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Numerical Investigation of the Effect of Weld Length and Sheet Thickness on Stress and Mechanical Characterization of the Diaphragm Bellows

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Abstract: Diaphragm bellows are one of the essential parts in sealings and rotary equipment which are affected by their design parameters. This paper investigated the effect of weld length and plate thickness, on the mechanical characterization of diaphragm bellows. The mechanical characterization includes stress distribution, bellows deflection, spring constant, and fatigue life of the welded metal bellows. Finite element analysis was employed to study the effect of weld length and sheet thickness on the diaphragm bellows. In this regard, 12 models were designed based on experimental parameters. The number and combination of tests were designed by the response surface method and the results were evaluated by ANOVA analysis. According to the results, if weld length and sheet thickness increase, the maximum stress and deflection of the bellows decrease, and the spring constant increases. The effect of sheet thickness on the behavior of the bellows is greater than weld length and it creates a limitation due to the effect on the spring constant. In the acceptable ranges of weld length and sheet thickness, based on fatigue analysis, the maximum life cycle is 1.2×10^6 and the minimum life cycle is 1.7×10^3.

Keywords: Diaphragm Bellows, Fatigue Life, Finite Element Method (FEM), Mechanical Characterization, Welded Bellows

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Research paper

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1 INTRODUCTION

Bellows are thin, flexible structures commonly used for sealing and in pressure piping systems because of vibrations during operations, assemblage deformations, and thermal effects [1-2]. Duffy et al. [3] used bellows in place of a piston in a motor to eliminate leakage and improve the efficiency of aircraft propulsion. Based on bellows configuration, there are two types of them: diaphragm or welded bellows and accordion-like or toroidal bellows. The mechanical behavior of the bellows is significantly affected by their geometry and shape. In practical applications, V-shape, U-shape, and S-shape bellows are common forms of accordion-like bellows [4].

Diaphragm or welded bellows are manufactured by alternately welding thin metallic circular disks at the inner and outer edges. Welding two disks creates one convolution and by welding numerous convolutions, a diaphragm bellows is manufactured [5]. This type of bellows has wide usage in mechanical seals of compressors, hydraulic accumulators and actuators. Most researchers focused on the mechanical characteristics of bellows with different designs and geometries. Tarabrin [6] studied the spatial bellows and formulated theoretical calculations regarding the bellows' stress-strain state while subjected to a longitudinal-axial compressive force.

Yuan et al. [7] investigated the behavior of reinforced S-shaped bellows under different conditions and found that stress is largely concentrated in the wave trough and also that, stress decreases as the number of convolutions increases. Gheni et al. [8] analyzed the stiffness and the flexibility of welded metal bellows numerically by changing the number of convolutions and found that stress has an inversely proportional relation with the number of convolutions but, after a certain number of increases in the number of convolutions, their data showed that the number of convolutions does not have much effect on the maximum stress.

Also, they presented that as the number of convolutions increases, the overall static stiffness shows a sharp decrease at first but the rate slows down. Xiang et al. [9] investigated load capacity and deformation and energy dissipation of different bellows joints and they discovered that the multi-convolution bellows joint had a load capacity comparable to the single-convolution joint. They also observed that the energy absorption increased proportionally with the number of convolutions. Li et al. [10] analyzed single-layer and double-layer S-shaped welded bellows subjected to axial force. They found that strain increases with compression load and that double-layer bellows are more resistant to elastic deformation.

Piao et al. [11] predicted the spring constant of welded bellows using numerical analysis results and bellows geometry and validated it with experimental data. Gheni et al. [4] in another study, analyzed the flexibility of the welded bellows after a shape optimization method was used. Cho et al. [12-13] created a program to determine the structural design of a welded metal bellows by changing the desired variables using commercial CAD software and ANSYS Workbench.

Nuer et al. [14] carried out a finite element analysis on a diaphragm bellows and a V-shape bellows and the results showed that the maximum stress in the diaphragm bellows is smaller than the maximum stress in the V-shape bellows.

There has been research conducted on the thickness of metal bellows. Prasanna Naveen Kumar et al. [15] analyzed the design parameters of metal bellows and showed that the wall thickness of the U-shaped bellows has a significant impact on the static mechanical behavior of the bellows. Yan et al. [16] studied the U-shaped metal bellows and concluded that grain size and wall thickness of bellows are major factors in their failure. A few research on the hydroforming process of bellows has also accounted for the wall thickness of bellows [17-19].

Jiang et al. [20] studied the welding process of bellows, forming, and the microstructure of the weld zone. They found one optimal welding condition based on microstructure analysis. Also, seam welding resulted in greater hardness than fusion welding. Guo et al. [21] examined welded bellows when subjected to tensile stress and determined that fatigue fracture began close to the weld. Krovvidi et al. [22] investigated the failure of welded bellows and determined that failure occurs at the inner weld of the bellows.

There have been many studies on accordion-like bellows over the years while lower research has focused on the diaphragm bellows. According to the literature review, the effect of weld placement and sheet thickness of the diaphragm bellows on mechanical characteristics and bellows behavior were not considered. In this research, the effect of weld length and sheet thickness on maximum stress, bellows deflection, spring constant, and fatigue life of the welded bellows have been investigated using the Finite element method, and the results were evaluated by variance analysis.

2 MATERIALS AND METHODS

The material of the diaphragm bellows was AISI 304 austenitic stainless steel. This is the common material used in metal bellows. Austenitic stainless steel is used in corrosive and high-temperature environments. It exhibits good mechanical properties in handling axial, lateral, and angular motions [15]. The mechanical properties of AISI 304 are presented in “Table 1”.

Table 1 The mechanical properties of AISI 304 [23]

Young's modulus	Poisson's ratio	Fatigue strength	Yield strength	Tensile strength
203 GPa	0.275	490 MPa	690 MPa	1030 MPa

To investigate the effect of weld length and sheet thickness on maximum stress, bellows deflection, spring constant, and fatigue life of the welded bellows, finite element (FE) and analytical methods were utilized. Numerical simulation was based on a practical bellows which consists of 10 convolutions, inner diameter 39 mm and outer diameter 49 mm, weld length 1 mm, and sheet thickness 0.15 mm. A sectional view of the diaphragm bellows and the plate geometry of the bellows is shown in “Fig. 1”. To examine the influence of weld length and sheet thickness on the performance of welded metal bellows, an axisymmetric model was developed in Abaqus commercial package. The inner diameter of the bellows does not change with varying parameters, and the outer diameter only varies by changes in the weld length of the bellows. In this model, the element type CAX4R was used to simulate the bellows behavior, and a 0.018 mm mesh size was selected for all models based on a mesh sensitivity analysis [24-25]. The results of the mesh sensitivity analysis revealed that the mesh size selected optimized the processing time and also provided high-accuracy outputs. Figure 2 shows the mesh configuration and boundary condition of the finite element model.

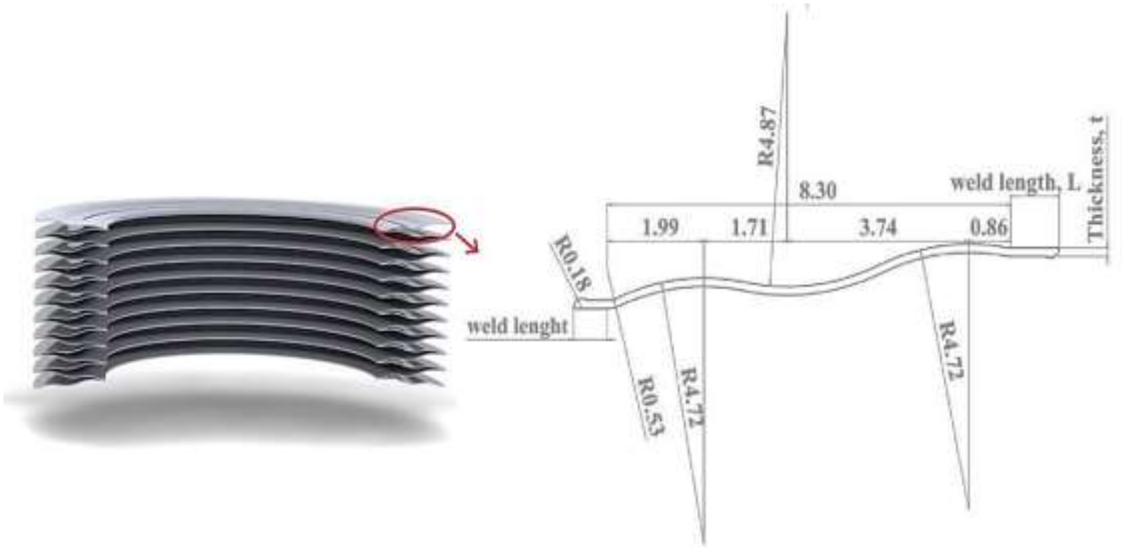

Fig. 1 Sectional view of the diaphragm bellows and the geometry of plates of the practical bellows (All dimensions in mm).

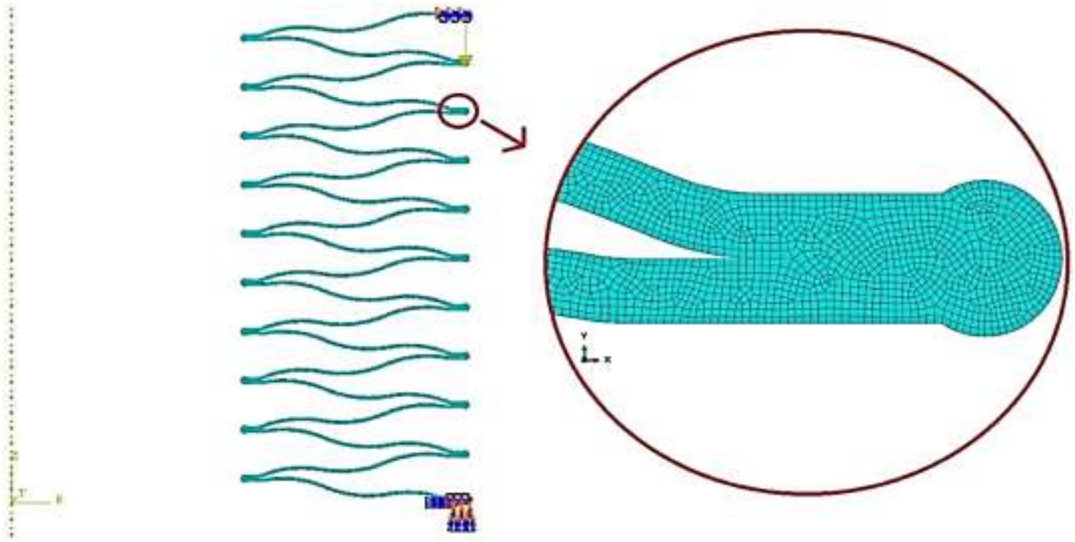

Fig. 2 Mesh configuration and boundary condition of the FE-model.

To determine the allowable range of the weld length of a diaphragm bellows, eight models with weld lengths of 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 mm were analyzed. Based on the practical weld length, eight different models with sheet thicknesses of 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, and 0.45 mm were simulated to determine the allowable range of sheet thickness. All models consisted of 10 convolutions and were compressed by a load of 10 kg. The quadric central composite response surface method was utilized to investigate the interaction between the effect of the parameters and the results were examined using ANOVA analysis. The analysis was computed using Design-Expert commercial software and, the set of experiments is presented in “Table 2”.

Table 2 Sequence of experiment

Run	Weld length mm	Sheet thickness mm	Maximum stress MPa	Deflection mm	Sprint constant kN/m
1	3	0.35	133.6	0.892	109.933
2	3	0.15	421.8	6.165	15.9059
3	1	0.35	158.5	0.8416	116.516
4	2	0.15	442	6.269	15.642
5	1	0.25	233.3	1.958	50.0817
6	1	0.15	483.4	6.519	15.0422
7	2	0.35	145.3	0.8597	114.063
8	3	0.25	213	1.982	49.4753
9	2	0.25	172.9	1.955	50.1586

To examine the fatigue life of the bellows, modified Goodman criteria [26] were utilized to predict the life cycle by developing an analytical model as a code in MATLAB software. Equation (1) presents the modified Goodman criteria for calculating reversible stress in fatigue phenomena, as follows.

$$\sigma_{rev} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}} \tag{1}$$

In these relations σ_{rev} is completely reversible stress, σ_a is the amplitude of the stress, σ_m is the mean stress, and S_{ut} represents tensile strength.

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}}$$

$$a = \frac{(fS_{ut})^2}{S_e} \tag{2}$$

$$b = \frac{-\log\left(\frac{fS_{ut}}{S_e}\right)}{3}$$

Equations (2) are used to evaluate the number of cycles that a mechanical component can undergo before failure. Where N is the number of cycles to failure, and Se is the endurance limit. a and b are constants defined respectively at 10^3 and 10^6 cycles for fully reversible stress on the S-N curve, and f is a fatigue strength fracture which is equal to 0.788 for this material [26]. Also, the spring constant was calculated using relation (3), in which k, F, and δ denote spring constant, applied force, and bellows deflection, respectively.

$$k = \frac{F}{\delta} \tag{3}$$

3 RESULTS AND DISCUSSION

Simulation of the practical bellows and the evaluation of their results indicated that the results have good agreement with the practical data and as both bellows and springs have low energy dissipation, the reaction force was used to validate the results. The external load applied to the bellows was 98.9 N (10 kg) and the reaction force of the simulation was 98.82 N which shows the results, with a 0.77% error, are acceptable. Investigating the stress contribution shows that maximum stress is concentrated where two plates are joined to make a convolution, and the critical point is located on the welded joints.

When the bellows is under compressive load, investigating the contribution of σ_y shows the rest of the bellows are under compressive stress, and an equilibrium of compression-tension is concentrated in the weld zone. Figure 3 illustrates the distribution of stress in the practical bellows (Run number 6 in “Table 2”).

Investigating the effect of sheet thickness and weld length on maximum stress and bellows deflection showed that increasing the sheet thickness from 0.1 to 0.45 led to an 84% reduction in stress and a 97% reduction in deflection. Inversely, increasing the weld length from 0.5 to 4 resulted in a nearly 20% decrease in stress and an 8% decrease in deflection.

Also, increasing thickness and weld length in their respective range causes an increase in spring constant by approximately 94% and 4%, respectively. Figures 4 and 5 indicate the effect of weld length and sheet thickness on stress, deflection, and spring constant of bellows.

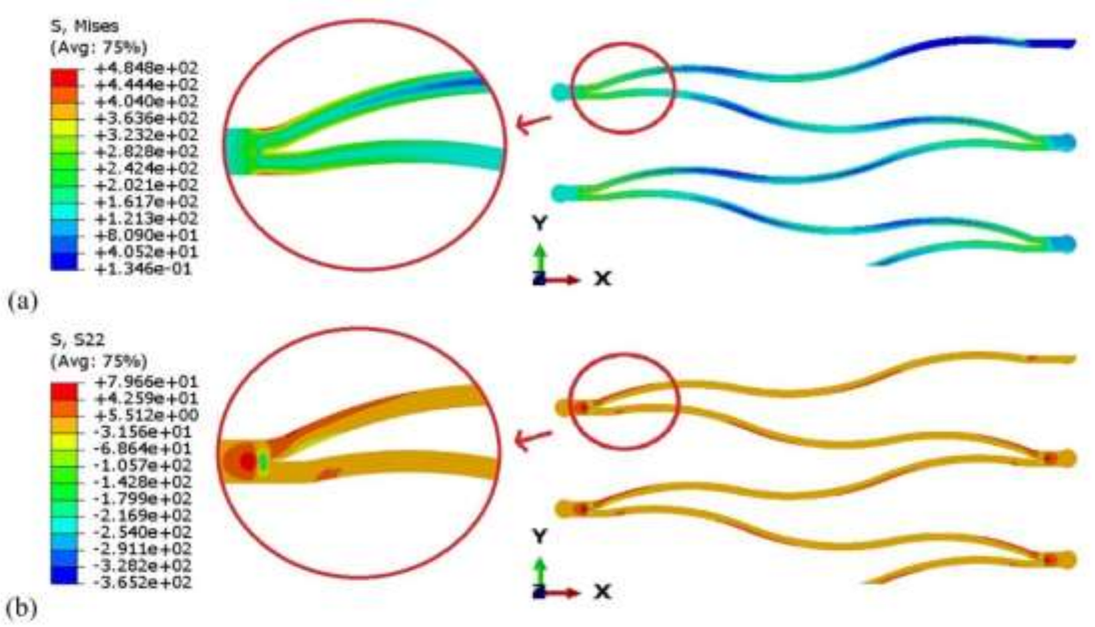

Fig. 3 Stress distribution in the bellows with 0.15 mm sheet thickness and 1 mm weld length: (a): effective stress, and (b): stress distribution in the vertical direction (σy).

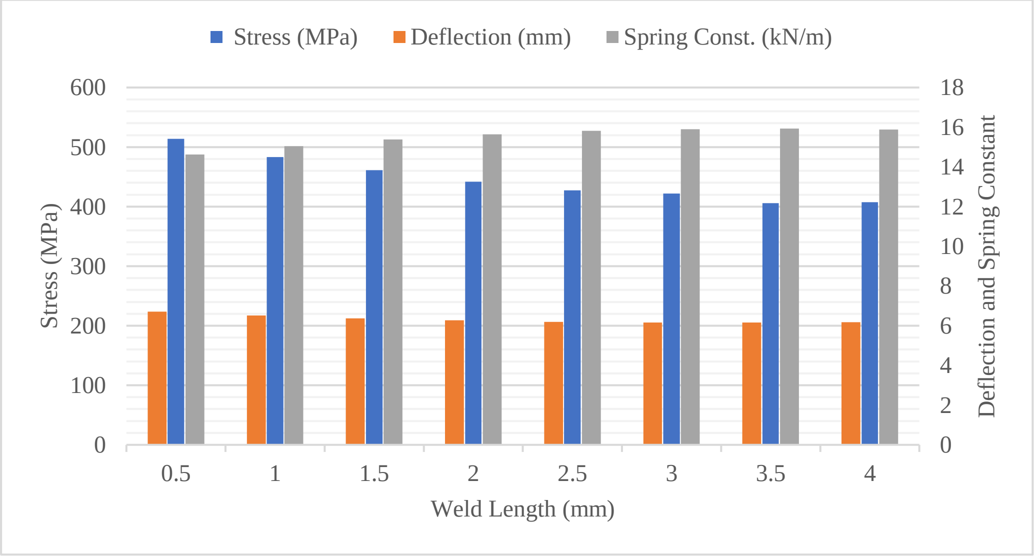

Fig. 4 Effect of weld length on the behavior of bellows.

In “Fig. 4”, studying the allowable range of the weld length shows that if the weld length is less than 1 mm, the maximum stress is over the fatigue strength which is not desirable for the bellows life that is because of stress concentration. Also, the weld lengths that are more than 3 mm do not affect the maximum stress significantly. So, the acceptable range of weld length is between 1 to 3 mm.

According to “Fig. 5”, if the sheet thickness is less than 0.15 mm, the maximum stress is over the yield strength and the plastic deformation occurs in the bellows. Also, if the sheet thickness is more than 0.35 mm, the change in maximum stress is not significant while deflection becomes limited and the spring constant extremely increases. Therefore, the acceptable range of sheet thickness is between 0.15 to 0.35 mm.

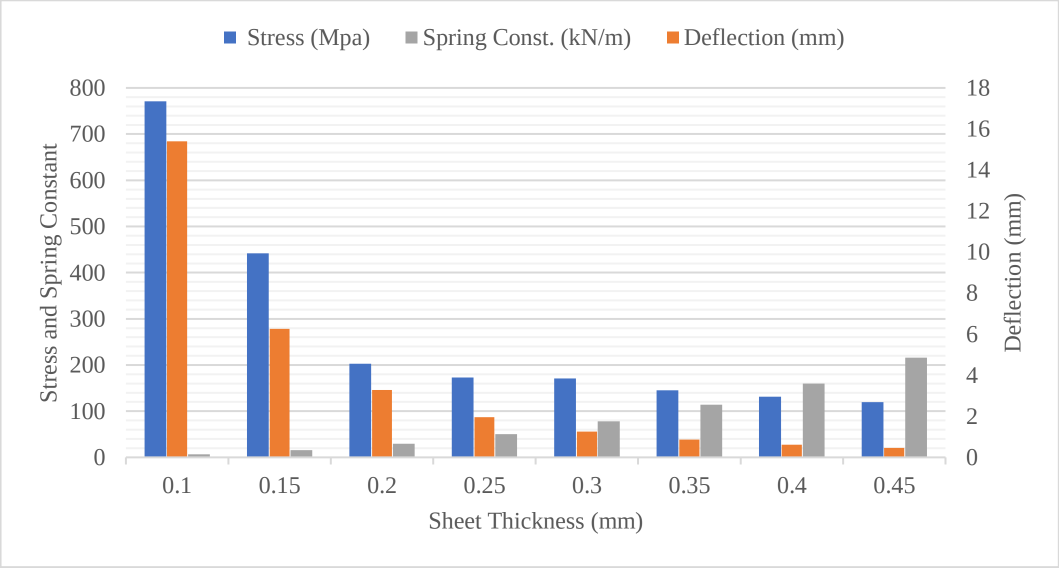

Fig. 5 Effect of sheet thickness on the behavior of bellows.

Investigating the results of analysis on weld length and sheet thickness showed, under a constant working force (10 Kg), with increasing weld length, the stress and deflection of the bellows decrease, and subsequently spring constant increases. Also, by Increasing sheet thickness, spring constant rises, and stress and deflection both fall. Therefore, an increase in sheet thickness has a greater effect on bellows behavior than an increase in weld length. But as the sheet thickness of the bellows becomes thicker, its spring effect becomes less effective and, diminishes bellows proficiency.

According to the determined range of sheet thicknesses and weld lengths, a set of experiments was designed using the response surface method and, the effects of both parameters on the mechanical behavior of the bellows were investigated. The designed experiments are presented in “Table 2”. Figure 6 shows the stress distribution on the two groups of bellows with 0.15 mm constant sheet thickness and different weld lengths, and 1 mm constant weld length and various sheet thicknesses (Runs 2-6 in “Table 2”).

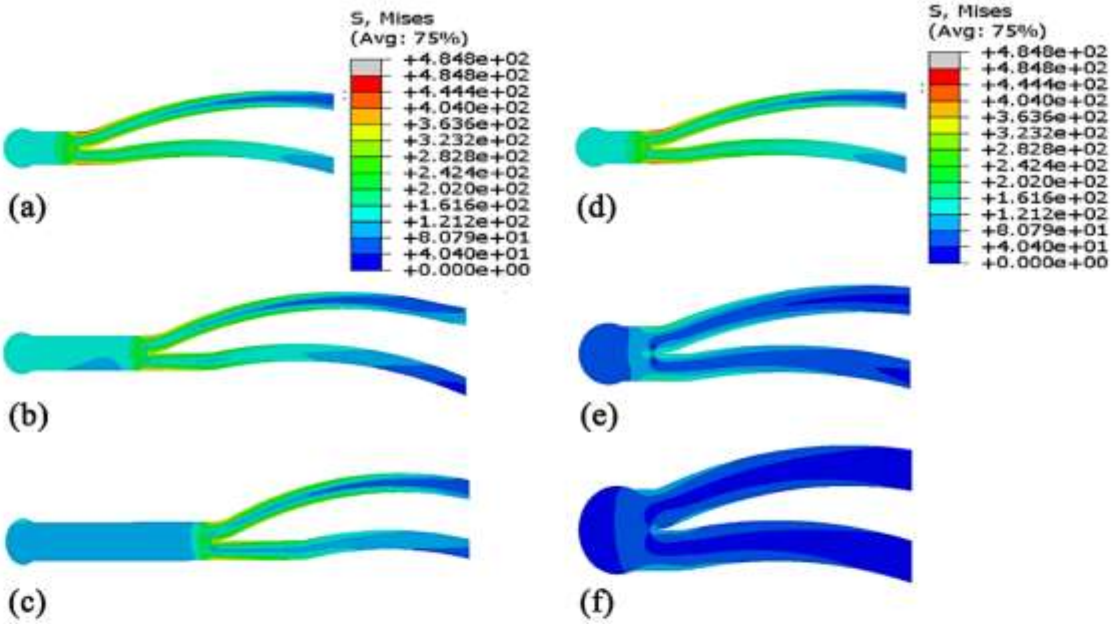

Fig. 6 The distribution of stress on bellows with 0.15 mm sheet thickness: (a): 1 mm, (b): 2 mm, (c): 3 mm weld lengths, and 1 mm weld length, (d): 0.15 mm, (e): 0.25 mm, and (f): 0.35 mm sheet thickness.

3.1. Effect of Weld Length and Sheet Thickness on Maximum Stress

Evaluation of the response surface results showed that there is a quadratic relation between weld length and sheet thickness with maximum stress of the bellows. The predictive model based on weld length (A) and sheet thickness (B) is presented in Equation 4. Based on the results, this model has a P-value of 0.0019 which shows the model is significant.

$$Stress\ (MPa) = +192.71 - 17.80 \times A - 151.63 \times B + 9.18 \times A \times B + 20.53\, A^2 + 91.03\, B^2 \tag{4}$$

The determination coefficient R^2 for this model is 0.9931 which indicates that the predicted values have a reasonable agreement with the numerical data. The linear pattern of the normal residuals plot and the plot of predicted-actual values show that there are no abnormalities in the data. Figure 7 illustrates the normal residuals plot and “Table 3” represents the result of ANOVA analysis

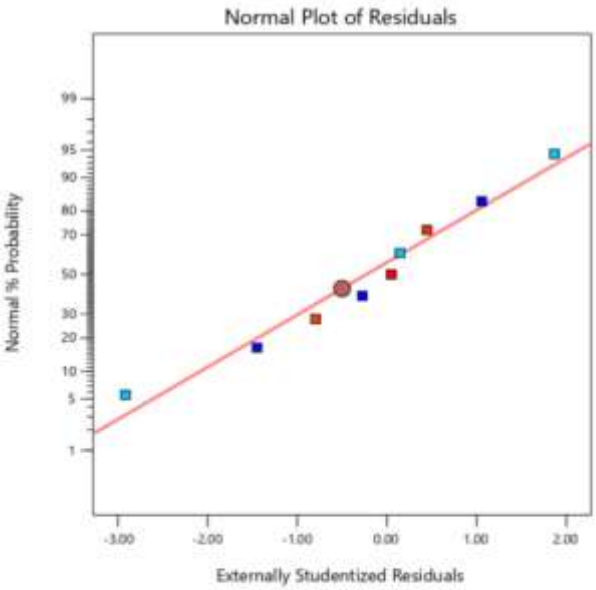

Fig. 7 Normal plot of residuals for maximum stress.

Table 3 ANOVA results of the model of maximum stress

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	157611.1	5	31522.23	86.6798	0.0019	significant
A-Weld length	1901.04	1	1901.04	5.2274	0.1063	
B-Sheet thickness	137956	1	137956	379.3514	0.0002	
AB	336.7225	1	336.7225	0.9259	0.4069	
A^2	843.2356	1	843.2356	2.3187	0.2251	
B^2	16574.14	1	16574.14	45.5755	0.0066	

With a comparison of P-values of weld length and sheet thickness, it is realized that the effect of sheet thickness on maximum stress is much greater than weld length. Also, their interactive effect on maximum stress according to their P-value is not significant. Increasing sheet thickness causes a steep decrease in maximum stress, and after sheet thickness reaches 3 mm, the decreasing rate slows down to near zero.

The slope of change in maximum stress under the effect of weld length is nearly constant compared to sheet thickness. Maximum stress occurs when sheet thickness and weld length are minimum and with increasing sheet thickness, the maximum stress decreases. Figure 8 shows the interaction contour of the weld length and sheet thickness on maximum stress.

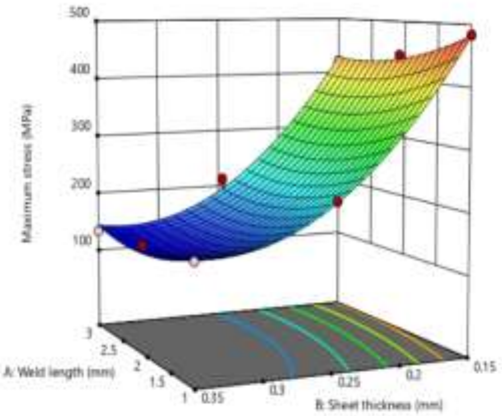

Fig. 8 The interaction contour of weld length and sheet thickness on maximum stress of bellows.

3.2. Effect of Weld Length and Sheet Thickness on Deflection

To predict the effect of the weld length and the sheet thickness on deflection, the following quadratic model is presented in Equation (5). The results show that the P-value of the model is 0.0001, which is lower than 0.05 and therefore it is a significant model. The determination coefficient R^2 for this model is 0.9998 which indicates that the predicted values have good agreement with the numerical data and linearity of the plots of normal residuals shows that there are no abnormalities in the data. Figure 9 illustrates the normal residuals plot and "Table 4" represents the results of ANOVA analysis.

$$\begin{aligned} Stress\ (MPa) = {} & +1.94 - 0.0466 \times A \\ & - 2.73 \times B + 0.1011 \times A \\ & \times B + 0.0317\, A^2 \\ & + 1.63\, B^2 \end{aligned} \tag{5}$$

Table 4 ANOVA results of the model of deflection

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	49.950	5	9.990	2491.640	1.27E-05	significant
A-Weld length	0.013	1	0.013	3.249	0.169	
B-Sheet thickness	44.606	1	44.606	11125.352	1.88E-06	
AB	0.040	1	0.040	10.197	0.049	
A^2	0.002	1	0.002	0.501	0.529	
B^2	5.288	1	5.288	1318.900	4.59E-05	

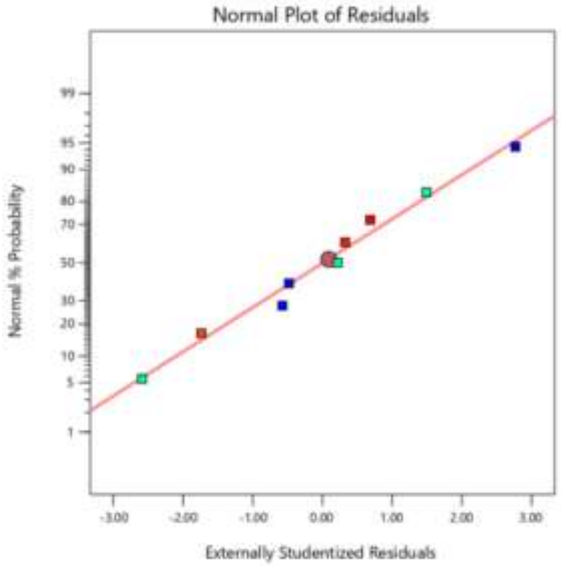

Fig. 9 The plot of residuals for deflection.

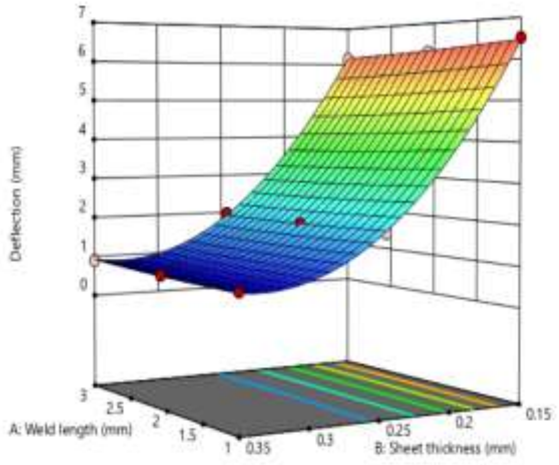

Fig. 10 The interaction contour of weld length and sheet thickness on bellows deflection.

According to the presented P-values of the weld length and the sheet thickness in "Table 3", the effect of sheet thickness on deflection is much greater than weld length and their interactive effect on bellows deflection is significant. As sheet thickness increases to 3 mm, there is a steep decrease in the deflection, and for more than 3 mm thickness the change rate slows down to a near-constant one. The deflection is highest when the sheet thickness and weld length are at their minimum, and lowest when they are at their maximum. The interaction contour of the weld length and sheet thickness on the bellows deflection is illustrated in "Fig. 10".

3.3. Effect of Weld Length and Sheet Thickness on Spring Constant

Equation (6) is a quadratic model to predict the effect of weld length and sheet thickness on the spring constant. According to the results, this model has a P-value of 0.0001 which shows that it is significant.

$$\begin{aligned} Stress\ (MPa) = {} & +50.21 - 1.05 \times A \\ & + 48.99 \times B - 1.86 \times A \\ & \times B - 0.4622\, A^2 \\ & + 14.61\, B^2 \end{aligned} \tag{6}$$

The determination coefficient R^2 for this model is 0.9999 which indicates that the predicted values have adequate agreement with the numerical data. Evaluation of the normal residuals plot shows that there are no abnormalities in the data. The normal residuals plot is illustrated in “Fig. 11” and “Table 5” represents the ANOVA results.

Table 5 ANOVA results of the model of spring constant

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	14846.31	5	2969.2619	4816.9378	4.72E-06	significant
A-Weld length	6.6699	1	6.6699	10.8204	0.0460	
B-Sheet thickness	14398.34	1	14398.3361	23357.9565	6.18E-07	
AB	13.8650	1	13.8650	22.4928	0.0177	
A^2	0.4272	1	0.4272	0.6931	0.4661	
B^2	427.0111	1	427.0110	692.7262	0.0001	

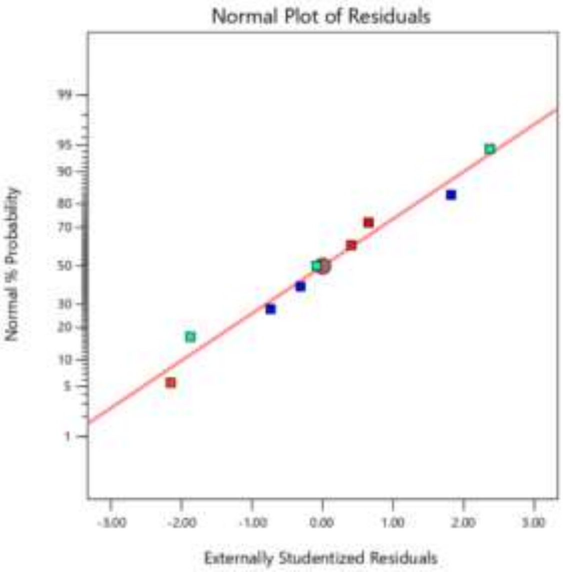

Fig. 11 The normal plot of residuals for spring constant.

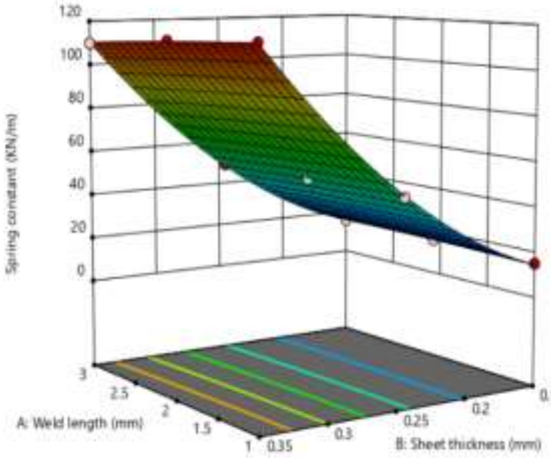

Fig. 12 The interaction contour of weld length and sheet thickness on bellows spring constant.

Investigating the P-values of weld length and sheet thickness indicates that both parameters are significant although the effect of sheet thickness is greater than weld length. Increasing sheet thickness causes to increase in the spring constant. The rate of variations spring constant under the effect of weld length is nearly constant compared to sheet thickness. Sheet thickness and weld length have a direct relation with the spring constant. Maximum spring constant occurs when the sheet thickness is maximum, and vice versa. Figure 12 shows the contour of interaction weld length and sheet thickness on spring constant.

3.4. Fatigue Life

As it has been displayed before, sheet thickness has a greater effect on the characteristics of bellows but due to its effect on deflection and spring constant, it can be indicated that it can bring certain limitations. According to the results and modified-goodman criteria, in weld length 2 mm with increasing sheet thickness from 0.15 mm to 0.35 mm, the life cycle of bellows increases from 2.95×10^3 cycles to 1.23×10^6 cycles. Also, in 0.15 mm sheet thickness with increasing weld length from 1 mm to 3 mm, the life cycle of bellows increases from 1.71×10^3 cycles to 3.90×10^3 cycles.

The increase in fatigue life is due to a decrease in stress and the maximum fatigue life with 1.23×10^6 cycles occurs in sheet thickness of 0.35 mm and weld length of 2 mm. The minimum fatigue life with 1.71×10^3 cycles occurs in sheet thickness of 0.15 mm and weld length of 1 mm, which shows that the effect of bellows design parameters is important on bellows fatigue life.

4 CONCLUSIONS

In this study, the effects of weld length and sheet thickness on the mechanical characteristics of welded bellows were investigated and the predictive models were constructed based on the response surface and ANOVA method. The summary of results is as follows:

- The results indicated that stress concentration occurs on the inside edges of the bellows where it is connected to the weld zone. Moreover, the acceptable range of the parameters was obtained.
- According to results, increasing sheet thickness and weld length causes a decrease in stress and deformation and increases bellows constant spring.
- It was realized that while both parameters affect the characteristic of bellows, the effect of sheet thickness was greater than that of the weld length.
- The effect of the parameters on the fatigue life of the bellows based on the modified-goodman criteria indicated that an increase in both parameters results in greater life cycles.

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