Hydraulic Expansion of Tube-To-Tubesheet Joints ; A Finite Element Analysis

U.A. Abdelsalam* and M.A.Dokainish**

*Graduate Student **Professor
Mechanical Engineering Department
McMaster University
Hamilton-CANADA
L8S 4L7

ABSTRACT

The integrity and quality of tube-to-tubesheet joints are of a prime concern in the heat exchangers industry. These joints become extremely critical when it comes to the nuclear-power plants. Three main techniques are in use to produce these joints, namely, mechanical rolling, explosive forming and hydraulic expansion.

In this paper the hydraulic expansion of tubes into tubesheets is modeled by the use of the finite element method. The model consists of a single tube and a surrounding sleeve with two dimensional axisymmetric geometry. The uniform pressure loading is incrementally applied on the inner surface of the tube end within the sleeve. Von-Mises yield criterion along with isotropic work hardening rule is implemented to cope with the plastic flow of the material. The updated Lagrangian description of motion is implemented in order to account for the geometric nonlinearities. The frictional contact between the outer tube surface and the tubesheet hole is modeled without recourse to any gap elements. This modelling is achieved by the use of the contact algorithm in the general purpose finite element program, INDAP. Friction action is accounted for through the use of Coloumb's friction law.

Several case studies are analyzed in order to investigate the main and interaction effects of the maximum applied hydraulic pressure and the initial radial clearance on the integrity and the quality of the expanded joint. The joint integrity is looked at in terms of the magnitude and distribution of the residual contact pressure. On the other hand the quality is assessed through the residual stress distributions along the tube wall.

This study shows that the finite element analysis is capable of simulating the T/TS joint closely enough to be considered as a standard tool in a design code. It offers a new insight into the explanation of the break-off of the joint strength as the expanding pressure level is increased beyond a well-defined optimum value. Exploring the interaction effect of both design parameters on both performance measures, it becomes possible to accommodate the differing conclusions reported in the published literature.

As a result of this investigation, the designer would acquire a better understanding of the complex deformation process, assess the quality of the joint and predict the effects of changing the two design parameters on the integrity and quality of the joint.

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I. INTRODUCTION

Tube-to-tubesheet rolled and hydraulically expanded joint manufacturing resembles the expansion fit where the slightly oversize tube would be chilled, inserted in the hole and allowed to expand against the tubesheet by warming up. However, the tube oversize is produced by deforming the tube ends plastically. This is done mechanically either by a roller expander or a hydroswage.

The rolled or expanded joint has to meet two principle requirements, namely, the leak-tightness and the structural integrity. A good T/TS expanded joint would ultimately have high residual contact pressure between the tube and tubesheet and low residual tensile stresses in the tube transition zone. The high residual contact pressure contributes to the joint leak-tightness and structural integrity while the low residual tensile stresses adds to the joint quality where the stress corrosion cracking is likely to occur.

The making of the rolled or expanded tube joints is by far the most repeatable process in the installation of shell and tube heat exchangers. As such, the reliability of the expanding process is of a prime importance. This essential reliability can not be achieved unless the deformation process is understood adequately.

The process of tube to tubesheet attachment through the rolled or expanded joints has been practicized since the nineteenth century. Being deceivingly simple, it has not been given much attention until the first English literature on the subject was published in 1927 [1]. This is followed by several experimental, theoretical and , more recently, finite element analyses. A detailed account of the previous studies in the literature is presented in the companion paper by Abdelsalam and Dokainish [2].

From the early stages of research studies, attention was mainly focused on the evaluation of the joint pull-out strength and the definition of an optimum joint. It has been always believed that the joint strength has an optimum value corresponding to an optimum degree of expansion. This phenomenon has been demonstrated experimentally by Oppenheimer [1]. He also reported that the holding strength is inversely proportional to the initial clearance. The same phenomenon has also been reported by Grimson and Lee [3].

Fisher and Cope [4], relying upon a series of experimental tests, concluded that this optimum holding strength corresponds to an optimum elongation of 0.02 in and it decreases as the initial clearance increases. Culver and Ford [5], using a special test rig, concluded that initial clearance is not a major factor in joint strength. This result has been reported again by Gaffoglio and Thiele [6].

Aldred [7] presented a comparison between three expansion theories published by Goodier and Schoessow [8], Sachs [9] and Krips & Podhorsky [10]. These expansion theories adopt a 2-D plane stress model. The conclusion was that under the same joining conditions, the three theories predict widely varying values for the residual contact pressure.

Soler and Hong [11] developed a special purpose incremental computer code based on a 2-D plane stress model where the geometry is idealized by a set of concentric membrane elements with the innermost element being the tube. This code gives the maximum possible residual contact pressure for arbitrary combinations of tube and tubesheet geometries and material properties. A detailed account of the theoretical basis along with the FORTRAN code list are provided in Singh & Soler [12].

The finite element method has been involved in the analysis of the T/TS joint by Wilson [13] who used the general purpose finite element program MARK-CDC. The residual contact stress was found to fluctuate between tension and compression because of the presence of the gap elements. Chaaban et al. [14], using the finite element technique, concluded that the increase in the initial clearance decreases the residual contact pressure. However it is suggested that the level of the applied pressure should be studied further in relation to the relative strength of the tube and the tubesheet materials and the initial clearance.

Because of the occurrence of leak incidences caused by stress corrosion cracking, the importance of the residual tensile stresses in the tube material became an active subject for research. Toba [15] showed that large tensile stresses remain on the inside surface of the tube in the vicinity of the expanded joint and the initial clearance has a profound effect on the residual stresses. He showed that closely fitted test pieces reduce the residual stresses and show good results in stress corrosion cracking tests.

Bazergui and Lemarquis [16] showed that a tensile stress peak of the order of 45 and 80 ksi on the outer and inner surfaces, respectively, exists in the non-heat-treated roller-expanded tube in the transition area. Heat treatment reduces this peak significantly. Unfortunately, heat treatment reduces the interference contact pressure dramatically. Urgami et al. [17] reported that the residual tensile axial stresses are not dependent on the expanding pressure.

Updike et al. [18,19] presented a mathematical model which is incorporated into a computer program to calculate the residual axial and hoop stresses in the tube transition zone. They used that program to come to the conclusion that the residual stresses in the tube transition zone are weakly dependent on the degree of expansion. However it is directly proportional to the initial clearance.

Using the finite element method, Scott et al. [20] concluded that the residual stresses are insensitive to changes in the expansion pressure. Chaaban et al. [21], showed that the increase in initial clearance increases the residual stresses in the transition zone and decreases the residual contact pressure. However, they noted that this is not a general behaviour since it is suspected it is sensitive to the expansion pressure and material properties. Taking the first step towards a thorough parametric study, Ma et al. [22], using the statistical design of experiments and the finite element method, showed that the tube yield stress is the most significant factor affecting the level of the residual stresses in the tube transition zone. This is followed by the expanding pressure, the Young's modulus of the tubesheet material and the Young's modulus of the tube material. The initial clearance as well as the yield stress of the tubesheet are found to be less significant.

In the above mentioned literature, the expansion theories and the finite element analyses were meant to model the rolled joint. However these studies in fact model the hydraulic expansion more closely. The hydraulic expansion was introduced as a solution to the problems encountered with the roller expanding. The probe can be pulled-out with ease after the pressure has been removed. the expansion zones can be accurately defined. No additional tools are required in cases where contact between tube and tubesheet is to extend over great lengths in order to achieve complete crevice closure. Unlike the roller expanding technique, hydraulic expansion provides a basis for calculating the expansion pressure required to achieve a desired adhesion pressure. A detailed description to the hydroswage system is presented by Krips & Podhorsky [10].

The main objective of this paper is to investigate the main and interaction effects of two design parameters on two performance measures. The considered design parameters are the expansion pressure level and the initial clearance and the performance measures are the residual contact pressure and the residual tensile stress along the tube surfaces.

II. FINITE ELEMENT MODEL

The hydraulic expansion of T/TS joint is modelled using the finite element method. The main objective is to explore the effect of the expansion pressure and the initial radial clearance on both the residual stresses and the residual contact pressure. It is assumed that the tube and tubesheet geometry and materials have already been selected to meet certain performance criteria according to the potential operating conditions. The task is to attach the tube to the tubesheet by expanding the tube using a hydraulic pressure applied on the inner surface of the tube and then unloading. A 2-D axisymmetric 8-node quadrilateral isoparametric finite elements with 2 d.o.f. per node are used. the total number of elements is 152 with a total number of nodes of 606. The uniform expanding pressure is applied incrementally using a multilineal time function with a total of ten load steps for loading and a single increment for unloading. The geometry, material properties, mesh and boundary conditions are shown in figure (1).

Unfortunately, the expansion process is in fact highly nonlinear in nature. Three different sources of nonlinearity are present, namely, geometric, material and contact.
In order to account for the geometric nonlinearities, in terms of large displacements and strains, the updated Lagrangian description of motion is utilized.

The material nonliearity is the result of the elastic-plastic character of the stress-strain relation. Since the plastic strains are path dependent, the solution has to be performed incrementally.

Neither the contact area nor the contact stresses are known a priori. Instead, all we know is that no overlap should occur and the contact stresses should be equal and opposite. This leads to the contact boundary conditions being in the form of inequalities and the problem becomes nonlinear.

Unlike the previous finite element analyses, the frictional interaction between the tube outer surface and the tubesheet inner bore is accounted for without recourse to any gap elements. Gap elements makes it necessary the matching between the surface nodes on both the tube and the tubesheet meshes. This restriction leads to the use of either very large number of elements for the tubesheet or to use elements with high aspect ratio. In other words, if we choose to use the gap elements we sacrifice one of two important qualities, namely, the run time economy and accuracy. In addition the residual contact stresses are found to fluctuate between tension and compression which is not acceptable in the contact region. The contact algorithm included in the general purpose finite element program INDAP uses the above mentioned two pieces of information along with the Lagrange multiplier method to perform an iterative scheme for solving the contact problem. The Coulomb's friction law is used with a coefficient of friction of 0.2 in all runs reported in this paper.

III. RESULTS & DISCUSSION

To start with, a 2^2 complete factorial experiment is adopted and it is found that there is a significant interaction effect between the initial clearance and the expansion pressure level. Since the 2^2 experiment results in a linear relationships, centre points were examined and it is found that the relations between the design parameters and the performance measures is strongly nonlinear. Therefore, it has been decided to examine several case studies within the range considered for both the expansion pressure level and the initial clearance.

A matrix of 63 case studies has been executed using the general purpose finite element program INDAP (Incremental Nonlinear Dynamic Analysis Program). Table 1 shows the cpu run time for each case where the average run time is approximately a three quarters of an hour. The rows of the matrix represents nine different values of the initial clearance while the columns correspond to different values for the uniform applied pressure. The clearances and the pressures are normalized with respect to the tube outer radius and the tube yield stress, respectively, as follows:

$c_n = (2c/d)*10^2$, $p_{en} = p_{exp}/S_y$ and $p_{cn} = p_c/S_y$

It should be noted that, in all presented plots, symbols represent the actual results obtained from the finite element analysis directly and lines represent sort of suitable polynomial fitting of these data points.

A comparison between the present analysis and two expansion theories is shown in figure(2). The joint strength is represented by the average value of the residual contact pressure distribution along the tube end outer surface. Figure(2) illustrates a completely new result which has never been reported in the literature; that is the possibility of detecting the peak-strength of the joint. This result has been reported previously using experimental techniques and attributed to the smoothening of the contact surfaces because of the relative axial sliding.

Unfortunately, this smoothening action could not be modelled by the finite element method. As such, it has been thought that the phenomenon of peak-strength of the joint can not be detected by methods other than experimental. However, the results of this study show that this is not the case and led us to think of a new explanation to the peak strength phenomenon.

Before going all the way into this task, let us first furnish an important piece of information which known a long time ago but never used in that perspective.

Goodier & Schoessow [8] presented a plot, based on their theoretical analysis, showing the effect of changing the relative magnitudes of the yield strengths of the tube and tubesheet materials. This plot is reproduced here in figure (3) for convenience. It can be seen from that figure that keeping the yield strength of the tubesheet material constant, as the tube yield strength increases, the residual contact pressure increases as well. This continues until we reach a certain limiting value of the tube yield strength beyond which the value of the residual contact pressure starts to decrease. Based on this result, Goodier & Schoessow concluded that a softer tube in a harder plate would be recommended.

How can we relate this conclusion to the results reported in this paper? Well, let us go back to the material properties used in the finite element modelling. We started with both materials having exactly the same material properties including the yield strength. As the expansion pressure increases, both the tube and tubesheet materials starts to deform. The tube material deforms drastically more than the sleeve and its yield surface grows rapidly with a rate higher than that of the sleeve. This can be seen in figure (4) which gives the effective stress at two different nodes on the tube and sleeve. The higher hardening rate of the tube material leads to an increase in the tube potential elastic recovery which ultimately leads to a decrease in the residual contact pressure.

This of course could not be demonstrated using the 2D plane stress models nor the axisymmetric models which use the gap elements. This peak appears to occur at an expansion pressure which equals the tube and tubesheet yield strength. However this last result is not a general statement since the analysis presented in this study assumes that both the tube and tubesheet are of the same material with exactly the same mechanical properties.

Figure (5) shows the effect of the expansion pressure level on the residual contact pressure for different values on the initial clearance. It can be seen that the same phenomenon of having a well-defined strength peak is clear for all clearance values considered. On the other hand, figure (6) shows the residual contact pressure as a function of the initial clearance at different values of expansion pressure. As would be expected, increasing the initial clearance decreases, significantly, the residual contact pressure since large clearances would enhance the hardening action on the tube material.

The maximum residual tensile stress has always been found to occur along the tube inner surface in the axial direction. Figures (7) and (8) give its value as a function of the expansion pressure and the initial clearance, respectively. In both figures, the interaction effect is obvious. For instance, at zero clearance, a 10% increase in the expansion pressure leads to about 50% increase in the maximum residual tensile stress. This reduces to only 10% at a clearance of 0.01 in.

IV. CONCLUSIONS

The hydraulic expansion of the tube-to-tubesheet joint manufacturing process is simulated by the use of the finite element method. Using a 2-D axisymmetric finite element model along with the general purpose finite element program INDAP, the following conclusions can be drawn:

1. By the proper usage of the finite element method, the phenomenon of having an optimum joint strength can be detected. This result could not be obtained by either the expansion theories nor the previous finite element studies.

2. Moreover, the results presented in this study offers a new explanation to the existence of a peak joint strength. This explanation relies upon the difference between the tube and tubesheet materials hardening rates.

3. Increasing the initial clearance decreases the strength of the T/TS joint significantly.

4. The maximum residual tensile stress is always on the inner tube surface at the tube transition zone in the axial direction. Increasing the initial clearance or the expansion pressure leads to a significant increase in the residual tensile stresses especially at lower clearances and pressures, respectively.

5. The interaction effect between the initial clearance and the expansion pressure is more pronounced for the residual tensile stress than the contact pressure.

NOMENCLATURE

E	Modulus of elasticity, psi.	E_{tan}	Tangent modulus, psi.
S_y	Yield strength, psi.		
a	Sleeve inner bore radius, in.	b	Sleeve outer radius, in.
c	Initial radial clearance, in.	c_n	Normalized clearance
d	Tube outer diameter, in.	h	Sleeve width, in.
p_{exp}	Expansion pressure, psi.	p_c	Residual contact pressure, psi.
p_{en}	Normalized expansion pressure $= p_{exp}/S_y$	p_{cn}	Normalized contact pressure $= p_c/S_y$
x	Radial coordinate, in.	y	Axial coordinate, in.

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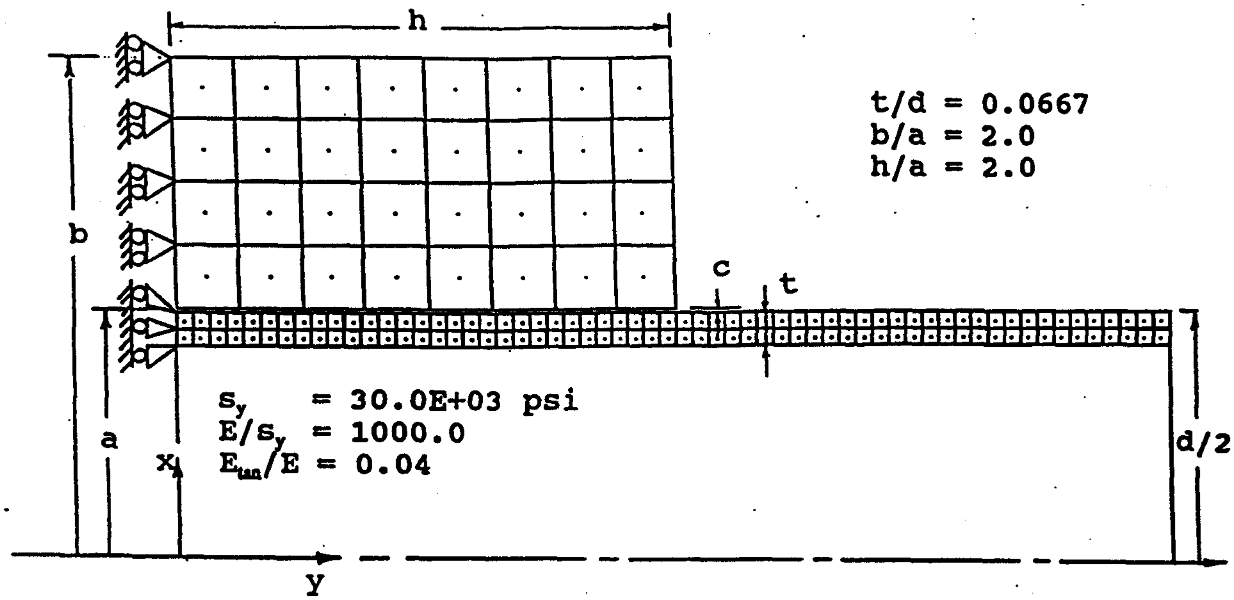


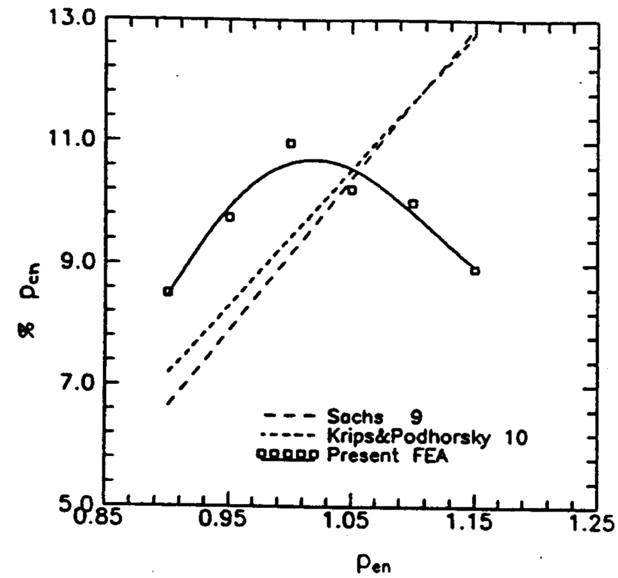
Figure(1): Geometry, Mesh and Boundary Conditions.

TABLE 1: CPU RUN TIME FOR THE MATRIX OF CASE STUDIES
hr:min:sec

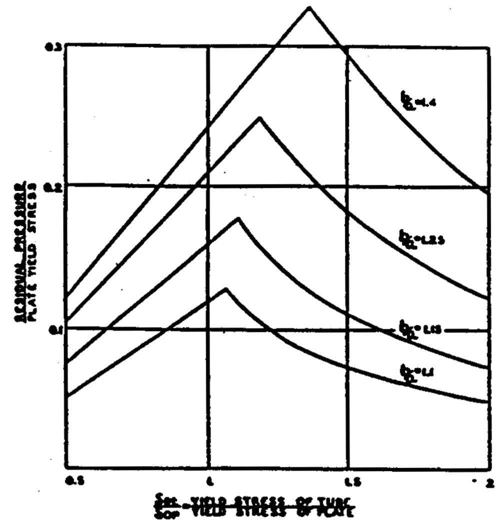
C_n \ P_{en}	0.9	0.95	1.0	1.05	1.1	1.15	1.2
0.0	0:23:07.38	0:23:49.56	0:27:18.34	0:29:38.23	0:43:21.32	0:41:41.16	0:37:29.54
0.25	N/A	0:44:11.39	0:44:31.21	0:55:22.92	1:03:01.40	0:55:03.57	1:06:29.26
0.5	0:35:05.32	0:40:35.80	0:49:00.99	0:50:04.32	0:56:11.18	1:03:53.70	0:59:03.16
0.75	0:34:40.28	0:35:21.05	0:41:02.85	0:45:15.46	0:59:35.34	0:57:54.97	1:00:47.78
1.0	0:32:18.57	0:35:54.24	0:37:17.28	0:45:13.52	0:49:49.41	1:06:40.92	1:06:57.42
1.25	0:34:16.17	0:34:47.86	0:36:49.77	0:42:02.28	0:52:11.82	0:52:20.80	1:13:31.97
1.5	0:35:51.96	0:40:48.86	0:36:11.54	0:44:22.79	0:48:35.74	0:51:52.21	0:57:34.99
1.75	0:35:35.95	0:37:27.91	0:40:51.67	0:40:50.64	0:45:58.95	0:52:04.15	0:58:09.04
2.0	0:37:34.67	0:36:33.16	0:36:52.21	0:42:48.07	0:48:01.60	0:48:36.16	1:00:00.08

Minimum :00:23:07.38
Maximum :01:13:31.97

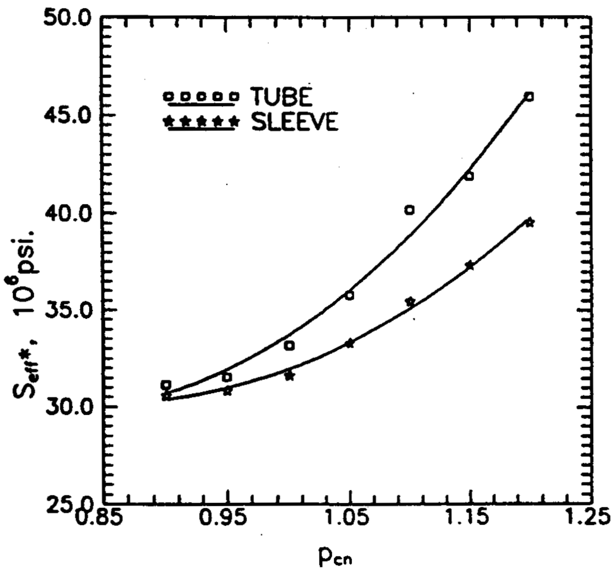
Total : 49:13:36.32
Average : 00:47:38.33



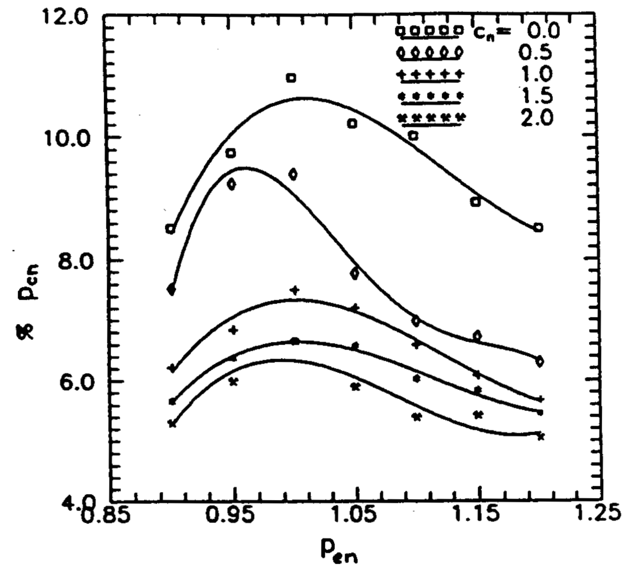
Figure(2): Comparison of Expansion Theories and FEA



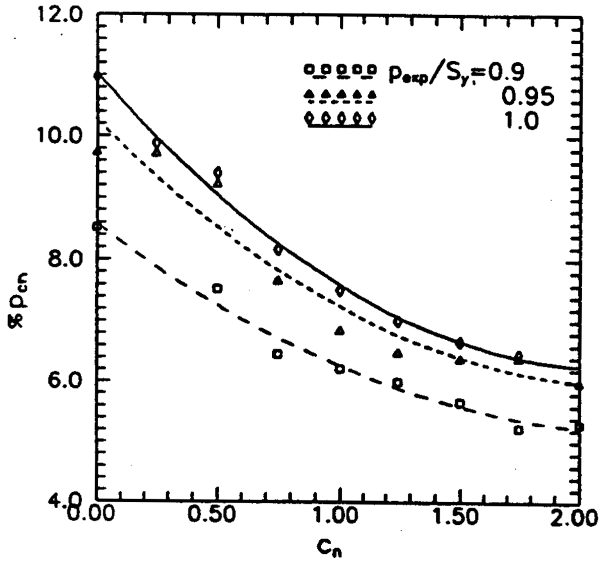
Figure(3): Effect of Hardening Tube.



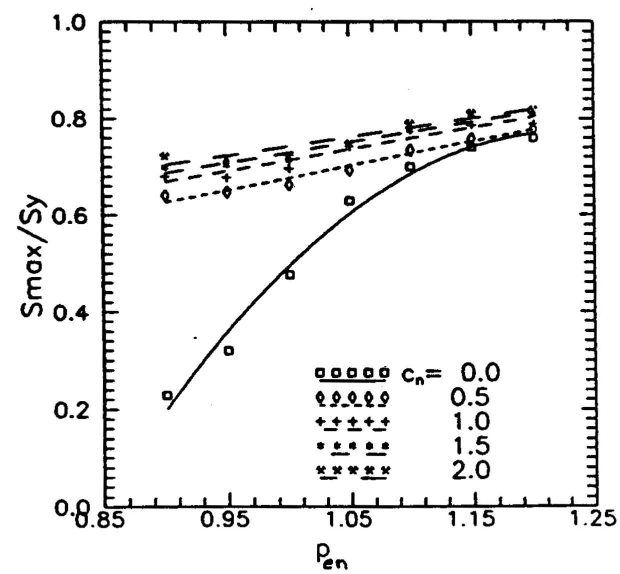
Figure(4): Tube and Sleeve Hardening Behaviour.



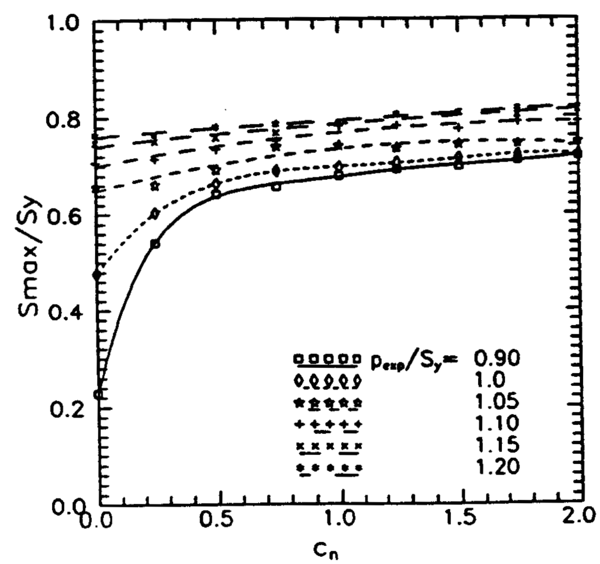
Figure(5):Residual Contact Pressure



Figure(6):Residual Contact Pressure.



Figure(7):Maximum Residual Tensile Stress.



Figure(8):Maximum Residual Tensile Stress.