Prediction of Dynamic Fracture in Pressurised Plastic Pipes

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ABSTRACT

This work presents a 3D coupled solid-fluid model for predicting fast fractures in pressurised plastic pipes. It is developed within a unified computational procedure where both solid pipe and pressurising media are discretised using the Finite Volume method. The coupling is achieved across the pipe-fluid interface (pipe bore) via newly developed interpolation procedure. Cohesive zone model, which describes the local separation (fracture) process, is incorporated into the model allowing the prediction of the crack growth along the pipe. The model is qualitatively validated against the Full Scale (FS) experimental observations on gas pressurised polyethylene (PE80) pipe.

INTRODUCTION

Most buried pipelines are made from advanced, special-purpose polyethylene resins. Although very tough under low loading rates and at temperatures above the glass transition, these materials are susceptible to catastrophic failure by *Rapid Crack Propagation* (RCP) under extreme conditions. A brittle crack initiated by impact or otherwise may run along a pipeline at speeds of 100-300 m/s, for as long as a pressurising medium remains inside the pipe.

A number of research groups have attempted to model this problem numerically. In particular, Southwest Research (1) developed a procedure using shell Finite Element method for the pipe and a Finite Volume (FV) method for the fluid. This approach is rather cumbersome and inefficient as it involves coupling of two different numerical schemes, and its applicability is restricted to thin-wall pipes due to shell assumptions. Further, this procedure cannot predict neither crack shape nor crack history. On the other hand, the Imperial College group has based its development on 3D FV method for both pipe and its content (2).

GENERAL SOLID-FLUID FINITE VOLUME MODEL

A coupling scheme is developed within single FV framework (3). Although a single domain approach might be favourable for its stability, the current model employs separate solution domains for solid and fluid due to simplicity in dealing with propagating cracks. It uses a common data structure, for both domains. This has several advantages over the use of different methods (e.g. FV for the fluid and FE for the solid). It enables internal transfer of information across the solid-fluid interface, avoiding the development, running and maintenance of an additional interface program. It is therefore much more efficient and economical. Furthermore, the implicit coupling, which is more accurate than the explicit one but requires iterations to converge the solid and fluid solutions within each time step, is easily achieved within a single numerical solution procedure.

Here, the fluid and solid parts of the solution domain have separate meshes, but there is a common interface between them. The solid and fluid models are combined within a single code FOAM [Field Operation And Manipulation, (4)] to model the transient behaviour of a flexible pipe containing a compressible fluid. The systems of equations are solved for each mesh, and interface conditions were exchanged: tractions from fluid to solid and velocities from solid to the fluid. Both meshes remain fixed during the calculations. Small-strain analysis was performed for the pipe and mesh distortions were neglected. Eulerian frame of reference was used for the fluid, as conventional in computational fluid dynamics, and the information about the motion of the neighbouring pipe wall is passed to the fluid boundary via pipe bore velocities (5). This introduces an error in the analysis, since the contact between the fluid and the pipe domains is not guaranteed. However, this error is thought to be within the second order spatial accuracy of the method and therefore should not affect results, unless very large crack opening and pipe flaps flaring are experienced.

PIPE RCP MODEL

There are two main issues which need to be addressed with special care in order to be able to predict RCP in pressurised pipes:

i) Predicting the crack propagation, i.e. the shape of the crack front and the crack history,
ii) Passing the information to the fluid domain about the transient crack propagation, which creates a gap through which the fluid can escape.

The first problem is solved by employing a local Traction Separation Law or Cohesive Zone Model (CZM) to describe the fracture process (6, 7). Crack initiation and subsequent growth can be determined directly in terms of CZM parameters: the strength of cohesion, critical separation distances and the area G_{D} under the cohesion-decohesion curve (Fig. 1.a). In the present work, a simple Dugdale model was employed, with prescribed constant cohesive stress t_c and crack resistance G_{D}, giving the critical crack opening displacement δ_c (Fig. 1.a). Although, in general, the knowledge of the crack path is not required, a straight axial path was assumed here for simplicity. However, no assumption was made regarding the crack front shape, which is, together with the craze extension in front of the crack, natural outcome of the analysis.

As regard the second issue, difficulties were experienced in coupling the fracturing pipe with the contained fluid. As the crack propagates and the pipe opens up, a special interpolation procedure was developed to pass this information across the interface to the fluid. This is because the crack-gap appeared creating the escape route for the fluid, which was no longer fully contained within the pipe (Fig. 1.b). The newly developed model is capable of simulating flow of incompressible or compressible fluid through the crack gap, which is potentially smaller than the discrete boundary representation (cell face). It was coupled with fracturing-pipe model by exchanging the pressure, velocities and crack geometry between fluid and pipe domains. In order to accurately capture the geometry of the crack and its influence on the flow field irrespective of the resolution of the solid-fluid interface (and without following the mesh lines of the initial surface), three possible modes of interaction between fluid surface and fracturing pipe were considered: 1) Fluid cell-face fully covered with pipe, 2) Fluid cell-face fully uncovered, and 3) Fluid cell-face partly covered. Coupling of the first two modes was straightforward. The third one was treated as a combination of the covered and uncovered part, each providing an appropriate contribution to the cell balance through a proportion of fixed-value (for covered part) and fixed-gradient (uncovered part) boundary conditions. This proportion was determined by calculating the (un)covered fraction of the cell area (Fig. 1.b). On the other hand, passing the pressure values from the fluid to the pipe bore was reasonably straightforward as all solid cell-faces on the interface were always fully covered by the fluid, and standard pressure interpolation suffices.

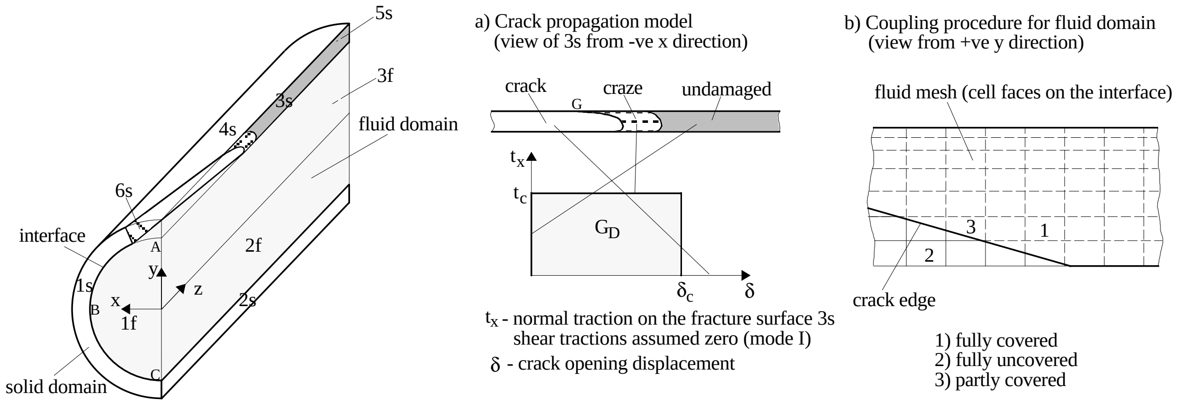

Figure 1: Solid and fluid solution domains: a) crack propagation model; b) coupling.

MODEL VALIDATION

The newly developed solid-fluid-RCP interaction model was validated qualitatively by simulating a gas pressurised, 3m long 250SDR11 PE80 pipe. For simplicity, the boundary conditions were chosen such that they would represent the FS test. The solid domain was discretised with 67968 cells (8 through the wall thickness, 36 circumferentially and 236 axially), while 77408 cells were used to represent the fluid domain (328 in the x-y base by 236 axially). The following boundary conditions were employed (see Fig. 1):

Solid domain: 1s, 2s and 5s – symmetry planes, 3s – cohesive zone model, 4s – traction free, 6s – prescribed x-displacement rate of 2.2 m/s (corresponding to chisel loading at 10 m/s speed) with z and y-tractions zero, followed by all tractions free for crack opening displacement > 25 mm.

Fluid domain: 1f, 2f – symmetry plane, 3f – fixed pressure and zero velocity gradient. The initial nominal pressure was set at p = 5 bars (absolute).

The following materials' properties, corresponding to 298 K, were used: 1) Solid (linear elastic Hookean sold): Young's modulus E = 2.5 GPa, Poisson's ratio ν = 0.4, mass density ρ = 940 kg/m^3, 2) Fluid (ideal gas): dynamic viscosity η =18.45 μ Ns/m^2, specific heat C_v = 717.86 J/kgK, Gas constant R = 287.14 J/kgK, density $\rho = p/RT$ (T absolute temperature). As for the cohesive zone model parameters, the craze stress t_c = 20 MPa and fracture resistance G_D = 5 kJ/m^2 were chosen, giving the critical crack opening displacement δ_c = 0.25 mm.

The computations were performed using a constant time step of 5 μs for both domains, and the solution was run for 0.01 s.

Figure 2 shows pressure profiles at three locations on the pipe bore A, B and C (see Fig. 1) at three different time instants: a) at time t = 3 ms, when the crack propagated about 0.8 m along the pipe, b) at t = 6 ms, when the crack length was about 1.65 m, and c) at t = 9 ms, with 2.4 m of the pipe being split-open by the crack. The crack history of the crack front point at the pipe outer surface (G) (see Fig. 1), is presented in Fig. 3.

Predicted results demonstrate remarkable resemblance with experimental observations from FS tests (8). The curved shape of the crack front leading at the bore and lagging behind at the pipe outer surface is well captured by the model, together with the pipe dimpling in the crack tip region. The model predicted pipe failure at an average speed of 262 m/s for a given nominal pressure of 5 bars, which also compares well with experimental observations. Pressure is shown to drop in front of the crack due to the decompression wave generated by the gas discharge through the crack, and it rapidly decays behind the crack tip due to this discharge (Fig. 2). It can also be noticed that the pressure distribution does not vary appreciably along the pipe circumference, which has been observed experimentally. Some oscillations of the crack speed can be seen along the pipe (Fig. 3), and this correlates with experimental observations from both FS (8) and small scale S4 tests (9).

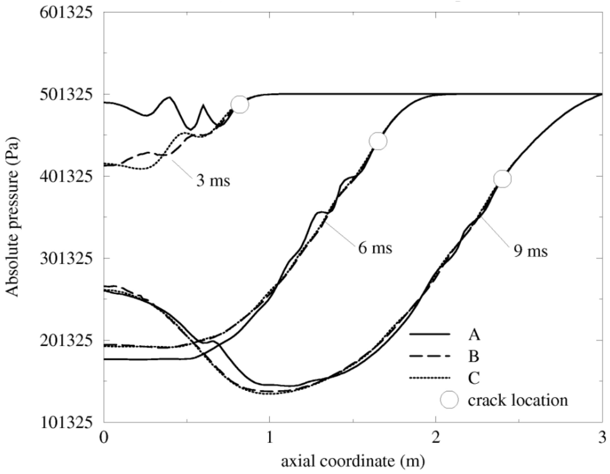

Figure 2: Pressure profiles along lines A, B and C at times 3, 6, and 9 ms.

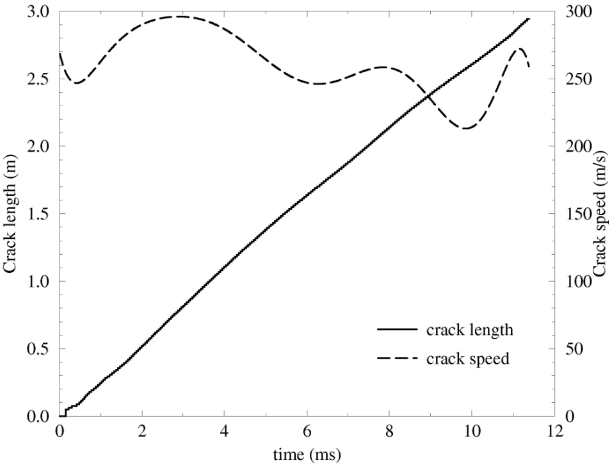

Figure 3: Crack history.

CONCLUSIONS

A powerful numerical tool was developed for predicting detailed behaviour of the coupled pipe-fluid-RCP system. The model predictions in terms of fluid flow and pressure distributions, pipe deformation and fracturing were validated qualitatively against FS test observations. Thus, the complex coupling procedure as well as the failure model were verified. Given the appropriate material data and testing conditions, the model can be used for accurate, efficient and economical calculation of critical pressure, for both FS and S4 tests. The final goal is to develop the model for predicting brittle-tough transition of plastic pipes, and for this to be achieved further work on traction-separation law is required.

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