ESTIMATION OF HYDRAULIC PRESSURE FOR EXPANSION OF HEAT EXCHANGER TUBES

D. P. Updike [*], A. Kalnins [*], and S. M. Caldwell [**]

ABSTRACT

The paper describes the development of a calculation procedure for determining the required hydraulic forming pressure for tube-to-tubesheet joints. The procedure has been incorporated into software, which is now being used in a fabrication shop environment. The bases for the computations, which are internal to the software, are principles of structural mechanics, easily measured dimensions, and material properties taken from mill test reports. The user of the software need not be well-versed in structural analysis. The basic idea behind the procedure is the separate treatment of the structural behavior of the expanded portion of the tube, the transition zone, and an axisymmetric sleeve model of the tubesheet. Precalculated solutions of the tubesheet are stored in nondimensional form in a data base. When these results are needed, they are retrieved from the data base, interpolated, and dimensionalized. Displacements and forces are then matched for equilibrium and compatibility during the hydraulic pressure cycle on the expanded section of the tube. The software, which produces results in a matter of seconds, calculates the peak hydraulic pressure, final dimensions, final contact pressure, and transition zone residual stresses corresponding to several degrees of expansion. After examining the trends, the user can select a desired degree of expansion and record the hydraulic pressure to produce it. This avoids the risk of overexpanding the ligaments in exchange for a very small increase in final contact pressure or holding force. The paper also compares measured final dimensions of some successfully formed joints with those predicted by the analysis.

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1. INTRODUCTION

Tube-into-tubesheet expansion is a manufacturing process. Properly designed tube-tubesheet joints must be easy to manufacture, and they must provide adequate tightness against leaking and adequate strength against possible pullout or pushout failure. The production of acceptable joints results from selecting the appropriate expansion process parameters. These include: (1) selection of the type of process, e.g., hydraulic expansion, roller expansion, etc.; (2) selection of the degree of expansion, e.g., peak pressure, torque, etc.; and (3) the selection of the length of the expanded section and type of grooving. In the past, guidance has been provided from the results of testing expensive mock-ups and of predictions from theoretical structural analysis models. When a new material combination or joint size is encountered, the manufacturing engineer must either use a trial and test procedure or become familiar with the structural analysis methods in order to set the joint manufacturing parameters. It would be beneficial to the manufacturing engineer to possess software that performs the analysis without the need to build and understand fully a complicated structural analysis model. Such software should be based on an acceptable structural model with very few inputs, and it should produce results quickly on a personal computer.

An excellent discussion of joint construction is given in the textbook [1] and article [2] by Yokell. Yokell writes about constructing a tight joint by creating what is the equivalent to an interference fit between the tube and tubesheet. If the resulting contact pressure due to the interference fit is sufficiently large, a tight and strong joint is achieved. On the other hand, situations may arise where an interference fit is not achieved. A thermal shrink fit method for creating the interference fit would require prescribing unrealistic tolerances for the tube outside diameter and tubesheet hole. In practice, the interference fit is achieved by expanding permanently the tube outside diameter relative to the hole. Two common methods for expanding the tube relative to the hole are hydraulic pressure expansion and roller expansion.

2. HYDRAULIC EXPANSION

During hydraulic expansion, pressure is applied within the tube to first expand the tube to contact the surface of the hole, then to expand both the tube and the hole, and then release the pressure. If the permanent circumferential strain of the tube, beyond what is necessary for closing the gap, is sufficiently larger than that of the hole, then an interference fit has been achieved.

Fig. 1 shows a sketch of the internal pressure versus radial expansion curve for the inner surface of the tube during the process. In Fig. 1, curve OAB describes the behavior while the gap is still open. The change in slope at point B is due to the added stiffness from expanding the tubesheet after contact is made. Curve BCD corresponds to the expansion of the tube and tubesheet, with BC representing elastic behavior in the tubesheet and CD the elastic-plastic behavior, when a plastic zone is developed around the hole. Curve DE shows the recovery of the inside diameter as the pressure is removed. Often, this process is carried out in two loading cycles. The objective of the first is the locking of the tube; that is, the elimination of the clearance by using a low pressure cycle such as OABHJ of Fig. 1. The second cycle, which is a high-pressure cycle corresponding to curve JHCDE in Fig. 1, is applied to provide a tight joint. In order to achieve an interference fit, contact pressure between the tube's outer surface and the hole must remain at the end of the process. If there is no contact pressure, then an interference fit has not been achieved. This will be the case if the tube's outside diameter recovers (springs back) more than the hole diameter. Whether or not this occurs depends on a number of parameters such as the peak expansion pressure used, the geometry of the tube and tubesheet hole, and the elasticity and strength properties of the tube and tubesheet materials. Clearly, it would be advantageous to estimate the residual contact pressure on the basis of a mathematical model, so that such cases may be found out before building an expensive mock-up.

3. JOINT FORMATION BY ROLLING

When a rolling process is used, the tube is expanded by inserting an expander tool, usually equipped with several rollers. During each pass of a roller, the tube wall is squeezed between the roller and the hole. This causes the tube wall to stretch circumferentially and possibly also bend in the section being squeezed. It may also cause some expansion and out-of-roundness of the hole. Eventually, the tube is expanded sufficiently relative to the hole to eliminate the initial clearance between the tube and the hole. During each pass of the roller, additional plastic strain is created in the tube and possibly also in the tubesheet, with some elastic recovery taking place after each roller pass. Finally, the expander is withdrawn, leaving the tube expanded into the hole. If the process has been successful, there will be adequate contact pressure between the tube and tubesheet.

An important aspect of the residual contact pressure is its distribution. It must be remembered that the joint strength (pullout or pushout resistance) is related to the average contact pressure, whereas leak-tightness is related to the probability of creating a leakage path through a channel of low contact pressure. If the mathematical model used is an axisymmetric one, then the calculations do not indicate circumferential variations in the final contact pressure. Clearly, the process of rolling requires an analysis by a nonsymmetric model, not because the overall deformations introduced by the process deviate significantly from symmetry, but because the local deformation and the recovery of the final pass may do so. Fig. 2 shows a schematic diagram of the roller loading at the tube inside diameter when a five-roll expander is used. It is for the reason of lack of approximate axisymmetry that the present analysis with its very simple model is not suitable for the study of roller expanding. For roller expanding, a finite element analysis is more appropriate. Significant progress of modelling the rolling process without invoking axisymmetry has been made by Metzger and Sauvé [3].

4. STRUCTURAL MODEL

4. 1. Axisymmetric Model

The structural model consists of just a few carefully selected axisymmetric parts which may be modified to model a wide variety of sizes and materials. It is expected to produce acceptable results for hydraulic expansion, which has axisymmetric loading. However, even in the case of hydraulic expansion, the tubesheet ligaments that surround the tube do not form an axisymmetric structure with respect to the tube axis. The ligaments are replaced in the model by an equivalent axisymmetric structure, a sleeve, having its dimensions and material properties chosen so that the analysis of the expansion process yields acceptable predictions regarding the final joint integrity and tube residual stresses. For hydraulic expansion, the ligaments are the only nonsymmetric feature. Once that is adequately simulated, everything is truly axisymmetric for hydraulic expansion. That is why the results of this paper are restricted to hydraulic expansion. Many features of this model have been discussed in previous papers by the authors. Ref. [4] contains details of the development of the model; Ref. [5] gives a summary; Refs. [6] and [7] present parameter studies for the transition zone stresses and contact pressures.

The parts of the axisymmetric model are the sleeve, expanded sections of the tube, and the transition zone, as shown in Fig. 3. Once the axisymmetric model is constructed, it is loaded and unloaded to simulate the cycle of expansion pressure. Plastic behavior of both the tube and the sleeve must be treated; otherwise, no interference fit can be achieved.

4. 2. Sleeve

The axisymmetric sleeve model is used to model the tubesheet material which surrounds the expanded section of the tube. The sleeve is a concentric hollow circular cylinder subjected to effective contact loading over its inner surface. The dimensions and material properties of the sleeve are to be chosen so that the sleeve model provides the same structural resistance to expansion as does the real tubesheet consisting of the surrounding ligaments and perforated plate with or without tubes locked in place. As mentioned previously, tube locking refers to a light expansion to close the gap between the tube and tubesheet, prior to forming the tight joint. When the tubes are locked, the adjacent tubes themselves provide a stiffening effect that must be considered when determining the effective dimensions and material properties of the sleeve. An effective sleeve length accounts for the fact that the tube is expanded over only the portion of the tubesheet thickness that lies between the seals of the hydraulic expander. Both front and rear unexpanded portions may lie outside the seals of hydraulic expander. These features are demonstrated in Fig. 4. The required material properties of the sleeve are its modulus of elasticity E and Poisson's ratio ν together with its stress-strain curve over the range of small plastic strains. Since the tubesheet material lies at the boundary adjacent to the tube being expanded, the material properties of the sleeve are assumed to be those of the tubesheet material, even though the resistance of the adjacent locked tubes of a different material is taken into account. In the present work, the stress-strain relation is approximated by a bilinear curve described by three parameters: the modulus of elasticity E, the effective yield stress, and the slope of the curve in the plastic range as shown in Fig. 5. Elastic unloading is assumed.

The geometric dimensions of the model are the effective inner radius, the effective outer radius, and the effective length. The effective inner radius is the radius of the hole into which the tube is expanded. The effective outer radius and the length are chosen so that the sleeve model provides the same resistance to expansion as does the real tubesheet consisting of the surrounding ligaments and perforated plate. In the computer program, the actual dimensions (hole size, pitch, pattern, tubesheet thickness, and location of the hydraulic seals are entered by the user and the effective dimensions are calculated from the algorithms. A procedure for obtaining the appropriate dimensions and material properties for the sleeve is discussed in another publication [8]. Chaaban, Ma, and Bazergui have also discussed this problem (see [9] and [10]). The structural behavior of a sleeve may be readily worked out for an elastic-plastic material with linear strain hardening.

During unloading, the sleeve springs back, so that the material unloads elastically. The springback is calculated by the familiar formulas for elastic behavior of thick-walled cylinders. Details of the load-unload behavior of the sleeve are presented in [4].

4. 3. Expanded Section of Tube

The internal pressure loading serves to expand both the contact and transition zones of the tube. The material stress-strain relation is assumed to be modeled adequately by a bilinear curve in both zones.

While the gap between the tube and tubesheet remains open, the expanded zone of the tube behaves as a cylindrical tube under internal pressure alone. After the gap is closed, a contact pressure develops between the tube and the sleeve, so that the tube is then under both internal pressure and external pressure. Usually, the gap-closing deflection and the expansion into the tubesheet is sufficiently large to render the expanded zone of the tube fully plastic; hence a fully plastic state was assumed. Further deformation of the expanded portion of the tube is governed by equilibrium considerations, together with the von Mises yield condition. The effect of strain hardening is accounted for by raising the yield in accordance with the expansion taking place (see [4]). Solutions applicable to the present problem may be obtained by using the boundary conditions of internal and external pressure.

If unloading behavior of the expanded zone is assumed elastic, then the change in displacement at the outer surface is given by the thick-walled elastic cylinder formula. Since yielding may occur in the rolled zone upon unloading, it is necessary to check the residual stresses, to be sure that they lie within the strain-hardened yield surface. If it is determined that yielding occurs, then suitable corrections are made to ensure that the residual stress state lies on the yield surface. Details of the calculation are presented in [4].

4. 4. Transition Zone

The structural behavior of the transition zone is considered for two reasons. First of all, the expansion of the zone itself may require significant forces. Secondly, the tube expansion process produces significant residual stresses, which may be calculated from the model. Details of the model of the transition zone are discussed in [4].

4. 5. Expander

Work of hydraulic pressure is used as the energy source for the tube expansion process. The pressure is applied to the inner surface of the tube over a length located between the seals. During the expansion process, the pressure is increased to a set value, held for the specified dwell time, and then released. It is this set value of pressure that is the major objective of the present analysis.

4. 6. Load-Up

The loading on the tube parts has been previously described. Calculation of the behavior of the tube-sleeve combination requires the satisfaction of equilibrium of forces and the matching of displacements. The required equilibrium equations have been worked out in Ref. [4]. The displacement of the outer surface of the tube is found by adding the initial radial clearance to the displacement at the boundary of the hole.

The solution state at maximum outward displacement may be found in terms of a parameter which sets the severity of expansion. In the present work the contact pressure is chosen for the parameter. All the necessary force and displacements at the end of load-up may be readily calculated (see [4]).

4. 7. Springback and Selected Residual Stresses

The spring back analysis is carried out in same fashion as the load-up analysis. However, owing to plasticity, the behavior is somewhat different from that during load-up. Details are presented in Ref. [4].

The residuals are the values of the variables which remain after the pressure is removed. The springback solution is checked for possible yielding during unloading. If such yielding is detected, suitable corrections are made in the analysis.

4. 8. Selection of Material Properties

The elastic modulus and the strain hardening slope for various materials are available from a user-selected data base. The user enters the yield stress, since it is highly sensitive to the material heat treatment and prior strain hardening. It has been shown from our experience with the program that the yield stress must be known quite accurately if a good value of hydraulic pressure is to be found from the analysis. For this reason the yield stress used in the calculations is taken from the mill test reports for the given tube and tubesheet materials. For the present application, handbook minimum yield stress values, owing to their conservativeness for structural design purposes, are not appropriate.

5. USE OF BATCH DATA

For simplicity, it is useful to use just one pressure setting for hydraulic expansion of all tubes from the same lot. In the fabrication shop setting, a batch of tubes from the same lot, or even several lots would be measured. The batch might consist of a random sample of all the tubes. In a similar manner, a batch of tubesheet hole diameters and pitch may be established. The program allows the user to input, one-by-one, the results of each measurement of tube or hole. It then calculates statistics such as the mean, standard deviation, maximum, and minimum, which are presented as data for the pressure setting calculation.

6. DATA BASE CONCEPT FOR RAPID CALCULATION

A data base is used in which all the lengthy incremental elastic-plastic results are precalculated for the sleeve and the transition zone. These analyses are run using a set of variables treated as nondimensional variables. By using the appropriate nondimensional variables, the results are stored compactly in the database. The use of the database saves considerable computer time, since the lengthy incremental plasticity calculations need not be performed over and over again. The stored data represent the results of a loading by pressure into the elastic-plastic range. At the time of execution of the program, the data is retrieved from the database and interpolated as necessary. Having the load-displacement relationship in non-dimensional form, the dimensional relationship between load and radial deflection is obtained by multiplying the nondimensional variables by the appropriate scaling parameters. Details of this procedure are presented in [4].

7. USE OF PROGRAM IN SHOP

Before fabrication it is necessary to measure the actual dimensions of a number of tubes and tubesheet holes so that as manufactured dimensions are used in the calculations. It is also necessary to calculate the material properties from the mill test reports of the materials actually used. For carbon steel the strain hardening slope is taken to be very small, say 0.5% of the elastic modulus. For other materials the strain hardening slope can be estimated from the difference between the yield strength and the ultimate strength. Next, the configuration of the expander is selected. In particular, the location of the pressure seals relative to the tubesheet faces is noted, since this information is used in the calculation. The data is then entered into the computer, which then calculates the hydraulic forming pressure required to produce various degrees of expansion. With each degree of expansion is given the following calculated results:

1. apparent wall reduction m defined by

$$m = [d'_i - (d_i - 2c)] / 2t$$

where d'_i is the calculated final inside diameter, d_i is the original inside diameter of the tube, 2c is the original diametral clearance (hole diameter - tube outside diameter), and t is the tube wall thickness. In the program m is multiplied by 100% so that it is expressed as a percentage.

2. peak hydraulic pressure

3. final contact pressure

4. calculated final inside diameter

5. estimated pullout force

8. EXAMPLE

Data for one case in which the program was successful is given in Table 1. The information from Table 1 was then entered into the computer to produce the report given in Table 2. On the basis of that report, the swage pressure was selected at 34000 psi.

9. COMPARISON OF PREDICTED AND MEASURED DIAMETERS

After the swaging operations were completed, the inside diameters of several tubes were measured for comparison with the predicted values. These values are given in Table 1 in the case of the example given above. As is seen from Table 1, the predicted value of 0.628 in. agrees well with the measured values of 0.628 to 0.631 in.

10. DISCUSSION

In some other cases where the program was used to calculate the hydraulic pressure, the agreement was not quite as good. However, it is believed that strong and tight joints were produced in these cases. For these cases further calculations using modified values of the strain hardening slope predicted final diameters which agreed with the measured values. Thus, it is seen that the predicted amount of deformation which occurs during the swaging process is quite sensitive to the selected value of the strain hardening slope.

11. CONCLUSIONS

A computer program for use by shop personnel has been developed to calculate the required peak hydraulic pressure for fabricating a tube-to-tubesheet joint. Although based on principles of structural mechanics usually employed by those in a design office or university setting, the actual software can be used by shop personnel. Experience with the program has revealed that good control of material properties is a requirement for making a good selection for the pressure. An example has shown how the hydraulic pressure calculated by the program was used to form successful joints.

12. REFERENCES

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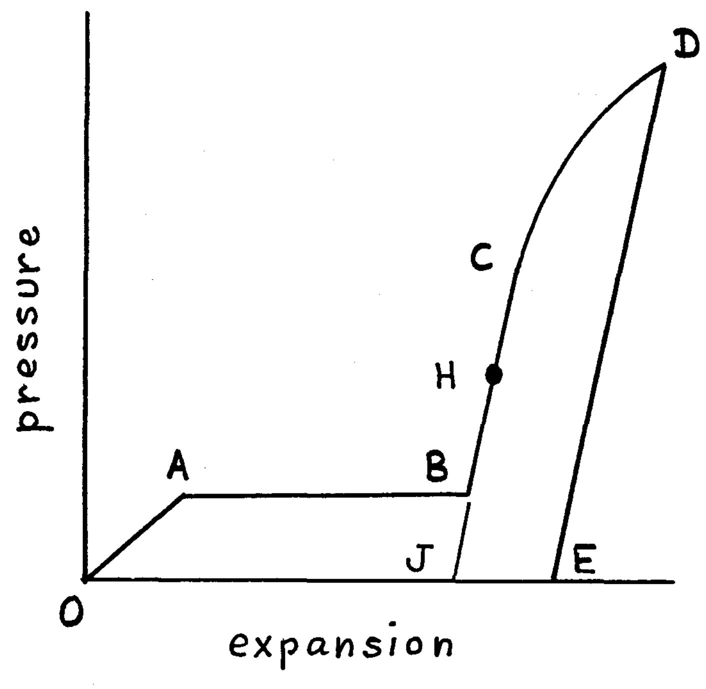

Fig. 1 Pressure vs. Expansion for Hydraulic Expansion.

TABLE 1: DATA FOR EXAMPLE

Conversion of Units:

1 in. = 25.4 mm
1000 psi = 6.895 MPa

Tube Data:

Tube Nominal O.D.: 0.750 in.
Nominal Wall Thickness: 0.065 in.
Measured O.D.: min = .750, max = .750 (10 measurements)
Measured I.D.: min = .618, max = .621 (10 measurements)
Material: SA 178-A-90A
Modulus of Elasticity: 29,000,000 psi
Yield Strength: 26,000 psi
Strain Hardening Slope: 3% of Modulus of Elasticity

Tubesheet Data:

Thickness: 2.625 in.
Swage depth: 2.25 in.
Pitch: triangular 0.9375 in.
Hole Diam.: min = .754, max = .756 (10 measurements)
Material: ASTM A516-86 Gr.70
Modulus of Elasticity: 29,000,000 psi
Yield Strength: 43,100 psi
Strain Hardening Slope: 3% of Modulus of Elasticity

Swaging Process

Peak pressure: 34,000 psi
Tube I.D. (after): min = .628, max = .631 (10 meas.)

TABLE NO. 2: REPORT FROM COMPUTER

This is KTZ Data File - Date: 07/30/93 Time: 16:50:25.16
TITLE: Example Problem of CNS Conf.

For TUBE: Pitch= 0.9375 1-Triangular KSHEL-TZ

TUBE DATA:	Tube OD	Thickness	Modulus	Yield	%Str-H
Current:	0.750	0.065	29000000	26000	3.00%

For TUBESHEET: Sleeve Dia. = 1.34362

TUBE SHEET:	Hole Dia.	Thk.	Clear.	Mod.	Yield	%Str-H
Current:	0.7557	2.625	0.0057	29000000	43100	3.00%

For EXPANDER:

Pressurized Length	Tube-side Unpr. L.	Eff. Sleeve Length
2.375	0.130	2.49

RESULTS:

DEX	Load-up Exp. Press.	Residual Contact Press.	I.D. of Tube After Exp.	App. % Wall Red.
3	33485.14	5670.80	0.62760	1.46 %
5	37393.61	6813.09	0.62878	2.37 %
7	38707.43	7093.77	0.63010	3.38 %
9	39683.90	7306.51	0.63143	4.41 %
11	41138.38	7298.83	0.63341	5.93 %
12	42102.63	7296.28	0.63473	6.95 %
13	43062.92	7295.35	0.63605	7.96 %

At DEX= 3, Selected Load-up Expansion Pressure= 33485

TABLE NO. 2, continued: REPORT FROM COMPUTER

RESIDUAL STRESSES IN TRANSITION ZONE OF TUBE: KSHEL-TZ
****

		MAXIMUM	MINIMUM
On the I.D. ==>	Axial Stress=	25930.83	2534.18
	Hoop Stress=	12529.28	-34202.29
On the O.D. ==>	Axial Stress=	-2534.18	-25745.24
	Hoop Stress=	-2924.53	-25512.68

Residual Contact Press.= 5670.80 Percent Wall Red.= 1.46%
Tube Pullout Force= 9272.58 Force to cause yield= 3636

I.D. of Tube:	before expanding=	0.6200	after=	0.6276
O.D. of Tube:	before expanding=	0.7500	after=	0.7574
Dia. of Hole:	before expanding=	0.7557	after=	0.7574

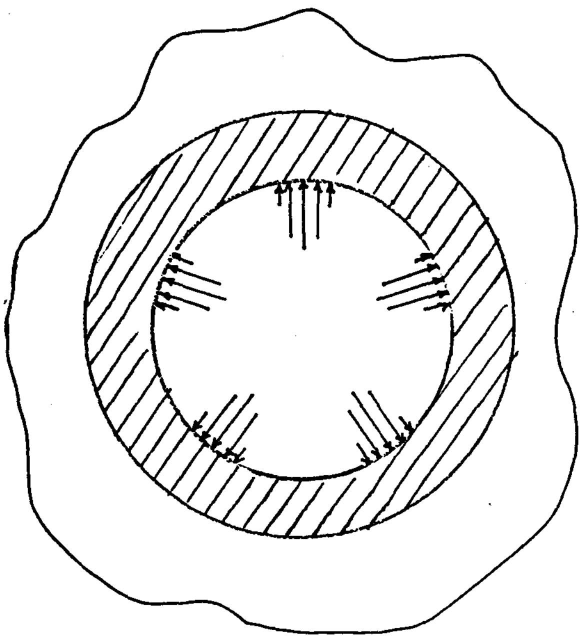

Fig. 2 Roller Loading Is Not Axisymmetric.

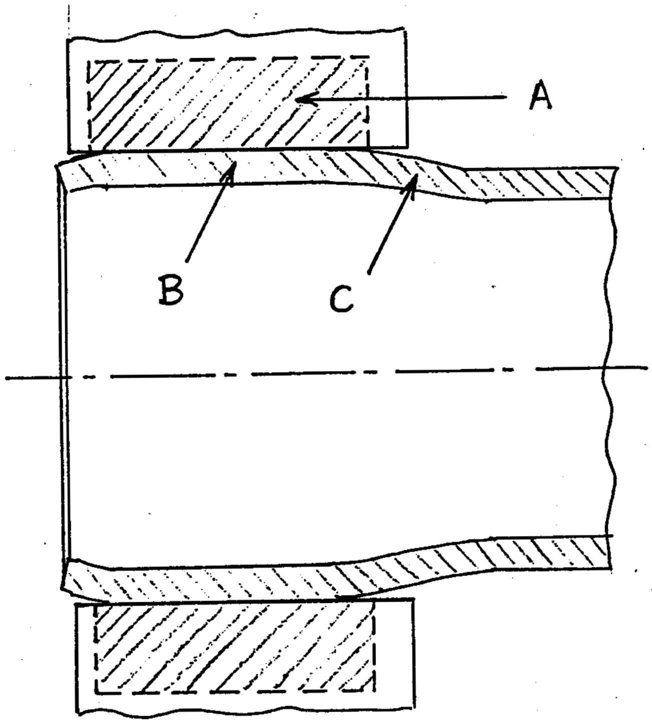

Fig. 3 Parts of Axisymmetric Model.
A. Sleeve
B. Expanded Section of Tube
C. Transition Zone

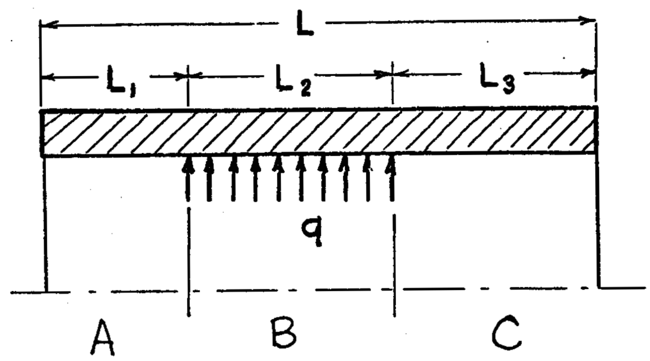

Fig. 4 Distribution of Contact Pressure on Tubesheet Hole.
A. Front Unexpanded Section
B. Expanded Section
C. Rear Unexpanded Section

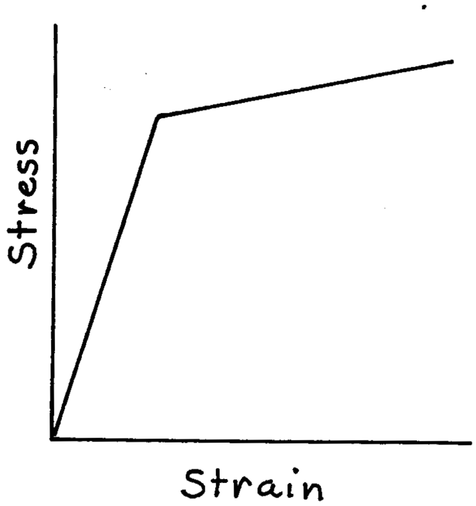

Fig. 5 Bilinear Stress-Strain Curve.