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Experimental Study on Local Plastic Collapse in A Plate Weakened by Two Collinear Cracks

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Abstract. Fracture and fatigue assessment of structures weakened by multiple site damage (MSD) currently represents a challenging problem. Here, we communicate the outcomes of an experimental study conducted on a plate weakened by two closely-spaced collinear cracks, which represents the simplest form of MSD. The experimental results are used to verify the predictions of a recently developed theoretical approach.

1 Introduction

MSD can undermine the overall strength and integrity of a structure. Due to the presence of mutual interaction between multiple cracks, the residual strength of structures with MSD can be significantly lower than those of structures with non-interacting cracks [1-4]. Advanced analytical approaches for the analysis of multiple crack problems are often based on the strip yield model, which was originally introduced by Dugdale [5] and Barenblatt [6]. The popularity of this model is due to the relative simplicity of the mathematical formulation, which allows for easy computation of various fracture controlling parameters, such as the crack tip opening displacement.

The residual strength of plate and shell components with MSD can be assessed using the plastic zone coalescence criterion [7-11], also known as the ligament yield criterion. According to the plastic zone coalescence criterion, the ligament between cracks is assumed to fail if the plastic zones of neighboring crack tips come in contact with each other. In [12], a theoretical model was developed to investigate the local plastic collapse conditions for a finite thickness plate weakened by two collinear cracks, based on the classical strip yield model and plasticity induced crack closure concept. The three-dimensional modelling predicted a strong influence of the crack interaction, material properties as well as the plate thickness on the local plastic collapse conditions.

In this paper, effect of the crack interaction and the plate thickness on the plastic collapse of the ligament between two closely spaced collinear cracks is investigated experimentally.

2 Theoretical Approach

A three-dimensional model for the evaluation of the residual strength of two collinear cracks of equal length was developed in [12] based on the strip yield model [5,6] and the plasticity induced crack closure concept [13-14]. In [12], the crack problem was formulated using the distributed dislocation technique, i.e. the cracks and plastic zone lines were represented by an unknown distribution of edge dislocations to stimulate strain nuclei [15]. The resulting governing equations were based on the 3D fundamental solution for an edge dislocation in a plate of finite thickness obtained in [16]. The governing equations were solved using the Gauss-Chebyshev quadrature and the numerical solution procedure is described in a number of articles by the authors [17-23].

3 Experimental Program

Fracture tests were performed to investigate the local plastic collapse phenomenon of the ligament between two collinear cracks subjected to remote loading. The tests were carried out in the LT orientation of specimens with respect to the rolling direction. The following sections provide details of the fracture tests and testing methodology.

3.1 Material property test and specimen preparation

The material used for the current study is aluminium alloy 5005 sheet. In accordance with ASTM E8M-04, material property tests were initially conducted on standard coupons cut out from the plates in the same orientation as to be used in the investigations of the local collapse conditions. The measured values for Young's modulus E, 0.2% yield strength σ_Y, corresponding yield

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strain ε_Y and ultimate strength σ_u were 62 GPa, 132 MPa, 0.0041 and 152 MPa, respectively. These values were obtained using an Instron tensile machine equipped with an extensometer. Further, six specimens in total were machined by using the water jet cutting technology to avoid any possible formation of heat damage. Each specimen contained two collinear slits of equal length of 10 mm and width of 2 mm. In order to investigate the crack interaction and plate thickness effects, six types of specimens were fabricated with three plate thicknesses ($2h$ = 1.2, 2.0 and 3.0mm) and two centre-to-centre distances of collinear slits ($2d$ = 20 and 25 mm). The specimen design is shown in Fig. 1a. To produce sharp cracks, the slits were notched with a 0.5 mm thickness saw, and after that, pre-cracked using a constant amplitude cyclic loading with $\sigma_{max}/\sigma_Y = 0.3$, $R = 0.05$ and 5 Hz as recommended by the ASTM standard. The measured fatigue crack lengths were typically 0.2~1.3 mm. The specimen preparation process was accomplished by attaching a strain gauge (FLG-1-23, gauge width 1.1mm) in the middle of the ligament between the two collinear cracks (see Fig. 1). The role of the strain gauge was to measure the applied tensile strain level and identify the plastic collapse conditions of the ligament based on the plastic zone coalescence criterion. In other words, the local plastic collapse conditions were assumed to occur when the strain level in the middle of the ligament reaches the yield strain of the material measured from coupon tests. The specimen dimensions after fabrication and pre-cracking are shown in Table 1.

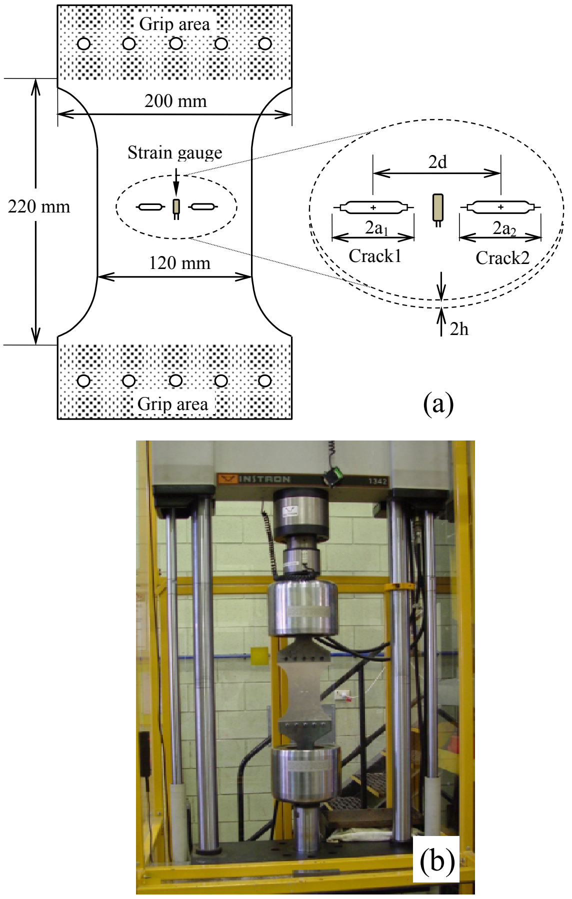


Figure 1. (a) Test specimen with two collinear cracks equipped with strain gauge, (b) Instron 1342 with a test sample.

3.2 Plastic collapse testing

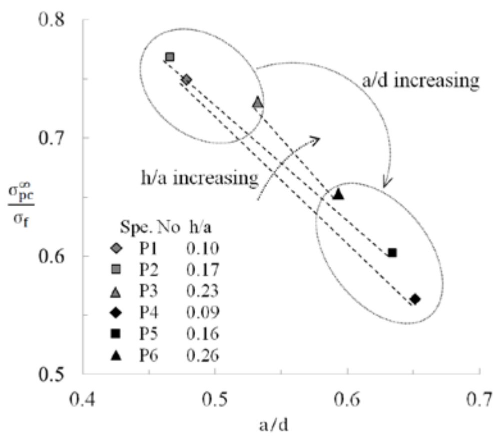
The plastic collapse tests were carried out under displacement control (elongation rate of 10 mm/min) using an Instron 1342 hydraulic machine (see Fig. 1b). Each specimen was stretched under tensile quasi-static loading until failure. The plastic collapse of the ligament is specified when the plastically deformed regions developed at the inner crack tips expand toward the centre of the ligament and come into contact. Accordingly, strain values were monitored at the centre of the ligament while the tensile loading increases. When the strain reached the yield strain of the material, the corresponding remotely applied stress value (net-section stress) was considered as the plastic collapse stress for the ligament yielding. The development of plastically deformed regions was visible with the naked eye. In all six specimens, no crack growth was observed. This was because the plastic collapse stress was below the critical applied stress needed for fracture initiation or sub-critical crack growth.

Table 1. Specimen dimensions after saw-cutting and pre-cracking (unit: mm).

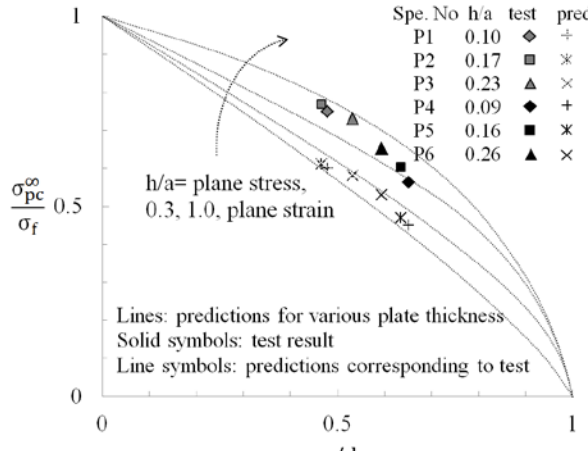
Specimen No.	2h	$2a_1$	$2a_2$	2d
P1	1.2	11.97	11.86	24.90
P2	2	11.6	11.86	25.16
P3	3	13.13	12.75	24.31
P4	1.2	12.78	12.88	19.69
P5	2	12.64	12.55	19.86
P6	3	11.03	12.15	19.53

4 Experimental Results

The results of the plastic collapse tests are shown in Fig. 2a. The results presented in this figure were normalised by the flow stress, or $(\sigma_Y + \sigma_u)/2$, of the material, and the normalised plastic collapse stress, $\sigma_{pc}^{\infty}/\sigma_f$, was plotted against the ratio of crack length to centre-to-centre distance of cracks, a/d, which is an indicator to the crack interaction effect. The variation of plastic collapse stress presented in Fig. 2a is the result of the combined effects of the crack interaction and plate thickness, which are characterised by different a/d and h/a.



(a)



(b)

Figure 2. (a) Measured plastic collapse stresses of six specimens having two collinear cracks, (b) Calculated and measured plastic collapse stress levels against crack length to separation gap ratio for different plate thicknesses.

It is virtually impossible to fabricate test specimens with the same geometry as the pre-cracking always produces some scatter. To investigate the effect of crack interaction (or influence of a/d on the collapse stress) the data points which have a similar h/a value are paired and connected with a dotted line in Fig. 2a. Due to a small number of tests the dependences largely provide a qualitative assessment of the crack interaction effect. The shift of the dotted lines highlighted by an arrow in Fig. 2a demonstrates the effect of plate thickness (or influence of h/a) on the local plastic collapse conditions. This figure also shows the effect of crack interaction on a plastic collapse stress. For the tested specimen geometries, on average, a drop of 20% in the plastic collapse stress was measured with an increase in a/d from 0.49 to 0.62 (27% increase). Overall, the plastic ligament collapse conditions were found to be highly dependent on both the crack interaction and the plate thickness. These trends have also been predicted by the three-dimensional strip yield model for two collinear cracks, which was presented in [12].

A comparison between the test results and theoretical predictions made using the theoretical model developed in [12] is shown in Fig. 2b. In this figure, the theoretical predictions (lines) of the plastic collapse stress normalised by the flow stress, $\sigma_{pc}^{\infty}/\sigma_f$, as a function of the ratio of crack length to centre-to-centre distance of cracks, a/d, are presented for four different plate thickness to half crack length ratios. This figure also displays the plastic collapse test results (symbols). The comparison reveals that the theoretical model leads to conservative estimates of the plastic collapse stress of the specimens. The predicted values are substantially lower than the corresponding test results with the relative error being about 21%. These discrepancies are due to the use of a strip yield model, idealised yield criterion and elastic-perfectly-plastic model of material behaviour.

However, it is highly noteworthy that the plastic collapse stress predictions show the same trends as the experimental results. Furthermore, the differences between the predictions and the experimental results are very consistent throughout the measured data, as shown in Table 2. This can imply the usefulness of the developed model if the disparity can be offset by employing an empirical value for the flow stress, σ_f, which is to some extent is a fitting parameter as highlighted in the previous sections.

Accordingly, the concept of using a fitting value of the flow stress, σ_f , in normalising the measured plastic collapse stress was utilized in this chapter. The introduced fitting flow stress in this context aims to compensate errors associated with the yield strip idealisation, idealised yield conditions and elastic-perfectly-plastic material behaviour. A remarkable reduction of the discrepancies between the experimental and theoretical results can be observed with this new value of the flow stress (177.5 MPA). The characteristic error is now around 1-2 % (see Table 2), which can be considered as an excellent agreement between theory and experiment.

Table 2. Predicted and measured plastic collapse stress to yield strength ratios.

Specimen No		P1	P2	P3	P4	P5	P6
Prediction	σ /σ	0.60	0.61	0.58	0.45	0.47	0.53
Experiment	σ /σ	0.75	0.77	0.73	0.56	0.60	0.65
	Relative error	20 %	21 %	21 %	20 %	22 %	18 %
	σ /σ	0.60	0.62	0.58	0.45	0.48	0.52
	Relative error	0%	1%	1%	0%	2%	-2%

5 Conclusion

An experimental program was developed for the investigation of the effect of crack interaction and plate thickness on the local plastic conditions of plate specimens having two collinear cracks subject to static tensile loading. In order to verify the theoretical three-dimensional strip yield model developed previously, a comparison between experimental results and theoretical prediction was conducted. The comparison revealed that the theoretical model considerably underestimated the residual strength of the specimens containing two collinear cracks. Even though the substantial offset between experimental results and predictions, the model predicted exactly the same trends as observed in the experiments. This signified its usefulness in assessing the coalescence and local plastic collapse conditions with the aid of a fitting value of the flow stress. This fitting value compensates the errors associated with various idealisations employed in the theoretical modelling. A remarkable agreement between the theoretical predictions and experimental results was observed if this fitting value of the flow stress was used in the modelling approach. In conclusion, it can be stated that the strip yield model combined with the best-fit flow stress is very effective in predicting the residual strength of plates weakened by two cracks. It is expected that the similar modelling approach will be also very effective in the analysis of other types of MSD.

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