

**Táňa HOLUŠOVÁ<sup>1</sup>, Stanislav SEITL<sup>2</sup>, Alfonso FERNÁNDEZ-CANTELI<sup>3</sup>****NUMERICAL SUPPORT OF EXPERIMENTAL COMPACT TENSION TEST  
ON CONCRETE CYLINDRIC SPECIMENS****Abstract**

The assessment of crack growth rate in quasi-brittle materials is lately very often studied problem of fracture mechanics. This contribution is focused on comparison of fracture parameters obtained from two fracture tests with similar shape of specimen – the wedge splitting test and the compact tension test. Both tests are applied on cylindrical specimens made from cement based composite. Numerical simulations for both configurations are performed in software ATENA. The amount of fracture energy consumed during fracture process has been compared for particular configurations.

**Keywords**

Fracture energy, crack growth, compact tension, wedge-splitting test, cement-based composite.

**1 INTRODUCTION**

Modern civil engineering strives for audacious, more slender and impressive structures representing at the same time effective, cheaper and safer solutions. Most of such constructions, as road bridges, highways viaducts and bridges over the railway and barrages, are built in concrete and work under highly demanding conditions, subjected not only to static but also to fatigue loads. This also applied for wind power stations, or parts of energetic devices. [11].

Under these extremely strained constructions fatigue cracks arise in these extremely strained constructions during their lifetime [16]. Therefore, determining the residual resistance or the intervals of regular controls based on the crack growth rate curve in those constructions damaged by fatigue cracks is necessary in order to achieve a safe design. Thus, the study of fracture behavior must be undertaken [9].

Quasi-brittle materials, to which the cementitious composites belong, are intrinsically highly heterogeneous materials. At a macrostructural level, such materials experience much more complex processes under cyclic load than, for instance, metallic materials [16].

In the previous decades several possible configurations of fracture tests were proposed for determination of fracture parameters of quasi-brittle materials. The best popular among the classic tests are the three (3PB) and four (4PB) point bending tests, see Karihaloo [7]. Nevertheless, the fabrication requires a big amount of material and specimens are too heavy thus becoming hard to manipulate in laboratory conditions. During the experimental programs, in particular related to three

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point bending testing, it was realized that the major fracture process is running over a small area of the specimen, the so called fracture process zone. This was corroborated by numerical analysis giving rise to the development of an alternative kind of fracture test – the wedge splitting test, conducted on small cubic or cylindrical shaped specimens. This test configuration was first proposed by Linsbauer et al. [12] and promoted by Brühwiler et al. [3]; a parametric study for the calculation of the stress intensity factor was published by Guinea et al. [5], and an over deterministic method (ODM) for the calculation of the first terms of Williams series was provided by Sobek et al. [15]. The crack growth rate resulting by the fatigue process in cementitious composites was handled, for instance, by Bažant et al. [1], [2], Lee et al. [11] and Seitl et al. [13], [14].

The fracture parameters determined from tests using concrete specimens fabricated under laboratory conditions are only representative of those in real constructions if their correspondence with the aged concrete is established. This requires drilling concrete cores from real structures to be extracted, from which samples are sliced as cylinder shaped specimens for wedge-splitting or modified compact tension tests.

The aim of this contribution is to evaluate the influence of shape and boundary conditions for both test configurations used for determining fracture mechanics parameters in concrete. The first test configuration handled is the wedge-splitting specimen (see Fig. 1) while the second one is the modified compact tension specimen (see Fig. 2), which represents an adaptation of the compact tension specimen regularly used by fracture tests on metallic materials [10].

## 2 TEST CONFIGURATIONS

Some basic information concerning test configurations is provided in the following. The wedge-splitting test, has been for a long time the matter of research on test configurations for determination of fracture mechanics parameters of quasi-brittle materials, see for instance Guinea et al. [5], Karihaloo et al. [8], Veselý et al. [17], [18] or Holuřová [6], while the modified compact tension test is a recent alternative awaken interest due to its simplicity [10]. Both tests are made of cylindrical specimens. The numerical calculation performed on both configurations is based on earlier studies and tests performed.

### 2.1 Wedge-splitting test

Wedge-splitting test (WST) is a standard fracture test for determination of fracture mechanics parameters of quasi-brittle materials [7]. Cubic or cylindrical specimens are used where the standard diameter or square side length are 150 mm. By cylindrical specimens a circle segment is cut off in order to guarantee good settlement of the steel platens.

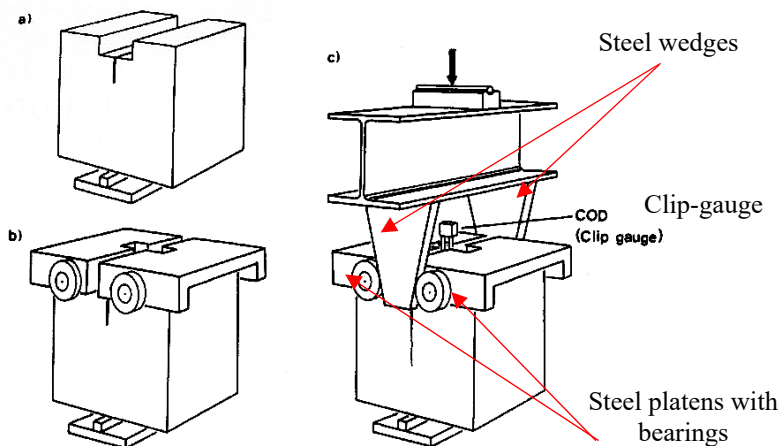


Fig. 1: WST principal: a) test specimen with starting notch; b) two steel platens with bearings; c) steel wedges inserted between bearings for splitting the specimen into two halves (taken from [3])

WST testing methodology was published for the first time by Linsbauer and Tschegg [12], who determined fracture-mechanics parameters of the concrete, in particular the fracture energy. Based on this paper, Brühwiler and Wittmann [3] placed this configuration between standard fracture mechanics tests. The WST configuration and the corresponding static load system are shown in Fig. 1.

## 2.2 Modified compact tension test

The compact tension (CT) test is mostly utilized for determination of fracture parameters in metallic materials what suggests the feasibility of its application to cementitious materials, such like concrete.

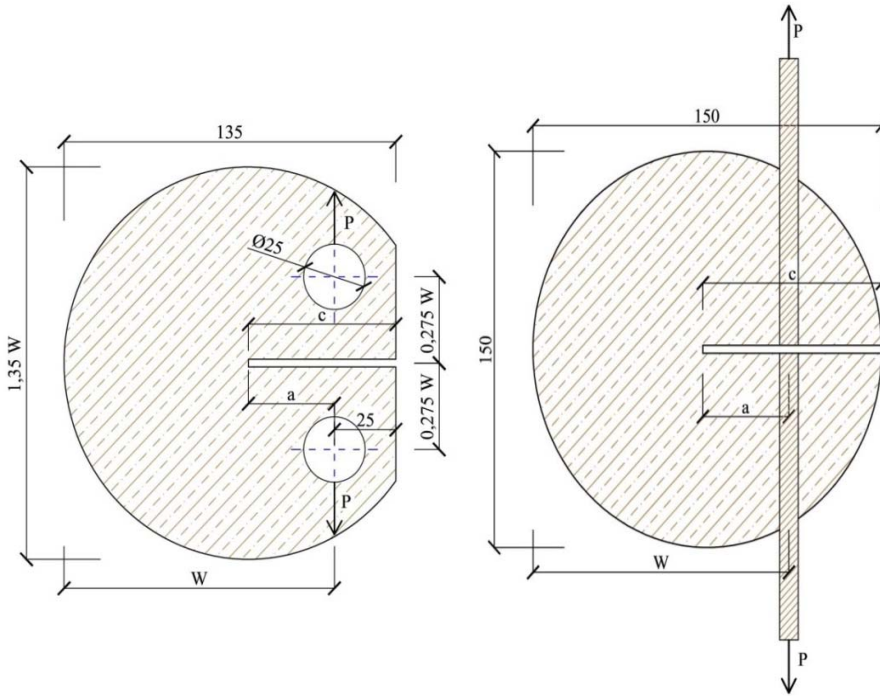


Fig. 2: Standard CT specimen for compact tension test: a) for metal materials; b) modified specimen for cement based composites

Despite the WST, where the loading is applied onto the specimen by a steel wedge across the bearings and the major load is divided into horizontal and vertical component, the CT specimen is equipped by grips and its splitting succeeds directly by horizontal forces. Nevertheless, due to the similarity between both specimens, the numerical and experimental results resulting from the WST test can be compared with those obtained by the modified CT test. The scheme and configuration of the test is shown in Fig. 2.

## 3 NUMERICAL SIMULATIONS

Numerical models are developed using the two dimensional software ATENA [4]. The cement based composite (concrete) is modeled as the so called 3D Non Linear Cementitious 2 material under plane strain conditions. A material modulus called Plane Strain Elastic Isotropic is implemented for modeling support, steel platens and steel wedge. The values of the cubic and tensile strength of concrete, Young's moduli of concrete and steel and steel density are listed in Table 1.

Tab. 1: Characteristics of concrete and steel

	Cubic strength $f_c$ [MPa]	Tensile strength $f_t$ [MPa]	Young's modulus $E$ [GPa]	Density $\rho$ [kg/m <sup>3</sup> ]
Concrete	30	2.568	32.29	2300
Steel	-	-	210	7850

The characteristic parameters from Table 1 are applied to the models implemented in ATENA 2D software. The finite element mesh is refurbished, and the model assumes only one support instead of two as in former works.

The monitoring points of the horizontal displacement for the CT specimen are located so that they reproduce exactly the displacement for WST specimens, see blue crosses in Fig. 3 and Fig. 5.

To achieve a parametric study, five relative notch lengths, the same for both configurations, are chosen, the difference only consisting in the actual starting notch length. The relative notch length  $\alpha$  is a dimensionless number defined as

$$\alpha = \frac{a}{W}, \quad (1)$$

where:

$\alpha$  – relative notch length [-],

$a$  – notch length measured from load axis [m] and

$W$  – specimen width, i.e., distance from the load axis to the opposite side of the specimen [m]

The individual relative notch lengths and actual notch lengths measured from the edge are shown in Table 2 (see also Fig. 3 and Fig. 5 for the WST and CT specimens, respectively):

Tab. 2: Selected values of relative notch lengths for considered WST and CT specimens

$\alpha$		0.08	0.1	0.125	0.15	0.2
$a$		9.6	12	15	18	24
$c$	WST	4.6	7	10	13	19
	CT	39.6	42	45	48	54

The loading curves for WST and modified compact tension in the diagrams are marked by red and blue colours, respectively, (see below).

### 3.1 Model WST

The WST model used in the calculation is based on the diploma thesis of the first author, see Holušová [6]. Figure 3 shows the numerical model of the test specimen used. The specimens of both configurations considered in the calculations show circular cross-section of diameter 150 mm and thickness 100 mm. A segment of 15 mm has been cut off on the top of the laboratory test specimen. Thereafter, a 30 mm wide and 20 mm deep groove is created. The steel platens, with the bearings at the end of both sides, fits into the groove riding the wedge during the test. The steel wedges, being initially placed on the groove edges, are pushed into the groove by rolling of steel bearings, which are anchored on the steel platens. Through these bearings, the actual load is applied on the specimen so that the steel wedge gradually penetrates into the notch splitting the specimen into two halves.

The blue crosses in Fig. 3 indicate the monitoring points of displacements in horizontal and vertical directions where the bearings are placed.

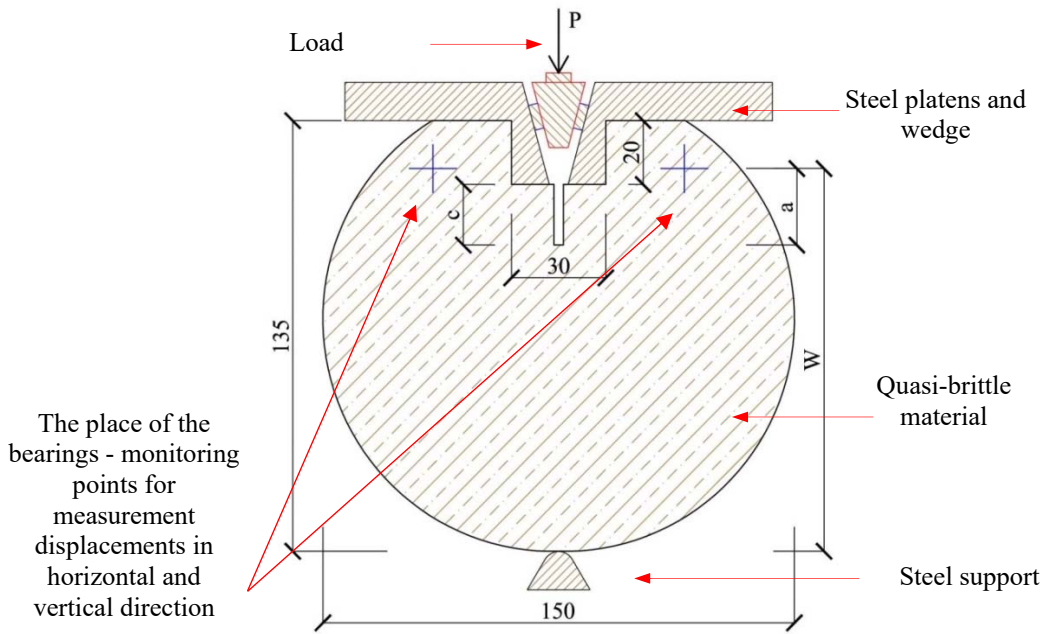


Fig. 3: Numerical model of the testing specimen for WST (taken and modified from [6])

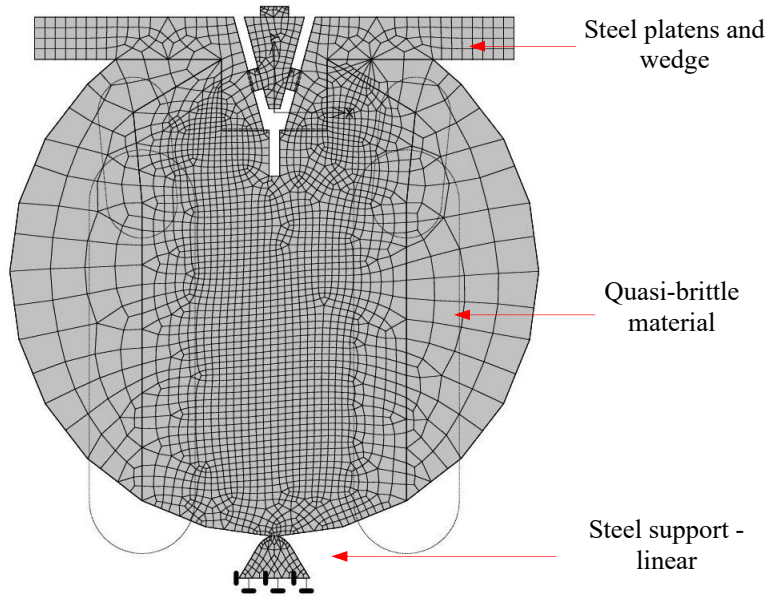


Fig. 4: Finite element mesh and boundary conditions for circular WST specimen

The finite element mesh used is shown in Fig. 4. The main fracture process is progressing along the specimen ligament, from the end of the starting notch to the bottom support, so that a denser mesh with element size 2 mm was selected there. The same element size was adopted for the support and wedge design. Only one support is assumed according to the extended experimental study of WST specimens now in progress at the Institute of Structural Mechanics of Faculty of Civil Engineering Brno University of Technology. The influence of the boundary conditions for cubic specimens for wedge splitting test was already studied by Veselý et al. [17].

### 3.2 Model CT

Figure 5 shows the specimen in circular version used in the modified compact tension (CT) test.

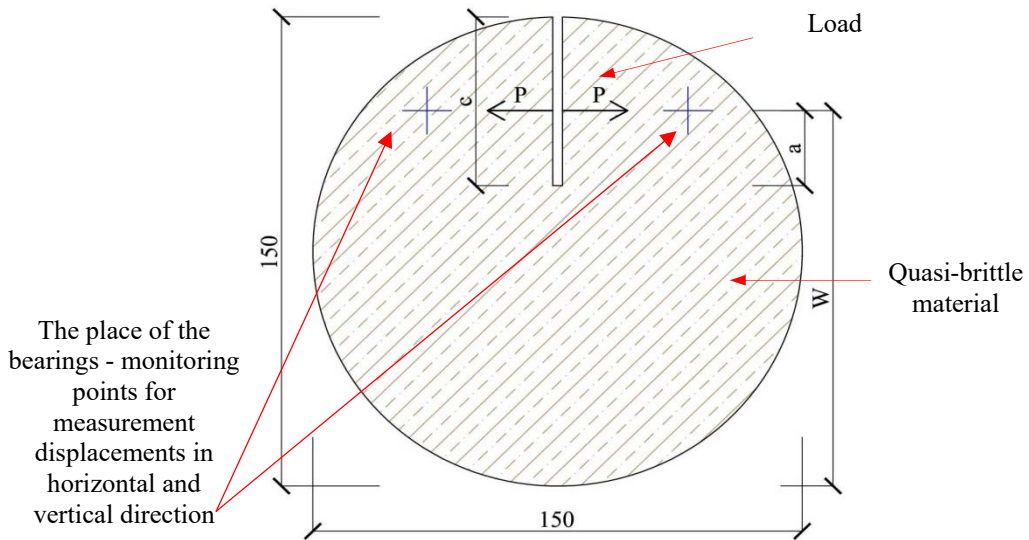


Fig. 5: Modified numerical model of test specimen for CT

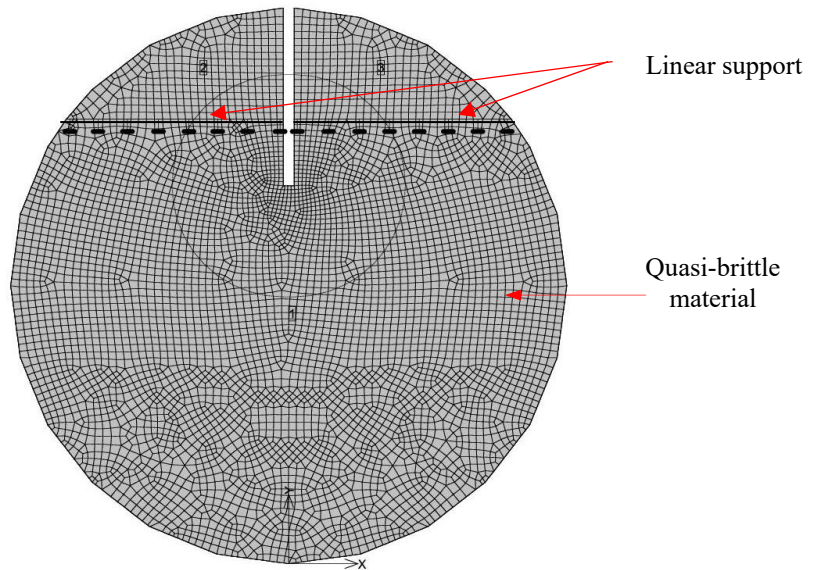


Fig. 6: Finite element mesh and boundary conditions for circular CT specimen

CT specimens for testing fare no needed to be modifying to right placing of the load apparatus. A starting notch is mechanized in the specimen, which acts as crack initiation. The CT specimens for concrete can be prepared as follow: two holes are drilled into the cylindrical specimen perpendicular to the crack notch at a suitable distance from the notch edge, inside which two steel corrugated bars are allocated and glued. The bars are gripped into the clamping jaws of the testing machine and pulled until fracture occurs by splitting the two halves along the crack.

In order to guarantee similarity with the WST test, the steel bars in the model are replaced by ideal lines, which simulate the pulling axis of the machine. The finite element mesh with the boundaries described above is shown in Fig. 6. The side length of the element is 2 mm with a mesh densification of 1 mm around the starting notch.

#### 4 RESULTS AND DISCUSSION

During the numerical simulations, the displacements on the load beam at the bearings for both types of configurations are monitored. All results are represented as loading diagrams L-COD (Load - crack opening displacement).

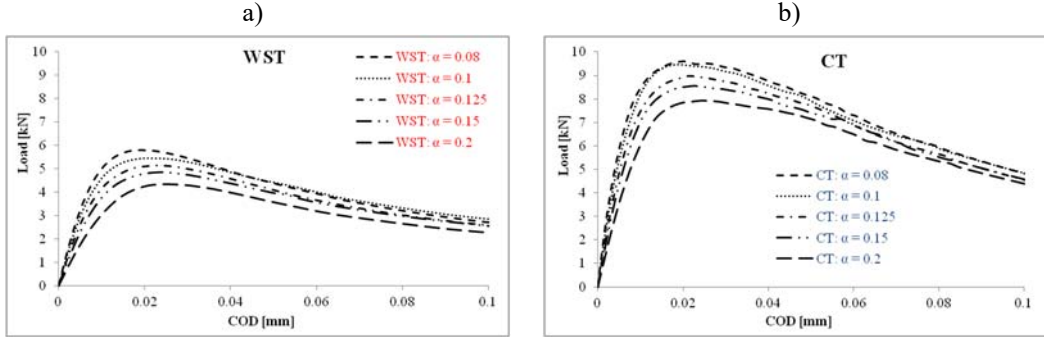


Fig. 7: Loading diagrams from numerical simulation for test with: a) WST and b) CT configurations

The individual loading diagrams for the WST and CT specimens are represented separately in Fig. 7a) and b), respectively. The diagrams show that the maximum load increases with growing relative notch length for both configurations whereas the different boundary conditions arising for both models lead in the case of CT configuration to a higher resistance against fatal break than in case of WST configuration. This can be easily observed in the diagrams of Fig. 8 by comparing the load curves for relative notch lengths 0.08 and 0.2. The maximum difference between the values appears in the interval (3.6 – 3.8) kN.

A comparison of total load diagrams for both configurations is shown in Fig. 9. The maximum load region is detailed separately on the right head corner of the figure. These diagrams are used for calculating one of the most important fracture parameters – the fracture energy.

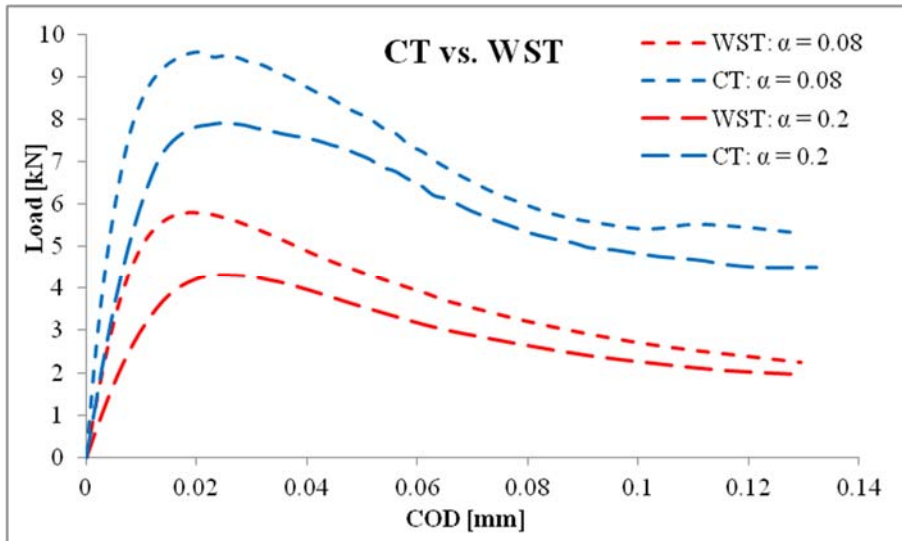


Fig. 8: Comparison of selected load curves of both test configurations

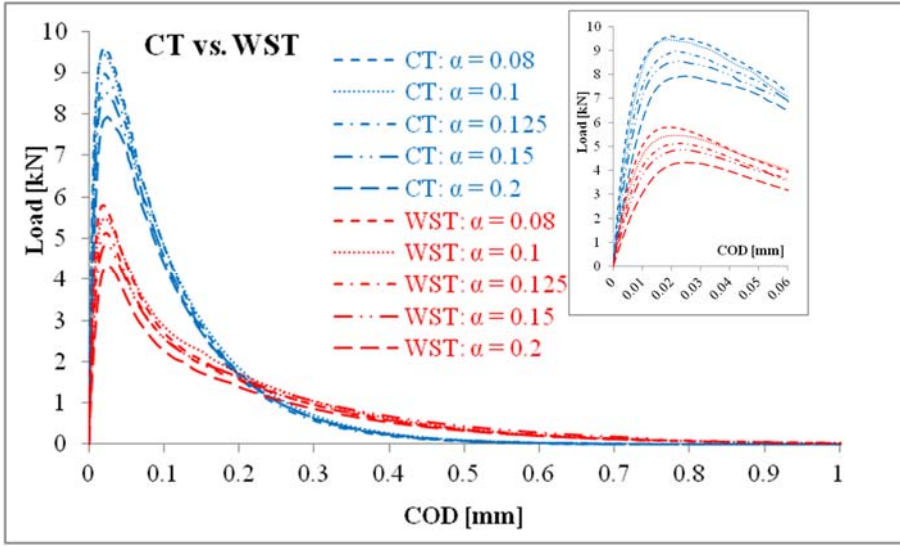


Fig. 9: Comparison of the loading diagrams for both test configurations and details around maximum loads

Since the fracture energy is the parameter commonly used for quantification of the material quality [7], as the amount of energy dissipated by crack growth spread through the specimen. Its evaluation is therefore included as a relevant information for comparison between the WST and CT load tests. The value of the fracture energy is given by equation (2):

$$G_f = \frac{W_f}{A_{lig}}, \quad (2)$$

where

$G_f$  – fracture energy [ $\text{J}/\text{m}^2$ ],

$W_f$  – work of fracture [J] and

$A_{lig}$  – area of the ligament [ $\text{m}^2$ ].

In Table 2 the values of the fracture energy are shown at the end of the fracture process, on the left for wedge-splitting test and on the right for compact tension test.

Tab. 2: Values of fracture energy for both test configurations

α 150	WST specimen			CT specimen		
	Starting notch length [mm]	Relative notch length α [-]	$G_f$ [ $\text{J}/\text{m}^2$ ]	Starting notch length [mm]	Relative notch length α [-]	$G_f$ [ $\text{J}/\text{m}^2$ ]
1	24.6	0.08	<b>83.1</b>	39.6	0.08	<b>109.1</b>
2	27	0.10	<b>88.5</b>	42	0.10	<b>113.1</b>
3	30	0.125	<b>83.9</b>	45	0.125	<b>107.0</b>
4	33	0.15	<b>88.4</b>	48	0.15	<b>110.8</b>
5	39	0.20	<b>79.9</b>	54	0.20	<b>112.0</b>

The difference between maximum and minimum values of fracture energy is less than 9.7 % for the WST and 5.4 % for CT configurations, respectively, while the average values of the fracture

energy are  $84.7 \text{ J/m}^2$  for WST and  $110.4 \text{ J/m}^2$  for the CT configurations, respectively. In the case of the CT specimen, the fracture energy values for CT specimens are higher than for the WST configuration. A possible reason arises from the gripping system, which constraints the load axis to be prescribed by the machine impeding a rotation of the individual parts of the specimen. Further influences are the specimen weight and the missing stress load at the end of the specimen. A correction about 24 % should be applied to the results from the modified compact tension test if comparable results to those for WST specimens are pursued.

The diagrams in Fig. 10 show, respectively, the final values of the fracture energy (left) and the gradual increase of these values during the load process (right), whereby a saturation of the fracture energy value at the end of the load process is unquestionable.

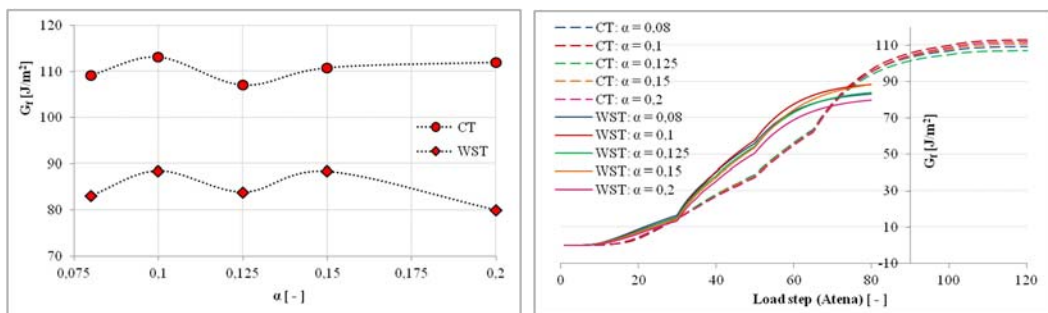


Fig. 10: Graphical representation of the growth of fracture energy

## 5 CONCLUSIONS

In this paper, two similar test configurations, namely wedge-splitting test, WST, and compact tension test, CT, are applied for determining fracture mechanics parameters.

The fracture energy values for different starting notch differ less than 9.7 % for the WST and 5.4% for the CT configurations, respectively proving that the latter is more stable. Though earlier studies state that the fracture energy is a parameter strongly dependent on the shape and configuration of the test load, the results obtained demonstrate that a stable fracture process for both test configurations is attained. In order to achieve agreement between the fracture energy values from both tests a reduction factor  $S_H = 0.76$  must be applied to the fracture energy values resulting from the CT tests.

The modified compact tension test, represents a relatively new methodology for determination of the fracture-mechanics parameters of quasi-brittle materials, in particular cement based composites, from which the crack speed growth through the specimen must be determined. This test is significantly easier to prepare and to perform under laboratory conditions, showing a stable fracture process and allowing the results obtained to be easily transformed into values corresponding to the WST test.

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