AN EXPERIMENTAL VERIFICATION OF NUMERICAL MODELS FOR THE FRACTURE AND FATIGUE OF WELDED STRUCTURES

EKSPERIMENTALNA VERIFIKACIJA NUMERIČNIH MODELOV ZA PRELOM IN UTRUJENOST ZVARJENIH STRUKTUR

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By allowing a more detailed analysis, numerical modelling has an important role to play in the development of structures. However, the results of a numerical model's analysis have to be verified with an experimental analysis for the application. Two full-scale welded-structure tests were used for the verification of the proposed numerical models. In the first case a pressure vessel pre-cracked in weld metal and instrumented for a *J*-integral measurement was tested. In this way the crack's driving force, expressed as the *J* integral, could be determined directly. The crack's driving force was calculated by applying the Ratwani-Erdogan-Irwin (REI) numerical model. The experimental results were compared to the values obtained with the REI model. In was shown that the application of the model produces conservative results and that the model can be applied for a structural integrity assessment of cracked pressure vessels. The second case was the welded structure of a rotor excavator. The critical welded components were modelled in full scale. The loading was recorded with strain gauges at critical locations, analyzed and elaborated in the form of the stress spectrum applied in the testing. The experimental results were compared to those obtained with numerical models. The comparison revealed that the model significantly overestimates the real cycle number for the fatigue limit. These two examples clearly demonstrated the complexity of the problem. In the case of the pressure vessel the model results are conservative, while those obtained for the fatigue are too optimistic.

Keywords: welded joint, numerical model, experiment, fracture, fatigue

Numerično modeliranje je zelo pomembno za razvoj struktur, ker omogoča bolj natančno analizo, vendar je potrebno rezultate numerične analize eksperimentalno verificirati. Dve varjeni strukturi sta bili uporabljeni za verifikacijo predloženih numeričnih modelov. V prvem primeru je bila preverjena posoda pod pritiskom z razpoko v zvaru. Posoda je bila instrumentirana za neposredno določitev *J*-integrala. Gonilna sila za propagacijo razpoke je bila izračunana z numeričnim Ratwani-Erdogan-Irwinovim (REI) modelom. Eksperimentalne rezultate smo primerjali z REI-vrednostmi. Pokazalo se je, da so rezultati modela konservativni pri oceni integritete v primeru razpoke v posodi pod pritiskom. Drugi analiziran primer je bila zvarjena struktura dela rovokopača. Kritični zvarjeni del je bil modeliran v pravi velikosti. Obremenitev je bila registrirana z merilnimi trakovi na različnih mestih, nato pa analizirana in predstavljena v obliki spektra napetosti. Rezultati preizkusa so bili primerjani z rezultati iz numeričnega modela. Primerjava je pokazala, da model pomembno preceni realno število obremenitev do utrujenostne trdnosti. Ta dva primera kažeta na kompleksnost problema. V primeru posode pod pritiskom so rezultati modela konservativni, v primeru utrujenosti pa optimistični.

Ključne besede: zvarni spoj, numerični model, preizkus, prelom, utrujenost

1 INTRODUCTION

The impressive developments in fracture mechanics and the numerical modelling of structures during the past 40 years has enabled the improvement of existing and the introduction of new methods for the evaluation of residual life and the assessment of structural integrity [1]. By applying these methods the service safety of structures has been increased and their life has been extended, resulting in significant cost savings. Today, numerical modelling is an invaluable tool for the design of different structures, as well as the manufacturing and use of steel structures, power and petrochemical plants, aircraft, machinery and vehicles. Welded structures have a very important role in many of these sectors and, therefore, require special attention. The reason for this is the possibility of cracks occurring in welded joints, which can endanger the structural integrity and nega-tively affect the service safety. Many standards and documents consider this structural integrity, and probably the most important is the SINTAP (Structural INTegrity Assessment Procedure) [2,3], which is based on fracture-mechanics analyses and experience with cracks in a welded structure [4]. The fracture-mechanics approach was applied with success and formally accepted in the case of the Trans Alaska Crude Oil Pipeline [5], for a "fitness-for-purpose" approach. The maximum allowed crack size was verified experimentally before the proposal for when and how to repair the cracks in welded joints. The most important conclusion in this investigation was that "fracture-mechanics analysis is an acceptable basis for an allowable exception from valid standards under circumstances, under the condition that this analysis provides a clear and conservative structural integrity assessment".

Numerical models are developed based on the available data, which do not necessarily coincide in all cases with the real situation. Two important requirements before the acceptance of a proposed model are:

1. the model has to be conservative in order to cover different circumstances,
2. the model must be experimentally verified.

Experiments with full-scale welded structures are not frequently performed, because they are connected with many problems in their organization and realisation, and, not surprisingly, they are very expensive. The obtained results are, however, generally valid for the tested structure and the applied testing conditions. For this reason, numerical modelling has an important role to play in the development of structures since it allows a more detailed analysis. In any case, it is questionable whether the results of the numerical model analysis represent the real situation of the considered structure, because a large number of influential parameters have to be considered. The answer to this question can only be obtained from a proper experimental analysis.

2 CRACK-GROWTH ANALYSIS WITH THE J-INTEGRAL

Two aspects of the J integral have to be considered for a structural integrity assessment. In the first the J integral is an elastic-plastic fracture-mechanics parameter that defines the cracked body's geometry and the loading (the crack driving force – CDF), and in the second it represents the crack resistance of the material (J_{Ic} and J–R curve) [6]. The fundamental difference between these two aspects is the crack-growth behaviour. In the first case the crack size is not variable and it is used as a parameter with the stress. In the second case, however, the crack growth is included. The criterion for the initiation of stable crack growth is mathematically defined as:

$$J(\sigma, a) \geq J_{Ic} \quad (1)$$

where $J(\sigma, a)$ is the crack driving force (CDF), depending on the remote stress, σ, and the crack length, a, whereas J_{Ic} is the material's resistance to the initiation of stable crack growth. In the case of elastic-plastic fracture mechanics the crack growth analysis is not restricted to the application of Equation (1), but also involves the stable crack growth and the condition for the initiation of its unstable spreading, e.g., the J–R curve, which is compared to the CDF using a convenient graphical method. The initiation of unstable crack growth is given by:

$$\frac{\partial J(\sigma, a)}{\partial a} \geq \frac{\partial J}{\partial a} \quad (2)$$

indicating that the increase in the CDF must be greater than the increase of the material's crack resistance for the same crack extension. When the value $J(\sigma, a)$ reaches the value J_{Ic} (1), (the intersection of the CDF

curve and the J–R curve), the stable crack growth is initiated, and it continues up to the instant at which $\partial J(\sigma, a)/\partial a$ becomes greater than $\partial J/\partial a$ (2), (the tangent of the CDF curve to the J–R curve) producing unstable crack growth. The extent of the stable crack growth, Δa, is the difference (on the abscissa) of the marked points A and a_o, including the crack-tip blunting.

A theoretical–analytical model, such as the Ratwani-Erdogan-Irwin (REI) model [7], can be applied for the CDF determination. The crack resistance can be determined experimentally, e.g., according to ASTM E1820 [8] or by applying the J-integral direct-measurement method [9].

3 VERIFICATION OF THE STRUCTURAL INTEGRITY ASSESSMENT MODEL

The conservative prediction of the structural integrity of a cracked welded structure means that the material's crack resistance is greater than the maximum CDF. Thus, it should be proved that the applied model for the CDF and the residual strength prediction is conservative. With this aim the experimental pressure vessel (**Figure 1**) was welded from high-strength low-alloyed SM80P steel (700 MPa yield strength class) 16-mm steel plates, applying a qualified welding procedure, and prepared for
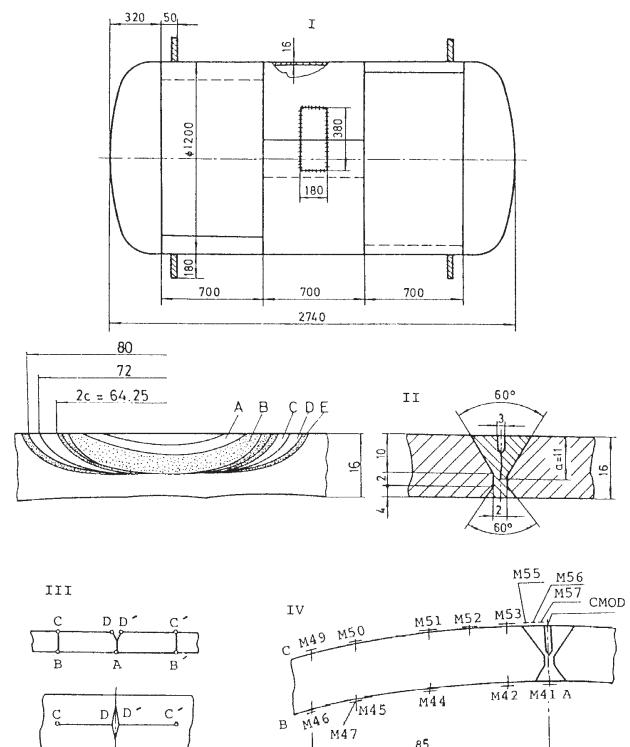
Figure 1: Experimental pressure vessel: I, shape and dimensions; II, detail of crack; III, integration path; IV, distribution of strain gauges. A notch. B fatigue pre-crack. C,D stable crack growth. E final fatigue
Slika 1: Eksperimentalna posoda pod pritiskom: I oblika in mere. II Detail razpoke. III pot integracije. IV Porazdelitev merilnih trakov za napetost. A zareza. B utrujenostna pred-razpoka. C, D Stabilna rast razpoke. E Končna utrujenost

the verification of the REI model [10]. This was performed using a J-integral direct measurement [9] on the fatigue pre-crack positioned in the WM (**Figure 1.II**). To prepare the fatigue pre-crack, a segment of size 180 mm × 380 mm, containing the SAW weld metal, was cut from the welded prototype. After machining the notch in the centre of the weld metal, a fatigue pre-crack was produced according to the standard procedure, and the segment was than re-welded in the pressure vessel. The properly selected contour DCBAB'C'D'', given in **Figure 1.III**, was covered by regularly distributed strain gauges, **Figure 1.IV,** and the clip gauge applied for the crack-opening displacement enabled a direct evaluation of the *J* integral. It is interesting to note that during the test the crack increased in length, from the initial value of $2c = 64.25$ mm up to 72 mm after the first stage and up to the final value of 80 mm measured after the experiment. The crack did not grow in terms of depth, as can also be seen in **Figure 1.II**.

The shell parameter λ, necessary in the next calculation for the crack length $2c = 64.25$ mm for the mid-thickness shell radius $2R = 1184$ mm, the wall thickness $W = 16$ mm, and the Poisson's ratio $\nu = 0.3$, is:

$$\lambda = \left[12(1 - \nu^2)\right]^{1/4} = \left[12(1 - 0.3^2)\right]^{1/4} \frac{32.125}{\sqrt{1184 \cdot 0.016}} = 0.6 \quad (3)$$

The crack driving forces for the axial surface crack in the pressure vessel were calculated using the REI model for this value of the shell parameter and expressed by the set of lines in **Figure 2**, depending on crack ratio, *a/W,* and the normalized pressures $pR/WR_{p0.2}$ (p is the applied pressure, $R_{p0.2}$ is the weld metal's yield stress). Point "A" is experimentally obtained at a pressure of 100 bar for the crack depth, measured after testing ($a = 11$ mm, crack ratio $a/W = 0.69$). For the same pressure CDF, calculated with the REI model for $a/W = 0.69$, is 40 %

Figure 3: Pre-cracked specimens (I – three-point bend specimen; II – tensile panel, III – details of surface cracks on tensile panels)
Slika 3: Preizkušanci s pred-razpoko (I – tritočkovni upogibni preizkušanec; II – natezna plošča; III – detalj; s površinskimi razpokami na nateznih ploščah)

higher than the point "A", indicating that the model is conservative and can be used for a structural integrity assessment.

For the *J-R* curve the determination of the SEN (B) specimen was selected (**Figure 3.I**) for the single-specimen technique (ASTM E1820), and instrumented tensile panels with a surface crack (**Figure 3.II**) for the

Figure 2: Crack driving forces with marked point "A" for the experimentally obtained *J* integral
Slika 2: Gonilna sila razpoke s točko A za eksperimentalno določen *J*-integral
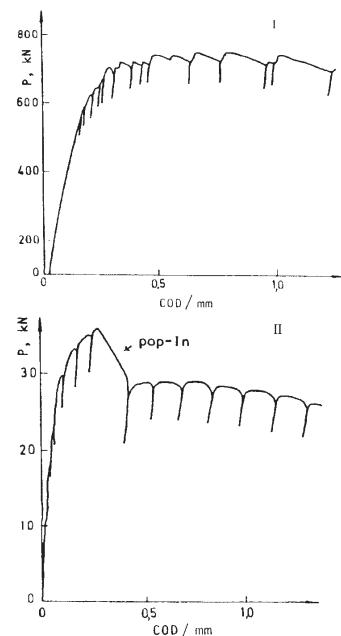
Figure 4. Typical plots of load, *P,* vs. crack-opening displacement (*COD*) for a crack in the HAZ (I – tensile panel; II – three-point bend specimen – arrow indicates "pop-in")
Slika 4. Tipične odvisnosti *P* od premika odprtja razpoke (*COD*) za razpoko v HAZ (I – natezna plošča; II – tritočkovni upogibni preizkušanec; puščica je označba točke "pop-in")
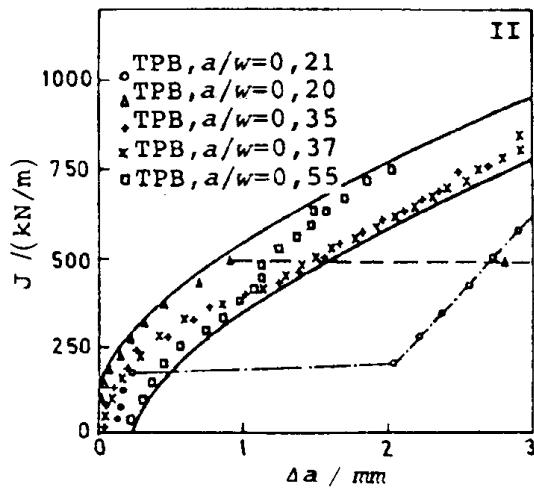
Figure 5: Scatter band *J–R* curves set of SEN(B) – TPB specimens for HAZ with two cases of pop-ins for *a/W* values 0.21 and 0.20
Slika 5: Trosenje območja krivulj *J–R* za SEN(B) – TPB-preizkušance za HAZ z dvema primeroma "pop-in" za vrednosti *a/W* 0,21 in 0,20

J-integral direct-measurement method [9]. The cracks located in the HAZ of the tensile panel are presented in **Figure 3.III**.

From the extended experimental program [10] the specimens precracked in the HAZ were selected as the most critical for the structural integrity assessment. The two plots of load vs. crack opening displacement are typical, one of the uniform form (tensile panels) and the other with "pop-in", indicating an arrested, rapidly growing crack (some of the SEN(B) specimens) (**Figure 4.II**). The derived corresponding *J-R* curves with critical SEN(B) specimens are presented in **Figure 5**.

The pop-in occurred only for the small ratio *a/W* = 0.21 and *a/W* = 0.20 in SEN(B) – TPB specimens of HAZ (**Figures 4 and 5**) indicating that a through crack can develop easily, which was not observed for tensile
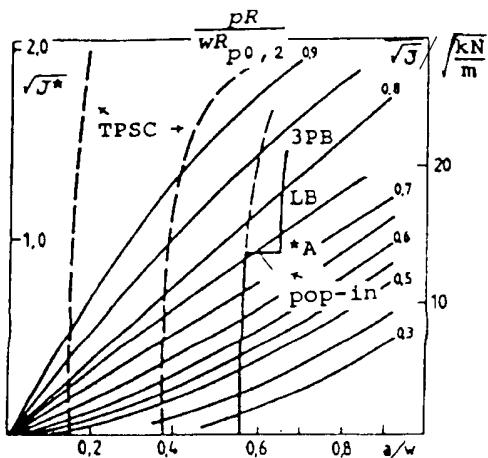
panels. In a real pressure vessel the crack is similar to that in the tensile panel and pop-in is not expected. The lower bound (LB) curve covers the pop-ins found during testing (**Figure 6**) and the obtained relations indicated that the structural integrity was not critical because of the crack ratio *a/W* = 0.548, the crack depth is a_o = 8.77 mm, the pressure of *p* = 120 bar, significantly higher than the operating pressure, can produce an unstable crack growth of an additional 0.8 mm, before the crack tip reaches the region of tougher material in which the crack can continue to grow under increasing pressure in a stable manner. A crack of that size is not probable in a real pressure vessel because much smaller cracks can be detected with non-destructive testing.

Thus, the structural integrity assessment of the cracked pressure vessel with the considered REI model is conservative and can be reliably applied.

4 VERIFICATION OF THE FATIGUE-CRACK GROWTH MODEL

Service fatigue cracks frequently occur in the welded components of rotor excavator bearing structures (**Figure 7**). The program of the performed investigation included the identification of critical regions, the measuring of strains with strain gauges in different service conditions, the determination of the stress spectrum, the model design of a critical welded joint and the model testing by constant amplitude load and using a defined stress spectrum. The obtained experimental results are compared to numerical solutions obtained by applying the linear fatigue-damage accumulation hypothesis by Palmgren-Miner [11], and a modified linear hypothesis, Corten-Dolan [12], Serensen-Kogaev [13] and Haibach [14].

Figure 6: Structural integrity assessment for HAZ *J–R* curves lower bound (LB), including specimens with pop-in
Slika 6: Ocena integritete strukture za HAZ *J–R*-krivulje spodnjega praga (LB) z vključenim "pop-in"
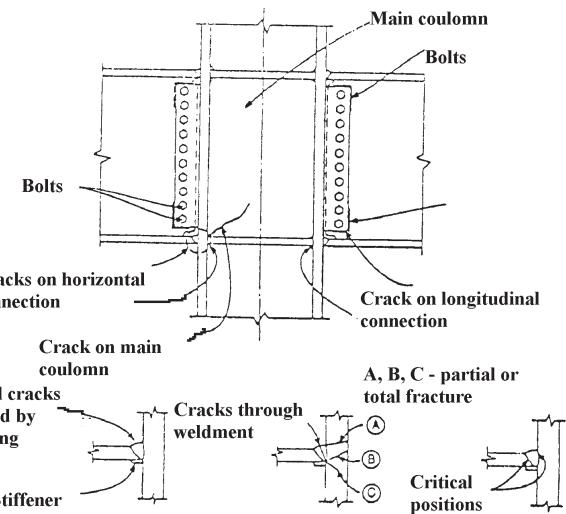

Figure 7: Cracks in critical regions of the welded components of a rotor excavator
**Slika 7:** Razpoke v kritičnih področjih zvarjenih komponent rotorja rovokopača
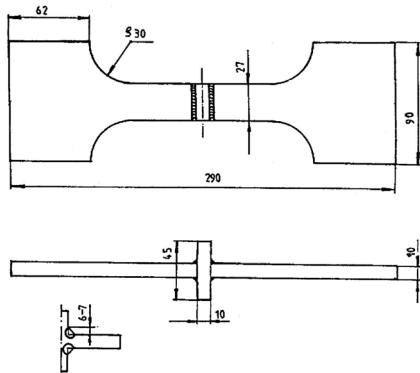
Figure 8: Specimen for fatigue testing, model of cross-welded joint of rotor excavator arrow
Slika 8: Preizkušanec za preizkus utrujenosti, model križno varjenega spoja konice rotorja rovokopača
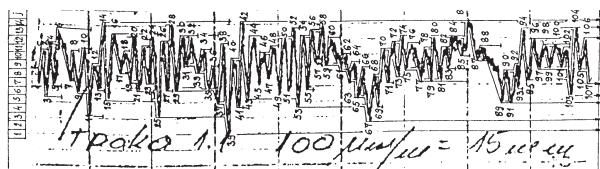

Figure 9: Stress variations measured in rotor excavator operation
Slika 9: Variacije napetosti, izmerjene pri delu rovokopača

Figure 10: Comparison of *S–N* curves, obtained experimentally with constant (F. S.) and a variable amplitude loading spectrum (stress spectrum) (A. S.) and calculated by linear accumulation hypothesis (Corten-Dolan – C-D, Haibach – H, Serensen-Kogaev – S-K and Palmgren-Miner – P-M)
Slika 10: Primerjava eksperimentalnih odvisnosti *S-N* s konstantno (F. S.) in spremenljivo amplitudo spektra obremenitve (spekter napetosti) (A. S.) in izračunane s hipotezo linearne akumulacije (Corten – Dolan – C-D, Haibach – H, Serensen-Kogaev – S-K in Palmgren-Miner – P-M)

The specimen for experimental fatigue testing was modelled as a critical cross-welded joint to simulate the bearing structure component exposed to cracking (**Figure 8**). The applied variable loading of the bearing structure consisted of transport (4 %), average operation (60 %) and full cut (36 %), as part of the digging process and by low-frequency self-vibrations. The time-dependent complex stresses of the structural elements are presented in **Figure 9**, as discriminated according to the stress origin in order to establish a stress spectrum simulating real-service loading [15]. The total spectrum of stress ranges also involved the pick loadings, representing 0.05 % to 10 % of the total operating time, which are so high that they can arrest the excavator operation. The experiments were performed at constant amplitude on a high-frequency resonant pulsator and by a defined spectrum on a servo-hydraulic closed-loop device. The obtained relations of stress, S, vs. the number of cycles, N, are presented in the double logarithmic diagram in **Figure 10**, designed as a F. S. for the constant amplitude loading ($S^{6.7}N$ = const), and as an A. S. for the simulating spectrum. The numerically obtained results for all the applied hypotheses are also presented for comparison.

The comparison of the fatigue testing results shows that the effect of the constant amplitude is more obvious (**Figure 10**), indicating that the structure in real operating conditions with a different amplitude can exhibit a longer fatigue life than expected, based on laboratory tests using a constant amplitude. The four hypotheses considered revealed a too optimistic fatigue

life compared to the experimental results, overestimating the number N_D for the fatigue limit. For this reason they should be applied with caution. It should be noted that the Haibach hypothesis is proposed for welded joints.

5 CONCLUSION

When applying the experimental results it is clear that the numerical models in the structural analysis have to be applied with a necessary caution because their efficiency is dependent on the considered influencing factors, since all the relevant factors and their real effect on the situation must be considered. It was found that in the case of a welded vessel exposed to internal pressure the applied model produces conservative – and thus acceptable – results, and that in the case of the fatigue of the rotor excavator's welded components the numerical model results overestimate the experimental values and cannot be applied as sufficiently conservative.

Acknowledgement

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