INVESTIGATING THE TENSILE FRACTURE BEHAVIOUR OF A MIDDLE STRENGTH ROCK: EXPERIMENTAL TESTS AND NUMERICAL MODELS

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Abstract: The adequate fracture investigation of geological materials, that show brittle behaviour with a large difference in tension and compression, is a persistent challenge especially when aiming to purposely build a reliable numerical modelling technique. The mechanical characteristics of a middle strength rock, namely Pietra Serena sandstone, are therefore investigated numerically in this study by means of a model that replicates the Brazilian splitting tensile test. An advanced material model implemented in LS-DYNA, namely the Karagozian and Case Concrete (KCC) model, is exploited and the results are compared to the conventional Mohr-Coulomb material model to show the capability of this model. Finally, the simulation results are validated by experimental data.

1. Introduction

This research work aims to investigate the mechanical characteristics of a middle strength rock with the focus on the tensile behaviour until to the formation of a crack. Brazilian Disk tests have been conducted for this purpose and the results are compared with the numerical simulations.

The maximum principal tensile stress is one of the most important parameters in the deformability of rocks. Due to several issues, including the poor tensile resistance of rocks, the performance of a conventional direct tensile test is particularly difficult. However, the tensile strength of a brittle material can be measured indirectly by means of the Brazilian test. The test consists in compressive loading applied to the cylindrical disk periphery. This loading condition initiates a fracture along the compressive diametral direction, where the maximum principle tensile stress is dominant. Therefore, the splitting tensile strength measured by the Brazilian test is representative of the maximum principle tensile strength of the material. The identification of the location where the maximum tensile strain takes place is another challenging issue. It can be described by a transition failure mode between a tensile failure mode that refers to the diametral splitting fracture, and a shear failure mode, associated to the parts close to loading platens [1].

The use of numerical modelling of materials in conjunction with realistic constitutive models is essential in stress analyses. In this application the numerical solver, LS-DYNA software, has been used due to the presence of a large library of material cards and the solvers capability to deal with a strong nonlinear case. The Finite Element Method (FEM) coupled to Smooth Particle Hydrodynamics (SPH) has been implemented as the numerical modelling technique of this study and the cylindrical specimen has been first modelled by Lagrangian solid elements. The elements who meet a certain failure criterion are subsequently eroded by means of an external eroding algorithm, and are then replaced with SPH particles. The FEM-coupled to the -SPH technique takes advantage of the accuracy of the Lagrangian finite elements (before the occurrence of high distortion) and of the capability of the SPH in dealing with large deformation, mesh distortion, etc.

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Focusing on the material constitutive law, the material model developed by Malvar et al., namely the Karagozian and Case Concrete (KCC) model has been used. It is one of the best models for interpreting the nonlinear stress-strain response of rocks [2]. In the third release of this material model in LS-DYNA, an automatic input parameter generation method, based on the unconfined compression strength was developed which facilitates the utilization of this model for most users.
The numerical results of the Brazilian test replicated by the KCC model are then compared with the conventional Mohr-Coulomb (MC) constitutive law. Finally, the mechanical properties of the Pietra Serena sandstone, experimentally investigated by means of a Brazilian test program, are used to validate these numerical analyses.

2. Methodology and Results

The experimental tests were conducted on four cylindrical specimens with a 40 mm diameter and a 20 mm length. All of these tests were performed according to ASTM standards [3].
The numerical modelling was performed by implementing two different material models, the KCC and the MC model. The KCC model, consists of three non-linear independent failure levels and twenty-two input parameters in the full input version mode. In the meantime two sets of independent tables are associated; one table is related to the Equation-of-State (EOS) for describing the rock compaction behaviour, and the other one is attributed to the damage evaluation parameters (λ) corresponding to the current failure surface (η) [4]. The input parameters of this material model, were previously calibrated for Pietra Serena sandstone under Unconfined Compression Test (UCT), which are described in [5]. However, the damage function (indicated by the set of $\eta - \lambda$ data) was changed to what is reported in [6]. The tension cut-off parameter (f_t) was calibrated in this study, whereas the UCT was unable to perform this calibration. The analyses performed for a wide range of f_t (3 to 9 MPa) showed that $f_t = 7MPa$ has the best convergence with the experimental results.
The MC model implemented in LS-DYNA, represents the granular materials and has one linear shear failure surface. The input parameters of this material model were also calibrated for Pietra Serena sandstone under UCT in [5]. Identical with the KCC, a tension cut-off (f_t) equal to 7 MPa was considered here.
The ultimate failure loads (f_u) from the experimental tests as well as the corresponding values form the numerical models are reported in *Table 1*. The Mohr-Coulomb model underestimated the average experimental results by an error of about 20%, while the Karagozian and Case Concrete model showed a precise response.

	Test #1	**Test #2**	**Test #3**	**Test #4**	**Test #5**	**KCC**	**MC**
$\boldsymbol{f_u[kN]}$	7.083	7.172	6.442	9.071	6.692	**7.104**	**5.772**
Average of Experimental results $\overline{\boldsymbol{f_{u_{exp}}}}[\boldsymbol{kN}]$						**7.292**	

Table 1. The ultimate failure loads of experimental tests and the numerical simulations

The stress distribution at the surface of Brazilian disk specimen in both the horizontal (perpendicular to the loading direction) and the vertical (parallel to the applied load) directions are shown in Figure 1. The stress concentration due to local contacts are located near the upper bearing surface as well as the lower compressive platen. The contours of the horizontal stresses, see *Figure 1.a)*, are almost uniformly distributed, in particular in the diametral direction of the disk. However, the vertical stresses in this direction are increased from the center of the disk towards the loading points. The stress contours shown in *Figure 1* are in accordance to the distribution of the stress analytic solution based on the Hondros equations reported in [7].
As visible in *Figure 2.a)*, the crack is propagated almost along the diametral direction, where the principle tensile stress reaches its maximum values. The same is true for the numerical results shown in *Figure 2.b)*, which is captured just one step after the failure. The shear failure mode located near the bottom contact point is shown in *Figure 2.c)* as well.

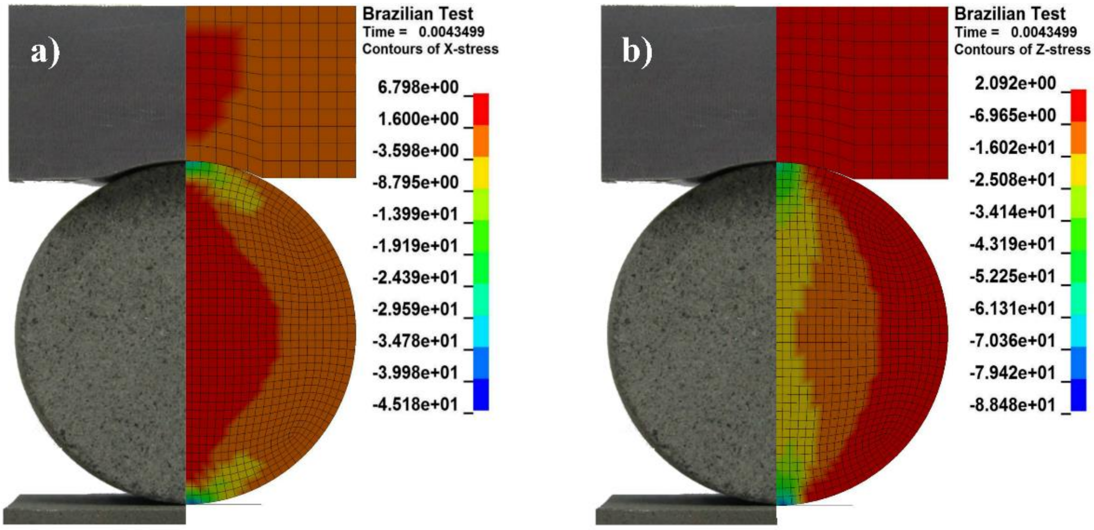

Figure 1. Distribution of the numerical stress solutions at the surface of the Brazilian disk specimen obtained by the KCC material model; *a)* horizontal stresses, *b)* vertical stresses.

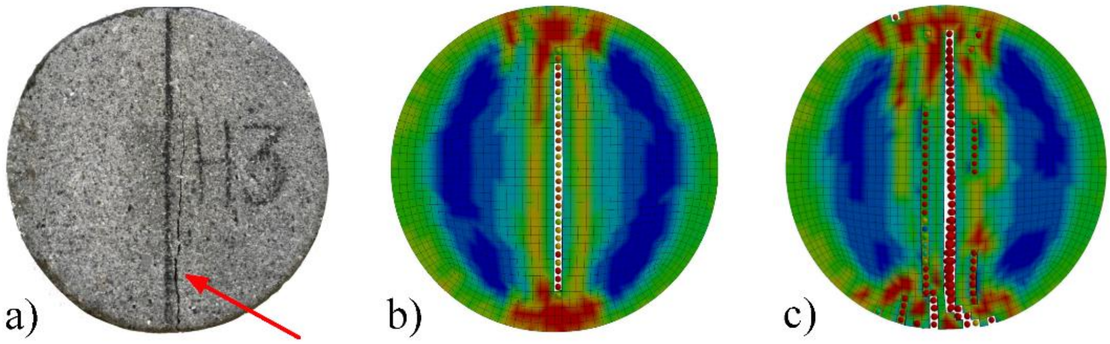

Figure 2. The crack propagation patterns; *a)* after experimental test, *b)* and *c)* one and two time steps after the failure of the numerical model (KCC), respectively.

4. Conclusions

The numerical modelling of the Brazilian (tensile splitting) test has been successfully developed. The Karagozian and Case Concrete model exhibits a significant improvement in numerically replication of the experimental test, in comparison to the conventional Mohr-Coulomb material model. Hence, the numerical simulations prove their capability to cope with the replication of the Brazilian disk test.

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