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The Effects of a Microhole in the First Convolution of a Bellows with Positive Rotation Angle on the Stress Behaviour

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A bellows is widely used as the element of an expansion joint in various piping system. It suffers from axial movement, lateral deflection and angular rotation caused by vibration, thermal expansion, etc. A bellows absorbs regular or irregular expansion and contraction. Although a number of studies on the behaviour of these movements for a non-defective bellows have been carried out, studies on this behaviour for a bellows with defect are very few. This paper studies the effects of a micro-defect on the stress behaviour of the bellows. While the distributions of micro-defect are various, the analysis is performed for the case, in which the defect is on the first convolution what is expected to incur the maximum stress. The von Mises stress distribution for the bellows and around the hole is obtained. In addition, the relationship between lateral deflection and positive rotation angle for the von Mises stress for the bellows with microhole is also obtained.

Key words: microhole, rotation angle, stress behaviour, lateral deflection.

1. Introduction

Stress analysis in the presence of defects and cracks is a vital part of failure assessment in the course of the service life of structures or parts weakened by defects. As distributions of defects and cracks are various, they pose quite a complicated stress analysis problem. Howland analysed an infinite plane perforated by a uniform row of interacting circular holes [1]. Since the appearance of Howland's article, a significant number of papers have been published dealing with a stress analysis utilizing numerical and analytical approaches in different regions containing cracks or defects. Haddon adopted complex variable and conformal mapping techniques to analyse the problem of two interacting unequal circular holes in an isotropic infinite plane [2]. Duan *et al.* introduced a complex body force density on the boundary of a hole [3]. Hu *et al.* studied the multiple-hole-crack interaction problem [4]. They modelled the holes and cracks as unknown pseudo-tractions and unknown distributions of dislocations, respectively, on the surface of these defects. A.R. Fotuhi *et al.* derived Cauchy singular equations for an infinite plane weakened by arbitrarily oriented curved cracks and cavities [5]. Most studies have focused on the stress analysis of a plane containing defects. Stress analysis for the defect in a plane is well researched, but insufficient research has been conducted on the stress caused by a defect in a curved surface. To analyse the stress caused by defects in a curved surface, the defect on a bellows is used.

The bellows is the flexible element of an expansion joint. It must be strong enough circumferentially to withstand the pressure and flexible enough longitudinally to accept the deflections for which it was designed, and as repetitively as necessary with minimum resistance. This strength combined with flexibility is a unique design problem that is not often found in other components in industrial equipment. Bellows are frequently used in pressure vessels or piping system, aerospace, micro- electro-mechanical and industrial systems, etc. They have the function of absorbing regular or irregular expansion and contraction in the system. and require high strength as well as good flexibility. The design, manufacturing and analysis of bellows are more complicated than of other general tubes. Numerous papers have dealt with various aspects of bellows failure, design, forming process and analysis. Kaishu Guan analysed and found the most probable reason for the failure of SS 304 bellows [6]. C. Becht IV reported the fatigue of bellows in a new design approach [7], and many other papers have focused on the design of bellows for manufacturing, and the bellows design itself. In the above references, it can be seen that the researches on the defective bellows are very few. This study analyses the stress behaviour caused by a defect on the bellows. As the bellows is loaded with combined tensile and compressive loadings during its service life, lateral deflection and positive angular rotation are used as boundary conditions. The study analyses the effects on the bellows stress of lateral upward deflection or lateral downward deflection with a positive rotation angle with respect to a micro-hole.

2. Analysis model

Figure 1 shows the bellows structure and the types of movement. Three types of movements: rotation angle (RA), lateral upward deflection (UD) and lateral downward deflection (DD) are used as boundary conditions. The micro hole is located on the top of the first root from the neck. Figure 1a presents the upward lateral deflection UD. The upward deflection in this study means that the lateral a)

b)

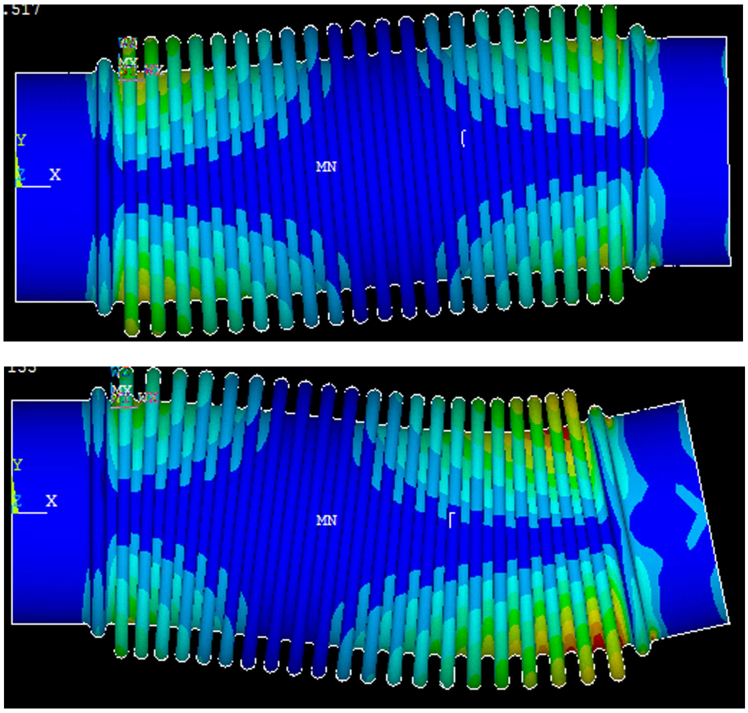

Fig. 1. a) Lateral UD, b) positive RA.

axis of the deflection is toward the microhole, and downward deflection means that the lateral axis of the deflection is in the opposite direction to the microhole. In addition, Fig. 1b shows a positive RA with no lateral deflection. In order to analyse the stress, RA is varied for a certain lateral deflection. One side is fixed, while the lateral deflection varies from 0 to 21 mm in an upward direction and a downward direction and the positive RA varies from 0 to 0.21 degree on the other side for the boundary conditions. The bellows is modelled with finite element code. It is meshed with eight-node shell elements and a elastic-plastic nonlinear analysis is performed. Table 1 presents the material properties and dimensions used in the analysis. The yield stress for the model used in the

Table 1. Material properties and geometric dimensions.

Tangent modulus [GPa]	Young's modulus [GPa]	Inner diameter of tube [mm]	Thickness [mm]	Diameter of microhole [mm]	Number of pitches	Type of element
1880	188	64.32	0.315	0.05	23	eight-node shell

* Height of first convolution: 4 mm, height of other convolutions: 10 mm.

study is 350 MPa and ANSYS was used as a FE-solver for stresses analysis. The height of the first convolution is 4 mm, and the others are 10 mm, and the pitch of convolution is 6.8 mm. The mesh consists of 112 800 elements or more.

3. Results and discussions

Figure 2 shows the von Mises stress of each longitudinal convolution line when a bellows is subjected to axial movement and these are the same results as those of Li Tingxin [8]. Figure 2a represents a top view of the von Mises stress distribution of the bellows, while Fig. 2b represents the von Mises stress distribution around the micro-hole by axial movement. In the case of a 1 mm axial movement, the maximum von Mises stress in the defect-free bellows is 18 MPa, and the maximum von Mises stress around the microhole in the bellows is 45 MPa, as shown in Fig. 2b. However, there would be a difference if lateral deflection and angular rotation were applied. The maximum von Mises stress due to lateral deflection lies in the convolution root near the neck on the extension

a)

b)

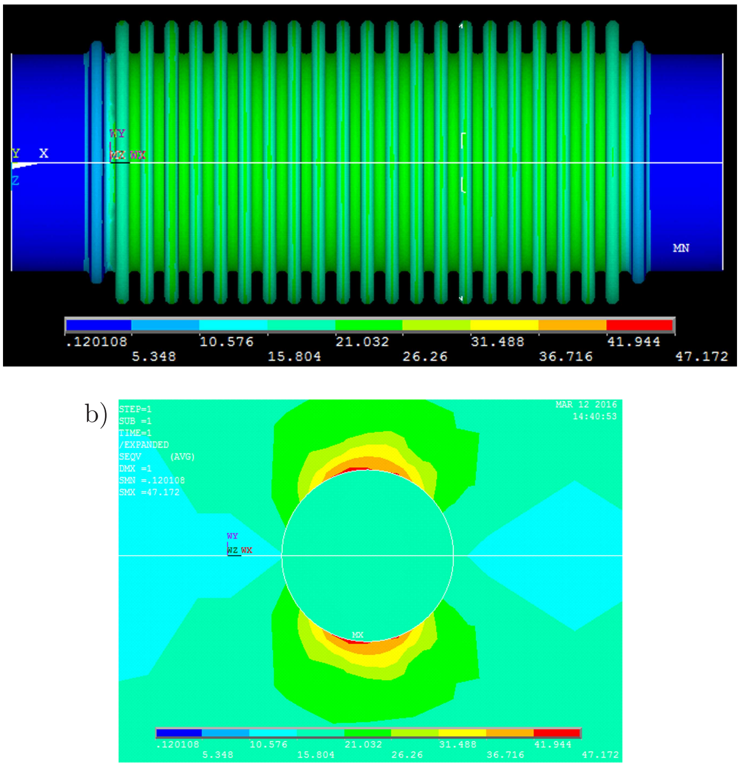

Fig. 2. a) σ_V by axial movement ($\sigma_{V\_\max} = 18$ MPa), b) σ_V by axial movement ($\sigma_{V\_\max} = 45$ MPa).

or the compression side at both end convolutions, and it is almost of the same magnitude in the four corners, as shown in Fig. 3.

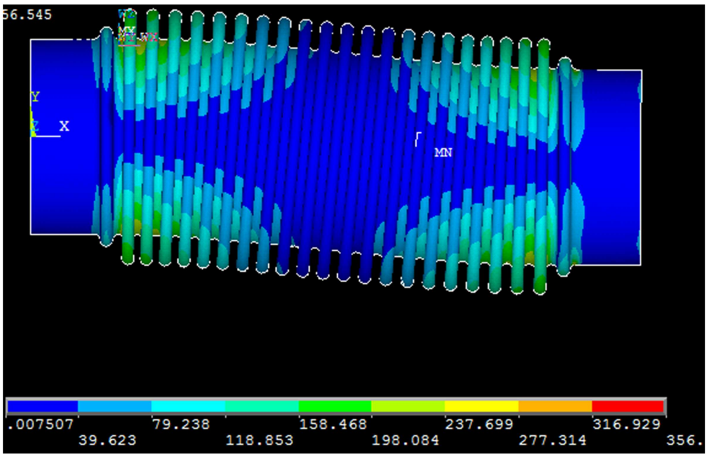

FIG. 3. σ_V by 0° RA and 7 mm DD.

In addition, the maximum von Mises stress due to angular rotation lies in the convolution root near the neck on the extension or the compression side at both end convolutions, and the stress distribution is different from each other in the four corners as shown in Fig. 4. Figure 5 presents the maximum von Mises stress $\sigma_{V\_\max}$ according to axial movement. The + symbol represents $\sigma_{V\_\max}$ in the case of a non-defective bellows, while ■ represents $\sigma_{V\_\max}$ around the hole tip. As the yield stress in the model is 350 MPa, the axial displacement by which the bellows yields can be known in Fig. 5. The axial displacement by which the bellows yields is 21 mm in the non-defective bellows, and 9 mm in the bellows with microhole. The stress concentration factor for the hole tip is 2.5 in this

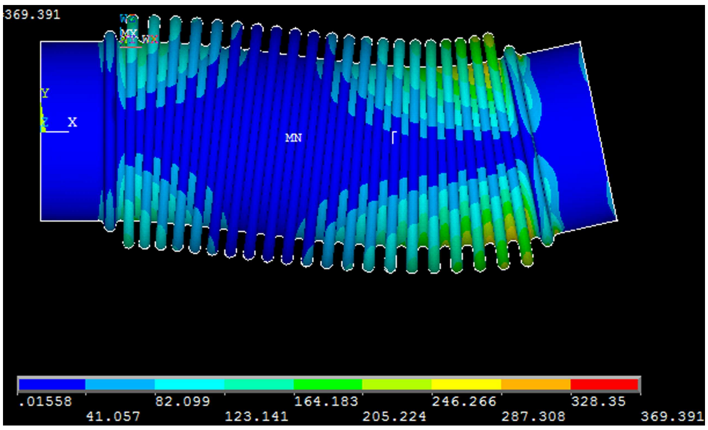

FIG. 4. σ_V by 0.07° RA and 0 mm DD.

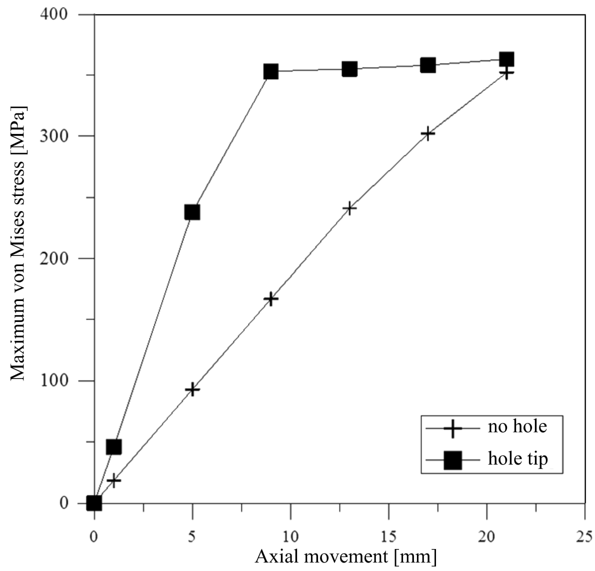

FIG. 5. $\sigma_{V\_\max}$ *versus* axial movement.

case. Figure 6 represents the maximum von Mises stress $\sigma_{V\_\max}$ at 0 mm lateral deflection according to the rotation angle. The symbol ■ represents $\sigma_{V\_\max}$ around the hole tip with lateral UD (σ_{vu}), □ represents $\sigma_{V\_\max}$ around the hole tip with lateral DD (σ_{vd}) and + represents $\sigma_{V\_\max}$ with no hole (σ_{vn}). The rotation angle by which the bellows yields is 0.09° in a defect-free bellows, with

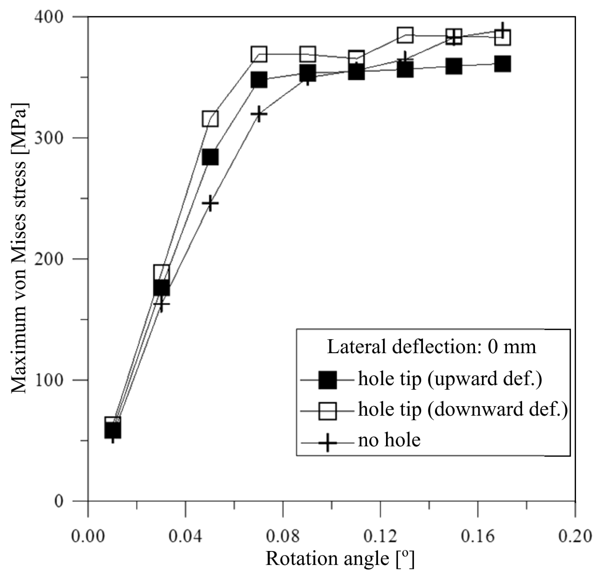

FIG. 6. $\sigma_{V\_\max}$ *versus* RA at 0 mm deflection.

0.07° in lateral DD and 0.06° in lateral UD. The stress concentration factor for the hole tip with DD is 1.2 in the case of angular rotation.

Figure 7 shows the relationship between the RA and deflection, in which the bellows behaves as elastic or plastic. Figure 7a represents the RA and DD relationship, while Fig. 7b represents the RA and UD relation. If the DD and RA are below the line, it is in the elastic range, while the upper part of line represents the plastic range, as shown in Fig. 7a. Figure 7b represents the elastic-

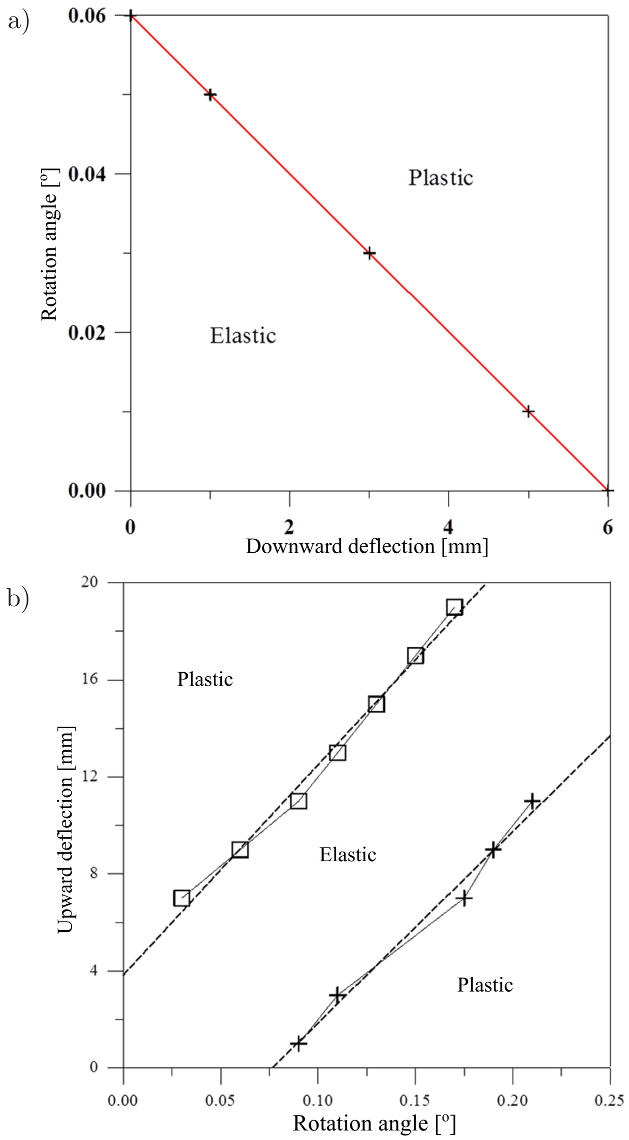

Fig. 7. a) Elastic-plastic boundary with DD and RA, b) elastic-plastic boundary with UD and RA.

plastic boundary with the UD and RA. The internal line segments are in the elastic zone and outside the area of the line is the plastic zone.

4. Conclusions

The results obtained in this study are as follows:

1. The stress concentration factor for the microhole in the bellows under axial movement is 2.5, and in the case of angular rotation it is 1.2. By comparing the results, it can be concluded that the stress concentration effects by axial movement are larger than those by rotation angle.
2. The elastic-plastic boundary with lateral deflection and positive rotation angle for the bellows is obtained.
3. The UD and positive RA relationship for which $\sigma_{V\_\max}$ of a non-defective bellows equals $\sigma_{V\_\max}$ around the hole is RA (degree) = 0.01 × UD (mm) + 0.02 for the model used in the study.

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