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A new impact test for the identification of a dynamic crack propagation criterion using a gas-gun device

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Abstract. The modelling of damage and fracture behaviour under high rates of loadings for metallic structures presents the more and more interests for engineering design, especially for crash phenomena. In order to perform a numerical simulation of such phenomena a crack propagation criterion must be identified using adapted laboratory tests. The objective of this paper is to present a new impact test intended for the identification of a cohesive crack criterion implemented into a home-made FEM code based on Extended Finite Element Method. Therefore, a double-notched specimen is impacted using a gas-gun device in order to obtain different crack paths depending on projectile speed. A post-impact macro-photographic observation allows to measure the crack path, the angles and the advancing length. These experimental results are used as input responses in the identification procedure for determining the crack cohesive criterion parameters. Some experimental results, for an aluminium alloy crack criterion identification, are presented to illustrate the proposed approach.

1. INTRODUCTION

The prediction of cracks behaviour for the structures sustaining dynamic loadings becomes the more and more important in our days either if these cracks are desirables or not. In the first case it's about of applications as projectile-target impact, when the interest is to obtain a perforation, while for the second case one must avoid the cracks initiation and propagation in order to preserve the security of transport means for example. Whatever the situation, simulations are conducted using FE codes in order to predict the behaviour of cracked structures and one needs to use for the numerical model a such called "crack propagation criterion" which must supply at each time-step simulation the answers to three main questions: when the crack growths, in which direction this crack will propagate and how far this fracture will propagate?

Several dynamic crack propagation criteria are presented in literature, based on energetic or physical concepts. In all cases constitutive parameters, function of material properties, must be identified. That's why experimental tests were carried out, associated to identification techniques, in order to find the values of these parameters. Some contributions were published concerning this kind of tests and the ones which inspired us belongs to Klepaczko [1] which proposed a double-shearing impact test, and to Kalthoff [2] which developed an impact test for studying the dynamic fracture modes. For the design of our test, aiming to identify crack propagation criteria, we used some ideas from the mentioned contributions and adapted it for the conditions of our impact laboratory. So, a gas-gun device was used for carry-out this test and its constructive characteristics played an important role for the experimental set-up of the test as will be detailed in the second section.

Experimental responses provided by this test are used for identify a crack cohesive criterion presented in the third section of the paper. The numerical simulation of the test, the principle of the identification technique and the results for a tested materiel makes the object of the fourth section. The conclusion and the improving perspectives of this works end this paper.

2. EXPERIMENTAL SET-UP

As mentioned in the introduction, a gas-gun device was employed to carry-out this test. It's about a 20 mm calibre gun, using a compressed oxygen-nitrogen mixture, able to launch cylindrical projectiles up to 350 m/s for a 30 gr mass. A detailed description of this machine, usually called Taylor gun, is given in [3].

The main idea of the test was to impact a projectile to a target in order to generate dynamic fractures for which the final propagation length and angle are different depending on impact speed. So, the target geometry was designed as shown on Figure 1, presenting two symmetrical notches. The projectile impacts between the notches and the shifted angles of these allow the initiation and propagation of two symmetrical cracks as one can observe on Figure 2(b) for the impacted target.

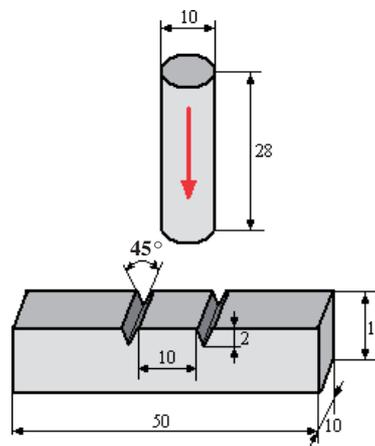


Figure 1. Fracture test scheme.

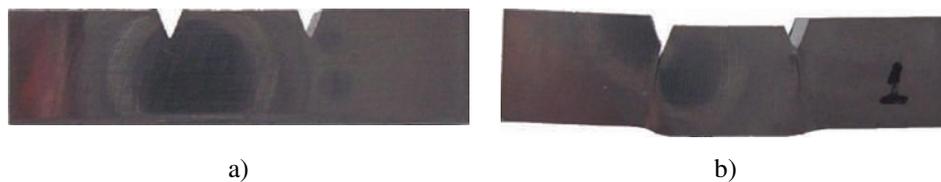


Figure 2. Real target specimens. a) Before impact, b) After impact.

Obviously, a symmetric impact with respect of the median plane of the target is the essential initial condition for obtaining accurate results for this test. So, the emplacement of the target into the impact chamber of the gas-gun must allow the positioning of the target for a right impact. A support for cylindrical targets was already present in the impact chamber and we decide to use it and to design an adapting device for our non-cylindrical target.

This adapting device is illustrated on Figure 3 and, besides the positioning of the target, having a heavy support body it provides an inertial mass difference ensuring the necessary conditions for dynamic cracks propagation.

The support cover, fixed by four well-balanced screws, keeps rigidly the specimen target with the support and the spacer wedges role is to introduce a free space between target and the hole bottom of the body support. The cover thickness and screws diameter was determined so that the elasticity effects

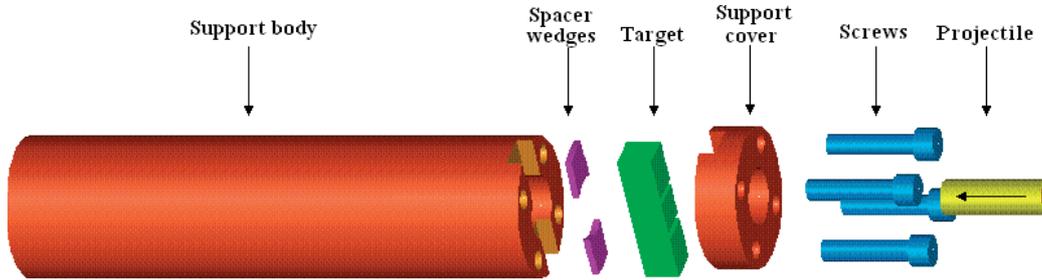


Figure 3. Experimental device for fracture impact test.

over the target during the impact to be limited. Once the support target placed into the impact chamber and right position fixed up, the test can be performed.

The impact speed range must be calibrate function of each tested material in order to obtain final crack lengths shorter than 8 mm (the distance between the bottom of notches and the opposite border of the target), avoiding the complete fracture. In this stage of this test development, the experimental responses provided and used by the identification procedure are the final length of the crack path and its orientation angle with respect of the impact axis. Future improvements are expected as mentioned in the final section of the paper.

3. COHESIVE CRACK CRITERION

The experimental responses of the presented fracture impact test were used to identify the parameters of the cohesive crack criterion. Further, basics on this criterion will be presented.

The main idea is to use the properties of the cohesive zone assumed in front of the crack tip, in the elaboration zone of crack. Considering a 2D cracked structure, one introduce the mathematical crack tip (i.e. the point where crack opening displacement vanishes) and the physical crack tip (i.e. the point of complete separation of crack lips). The cohesive zone ranges between these two points.

A cohesive law is considered along this zone. This one is linking two parameters of the model: the critical opening displacement corresponding to physical crack tip for a complete separation, noted δ_{crit} , and the maximal value of cohesive stress at the mathematical crack-tip, noted σ_{max} . These are the criterion parameters to identify. The magnitude of the cohesive stress decreases as the crack opening displacement increases along the cohesive zone and the relationship between these two parameters, widely accepted in literature is the linear one. On the Figure 4 one can see the graphical illustration of this law, the area under the curve matching the fracture energy:

$$G_F = \frac{\delta_{crit}\sigma_{max}}{2} \quad (1)$$

This crack propagation criterion was implemented in a home made FE code called DynaCrack [4], based on Extended Finite Element Method (XFEM)[5]. This method allows a direct evaluation of the crack opening displacement and the crack will propagate if this one exceeds the critical value, δ_{crit} , inside of cohesive zone. The propagation direction is determined using the well known maximum circumferential stress criterion. The particular approach adopted for this implementation of XFEM, restricting the position of the crack tip to the element edges, provides the crack propagation speed automatically since the crack tip is allowed to advance one element at a time.

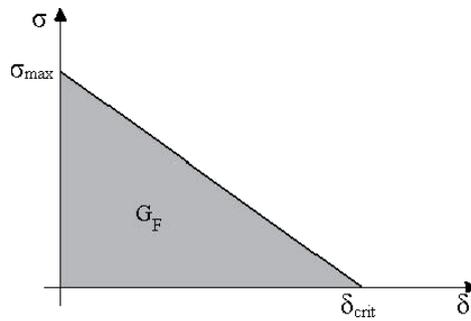


Figure 4. Linear cohesive laws graphic.

4. NUMERICAL SIMULATION AND IDENTIFICATION RESULTS

Numerical simulation of this impact fracture test was performed for applying the identification procedure in order to find the numerical values for the crack cohesive criterion parameters.

Using DynaCrack code mentioned before, the numerical model was built respecting the initial and boundary conditions as shown on Figure 5(a) where the initial mesh of the model is presented. One takes into account the geometrical symmetry of the target and for modelling the impact conditions, the projectile mass was distributed over the impacted face nodes and the impact speed was introduced as initial speed on the same nodes. 4-nodes quadrilaterals elements were considered and a finer meshing was performed for the expected crack zone.

As example, an aluminium alloy was tested to identify the numerical values for cohesive crack criterion. An elasto-dynamic analysis was done using as material properties: mass density $\rho = 2780 \text{ kg/m}^3$, Young modulus $E = 73.1 \text{ GPa}$ and Poisson coefficient $\nu = 0.33$. On Figure 5(b) one can see the numerical shearing field at the end of the analysis for an impact speed of 67.52 m/s . A final advancing of the crack over 9 elements, corresponding to a final length of 3.6 mm (the corresponding experimental value is 3.45 mm) was reported in this case.

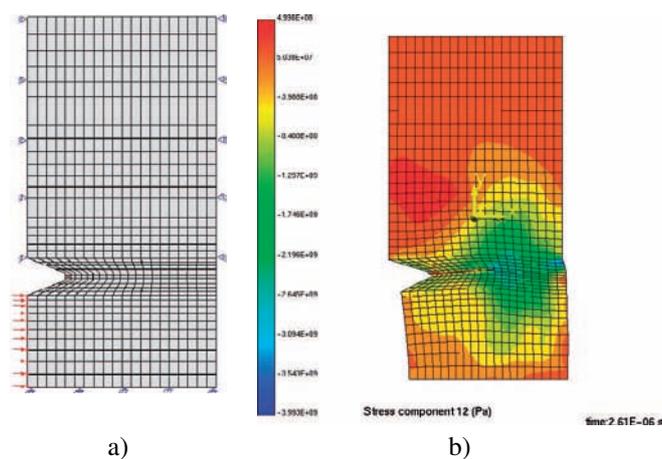


Figure 5. Numerical model of fracture impact test. a) Mesh, initial and boundary conditions, b) Shearing field at the end of analysis.

Table 1. Experimental data and identification results for cohesive crack criterion.

Test	Impact speed [m/s]	Crack length [m]	δ_{crit} [m]	σ_{max} [MPa]
1	40.66	$5.04 \cdot 10^{-4}$	$8.25 \cdot 10^{-6}$	690
2	51.39	$7.11 \cdot 10^{-4}$	$8.96 \cdot 10^{-6}$	550
3	67.52	$3.45 \cdot 10^{-3}$	$9.86 \cdot 10^{-6}$	480
4	71.78	$4.12 \cdot 10^{-3}$	$10.45 \cdot 10^{-6}$	465
5	77.84	$4.45 \cdot 10^{-3}$	$11.70 \cdot 10^{-6}$	462

A number of 5 tests was realised using targets made from this material, impacted by projectiles launched with different speeds. Speed values and corresponding experimental final crack lengths are presented in Table 1. For the adopted speed range, the experimental orientations of the cracks paths were quite identically, about 23° , while the numerical values were around 20° .

The cohesive crack propagation model parameters were identified, for each test, using a combined Monte-Carlo+Levenberg-Marquardt procedure [6]. The principle of this identification procedure is to perform a minimisation between experimental responses of the impact test and the corresponding numerical ones using firstly an exploration algorithm (Monte-Carlo) followed by a refinement of the optimisation by Levenberg-Marquardt algorithm. The experimental responses used in this case were only the final crack lengths since non-significant differences between crack path orientations were reported.

The results of identifications are presented in Table 1 and the first observation is that concerning the quite important differences between the numerical values of the identified parameters. This can be explain essentially by the particularities of XFEM implementation in our home-made code. Actually, in this stage of its development, DynaCrack is able to perform only elasto-dynamic analysis and the presence of the elastic waves reflections were observed leading to some perturbations over the crack propagation. The planned implementation of an elasto-plastic analysis in this code will solve this problem.

For the final values of cohesive crack criterion, the mean values were adopted: $\delta_{crit} = 9.85 \cdot 10^{-6}$ m and $\sigma_{max} = 550$ MPa.

5. CONCLUSION

A new impact test was developed in order to study the dynamic crack propagation. The main objective was to obtain experimental responses useful to identify crack propagation criteria. For the proposed test, the target geometry allows to obtain different crack paths function of impact speed and the final geometry of these cracks are used as experimental responses for the identification procedure. A gas-gun device was adapted, adding a new target support, to perform this test. Some improvements of the experimental set-up are planned, such as equipping the target with fracture extensometry gages for recording the crack time initiation, useful as experimental response.

The numerical modelling by DynaCrack was achieved in an elasto-dynamic approach and the future development of this code will allow to take into account the plastic behaviour of the materials leading to more accurate results.

As an example, the proposed cohesive crack criterion parameters were identified for an aluminium alloy using the experimental responses supplied by 5 impact tests. Note that the numerical values of the identified parameters are accurate strictly for the mentioned conditions of numerical analysis.

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