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Finite element prediction of the contact pressure distribution in a hydraulically expanded tube-to-tubesheet joint

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Abstract

The hydraulic expansion of the tube-to-tubesheet joints is modelled using a 2-D axisymmetric elasto-plastic finite element model. The contact interaction between the tube and the sleeve is handled by an in-house contact algorithm. The residual contact traction and the joint structural strength are examined against the expansion pressure and the initial radial clearance.

1. Introduction

The hydraulic expansion of tube-to-tubesheet joints is a common practice in the assembly of shell and tube heat exchangers. The basic idea of the expanding process is to deform the tube beyond the elastic limit while minimizing the plastic deformation of the tubesheet. Upon the release of the expanding force, the tubesheet material springs back more than the tube material exerting a residual contact pressure which holds the tube tight in the tubesheet hole. In terms of quality, the basic requirements of a successful joint are the leak-tightness and the low residual tensile stresses in the tube transition zone. On the other hand, a reasonable residual normal contact pressure is needed for the joint integrity.

Despite its long involvement in diverse industrial applications, the expanded joint still presents a serious source of loss of production in the power industry in particular. This deficiency is a result of the lack of a well-defined design procedure which is based on a full understanding of the complex deformation processes involved in the manufacturing and during operation. A detailed account of the related literature is provided by Abdelsalam and Dokainish [1].

Several experimental studies were conducted mainly to measure the holding force of the expanded joint against axial pull-out or push-in loads. Oppenheimer

[2] pointed out to the fact that the residual contact pressure is only a measure of the pure holding force. The thick-cylinder theory was used to estimate the residual contact pressure using measurements of the elastic recovery of the tube upon removal of the plate or vice versa. Grimison & Lee [3] found that there is a well-defined optimum for the joint strength which breaks off upon further expanding beyond a well-defined degree of expansion. The break-off the joint strength is thought to be a result of the smoothing action of the sliding surfaces during expansion as suggested by Fisher & Cope [4]. Another explanation to the same phenomenon was proposed by Abdelsalam and Dokainish [5] realizing the fact that even for the same material properties the rate of strain hardening of the tube material at the contact interface is faster than that of the tubesheet. This leads to increasing potential for the tube to spring back with a higher rate than that of the tubesheet which results in a lower residual contact pressure. A variety of measures for the degree of expansion have been suggested. Among these measures are the partial and total extrusion, wall-thickness reduction, increase in the tube inner diameter, mandrel travel and rolling torque [4,6]. Krips & Podhorsky [7] introduced the hydraulic expansion and used the hydraulic pressure as the measure of the degree of expansion.

The first finite element model appeared in the literature was presented by Wilson [8] where a 2-D axisymmetric model is adopted. This is followed by a 2D plane stress seven tube model [9-11] to account for the effect of the adjacent tubes in a tube-to-tubesheet attachment. A 3-D model is presented by Metzger & Sauve [12] where five rigid rollers were given a prescribed rotation and radial expansion. This was the first and only attempt to model the rolling process since the 2-D axisymmetric model takes care of the hydraulic expansion only. However, due to the complexity of the 3-D analysis, no relevant practical conclusions could be drawn.

This paper is aiming at fulfilling an industrial need for numerical simulations of the hydraulic expansion of tube joints. A 2-D axisymmetric model with 8-node isoparametric finite elements is adopted. An elastic plastic material model along with a kinematic work hardening criteria is used. The load is applied through a uniformly distributed pressure on the inner surface of the tube end within the length of the sleeve. The contact interaction between the tube outer surface and the tubesheet hole is handled by a robust contact algorithm which can deal with general contact problems in engineering applications. The effect of the expansion pressure and the initial radial clearance on the residual contact traction and the joint structural strength is explored.

2. Finite Element Model

Neglecting any out-of-roundness in both the tube and the sleeve, the mathematical model for the hydraulic expansion reduces to an axisymmetric deformation process. Figure (1) shows the geometry of the model and the mechanical properties of the material. Both the tube and the sleeve have the same mechanical properties.

A total of 560 isoparametric quadrilateral 8-node elements and 1988 nodes are used in the finite element model as shown in figure (2). The mesh is refined at the middle of the tube at the location of the transition zone where higher gradients for the deformations are expected. The displacement boundary condition is an axial constraint of all nodes on the left side of both the tube and the sleeve.

The contact interaction between the tube outer surface and the sleeve inner surface is accounted for using an in-house contact algorithm. In a general contact problem, neither the contact area nor the contact traction are known a priori. All what is known is that the contacting bodies should not overlap and the contact traction on the contact surfaces should be equal and opposite. In addition, if friction is to be included, the contact traction should follow a specified friction law. The basic idea of the contact algorithm is to apply the load incrementally and search for any compatibility violation. The contact constraint equations are formed for all detected overlapping nodes. Two equations per node, in the normal and tangential local directions, are needed for contact problems with friction. If the contact constraint equations are augmented with the system of equilibrium equations, we end-up having zero elements in the diagonal of the augmented coefficient matrix which represents a numerical difficulty. As such, the system of equations is solved on a matrix level for the incremental nodal displacement vector and the normal and tangential contact nodal force vectors.

Two nested iteration loops are designed to solve the contact problem in the normal and tangential directions within each global nonlinear displacement iteration loop. In the normal iteration loop, the normal contact forces needed to remove the overlap are obtained. All contact nodes with tensile normal traction are released. On the other hand, in the tangential iteration loop the tangential contact forces are estimated and checked against the specified friction law. The details of the algorithm and its computer implementation are given in [13,14]. This contact algorithm is implemented in a modular in-house general purpose finite element program, INDAP [15].

3. Results & Discussion

The factors affecting the integrity and the quality of the expanded tube joints are counted to more than 15 individual geometric, material and manufacturing factors. In this paper, it is assumed that the dimensions and the material properties have been already selected and kept constant. The only variables to be accounted for are the expansion pressure and the initial radial clearance. The focus is on the joint strength and its structural strength.

As reported in a previous publication [5], a 5x7 matrix of case studies have been executed in order to explore the main and interaction effects of the expanding pressure and the initial radial clearance. Based on these results, a new explanation was suggested for the break-off the joint strength if the tube is expanded beyond a well-defined optimum strength. In this paper, this explanation is enhanced by looking at the distribution of the residual contact pressure and the final shape of the expanded tube. This will be based on seven expansion pressure values and five initial clearance values. The expansion pressure runs form 25.5 ksi to 34.5 ksi in increments of 1.5 ksi. These values corresponds to 0.85 to 1.15 of the tube yield strength. The initial clearance values run from zero to .005 in in increments of .00125 in.

The results reported in this study are obtained from the execution of the general purpose finite element program, INDAP [15] on a silicon graphics work station IRIX 2.5. The average cpu run time for the finite element model shown in figure (2) is two hours.

One of the great advantages of the finite element method is its ability to track the deformation process during loading and unloading giving a comprehensive set of results for displacements, strains and stresses everywhere in the model.

In figure (3) the radial displacements of the inner and outer tube surfaces at maximum loading and after complete unloading are plotted. As can be seen, the tube is divided into three distinctive zones. The expanded zone, the transition zone and the rest of the tube. The deformed shape of the outer surface of the tube of the expanded tube is slightly off cylindricity. This becomes an important observation if we recall that the joint strength is composed of two distinctive ingredients. These are the residual contact normal traction and the resistance against pull-out or push-in loads provided by the sleeve as a result of being away form complete cylindricity. In figure (3), if the sleeve is held in place and the tube end is pulled to the right, the axial load at which the tube starts to slide away form the sleeve is called the pull-out load. On the other hand, if the tube is pushed to the left into the sleeve, the load is called the push-in load. For the particular case depicted in figure (3), the slope of the expanded tube suggests that the joint would be stronger in the pull-out since rather that the push-in direction.

In figure (4) the distribution of the maximum and residual contact normal traction is shown. Despite having a very high contact pressure at maximum loading the residual contact pressure is roughly 15% of its maximum value. The distribution of the contact pressure is almost uniform. It should be noted here that the wave shape of the distribution is due to the node spacings on the sleeve side. This would call for further mesh refinement but it is not necessary.

The effects of increasing the expansion pressure and the initial radial clearance on the residual contact force is shown in figure (5). The contact Force, F_n, in this figure is defined as the normalized integrated sum of the residual contact traction in the normal direction multiplied by the coefficient of friction and is given by

$$F_n = \mu \int_{A_c} t_N \, dA \; / \; \left[\pi (r_o^2 - r_i^2) \, S_y\right]$$

where,

- A_c is the contact area,
- t_N is the distributed residual normal contact traction,
- μ is the coefficient of friction (taken as 0.2 in this paper).
- S_y is the tube yield strength and
- r_o, r_i are the outer and inner radii of the tube, respectively.

The normalized clearance, c_n, shown in figure (5) is given by

$$c_n = (2c/d) * 100 , \qquad d = 2r_o$$

As the expansion pressure increases, the residual contact force increases to a well-defined maximum value beyond which any increase in the expansion pressure leads to a decrease in the residual contact force. The optimum value for the expansion pressure, for this particular geometry and material properties, lies between 0.9 and 0.95 of the yield strength. The reduction in the residual contact pressure is attributed to the effect of the strain hardening encountered by the tube and the sleeve at the contact interface as explained in Abdelsalam & Dokainish[5]. This behaviour agrees with the experimental results reported by Fisher & Cope [4].

On the other hand, the increase in the initial radial clearance decreases the residual contact force. Approximately, 30% loss of the residual contact force is encountered for a 0.005 in. initial radial clearance. This in fact is a result of the rapid increase of the tube spring-back due to the tube strain hardening before even touching the sleeve.

It should be noted here that there exists an interaction effect between the expansion pressure and the clearance. In other words, the effect of the expansion pressure is dependent on the clearance value and the effect of the clearance is dependent on the expansion pressure as illustrated in Abdelsalam & Dokainish[5].

Looking closely at the distribution of the normal contact traction, it can be observed that the increase in the expansion pressure beyond the optimum value shrinks the contact area in addition to the decrease in the residual normal traction as shown in figure (6). This observation is very important since it points-out two new results. Firstly, the explanation of the break-off the joint strength is enhanced where the decrease in the residual contact traction as a result of the increase in the tube potential to spring back and the decrease in the contact area are acting together to result in an overall decrease in the joint strength. Secondly, the increase in the expansion pressure beyond the optimum value not only decreases the holding force, but also defies the attempt to close the crevice completely.

In figure (7) the residual displacements of the tube outer surface is plotted for the different expansion pressure values. It can be observed that the slope of the expanded region is reversed as the pressure increases. This observation lead to the conclusion that the joint starts with a higher pull-out strength and as we use higher pressure, the slope is reversed and the joint becomes weaker in the pull-out sense and stronger in the push-in direction. This observation explains the discrepancy in the data obtained experimentally in pull-out and push-in tests.

4. Summary

The finite element method is used to study the contact pressure distribution in the hydraulic expansion of tube-to-tubesheet joints. A 2-D axisymmetric model is adopted along with an elastic-plastic material model and a versatile contact algorithm.

It is found that the increase in the expansion pressure increases the residual contact traction which adds up to the joint strength. However, as the pressure is increased beyond a well-defined optimum value, the residual contact traction decreases and the contact area shrinks leading to a decrease in the joint strength. In addition, the increase in the expansion pressure decreases the pull-out strength due to the slope change in the final shape of the tube expanded region. Moreover, the increase in the expansion pressure defies the attempt to close the crevice.

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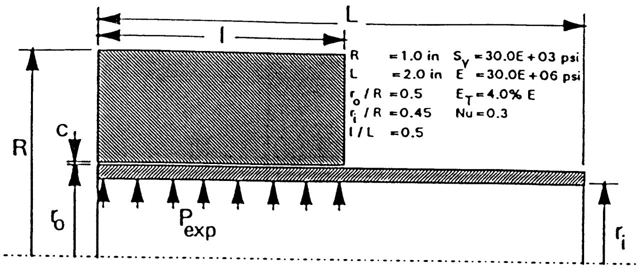

Figure 1: 2D Axisymmetric Matematical Model

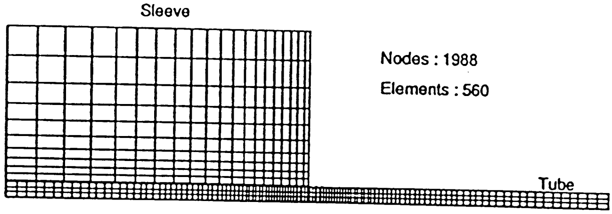

Figure 2: Finite Element Mesh

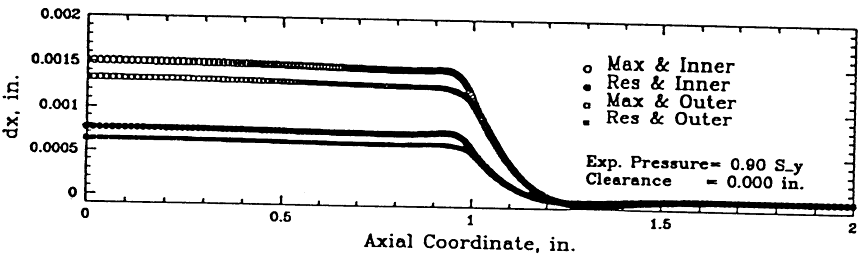

Figure 3: Tube Radial Displacement Distributions.

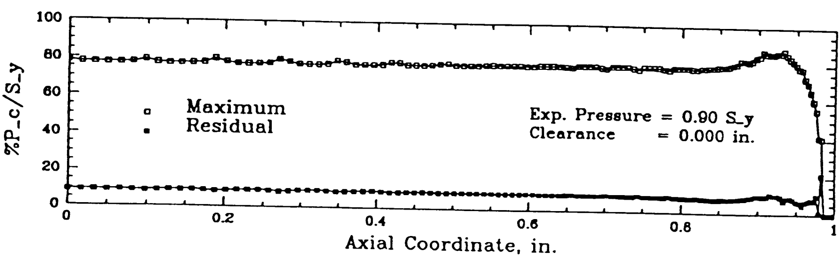

Figure 4: Distribution of the Contact Traction.

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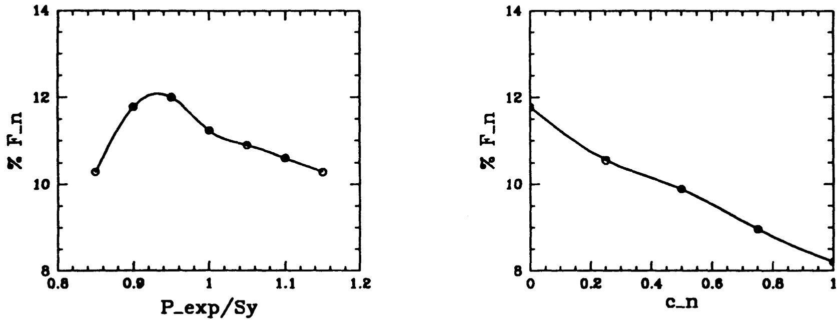

Figure 5: Residual Contact Force.

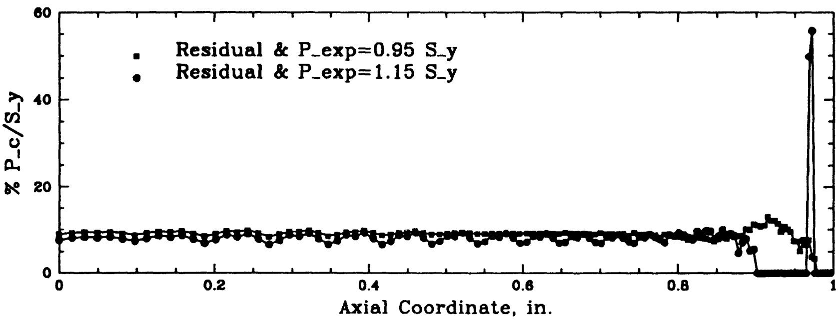

Figure 6: Distribution of Normal Contact Traction

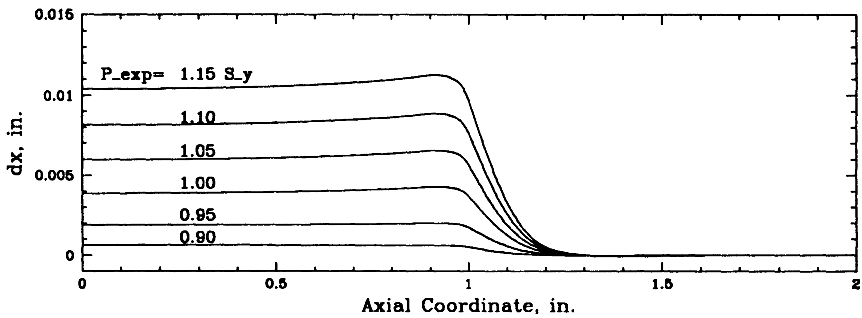

Figure 7:Residual Radial Displacement of Tube Outer Surface