characteristics

A. Vinoth^{*}, B. Vignesh, Lakshya Khurana, and Aditya Rai

Department of Mechanical Engineering, SRM University, Kattankulathur - 603203, Tamil Nadu, India; avinot@gmail.com

Abstract

Objectives: A bellows expansion joint is an assembly of two or more bellows which help to tackle expansion or contraction in the system where it is designed to fit in. It was found, various independent researchers did lot of research in the design and geometry of bellows expansion joint but a review of all is scare, we have put forth the different possible features of bellows design in this paper. **Methods/Analysis:** The bellows, consisting of one or more convolutions, are designed to offer further agility in the configuration of piping structures and pressure vessel applications involving thermal expansion and relative movement in system. Numerous researchers have conducted studies on bellows expansion joints with the help of standards such as ASME and EJMA. They have wide applications and are understood as a significant. Thus various parameters pertaining to the design of bellows expansion joints, which affect the characteristics of the system, have been reviewed. **Findings:** From this review, it can be said that for all the design condition, there was not bellow geometry or design parameters are superior. Under such designs based on the standards, it is expected to perform exhaustive analysis involving sound engineering judgment. Meanwhile, the choice of bellows expansion joint is sufficiently broad depending upon the applications. **Improvement:** Certainly there is still room for new design principles and analysis based on analytical, experimental and FEA studies. Particularly, study of bellows subjected to torsions may be done as little is found in the literature and the existing standards.

Keywords: Bellows Expansion Joints, Buckling, Fatigue, Shape of Convolution, Vibration

1. Introduction

Often, thermal expansion, vibration, equipment movement, or abrupt changes in system pressure leads to detrimental movements in a piping structure. These changes affect the system and thus calls in for an additional mechanism to balance the movements and pressure changes in the piping system, ducts or pressure vessels, and the supporting medium. This additional supporting element is called the bellows expansion joint comprising of one or more convolutions (bellows) with ends anchored to the pipeline. These compensators are devised to take in movements that occur in a stationary position, angular rotation, lateral deflection or any combination of the three.

Numerous researches have been conducted on bellows expansion joints, of which the work of Andersson^{1,2} is considered a breakthrough. His theoretical calculations form the basis of other publications and standards such as the pressure vessels and piping codes of ASME. However, the most authoritarian and comprehensive text is that of the Expansion Joint Manufacturers Association (EJMA)³, which combines the knowledge and field experience of leading manufacturers of bellows expansion joint.

This paper presents a review of structural analysis of bellows expansion joints with emphasis on application areas and effective parameters involved in its design

2. Application Areas

Bellows expansion joints have wide application in heat exchangers, automobile exhaust system, piping system, refineries, power stations, satellite launch vehicles, chemical plants, HVAC systems and pressure vessels.

2.1 Automobile Exhaust System

Running engines cause vibration of the exhaust system as well as other systems. Due to rolling of the engine, the exhaust system is subjected to axial and bending deflections which necessitate the use of bellows expansion joint in the system. Installation of bellows also assures proper functioning of catalytic converter as any failure would significantly affect emissions.

Broman et al.⁴ have investigated a procedure for modelling bellows expansion joints of automobile exhaust system by Finite Element Analysis (FEA) using beam element in the I-DEAS software. They conducted a study on the behaviour of the bellows when subjected to bending in addition to its axial and torsion characteristics. They also analysed their interface with the other components of the system. A gas-tight bellow with U-shaped convolutions was considered. The axial, bending and torsional stiffness were calculated using EJMA formulae. The governing differential equations were also formulated. These equations were solved by creating beam finite model of bellows with fixed boundary conditions at both ends. The procedure devised was verified by Investigational conclusions from other researchers: Jakubauskas & Weaver^{5,6}. They were found to be in good agreement indicating that bellows can be modelled by beam elements. It was also pointed out that torsional frequencies are elevated than axial and bending natural frequencies, but they are significant in the case of a curved exhaust system.

2.2 Nuclear reactor

The FBTR's (Fast Breeder Test Reactor) starting, power control and the shutting down process are managed using a Control Rod Drive Mechanism (CRDM). They have bellows made of metal to isolate the coolant and vapour of sodium which is radioactive, from the upper regions of CRDM and containment wall.

Shaikh et al.⁷ investigated the cause of failure of bellows made of AM 350 grade steel used in the CRDM when subjected to helium leak testing. The heat treatment done did not follow ASTM recommended practices, since tempering was done at 848 K instead of 728-813 K recommended. The bellow was kept in storage for 13 years, wrapped with corrugated paper and a free covering of polyethylene sheet. After 6 years, an air tight bag with silica gel was used in repackaging the same. After rigorous testing, the bellow failed the helium leak test, due to a leak on a single convolute. A chain of metallurgical investigations were performed on the bellows at high magnification using Scanning Electron Microscope (SEM). EDAX analysis of corrosion products was also done which showed that the pits contained chlorides, potassium, silicon and calcium. Due to the humid coastal climate of Kalpakkam, AM350 bellows often fail due to crevice corrosion near the welding points. It was found that that the reason behind the failure of bellows was due to the corrosion in the pits in a hot, humid and saline environment for a long time. It is suggested that suitable storage measures, by applying lubricants like grease and by using air tight packets with silica gel would prevent such failures in the future.

2.3 Aerospace

For the purpose of transferring liquid fuel and oxidizer propellant tanks of satellite launch vehicle austenitic AISI 304L stainless steel bellows are used. It is made by TIG welding, a ring forged and machined with cold thin rolled sheets as plies and then it is subjected to post weld pickling and passivation techniques.

Jha et al.⁸ came across leakage issues in such bellows usually along the fusion line of ring to ply weld. The synergistic effect of chloride ions from saline environment and thermal stresses from welding were identified as the main cause of failure. Difference in heat dissipation and inappropriate control of heat input are the main causes of failure with non-uniform weld bead; the other results were attributed to the lack of fusion of plies and adverse microstructure. Viewed with stereo-microscope at 40x magnification showed that majority of the weld on the circumference has a non-uniform weld bead which is independent of the weld parameters lead to unequal heat input causing complex thermal stress distribution (also leading to cracks on ring surface) and it was observed that many pieces of weld were cut off along the bellow axis. For the proper welding of the bellow uniform heat input and adequate fusion are very important. Proper run of welding arc, fixturing, adequate heat input, and ascertaining that no strip is in between plies are recommended.

2.4 Piping system

Corrugated flexible metal hoses are an integral part of liquid transport system, protective hose for electrical cables, vibration de-coupler in exhaust systems, medical equipment, measuring and control equipment. They can endure corrosion, high pressure and offer maximum leak tightness which is appropriate for the transmission of hot and cold substances. Pierce & Evans9 took a hose and filled it with water, and then a K-bottle of nitrogen was used as the pressure agent. They used two video recorders to analyze the fine points like internal pressure and the protraction of the test hose; this record could be studied as well as be used to add value to a Finite Element Model (FEM). The inference from the study was used to build a FEM and also to find the root cause of the system failure. The burst failure happened at a lower pressure as the slit between the braid and bellows enlarged. The contact support from the braiding does not crop up until the internal pressure is higher than what is in a set up that has a smaller slit. So, there is a need for the bellows to endure the stress without any support from the braid. Thus, the internal pressure capability of non-reinforced bellows is considerably lower than reinforced bellows. This pressure is directly proportional to the coefficient of friction and it tends to increase as the coefficient of friction rises. Upon combining the physical facts that caused break down and the FEM, the following conclusion relating to the failure is put forth: The primary two reasons that result in the bursting of the bellows preceding braid failure are the existence of too much gap and if the coefficient of friction is too little. This failure will represent the in-plane squirm failure due to lack of support from the braid.

2.5 Petrochemical Plant

In petrochemical refineries, a Pressure Safety Valve (PSV) is used to release substance when the pressure or temperature exceeds preset limits. It is a direct loaded safety valve in which the inner components are protected against the effects of the fluids by a bellows. The bellows is such that it compensates for influences of backpressure.

Panda et al.¹⁰ investigated a series of three continuous instances of failure of bellows in a particular PSV. The PSV, with 316L grade austenitic stainless steel bellows, was placed on vacuum gas oil service vessels in a hydrocracker unit. Metallurgical study of the failure of bellows showed that Stress Corrosion Cracking (SCC) was the cause behind the failure. The SCC was found to be initiated in the bellows due to high concentrations of chloride ions in the granulated activated carbon of Heavy Poly Nuclear Aromatics (HPNA) absorption bed located upstream the process flow line. The patch up work of the HPNA bed revealed that the source of chloride ions was attributed to the deposition of carbon soot on the body of the PSV. The intergranular nature of the crack propagation was attributed to the presence of stress induced martensite phase in the microstructure of the formed sheet material.

The turbo expander generates electricity using the hot effluent gasses from the Fluid Catalytic Cracking unit (FCC) in petrochemical plants. A movement test was conducted on a metal bellows expansion joint which was designed according to the EJMA code, with diameters ranging from 0.457 to 2,898 mm of Inconel 625 LCF materia¹¹. Sixteen hinged and gimbal bellows were tested using a digital dynamometer. The expansion joint was pressurized using water. The expansion joints were tested in steps of 0.5 degree increment until the design angle value. It was found that the stiffness factor is directly proportional to the pressure increase which confirms the pressure stiffening effect. The theoretical cold stiffness factor was calculated by EJMA code. The theoretical stiffness factor varied from the one obtained from the movement test. These differences may affect the behaviour of expansion joints in industrial systems. These tests highlight the significance of the pressure-stiffening effect, and highlight the need to incorporate them better into stiffness calculations of expansion Joints. The effect of friction forces is significant, but since there is no reference in EJMA codes, friction reduction devices are to be used.

3. Effective Design Parameters

3.1 Forming Process

The bellows plays the role of the vital unit in an expansion joint. Upon completion each of the bellows are found to have distinct features. The geometry and the material of the bellows are always dependent on parameters like pressure capacity, spring rate and cycle life. The manufacturing process of the metal bellows consists of the several methods such as elastomeric, expansion, hydraulic, pneumatic and tube forming, rolled convoluted sheet, roll forming, rolled ring, press brake forming and combined forming.

Lee¹² studied the forming parameters like wall thickness of the preformed tube, the pressure applied during tube-bulging and the die stroke for the folding stage of a metal bellows manufactured. A Finite Element Analysis (FEA) using PAM-STAMP was applied to the tube bulging and folding process. The analysis revealed that displacement of the Crown Point at the folding stage increased rapidly as the die stroke increased compared with other two parameters. The same phenomenon was observed during spring back stage. The analysis revealed that the die stroke is the most influencing factor on determining the final convolution shape of the bellows.

3.2 Shape of Convolution

Bellows expansion joints are designed for either circular or rectangular ducts. Further, they may be reinforced, unreinforced or toroidal (see Fig. 1).

$D_{m} = D_{b} + w + t;$	mean diameter of convolutions		
D _b	Bellows inside diameter		
$t_{\rm p} = t(D/D_{\rm m})^{1/2}$	Bellows material thickness for		
one ply			
W	Convolution depth		
t	Nominal thickness of one ply		
q	Bellows pitch		

In general the toroid perimeter of bellows is less. Hence, Professor Qian's Toroidal shell theory was used and the elastic solution to bellows under displacement and pressure conditions was obtained¹³. Considering the bend to be well proportioned to the middle line of width of annular plate, it is enough to study sector convolutions. The Four types of solutions arrived at were the general solution of a toroidal shell and annular plate, boundary and link equation and theoretical proof of elastic solution. This analysis simplifies the calculations by assuming the bellows to be curved beam. Analysing this way, we get the theoretical solutions in tune with the results obtained from the experiments performed over a range of elasticity. Hence conclude that the investigation methodology of the theoretical paper work is right and can be used in the engineering design and analysis of bellows.

Sen & Adeli¹⁴ proposed a new metal expansion joint for industrial plants by providing a bubble in the centre of the single expansion joint in order to increase its flexibility. The work was carried out due to large lateral movement requirement and the limited space availability for expansion joints in a typical power plant. The proposed bubble joint has a bubble centered in the single expansion joint which protrudes from the joint. It is most suitable for rectangular shaped ducts. The bubble is placed in a direction parallel to the shear movement direction and placed at the midpoint of the joint. The expansion joint is fabricated with convolutions similar to traditional metal expansion joint. The bubble joint's lateral movement capacity with four V-shaped convolutions was examined by finite element simulation using ANSYS. Nonlinear effects on geometry and material were also taken into consideration. Four-node shell elements with six degrees of freedom were used. The slotted and continuous joint were analysed to compare the efficacy of the expansion joint with and without the bubble. The slotted joint had lower maximum displacement than continuous joint. Similar observations were found for minimum and maximum von-mises strain. It was also found that continuous joint behaved more nonlinearly than the slotted joint.

Conventional bellows are not capable to take in torsional deformations and the instability of deformations under cyclic loadings. To sort out this issue a new type of bellows namely Double Convolution Bellows (DCB) were designed by Igi et al¹⁵. There are two directions in which the convolutions are prevalent in the new type: the longitudinal direction same as the conventional bellows; and the other in the lateral direction. The mechanical characteristics of DCB are summarised in Table 1.

SCB and DCB.Source: Igi et al 15				
	Conventional bellows(SCB)	New type bellows (DCB)		
Convolution	Main circular convolution	First, main circular convolution; and second sub lateral (root		

Table 1. Comparison of mechanical characteristics of
SCB and DCB .Source:Igi et al15

	00110110(002)	(202)
Convolution	Main circular convolution	First, main circular convolution; and second, sub lateral /root reinforcement
Thickness at the crest	Reduced	Nearly equal to that of root
Instability in the deformation	Unstable deformation	Stable; no instability disappeared even without ring spacer
Advantage and disadvantage in design	Simple, less flexibility	More flexible; but more complex in shape
Torsion	Less flexible	More flexible
Fatigue	Short life	Longer life

3.3 Fatigue

Fatigue is an important parameter in design of bellows expansion joints. The regions with high elasto-plastic strain in the bellows go through cyclic loading which lead to cyclic strains beyond a comparative boundary for the materials. Plastic strain concentration may also occur at high strain levels.

The current industry approach utilizes experimental facts from the testing of bellows. This testing is not cost effective. Strain concentration is the factor that accounts for the variations between bellows and polished bar fatigue behaviour, as well as that between reinforced and unreinforced bellows. Hence, understanding strain concentration effects play an important role in assigning reliable fatigue curves to materials that have not been tested. The results of Becht's¹⁶ study of reinforced and unreinforced bellows indicate that strain concentration becomes significant for values of non-dimensional parameter QW less than 0.45 and it increases with QDT. The reinforced and unreinforced bellows fatigue data was calculated according to EJMA standards with some modifications to account for the surface finish, plastic strain concentration, and the variations between polished bar and actual bellows fatigue test. The fatigue test data indicate that a single fatigue curve could be used for both reinforced and unreinforced bellows, and it could also be compared with polished bar fatigue data.

The fatigue life of metal expansion bellows is reduced by the presence of corrosive media¹⁷. Material selection based on the operating medium also plays a major role. A material with superior anti-corrosion feature must be used for the inside layer in the design of a multi layer expansion joint. Lowering the concentration of chloride ions and deoxidizing the environment are the two vital factors in medium treatment. Some instances may call in for expansion joints of outer-pressured type that paves way for the balance solution to flow through the discharge valve at the lower end leaving the surface of the expansion joints free from deposits or any other concentrates. Based out of elastic-plastic calculations Tanaka¹⁸ formulated a procedure for determining the low-cycle fatigue life of bellows attributed to fully reversed loading. The theoretical results were compared with experimental data for evaluating the efficacy of this procedure.

3.4 Vibration

Gerlach¹⁹ formulated a simple procedure for computing the natural frequency of bellows. For a bellow with N convolutions a system comprises of 2N-1 identical masses and connected to 2N identical springs. The natural frequency of the system is found out by calculating the elemental mass, added mass and elemental stiffness. This method is highly efficient for lowest vibration modes.

EJMA has a method for calculating the same by assuming the bellows to be a continuous elastic rod. This method however does not take into account the mass resulting from simple translation of the fluid between undeformed convolutions.

Jakubauskas²⁰ investigated the effect of fluid mass in bellows expansion joints during axial vibrations, assuming the total fluid mass mf, per unit length to comprise of two components: mf1, rigid convolution motion in the transverse direction; mf2, convolution distortion component. Jakubauskas & Weaver^{5,6} derived an expression for the transverse natural frequency, assuming the total fluid mass mf, per unit length to comprise of three components : mf1,rigid convolution motion in the axial direction; mf2, convolution distortion component; mf3, associated with motion in return flow in central area of cross section. The percentage error found by this method was much less compared to that of standard EJMA or Gerlach method, indicating the importance of return flow added mass component for axial vibrations and the distortion component for transverse vibrations. Furthermore, the percentage error in EJMA method was found to increase with higher modes of vibration.

Li et al.²¹ present equations to calculate the axial and lateral natural frequencies of single bellows with boundary conditions as a cantilever setup; one end fixed and the other end attached to weight; both ends fixed

However, the bellow ends might be welded to a small pipe spool that has a lumped mass such as a valve or an instrument. Radhakrishna & Kamameswara Rao²² developed a theoretical method for determining the effect of considering the pipe as elastic and partially restrained and the influence of elastic restraints on axial natural frequencies. A number of differential equations were derived and employed by this refined method and the results were compared with the standard test results of Li et al²¹.

Simplified methods have been developed to evaluate the seismic response and natural frequencies for axial and lateral modes²³. For the lateral vibration modes, the effect of fluid-structure interaction was also taken into consideration. The experiments were made on a seismic table in the axial and lateral directions. In the corresponding FEM analyses, beam elements were used with the nodes located at the crown of each convolution. Then, a series of Eigen value analyses, spectra modal and modal time history analyses were carried out. The natural frequencies were examined up to the third mode for both axial and lateral directions while the seismic response was limited to fundamental mode. For the axial modes, a very good agreement was seen between experimental and numerical data. For the lateral modes, analysis results except the EJMA Standards agree with test results. This anomaly is because the effect of rotational inertia is not accounted for in the EJMA formula. The results of the FEM and experimental modal time history were also in good agreement, indicating the validity of the method presented.

3.5 Media Containment

Bellows used in containment systems are designed to permit comparative movements involving the components in piping and containment wall in Boiling Water Reactors (BWR) and have effectively carried out this operation while withstanding containment leakage soundness. Two plies of stainless steel are used in the construction of these bellows and a thin wire mesh is used to set the apart. The outer ply plays the role of a shield that prevents leakage by pressurizing the space between plies.

There may be instances of accidents where the bellows may be exposed to high temperature, pressure and other deflections. Lambert & Parks²⁴ studied the options to foresee the pressure and deformation conditions that would cause leakage by subjecting bellows of various geometries (number, depth, pitch and shape of convolutions and ply thickness) to various combinations of internal pressure, temperature and deflections. The test results indicate that bellows are able to withstand extreme loads while remaining leak tight. Due to the unique design of universal bellows expansion joint they were able to withstand more extreme lateral displacements. Shallow convolutions were found to develop fewer tears at low lateral displacements compared to deep convolutions. Bellows capacity was found to be degraded by temperature. It was also found that the containment bellows remain leak tight till the point of full axial compression and cause large leakage during additional outward movement of the containment.

Brown & Tice²⁵ investigated the performance and long-term integrity of bellows expansion joint in containment systems so as to determine the leak areas and leakage rates, useful life and the replacement effectiveness. Crack growth from corrosion and fatigue mechanisms were also studied. Metallurgical examinations of bellows revealed that bellows fail due to Transgranular Stress Corrosion Cracking (TGSCC). In installations of new bellows assemblies, initial Local Leak Rate Testing (LLRT) values were found to be zero or negligible. The measured leak rate was stable for a period of time. After approximately 5 to 15 years of service, increased leakage rates were observed. It was pointed out that it is not possible to accurately determine LLRT due to close proximity of plies. Hence, non-linear FEM methods were employed to find leakage rate by treating the cracks as orifices. It allowed finding the permissible crack sizes for evaluating usability of bellows with cracks. Also, a corrective action decision tree was formulated to determine the life extension of given bellows elements and the corrective actions for fault repairs.

3.6 Buckling

The phenomenon of buckling was first studied by Haringx²⁶ who showed that due to internal pressure acting on the bellows expansion joints the same will go through buckling much in the same way as an elastic strut may buckle under an axial load. Newland²⁷ extended this analogy on combining two bellows by means of a rigid pipe with desired length which in turn to a universal expansion joint. The buckling pressure was found to depend on the length ratio of bellows and the rigid connecting pipe, and the lateral spring stiffness of the supporting structure. Thus, by providing a correctly designed support the buckling pressure can be increased to a great extent.

Snedden²⁸ produced design guidelines, to avoid bellows buckling, and procedures for determining the stability of bellows subject to either small or large displacements and for strength of bellows lateral supports. The lateral stiffness of the convolution for small elastic deformations was derived using beam theory. A method of determining the angular stiffness of the convolution was formulated by describing the bending momentrotation characteristic by means of a tri-linear function having three distinct regions: elastic, elastic-plastic and contact regions. Use of such supports is recommended that are capable of sustaining the destabilising force due to buckling pressure.

The dynamic buckling behaviour of bellows expansion joint was studied by Ooka et al²⁹. This study was necessitated because of the impulsive pressure loadings in the secondary piping systems of Liquid-Metal Fast-Breeder Reactors (LMFBRs). The effects of duration and peak value of pressure for different number of convolutions were studied using calibrated pressure waves produced by slow explosives in a water loop. An analytical method for determining dynamic buckling pressure was also formulated; the results of which were in good agreement with experimental results. Based on the experimental study, it was concluded that:

(a) The buckling strength of the bellows increases when the duration of the pressure wave is shorter than a certain critical value.

(b) The buckling mode is the root-bulge type for small number of convolutions. For large number of convolutions, root-bulge mode occurs for a short duration of pressure wave and column-squirm mode occurs for a long duration.

(c) The pressure impulse is a useful parameter to evaluate the dynamic buckling characteristics of bellows.

4. Conclusion

The available literature on bellows expansion joints was considered to present the review of previous research. From the results of previous works, it can be said that no one bellows geometry and other design parameters are necessarily superior for all design conditions. Under such designs based on the standards, it is expected to perform exhaustive analysis involving sound engineering judgment. Meanwhile, the choice of bellows expansion joint is sufficiently broad. Certainly there is still room for new design principles and analysis based on analytical, experimental and FEA studies. Particularly, study of bellows subjected to torsions may be done as little is found in the literature and the existing standards. Also, existing standards are applicable only for U-shaped and toroidal bellows. The effects of different shapes of convolutions need to be examined more thoroughly.



Figure 1. Schematic of a unreinforced and reinforced bellows.

5. References

- Andersson WF. Analysis of stresses in bellows, Part I design criteria and test results. Atomic International, NAA-SR-4527, United States Atomic Energy Commission. 1964.
- 2. Andersson WF. Analysis of stresses in bellows, Part II mathematical. Atomic International, NAA-SR-4527, United States Atomic Energy Commission. 1965.
- 3. EJMA, Standards of the Expansion Joint Manufacturers Association, ninth edition. 2008.
- Broman GI, Jonsson AP, Hermann MP. Determining dynamic characteristics of bellows by manipulated beam finite elements of commercial software. International Journal of Pressure Vessels and Piping. 2000; 77(8):445–53.
- Jakubauskas VF, Weaver DS. Transverse vibrations of bellows expansion joints -Part I: Fluid added mass. Journal of Fluids and Structures. 1998; 12(4):445–56.
- Jakubauskas VF, Weaver DS. Transverse vibrations of bellows expansion joints- Part II: beam model development and experimental verification. Journal of Fluids and Structures. 1998; 12(4):457–73.
- Shaikh H, George G, Singh Khatak H. Failure analysis of an AM 350 steel bellows. Engineering Failure Analysis. 2001; 8(6): 571–6.
- Jha Abhay K, Diwaker V, Sreekumar K. Metallurgical investigation on stainless steel bellows used in satellite launch vehicle. Engineering Failure Analysis. 2006; 13(8):1437–47.
- 9. Pierce S, Evans J. Failure analysis of a metal bellows flexible hose subjected to multiple pressure cycles. Engineering Failure Analysis. 2012; 22:11–20.
- Panda B, Sujata M, Madan M, Bhaumik SK. Stress corrosion cracking in 316 stainless steel bellows of a pressure safety valve. Engineering Failure Analysis. 2014; 36:379–89.
- Veiga, Jordana LBC, Medeiros J, Carlos Veiga J. Analysis of expansion joints movement test in FCC unit. International Journal of Pressure Vessel Technology, ASME. 2014; 136(5):1–7.
- Lee SW. Study on the forming parameters of the metal bellows. Journal of Material Processing Technology. 2002; 130-131: 47–53.
- Li Y, Sheng S. Strength Analysis and Structural Optimisation of U-shaped bellows. International Journal of Pressure Vessels and Piping. 1990; 42(1):33–46.
- Sen K, Adeli H. A new steel expansion joint for industrial plants: Bubble joint. International Journal of Pressure Vessels and Piping. 2006; 83(6):447–63.

- 15. Igi S, Katayama H, Kawahara M. Evaluation of mechanical behaviour of new type bellows with two-directional convolutions. Nuclear Engineering and Design. 2000; 197:107–14.
- Becht C. Fatigue of bellows, a new design approach. International Journal of Pressure Vessels and Piping. 2000; 77(13): 843–50.
- 17. Zhu YZ, Wang HF, Sang ZF. The effect of environmental medium on fatigue life for u-shaped bellows expansion joints. International Journal of Fatigue. 2006; 28(1):28–32.
- Tanaka M. Fatigue life estimation of bellows based on elastic-plastic calculations. International Journal of Pressure Vessels and Piping. 1974; 2:51–68.
- Gerlach CR. Flow induced vibrations of metal bellows, ASME Journal of Engineering for Industry. 1969; 91(4):1196-202.
- Jakubauskas VF. Added Fluid Mass for Bellows Expansion Joints in Axial Vibrations. Journal of Pressure Vessel Technology ASME. 1999; 121(2):216–9.
- Li T, Guo B, Li T. Natural Frequencies of U-shaped bellows. International Journal of Pressure Vessels and Piping. 1990; 42(1):61–74.
- 22. Radhakrishna M, KameswaraRao C. Axial vibrations of U-shaped bellows with elastically restrained end conditions. Thin-walled structures. 2004; 42(3):415–26.
- Morishita M, Ikahata N, Kitamura S. Simplified dynamic analysis methods for metallic bellows expansion joints. Journal of Pressure Vessel Technology, ASME. 1991; 113(4):504–10.
- Lambert LD, Parks MB. Experiments to evaluate behaviour of containment piping bellows under severe accident conditions. Nuclear Engineering and Design. 1996; 163(3):287–99.
- Brown JA, Tice GA. Containment penetrations- flexible metallic bellows: Testing, safety, life extension issues. Nuclear Engineering and Design. 1993; 145(3):419–30.
- 26. Haringx JA. The instability of bellows subjected to internal pressure. Philips Research Report 7. 1952; 189–96.
- 27. Newland DE. Buckling of double bellows expansion joints under internal pressure. Journal Mechanical Engineering Science. 1964; 6(3):270–7.
- 28. Snedden NW. Analysis and design guidance for the lateral stiffness of bellows expansion joints. Thin-Walled Structures. 1985; 3(2):145–62.
- Ooka Y, Yoshie S, Morishita M, Tsukimori K. Dynamic buckling characteristics of bellows under pressure waves. International Journal of Pressure Vessels and Piping. 1990; 44(1):137–58.