Numerical simulation of ductile fracture in modified Arcan test

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Abstract

In this study, the experimental results from a modified Arcan test on dual-phase steel are revisited in order to assess a numerical modelling approach for ductile fracture. This experiment is chosen since it displays a complex crack-path that undergoes three phases: fracture initiation and crack propagation with transition from Mode I to Mode II. A significantly larger amount of plastic dissipation is observed in the material at the point of fracture initiation compared to the material points along the crack-path. A numerical approach that is capable of capturing this complex crack-path is believed also to give good predictions in other complex fracture problems. The numerical simulations of the modified Arcan test are run with the nonlinear Finite Element (FE) code IMPETUS Afea Solver. Elements with tri-linear shape functions are utilized in combination with explicit time integration. The plastic behaviour of the material is modelled by the elastic-viscoplastic $J_2$ flow theory using the Voce work-hardening rule. Both element erosion and node-splitting techniques are tested in order to simulate the crack propagation. It is shown that the node-splitting technique with a crack-tip enhancement gave the best prediction of the three different phases of the crack propagation.

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1. Introduction

With the increasing computational power available for engineers, increasingly complex phenomena can be included in numerical simulations. Due to the computational costs and the lack of accurate models, predictions of complex ductile crack paths are not included in FE simulations of crashworthiness made by e.g. the automotive industry.

Several criteria have been proposed in the literature to describe ductile fracture. Most of these criteria can be expressed as a damage variable that accumulates with plastic straining. The damage can be coupled with the constitutive equations, e.g., Gurson (1977) and Lemaitre (1992), or the yield criterion, plastic flow and strain hardening can be unaffected by the damage, e.g. Cockcroft and Latham (1968), and Johnson and Cook (1985).

In FE models, crack propagation can be simulated by several different methods, such as element erosion, node splitting, cohesive elements, remeshing adaptivity and the extended finite element method. Which method that is the most appropriate, depends on the problem at hand.

In this paper, a complex ductile crack pattern in a modified Arcan test is examined and simulated by FE models. The criterion presented by Cockcroft and Latham (1968) is used to predict ductile fracture, and both element erosion and node splitting have been tested in order to simulate the crack propagation.

2. Experimental

2.1. Material and mechanical test set-up

The 45° modified Arcan test presented by Gruben et al. (2011) is revisited and examined in more detail. The specimen was cut from a 2 mm thick sheet made from a low strength-high hardening dual-phase steel, Docol 600DL, delivered by Swedish Steel AB (SSAB). Fig.1(a) gives the Cauchy stress vs. plastic logarithmic strain curve derived from a uniaxial tensile test conducted in the rolling direction of the sheet. From uniaxial tensile tests carried out at 0°, 45°, and 90° to the rolling direction, it was found that the material displayed in-plane isotropic properties in terms of strength, plastic flow and ductility. The modified Arcan test set-up is shown in Fig. 1(b), where it can be seen that the specimen is bolted to brackets that are connected to the hydraulic actuator. Fig. 1(c) gives the geometry of the notched Arcan specimen. The modified Arcan test was carried out in a hydraulic testing machine in room temperature and under displacement control. The test duration was 765 seconds and the effective strain rate at the point of fracture initiation was approximately $10^{-3}$ s$^{-1}$. More details regarding the experimental tests can be found in Gruben et al. (2011).

Fig. 1 (a) Cauchy stress vs. plastic logarithmic strain curve for the Docol 600DL material, (b) modified Arcan test set-up and (c) modified Arcan specimen geometry.
2.2. Experimental results

The fracture process in the modified Arcan test consisted of three distinct phases:

- **Phase 1: Fracture initiation.** Fracture occurred in the notch after substantial strain localization in a region approximately the size of the sheet thickness (i.e., local necking).

- **Phase 2: Mode I crack propagation.** The crack tip that occurred after fracture initiation led to further strain localization in a shear band followed by Mode I crack propagation that was eventually arrested.

- **Phase 3: Mode II crack propagation.** After the arrest, local strains were built up in the remaining part of the specimen before a sudden Mode II crack propagation (i.e., in-plane shear) occurred.

During the cause of crack propagation, large rigid body rotations occurred in the specimen due to the pinned connection between the hydraulic actuator and the brackets holding the specimen. Fig. 2(a) shows the three distinct regions corresponding to Phase 1, 2 and 3 along the crack path. Fig. 2(b) shows a close-up of the fracture initiation region that is subjected to local necking, while Fig. 2(c) shows the thickness of the specimen along the crack path. As can be seen, the thickness at fracture is 1.2 mm in Phase 1, approximately 1.7 mm in Phase 2, and up to 2.4 mm in Phase 3. Fig. 2(d) shows a close-up of the in-plane shear fracture in Phase 3. By considering the change in thickness, the strains in Phase 1 and Phase 3, as measured on a macro scale, are much larger than the strains in Phase 2. This is confirmed by optical measurements as illustrated in Fig. 2(e-f). Fig. 2(e) shows the effective strain on the surface of the specimen. The effective strain at fracture for the elements along the crack path, from #1 at fracture initiation and up to #52 as the last element in Phase 2 is plotted in Fig. 2(f). Unfortunately, too large deformations occurred in Phase 3 to allow good optical measurements. The optical measurements were carried out using an in-house digital image correlation (DIC) software (Fagerholt et al., 2013).
The three phases can be recognized in the force-time curve shown in Fig. 2(g). When fracture initiates, a rapid drop in the force level appears during Phase 2, then the force level flattens out, before the sudden Mode II fracture in Phase 3.

3. Numerical modelling

The boundary conditions (BC) of the modified Arcan test involve brackets bolted to the specimen and pins fastening the brackets to the hydraulic actuator. In order to get as realistic BCs as possible, the in-plane displacement fields in specified nodes surrounding the crack-path were extracted from the experiment by DIC and used directly as input in the numerical models. Thus, for each node \( i \) the displacement \( u(t) \) was collected and applied in the numerical models within the time interval \( 0 \leq t \leq 765 \text{s} \). An appropriate spatial scaling was applied where the pixel/mm ratio was 38.76. Fig. 3(a) shows the positions at which the displacements were collected.

The DIC mesh shown in Fig. 3(a) with quadrilateral elements was used as a basis to generate a FE mesh with hexahedral elements for use in the simulations, see Fig. 3(b). The hexahedral mesh was refined in the central part of the model with an element size of approximately 0.7 mm, giving three elements through the thickness. Tri-linear solid elements with selectively reduced integration were applied together with explicit time-integration in the commercial software IMPETUS Afea Solver (IMPETUS, 2013). The critical time step was set to 0.01 s to give a reasonable computational time. It was made sure that the mass scaling did not alter the numerical results. An elastic-viscoplastic model was used including the von Mises yield function, the associated flow rule and the Voce hardening rule. In the plastic domain, the von Mises effective stress is expressed as

\[
\bar{\sigma} = \left( \sigma_0 + \sum_{i=1}^{2} Q_i \left(1 - \exp(-C_i p)\right) \right) \left(1 + \frac{p}{\dot{p}_0}\right)^C
\]

where \( \bar{\sigma} \) is the flow stress and \( p \) is the equivalent plastic strain. The parameters \( \sigma_0 \), \( Q_i \) and \( C_i \), \( i=1,2 \), govern the work hardening of the material, while \( \dot{p}_0 \) and \( C \) are strain rate sensitivity parameters. The values of these parameters for the Docol 600DL material were found by Gruben et al. (2011) and are summed up in Table 1. Ductile failure was predicted by the Cockcroft-Latham (CL) criterion (Cockcroft and Latham, 1968)

\[
D = \frac{W}{W_C}, \quad W = \int_0^p \langle \sigma_1 \rangle \, dp, \quad \langle \sigma_1 \rangle = \max(\sigma_1,0)
\]

where \( \sigma_1 \) is the major principal stress, \( W \) is the Cockcroft-Latham integral, and \( W_C \) is the fracture parameter. Fracture is assumed to occur as \( D \) equals unity. The value \( W_C = 1100 \text{ MPa} \) was used in the numerical models as this gave a good prediction of fracture initiation. The mesh is constructed to allow for crack propagation in the same region of the specimen as observed in the experiment, although there is no restriction on the direction of the crack-path.

A total of three FE models are presented in this study. Apart from the handling of crack-propagation, the models are identical. Both the element erosion and node-splitting techniques available in the code were tested to describe the crack propagation. When using element erosion, the element loses its deviatoric strength when the fracture criterion
is met in one or more integration points. A propagating crack is thus treated as a series of fracture initiations. In the node-splitting technique additional nodes are added to the mesh in order to allow for the generation of new crack plane(s) between the elements. If two elements share the same nodal position, one extra free node is added to this position. If four elements share the same nodal position, three extra free nodes are added and so on. The free nodes follow the original node until a potential node split. The damage at a node is estimated as the maximum of all the integration points in the elements connected to the node. If the damage equals unity at a node, a free node is used to generate a new crack plane. The normal to the new crack plane is defined as closely as possible to the major principal stress direction with the given spatial discretization.

A modification in order to better capture Mode I crack propagation is applied in one simulation. This modification is only available with node splitting, and is only activated for the elements connected to a crack-tip. Here a scaling function \( f \) is applied to the CL criterion in order to take into account plastic localization over a spatial distance much smaller than the element size. The enhanced criterion is evaluated in all the closest integration points around the crack-tip and is expressed as

\[
f \cdot W > W_C \quad (3)
\]

The function \( f \geq 1 \) is optimized for the different element types available in the IMPETUS Afea solver and is proportional to \( \sqrt{d \cdot W_C / GI} \). Here \( d \) is the closest distance from the integration point to the crack-tip, and \( GI \) is a material parameter. \( GI \) was set to 1100 J/mm² in this study.

| \( \sigma_0 \) [MPa] | \( Q_1 \) [MPa] | \( C_1 \) | \( Q_2 \) [MPa] | \( C_2 \) | \( \varepsilon_0 \) | \( C \) |
|-------------------|----------------|------|----------------|------|---------|------|
| 283.3             | 268.3          | 39.38| 396.6          | 5    | 0.001   | 0.005|

4. Results and discussion

The force-time curve, the thickness and the equivalent plastic strain along the crack-path are the response parameters used for assessing the FE simulation results. In all the simulations, the same response is expected before fracture initiation.

In the simulation with the element erosion technique, the direction of the crack-path diverged somewhat from the direction observed experimentally; however, the major difference was that the crack propagated much more slowly than in the experiment. Fig. 4(a) shows that the crack has not propagated through the specimen at \( t = 765 \) s, and Fig. 5 shows that the force level was much higher in the simulation after fracture initiation. At the point of fracture initiation the thickness was measured to 1.2 mm as in the experiment, but in Phase 2, the thickness was significantly smaller in the simulation, namely 0.9 mm on average versus the experimentally obtained 1.7 mm, see Fig. 4(a) and Fig. 2(c). As shown by the contours of equivalent plastic strain in Fig. 4(a), the strains are significantly larger along the crack-path in the simulation. The large strains and the thinning along the Phase 2 crack-path are caused by a local neck that is enforced in this model since the elements are too large to capture the extreme strain localization at the crack-tip. The element erosion technique is thus incapable of capturing the higher speed of the crack propagation due to the strain localization at the crack tip. An approach that might improve the predictions with element erosion has been proposed by Unosson et al. (2007). Another alternative would be to use a sufficiently fine mesh to resolve the strain gradients at the crack tip, but this would require too small elements for practical engineering problems.

Fig. 4 Crack-path at \( t = 765 \) s in simulations with (a) element erosion, (b) node-splitting and (c) Mode I enhanced node-splitting. Thicknesses at various locations are marked. The contour plots are of equivalent plastic strain in the range 0.0-0.8.
The simulation with the node-splitting technique share many similarities with the simulation applying element erosion. As seen in Fig. 4(b), the crack-path does not run through the specimen, and the force-time curve overestimates the strength after fracture initiation, as shown in Fig. 5. The thicknesses in Phases 1 and 2 are also in this simulation about 1.2 mm and 0.9 mm, respectively. Again the strain localization at the crack tip is not accounted for and the strains are smeared out over a larger region along the crack path, as indicated by the plastic strain contours in Fig. 4(b). On the other hand, when Mode I enhancement is applied, the crack-path runs through the specimen as in the experiment; see Fig. 4(c), and the force-time curve fits the experimental data, as shown in Fig. 5. The thickness is 1.2 mm in Phase 1, while it is 1.5 mm in Phase 2 and at the start of Phase 3.

At the end of Phase 3, the thickness is 2.3 mm, which is close to the experimental value of 2.4 mm. This shows that the transition from Phase 2 to Phase 3 is captured. It is seen by the contour plot in Fig. 4(c) that the strains in Phase 1 are significantly larger than in Phase 2, and that the strains increase before global failure. Clearly the model using Mode I enhanced node splitting is capable of capturing the complex crack-path displayed in the modified Arcan test. The computational times in the three simulations were approximately the same.

5. Conclusions

The experimental results from a modified Arcan test is revisited and processed in order to evaluate different approaches for simulating crack propagation within the framework of the finite element method. The element erosion and the standard node-splitting techniques do not account for the strain localization at the crack-tip, and a local neck is forced to appear before fracture, thus slowing down the crack propagation. An enhancement in order to better predict Mode I fracture with node splitting led to results very close to the observed experimental data.

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