MODELLING OF CRACK ARRESTORS ON GAS-PIPELINES

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ABSTRACT

Design of gas pipelines implies demanding tasks such as the definition of material requirements in terms of ductile fracture propagation control. This task is especially challenging when high strength steels (like X100 and beyond), whose use is imposing as a result of the consolidated worldwide trend towards the realization of long distance/high pressure gas pipelines, are considered. In fact as recent research projects clearly demonstrated (Mannucci [1], Demofonti [2] and Papka [3]) it is not possible to rely on the self-arrestability of such a class of high strength steel and as a consequence new solutions must be adopted, especially when severe operating conditions (rich gas, low temperature, etc.) are envisaged. In this context, the adoption of additional mechanical devices, such as Crack Arrestors (CA), represents a valid alternative since, if properly designed, they can externally provide a structural positive contribution in terms of resistance opposed to ductile fracture propagation. Optimal design of CA presupposes the knowledge of the efficiency of each possible CA type, but also the influence of its main geometric parameters (thickness, radial clearance, axial length…) on the constraint applied on fracturing pipe, in the specific operative condition. The use of a specific finite element code named PICPRO, which was developed by CSM jointly with the University of Tor Vergata and actually used in the frame of a BP project, allows to perform numerical simulations of running shear fracture along a pressurised steel pipeline also considering the constraint applied to the running fracture by the crack arrestor; PICPRO was used to perform a rapid comparison within all the potential CA solutions and it allowed the successful identification of the best one for the case under consideration (Mannucci [1]). In the present paper some new algorithms, expressly developed to simulate crack advance inside a crack arrestor, are presented. Exploration of main CA design parameters imposes the use of algorithms different from those based on the search and application of contact elements, in order to reduce calculation time and to give the possibility to perform an higher number of simulations. Hence, two new algorithms are on purpose developed and hereby presented: the first one for the evaluation of the interaction pipe-CA and the second one for managing the fracture propagation criteria even if crack flanks cannot freely open because of crack arrestor presence.

1 INTRODUCTION

The use of a finite element code to simulate the constraint effect of a Crack Arrestor (CA), assembled across a pipe, gives the opportunity to investigate the influence of main design parameters (i.e. thickness, axial length, radial clearance, material…) of a lot of different types of CAs, thus representing a valid help in the choice of the crack arrestor to use, able to induce an arrest in a possible fracture propagation. Explicit code PICPRO, jointly developed by the University of "Tor Vergata" and the Centro Sviluppo Materiali S.p.A., fits this purpose. It is based on the use of a cohesive zone model that considers a gradual nodal release to account for material ductility (Salvini [4]); the code is able to manage fracture propagation both for laboratory specimens and for pressurised pipelines, pipes or vessels. The code is, within the present context, appropriately upgraded to make it able to manage crack advance when interactions between pipes and CA occur. This feature is gained by means of suitable algorithms for the direct evaluation of constraint applied by the CA and its effect on fracture propagation speed in transient regime.

The main idea is to focus the modelling of CAs to correctly represent the forces exchanged with the pipe rather than to make a geometric modelling of the CA itself. According to this position, a standard finite element named CA or similar has not been developed, but appropriate local hoop loads are calculated at any time during the burst event.

2 NUMERICAL MODEL FOR THE CRACK ARRESTOR CONSTRAINT

PICPRO does not use conventional contact algorithms to simulate interactions coming up between the surfaces of the pipe and the crack arrestor (CA) installed over the line, when fracture occurrences cause flap opening. The search of alternative solutions represents a very useful task to account for the constraint exerted by the CA without excessively increasing the computation time. The importance of this requirement becomes more evident when considering the nature of PICPRO, that is an explicit code, and the necessity to carry out a large number of simulations to investigate the effects of main design parameters of different CA types. A large effort has been spent for developing a finite element model, giving accurate results, even if it is based on a smart algorithm. PICPRO considers the CAs as made of a sequence of "virtual strips", disposed for the whole CA length, each one characterised by a longitudinal length which is typically one tenth of the diameter. In order to streamline the whole numerical procedure the following hypotheses are adopted, based on the concept that, a CA, whatever type is, opposes to fracture propagation restraining the pipe flap opening and behaves like a local ring as it is sketched in Figure 1:

- *flexional stiffness is neglected, both for longitudinal and circumferential direction;*
- *only radial interaction between the CA and the pipe is taken into account, in other words no contact friction is considered;*
- *strips can break when circumferential strain reaches its ultimate value; no fracture criterion is considered. CA rupture initiates in correspondence of CA edges (beginning and end of CA), where the constraint effect is lower and the greatest deformations are located;*
- *fracture can advance only in longitudinal direction, whereas no crack deviation or pipe severance are admitted.*

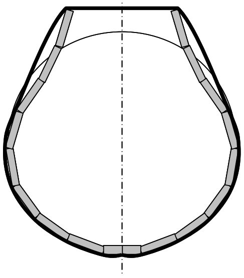

Figure 1: Circumference calculation in presence of change of concavity.

The reliability of all above hypotheses has been accurately verified having recourse to a FE commercial code (ANSYS®), able to take into account also flexional stiffness and friction. For each hypothesis two numerical simulations have been performed (Fonzo [5]), comparing results in terms of instantaneous stresses, accumulated strains and displacements: the first one considers valid the hypothesis itself and the second one refuses it. As mentioned above, PICPRO does not perform the search of contact elements: it considers an equivalent contact pressure to be applied on pipe elements that interact with the inner surface of the strip. The whole CA constraint algorithm can be viewed as subdivided in a series of steps, here reported:

(i). PICPRO calculates the length of the pipe outer circumference, taking into account pipe opening in the section considered. More precisely, the total circumference length is calculated adding the outer deformed circumferential length of the main pipe and the Crack Opening Displacement (COD) in correspondence of the considered strip, i.e. the distance between the two fracture surfaces. (Figure 2). This procedure is repeated for all strips, that behave independently each other; moreover, in order to obtain a more significant and stable value, equivalent circumference length is calculated averaging the values at the end and at the beginning of each strip. The pipe and the relative strip are considered in contact when outer pipe circumference length is numerically equal or higher than the inner CA one. In other words, the model considers the contact as extended all over the strip surface. Unique exception is represented by zones where a change of concavity does occur, with respect to the undeformed one. In these zones, the circumferential length is calculated simply replacing the actual deformed profile by a rectilinear one, with null curvature (as shown in Figure 1). This assumption is comprehensible imagining the CA behaviour similar to that of a restraining ring;

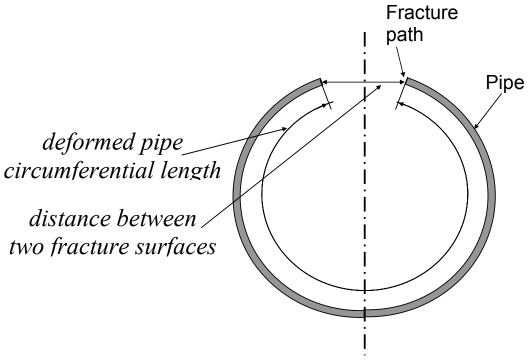

Figure 2: Pipe opening measure.

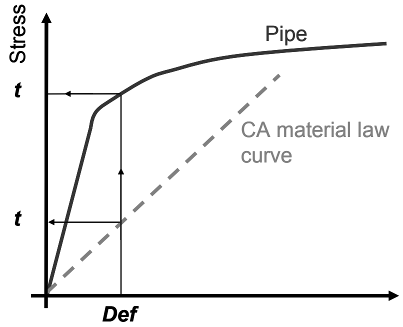

Figure 3: True stress vs. True strain material curve.

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(ii). at each time step, the equivalent circumferential strain (Def) is calculated as the difference between the total circumferential length of the pipe outer surface (PL) − estimated at point (i) − and the circumferential length of the crack arrestor (CAL). Being the circumference length calculated as an average between those at the ends of the strip, strain is related to the middle of the strip. Circumferential strain can be calculated by the following equation:

$$\mathrm{Def} = \frac{\mathrm{PL} - \mathrm{CAL}}{\mathrm{CAL}} . \qquad (1)$$

When no contact occurs, the circumferential strain is set to zero;

(iii). PICPRO calculates the corresponding hoop stress, through the true stress – true strain CA material curve that is supposed to be known by the CA supplier (Figure 3) or by means of a traditional finite element analysis of the CA itself (performed to find an equivalent material curve). Thanks to the hypotheses made the model can be considered one-dimensional;

(iv). referring to the hypothesis of no friction between the interacting surfaces, circumferential stress (t) keeps constant along the strip in circumferential direction. Of course, the resulting constraint due to the presence of the CA is exerted in radial direction (only in this direction, having neglected any type of friction), so that a pressure between surfaces in contact has to be applied.

The interaction is accounted for applying an equivalent element pressure on each element of the pipe in connection with a CA, whose value is a function of the local curvature (Figure 4). In other words, although the CA strip is uniformly stressed in circumferential direction, pressure can vary along the strip being its entity dependent on the local curvature, through projection of (t) on the radial direction.

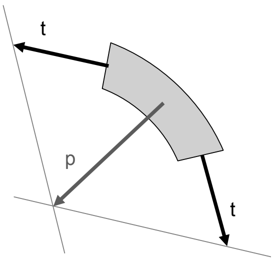

Figure 4: Pressure, function of local curvature.

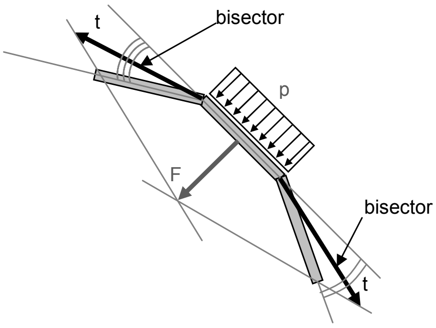

Figure 5: Element pressure evaluation.

More precisely, for each element, tensile stresses (t) are taken into account applying them to the element edges (i.e. those aligned with the longitudinal element direction) directed as the bisectors of the angles existing between the element considered and those adjacent in the circumferential direction (Figure 5). Resulting virtual force (F) is therefore calculated starting from tensile stresses by means of a vector sum, whereas the equivalent pressure (p) can be easily calculated as follows:

$$p = \frac{F}{\text{element area}}. \tag{2}$$

When the first node of the strip, attached to the crack flank, is accounted, punctual contact has been considered: thus, equivalent pressure resulting for the first element is replaced by a force concentrated at the first node. Because of concavity change typically occurring in the vicinity of crack flanks, tensile stresses used for calculating the nodal force, will be directed as shown in Figure 6.

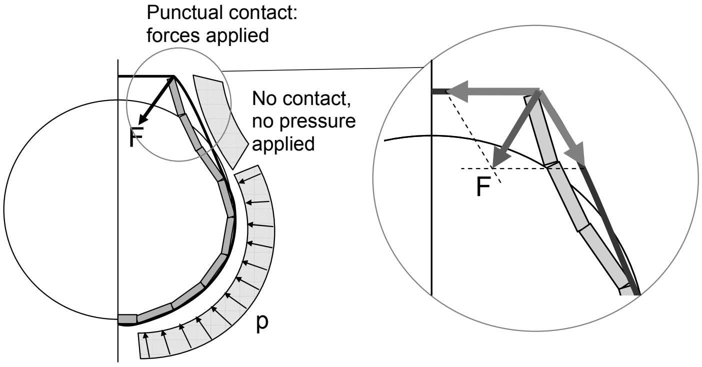

Figure 6: Punctual contact.

The whole procedure is independent of the pipe mesh and it allows to accurately simulate the CA constraint effect without spending a lot of time in the search of all elements in contact.

3 ALGORITHM FOR FREE FRACTURE PROPAGATION

The presence of a crack arrestor in a gas pipeline, where a crack is propagating, always leads to a transient phase during which fracture speed varies as a consequence of the constraint effect exerted in opposition to crack and flap opening. As a matter of fact it appears evident that the variability of all parameters characterising the phenomena must be taken into account. From fracture mechanics point of view it is important to know the value of fracture-characterising parameter at each time step to evaluate whether critical material conditions are reached and a fracture propagation act occurs. The choice of a proper parameter is a key point when simulating fracture propagation in transient regime, particularly when a crack arrestor is mounted on the line. Fracture parameter which PICPRO is based on is the Crack Tip Opening Angle (CTOA); by the comparison between the CTOA calculated by the model (which is the geometrical angle at the crack tip) and the CTOA critical of the material (measured by proper laboratory tests, Demofonti [6]), it is possible to predict the fracture arrest or propagation. When running shear fracture is impeded by a CA, the constraint effect due to the CA presence definitely affects the CTOA value which has to be measured by the code itself. Therefore, typical fracture algorithms, based on a *step by step* comparison between actual and critical value of CTOA in the attempt to establish critical material conditions and to estimate crack speed (Fonzo [7]), become ineffective. As a valuable alternative solution, when simulating the effect of CA, the use of fracture algorithms based on local energetic consumption has been considered; the code calculates the energy consumption involved for new crack surfaces formation during the gradual node release inside the Fracture Process Zone (Salvini [4]). More precisely, the work done by the nodes released can be calculated as follows:

$$\Delta E = 2\,B \int_{0}^{\Delta_{FPZ}} \left[\sigma_c(x)\;\Delta V(x)\right] dx\,, \tag{3}$$

where B is the wall thickness, σ_c the cohesive stress, V the nodal displacement (crack half-opening), x the nodal distance from the crack tip and Δ_{FPZ} the dimension of the Fracture Process Zone. Use of this algorithm does not require the knowledge of material toughness; on the contrary users can impose a crack advancing at constant speed with the aim to reach stable propagation conditions (characterised also by a stable gas decompression, i.e. gas equilibrium in front of the crack tip) in zone far from the CA, where PICPRO calculates energy spent for fracture surfaces formation for a distance L, enough long as to ensure an averaged value not affected by numerical scattering. The so calculated energy E_L, for unit length, can be considered as the critical value of fracture parameter that has allowed crack advance just at the imposed constant speed. Basing on the knowledge of stationary propagation, by a simple energetic proportion it is now possible to estimate the energy ΔE_D associated with a little advance Δa:

$$\frac{E_L}{\Delta E_D} = \frac{L}{\Delta a}\,. \tag{4}$$

Finally the unknown value of crack advance, in stationary conditions, can be estimated as follows:

$$\Delta a = \frac{\Delta E_D}{E_L}\,L\,. \tag{5}$$

Then, fracture can be driven by an energetic algorithm, allowing PICPRO to completely manage crack in free propagation mode, before the crack tip enters in a pipe zone where a transient phase is expected (as in the case of a CA). As a matter of fact, the value of ΔE_D, calculated at each time step, is strongly influenced by the CA constraint and resulting crack speed could be far from the value corresponding to stable propagation (which eqn (4) is based on). For a predictive and conservative simulation, E_L could be estimated imposing a crack speed of about 350 m/s, corresponding to the maximum value observed in experimental full scale burst tests. Just to mention that the model has been successfully validated by the comparison with the experimental results of recent full scale burst tests carried out on X100–X120 steel pipes, such as BP test (Mannucci [1]), Demopipe 2003 test (Demofonti [2]) and ExxonMobil test (Papka [3]) where crack arrestors were installed on real pipeline test sections and tested in terms of their actual fracture arrest capability .

4 CONCLUSIONS

The constraint effect of a CA can be conveniently investigated through Finite Element simulations using the algorithm proposed in this paper, that is a valid alternative to the conventional contact algorithms: as a matter of fact it allows to perform a large number of numerical simulations and thus to investigate how the constraint applied is affected by the main design parameters. The use of such model must be coupled with a fracture algorithm, able to manage crack advance also in transient regime, that is mandatory to consider when an interaction between the main pipe and a crack arrestor occurs. The fracture algorithm here proposed is based upon energetic calculation, being not bonded with typical fracture parameters (i.e. CTOA) that lose their physical meaning and usability when crack flanks opening is constrained by a CA. The presented algorithms have been implemented in an existing finite element model (PICPRO) able to simulate the running shear fracture in pressurised steel gas pipelines, and allowed to correctly predict the full scale experimental behaviour of CAs recently tested in full scale burst tests on X100–X120 steel pipe.

5 REFERENCES

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