Dynamic crack propagation of prestressed metallic structures: an experimental-numerical approach

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Keywords: dynamic, fracture, cohesive zone, strain rate, barrel, plate, explosion

Abstract. Failure of structures due to dynamic crack propagation is the objective of this paper. An experimental-numerical approach is followed. A number of cases have been investigated, including failure of prestressed plates, pressurized barrels and an LPG road tanker. Fracture is described by means of a cohesive zone model. The crack speed is governed by the dynamic fracture toughness, which is determined from the crack speed via an inverse procedure.

Introduction

Dynamic crack propagation of ductile metallic materials is the subject of this paper. A typical example is the rupture of a gas pipe, where a propagating crack may cover very long distances, until it finally stops (arrests) when it finds a tougher material or loses energy. Crack speeds of 200-300 m/s are typically observed and reported in literature. Another example is the explosion of a road tanker containing a liquefied pressurized gas, e.g. LPG. Failure usually initiates by a small crack, which propagates, causing the tank collapse. Due to the sudden failure of the tank a so called BLEVE (boiling liquid expanding vapour explosion) can occur, depending on the failure time, i.e. the crack velocity. The third example is the explosion of a small bomb in an airplane. The explosion usually leads to the formation of a crack, which propagates along the weakest points of the fuselage. These examples are shown in Figure 1.

The prediction of the crack speed is important, since it can help to devise arrest measures, and thus control the damage. The crack speed is closely linked to the fracture toughness. The tougher the material, the lower the crack speed. In addition, the dynamic fracture toughness of ductile metallic materials is lower than the static toughness (see ref. [2]). The dynamic fracture toughness is often obtained from impact tests, e.g. Charpy tests, using empirical correlations, which are prone to errors. From a theoretical point of view, the speed of crack propagation is limited by the Rayleigh wave speed, approximately 3000 m/s for steel, and 2800 m/s for aluminium. In practice, the dynamic crack speed of ductile metallic materials is an order of magnitude lower (200-300 m/s), due to the toughening effect of plasticity, microscopic void growth, etc. Due to the rupture of the material, dynamic crack propagation causes an unloading stress wave, travelling faster than the crack.

In this study, dynamic fracture of simple steel and aluminium metallic structures is studied, from an experimental and a numerical point of view. The dynamic fracture toughness is obtained via an inverse procedure, based on the crack speed. Dynamic crack propagation is the object of two research projects at TNO, which have contributed to this research, one concerning the safety of explosions in tunnels (Delft Cluster project ‘Bijzondere belastingen’), and the other, which investigates the behaviour of a civil aircraft fuselage under blast and fire (EU-VULCAN project).

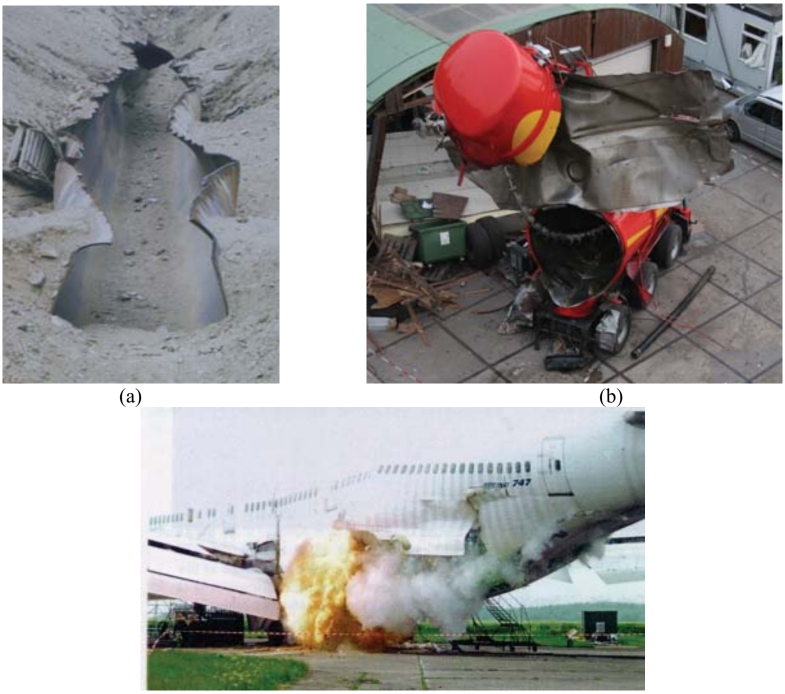
(a) (b) (c)

Figure 1 (a) full scale burst test of gas pipeline [1]; (b) explosion of a road tanker (2008); (c) explosion of airplane (DERA test, 2001).

Approach

The experiments studied in this paper are simulated using an explicit finite element code (LS-DYNA) [3]. Explicit codes are suitable to describe highly transient phenomena, such as dynamic crack propagation. Fracture is described by means of cohesive zones. Cohesive zones lump the nonlinear behaviour of the Fracture Process Zone (FPZ) in an element of negligible width, with a nonlinear traction-opening curve (see Figure 2). Different types of cohesive laws can be found in literature, most of them displaying some short of softening behaviour. Among them, strain rate insensitive models (damage, nonlinear elastic, or elastoplastic) are the most common. Metals, h however, are strain rate dependent materials, so it seems logical to incorporate this strain rate dependency in a cohesive law, as it has been done in ref [4-7]. In ductile fracture, the stress triaxiality plays an important role, which can be in incorporated in the cohesive law [8]. These advanced cohesive zone models are not available yet in commercial codes. In this study, an existing LS-DYNA damage strain-rate independent cohesive zone model is used (*MAT_COHESIVE_GENERAL), which can describe mixed mode fracture. The strain rate dependency of the bulk material is accounted using a von-Mises elastoplastic model (*MAT_PLASTIC_KINEMATIC). The implementation of strain-rate effects in the cohesive law is the object of an investigation at TNO.

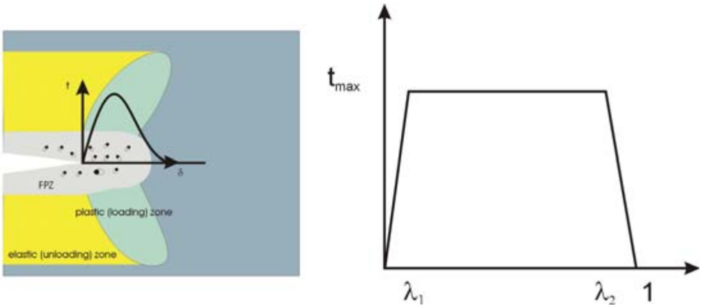

Figure 2 (left) detail of the crack tip during dynamic crack propagation, fracture process zone (FPZ) and cohesive traction-opening curve; (right) simplified cohesive traction-opening curve (LS-DYNA model).

Prestressed plates

Dynamic crack propagation on duplex steel plates is investigated. This type of steel is used in pressurized gas road tanks. The dimensions of the plates are 800 mm (width) by 1500 mm (length), and are 1.5 mm thick. The plate is prestressed at stress 625 MPa, which is larger than the yield stress (480 MPa), and then a crack is initiated using a 200 mm long explosive line charge, oriented perpendicular to the loading direction. As a result, a crack propagates in mode-I. During crack propagation, the internal energy stored in the plate is released and is transformed into fracture energy, and kinetic energy. Strains on the plate are registered using strain gauges. The applied force and the overall elongation of the plate are measured, and the crack path is recorded using a high speed camera. In the simulations, cohesive elements are placed along the crack path, and the plate is modelled with solid elements. Figure 3 shows the experimental setup, and a close-up view of the simulated and observed crack tip.

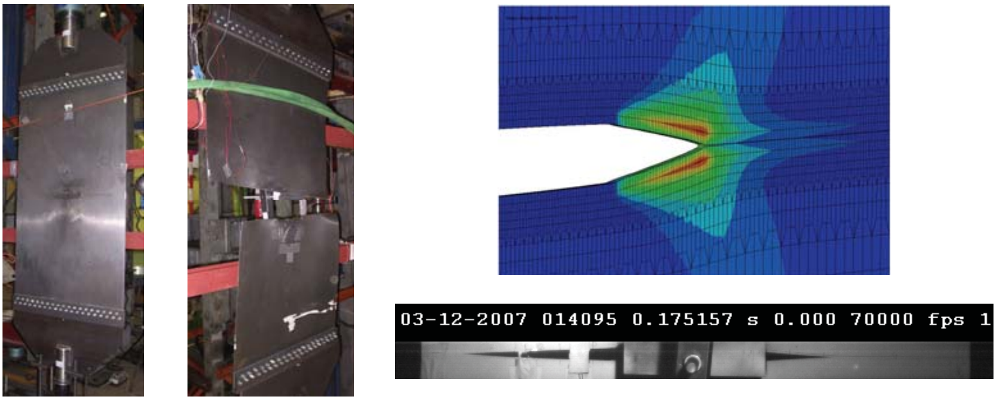

Figure 3 Tensile test setup to measure the crack speed of a prestressed steel plate. (left) before crack propagation; (middle) after crack propagation; (right-top) FE model with cohesive elements, stress field at the fracture process zone; (right-bottom) high speed photograph of propagating crack.

Figure 4 shows von-Mises stress snapshots during crack propagation. The simulated crack speed is shown in Figure 5. The crack speed grows monotonically, but it does not reach its maximum asymptotic value. This indicates that the plate is too short. The local fluctuations of the speed are likely caused by the stress reflections on the boundaries. The crack speed strongly depends on the dynamic fracture toughness. From literature, a value of Gf=55 N/mm was adopted. This lead to a too high crack speed, near 800 m/s (and increasing), compared to the crack speeds found in literature (between 200 and 300 m/s). The actual dynamic fracture toughness must then be higher, and should vary with the crack speed, i.e. strain rate. Yet, this can only be achieved with a strain-rate dependent model. In the next sections, the dynamic fracture toughness is obtained via an inverse procedure.

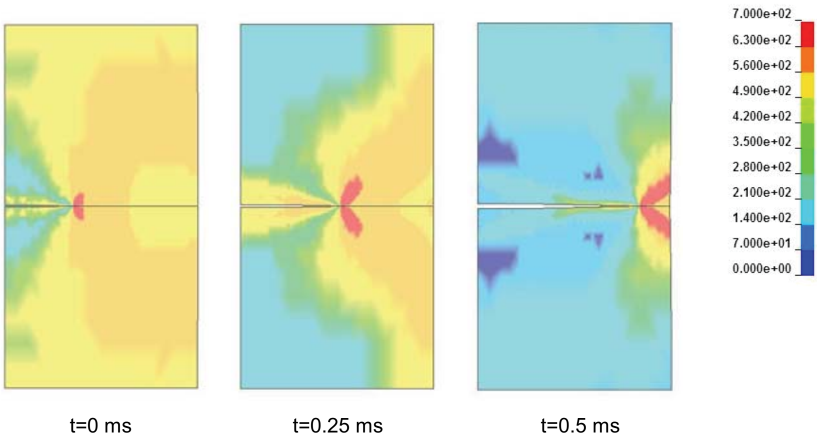

Figure 4 Von-Mises stress snapshots during crack propagation.

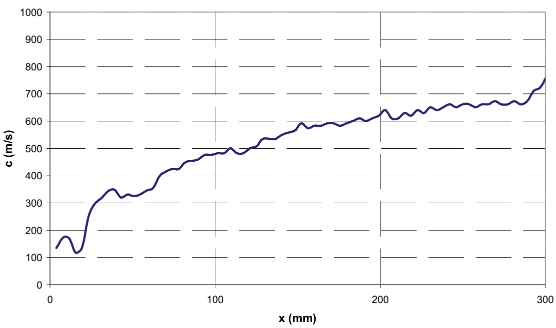

Figure 5 Simulated crack speed versus distance.

Pressurized barrel

A 1.2 m diameter barrel was tested, which represents a 1/3 scale model of an idealised aircraft fuselage, in order to reduce both test complexity and costs The barrel is made of 1 mm thick Al 2024-T3 plate and is pressurized to 2-3 bars. A crack is initiated in the axial direction by using an explosive charge, like in the prestressed plate discussed above. As a result, an axial crack will propagate in mode-I, until it meets the rigid top and bottom ends, and then continues in mixed mode. During the test, the internal pressure, the strains at some locations and the crack tip position are monitored. Because of the growing opening, the internal pressure drops, until it equals the atmospheric pressure. The measured pressure is applied as boundary condition to the FE model. CZ's are placed along the failure lines, i.e. axially along the explosive charge and circumferentially, along the top and bottom planes. See Figure 6.

Figure 6 Failure of a pressurized aluminium barrel. (left) setup with measuring devices, (middle) barrel after explosion; (right) FE model, stress field during crack propagation.

The influence of the fracture toughness on the crack speed is shown in Figure 7. The dynamic fracture toughness, roughly G_f=75 N/mm, is obtained in an inverse manner, based on the measured and simulated crack speeds. This value is in agreement with literature [9].

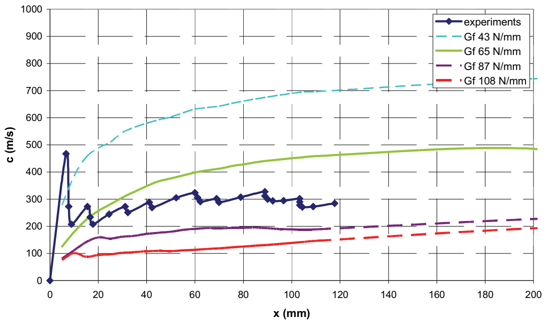

Figure 7 Crack speed versus distance. Experimental and simulated curves for different fracture toughnesses.

Failure of an LPG tank

Failure of an LPG tank may lead to a BLEVE of catastrophic consequences to the surroundings. A BLEVE is the explosive evaporation process as a consequence of the rupture of a pressure vessel containing a liquefied gas. To tackle this problem, one needs to solve three coupled problems: (i) nonlinear plasticity, (ii) fracture and (iii) gas dynamics. The approach that we have followed is described here. The nonlinear fracture mechanics problem (i-ii) is simulated in LS-DYNA, following the same approach as above. The gas dynamics problem (iii) is studied using a computational fluid dynamics (CFD) code [10, 11]. The tank failure time is used a boundary condition of problem (iii). The resulting pressure distribution in (iii) is used as boundary conditions of the problems (i) and (ii). This will give a certain failure time, which is compared with the failure time assumed in (i).

A representative LPG tank is studied, with a length of 12 m, a diameter of 2.5 m, and a thickness of 10 mm. The tank is made of steel P460 (Dillinal Di 460/630 N). Cohesive zones are placed along the interface between the liquid and the vapour phase, since this is a common crack initiation location due to the difference in temperature between the two phases. Likewise, CZ elements are placed along the tank ends, which correspond with weld lines, where fracture is likely to occur. See Figure 8.

Figure 8 Representative LPG tank, with cohesive zones (red lines).

Figure 9 shows the Lagrangian and the Eulerian mesh used in the solid mechanics and the CFD model respectively. The Lagrangian mesh is made of shell and CZ elements.

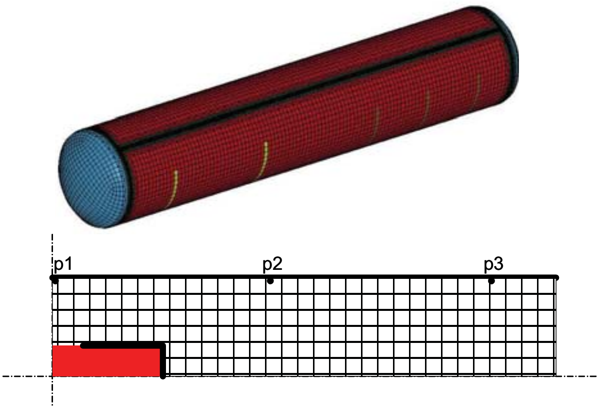

Figure 9 (above) nonlinear fracture mechanics problem, with Lagrangian finite element mesh; (below) CFD problem, with Eulerian mesh (the tank is represented in red).

Not knowing the dynamic fracture toughness of this material, this was estimated to be G_f=500 N/mm via an inverse modelling technique, based on the expected crack speed of 300 m/s. See Figure 10. The analyses have shown that a typical time scale for the loss of structural integrity of the vessel is equal to approximately 25 ms, which is "instantaneous" from the gas-dynamics point of view. Hence the mechanical fracture problem and the gas dynamics problem can be studied separately, by assuming instantaneous failure of the tank. A sequence of von-Mises stress plots is shown in Figure 11, which illustrate the failure mode.

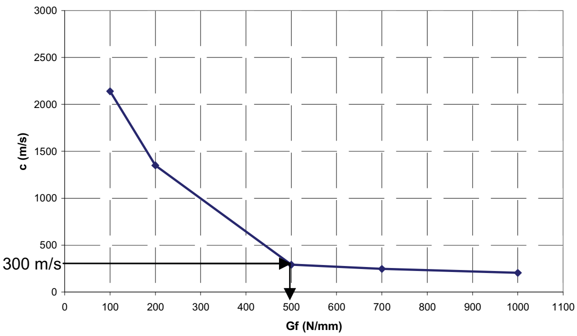

Figure 10 Inverse analysis for the determination of dynamic fracture toughness, based on crack speed.

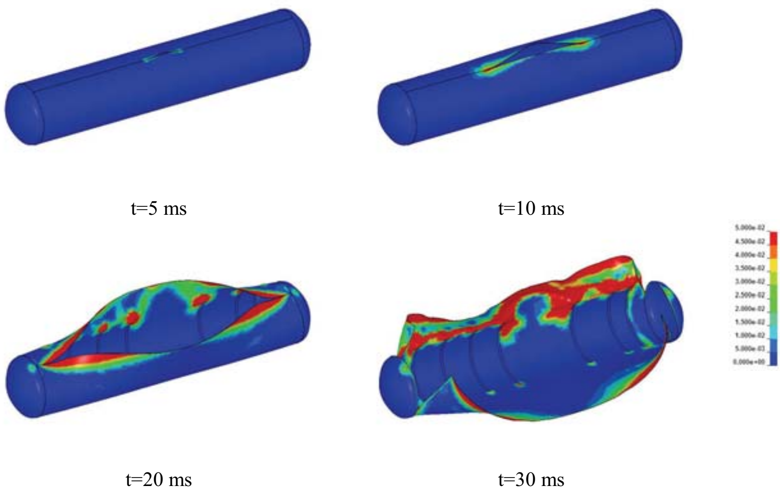

Figure 11 Equivalent plastic strain plots (MPa) during the tank failure.

Conclusions

Dynamic crack propagation of prestressed metallic structures (a prestress plate, a pressurized barrel and an LPG road tanker) has been investigated, from an experimental and numerical point of view. The CZ model has proven to be able to describe the failure mechanisms correctly. The dynamic fracture toughness must be determined in order to have a good quantitative agreement. The dynamic fracture toughness is not a constant, since it depends on the strain rate and thus on the crack speed. The dynamic fracture toughness is usually determined via impact tests (e.g. Charpy test), using empirical correlations, which are always prone to errors. In this study, the fracture toughness, i.e. the area under the traction displacement curve of the CZ model, has been obtained in an inverse manner, from the measured (or estimated) crack speeds. Strain rate independent CZ's have a constant fracture toughness. This is acceptable when a crack propagates at a constant speed (usually the asymptotic speed), and it remains constant. Yet, when the crack speed is not constant (e.g. because of spatial toughness variations, or because the crack just started to propagate and has not reached its maximum speed yet), neither the strain rate, nor the dynamic fracture toughness is constant. In this case a strain-rate sensitive CZ is more appropriate. This is the object of an investigation at TNO.

Acknowledgments

The authors would like to express their gratitude to the EU project VULCAN and the Dutch Delft Cluster project "Bijzondere Belastingen" (CT01.21), and in particular, F. Soetens, C. Wentzel, J. van Deursen, Bert van den Berg and all the members of the "blast team".

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