Numerical and Experimental Investigation to Evaluate Shape Evolution of Fatigue Cracks in Notched Elements

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ABSTRACT. *In this paper an investigation of shape evolution of fatigue crack is exposed. A numerical model able to foresee the local growth of a border crack is first presented. The numerical model is based on 3D FEM calculation of singular stress field along the crack boundary, obtained by a dedicated pre-processor able to insert an arbitrary shaped crack in the analysed component. The crack evolution is simulated by means of a step by step basis advancing model. The crack growth is governed by a driving force dependent by the local fracture parameters and taking into account eventual plasticity induced by a notch. To assess the reliability of the presented model an experimental evaluation was conducted inserting an artificial starting crack in the specimens. The use of non destructive testing procedures made possible to follow the crack evolution during fatigue life. Crack extent and shape, and its evolution at different step of fatigue life are measured by means of radiographic method and penetrant liquid.*

INTRODUCTION

Damage tolerant design methodologies allow to achieve best performance from structural components but require reliable tools for the prediction of crack evolution. In fact is important to predict, with a safety margin, the residual life of defected component.

Several studies were addressed to the problem of crack propagation achieving a deep insight about this phenomenon by means of experimental, theoretical and in recent time, fine detailed numerical simulation [1].

In this work a quite general purpose tool developed at Department of Mechanical Engineering of Rome University "Tor Vergata" [2], was used and refined for a specific problem of practical interest: the study of evolution of a corner crack emanating from an hole.

Several contributions about crack propagation at holes are present in literature. For instance in [3] a detailed numerical study is presented about propagation of a crack of various starting shape; in [4] experimental results about shape evolution of a crack emanating from an hole is reported. However the effect of notch plasticity on crack shape evolution is not covered, i.e. only high cycles fatigue is handled.

Even though high cycle fatigue crack shape evolution could be modelled by a local extension of Paris law, such approach works very well in internal regions, where local plain strain state is present, but is very cumbersome to apply for point at free face of the component. In [5] a variational approach is proposed to alleviate this problem.

For notched element the problem is complicated if a plastic field is produced by external load at notch root, because there is an interaction between local plastic zone at crack tip and K-dominance is lost. A comprehensive investigation about short crack emanating at notch is reported in [6] where experimental results were fitted very well by means of a two stages propagation model, considering first a plastic strain driven propagation and then a stable crack growth, modelled by means of the Paris Erdogan law. However this study regards simple geometry with straight front crack.

According to the two stage model, in this work a numerical modelling of crack shape evolution is presented, extending the method based on local application of Paris law, including in the driving formulation the local plastic strain effect.

A specific software was developed to automate the preparation and the analysis of three dimensional finite element model of cracked elements. Many component shapes may be handled, and in this work the attention was focused on the propagation of corner crack emanating from an hole of a rectangular plate. Both elastic and non linear elastic plastic analysis are easily conducted on cracked parts, with arbitrary crack shape, in order to evaluate the local driving force to assess the shape evolution. Software tool allows to perform one step calculation, in which fracture parameters are evaluated to verify the stability of an arbitrary shaped crack at desired load level. Furthermore a fully automatic crack advancing algorithm is implemented, that allows to follow crack growth during fatigue life of the component under load or displacement control.

The reliability of the code was already tested by means of literature experimental data for high cycle fatigue as exposed in [2]. To verify the prediction at high loads, with plasticity at notch root, a set of experimental test was conducted.

A material widely used in machine design was chosen, C40 steel, and was tested, first monotonically and then cyclically, to evaluate actual parameters.

To investigate crack shape propagation at holes, rectangular bar specimens with a central hole were manufactured with the material previously investigated. In the symmetry plane of loaded bars a corner crack starter was inserted by means of a circular mill 0.45mm thick, with three different depth.

NUMERICAL MODEL

As mentioned in the introduction, numerical simulations were performed by means of a dedicated software [2] that was further improved for this study.

Evaluation of local crack speed was performed according to the local driving force, using a plastic strain law for notch influenced regions (Eq. 1), and the local Paris law for linear elastic regions (Eq.2).

$$\frac{da}{dN}(\xi) = C_1 \varepsilon_a^{m_1} \{\Delta_n - [a(\xi) + e(\xi)]\} \quad (1)$$

$$\frac{da}{dN}(\xi) = C(\Delta K(\xi))^m \quad (2)$$

The local extension of Ahmad and Yates elastic plastic model [6] is easy to understand if the cracked body is thought to be divided in a series of parallel strips as exposed in Fig. 1.

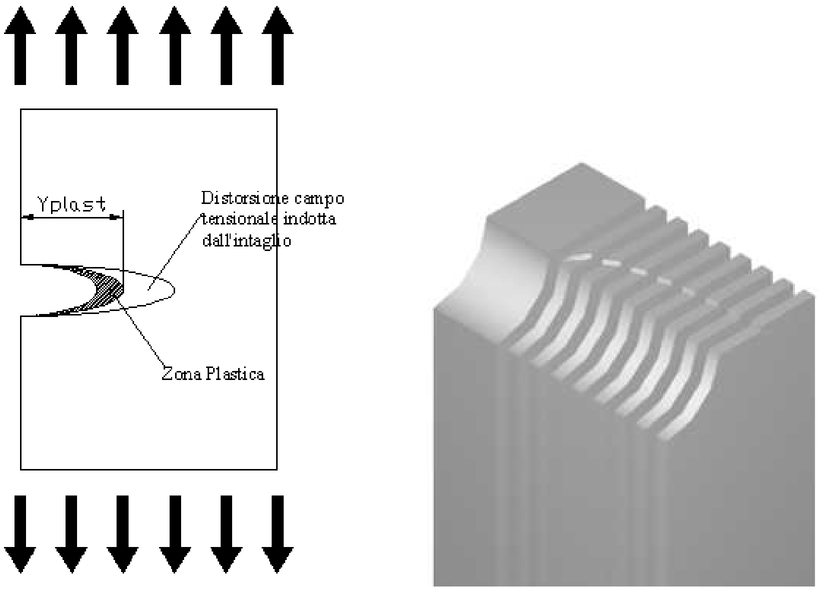


Figure 1. Extension of elastic plastic model to a three dimensional problem.

At each calculation step, an elastic plastic analysis is conducted to evaluate notch induced plasticity. Crack speed is then assessed by means of the proper parameters.

All numerical simulations were performed imposing a fixed displacement at boundary. For this reason the loss of cross section, produced by crack advancing, is compensated by external load decreasing. This loading control maintains about constant the notch plasticity level during the crack growth.

For low load levels, the propagation is fully governed by the linear model and high cycle fatigue occurs, while for higher loads fatigue is governed by plastic strain. Load levels chosen for calculations and experiments fall in the transition region, because the occurrence of both mechanisms complicates crack growth and makes more interesting the study.

EXPERIMENTAL

The experimental analysis was carried out in two different steps: the first one was the characterisation of the material investigated, a C40 steel, the second was the study of crack propagation in notched specimen.

All the tests in this work have been carried out with a 250 kN servohydraulic test machine under displacement control in fully reversed tension-compression loading. A frequency of 1 Hz has been used. The waveform of a dynamic load cycle has been set sinusoidal. Displacement control has been achieved using an extensometer.

Material Testing

The specimens to determine material static and cyclic constants, have been built according to the ASTM E606-92 standard [7]. Starting from a 20 mm diameter round bar, a smooth hourglass specimen, having the aspect of Fig. 3, with a minimum section diameter of 10 mm has been obtained (see Fig. 2 drawing for details). Prescribed shape guarantees a buckling stability of the specimen during compression.

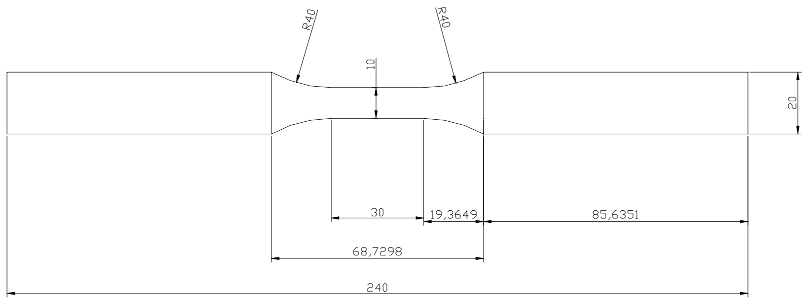


Figure 2. Drawing of specimen adopted for material testing.

Figure 3. Actual specimen adopted for material testing.

Traction tests to find σ_{sn}, σ_r and E, and fatigue tests to find the coefficients of Coffin-Manson equation (Eq. 3) and of Ramberg-Osgood curve (Eq.4) have been performed. The results are reported in Table 1.

$$\varepsilon_{at} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (3)$$

$$\varepsilon_{at} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{\frac{1}{n'}} \qquad (4)$$

Table 1. Material testing result.

Monotonic parameters			**Coffin Manson parameters**				**Cyclic parameters**	
σ_{sn} N/mm^2	σ_r N/mm^2	***E*** N/mm^2	σ'_f N/mm^2	ε'_f	***B***	***C***	***H'***	***n'***
470	840	205000	871	0,2	0.07698	0.78812	814.1	0.0975

Crack Propagation Testing

As exposed in the introduction, crack propagation was investigated for a rectangular bar with a circular hole, a kind of geometry recurring in practical applications. The specimens have been realised starting from round bar (20 mm diameter) of the same production stock used for material testing, machined to obtain a rectangular section of 14 mm X 7 mm, with a central hole of 5 mm diameter.

To create a corner crack starter of known shape, a slit was inserted in the plane perpendicular to the specimen axis, and passing to the axis of the hole, by means of a circular mill (t=0.15mm,ϕ=50mm).

Three different depths of the slit has been realised to investigate the influence of this initial shape on the phenomenon of crack propagation: 0.2 mm (see Fig. 4), 0.6 mm (see Fig. 5) and 1 mm (see Fig. 6).

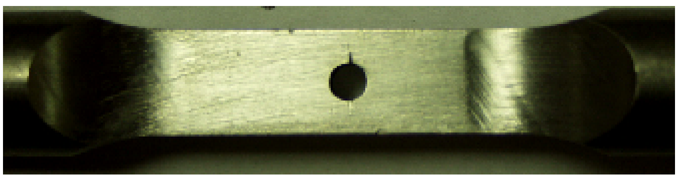


Figure 4. 0.2 mm pre-cracked specimen.

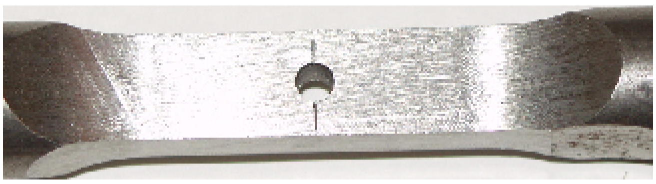


Figure 5. 0.6 mm pre-cracked specimen.

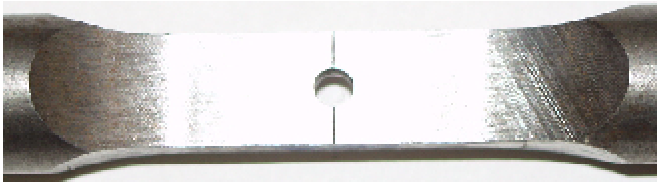


Figure 6. 1 mm pre-cracked specimen.

For all these configurations, tests has been carried out under displacement control in fully reversed loading at load ratio R = (min. load/max. load) = -1 and nominal strain amplitude between 0.2 % and 0.1 %. The displacement control has been realised with an extensometer of 25 mm with a possible movement of ± 5 mm.

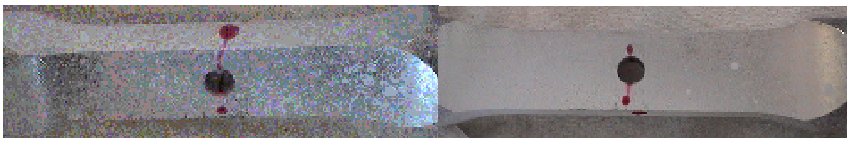
Crack growth in the specimens was monitored using penetrant liquid method and radiographic method [8].

RESULTS AND DISCUSSION

The crack growth has been verified with penetrant liquid and radiography. Some examples are reported in Figs 7, 9 and 10, that show how is possible to highlight the crack and to understand its growth characteristics.

It has to be noticed that the crack begins to propagate after a lot of cycles. The reason is that the artificial cut is not a real crack starter. Thus the number of cycles required to have a detectable crack growth are not properly the cycles necessary to the crack propagation, but the first part of the experiment is necessary to nucleate the crack. As example for the cut of 1 mm, with ε=0.1% the crack propagates in the last 4000 cycles of 24.000 total cycles made.

Experiments results tell us that the shape of the crack can be elliptical or linear, depending on the deformation and on the depth of the slit, but in the majority of the case studied it has been verified a planar crack, due to the symmetry of design and load.



a) b)

Figure 7. Liquid penetrant control; a) frontal-lateral, b) posterior (0.2mm,0.15%).

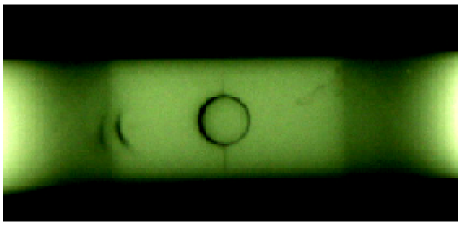
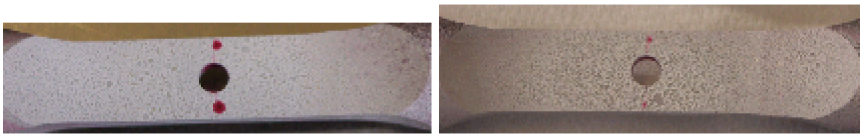


Figure 8. Radiographic control of a crack(0.2mm,0.2%).

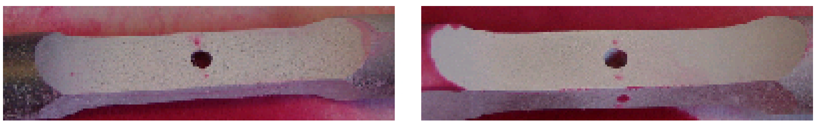
Table 2. Experimental results for pre-cracked specimens.

Depth mm	**Strain** %	**Number of Cycles**	**Load** kN
0.2	0.2	2400	27.3
	0.15	7700	acquisition lost
	0.1	63500	17.0
0.6	0.2	1650	28.7
	0.15	7700	23.5
	0.1	To be tested	To be tested
1	0.2	720	31.8
	0.15	3400	24.2
	0.1	24000	18.3



a) b)

Figure 9. Penetrant liquid on a linear crack; a) frontal, b) posterior (0.2mm,0.2%).



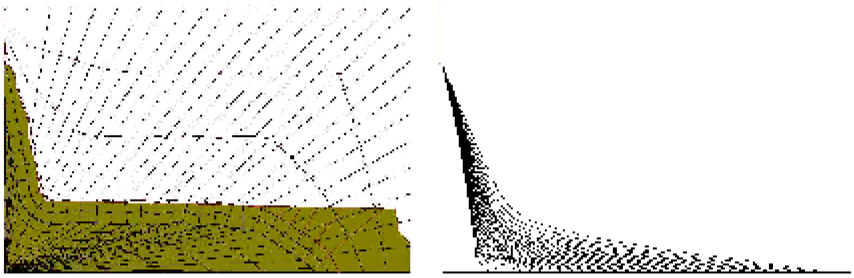
a) b)

Figure10. Penetrant liquid on the posterior part of two specimens with slit 0.6mm a) ε=0.2% ; b) ε=0.15%.

Figure 7 shows a liquid penetrant control of an elliptical crack, and Figure 9 shows the same control made on a linear crack.

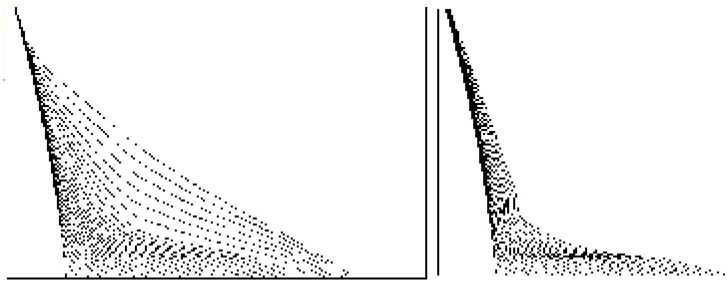
In the case of the 0.6 mm crack starter, it has been viewed that the shape of the crack changes varying the deformation imposed. In fact, how can be seen in Figure 10, increasing the deformation, the crack propagates faster in the direction of the hole, while in presence of lower deformation, the crack propagates faster on the surface, following a shape similar to the one imposed by the starter.

Numerical simulation results are exposed as follows. Figures 11 (a) and 11 (b) show the crack front evolution starting from a 0.6 mm depth starter, at two displacement levels.



a) b)

Figure 11. Predicted crack front evolution at two strain levels for 0.6 mm crack: a) ε=0.2% ; b) ε=0.15%.



a) b)

Figure 12. Predicted crack front evolution at two strain levels for 1 mm crack: a) ε=0.2% ; b) ε=0.15%.

Predicted crack front evolutions of 0.6 mm starter, fit well with the experimental measure. Figure 12 shows that in case of higher deformation the crack propagates mainly in the hole zone, while in case of lower deformation the crack propagates also near to the surface.

In case of starter slit of 1 mm, the simulation (reported in Fig. 12) gives similar results. Experiments show the crack propagates on a 45° plane, starting from the region where the starter reaches the lateral sides of the specimen. Since the numerical model is designed for crack that propagates in the symmetry plane, a good agreement between experiment and simulation was not obtained for this condition.

CONCLUSIONS

In this work the problem of fatigue crack growing was investigated both numerically and experimentally.

In particular numerical and experimental crack growth investigations were addressed to establish crack propagation mechanism.

After material characterisation, a series of fatigue test on rectangular bars with a central hole were performed under displacement control. The effect of loads was investigated choosing three load levels tuned to have incipient plasticity or a finite extension plasticity at notch root.

To promote a corner crack propagation, various shapes of crack starter were investigated.

On the whole, nine case were investigated experimentally.

The same experiments were performed numerically, focusing the attention for four cases considering only higher load for two starter geometry. Quite good agreement was obtained between predicted and observed crack propagation for 0.6 mm starter. As far as the 1 mm starter propagation is concerned, a crack kinking on the lateral surface was observed experimentally in transversal direction, that at the moment cannot be handled by the simulation code.

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