EXPERIMENTAL STRESS ANALYSIS OF AN EQUAL DIAMETER CYLINDER-CYLINDER INTERSECTION SUBJECTED TO EXTERNAL LOADS

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SUMMARY

In recent years a great deal of effort has been directed towards the development of theoretical solutions, and the accumulation of experimental data to predict the elastic and post-yield behaviour of cylinder/cylinder intersections subjected to internal pressure and external loads. Most of this work has been concerned with intersections having a mean diameter ratio $dm/Dm \leqslant 0.5$, and it has been acknowledged recently that further work is required on the range $0.5 \leqslant dm/Dm \leqslant 1.0$.

The present paper describes a programme of tests now underway on a series of five equal-diameter, flush cylinder/cylinder intersections. The tests will be complementary to a series conducted recently in the U.K. (see: E. Procter and J.T. Strong "Pressure Tests on Flush Cylinder-Cylinder Intersections: Elastic and Elastic/Plastic Behaviour." C.E.G.B. Berkeley Nuclear Labs., Rep. No. RD/B/N2244 Feb. 1972), together with a programme of work presently running in the U.S.A. (see: J.P. Callahan, "Summary of Studies of Nozzle-to-Pressure Vessel Attachments having Diameter Ratios (d/D) of 0.5 or Greater." O.R.N.L. Rep. May 1972). The parameters involved in the present study are as follows:

Model Number	Run Pipe Mean Diameter Dm (m)	Run Pipe Thickness (T mm)	dm/Dm	Dm/T ($= dm/t$)
1	10.55 (0.268)	0.15 (3.8)		70
2	10.28 (0.261)	0.42 (10.7)		24.5
3	10.05 (0.255)	0.65 (16.5)	1.0	15.5
4	9.75 (0.248)	0.85 (21.6)		11.5
5	9.40 (0.239)	1.25 (31.8)		7.5

Each of the five configurations has been carefully machined from carbon steel piping, prior to welding, and the above figures are the finished sizes.

The objectives of the tests are:

(a) To obtain elastic stress concentration factors for internal pressure loading.
(b) To investigate elastic stressing and flexibility of the junctions when subjected to a range of external loads.
(c) To investigate the effects of superimposing internal pressure and external loads, and
(d) To investigate post-yield behaviour under internal pressure. Information will be obtained on shakedown and limit factors for each of the junctions in the series.

The paper describes the technique that has been developed for the external load tests. A series of adjustable flanges are employed, through which the various loads can be applied, thus obviating the need for a large complex loading frame. The results of the first of the ex-

1. Introduction

In recent years an enormous amount of effort has been directed towards the development of theoretical solutions, and the accumulation of experimental data to predict the elastic and post-yield behaviour of cylinder/cylinder intersections subjected to internal pressure and external loads. The non-symmetry of the junction complicates the theoretical analysis, while combinations of the various dimensional parameters, would make a completely comprehensive experimental study an impracticable proposition. Most of the earlier efforts were concerned with junctions having a mean branch/run pipe diameter ratio $d_m/D_m \leq 0.5$, and more recently it has been acknowledged that further work is needed to cover the range

$$0.5 \leq \frac{d_m}{D_m} \leq 1.0.$$

The external loading on a cylinder/cylinder junction can be complex, consisting of combinations of any or all of the various load categories shown schematically in Fig. 1 (shear forces are not considered). This indicates that when axial thrusts, bending moments and twisting moments, applied either to the branch pipe or one or both of the limbs of the main pipe, are considered, then there are 12 different load categories involved. To complicate the issue still further, it has been suggested that the principal of superposition may not apply to cases of combined loading (i.e. internal pressure and external loads), although to what extent this is so has still to be clarified [1].

When designing pressure vessel components such as cylinder/cylinder junctions, in the absence of creep, it is recognised that there are three factors of importance, in addition to the basic properties of the vessel material. These are:

1. Maximum equivalent stress concentration factor (S.C.F),
2. Shakedown factor, defined as:

$$\frac{\text{Maximum load at which shakedown occurs}}{\text{Load for first yield}},$$

and 3. Limit Load factor, defined as

$$\frac{\text{Limit load}}{\text{Load for first yield}}$$

The Limit Load factor is of importance for vessels designed for a very small number of operating cycles, and relates also to the over-pressure tests that most vessels are subjected to. The Shakedown Factor decides at what maximum load or pressure the component will continue to operate elastically. The stress concentration factor allows a fatigue check to be conducted on the basis of the anticipated cyclic life of the component. The objective of present and past work, both theoretical and experimental, have normally been directed towards obtaining one or more of the above factors for some range of geometries and loadings.

There are a number of groups at present working on the development of suitable computational techniques using thin shell equations or finite element techniques, and some headway has been made in the case of the elastic analysis for internal pressure loadings and some external loads. [2] to [7]. This work has however been restricted so far to small diameter ratios and/or large diameter/thickness ratios. Lekkerkerker [8] has summarised recent analytical efforts to determine stresses near cylinder/cylinder intersections and concludes that the problem of the large diameter ratio intersection is far from solved.

Ref. [5] also reports on work being conducted in the U.S.A. into methods of predicting Limit Loads for branch connections. These include upper and lower bound methods for configurations with diameter ratios up to unity, and are applicable to internal pressure, and in-plane and out-of-plane moments. The techniques being developed appear to be confined to configurations where $\frac{D_m}{T} \geqslant 20$.

A series of internal pressure tests on 13 cylinder/cylinder intersections, manufactured as standard production units, has recently been completed by Proctor and Strong [9]. The configurations tested included one case with d_m/D_m of unity and the range covered was $0.25 \leq \frac{d_m}{D_m} \leq 1.0$. Elastic stress concentration factors were measured and compared with those used in Money's proposals [10]. Following the elastic tests, the post-yield behaviour of six of the branches was investigated and shakedown factors obtained. No external load tests were performed.

Having briefly summarised the past and present work, it appears that despite the considerable effort that has been expended on the problem, there is still a need for further experimental work on the large diameter ratio problem, particularly in view of the difficulties involved in producing a satisfactory analytical solution.

It is the writer's opinion that the tests described in this report, on a series of five equal diameter cylinder/cylinder intersections, can provide a useful contribution to the present knowledge on the subject. The series includes internal pressure and external load tests, and combinations of these in the elastic range, together with a study of post-yield behaviour under internal pressure.

2. Scope of Tests

The parameters involved in the present study are tabulated in the Abstract of this paper. The branch and run pipes are of equal thickness, and the diameter/thickness ratio varies in the range $7 \leq \frac{D_m}{T} \leq 70$.

2.1 Manufacture

There is no added reinforcement apart from the weld, the details of which are given in Fig. 2 for model 3 as typical of the series. Extension pieces of length 3 ft (0.91 m) are butt-welded to the three limbs of each of the junctions to facilitate the application of external loads. All pipes were subjected to a stress relief heat treatment in the as-received condition to minimise distortion during machining. Both pipes comprising each junction, have been machined inside and outside followed by boring of the general intersection shapes. Final weld preparation was by hand grinding. The junctions were then welded, followed by a radiographic inspection and a stress relief heat treatment. The extension pieces are welded in place on completion of the internal strain gauging.

2.2 Test Sequence

1. Each intersection will be subjected in turn to the external load categories indicated in Fig. 1. The results from these tests will include, (a) Distribution of stresses including the magnitude and location of the maximum equivalent elastic stress concentration factor (S.C.F), and (b) Flexibility factors where appropriate.
2. Each intersection will be subjected to internal pressure from which, in the first instance, elastic S.C.F.s will be obtained. These will be compared with the Money

curve [10] which indicates an S.C.F. range from approximately 3.0 to 5.0 for the present range of geometries.

3. Some tests, yet to be decided in detail, will be conducted to examine the case of combined internal pressure and external loading.
4. Each intersection will be subjected in turn to internal pressure post-yield tests from which Shakedown Factors and Limit Factors will be obtained. A check will be made on the amount of plastic flow at Shakedown.
5. Where possible the final bursting pressures for each junction will be obtained to give the margins of bursting pressure over Limit Pressure, the latter being defined by say 1% permanent strain at the highest S.C.F. location.
6. One alternative to item 4 above which will be considered, will be to investigate the post-yield behaviour of one or two intersections when subjected to say in-plane, or out-of-plane moments.

2.3 Strain Gauging

The gauges being used for the tests are 3-gauge, 45° rosettes with a gauge length of $\frac{1}{8}$ inch (3 mm). High elongation gauges are being used for the post-yield tests.

The question of locating the strain gauges to measure maximum stresses in each of the 12 external load categories is complex. In a recent test [11] on a 24 inch (0.6 m) diameter equal-tee, shaped junction, the maximum stress locations were found to vary considerably for the different external load categories applied. A total of 230 three-gauge rosettes were used in this test, and in another recent test [4] on an intersection having a d_m/D_m of 0.5, 322 three-gauge rosettes were used. Due to financial, time, and recording equipment restrictions it has been impracticable to consider using this number of gauges in the present test series, and a compromise has been reached in the case of the tests on Model No. 3 where 72 rosettes have been attached. These have been concentrated in one quadrant, with a few additional gauges to check for symmetry. Gauges have been located around the inside intersection line (crotch line), and on the branch and run pipes as near to the weld as possible, at intervals of $22\frac{1}{2}^{\circ}$ around the quadrant. The remaining gauges have been located mainly on these $22\frac{1}{2}^{\circ}$ generators to measure die-out of stress away from the junction, with some additional gauges located at 45° intervals around the junction.

2.4 Loading Technique

Initially the problem of designing a loading framework capable of applying all forms of external load to the junction appeared to be formidable, and although such frameworks have been designed for a similar task [11], the cost involved would have been too great for the present test series.

The problem has been overcome by testing two of the junctions together such that they each act as a support frame for the other. In order to apply the loads to the pipes and at the same time maintain circularity and minimal local stress at the load application points, a series of radially bolted flanges have been designed and fabricated. The technique for using these flanges is illustrated in Fig. 3 using the in-plane moment arrangement for Model 3 as an example. The radial set-screws have a knurled cup end such that when they are tightened up they bite into the pipe material. In this way, in-plane and out-of-plane moments, and axial thrust can be applied to the junctions. A pilot test was run to determine whether the set-screws were capable of taking the sideways thrust required for some tests, and the results confirmed that they could. In the case of the thinner models, internal flanges will also be utilised to prevent crushing of the pipes at the load application points.

2.5 Statement of Progress

Model 3 has been strain gauged and tests completed on in-plane, out-of-plane and twisting moment loadings applied to the run pipe. (Load categories 1, 2 and 3 in Fig. 1). Models 2, 4 and 5 have been welded and strain gauging is underway.

3. Discussion of Results

The following results relate to the in-plane (M_I), out-of-plane (M_0) and twisting moment (M_T) tests on Model 3. Each of the three loadings was applied through the run pipe, with no external restraint applied to the branch pipe. As can be seen in Fig. 3, the extension pipe was not welded to the branch pipe for these tests, so as to allow access to the internal strain gauges in the event of faults occurring.

3.1 Stresses

For each of the three load categories the moments were applied in about 8 increments. Strain gauge readings were produced on punched tape and fed into a computer programme which gave the following output:

1. Maximum and minimum principal stresses and their equivalent S.C.Fs.,
2. Angle of maximum principal stress,

and 3. Hoop and axial stresses and their equivalent S.C.Fs.

As would be anticipated, the principal stresses tended to be in the hoop and axial directions for the in-plane and out-of-plane moment loadings, but not for the twisting moment case. Principal stresses for the three load categories are therefore not directly additive. However to simplify the presentation of results at this stage, only hoop and axial stress distributions are presented in detail. The most useful form of presentation would appear to be that used in Fig. 4. This gives the hoop and axial S.C.F. (K in Fig. 4) distributions for the three load categories, around the junction,

a) at the crotch line,
b) on the run pipe adjacent to the weld, and
c) on the branch pipe adjacent to the weld.

(The S.C.Fs are defined on the basis of the nominal bending and shear stresses $\frac{M_I D}{2I}$, $\frac{M_0 D}{2I}$ and $\frac{M_T D}{2J}$ in the plane pipe).

Using the results in Fig. 4 it is possible to determine the stress situation at any point around the junction for any combination of the three load categories. It is important to appreciate that the signs of any of these distributions could be reversed, depending on the sign of the applied moment. For example it is clear that the point on the run pipe at $67\frac{1}{2}^{\circ}$ from the datum is important. It would be possible, depending on moment directions, to have additive axial S.C.Fs of 2.08, 1.65 and 5.55 for the M_I, M_0 and M_T cases respectively. The K_P values given in parenthesis in Fig. 4 are the maximum principle S.C.Fs at the points indicated.

In Fig. 5 the hoop and axial stress distributions for the three forms of loading are given for the transverse section of the junction.

In concluding the presentation of the stress results, the areas of maximum stress, are summarised in Table I.

3.2 Flexibility Factors

Since flexibility of pipework systems is important, flexibility factors have been determined for each of the three load categories in the directions of the applied moments. Flexibility factors K_θ have been defined as in (12).

i.e. Flexibility factor $K_\theta = \dfrac{\theta_e}{\theta_c/L}$

where θ_c = excess rotation due to branch

$= \theta_m - \theta_c$

θ_m = measured rotation over length L including branch,

and θ_c = calculated rotation over length L for plain pipe = $\dfrac{ML}{EI}$

Having determined K_θ for a given form of loading, the rotation over any length is then

$\theta = \theta_c + \dfrac{K_\theta M}{EI}$ for the in-plane and out-of-plane load categories and,

$\theta = \theta_c + \dfrac{K_\theta M_T}{GJ}$ for twisting moment.

Flexibility factors were determined in the tests by measuring the relative rotation of two rods welded to the run pipe on either side of the junction. These can be seen in Fig. 3 for the in-plane moment case. The results obtained are given in Table II. It should be noted that K_θ has units of length and hence values are given in Table II in both Imperial and S.I. units.

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Table I Maximum Stress Concentration Factors

Load Category	Maximum Equivalent SCF (K_p)	Location
In-plane-moment	3.48	Inside surface opposite weld (See Fig. 5)
Out-of-plane moment	1.68	As above and also at $67\frac{1}{2}^{\circ}$ on outside run pipe (See Fig. 4)
Twisting Moment	7.10	At crotch line, 45° from datum (See Fig. 4)

Table II Flexibility Factors

Load Category	Flexibility Factor K_θ in (m)
In-plane moment	59 (1.50)
Out-of-plane moment	26 (0.66)
Twisting moment	17 (0.43)

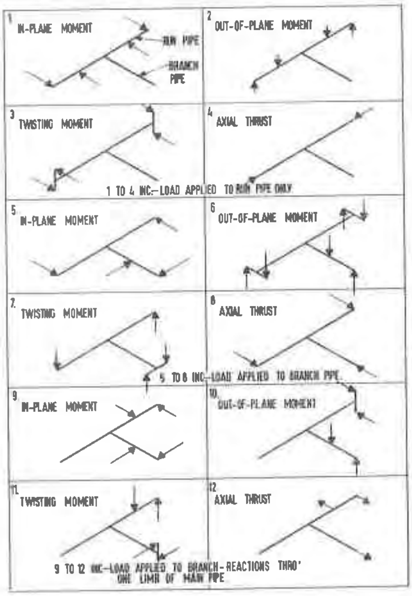


Fig. 1 Pictorial Description of Load Categories

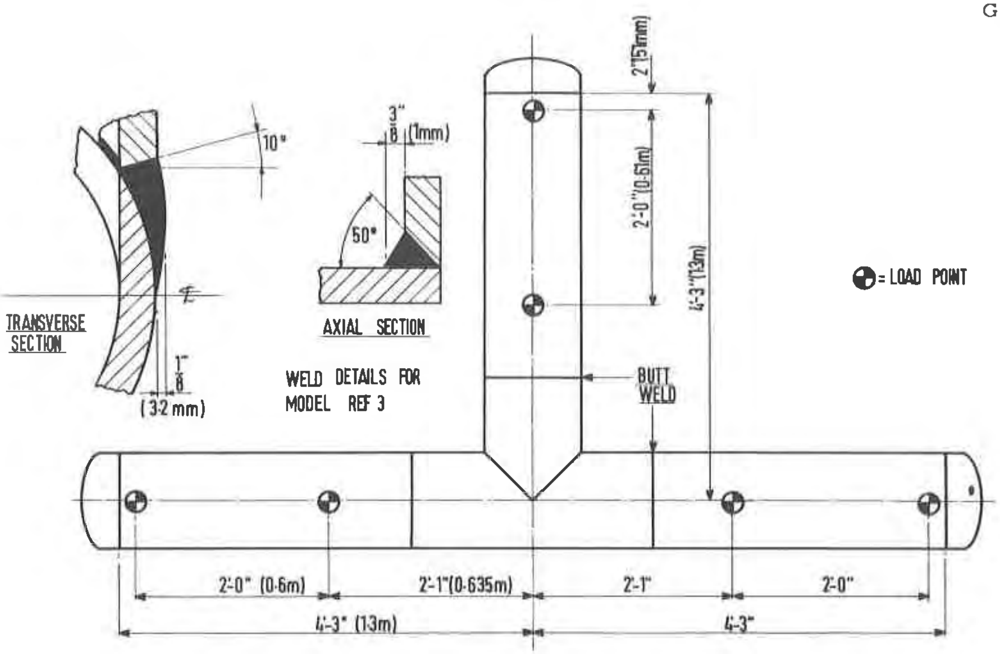


Fig. 2 Complete Junction with Extensions for External Load Application

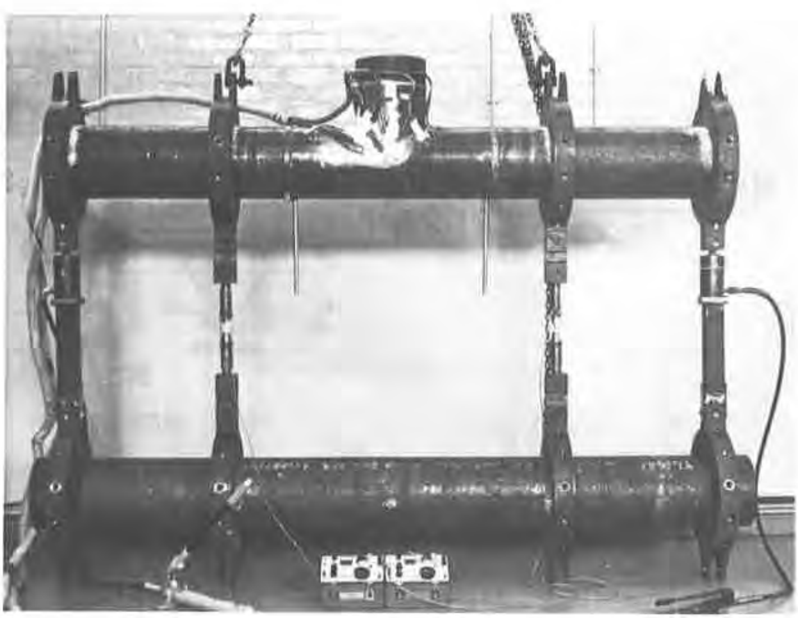


Fig. 3 Arrangement for In-plane-Moment Test

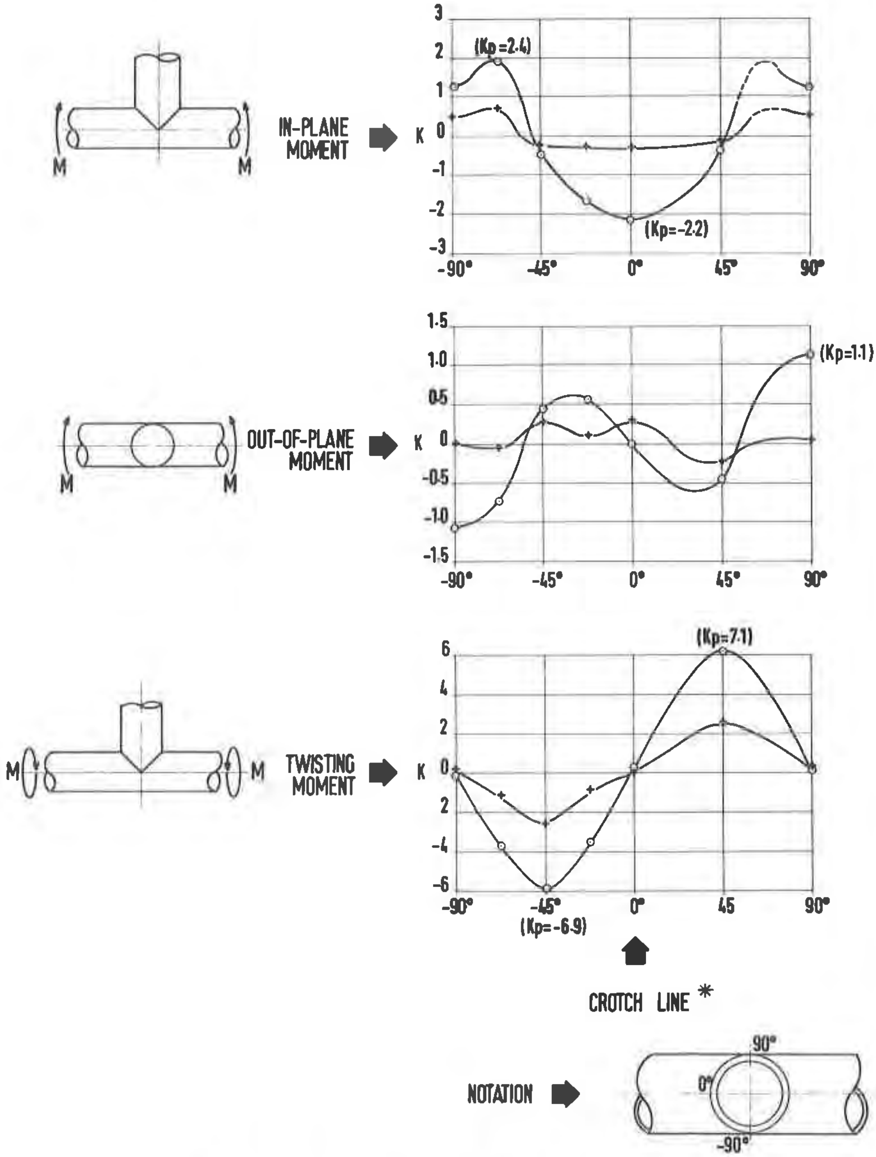
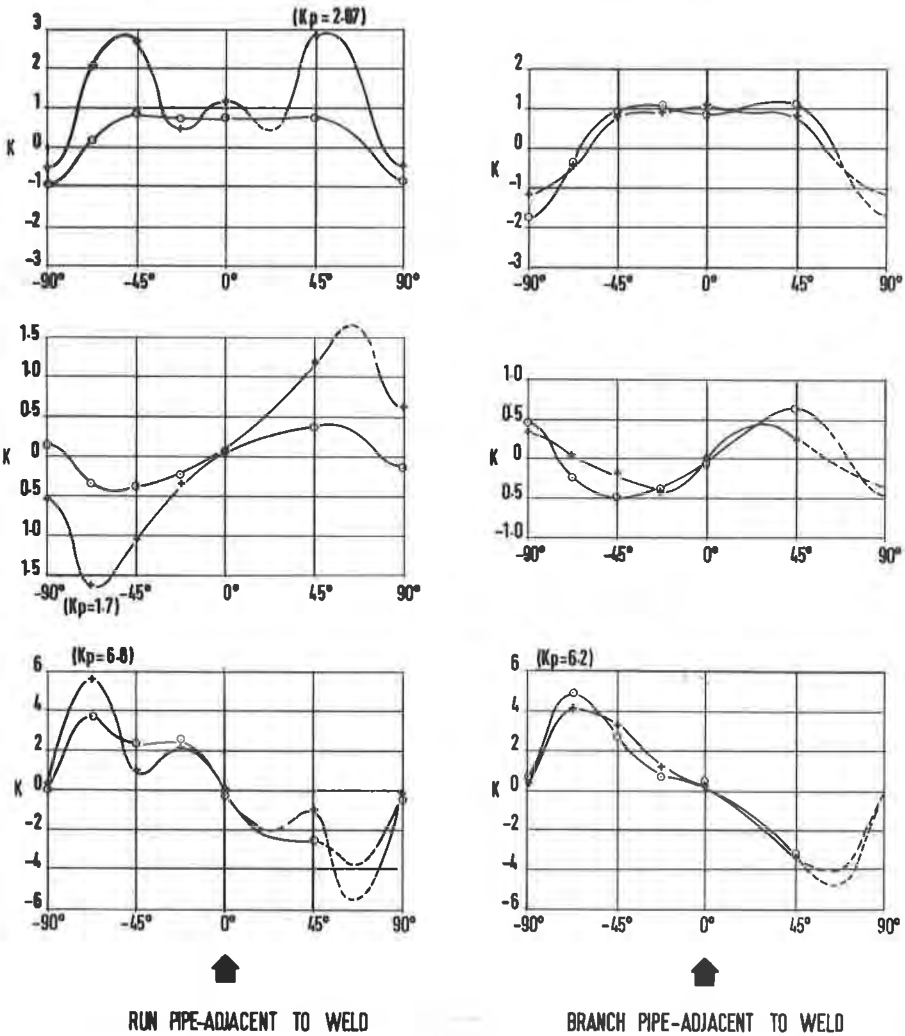


FIG. 4 STRESS DISTRIBUTIONS AROUND JUNCTION DUE TO IN PLANE, OUT OF PLANE, AND TWISTING MOMENTS APPLIED TO RUN PIPE.



○ HOOP STRESS
+ AXIAL STRESS

*NOTE:-
IN THE CASE OF THE CROTCH LINE, "HOOP" & "AXIAL" ARE USED WITH RESPECT TO THE BRANCH PIPE.

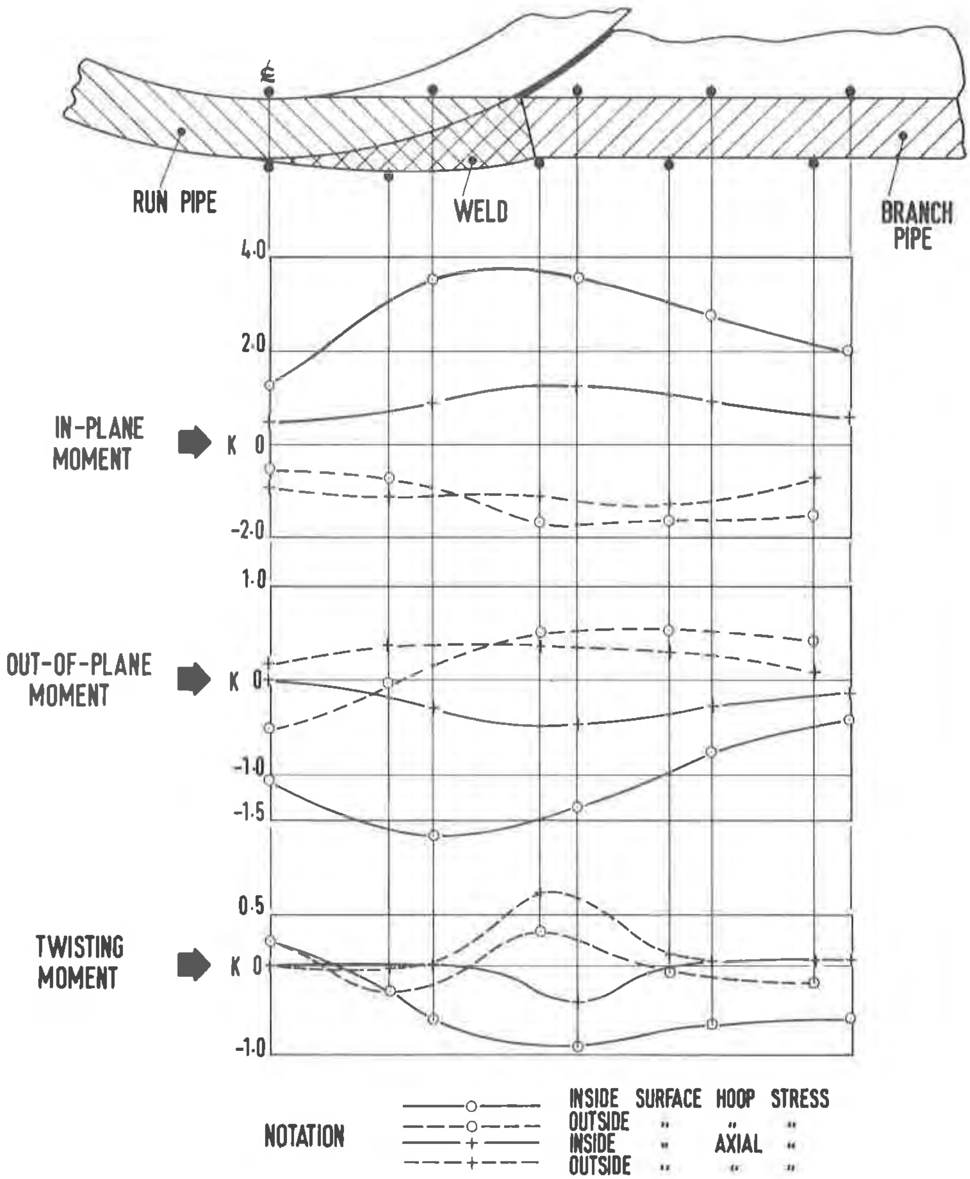


Fig. 5 Stress Distributions at Transverse Section