BEHAVIOR OF CRACKED BRANCH PIPES SUBJECT TO OUT OF PLANE BENDING

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ABSTRACT

This article presents the results of a test campaign on the behavior of cracked branch pipes subject to increasing out of plane bending. A number of tests were conducted to investigate the influence of a weld or of the internal pressure on the maximum or crack tear initiation loadings. To supplement the test results, a numerical analysis was performed to calculate the stresses around the junction and the values of J *and* K *for a semi-elliptical crack.*

KEY WORDS

Nozzles, Maximun load, Crack tearing, J integral.

INTRODUCTION

As part of a joint project between the CEA, EDF and Framatome, aimed to investigate the mechanical behavior of cracked branch pipes subject to out of plane bending, a series of tests named PIQFLEX was conducted at CEA/DMT. The objective was to investigate the initiation conditions of semi-elliptical cracks present at the intersection of the Tees and subject to increasing out of plane bending loads. Various configurations were adopted to analyze their influence on local behavior (crack tearing initiation) and global behavior (maximum loadings). They were concerned with the weld at the junction and the internal pressure. To limit manufacturing defects, the branch pipes were obtained by machining thick pipes. Spool pieces of the same material were added to deviate from the boundary conditions of the singular zones.

The material employed was a ferritic steel. The tensile tests were performed on smooth specimens and the ductile tearing tests were performed on CT specimens in order to complete the experimental base.

To back this experimental study, a numerical analysis was conducted to determine the stress and strain distributions in the volume surrounding the junction and containing the crack. The calculations were elastic or elasto-plastic, with or without cracks, and were carried out using a combination model developed for the test campaign. This model was validated by comparison with experimental measurements. The calculation also gave us the values of K and J for a semi-elliptical crack similar to the experimental crack, and for the initiation loading.

TEST CAMPAIGN

Preparation of Tees.

The mock-ups prepared represented 1/3 scale models of VVP branch pipes used in French PWR reactors. To demonstrate the influence of the welded joint on the behavior of the structure, two preparation methods were adopted. For weld-free branch pipes, the junction was machined in a thick TU52B pipe of ferritic steel (Figure 1). For branch pipes with a weld, a groove in the shape of the 45 degree Vee was machined along the line defining the intersection of the two cylinders, before finishing the junction. This groove was then filled with filler material by TIG electrode (Figure 2).

Finishing was carried out after stress relief heat treatment at 590°C. For some branch pipes, a notch was machined at the junction boundary using a 1 mm milling cutter to a width of 20 mm and a depth of 1 mm. Three spool pieces of the same material were then welded (Figure 3) to give the branch pipe its final dimensions. These were sufficiently long to prevent the flanges from disturbing the ovalization created by the out of plane loading.

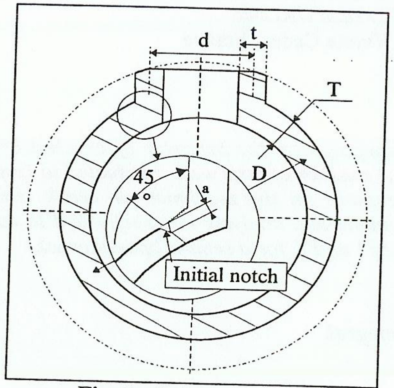

Fig. 1 : Tee preparation

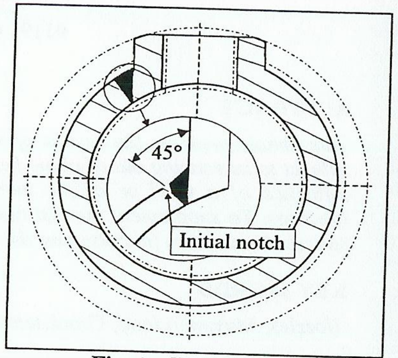

Fig. 2 : Tee with weld

Test matrix

Table 1 lists the tests performed for the series. Two different thick pipes served as the raw material for the Tees. This explains the differences in numbering of the mock-ups.

***Table 1** : Description of the tests*

Material	Branch pipe	Weld	Notch	Loading
pipe 1	2	no	no	bending
pipe 1	3	no	yes	bending
pipe 1	4	no	yes	bending
pipe 2	5.5	yes	no	bending
pipe 2	5.6	yes	yes	bending
pipe 2	5.7	no	yes	bending + pressure
pipe 2	5.8	yes	yes	bending + pressure

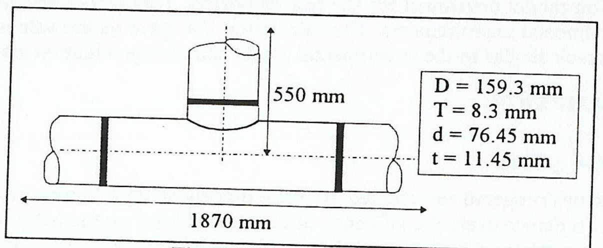

Fig. 3 : Global dimensions

Test procedure

The test consisted in imposing a displacement at the branch end using a slaved hydraulic press, with both ends of the run embedded.
However, if the branch pipe had a notch, a first pre-cracking phase was applied to create a crack from the notch. This was achieved by an imposed cyclic displacement at the branch end, with global behavior remaining elastic. Fatigue propagation of the crack was monitored visually and by measuring the Electric Drop Potential on either side of the crack (Figure 4).
With bending plus internal pressure loading, water was injected into the branch pipe before the bending of the Tee, up to a pressure of 12 MPa. This reproduced the membrane circumferential stress intensity induced in the branch of the real branch pipe.

Acquisition

Acquisition, which was carried out in the plane of symmetry of the branch pipe (Figure 4), consisted of displacements at Branch end U_1 and U_2, the three rotations β_1, β_2 and β_3, ten strain gauges (longitudinal and circumferential) J_1 to J_{10}, two ovalization measurements, and, in the presence of a crack, the crack opening angle and the EDP in the place of gauges J_9 and J_{10}.
The crack opening angle was obtained by means of two gauge clips mounted on brackets of different lengths (Figure 5) attached to either side of the initial notch. Note that no gauges were placed inside the branch pipe (gauges J_1 to J_4) if the test was conducted with internal pressure.

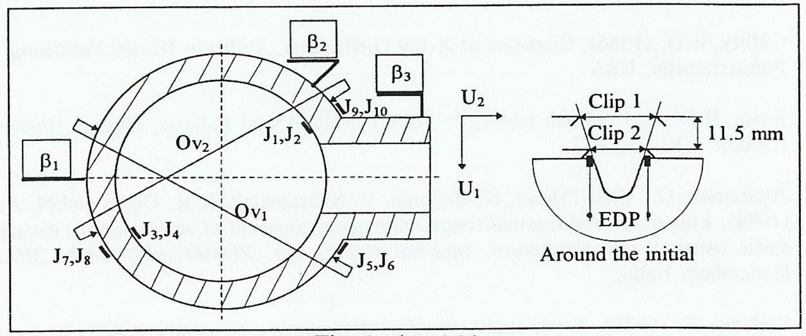

Fig. 4 : Acquisition

Results

Load/imposed displacement curves (Figures 5 and 6) : The experimental load/displacement curves show that the presence of a weld or of a crack does not alter the overall behavior of the structure, although the crack has propagated through the thickness of the run and penetrated its wall. Only the pressure tends to increase the strength of the Tee. This behavior is explained by the presence of local plastic buckling which occurs before the global limit load of the junction, and was already identified by [1,2,4].

If the branch pipe is subject to internal pressure, this radial displacement is limited [3,5], which increases the global rigidity. This is observed for branch pipe 5.7, up to the penetration of the crack, after which the internal pressure can no longer be maintained.

Comparison between the different tests : For each test, Table 2 shows the maximum loading reached at branch end by the branch pipe, the excessive strain loading, defined by the loading at which the imposed total displacement is equal to twice the elastic displacement, and, if the branch contains a crack, the propagation initiation loading. This is determined by the offset method on the opening angle/imposed displacement curve. This method is sensitive for this material and is confirmed by EDP measurements, but does not help to determine which propagation is associated with the initiation. The table conforms the results observed on the load/displacement curves.

Table 2 : Experimental results

Branch pipe	F_m (maximum) (kN)	F_e (excessive strain) (kN)	F_i (Crack initiation) (kN)
2	28.0	23.4	-
3	27.7	23.4	21.0
4	27.8	23.8	21.8
5.5	28.5	24.3	-
5.6	28.4	23.8	22.6
5.7	-	24.1	15.9
5.8	-	24.3	19.2

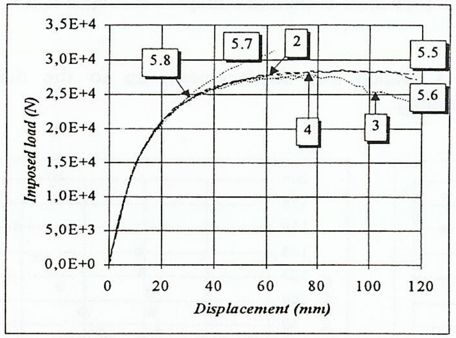

Fig. 5 : Load / Displacement curves

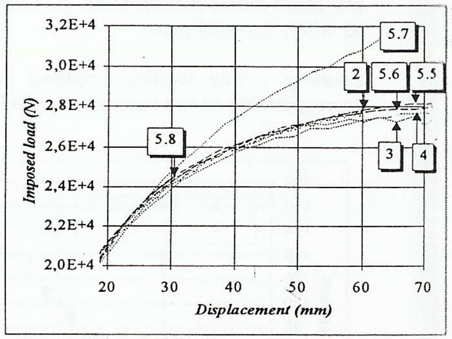

Fig. 6 : Load / Displacement curves (Zoom)

CHARACTERIZATION

Tensile curves

The two TU52B steel pipes which were used to prepare the branch pipes were characterized by means of tensile test specimens taken at the two ends of the pipe and in the axial and circumferential directions. The average characteristic values are given in Table 3.

Table 3 : Mechanical properties

Pipe	E (MPa)	σ_y (MPa)	σ_u (MPa)	$\sigma_{flow} = (\sigma_u+\sigma_y)/2$ (MPa)
1	197,000	370	680	525
2	212,000	332	563	

The properties of both pipes were similar. This explains the slight differences between the tests of the series (Figures 5 and 6).

J/δa curve

Ductile tearing tests were performed on CT12 specimens taken from pipes 1 and 2 in the longitudinal and circumferential directions, in order to determine the J/δa curve of the material and the J_{IC} values at initiation. The experimental procedure was the method of uninterrupted loadings, given by standard CFR [6,7], in which the J parameter is evaluated from the load/opening curve of the test, and in which δa corresponds to the average advance of the front after the test. The characteristic values obtained for pipe 1 are :

$$J_{0.2} = 223 \text{ kJ/m}^2 \text{ - } dJ/\delta a = 149.6 \text{ MPa}$$

The points corresponding to pipe 2 are slightly lower than those of pipe 1, and, if they are used to determine $J_{0.2}$, they only reduce the ductile tearing strength by 2 kJ/m². As for the tensile tests, the properties of both pipes are similar.

FINITE ELEMENT CALCULATIONS

A numerical analysis was performed to back the tests, in order to reproduce the measurementstaken, and also to demonstrate numerically the influence of the crack, of the weld, and of the pressure on the behavior of the branch pipe. The calculations were carried out using the Castem 2000 code [10] developed at the CEA.

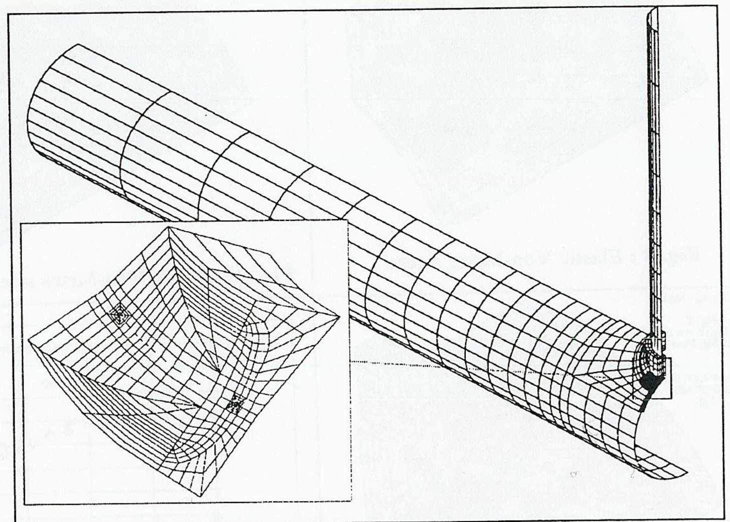

Fig. 7 : Mesh of a the Tee with defect.

Elastic modeling of branch pipe 2

A first calculation was performed to validate the meshing method employed, by comparison with the test without notch and without weld. To do this, the elastic behavior of the structure was compared with the global behavior, by means of the initial slopes.

Meshing : To limit the size of the calculation, a combination meshing principle was used for one-quarter of the branch pipes. Symmetry and anti-symmetry served to complete the structure. The mesh, consisting of quadratic isoparametric elements, has 820 massive elements with 15 or 20 nodes, 375 shell elements with 8 nodes, making a total of 5567 nodes.

Material : The elastic properties employed are : E = 197,000 Mpa - $\nu = 0.3$

Loading : Loading was an imposed displacement at branch end.

Results : Table 4 gives the calculation results compared with the elastic slopes of the different displacement transducers of the test and of the gauges present on the massive part of the mesh. The difference between the global response of the structure and that of the calculation is virtually nil. This validates the model employed. In general, on account of the experimental dispersions , the calculations results show very good agreement with the test results.

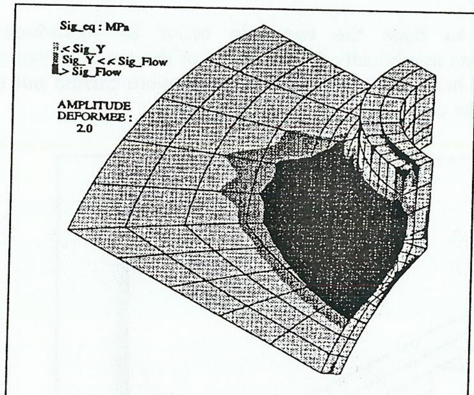

Fig. 8 : Elastic Von-Mises stress.

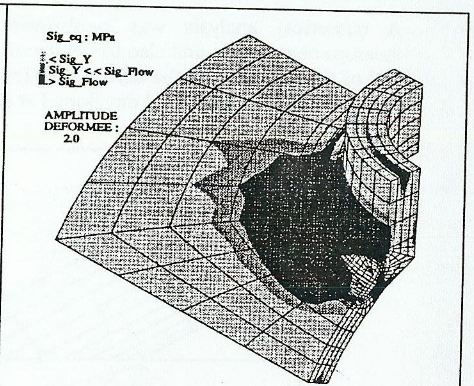

Fig. 9 : Elastic Von-Mises stress with crack.

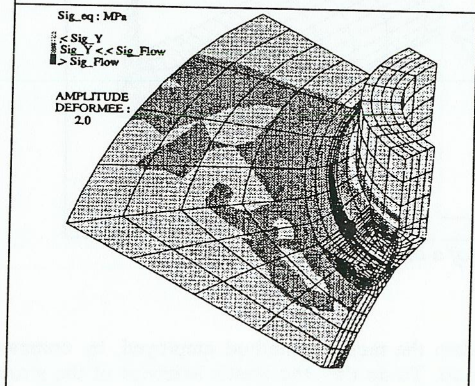

Fig. 10 : *Elasto-plastic Von-Mises stress.*

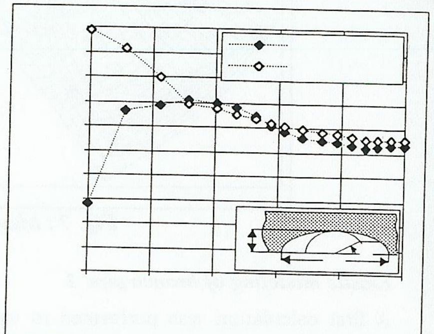

Fig. 11 : *Elastic and elasto-plastic J*

Table 4 : *Test/calculation comparison*

	F (N/mm)	β_1 (°/mm)	β_2 (°/mm)	β_3 (°/mm)	O_{V1} (m/m)	O_{V2} (m/m)	J_1 (%/mm)	J_2 (%/mm)	J_9 (%/mm)	J_{10} (%/mm)
Test	1,73E+3	3,51E-2	-5,62E-2	1,03E-1	8,35E-2	-1,70E-1	-3,18E-3	-2,27E-2	2,67E-3	4,08E-2
Calcul.	1,72E+3	4,16E-2	-6,41E-2	1,11E-1	1,09E-1	-1,09E-1	-4,76E-3	-2,80E-2	4,71E-3	6,03E-2

Elastic and elasto-plastic calculations of branch pipe 3

These calculations help to demonstrate the influence of the crack on the stress distribution in the junction. In addition, they give the values of K and J for a semi-elliptical crack similar to the experimental crack and for the initiation loading.

Meshing : The combined meshing principle already employed is maintained here with one crack, modeled by double nodes in the surface representing the intersection of the two cylinders (Figure 7). The anti-symmetry hypothesis is maintained to limit the calculation, despite the presence of the crack. This implies that the crack has little influence on the global behavior of the structure. This new mesh represents 1280 massive quadratic elements and 330 shell elements, making a total of 7335 nodes. The crack is modeled by a half-ellipse similar to the pre-crack defect measured on the branch pipe after complete collapse. Its depth is a = 3 mm and its width 2.c = 24 mm.

Loading : The loading imposed is a branch end displacement, up to the displacement corresponding to the excessive strain loading.

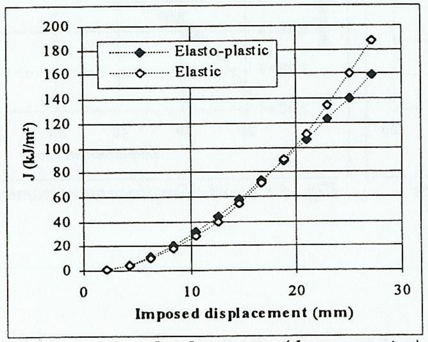

Fig. 12 : *J vs displacement (deepest point)*

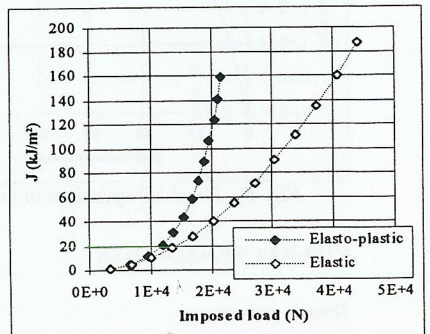

Fig. 13 : *J vs load (deepest point)*

Results : The Von Mises equivalent stress distributions are shown in Figures 8 to 10 for the initiation load of branch pipe 3, respectively for the branch without notch (elastic calculation) and the elastic and elasto-plastic calculations with notch. The crack only locally modifies the elastic stress field. By contrast, in the elasto-plastic domain, since the loading is global bending, the local stress field around the crack is diminished by the stress redistribution along the junction. The elastic and elasto-plastic values of J for the initiation loading and along the crack front are given in Figure 11. These curves show that the elasto-plastic and elastic values are very close to each other. This is true, even though the stress level around the crack is lower for the non-linear calculation: the strains around the crack front offset the lower stresses.

Only at the edge of the crack does a wide difference appear by a drop in triaxiality with the elasto-plastic calculation. The values of J from the elasto-plastic calculation are lower than the value of J_{IC} measured on CT. They reach a maximum of 140 kJ/m² against 223 kJ/m² for J_{IC}. Yet this difference is small given the approximation made on the form of the crack and the loading mode to which the crack is subjected : as shown by [8,9], the crack is subject to a combination loading mode, whereas the test on CT is in pure I mode.
The elastic and elasto-plastic values of J are shown all along the crack depth loading in Figure 12. It may be observed that, for the same imposed displacement, and after a high displacement level, the values calculated accounting for plasticity are lower than the elastic values. This is due to the lower stresses induced by plasticity and by the loading distribution in the junction. However, if J is expressed as a function of the imposed load (Figure 13), the elasto-plastic values become much higher than the elastic values.

CONCLUSIONS

An experimental and finite element study is described in this article. From the testing standpoint, it shows that the global behavior of the structure is barely influenced by the presence of the weld or the crack. Only pressure tends to rigidify the branch pipe for high loadings. The finite element calculations helped to simulate two tests. Elastic and elasto-plastic stress distributions in the junction, with or without crack, are thus calculated and reveal a substantial redistribution when plasticity appears. For the cracked branch pipe, the values of J for the initiation loading are similar to the values of J_{IC} determined on CT.

REFERENCES

[1] J. Schroeder, Upper bounds to in plane and out of plane limit couples applied to branch/pipe diameter ratios smaller than 0.8. *Proc.2nd Int.Conf.on Pressure Vessel Technol., San Antonio, September 1973, paper I22*
[2] F. Ellyin and N. Turkhan, Out of plane limit couples of nozzles in cylindrical vessels of branch pipes in Tee connection. *Proc.2nd Int.Conf.on Pressure Vessel Technol., San Antonio, September 1973, paper I26*
[3] F. Ellyin, Plastic limit load on intersection cylinder. *Int.Conf. on Struc. Mech. in Reactor Technol., San Francisco, 1977, paper G8/6*
[4] J. Schroeder and P. Tugcu, Plastic stability of pipes and Tees exposed to external couples. *WRC Bulletin 238, June 1978*
[5] F. Ellyin, An experimental study of plastic response of branch pipe Tee connection subjected to internal pressure, internal couples and combined loadings. *WRC Bulletin 230, September 1977*
[6] ISO 6892, Tensile test, International standard, 1984
[7] ISO R783, Mechanical tests of steel at elevated temperature, Recommendation, 1968
[8] Z.Z. Du and J.W. Hancock, Stress intensity factors of semi elliptical cracks in a tubular welded joint using line spring and 3D finite elements. *J.Pressure Vessel Technol., Vol.111, August 1989, pp.247-251*
[9] X. Huang and J.W. Hancock, The stress intensity factors of semi-elliptical cracks in a tubular welded joint under axial loading. *Eng.Frac.Mech., **30** (1) 25-35 (1988)*
[10] Castem 2000, User Manual, 1995