Numerical-Experimental correlation of failure severity in seamless tubes

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Abstract: The investigated components are seamless tubes used as housings of hydraulic cylinders mounted on earth moving machines. Accidental high working loads such overloads or machine misusing can be probable during their life, in this perspective, the failure mode and the limit load over which a rupture can be expected becomes extremely important. With the aim of investigating the failure severity of these components, a crack modeling for stress analysis has been performed.

A 3D model including cracks dimensions and boundary conditions identical to those used for the full -scale experimental tests is proposed. The calculations have been validated using the full scale -tests results performed on seamless tubes containing artificial defects and tested under critical conditions. Numerical results compared with experimental data exhibits maximum error less than 8% using Abaqus Explicit for the ductile fracture modeling. Moreover, excellent results were achieved in predicting the failure mode for the investigated cases. In the case of XFEM modeling, the differences between laboratory and simulation burst pressure increases to 18% due to the use of artificial stabilization to avoid convergence difficulties.
Keywords: failure mode, fracture mechanics parameter, ductile fracture, X-FEM, full scale tests

1. Introduction

In the last years Finite Element Analysis (FEM) has been evolved as a powerful tool to support engineers in various fields of product development and research. Based on the continuous increasing of computational capabilities, these techniques become more and more attractive for applications where the reduction in cost and time becomes extremely important. Furthermore, the numerical simulations provide an additional potent tool for the effective development of competitive products.

In the present paper, an application based on finite element analysis is shown to assess the fracture mode and limit load of seamless precision tubes made of new steel grades. These products and materials are addressed to be used for hydraulic cylinder applications, as actuators that converts hydraulic energy into mechanical energy and are employed in earth moving machines, cranes, presses, industrial machineries. Due to the internal pressure, the main stress of this component is circumferential (hoop stress), the longitudinal stress being about one half.

The tubular products commonly available on the market for this application are in accordance to the E355 Stress Relieved (SR) grade of the European standard EN 10305-1 [1]. No minimum impact energy is required. For special applications, the Market needs cold drawn tubes with higher yield strength and a minimum longitudinal toughness (normally 27 J at -20°C).

It is worth to remark that precision tubes are cold drawn tubes and the manufacturing process introduces work hardness with consequent low toughness levels and a strong anisotropy between longitudinal and transverse direction.

Cylinder housings are generally designed for an infinite fatigue life due to the very high number of cycles required during service life. Nevertheless, accidental high working loads such overloads than can lead to loads values well over the working loads under normal conditions can be probable during their life. In this perspective, the failure mode and the limit load over which a rupture can be expected become extremely important. From the engineering point of view, high tensile properties, high fatigue resistance and good toughness are required.

Nowadays different international defect assessment procedures [2-3] consider the fracture toughness the “key” parameter which governs the integrity and safety in service conditions. Fracture toughness at the minimum operating temperature is an essential requirement in order to have “leak before break” behavior, avoiding in this way brittle fracture, which involves a dangerous situation.

In this context, TENARIS has developed new steel grades to manufacture seamless precision steel tubes in cold drawn and stress relieved condition, with minimum YS from 540 MPa to 650 MPa improving the combinations of toughness and strength.

In order to underline the advantages of using a high toughness steel for the hydraulic cylinders design, an experimental plan based on small scale and full scale tests was implemented. In particular, a complete mechanical characterization as well as mechanical fracture tests has been carried out on a high toughness steel grade (HT). Moreover, with the aim of determining experimentally the limit load and the failure mode, full scale burst tests have been performed. Previously, different steps were performed on full scale tubes in order to set up the burst tests. Artificial defects are machined on the external surface and then pre-cracked in fatigue in order to obtain different final crack depths. Resuming, an experimental investigation based on the tests describes previous are rather costly due to their complexity.

Analysis results based on Abaqus code (release 6.10-EF1) [4] are reported as comparison to the experimental data. Two models have been used, Abaqus Explicit for the ductile fracture modelling and XFEM.

2. Experimental tests

As already mentioned, with the aim of validate the new high toughness steel grade performance under severe conditions a series of experimental tests has been carried out. At this purpose, the tests were performed at a temperature of -20°C and divided in:

- Small scale tests:
    - Fracture toughness tests in term of J parameter
    - Mechanical and cyclic tests
- Full scale tests:
    - Precracking in fatigue of tubes containing artificial defects
    - Burst tests

2.1 Fracture toughness tests

The most important material property which governs the fracture analysis is toughness. Nowadays a multitude of definitions and related measurements can be carried out [5-6], one of most advanced and complete is the Master Curve determination [5]. It is a statistical, theoretical and micromechanism based methodology for fracture toughness analysis in the ductile to brittle transition region, taking simultaneously accounts for the scatter, size effects and temperature dependence of fracture toughness. These measurements allow the determination of a reference temperature T_0, defined as the temperature at which the mean value of fracture toughness K_{med} is 100 MPa√m, and the transition curve, defined in a range To +/- 50°C, that characterizes the fracture toughness in ductile to brittle transition region. The experimental measurements of fracture toughness in terms of J parameter were based on ASTM E 1921 standard [5] using C(T) 0.5 inch specimens extracted from tubes in the transverse direction (which corresponds to the flaw orientation in the structure).

For the present investigation, the fracture toughness at -20°C has been used, J=65 kJ/mm^2.

2.2 Monotonic and cyclic tensile tests

In order to characterize the mechanical behavior of the material, monotonic and LCF (low cyclic fatigue) tensile tests were carried out. The specimens were tested using a MTS facility, the cross-head speed was fixed at 2 mm/min and specimens were equipped with a 12.5 mm extensometer. Cyclic tests were carried out in order to characterize the cyclic behavior of the material. The tests were performed by the same facility used for tensile tests at a frequency of 2 or 0.5 Hz depending on the applied strain amplitude. The strain-controlled tests were carried out using the “single step” method. Hysteresis loops were recorded in the middle of each single strain block and, for the determination of the cyclic curve, the stabilized hysteresis loops relative to the block at 50% life were considered. Finally, in Figure 1 the comparison of the tensile and cyclic curves is presented. It can be noted the softening behavior of the material subjected to cyclic loading.

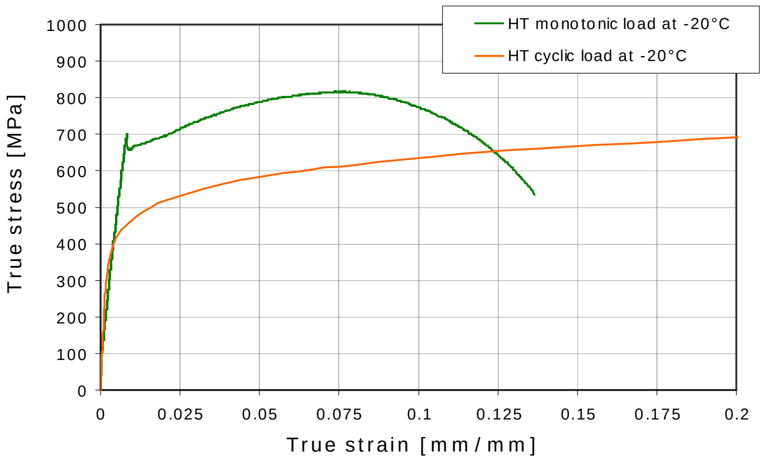


Figure 1 - Comparison between monotonic and cyclic curves

2.3 Burst tests

In order to characterise the different crack depths behaviour on the limit load, artificial defects using electro-discharge machining (EDM) with depth equal to 5% of the wall thickness have been placed in the middle of the full scale samples. These initial artificial defects (see Figure 2) can be considered as semi-elliptical shaped with a ratio a/c = 0.2 (a = defect depth, c = semi-length of the defect).

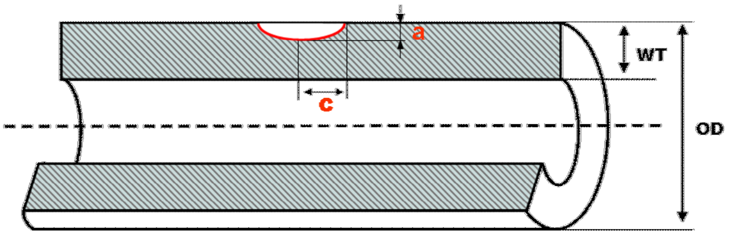


Figure 2 - Tube containing an initial semi-elliptical defect

These initial artificial defects were then pre-cracked by fatigue until they reached the final target depth. A special facility was used in order to carry out tests with fluctuating internal pressure. The equipment used is an internal pressure system specifically designed to perform tests on tubes for hydraulic cylinders. The crack depths were controlled and monitored using a measurement device based on potential drop method with alternating current: via two current poles located left and right to the crack a constant alternating current is passed into the workpiece. In Figure 3 the final shape and crack depths are reported: crack length (2c) on the X-axis and crack depth (a) on the Y-axis. After the tests, the specimens were opened and the two crack dimensions (a) and (2c) were measured.

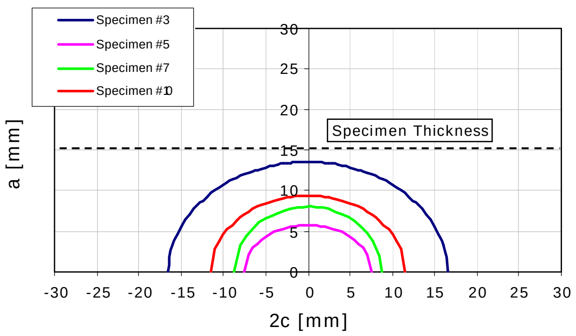


Figure 3 – a) Final crack depths and shape; b) Full scale specimens with caps used for the burst tests

In order to validate experimentally fracture failure mode and limit burst pressure of the investigated steel grades and tube dimensions, a series of burst tests was set up. The device is reported in Figure 3b. After fatigue pre-cracking, the tubes were cap ended through welds and for avoiding high pressurised volume aluminium filler bars were used. The tests were performed at -

20°C, the tubes being pressurized with alcohol water and a thermocouple being used for the temperature control (see section 4.1.1 for the experimental results).

3. FEM analysis

Experimental tests, and in particular full scale tests (section 2.3) are rather complex and expensive. This fact is magnified if the number of tests to be performed becomes consistent. As a consequence, the aim of this study is to understand if the implementation of a numerical model can effectively predict the experiments and then reduce costs and save time.

Creating a numerical simulation that can be introduced in a consolidated work-flow and can replace part of it requires few important steps summarized as follows:

1. Choose the experimental test;
2. Define and calibrate the material model;
3. Choose the numerical method that can reproduce the experiment.

3.1 Experimental test

Considering that the goal of the initial research activity was to investigate the limit load and failure mode of the seamless tubes in presence of defects, the most representative test is the full scale burst tests. Moreover, the different preliminary small scale tests described in the previous sections are necessary for a better understanding of the phenomenon, but not least to reproduce analytically the full scale results as well as it was reported in [7]. As a consequence, it was decided that the numerical simulations to be performed have to reproduce the burst tests summarized in Table 1. Tubes geometries, crack dimensions and burst internal pressure are reported. The specimen #3 was used to calibrate the model, the analysis being performed for all other cases.

	Specimen #	Defect depth (a) [mm]	Defect length (2c) [mm]	a/c	Thickness (t) [mm]	Burst pressure P_{burst} [bars]
HT Grade	3	13.5	33	0.8	14.75	1382
	5	5.8	15	0.77	14.7	1653
	7	8	17.5	0.91	14.6	1588
	10	9.4	23	0.82	14.5	1510

Table 1 - Experimental burst tests results

3.2 Definition and calibration of the material model

As already mentioned, the material used is a high toughness steel grade (HT), the full experimental characterisation being performed at -20°C. In order to calibrate the numerical model, the material properties have been assigned as follows:

- In the neighborhood region around the crack, the assigned material properties correspond to the cyclic tests; this because prior to burst test the full scale specimens were pre-cracked in fatigue.
- For the remaining part the engineering true stress – true strain curve measured at -20°C has been used.

- Fracture energy is used in term of integral J at -20°C.

It is worth to underline some hypothesis and simplifications adopted for the material:

- The used true stress – true strain curves (σ – ε) are not strain-rate dependent. In this case, the approximation is due to the fact that the phenomenon is practically quasi-static before the instantaneous final rupture.
- In order to simulate the cyclic behaviour of the material at -20°C, the cyclic curve at room temperature reported in section 2.2 has been scaled by a factor of 4%. Experimental evidence shows that between room and low temperatures the cyclic behaviour changes with the same factor of the tensile properties. At this point, the ratio between the yield and ultimate stress at room and low temperature has been calculated and used to scale the cyclic curve.

In Abaqus the definition of the material is based on the combination of complementary behaviors. A typical tensile test result (in terms of • -•) is proposed in Figure 4; it is possible to divide this curve in 2 parts that are **Elastic** (A) and **Plastic** (B).

- **Elastic:** It corresponds to the tangent to the initial curve; in our simulation must be a function of temperature.
- **Plastic:** this part can be function of temperature and strain rate. Abaqus needs the •$_{true}$-• plastic curve; during the plastic deformation is possible to introduce a *Damage Initiation and Evolution Criteria*.
  For metals Abaqus provides two comprehensive mechanisms of damage initiation: ductile and shear. In the present study a ductile damage Initiation is used for the Explicit model, while a simpler one (based on maximum allowable principal stress) is used for the XFEM as ductile one is not yet available.
  Ductile Criterion: The model generally assumes that the equivalent plastic strain at the onset of damage, •$^{pl}_{D}$, is a function of stress triaxiality and strain rate:
  $$\varepsilon_D^{Pl}(\eta,\dot{\bar{\varepsilon}}^{Pl})$$
  where • is the stress triaxiality and $\dot{\bar{\varepsilon}}^{Pl}$ is the equivalent plastic strain rate. The criterion for damage initiation is met when the following condition is satisfied:
  $$w_D = \int \frac{d\bar{\varepsilon}^{Pl}}{\varepsilon_D^{Pl}(\eta,\dot{\bar{\varepsilon}}^{Pl})} = 1$$

For the present case, the •$^{pl}_{D}$ is considered constant for both triaxiality and strain rate. This, because the triaxiality is higher enough to be considered in the range of the flattening effect, whereas the strain rate is constant due to the static behavior of the phenomenon.

Once the corresponding initiation criterion has been reached, a Damage Evolution law describes the softening of the yield stress and the degradation of the elasticity.
There are two options to define the evolution of the damage: one is based on the stress - displacement response, while the other one on fracture energy.

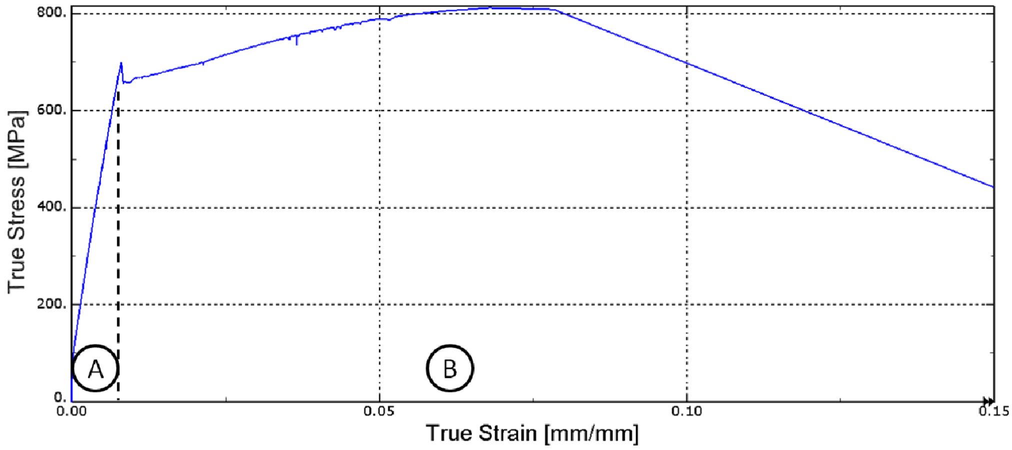


Figure 4 – Typical test results

3.3 Numerical Methods

Two numerical methods have been investigated: ductile fracture modelled in Abaqus\Explicit (see section 3.3.1) and the new XFEM capability based on Abaqus\Standard (see 3.3.2).

3.3.1 Ductile Damage with Abaqus\Explicit

Using this method, the damage was simulated by use of the element deletion when the equivalent plastic strain (function of triaxiality) reaches the critical value.

- **Model**

  In Figure 5a the full geometry of the tube is reported, but exploiting the symmetries, the analysis was performed for a 1/8 of model in order to reduce the simulation time (see In Figure 5b).

- **Step**

  The time of the experimental test is about 1 minute. Simulating longer than few seconds with an Explicit code is critical due to the propagation of the numerical error. The phenomenon is essentially static until the opening of the initial crack, after this point the analysis is dramatically dynamic. In order to take into account of these two behaviors, the numerical model was divided in two phases: the first one is essentially quasi-static (so it is possible to use a very large mass scaling), while the second one is purely dynamic. Between the two phases it is introduced an intermediate step in which the mass scaling is deactivated and the real mass of the component is reinitialized:

*Step, name=Step-1_Static *Dynamic, explicit *Fixed Mass scaling,dt=1e-5	*Step, name=Step-2_tmp *Dynamic, explicit *Fixed Mass scaling *Variable Mass scaling	*Step, name=Step-3_Dynamic *Dynamic, explicit

- **Boundary Conditions & Load**

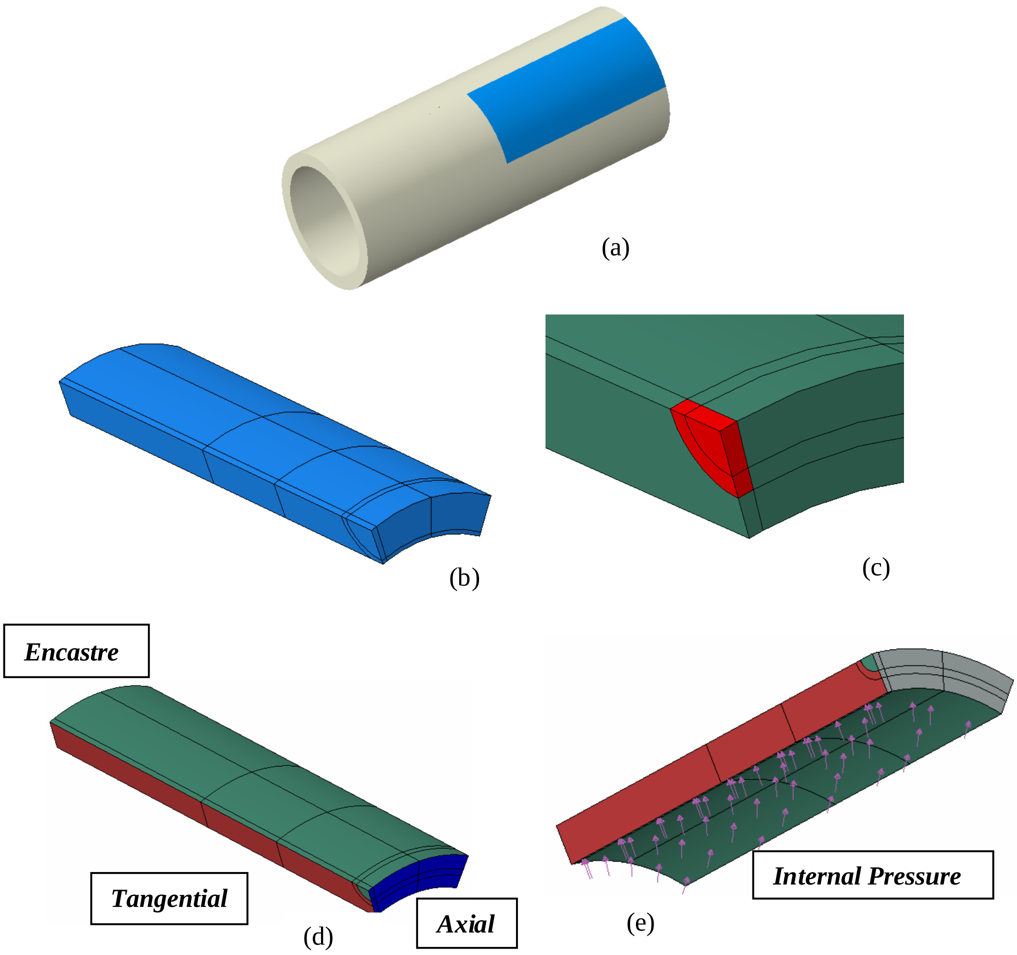
  The used boundary conditions are (Figure 5d):

  - Tangential and axial Symmetry to reduce the model
  - Encastre at the end of the tube to simulate the welding

  A pressure is applied to the inner surface of the tube with a ramp of 0 to 1600 bar (see Figure 5e).

- **Mesh**

  C3D8R: An 8-node linear brick, reduced integration, hourglass control (see Figure 5f).



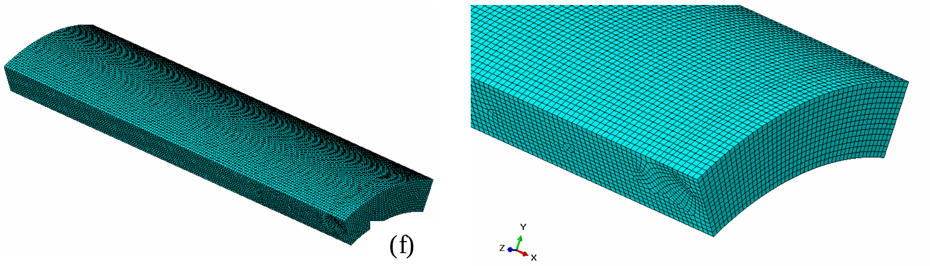


Figure 5 – a)Global model; b) simplified model; c) crack position; d) boundary conditions; e) internal pressure load; f) Mesh details

3.3.2 XFEM with Abaqus\Standard

Abaqus' Extended Finite Element Method (XFEM) is based on a solution-dependent crack initiation and propagation path; it alleviates the shortcomings associated to the conventional methods in which (a) the mesh must conform to the geometric discontinuities and (b) considerable mesh refinement is needed in the neighbourhood of the crack tip to capture the singular asymptotic fields adequately.

- **Model**

  Trying to avoid convergence difficulties due to initial crack tangential to element boundaries, a 1/4 model is simulated (not 1/8 as in the Explicit model).

- **Step**

  For the same considerations of the previous paragraph, the numerical model is divided in two different phase: the first step is static, while the second one is dynamic.

*Step, name=Step-1_Static *Static	*Step, name=Step-2_Dynamic *Dynamic, implicit

- **Interaction**

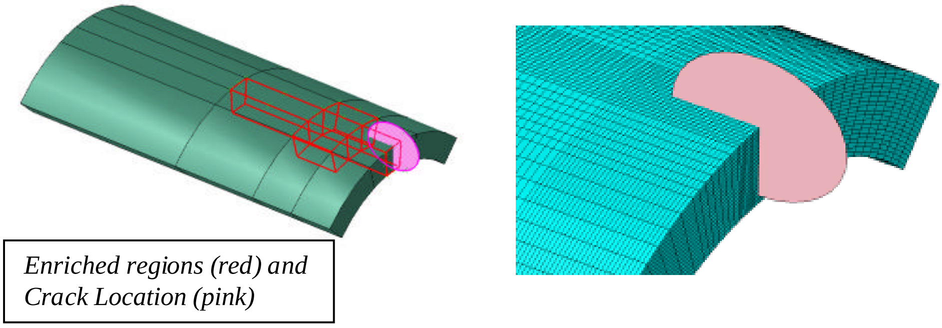
  The only interaction used is the activation of the presence of discontinuities in an element by enriching degrees of freedom with special displacement functions (Figure 6a).

- **Boundary Conditions & Load**

  The same as for the Explicit model.

- **Mesh**

  C3D8: An 8-node linear brick, full integration, hourglass control (see Figure 6b).



a) b)

Figure 6 – a) Enriched region used for the interaction module; b) Mesh detail

4. Results FEM vs. Burst

The comparison between the numerical model results and experimental full scale burst tests are reported in terms of:

- *limit loads* – analysis based on ductile damage model has been performed for all 4 cases, one additional analysis by means of XFEM being proposed.
- *failure modes* – considering that one of the key factor that governs the failure mode phenomenon is the fracture toughness of the material, the behaviour of the high toughness steel grade was compared with that of a low toughness steel grade (called LT).

4.1 Limit load comparison: FEM vs. Experimental tests

4.1.1 Results for Ductile Damage

Experimental and numerical results are reported in Table 2 and in Figure 7, an error of a maximum 7.6% being found. In Figure 9 the results in terms of Von Mises stress contour and Equivalent Plastic Strain (Peeq) for the specimen #3 before and after the crack opening are reported. Finally, in Figure 8 the perfect match between experimental and numerical •-• curves is shown.

	Specimen #	Defect depth (a) [mm]	Defect length (2c) [mm]	a/c	P_{burst} Experimental [bars]	P_{burst} Numerical [bars]	• %
HT Grade	3	13.5	33	0.8	1382	1496	7.6
	5	5.8	15	0.77	1653	1685	1.9
	7	8	17.5	0.91	1588	1695	6.3
	10	9.4	23	0.82	1510	1575	4.1

Table 2 - Experimental vs. numerical burst tests results for ductile damage model

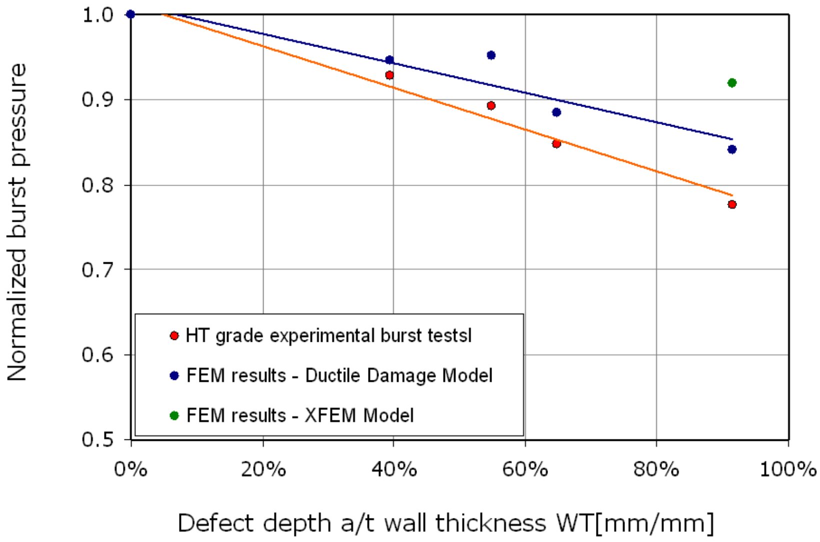


Figure 7 - Normalized burst pressure vs. defect depth

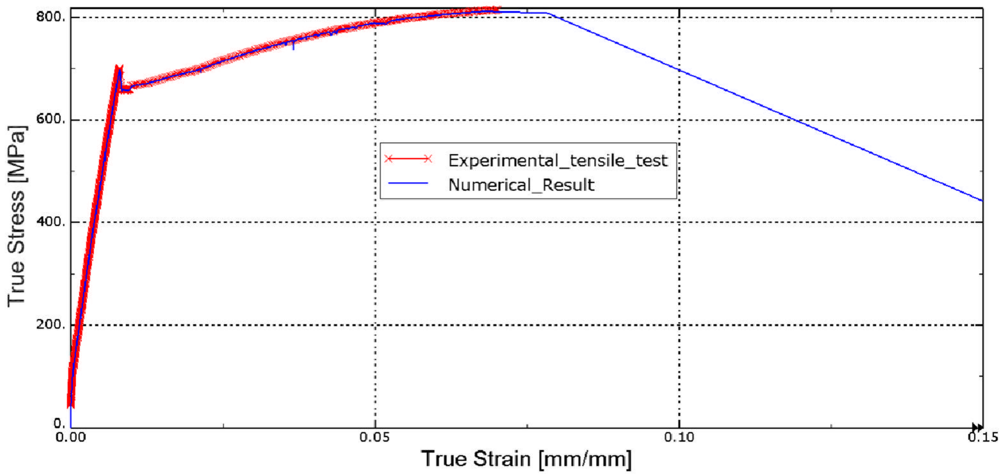


Figure 8 - Stress vs. Peeq: numerical and experimental

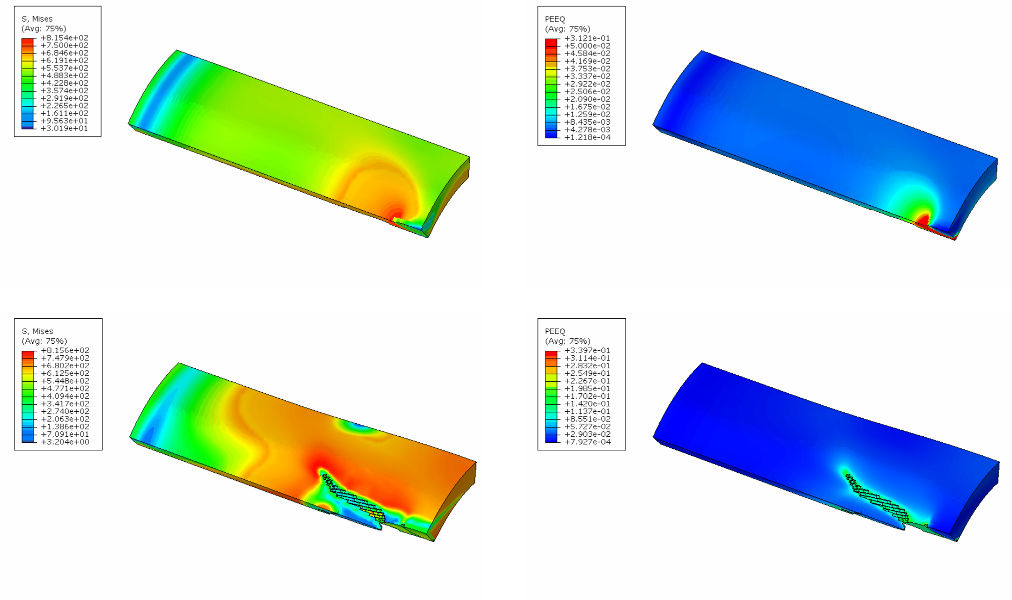


Figure 9 - Von Mises stress and equivalent plastic strain

4.1.2 XFEM method

One additional numerical analysis using XFEM module has been performed for specimen #3, the result is reported in Table 3. Note the important difference and the 18% error with regards to the experimental test. This difference is due to the large viscous stabilization introduced in the material in order to avoid the convergence difficulties. This is a nowadays limitation of the implicit code, indeed using the dynamic method (instead of the static one) it is quite difficult to resolve very rapid crack instability and extreme discontinuities.

HT grade	Specimen #	Defect depth (a) [mm]	Defect length (2c) [mm]	a/c	P_{burst} Experimental [bars]	P_{burst} Numerical [bars]	• %
	3	13.5	33	0.8	1382	1636	18.4

Table 3 - Experimental vs. numerical burst tests results by means of XFEM method

4.2 Failure modes comparison: FEM vs. Experimental tests

4.2.1 High Toughness and Low Toughness materials

In Figure 10 and Figure 11 the comparison (experimental vs. numerical respectively) of the failure mode is shown. In particular, specimen #3 was selected for this investigation. The ductile damage gives excellent results (both in terms of limit load and failure mode) with a high toughness material. A burst analysis with a low toughness material was also done demonstrating that the numerical model capability using this technique is still satisfactory.

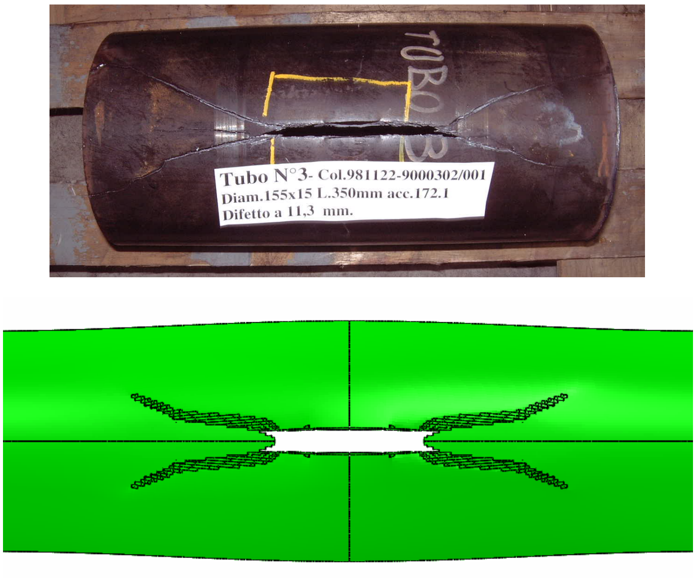


Figure 10 - Failure mode of a high toughness material (specimen #3)

Figure 11 - Failure mode of a low toughness material (specimen #6)

5. Summary and conclusions

Components such hydraulic cylinders can be accidentally subjected to overloads and/or operate in severe environmental conditions than can lead to loads values well over the working conditions; so the failure mode and the limit load over which a rupture can be expected become extremely important. Complicate and costly experimental tests have been performed in order to investigate the failure severity and performance of these components. In order to save excessive costs and time of the laboratory tests, numerical implementation of the full scale burst tests of tubes containing fatigue defects has been proposed in the present paper.

Four different cases have been simulated using the ductile damage model and one additional analysis with XFEM capability of Abaqus 6.10-EF1. Moreover, the material implementation has been made using small scale experimental tests results in terms of tensile, cyclic and fracture toughness at -20°C. Finally, the comparison reported in Figure 7 shows a good agreement between FEM ductile damage model and experimental results, an error of maximum 7.5% being found. The proposed XFEM model shows a higher error, around 18%, mainly due to the use of artificial stabilization in order to avoid the convergence difficulties of the model for cases which involve rapid crack instability similar, such as burst tests.

The following steps are suggested in order to further develop of the methodology: implement the XFEM capability in the Explicit code and add new damage initiation criteria in the material definition.

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