A numerical study of two different specimen fixtures for the modified compact tension test – their influence on concrete fracture parameters

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ABSTRACT. The modified compact tension test (MCT) may represent a new test configuration for the performance of static and other kinds of fatigue tests on concrete-like materials. Core drilling can be employed to obtain specimens which are cylindrical in shape and have a standard diameter of 150 mm, this being appropriate for the determination of the residual life of structures. This contribution focuses on the evaluation of MCT specimen fracture behavior during static tests. Cracks evolution are simulated numerically using ATENA finite element (FE) software, while the results are represented as L-COD diagrams, i.e. load vs. crack opening displacement measured on the loading axis. After numerical calculations, the results for two different fixtures are compared and the advantages or drawbacks for each solution are discussed.

KEYWORDS. Modified Compact Tension Test; Fracture Parameters; Cementitious Composites; FEM.

INTRODUCTION AND MOTIVATION

Knowledge regarding the fracture mechanics behavior (parameters) of the most common building material, concrete, plays a significant role in the determination of the residual life of previously built constructions. This is especially true for concrete used in buildings after several years of aging. Drill cores commonly used for the determination of concrete age, can be extracted from real (existing) structures. Cylindrical specimens with the selected thickness can be cut from the drill cores. This kind of specimen can be used for the modified compact tension test (MCT), whose numerical evaluation is useful for the determination of relevant fracture-mechanics parameters of concrete

or cement based composites [1]. The common fracture-mechanics test methods for concrete in laboratory conditions are three-point bending (3PB) and four-point bending (4PB) tests, which are both performed on concrete beams of specific dimensions [2]. The specimen for the MCT test is similar to specimens used for another standardized fracture-mechanics test, the so-called wedge-splitting test (WST) [3], for which cubic and cylindrical specimens can be used. The MCT specimen is similar to standard compact tension (CT) test specimens, which are used for fracture and fatigue parameters of metallic materials [4]. The fracture mechanics parameters and fatigue behavior of quasi-brittle materials, which is currently research topic, see following references: the experimental [5-8] and numerical [9, 10].

Previous numerical studies of the modified compact tension test were focused on comparing the fracture energy values that are obtained from the 3PB, WST and MCT [11], or on investigating the influence of the location of the steel bars [12]. Also, measurements were obtained during the experimental test by an ARAMIS 3D optical camera system, and the quality of the numerical model was evaluated [13]. The numerical evaluation of the use of this type of configuration to determine the fracture energy of concrete was performed with ABAQUS software [14].

The aim of this contribution is the comparison of two different specimen fixtures and their possible use during experiments from the numerical point of view. The idea of using eye nuts at the ends of the steel bars (see Fig. 3b) is to avoid an undesirable moment (which could arise due to the way the specimen is held in the grips during the test) and render the experimental set-up as close as possible to that employed in the standard CT test. The fracture energy is calculated according to RILEM recommendations [15] from loading curves obtained from numerical simulations performed with ATENA 2D FE software [16]. Finally, the results are compared and discussed.

MODIFIED COMPACT TENSION SPECIMENS

As mentioned above, the geometry of MCT test specimens is derived from that of the original standard compact tension test specimen. It is well known that concrete-like materials exhibit good behavior in compression and poor behavior in tension. On the other hand, metallic materials are well known for their high quality in tension and somewhat lower in compression performance due to buckling. When combined, these two materials create optimal construction material. The tests mentioned above represent standard tests for determining the fracture mechanics parameters of concrete-like materials. Typically, specimens for 3PB and 4PB tests are block shaped (their length is significantly greater than their other two dimensions). Cubic and cylindrical specimens are typically used for the WST; in this respect it is similar to the MCT test, for which these shapes can also be used.
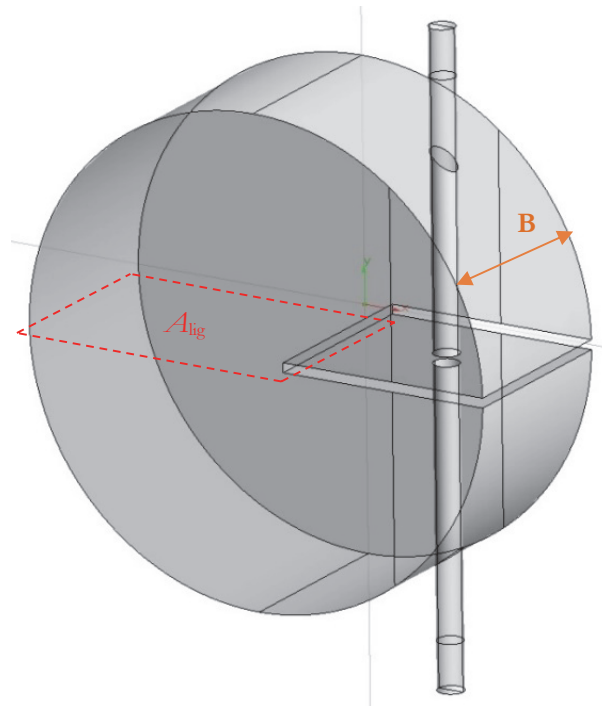

Figure 1: Visualization of a modified compact tension specimen in 3D format.
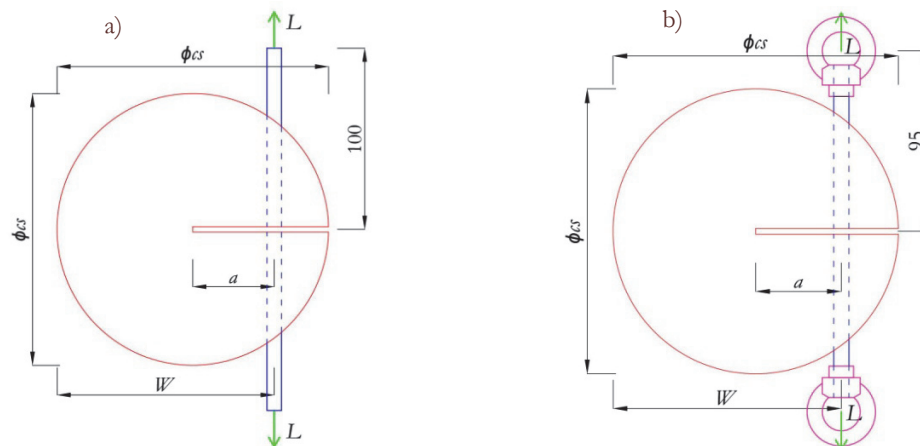
Figure 2: Schematic diagram of a modified compact tension test with dimensions in 2D: a) current set-up; b) set-up with eye nuts at the ends of the steel bars.
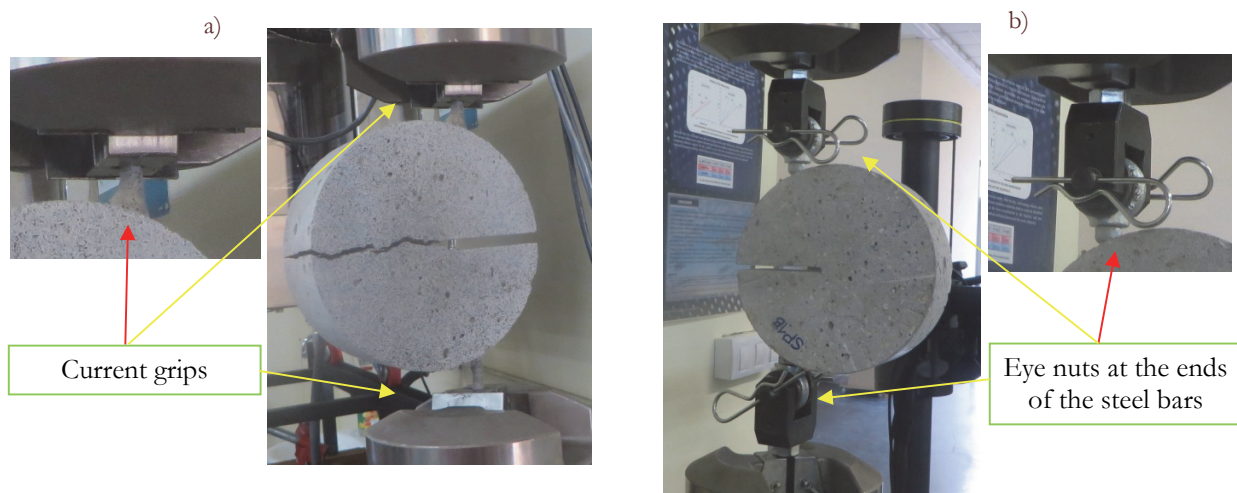

Figure 3: Attachment of an experimental specimen to a servo-hydraulic test machine. According to the schematic diagram above: a) current set-up - attachment without torsion; b) set-up with eye nuts in the ends of the steel bars.

In studied case the cylindrical shape was chosen because such specimens can be conveniently created from drill cores, cylinders usually used for evaluating the age and condition of material taken from existing structures. The MCT test specimen can be prepared as follow: the holes are drilled from the sides of the specimen, perpendicular to the starting notch, so that the steel bars can be allocated and glued inside of the specimen. The values in Tab. 1 show the predicted dimensions of the MCT specimens used for numerical calculations and also for the intended experimental procedure, where:

ϕ_{cs} is specimen diameter [mm],
W is specimen width, i.e., the distance from the load axis to the opposite side of the specimen [mm],
a is notch length measured from the load axis [mm],
B is specimen thickness [mm],
ϕ_{sb} is the diameter of the steel bars [mm],
α is relative notch length [-] and
A_{lig} is the area of the ligament [mm²].

Specimen dimensions	ϕ_{cs} [mm]	W [mm]	a [mm]	B [mm]	ϕ_{sb} [mm]	α [-]	A_{lig} [mm²]
	150	120	36	60	8	0.3	5 040

Table 1: Used dimensions of the MCT specimens in numerical study.

The ligament area, marked as A_{lig} (area marked by red dash lines Fig. 1), is defined as the fractured area and is calculated as the product of the length of the ligament and specimen thickness (B). The parameter α (relative notch depth) from Tab. 1 is defined as follows:

$$\alpha = a/W \tag{1}$$

In Fig. 2 a schematic diagram of a modified compact tension specimen is shown together with the aforementioned dimensions of the specimens. For a better visualization of how the attachment of the specimen to the apparatus would look during a real experimental procedure, specimens with both types of attachment are shown in Fig. 3.

NUMERICAL SIMULATION

Numerical simulations are performed with ATENA software [16], which is based on the finite element method (FEM). This software has been specifically developed for applications connected with concrete structures. This program is used for numerical support in the experimental testing of the MCT test. The MCT dimensions used to create the numerical models are listed in Tab. 1.

The MCT specimen is created from two material components, concrete and steel. In the numerical simulations the numerical material called 3D Non Linear Cementitious 2 (3DNL) was used in plane stress conditions for the concrete part. As regards the steel bars, the numerical material called Plane Stress Elastic Isotropic (PSEI) was used. The selected input parameter for the numerical study is the cubic strength f_{cu} [MPa] in the case of 3DNL. It was used 8 various f_{cu} values ($f_{cu} \in \{10, 25, 37, 45, 55, 67, 75, 85\}$ MPa) corresponding to the cubic strengths of different classes of plain concrete. The program calculates the other mechanical parameters for material model (the values of other relevant input parameters are left as default values generated by the program). The input parameters of the 3DNL numerical material are summarized in Tab. 3; those for PSEI are in Tab. 2.

The typical length of the element sides of the finite element mesh of the numerical models is 2 mm; the length is refined to 1 mm around (in the vicinity of) the starting notch. The finite element mesh, boundary conditions and numerical models of the MCT test – with the specimen held by grips and with the eye nuts in the ends of the steel bars – are shown in Fig. 4.
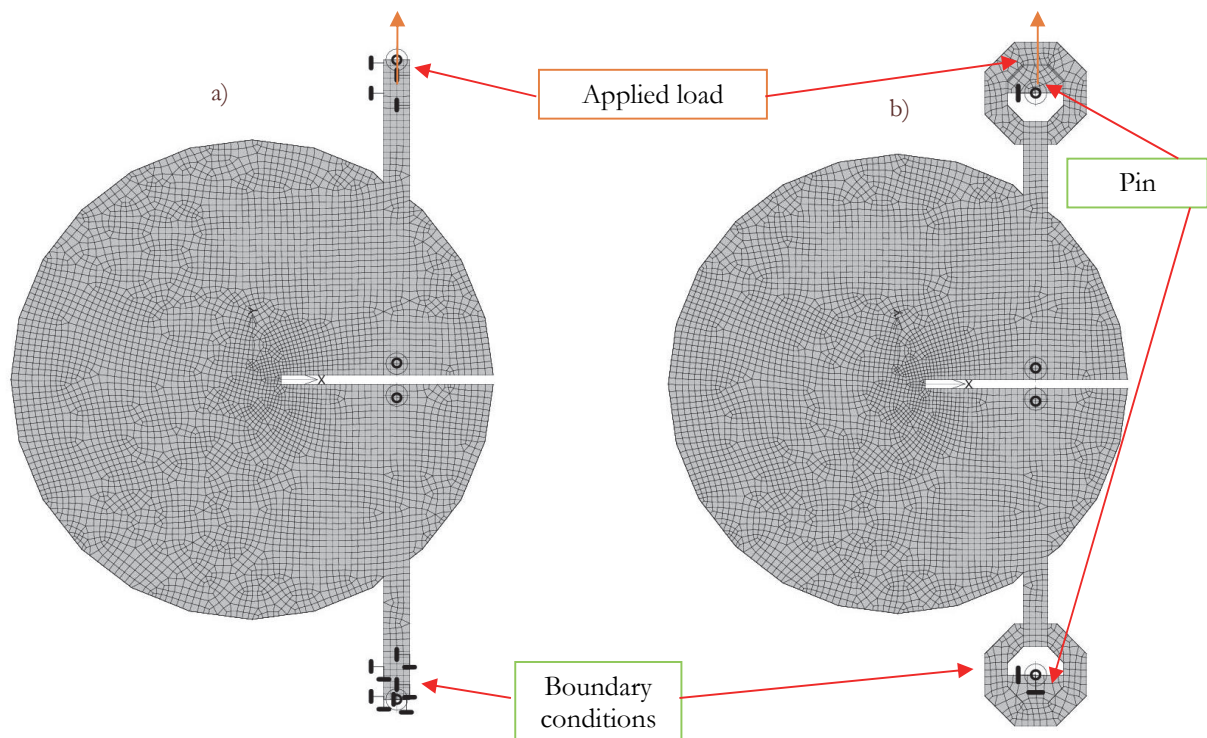

Figure 4: Numerical models of the modified compact tension test with boundary conditions: a) current grips; b) with eye nuts.

Steel / Plane Stress Elastic Isotropic	
E [MPa]	210 000
μ [-]	0.3
ρ [kg/m³]	7 850

Table 2: Input parameters of the Plane Stress Elastic Isotropic numerical model for steel bars.

Concrete / 3D Non Linear Cementitious 2								
f_{cu} [MPa]	10	25	37	45	55	67	75	85
E [MPa]	18 470	28 060	33 010	35 570	38 170	40 610	41 890	43 170
f_t [MPa]	1.114	2.052	2.665	3.036	3.471	3.959	4.268	4.640
f_c [MPa]	8.5	21.25	31.45	38.25	46.75	56.95	63.75	72.25
G_f [J/m²]	27.85	51.30	66.62	75.91	86.77	98.98	106.7	116
μ [-]	0.2							
ρ [kg/m³]	2300							
Fixed crack model coefficient	0.5							
Aggregate size [m]	0.02							

Table 3: Input parameters of the 3D Non Linear Cementitious 2 numerical model for concrete.

RESULTS AND DISCUSSION

The numerical results are presented via L-COD diagrams for studied cases; selected examples are shown in Figs. 5-6. The horizontal axis represents the displacement, in this case the crack opening displacement (COD) measured on the loading axis (labeled COD_F in the diagrams) and also on the axis of the steel bars. The vertical axis is represented by the applied load, giving us the Load-COD diagrams.

The fracture energy value was also calculated and compared for all curves. Fracture energy (G_f) is a relevant fracture parameter which characterizes concrete. Its value is obtained from work of fracture (W_f) divided by the area of the ligament (A_{lig}). The work of fracture value corresponds to the area under the corresponding curve. The applicability of the MCT test for the determination of the fracture energy of concrete was investigated with promising conclusions (see [17]).

Fracture energy G_f [J/m²]								
f_{cu} [MPa]	10	25	37	45	55	67	75	85
Current grips	48.61	95.52	120.95	134.93	134.08	211.48	218.68	225.25
Eye Nuts	31.01	67.58	90.15	103.16	122.73	135.66	148.20	163.35
Ratio Eye/Curr	0.638	0.708	0.745	0.765	0.915	0.642	0.678	0.725

Table 4: Fracture energy values calculated according to RILEM recommendations and obtained from loading curves from numerical calculations.

The fracture energy values calculated from loading curves are shown in Tab. 4. According to the results obtained from numerical simulations, the loading curve for the value f_{cu} = 55 MPa with the current grips shows a significant anomaly. In the other cases, the use of eye nuts at the ends of the steel bars plays a significant role. The curve of the fracture energy values from the numerical models in which eye nuts were used display approximately the same trend as the input fracture energy values. Tab. 4 contains the calculated ratios between the values obtained from the loading curves for the numerical

model with eye nuts at the ends of the steel bars and the model featuring the current method by which the specimen is gripped by the test apparatus. Except the ratio for f_{cu} = 55 MPa, the ratios range is from $0.63 − 0.76$. For better clarity Tab. 4 is reproduced as a graph in Fig. 7.
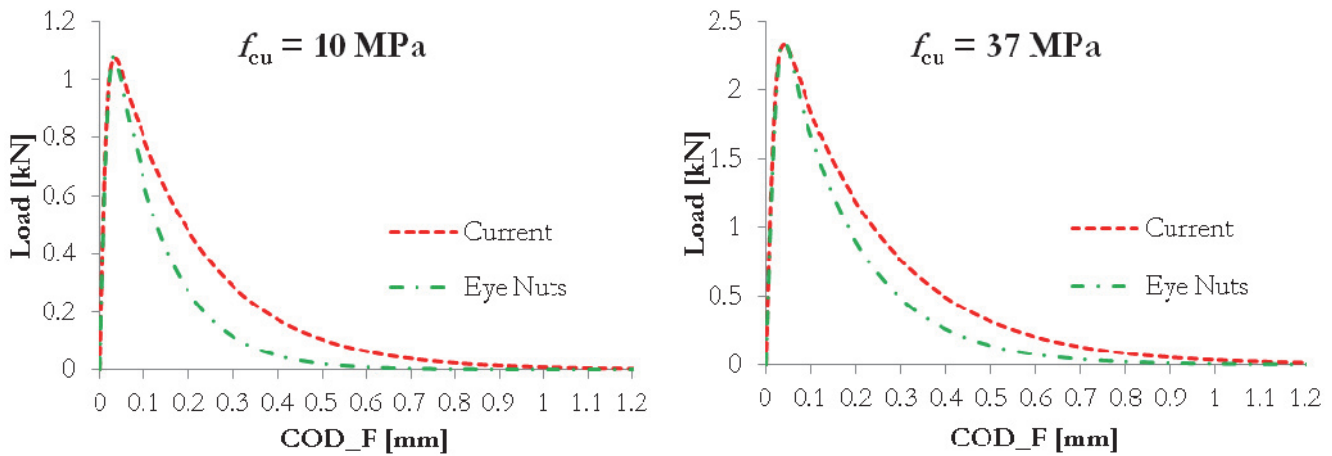

Figure 5: The final Load-COD_F diagrams for f_{cu} 10 and 37 MPa used for the calculation of fracture energy values.
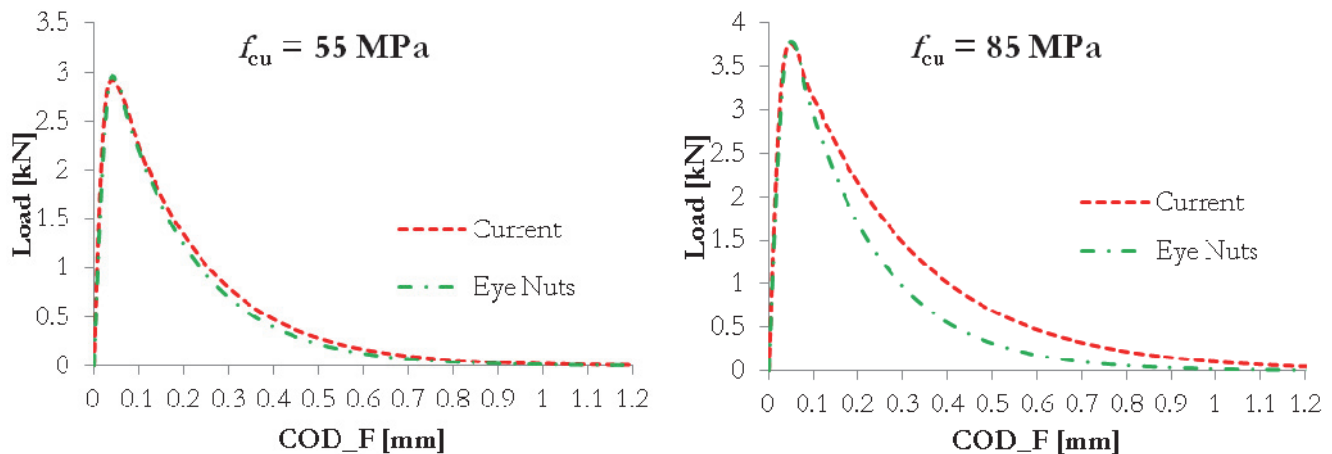

Figure 6: The final Load-COD_F diagrams for f_{cu} 55 and 85 MPa used for the calculation of fracture energy values.

CONCLUSION

The numerical simulations of the modified compact tension test were performed with the use of ATENA 2D finite element software. A cylindrical shape was chosen for the specimen, the dimensions of MCT are listed in Tab. 1. Eight cubic strength values (f_{cu} ∈ {10, 25, 37, 45, 55, 67, 75, 85} MPa) were considered as input values for the numerical model used for the concrete part of the structure, 3D Non Linear Cementitious 2.

The results are presented by the Load-COD_F diagrams and by the fracture energy values calculated according to RILEM recommendations [15] and summarized in a graph depending on input cubic strength values.

From the numerical point of view, the results show that the use of eye nuts at the ends of the steel bars plays a significant role on the behavior of the conducted test. Nevertheless the obtained fracture energy curves show the same trend as the curve of input fracture energy values. In further research and experimental procedures it is recommended that eye nuts are used at the ends of the steel bars in order to avoid undesirable moment.

The current method by which the steel is gripped by the test machine does not allow torsion at the ends of the steel bars. This can cause undesirable moment to arise, along with the deformation of the steel bars as you can see in Fig. 8 a) – marked by the red line (at the start point of the loading process) and by the green line (at the end point of the loading

process). To avoid this situation, the use of eye nuts at the ends of the steel bars could be the solution. The eye nuts are allowed to rotate around the pin, which is fixed (see Fig. 8 b)).
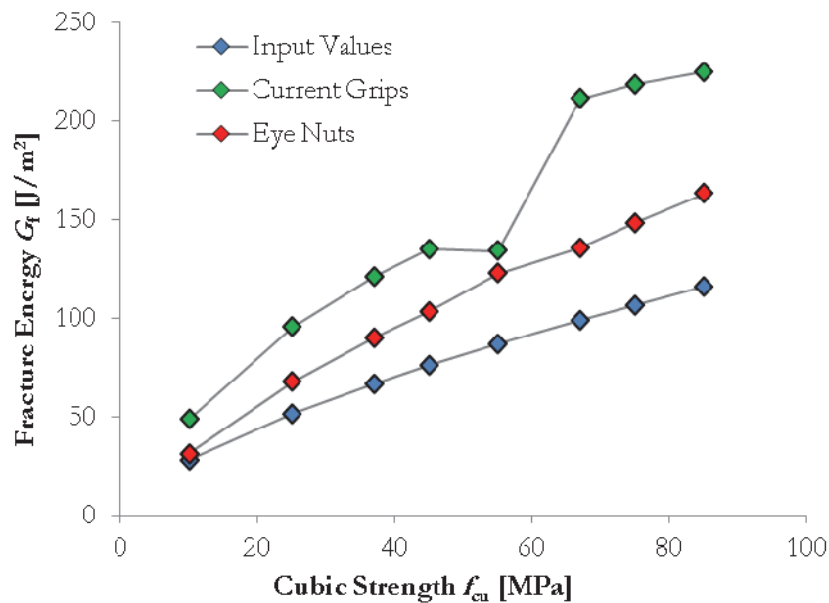

Figure 7: Fracture energy – input values and those obtained from numerical results.
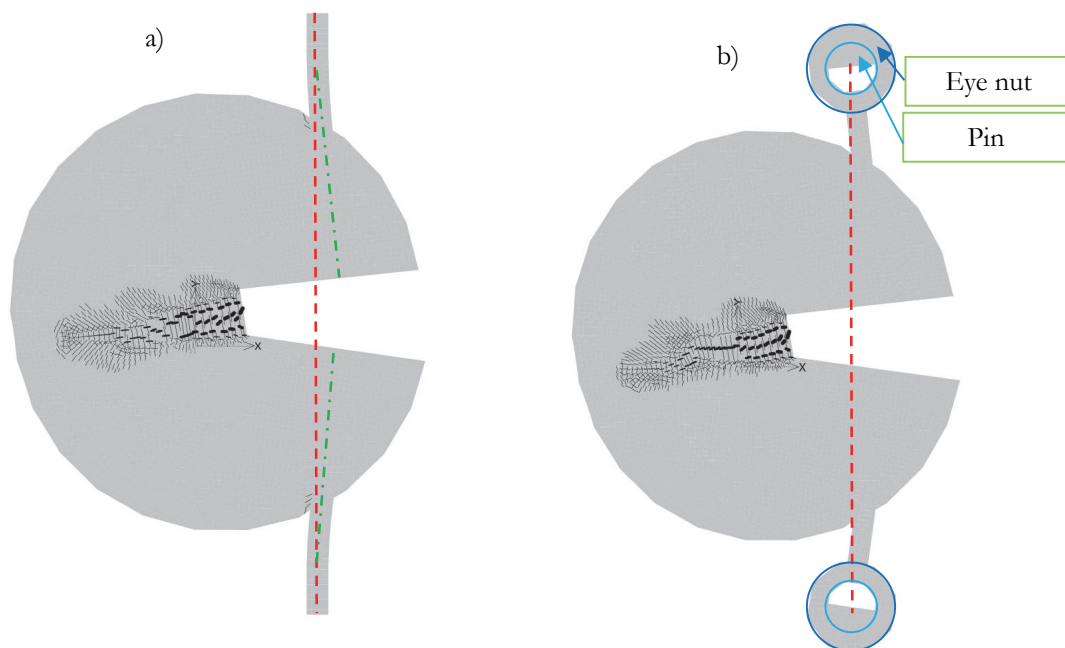

Figure 8: Results of MCT numerical models with cracks – deformed models magnified 200 times.

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