J Integral as a Measure of Crack Driving Force in Full-scale Pressure Vessel Test

S. SEDMAK*, T. ADŽIEV**, B. PETROVSKI*
and A. SEDMAK***
**Faculty of Technology and Metallurgy, University of Belgrade, Yugoslavia*
***Faculty of Mechanical Engineering, University "Ciril and Methody", Skopje, Yugoslavia*
****Faculty of Mechanical Engineering, University of Belgrade, Yugoslavia*

ABSTRACT

Direct measurement of J integral enables the evaluation of crack driving force in full-scale pressure vessel test. The axial notch was positioned with the tip in heat-affected-zone of weldment, obtained by submerged-arc welding. The test has been instrumented by strain gauges along J integral path and by crack mouth opening displacement gauge. Residual stresses, caused by cold forming and welding, were measured according to ASTM E837 method before pressurising. The experimentally obtained results for pressure dependance of J integral has been compared with crack driving force model, developed by Ratwani, Erdogan and Irwin.

KEYWORDS

J integral; crack driving force; pressure vessel test; residual stress; weldment; CMOD; residual strength model.

INTRODUCTION

The existance of cracks can not be completely excluded when the safety of welded structure is considered (Nichols, 1984). Therefore, the analysis of crack significance should be required additionally in consideration of operational safety of welded structure. On the other hand, the detection of cracks is limited by the capacity of applied equipment for non-destructive testing, and even in the case of strict requirements, very small cracks could be undetected after fabrication. These cracks could be prone to initiation and propagation under load and environment conditions. In the case of storage tanks, for example, after the final non-destructive inspection pressurising test up to 50% higher pressure level compared to nominal pressure is required by existing codes. The occurance of cracks in some storage tanks produced of micro-alloyed steel before operation is proved recently by post-pressurising non-destructive control, although these tanks had been accepted according to regular non-destructive control and pressurising test. The application of existing codes in such cases is questionable, and further improvement has been expected in requirements for safe operation.

In some pressure vessels repairing of cracks or other defects could not be avoided. The decision for crack repairing is usually supported by crack significance analysis.

One of convenient approaches in crack analysis could be the comparison of crack driving force (CDF) in the structure and material crack resistance properties. The experimental method of J integral direct evaluation, introduced by Read (1983), was applied for crack-driving force determination at different pressure levels in full-scale pressure vessel test (Sedmak and Petrovski, 1987). This experimental result was compared to CDF (Sedmak, Petrovski and Drenić, 1986), calculated according to the model, developed by Ratwani, Erdogan and Irwin (1974). It has been shown that the applied model is conservative and the residual strength prediction, based on material crack resistance in the form of J_R curve, is on the safe side in this case (Sedmak and Petrovski, 1986). The behaviour of cracked weldment in full-scale pressure vessel test is affected by several effects, that act simultanously in a complex way. Position of crack tip, heterogeneity of microstructure and mechanical properties, stress concentration, weld metal matching and residual stresses could be mentioned as most important effects for pressure vessel safety, and the magnitude of CDF is depended upon all of them. The separation of individual contribution of these effects in J integral directly measured value in pressure vessel test is a difficult task and should be considered step by step.

CRACK DRIVING FORCE FOR PRESSURE VESSEL

Experimental pressure vessel is presented in Fig. 1, with crack shape and dimensions.

Based on the Barenblatt-Dugdale model of crack tip plasticity, Ratwani, Erdogan and Irwin (1974) have derived following equations for J integral calculation:

$$J = \frac{8}{\sqrt{3}} \frac{c\sigma_Y}{E} [\frac{\delta_o}{d_1} + \frac{\theta_2}{d_2} (0.5 - \frac{a}{W})] \qquad d_1 = \frac{4c\sigma_Y}{E} \qquad d_2 = \frac{4c\sigma_Y}{WE} \tag{1}$$

for cylindrical shell of radius R and wall thickness W, containing a surface crack of length 2c and depth a, with the shell parameter

$$\lambda = [12(1 - \nu^2)]^{1/4} \frac{c}{\sqrt{RW}} \tag{2}$$

Here, E is elasticity modulus and ν Poisson's ratio, σ_Y is yield strength, δ_o is crack opening displacement and θ_2 rotation angle of crack surface. The ratios δ_o/d_1 and θ_2/d_2 are given by Ratwani, Erdogan and Irwin (1974) for different shell parameters λ and pressure values p.

Set of CDF curves for notched pressure vessel (Fig. 1) is presented in Fig. 2.

EXPERIMENTAL RESULTS

The pressure vessel had been fabricated by submerged-arc welding of 20 mm thick E460 steel plates, product of Steelworks - Skopje. The yield strength of E460 steel is σ_Y=460 MPa and the tensile strength σ_u=650 MPa. By properly selected wire-flux combination the overmatching effect in welded joint was achieved.

The pressure vessel had been prepared and instrumented in accordance with the experimental program, that included the measurement of residual stresses and direct evaluation of J integral. The sample 400x400 mm ("A" in Fig. 1a) had been cut out for machining: two notches (Fig. 1c), the main C1 and

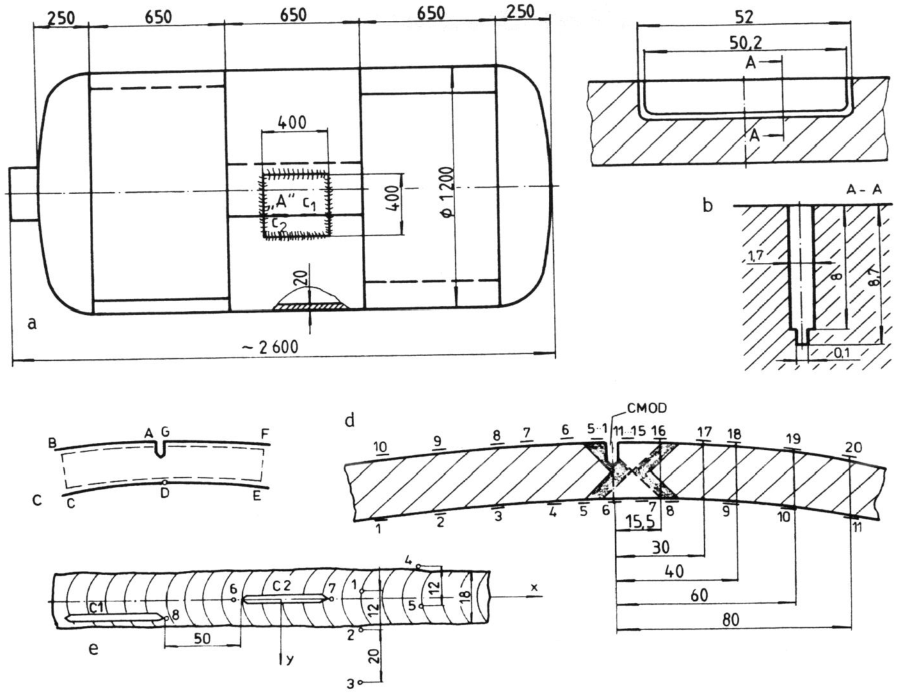

Figure 1. Pressure vessel (a), crack shape (b), J integral path (c), instrumented by strain gauges around C1 notch and CMOD gauge (d), and residual stress measuring points (e)

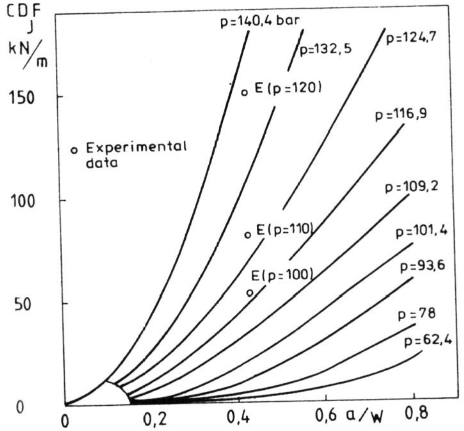

Figure 2. Crack driving force expressed by J integral for different pressure levels in experimental pressure vessel against normalized crack depth a/W (model Ratwani, Erdogan and Irwin)

additional C2 had been made by electrical discharge machine, with the tip sharpened in final stage to 0.1 mm (Fig. 1b). The sample had been welded by manual arc welding in the original position on the pressure vessel.

The selected J integral contour (Fig. 1c) had been instrumented by strain gauges (marked by 1-10, 11-20 on the outer, notched side and by 1-11 on inner side, Fig. 1d) and by crack mouth opening displacement (CMOD) gauge. For overall strain and stress control, several strain gauges were positioned in specified area, remote from main notch C1. Around the same weldment, in the region of C2 notch, strain gauges were positioned for residual stress measurement (ASTM E837 Hole Drilling Strain Gage Method) (Fig. 1e).

The residual stresses were measured before pressurising. Strain distribution and CMOD were monitored for specified pressures during pressurising for J integral direct measurement. The test was performed in as-welded condition.

Residual stresses

Typical results of residual stress measurement are presented in Fig. 3. It is to be mentioned that notch C2 is less deep than notch C1 and served only for simulation of stress field around notch C1 ends regarding residual stresses.

The distribution of σ_{xx}^{RS} is regular and scattering of values could be explained by the capacity of applied measuring method, on one side, and by mutual effects of shrinkage during welding and stiffness of a structure, on the other side. Stress relaxation by machining of notch contributed to reduction of residual stresses in points 6 and 7 compared to the stresses in points 1 and 5.

However, component σ_{xx}^{RS} is in tension in all measuring points. This is not the case with σ_{yy}^{RS} component. In several points (2, 4, 5 and 7) σ_{yy}^{RS} is tensile stress, in the others (1, 3 and 6) it is compressive stress, and such behaviour of this component imposes some difficulties in explanation. It is not quite clear how to explain the difference in sign for points 1 and 5, and for points 6 and 7. The tensile σ_{yy}^{RS} component contributes to the augmentation of crack driving force and crack opening, e.g. in point 7.

Strain distribution along J integral path

The distribution of stress component ε_{yy} along the J integral path is required for J integral direct measurement. This distribution is shown in Fig. 4 for three selected pressure levels on both outer and inner sides.

The notch tip position in heat-affected-zone has produced the irregularity of ε_{yy} strain component distribution, expressed by different values on notched side (strain gauges 7 and 17 on outer side for high pressure of 145 bar). The heterogeneity of welded joint and residual stresses contribute additionally to above mentioned irregularity.

J integral direct evaluation

The fundamental definition of J integral, given by Rice (1968) is

$$J = \int_{\Gamma} (W dy - \vec{T} \frac{\partial \vec{u}}{\partial x} ds) \qquad (3)$$

where W is strain energy density, $\vec{T}$ traction vectors, $\vec{u}$ displacement vektor and s arc length along the path.

For the path ABCDEFG, defined in Fig. 1c, J integral reduces to (Read, 1983)

$$J = SW_{ucr} + SW_{cr} - ST \qquad (4)$$

where SW_{ucr} and SW_{cr} stand for strain work density contribution of uncracked and cracked side, respectively, both measured in positive y direction, and ST is contribution of traction-bending term $\vec{T}(\partial\vec{u}/\partial x)ds$.

Assuming elastic-perfectly plastic behaviour (the error could be ignored compared to values of elastic strain work), it follows

$$W = \frac{E\varepsilon_{yy}^2}{2} \text{ for } \varepsilon_{yy} \leq \frac{\sigma_Y}{E} \quad W = \frac{\sigma_Y^2}{2E} + \sigma_Y(\varepsilon_{yy} - \frac{\sigma_Y}{E}) \text{ for } \varepsilon_{yy} > \frac{\sigma_Y}{E} \qquad (5)$$

and the term Wdy could be obtained by numerical integration along the path contour.

The component T_y of traction vector $\vec{T}$ is dominant ($T_y = \sigma_{yy}$). The acting bending term $\partial u_y/\partial x$ across the thickness W=20 mm is approximated by

$$\frac{\partial u_y}{\partial x} = \frac{u_y(C) - u_y(B)}{x(C) - x(B)} = \frac{u_y(C) - u_y(B)}{20} \text{ (similar expression for the other half)} \qquad (6)$$

and

$$u(B) = \int_B^A \varepsilon_{yy} dy + CMOD + \int_G^F \varepsilon_{yy} dy \qquad u(C) = \int_C^E \varepsilon_{yy} dy \qquad (7)$$

This approach requires CMOD values for different pressure levels: they are plotted in Fig. 5, together with J integral and hoop stress

$$\sigma_{yy} = \frac{E}{1-\nu^2} (\varepsilon_{yy} + \nu \, \varepsilon_{zz}) \qquad (8)$$

where ε_{yy} and ε_{zz} are strain components in point remote from the notch.

For comparison, the membrane stress is calculated from $\sigma_c = pR_o/W$ and presented in Fig. 5 by dashed line (R_o=580 mm stands for inner radius).

All data relevant for this method is given in Table 1.

Table 1. Data obtained by J direct measurement technique

P,bar	SW_{ucr} kN/m	SW_{cr} kN/m	$SW_{ucr}-SW_{cr}$ kN/m	CMOD µm	u(C) µm	u(B) µm	σ_{yy} MPa	ST kN/m	J kN/m
20	0.993	0.144	0.849	30.2	21	30	52	-0.511	1.359
40	3.799	0.527	3.271	61.1	40	66	109	-2.828	6.100
60	7.928	1.190	6.738	89.4	58	102	166	-7.307	14.046
80	12.708	2.570	10.138	121.5	74	144	225	-15.730	25.868
100	18.476	5.667	12.811	181.9	92	217	305	-38.126	50.936
105	20.245	7.115	13.130	211.3	98	251	341	-52.032	65.162
110	22.253	8.544	13.709	241.5	105	285	372	-66.705	80.414
120	35.600	15.049	20.551	362.2	142	423	460	-129.031	149.583
140	78.628	58.137	20.491	671.7	236	838	460	-276.893	297.384
145	87.742	75.634	12.107	769.8	255	973	460	-330.095	342.202

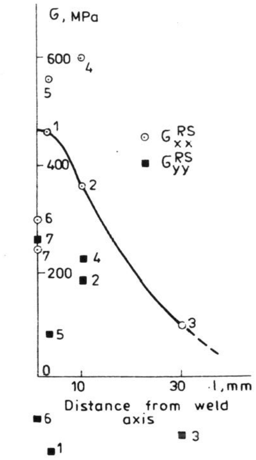

Figure 3. Residual stress components σ_{xx}^{RS} (o) and σ_{yy}^{RS} ( ) in the notched region of weldment

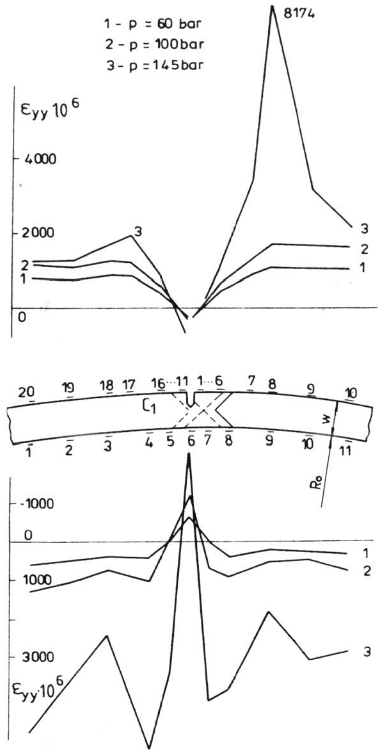

Figure 4. The distribution of ε_{yy} strain component along J integral path

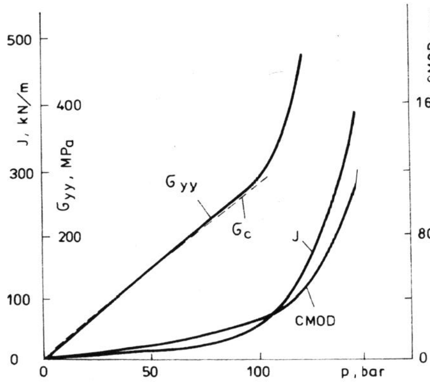

Figure 5. Pressure dependance of CMOD, hoop stress σ_{yy}, calculated from measured strains, membrane stress according to $\sigma_c = pR_0/W$, and directly evaluated J integral

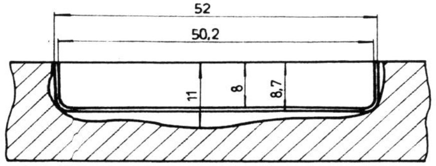

Figure 6. Crack shape and dimensions after test

DISCUSSION

In this experiment J integral is directly measured in real conditions of fullscale test and all effects contributed to its value (pressure level, strain and stress field around the crack tip, heterogeneity of microstructure and of mechanical properties, residual stresses). It was not possible to separate individual contribution of so many effects. However, some relation could be considered.

The final crack shape after test is presented in Fig. 6. Notch initiated into crack under loading and crack developed for maximum 2.3 mm in depth. One can suppose that plastic zone at the notch tip preceded crack initiation, and that the pressure of about 105 bar (Fig. 5) could represent the load level for J_{Ic} value, as it follows from the plot J integral vs. pressure. It is very interesting to compare J integral with CMOD (Fig. 7). The linear relationship is extended even in the region of crack growth, indicating mutual replacement between the two parameters.

It is possible now to compare the experimental data for J integral with the CDF values calculated from applied model. Experimentally evaluated J integral is plotted in Fig. 2 for crack depth ratio ($a/W=8.7/20=0.435$) and for different pressures, marked in points E. It is obvious that for the same pressure level CDF obtained in experiment is higher than the value calculated from applied model, indicating that acting CDF is higher than predicted from the model in this case. This relation between CDF values, calculated from model and obtained in experiment, remains the same for all applied pressure, as it is presented in Fig. 8 for the dimensions of notch and pressure vessel.

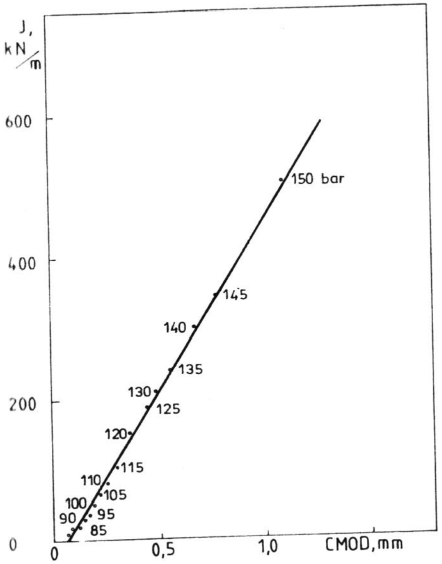

Figure 7. Experimental J integral vs CMOD

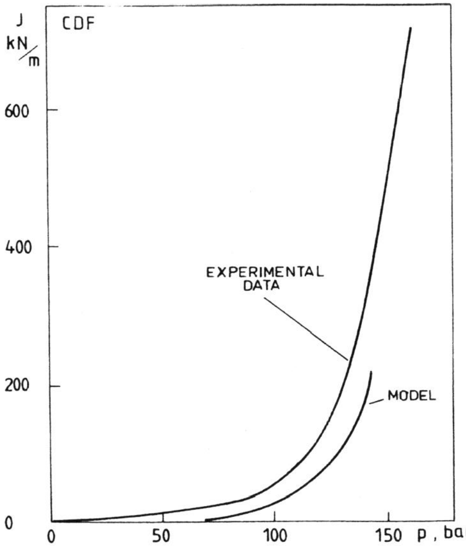

Figure 8. J integral from Ratwani, Erdogan and Irwin model and obtained in experimental analysis

Previous similar test (Sedmak, Petrovski and Drenić, 1986) had been performed with undermatched weld metal, with fatigue pre-crack of 11 mm and a/W=0.69, in as-welded condition, and crack developed in length, but not in depth. Such behaviour in crack growth is completely different in actual case, where crack developed in depth but not in length. As it is mentioned already, the applied CDF model is conservative in the previous case, and it is not conservative in the actual case.

It is quite clear that complete understanding of individual effects on overall CDF behaviour in cracked pressure vessel requires further experiments. One of possible direction could be the analysis of residual stresses effects, performing the experiments with pressure vessel in stress relieved condition.

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