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PARAMETRIC EVALUATION AND STRATEGY FOR DESIGN OPTIMIZATION OF EXPANSION BELLOWS

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Abstract

Thermal expansion and vibration in piping and other equipment components are commonly observed conditions for process/power plant industry in which piping and other components are subjected to changes in temperature, pressure as well as dynamic loadings. Such temperature changes under constrained conditions may lead to differential thermal expansion and hence failure due to high thermal stresses. In such cases, Expansion joints are used to compensate for these thermal expansions/contractions in the system while sustaining the other service conditions. Expansion joints are designed on the basis of various codes/standards like American Society of Mechanical Engineers (ASME) (appendix 26), Expansion Joint Manufacturers Association (EJMA), European Standard (EN standards), Tubular Exchanger Manufacturers Association (TEMA) etc. these codes provide the design for most essential part in expansion joint (bellows). But it is found that the expansion bellows get overdesigned due to improper selection procedure. So still there is scope for optimisation in selection of expansion bellow. Considering this need a parametric study based on a practical example was done to find the effective design parameters. Based on the results of the parametric evaluation as well considering the design codes and standards, an iterative logic was developed for design of expansion bellows and then further it is coded as MS EXCEL macros. This logic was validated with the FEA to check its validity. This logic can provide an optimum design of expansion bellow generated using EXCEL macros program best suited for given input conditions.

keywords: Expansion joint, Parametric Study, Optimization of Bellows, Algorithms, Pressure Vessels.

1. INTRODUCTION

Metal bellows and bellows expansion joints are the units that are placed in piping systems to absorb the thermal growth of the pipe. Periodic heat up and cool down of piping system, creates differential expansion in piping systems. This differential expansion is absorbed by expansion joints. Sequence of piping system being heats up and cools down is considered as 1 complete cycle.

The main component of expansion joint that performs the important work is bellows. The design procedure of a bellows starts with the Material selection and for that it's necessary to analyze the requirements and operating conditions. Material selection is an important step in expansion bellow design as it will directly affect the life of expansion joint as well the safety requirements of equipment. In next subsequent steps the dimension of bellows is decided and checked for allowable stresses as well the life of bellow. The desired life cycle of the bellows or expansion joint must be determined in order to determine the bellows dimensional parameters like thickness and number of plies. Single-ply metallic bellows is satisfactorily being employed in applications involving not much of displacement arising out of heating and cooling cycle. Multi-ply metal bellows is better solution in some special conditions involving vibration loads along with general thermal cycle.

For design of bellow some codes/ standards already exists like American Society of Mechanical Engineers (ASME) [1], Expansion Joint Manufacturers Association (EJMA) [2], European Standard (EN standards) [3] etc based on various criterions of failure. These codes/ standards give the direction for design. Researchers Anderson [4], Charles Betch [5] worked to develop as well to validate these code/ standards. Researchers also worked on the performance characteristics of expansion bellow extensively. Kim, J. B [6] has worked on the effect of convolution geometry on stresses generated in U shaped expansion bellow. Studies are also conducted on stability of bellow. In this direction, Y.Ooka et al. [7] carried out a simplified analytical investigation to get the relation between the pressure intensity and buckling of bellow. Furthermore research was carried out in deriving the fatigue life equation of bellow. Stelmar, S. [8] conducted many experiments and collected data sets to generate fatigue curve that is more reliable

S. K. Makke et al. [9] performed some analytical calculations for allowable movement cycles and gave its validation. The effect of environmental parameters on life of bellow was also investigated by Vishnu Rajan in study [10]. The investigation has showed the effect of environmental medium and flow induced vibrations. It has been concluded that these loads are vital and more attention shall be given while dealing life for bellow. Also Masanori Ando showed various modes of failure for expansion joints through study [11].

S. H. Gawande et al. [12,13] had carried out analytical and simulation study for characteristics of U shaped metallic bellows. Study carried out an investigation on the performance of the metal expansion bellows as per the ASME and EJMA standards. Tuhin Halder et al**.** [14] carried out a parametric study on U shaped expansion bellow and validated with FEA.

The literature available shows that lot of research work in various fields regarding expansion joints was done until now but there still scope to find the optimum design for expansion joint.

2. DESIGN BACKGROUND

In this study the author focused on parametric evaluation of bellow to get the appropriate inputs for design. For that purpose, the author follows some already existing codes/ standards. The codes / standards give the basic formulas (refer Eq. 1 to 7) to calculate the various stresses (refer Eq. 1 to 5) generated in bellows, the instability pressure limits (refer Eq. 6) and the fatigue life of bellow (refer Eq. 7) etc. Based on this, the general methodology to design a bellow can be summarized as below:

- Step 1: Deciding operating parameters based on thermal design (operating pressure and temperature).
- Step 2: Deciding the material based on operating parameters and surrounding environment.
- Step 3: Obtaining material data from standard references or codes (allowable stress, yield stress, modulus of elasticity, poisons ratio etc).
- Step 4: Deciding other geometrical parameters based on code like pitch and height of convolution, number of convolution, thickness of ply etc.
- Step 5: Based on trial and error method fixing the parameters.
- Step 6: Calculating values of additional factors like, etc. to convert the evaluation of parameters of U convoluted bellow into simple striped beam model.
- Step 7: Evaluating various stresses on bellow and checked for allowable stress.
- Step 8: Then bellow is checked for column stability and in-plane stability,
- Step 9: Calculating bellow life.

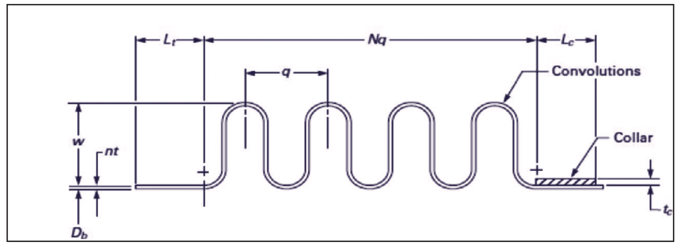


Figure 1: Unreinforced bellow configuration. [1]

Figure 1 shows the schematics of an unreinforced bellow in which is Diameter of bellow, is Height of bellow, is Pitch of convolution, is Thickness of bellow ply, shows Number of plies, is Number of convolutions, is Length of tangent, is Thickness of collar and is length of collar [1,2,3].

As per ASME code the stresses that are being generated in bellows during its working period are Bellows tangent circumferential membrane stress (S_1) (refer Eq. 1) due to internal pressure P.

$$S_1 = \frac{P(D_b + nt)^2 L_t E_b k}{2(nt(D_b + nt)L_t E_{bo} + t_c E_c L_c D_c k)} \tag{1}$$

The Condition to be checked for safety is, where S = Allowable material stresses for bellow at designed temperature. Further, bellows collar tangential circumferential membrane stress (S_1') due to internal pressure is also can be predicted based on Eq. 2.

$$S_1' = \frac{P D_c^2 L_t E_c k}{2(nt(D_b + nt)L_t E_b + t_c E_c L_c D_c k)} \tag{2}$$

Here, the condition to be checked for safety is , where is longitudinal weld joint efficiency factor for collar; is Allowable material stresses for bellow collar at designed temperature.

Then Bellow circumferential membrane stress on bellows end convolution due to internal pressure($S_{2,E}$) and bellows intermediate convolution due to internal pressure ($S_{2,I}$) is predicted by Eq. 3

$$S_{2,E} = \frac{P(D_m q + L_t(D_b + nt)}{2(A_c + nt_p L_t + t_c L_c)} \;\&\; S_{2,I} = \frac{PD_m q}{2A_c} \tag{3}$$

Here the condition to be checked is. After that Bellows meridional membrane stress (S_3) due to pressure and Bellows meridional bending stress (S_4) due to pressure can be estimated from Eq. 4.

$$S_3 = \frac{Pw}{2nt_p} \;\&\; S_4 = \frac{P}{2n}\left(\frac{w}{t_p}\right)^2 C_p \tag{4}$$

The condition to be checked is (Below the creep range), where is Material strengthening factor. Then Bellows meridional membrane stress (S_5) due to deflection and Bellows meridional bending stress (S_6) due to deflection can be estimated from Eq. 5.

$$S_5 = \frac{E_b t_p^2 \Delta q}{2w^3 C_f} \;\&\; S_6 = \frac{5E_b t_p \Delta q}{3w^2 C_d} \tag{5}$$

where, is the total equivalent axial movement of bellows, and , , are Bellow factors that relate the design calculations of U shaped convoluted bellow with the simple strip beam.

We also check for stability of bellow as, Limiting internal pressure based on column instability () and is limiting internal pressure based on in-plane instability () (refer Eq. 6)

$$P_{sc} = \frac{0.34\pi K_b}{Nq} \;\&\; P_{si} = \frac{(\pi - 2)AS_y^*}{D_m q\sqrt{\alpha}} \tag{6}$$

where, is the axial spring rate of bellow. Finally we calculate the Fatigue life of bellow () given by the Eq. 7,

$$N_{alw} = \left(\frac{K_o}{K_g\left(\frac{E_o}{E_b}\right)S_t - S_o}\right)^2 \tag{7}$$

where, = Fatigue strength reduction factor, and are Young's modulus at operating temperature for bellow and at room temperature respectively and is the total stress.

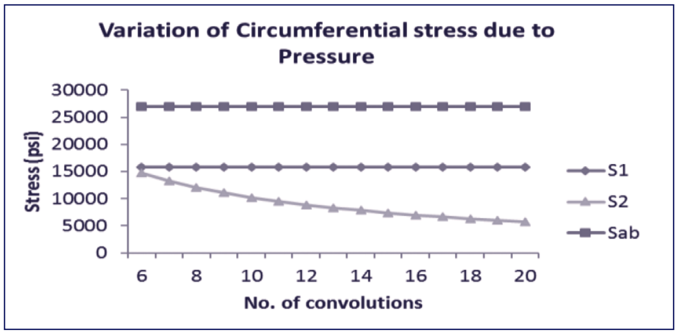
3. PARAMETRIC EVALUATION

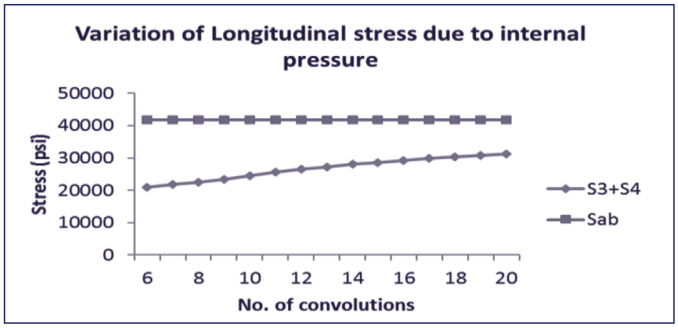
Typical sample cases were examined, to check how design of bellow varies with respect to one or more of its input parameters. By setting a list of alternative values to each input parameter, the behavior of bellow with respect to design aspects such as stresses, spring rate, life of bellow etc. was examined. The results of all such parametric studies are indicated in the form of graphs which helps to understand the impact of such input parameters on Bellow design.

Usually, the effects of changing input parameters on the results are made to improve the design aspect(s). We should focus on the variables whose range of variation is expected to have the largest effect on the results. It's usually good to start with one parameter as variable, after checking its effect two or more can be added to analyses the cumulative effect. It becomes more important as well challenging to understand the results when varying more than 2 or 3 parameters in combination.

1. Parametric evaluation of Unreinforced bellows based on variation in number of convolutions (N)

The number of convolution of bellow is crucial parameter, which greatly affects the stability of the bellow. In this study, number of convolutions is varied from 5 to 20 in such a way that the active length of bellow has been kept constant. Various plots demonstrating variation of stresses and life of bellow against number of convolution of bellow are shown in following (refer Figure 2).





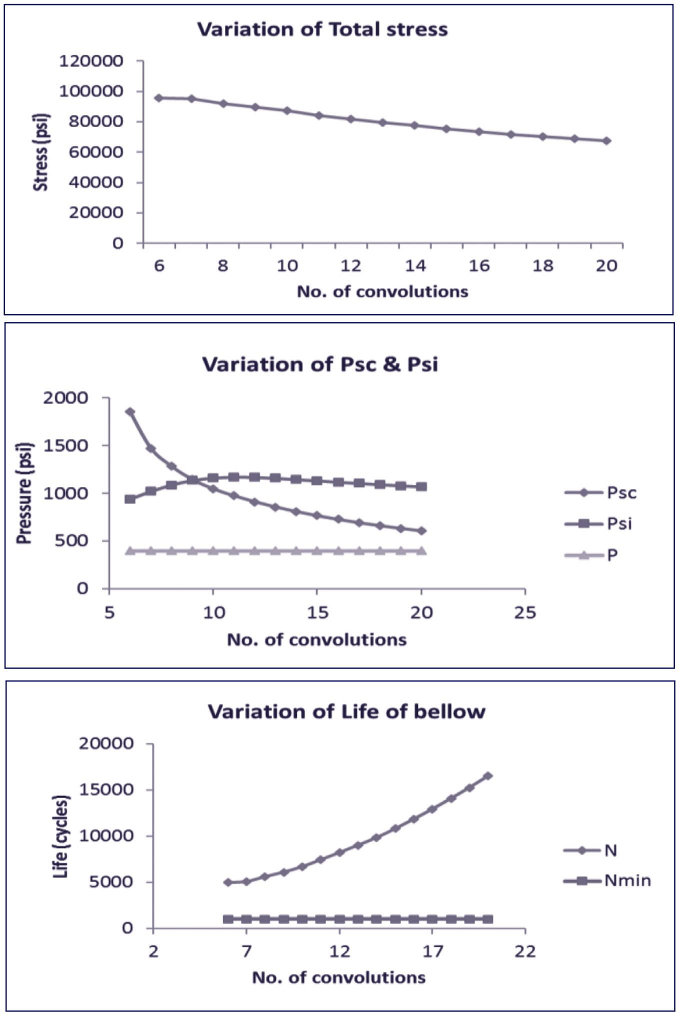


Figure 2: Variation of (a) Circumferential Stress against Number of convolutions (b) Circumferential Stress against Number of convolutions (c) Longitudinal Stress against Number of convolutions (d) Pressure against Number of convolutions and (e) Life in cycles against Number of convolutions

Observations based on above study:

• With increase in number of convolutions pitch of convolution decreases, resulting decrement in the circumferential stresses (refer Figure 2 (a)) on bellow and increment in the meridional bending stresses due to pressure (refer Figure 2(b)).

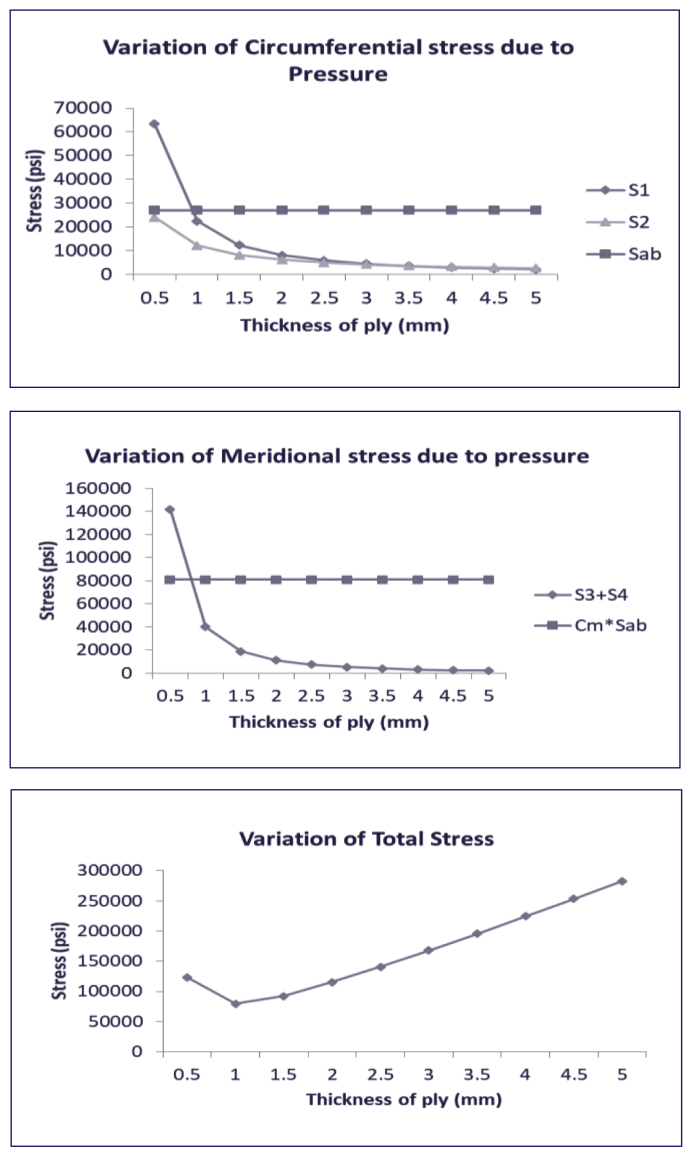
• As number of convolutions increases there is net decrease in the spring rate leading to decrease in total stress value (refer Figure 2(c)) and column instability pressure. Further it is also observed that as circumferential pressure decreases with increase in number of convolutions (refer Figure 2 (d)).

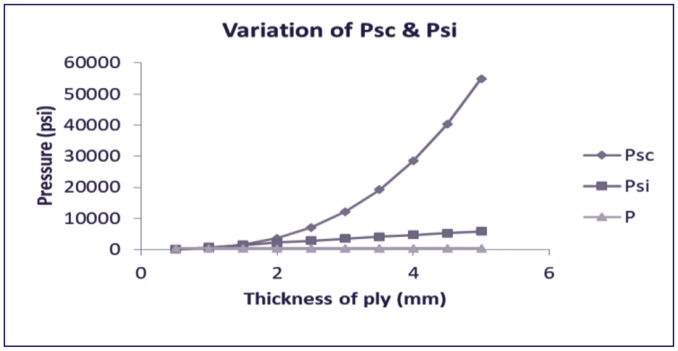
• The graph of the total stress descends, resulting substantial increment in the life of bellow (refer Figure 2 (e)).

Thus the optimum numbers of convolutions have to be decided to maintain balance between improvement of fatigue life due to lower stresses and decrease in stability of bellow. Additionally, ease of fabrication is also to be considered while deciding upon maximum number of convolutions.

2. Parametric evaluation of unreinforced bellows based on variation in thickness of bellow (t)

The thickness of the bellow certainly affects almost all stresses that are generated in expansion bellow. For understanding the effect of thickness on bellow design, the thickness was varied from 0.5 mm to maximum of 5 mm. Figure 3 shows variation of design aspects with respect to thickness of ply.





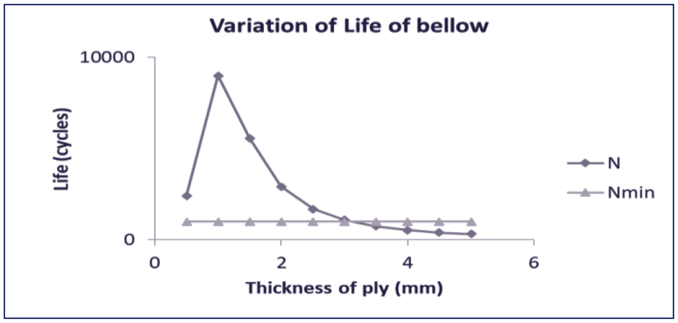


Figure 3: Variation of (a) Circumferential Stress against thickness of ply (b) Meridional Stress against thickness of ply (c) Total Stress against thickness of ply (d) Pressure against thickness of ply and (e) Life against thickness of ply

Observations based on above study are as follows:

- The circumferential stresses (refer Figure 3 (a)) and the meridional stresses decreases with increase in thickness of ply (refer Figure 3 (a) and (b))

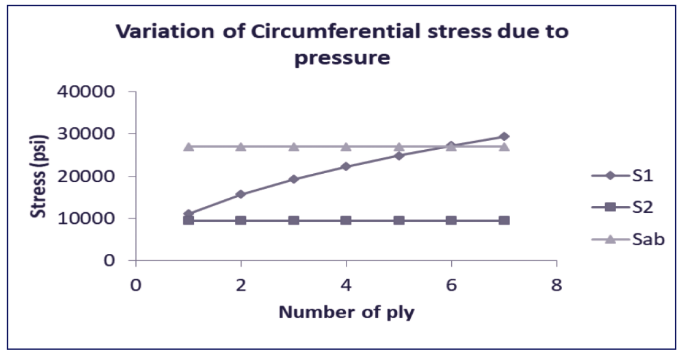
- As the thickness per ply increases, the spring rate of bellow increases, leading to increase in the value of longitudinal stresses and column instability pressure (refer Figure 3 (d)).

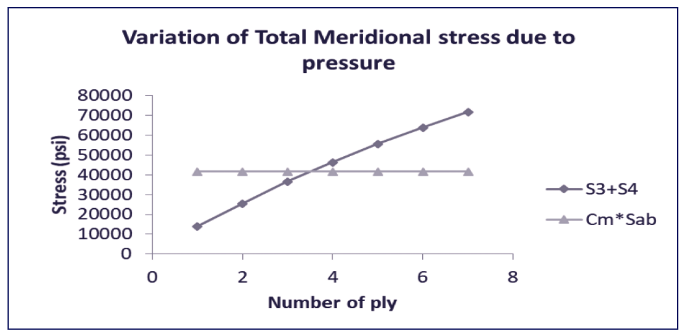
- Instead the fact that the membrane stress in bellow per ply is decreasing with increasing in the thickness value but at the same time the bending component is increasing substantially which results in increment in the value of total stresses (refer Figure 3 (c)), causing decrement in the fatigue life of bellow (refer Figure 3 (e)).

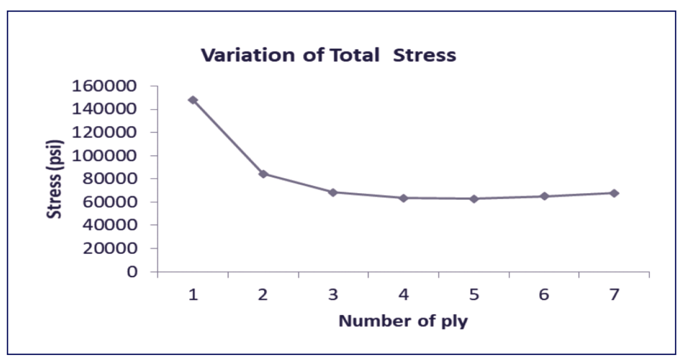
From above observations it's clear that, in order to accommodate safety and minimum required life of bellow there should be balance between the bending and membrane stress value. For that purpose, it's recommended to have the thickness of bellow limited up to 3 mm (0.1181 in).

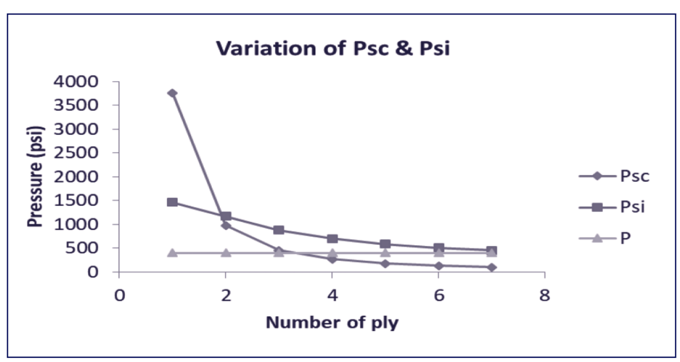
3. Parametric evaluation of Unreinforced bellows based on variation in Number of plies(n):

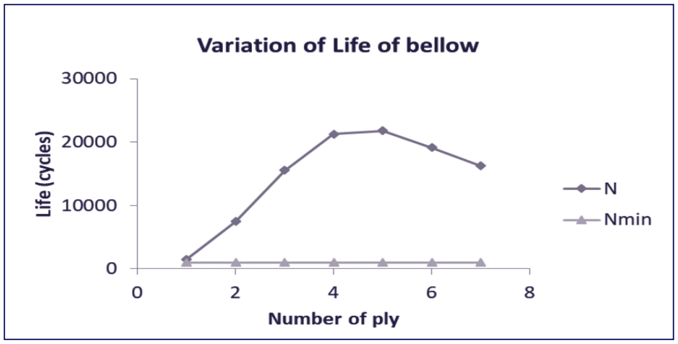
Expansion bellows are fabricated from single or multiple sheets of metal to get desired thickness of bellow. Number of plies significantly contributes to design of bellow. Thus deciding the optimum number of plies at design stage is very important. In the parametric study, the numbers of plies are varied from l to 7 in such a way that the total thickness remains same. Figure 4 illustrates variation of various design aspects in response to number of plies.











Observations based on above study:

- As the total thickness was kept same there was no variation observed in circumferential stresses of bellow (refer Figure 4 (a)), but the tangent circumferential stresses increases (refer Figure 4 (a)).

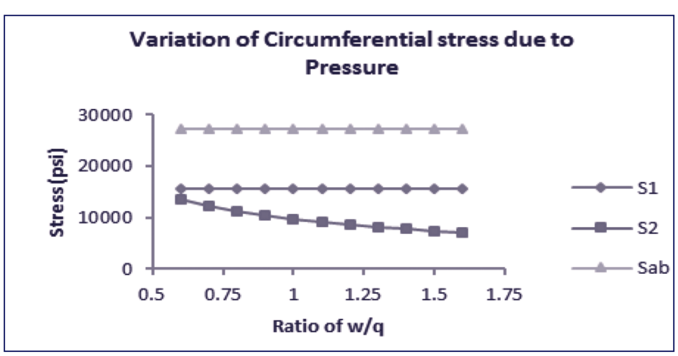
- The meridional stresses increase drastically as there is thinner material per ply (refer Figure 4 (b)). Further decrease in pressure is observed with increase in number of ply (refer Figure 4 (c)).

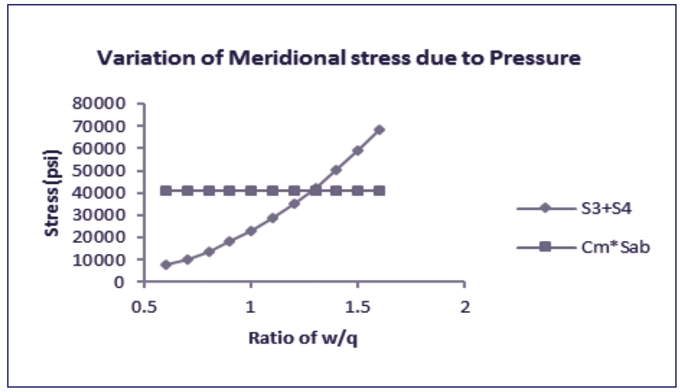
- This lead to decrement in the value of total stress (refer Figure 4 (c)) as well increment in the value of life of bellow (refer Figure 4 (e)). Because of thinner material per ply, the spring rate decreases, which results in decrement in column and in-plane instability pressures.

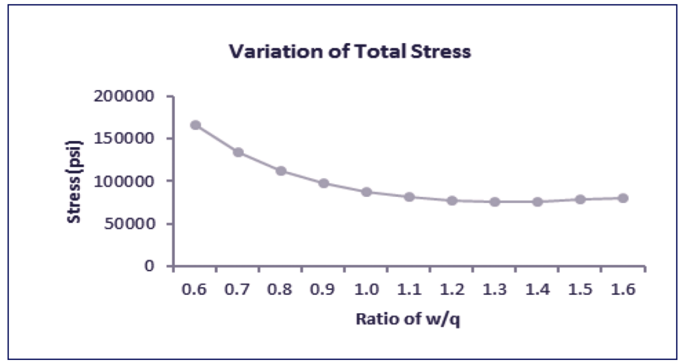
However, the single ply bellows are considered to be more cost effective compared to multi-ply design but multi-ply design is also considered as fail-safe design option as leakage of inner most ply may not lead to sudden failure. In case of multi-ply design, the recommended number of plies as per various Codes and Standards are up to 5.

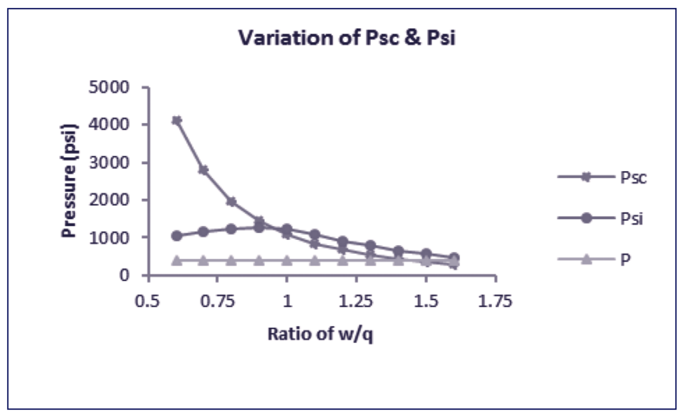
4. Parametric evaluation of Unreinforced bellows based on variation in ratio of height to pitch of bellow (w/q):

While studying the effect of w and q, it has been observed that the design of bellow greatly affected by variation of these parameter. So cumulative effect of two parameters viz, height and pitch was checked. The ratio of w/q was varied from 0.6 to 1.7 to understand behavior of bellow as a result of this variation. Figure 5 shows variation of various design aspects with variation in ratio of height to pitch.









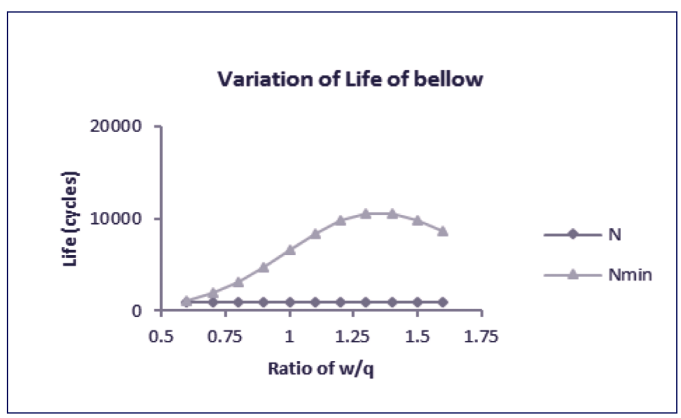


Figure 5: Variation of (a) Circumferential Stress against ratio w/q (b) Meridional Stress against ratio w/q (c) Total Stress against ratio w/q (d) Pressure against ratio w/q and (e) Life against ratio w/q.

Observations based on above study:

• As the ratio of height and pitch increases, the mean diameter of bellow also increases leading to reduction in value of circumferential stresses (refer Figure 5 (a)) and increment in value of meridional stresses (refer Figure 5 (b)).

• As the difference between height and pitch increases the spring rate of bellow decreases, resulting a reduction in the value of total stress (refer Figure 5 (c)) and ultimately increment in life of bellow (refer Figure 5 (e)).

• With decrease in spring rate, column instability pressure and in-plane instability pressure decreases (refer Figure 5 (d)).

From above study it was clear that with increase in height of convolution the instability pressure decreases but increasing width may provide bigger convolutions height with stable instability pressure, so to maintain that appropriate height to width ratio should be selected. The study shows that this ratio can be varied from 1 to 1.2 for optimum results.

4. METHODOLOGY TO DEVELOP NUMERICAL TOOL

As previously discussed, this study was carried out for selection of proper design of expansion bellow. The Total stress or eventually the fatigue life of bellow can be taken as primary factor for optimization. But considering only Life will not give us the perfect design. So a methodology was developed to get that perfect design based on the observations from parametric study and data available from code. The learning's from parametric study were incorporated in Excel based program which will provide optimum design.

The developed numerical tool took all required conditions and iterates between the ranges discussed in above, to give a set of iteration that follows the minimum life criteria either specified by designer or customer. To obtain the desired results the elimination of undesired iterations was based on various criteria's. The first elimination was done for minimum number of plies, the lower the plies the lower will be the cost of bellow. If customer or designer wants design iterations of particular no. of plies, then such option is also available with the tool to set the desired number of plies. Now the optimum design should carry minimum spring rate. Spring rate of bellow is function of thickness of ply (t), height of bellow convolution (w) and the no of convolutions (N). The lowest spring rate model available for each thickness of ply was separated. So considering the effect of thickness on spring rate the elimination of iterations was chosen to be separate for each applicable thickness. The applicable thickness was calculated based on the formula provided by the regular thin vessel theory. The iterations with thickness less than applicable thickness were eliminated. Then a particular set of iterations for particular thickness was obtained and from that iteration with minimum spring rate was chosen. So finally the designer has different design options for different thicknesses. Then the designer a select the design based on the availability of material thickness or manufacturing limitation of their plant.

5. RESULTS AND VALIDITY OF METHODOLOGY

To analyze the methodology, a typical example was chosen. Table 1 shows the design conditions required in the analysis of bellow.

Design parameters	Symbol	Specification
Operating Pressure	P	50(Psi)
Operating Temperature	-	545(°C)
Expansion joint material	-	Inconel 625
Expansion joint type	Single unreinforced type (in as formed condition)	
Internal diameter of bellow	Db	39.38 (in)
Length of bellow tangent	Lt	0.7874 (in.)
Length of bellow	Lb	9.527 (in)
Young's modulus for bellow and at operating pressure	Eb	2.56E+07 (Psi)
Young's modulus for bellow at room temperature	Eo	2.99E+07(Psi)
Axial displacement	x	0.1968 (in.)
Lateral displacement	y	0.07874 (in.)
Angular deflection	ɵ	0 (Deg.)

Table 1: Operating conditions

For the required conditions, the bellow was designed using our methodology to get optimum designs for available thickness of plies. The list of performance parameters in design given by suggested methodology is shown in Table 2. Here the geometrical parameters are taken in inches and stresses are represented in pound per square inches (psi). Further these parameters are expressed in the schematic diagram of bellow shown in Figure 1.

Design Parameter	Different Designs Available with different thicknesses								
w (in)	4.1338	4.1338	3.3622	3.1260	2.7297	2.4016	2.2441	2.0078	1.7542
q (in)	3.8582	3.8582	3.0866	3.0866	2.5722	2.2047	2.2047	1.9291	1.7148
t (in)	0.1250	0.1094	0.0938	0.0781	0.0703	0.0625	0.0563	0.0500	0.0438
N	4.00	4.00	5.00	5.00	6.00	7.00	7.00	8.00	9.00
np	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
weight	722.62	632.42	551.51	436.57	407.58	370.12	317.37	287.16	248.57
S1 (Psi)	3946.61	4819.65	6070.71	7976.54	9340.12	11142.5	13047.9	15566.4	19015.1

S2E (Psi)	5348.80	6108.96	7205.54	9031.96	9984.62	11321.4	13085.4	14860.6	17516.7
S2I (Psi)	4442.23	5073.59	5746.53	7261.84	7711.88	8437.73	9853.74	10836.8	12483.1
S3 (Psi)	680.16	777.16	733.40	816.74	790.18	780.23	809.10	812.97	810.23
S4 (Psi)	15382.8	19818.1	18105.2	21714.9	20891.6	20701.0	21645.0	22149.2	21934.2
S5 (Psi)	1685.58	1313.02	1410.67	1204.16	1223.68	1217.21	1187.69	1147.96	1159.72
S6 (Psi)	178532	154007	164037	152600	154531	154800	154871	152657	155108
St (Psi)	191462	169736	178635	169576	170932	171054	171777	169878	172189
Psc (Psi)	1876.00	1278.71	1177.96	838.03	766.57	677.90	595.35	511.56	452.23
Psi (Psi)	493.38	390.18	411.38	338.82	341.86	332.10	301.02	282.22	257.25
Nc (cyls.)	7022.97	12604.9	9798.61	12664.4	12172.0	12128.8	11877.6	12552.4	11737.5
Ac (in^2)	2.5386	2.2217	1.5521	1.2237	0.9547	0.7444	0.6359	0.5041	0.3876
fi (lb/in)	72612.2	49493.4	56993.2	40546.2	44507.4	45918.1	40326.6	39600.3	39384.8
Kb (lb/in)	27094.1	18467.7	17012.9	12103.3	11071.5	9790.64	8598.44	7388.13	6531.48

Table 2: Various designs by proposed methodology.

Now the design can be selected based on the material availability (thickness of ply) or manufacturing limitations (Number of convolutions).

6. FUTURE SCOPE

In this study we mainly concentrated on the dimensionally important parameters only, the impact of other parameters (length of bellow, length of tangent etc.) can be a search area. The tools introduced are not able to select material by their own; someone may introduce features so that it can give appropriate selection of material automatically to avoid the mistakes of beginner designers and the loss of money as well.

7. CONCLUSION

From above study, a designer can get the feel of parameters that affects the bellow design. Based on results, proposed methodology can provide different designs for same operating conditions. These all design alternatives are compliance of different standards such as American Society of Mechanical Engineers (ASME), Tubular Exchanger Manufacturers Association (TEMA), Expansion Joint Manufacturers Association (EJMA) etc. Among these different alternative design solutions, the proposed design methodology provides an optimum design. Further, this optimized methodology reduces time for designing in selection of bellow for a particular application. This quick convergence on design solution along with optimum parameters is the key merits of the approach.

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To,

Dear Members, Readers, Students & Well-wishers

Wishing you and your family, a very Happy & Prosperous New Year

DV Bhagat
National Chairman, IIIE