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Numerical Simulations of a Wedge Splitting Test for High-Strength Concrete

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Abstract

The paper presents results of wedge splitting tests (WST) for high-strength concrete performed in a laboratory and an attempt to develop a numerical model of the test. Characteristics of high-strength concretes as well as the experimental setup of WST are presented. The numerical simulation is performed in Simulia Abaqus software and the outcomes are compared to experimental values.

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Keywords: wedge splitting test; high-strength concrete; Finite Element; Abaqus; concrete cracking;

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1. Introduction

The main goal of this paper is to compare results from experimental and numerical analysis of a wedge splitting test for high-strength concrete. The experimental part of the research was performed by the Students Scientific Association of Building Materials Engineering within a Rector's grant "A study on technical characteristics of advanced cement concretes" [1]. The numerical simulations were developed by the members of the Students Association of Numerical Modeling in a general purpose software Simulia Abaqus 6.11.

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2. High-strength concrete

According to the EN-206-1 standard, a high-strength concrete is a concrete of compressive strength class minimum C50/C60 for normal concrete or dense concrete and higher than LC50/55 for light concrete [2].

High-strength properties of the concrete mixture are obtained by modifying the composition with appropriate additives and reduction of the water - cement ratio. Micro-fillers, such as fly ash and silica fume, are added to obtain a denser structure and a greater contact surface between aggregates and cement paste. Water - cement ratio in this type of concrete should be less than 0.4, usually in the range of 0.21÷0.38. Those values can be achieved due to usage of various kinds of plasticizers and super plasticizers. Selecting a proper type of aggregates is also critical. Their strength, size and shape should be considered. Crushed-stone aggregates obtained from high-strength rocks (>150MPa), such as granite, syenite or basalt, have the highest quality. The shape should be close to cubic and the surface should have an appropriate roughness.

The high-strength concrete composition is presented in table 1.

Table 1. High-strength concrete composition.

Ingredient	content [kg/m^3]
cement CEM I 42.5R	450
water	144
microsilica	31.5
sand 0/2	924
granite 2/4	459
granite 4/8	498
superplasticizer	9

3. Wedge splitting test

Wedge splitting test is a test method useful especially for testing fracture properties of brittle materials such as concrete, due to the well-controlled crack width development [3,4]. WST is widely used in testing various types of concretes [5, 6, 7]. It is a suitable method for establishing splitting tensile strength, which is related to tensile strength and fracture energy. Although concrete is not expected to withstand tension, establishing this value is necessary to determine critical load causing cracking.

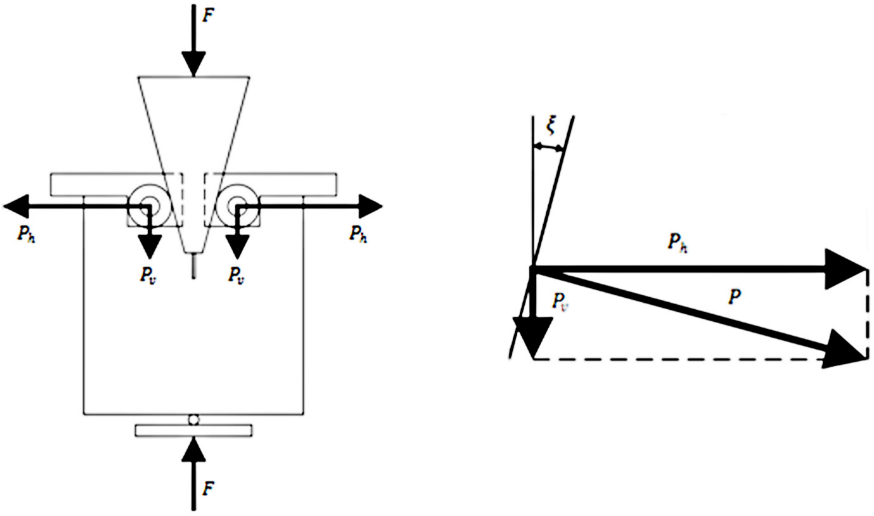

Fig. 1. Geometry and loading of a WST specimen.

Fig. 2. Experimental setup of the wedge splitting test.

Specimens are prepared in a similar way as for a compressive strength test. The only difference is a starter notch and a guiding groove, which allows mounting a loading mechanism (see Fig. 1 and Fig. 2). Aslit is sawn to produce the crack initiation location. In the test a wedge is pushed vertically down, progressively loading the specimen. A monotonic compressive load F is transformed into tensile loading P_h causing a lateral opening in the notch to appear.A crack starts to propagate in a stable way and grows until the sample is split up.

During the test, a representative displacement, Crack Mouth Opening Displacement (CMOD), and applied vertical load are measured. Horizontal splitting force is established from force equilibrium as following: $P_h = F/(2\tan\xi) = 5.715F$, where $\xi = 5\,\text{deg}$ is half of the wedge characteristic angle (see fig. 1). The influence of vertical load component is often neglected as its value is small comparing to P_h. The same approach is taken in this study. Friction in roller bearings is also neglected. A diagram of splitting force versus CMOD is prepared to determine the value of fracture energy G_F as the area under the curve divided by fracture surface.

4. Numerical model

In Abaqus software three constitutive models for concrete cracking are provided: smeared cracking (only in Abaqus/Standard), brittle cracking (only in Abaqus/Explicit) and damage plasticity (in both programs) [8].

In the paper damage plasticity model is considered as it is the most general. It can be used for modelling concrete and other quasi-brittle materials under arbitrary loading conditions, including cyclic and dynamic loading. It ought to be brittle behaviour of concrete, cracking in tension and crushing in tension, which appears in low confining pressures. Plain and reinforced concrete structures can be considered. To represent inelastic properties of concrete, the model is based on the assumption of isotropic damaged elasticity along with isotropic tensile and compressive plasticity. It takes into account different degradation of elastic stiffness and yield strengths in tension and compression. Softening behaviour in tension is also considered.

Input data for the damage plasticity material model [8] were determined by using the experimental values from [1]. Tensile strength f_t was established by averaging the data from a series of the tensile splitting tests. Compressive strength f_c was obtained from uniaxial compressive tests. The elastic properties ν and E were calculated according to procedure presented in [9]. According to [10], the typical value range for dilatation angle ψ is between 30÷40°. The most satisfying results were obtained with the ψ =30°. To define α parameter, the biaxial compressive test and uniaxial tension stress should be conducted. In accordance to [11] parameter α could be assumed equal 1.16. To obtain the K parameter, triaxial tests of concrete should be performed. Typical value range for K is between 0.64÷0.8 [10, 12]. In the numerical experiment various values were tested and the influence of this parameter is not significant. Material parameters finally adopted are summarized in table 2.

Table 2. Input data for the numerical model.

Parameter	Symbol	Value
Density	$\rho\left[\mathrm{kg/m^3}\right]$	2565
Elastic modulus	$E[\mathrm{MPa}]$	40700
Poisson's ratio	ν	0.20
Dilation angle	$\psi[\mathrm{deg}]$	30
Coefficient	α	1.16
Void ratio	e	0.01
Bulk modulus …	K	0.66
Viscosity parameter	-	$1\cdot10^{-5}$
Tensile strength	$f_t[\mathrm{MPa}]$	6.22
Compression strength	$f_c[\mathrm{MPa}]$	78.2

In order to simplify the model, only half of the specimen was analyzed, taking into account symmetry conditions. Load and boundary conditions are shown on fig. 3. As the right edge of the model is laying on the symmetry axis, horizontal displacements were set to zero there. Also, one of the nodes at the bottom edge was fixed, to represent the support. Loading was applied by a prescribed horizontal displacement $U(t)=2\,\mathrm{mm/s}$ as an equivalent of the loading mechanism. The specimen was meshed with triangular 3-node plain strain finite elements CPE3 with linear shape functions. The mesh was irregular and the crucial regions were covered with a finer mesh (fig. 3).

The fracture process zone in this model is a fictitious line crack that transmits normal stress which is a monotonically decreasing function of the opening displacement. The most common form of this function is a bilinear approximation. Different evolution functions were considered. The difference between the curves is the value of $f_t^{\backprime}$- the stress at which the bilinear function changes slope. A function with $f_t^{\backprime}=1/3\,f_t$ was chosen as a reference tension softening curve [13].

To achieve the convergence of solution, it was necessary to use a viscoelastic regularization of the constitutive equations, with a viscosity parameter small compared to the characteristic time increment, as advised in [2]. Moreover, the value of the final stress was assumed to be equal to 0.02 MPa. When it is set to zero, then the simulation ends with error and results cannot be obtained.

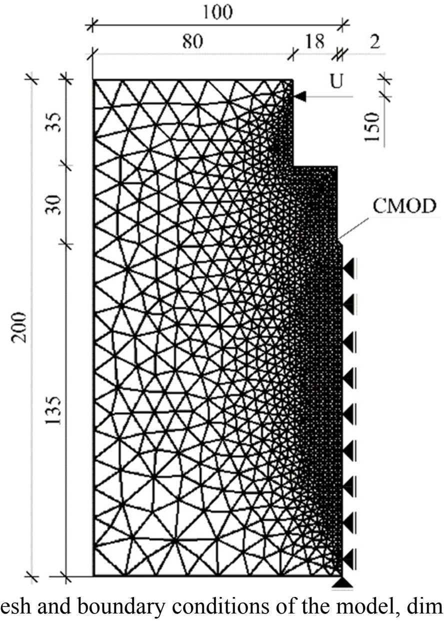

Fig. 3. Geometry, FE mesh and boundary conditions of the model, dimensions given in [mm].

The entire model was created with a parameterized python script, developed by the members of the Students Association of Numerical Modeling. Thanks to the adopted parameterization every aspect of the model could be easily changed - mesh, material properties, geometry, load and boundary conditions. The script allows conducting various numerical tests in a very convenient way. It also automates acquiring the output data. Crack opening displacement is calculated as double horizontal displacement of the node highlighted in the fig. 3 (CMOD). The value of the splitting force is established as a sum of horizontal reactions in the supports at the right hand side edge.

5. Comparison of numerical and experimental results

The results obtained in the experiments for three specimens are shown in table 3 along with the mean value of the fracture energy. The splitting force versus CMOD curve derived from experiment is shown in fig. 4b and compared to a curve obtained from computations.

Table 3. Test results for high-strength concrete.

Specimen number	Splitting force P_h [kN]	Fracture energy G_F [N/m]	Mean fracture energy [N/m]
1	9.83	99.70	98.08
2	10.26	101.13	
3	8.85	93.40	

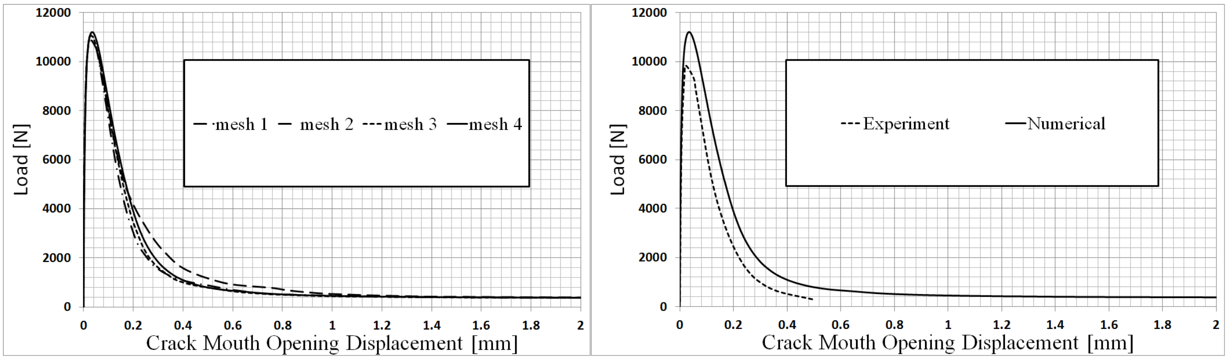

Fig. 4.(a) Convergence analysis; (b) Comparison of experimental and numerical results.

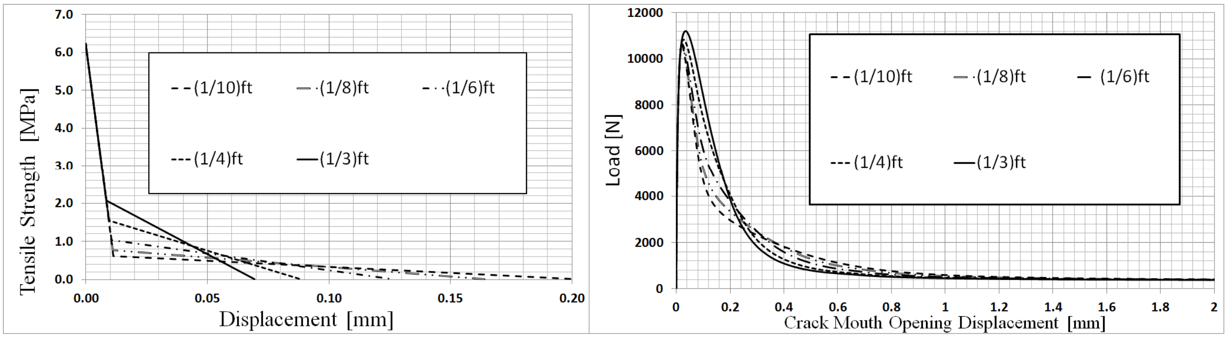

Fig. 5. (a) Tension-softening curves; (b) Force-CMOD curves for different tension-softening functions.

Figure 4a shows a comparison of graphs obtained for four cases of different finite element mesh density. Mesh 1 is the coarsest (294 elements) and the mesh 4 is the finest (2460 elements). The finest mesh was used for further computations.

Various tension softening curves were considered (see fig. 5a). The area under the softening curve is the same in all cases so that the value of the fracture energy of the material is preserved. High influence on the Force-CMOD curve can be seen in fig. 5b. There is no certain way to establish tension softening function (it even does not have to be bilinear) and therefore the further research in this subject should be taken.

The comparison of the numerical and experimental results is shown in the figure 4b. The maximum splitting force from the test is 9.8 kN, when the numerical approximation gives 11.2 kN. The area under the splitting force versus CMOD curve represents total fracture energy per unit area of the crack plane. A mean value of 98 N/m was obtained in the experiment. The curve derived from the computations was subjected to change due to the nonzero final stress. The influence of this assumption is apparent in the softening zone, therefore its value was subtracted in this region. The computational fracture energy equals 132 N/m.

The differences in the results may be caused by several factors. Neglecting the vertical load component, which in fact appears in the experiment, can be one of them. In accordance to [14], doing this simplification can cause the maximum splitting force to be overestimated by ~10%. Moreover, it can be seen that the splitting force does not tend to zero at the end of computations. This is the effect of the assumption that the stress after cracking is not equal zero. The other reason might be that the model in not sufficiently detailed. The assumed material model can also be an influence. It does not allow for element removal or crack propagation inside of elements. Therefore the model can become too stiff.

6. Conclusions and further research

The paper covers the subject of experimental wedge splitting testing of high-strength concrete and developing a numerical model of this test.

The current model slightly overestimates the value of fracture energy established in the experiment. The reasons could be of a different nature and will be the subject of further study. It will cover, among others, creating a more detailed model with the loading mechanism included. Usage of other finite element formulations, such as extended finite element method (XFEM), will also be considered.

Further research is planned on advanced cement concretes and their adhesion to high-strength concretes. Numerical simulations of these tests will be prepared as well.

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