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Fracture modeling of damaged stiffened panels under lateral pressure load

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Abstract

Numerical modelling and simulations were carried out in order to analyze fracture mechanisms for stiffened panels, damaged by a single and multiple cracks, and subjected to lateral pressure. For that purpose finite element models for stiffened panel specimens were developed using shell elements. Material property data used in the simulation were obtained from the tensile test and fracture test on a centrally notched tension specimen. By implementing elastic plastic fracture mechanics concepts (EPFM) critical pressures associated with fracture onset in the specimens were assessed based on the critical *J*-integral and CTOD parameters. Simulated critical pressure loads for stiffened panel specimens were compared with experimental results and a good agreement was observed. The developed procedure can be applied to real thin-walled structures.

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Keywords: Modeling; Elastic-plastic fracture mechanics; *J*-integral; CTOD; Stiffened panel

1. Introduction

In thin-walled structures such as aircraft fuselage or ship hull girder, fatigue cracks initiate at stress concentration sites and propagate in stable manner under cyclic service loading. Cracks may further grow to a critical size, which leads to an instantaneous failure of the structure under an extreme loading condition. The multiple-site damage (MSD) problem of riveted lap joints in aircraft fuselages has drawn much attention after the Aloha accident. Schijve

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(1995) showed that small MSD cracks can significantly reduce the load for unstable crack extension. Dexter et al. (2003) analyzed the growth of long fatigue cracks in box girders with welded stiffeners. Cyclic tension fatigue tests were conducted on approximately half-scale welded stiffened panels to study the propagation of long cracks in a ship deck structure. Božić et al. (2013) studied the influence of welding residual stresses in stiffened panels on effective stress intensity factor values and fatigue crack growth rate. The study showed that high tensile residual stresses in the vicinity of a stiffener significantly increase the crack growth rate, which was in good agreement with experimental results. Sumi et al. (1998) and Božić (2002) studied fracture of stiffened panels with multiple-site damage, by using various stiffened and unstiffened panel specimens subjected to lateral pressure.

Nomenclature

J, J_c	J-integral, the critical J-integral value
δ_t, δ_{tc}	crack tip opening displacement (CTOD), the critical δ_t value
W	strain energy
σ_{ij}	stress tensor
ε_{ij}	strain tensor
$\mathbf{T}$	traction vector
$\mathbf{u}$	displacement vector

This paper presents an experimental and FE analysis of fracture behavior of stiffened and unstiffened specimens subjected to lateral pressure. In order to investigate crack propagation, crack curving, crack arrest and mode of failure of multiple-site damaged stiffened panels subjected to pressure load, pressurized tests have been carried out. Small scale size specimens with a previously machined single crack or an array of cracks along a straight line, (MSD), were loaded applying uniformly distributed lateral pressure until cracks propagated. An oil pressurized tank, was used for loading. During the loading, specimens undergo large deflections and significant membrane strains occur. Prior to final failure considerable plastic deformations take place along the ligament, particularly in the crack tip region. The elastic plastic fracture mechanics concept (EPFM) was employed in numerical analyses, as large scale yielding occurred in ligaments of fractured pressurized specimens. The J-integral and crack tip opening displacement (CTOD) values were inferred from finite element simulation results by using postprocessor routines ANSYS (2009). In the FE simulations the true stress-strain curve determined from tests on tension test specimens has been used. In order to determine material's resistance to crack propagation, fracture tests were carried out on centrally notched tension plate specimens. It was observed from fracture tests, that in the crack tip region significant plastic deformations occur, and that prior to failure, the complete ligament yielded plastically.

2. Experimental Fracture Analysis for Pressurized Stiffened Panel Specimens

2.1. Tensile test and fracture test for a centrally notched plate specimen

Tensile test specimens have been tested in a standard tensile-testing apparatus with a screw-driven, constant speed moving crosshead. The specimen's geometry and measured strain-load data are given in Fig. 1. The material properties as obtained by Sumi et al. (1998) are shown in Table 1.

Table 1. Material properties and chemical composition.

Mechanical properties							
Material	E- Young's modulus		ν - Poisson's coefficient		σ_0 - Yield strength		σ_{ul} – Ultiumate strength
AlMg1.5	70000 MPa		0.3		182 MPa		231 MPa
AlMg2.5	70000 MPa		0.3		- (not measured)		< 200 MPa*
Chemical composition (%)							
	Al	Cr	Cu	Fe	Mg	Si	Zn
AlMg1.5	96,3-98,9%	<0,1%	<0,2%	<0,7%	1,1-1,8%	<0,4%	<0,25%
AlMg2.5	95,7-97,7%	0,15-0,35%	<0,1%	<0,4%	2,2-2,8%	<0,25%	<0,1%

*manufacturer's specification

The material of the specimens was an aluminum alloy plate of the thickness, t = 2mm, (AlMg1.5). According to the load-strain diagram in Fig. 1, this material has sufficient toughness. For material (AlMg2.5) the values in Table 1 are given according to the manufacturer specification. In order to determine the material resistance to fracture onset centrally notched (CN) plate specimens were pulled in a tensile-testing machine with slow speed moving head, until collapse of the AlMg1.5 aluminum alloy plate specimens of the thickness t = 2mm. The specimen geometry is shown in Fig. 2.

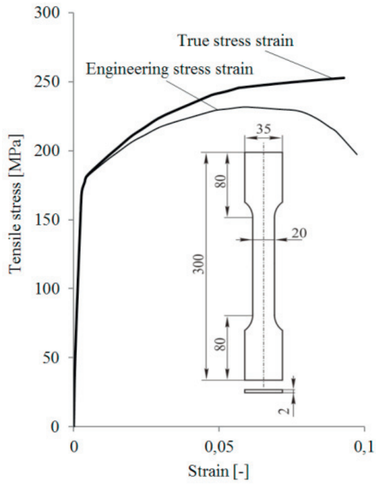

Fig. 1. Engineering and true stress-strain curve of the flat tensile test specimen.

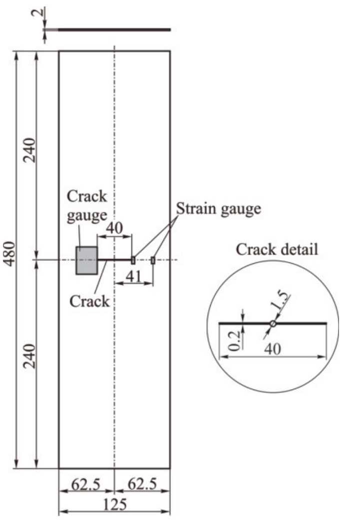

Fig. 2. Centrally notched tension plate specimen, CN.

It was observed that at maximum load the specimen undergoes significant elongations, during which the plate contracts at the crack tips, and the crack propagates slowly by stable plastic fracture. As the crack propagates the loading force decreases and rapid plastic fracture occurs. It was observed that ligaments were completely plastically yielded prior to failure.

2.2. Fracture test for pressurized plate and stiffened panel specimens

Pressurized tests have been carried out for four different types of specimens: the plate with a single central crack, PPR-1, the plate with three cracks, PPR-3, the stiffened panel with a single crack, SPPR-1, and the stiffened panel with three cracks, SPPR-3. Main parts of the pressurized test equipment used for loading are: oil pump, pressurized tank, measuring devices, amplifiers and recording equipment, as given in Fig. 3.

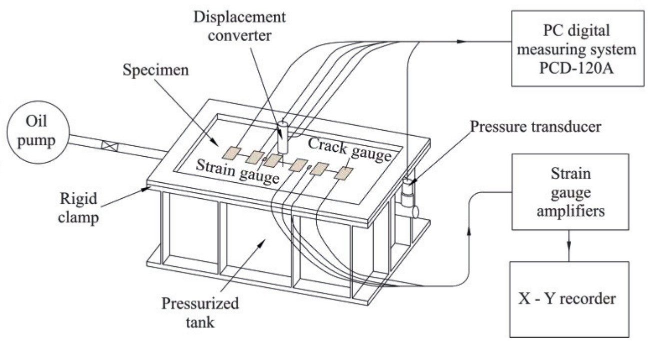

Fig. 3. Scheme of the pressurized test equipment.

The specimens were fixed by bolts to the pressurized tank. To prevent oil leakage through the cracks, a rubber sheet was sealed with silicon rubber on the bottom surface of the specimens prior to the test. Specimens after pressurized tests are shown in Fig. 4. Plate specimens PPR-1 and PPR-3 are made of aluminum plate of thickness t = 2 mm, (AlMg1.5). Stiffened panel specimens were machined from a plate of thickness 22 mm (AlMg2.5). Along the edges a specimen is fixed to the pressurized tank by bolts. The effective size of a specimen which is exposed to the loading pressure is 250x500mm, and the crack geometry is the same as for the CN specimen, as given in Fig. 2. Under loading the pressurized specimen undergoes large deformations and consequently membrane strains occur. Large scale plastic yielding appeared in all specimens. In specimens with a single crack the rapid crack propagation lasted until the driving force (oil pressure) was exhausted. For specimens with three cracks after stable fracture, instantaneous plastic fracture occurs and cracks collide. In case of the stiffened panel with a single crack, SPPR-1, rapid crack propagation, which follows stable fracture, could be arrested by the intact stiffener.

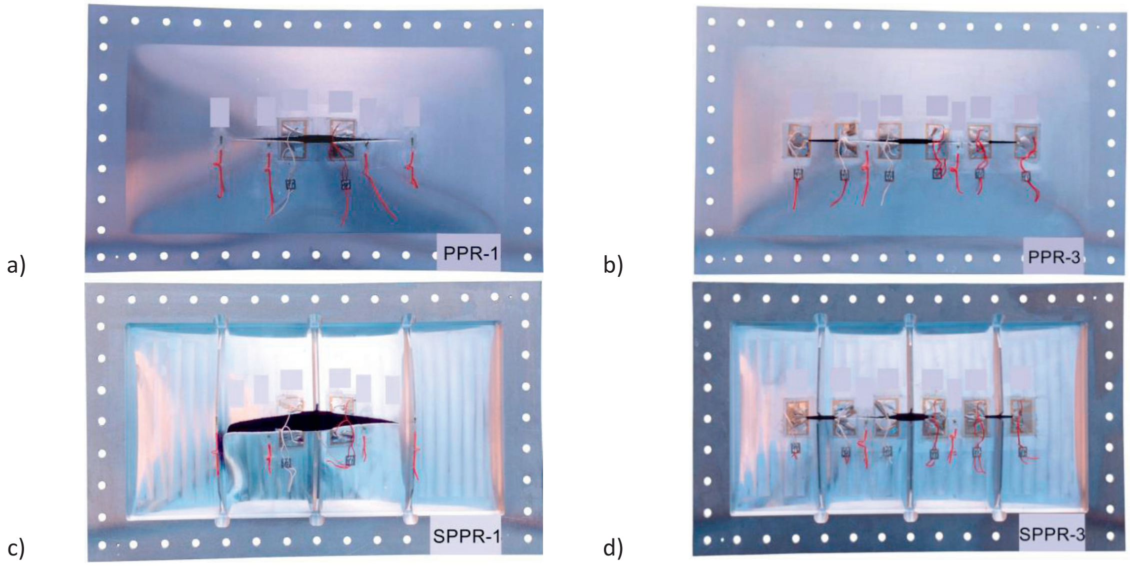

Fig. 4. Specimens after pressurized test: a) PPR-1; b) PPR-3; c) SPPR-1; d) SPPR-3.

3. Finite Element Fracture Analysis for Stiffened Panels under Side Pressure

Large deformation, elastic plastic finite element analyses were carried out for centrally notched plate specimen under tensile load and for stiffened and unstiffened specimens subjected to side pressure. Material plasticity behavior was taken into account in all simulations. The true stress-strain curve shown in Fig. 1 was used as input data in FE analysis. The multilinear isotropic hardening model, based on von Mises yield criteria coupled with an isotropic work hardening assumption was used. Eight-node shell elements were used in modelling, where the crack tip was meshed with triangle elements, with three nodes tied into one at the crack tip, ANSYS (2009). The elastic plastic fracture mechanics concept (EPFM) was employed in numerical analyses of fracture in pressurized specimens, as large scale yielding occurred in ligaments. The J-integral and CTOD values with respect to applied pressure were inferred from finite element simulation results by using postprocessor routines, ANSYS (2009). The J-integral introduced by Rice (1968) is defined as a path independent integral,

$$J = \int_{\Gamma} \left(W \mathrm{d}y - T_{\mathrm{i}} \frac{\partial \mathrm{u}_{\mathrm{i}}}{\partial x} \mathrm{d}s \right) \tag{1}$$

where the strain energy W is given by

$$W = \int_0^{\varepsilon} \sigma_{ij} d\varepsilon_{ij} \tag{2}$$

and $\boldsymbol{\varepsilon} = [\varepsilon_{ij}]$ is the strain tensor, Γ is a path surrounding the crack tip, as shown in Fig. 5. **T** is the traction vector defined according to the outward normal along Γ, $T_i = \sigma_{ij}n_j$, **u** is the displacement vector and ds is a line element along Γ. The crack tip opening displacement (CTOD), δ_t is a measure of crack tip blunting and is usually defined as the distance between the intercepts of two 45° lines with the deformed crack profile as illustrated in Fig. 6.

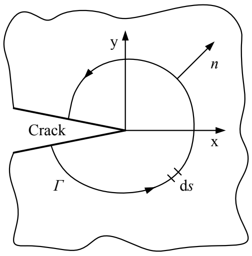

Fig. 5. J-integral contour path surrounding a crack tip.

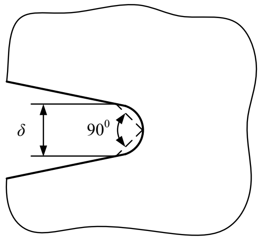

Fig. 6. Definition of the CTOD parameter, δ.

In FE analyses for CN specimens a uniform displacement at the end of specimens has been incrementally increased in load steps. At the maximum load associated with fracture onset the critical J-integral value and critical crack tip opening displacements were estimated as J_c = 360 MPa mm, δ_{tc} = 1.85 mm, respectively, as obtained by Sumi et al. (1998) and Božić (2002). For pressurized specimens the pressure load was increased incrementally in steps of 100 kPa, and the total ranges of applied load were similar to those registered in the experiment. Fig. 7 shows the von Mises stress distribution in pressurized specimens for a pressure load of 600 kPa.

It is assumed that critical J_c and δ_{tc} values obtained for the CN specimen can be used for estimation of fracture onset in pressurized specimens. Figs. 6 and 7 show J-integral and CTOD values with respect to the applied pressure load. In Fig. 8 a line is plotted for J_c and the intersection with the J curves for pressurized specimens gives the estimated critical pressure. In a similar manner the critical pressures were estimated based on δ_{tc}, as shown in Fig. 9. Results for the estimated critical pressures based on J_c and δ_{tc} are given in Table 2.

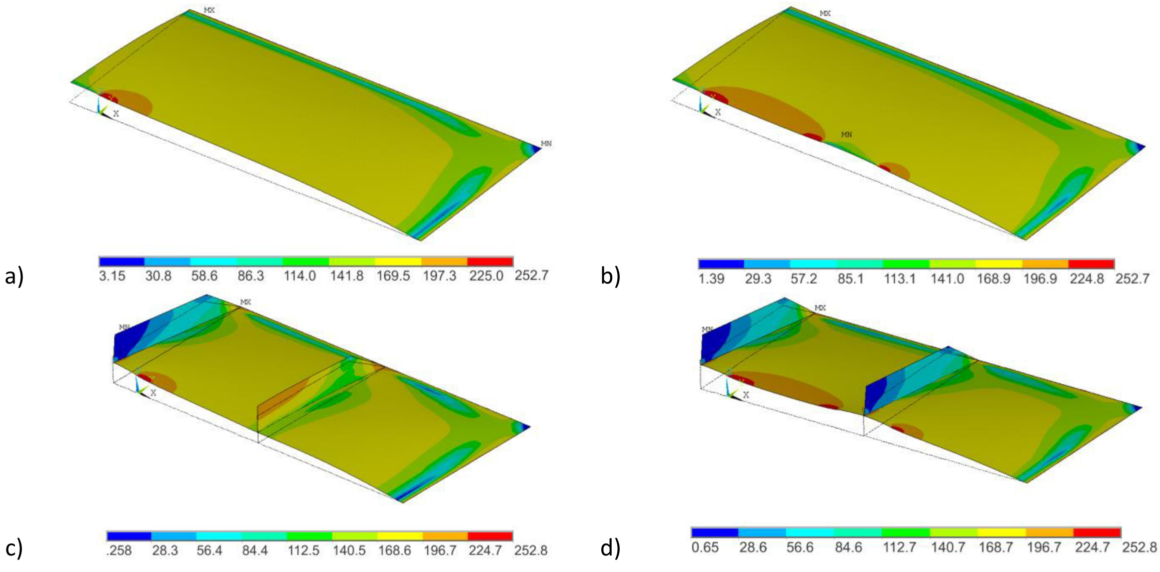

Fig. 7. σ_{eqv} for the pressure p = 600 kPa for specimens: a) PPR-1; b) PPR-3; c) SPPR-1; d) SPPR-3, given in Fig. 4.

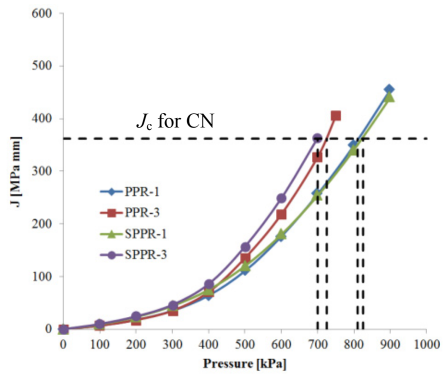

Fig. 8. J-integral values for pressurized specimens.

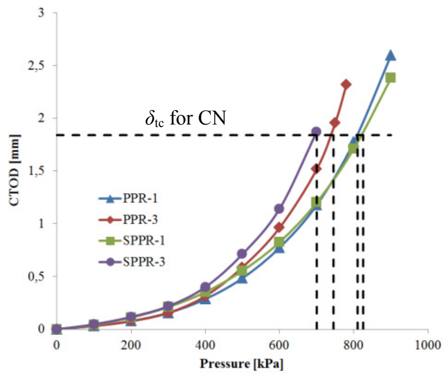

Fig. 9. CTOD values for pressurized specimens.

Table 2. Assessed critical pressures compared with experimental results.

Specimen	PPR-1	PPR-3	SPPR-1	SPPR-3
Critical pressure – experiment [kPa]	900	750	780	680
Critical pressure based upon J_c [kPa]	810	725	825	700
Critical pressure based upon δ_{tc} [kPa]	810	745	825	700

Assessed critical pressures for unstiffened specimens are slightly lower and for stiffened panel specimens slightly higher, compared to experimental results. This could be due to imperfect clamping conditions in the experiment and also due to slightly different material properties of the two considered materials.

4. Conclusion

Fracture mechanisms of stiffened panels, damaged by a single and multiple cracks, subjected to lateral pressure have been analyzed. In the finite element models an elastic-plastic fracture mechanics concept (EPFM) was implemented and critical pressures associated with fracture onset in the specimens were assessed based on the critical J_c and δ_{tc} parameters, obtained from fracture tests for a centrally notched tension specimen. Numerical results of fracture analyses of stiffened panel specimens were compared with experimental results and a reasonably good agreement was observed. The developed procedure can be applied to real thin-walled structures.

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