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NUMERICAL STUDY OF FAILURE OF CEMENTITIOUS COMPOSITE SPECIMENS IN MODIFIED COMPACT TENSION FRACTURE TEST

Abstract

The paper introduces a numerical analysis of failure process in specimens loaded in modified Compact Tension (CT) test configuration which are intended to be used for estimation of fracture parameters of quasi-brittle cement-based materials, including the extent of the fracture process zone. Specimen set (consisting of three sizes), designated to future testing in lab by X-ray imaging, was modelled in ATENA 2D finite element method software. Several variants of the tensile load eccentricity, the way of the load application and the initial crack length were considered in order to optimize the range of demanding experiments.

Keywords

Compact tension test, quasi-brittle fracture, fracture process zone, numerical simulation, cohesive crack model.

1 INTRODUCTION

Values of fracture parameters – acting as inputs in the models for description of the fracture behaviour of materials – determined from the records of fracture tests by nowadays available and recommended methods are dependent not only on the size and shape (even in small details, e.g. [1,2]) of the test specimen, but also on the boundary conditions during the tests. Especially in the field of quasi-brittle fracture, it is spoken about the size effect, the influence of geometry (shape effect) and the effect of free surfaces (boundary effect) on the values of calculated fracture parameters in this context [3,4].

To eliminate (or to recognize) these effects from the results of loading tests one should take the material failure propagation and distribution in the so-called fracture process zone (FPZ) into account The extent of this zone is related to the stress state, determined by the boundary conditions and the shape of the body – the level of constraint of stress and deformation around the propagating crack differs with different test specimen shape and different loading. How and to which extent this phenomenon can be used for determination of the real values of fracture characteristics of quasi-brittle materials is the subject of performed research, part of which is presented here.

In this paper, the authors propose a modification of the Compact Tension (CT) test for its use in the case of quasi-brittle material testing. Variations of eccentricity tensile forces cause significant changes in the stress distribution in the tested specimens (and thus the constraint of stress and deformation near the crack tip). A series of these modified specimens is currently under preparation for testing in the laboratory using radiography (via methods introduced e.g. in [5,6]). Due to limited

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possibilities of the experimental equipment that will be used for such testing it is necessary to use specimens of (relatively) very small dimensions (in relation to conventional dimensions of specimens made of cementitious composites that are determined by the size of aggregates).

2 NUMERICAL STUDY

Three sizes of specimens (marked as L, M and S – large, medium and small) were selected for the conducted experiment to study the above-mentioned influences (size, shape, boundary effects). Moreover, different eccentricities of tensile load (marked as A to C, see below) were considered to achieve different levels of constraint. One of the tasks of the numerical study was the investigation and optimization of the tensile load application on the specimen, which (due to the low tensile strength of the studied cementitious composites) causes complications during conducting of the tests – there were considered different variants of loading platens and their connection with the test specimen, as well as slight modifications in the specimen shape; then, the response of the specimen was observed in dependence on the length of the notch (simulating initial crack).

2.1 Considered variants of modCT test configuration

Regular CT test (see the schema in Fig. 1 left) consists in splitting of the compact body by the eccentrically imposed tensile force. It is frequently used for testing of metallic materials (steel, aluminium, etc. – i.e. materials with relatively high tensile strength in comparison to cementitious composites). Points of the tensile load application are placed into openings in the specimen, namely into the drilled holes; the load is imposed through pins inserted into these openings. However, several problems come out in the case of quasi-brittle materials. And this is both with the creation of the openings (for input of the load device pins) and then with the actual loading of the specimens. It has been found that damage occurs in the specimen in the contact of the opening and the pin imposing the load during numerical simulations of the CT specimen (from quasi-brittle material) (Fig. 1 right). Such behaviour during the real experiment would cause whole result completely unexploitable.

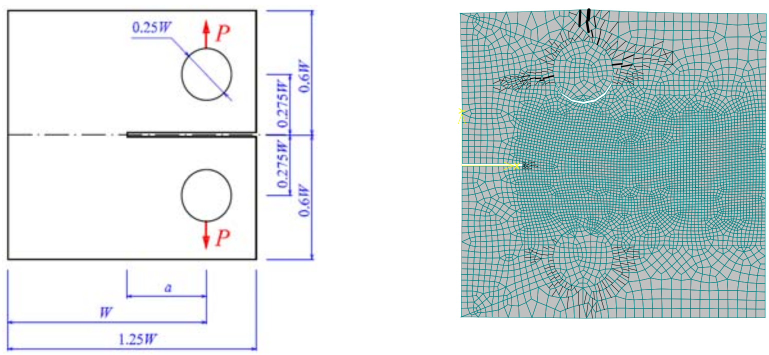

Fig. 1: Schema of the classical CT geometry (left), an example of the simulated fracture in the quasi-brittle specimen (variant with no platens, direct contact of the pin and the specimen) (right)

From this reason alternative ways how to apply the tensile load to reach failure initiated exclusively from the notch were sought. Considered configurations of modified CT test – differing in the way of the tensile load application with assistance or directly through metal platens (made from steel; concerning radiography techniques it is preferable to use a suitable lighter material that does not cause shading and reflection of X-rays, e.g. duralumin or carbon fibre composites) – are summarized in the following figures.

Fig. 2 shows the configuration where the upper and bottom side of the specimen (those which are perpendicular to the tensile force direction) are stiffened by platens preventing the above-described failure; the way of imposing the load through the openings in the specimen is kept without changes.

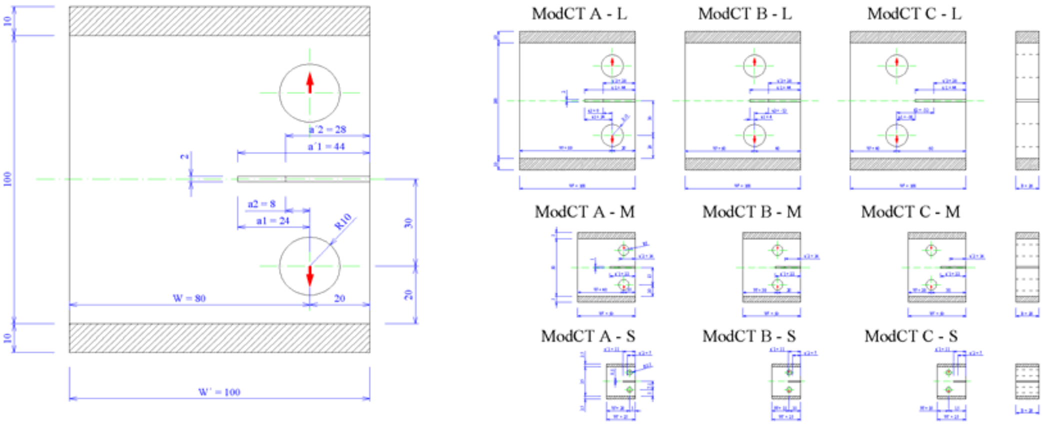

Fig. 2: Example of one of the considered variants of modCT specimens: geometry of the test specimen with platens (left), the complete specimens set (L, M and S) with different eccentricities (A, B and C) (right)

Fig. 3 depicts a variant where the platen is set into the specimen during its preparation. The opening for the loading pin is already created in the platen to avoid any further arrangements of the specimen after its removal from the mould. The adhesion of the cementitious specimen and the platen is supported by inserting of the reinforcing bars/bolts. A narrowing (cutting off – the dog-bone shape) of the specimen is performed in the area of the ligament to increase the stress concentration aiding more reliable crack initiation from the notch tip.

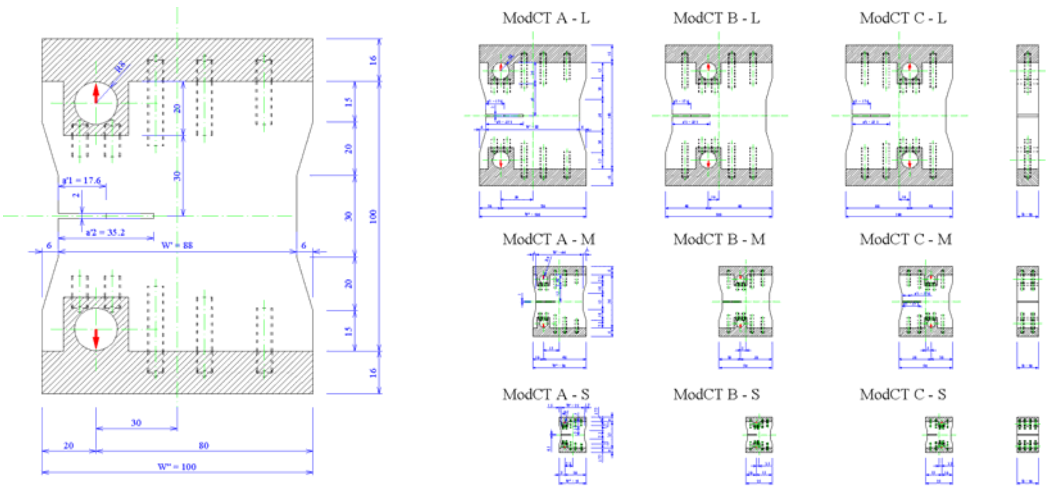

Fig. 3: Configuration with dog-bone specimen shape and platens connected with the specimens by the reinforcing bolts (dashed) (left), complete specimens set (right)

The configuration shown in Fig. 4 combines two previous variants. Differences are in fixation of loading platens, which are intended to be glued (perfect contact of the body and the platen is expected). A slight difference is also in the smooth curve of the dog-bone shape. In the mentioned figure, the inner space of the loading device (designated for radiography) is indicated – it is clear that for the largest specimen with the greatest eccentricity of the tensile force (configuration A – L) some adjustment of the loading device will be necessary to design.

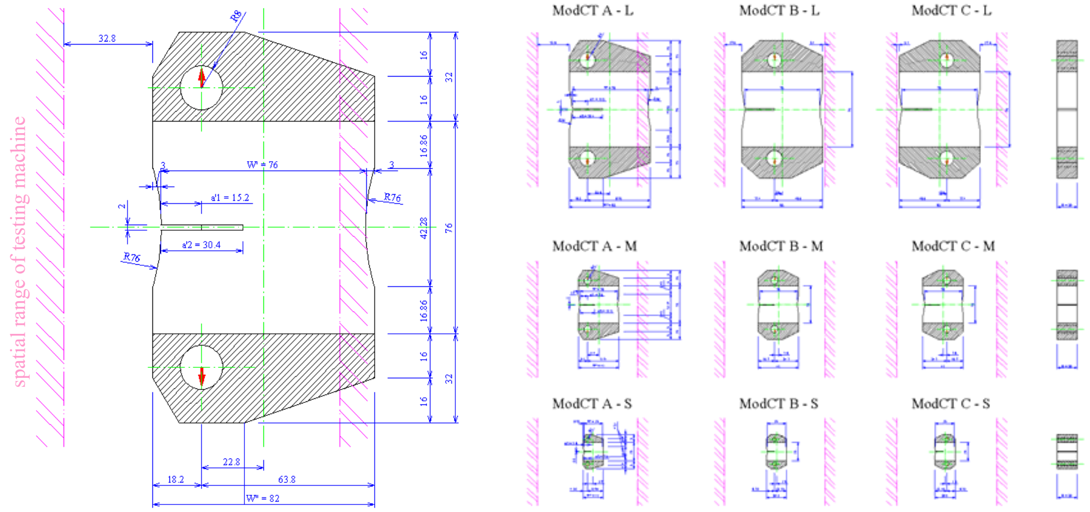

Fig. 4: Configuration with glued platens and smooth curve dog-bone shaped specimen; spatial limits of the chamber of the testing machine are indicated (left), complete specimens set (right)

2.2 Position of applied load, initial crack length

Variants in position of the applied tensile load and the notch length were considered to achieve differences in the FPZ properties. Previous figures show three sizes of considered specimens, including the position of the load. Letter A in a name of the variants indicates that a tensile load is applied closest to the edge of the modified CT specimen in which a notch is formed (eccentricity of tensile force is $0.3W'$ – W' is the specimen width in the narrower section, see the figures on the left); B represents the load which resultant is closer to the axis of symmetry of the specimen from the notch side (eccentricity of $0.1W'$); and finally, in the C case, the load resultant follows immediately after the symmetry axis (eccentricity of $-0.1W'$). The notch length (initial crack) a was chosen at values of the ratio of $a/W' \in \langle 0,1;0,6 \rangle$.

2.3 Numerical tool

Numerical models were created in ATENA 2D [7] software allowing nonlinear analysis of damage of structures by cracks; the crack formation and propagation during the loading process. It consists of nonlinear material models (plasticity, damage, fracture) to simulate the real behaviour of cement-based composites. The fracture-plastic model for concrete used in the simulations combines constitutive models for failure in both tension (fracture) and compression (plasticity). The fracture model is based on the classical orthotropic smeared crack formulation with implementation of crack band model (cohesive crack model). Includes Rankine failure criterion, exponential softening and can be used with a model of the rotating or fixed crack (or their combination). The plasticity model with softening/hardening is based on Menétrey-William failure surface.

Fracture-plastic material model (referred to as *3D Nonlinear Cementitious 2* in the software) was used for cementitious composites described above with the parameters kept at their default values (generated by program from cube strength f_{cu} = 40 MPa). Material of loading platens and pins was modelled as the elastic isotropic one with parameters of values usual for steel. The problem was modelled in 2D under plane strain conditions.

Examples of finite element mesh are shown in Fig. 5 for the selected numerical models of the considered variants.

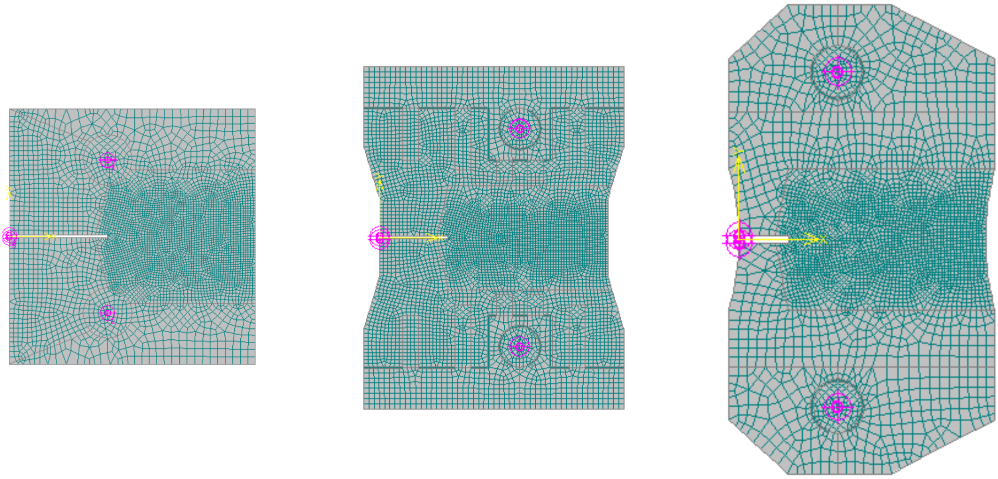

Fig. 5: Numerical models of chosen variants of the modCT specimens (see sketches in Fig. 2 to 4)

Progression of the test was simulated by increase of the mutual displacement of the loading pins (lower fixed, upper traversable); apart from this parameter also the reaction due to the displacement increase mentioned above and the crack mouth opening displacement were monitored (monitoring points are shown in Fig. 5). Nonlinear calculation was led by the Newton-Raphson method.

3 RESULTS, DISCUSION

Fig. 6 shows examples of failure extent simulated in the ATENA 2D software for selected variants differing in the load application. The variant on the left includes a simple platen (see Fig. 2), the crack pattern in the finite element mesh is shown for a model with the a/W' ratio equal to 0.2. It is obvious that the fracture propagates not only from the notch tip; this trend is especially pronounced in the cases of short notches (failure initiates and propagates from the contact point of the specimen and the loading pin). In Fig. 6 middle, there is shown one of the considered modifications of this variant, which is focused on the reinforcement of the specimen body in the vicinity of the openings for the loading pins, namely the variant with radial reinforcement (including the tension stress value in it). Various modifications of radial and tangential reinforcement by steel wires or by inserted sleeves (including radially welded bolts) were considered in the simulations. These variants haven't been further developed due to lack of functionality or/and expected large production demandingness. The crack pattern for variant with platens and coupling bolts (see Fig. 3) for $a/W' = 0.3$ is shown in Fig. 6 right; required crack propagation along the entire width of the specimen without (substantial) parasitic damage in other areas of the specimen is observed.

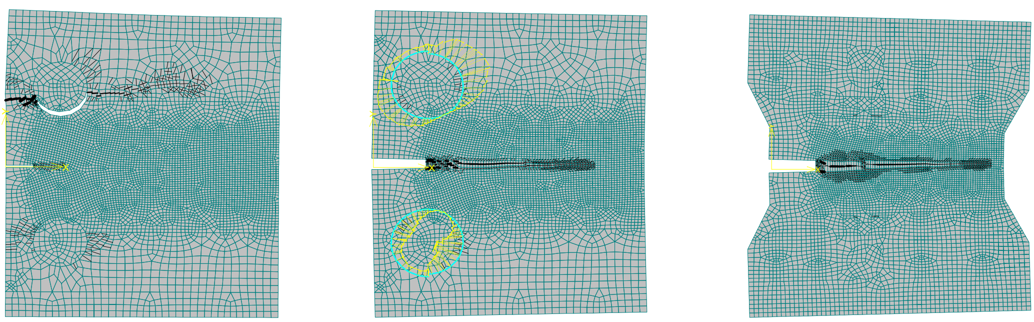

Fig. 6: Display of crack pattern, deformed shape and FE mesh for chosen variants of models

Differences in the extent and location of fracturing in the specimens are shown in subsequent series of figures (Figs. 7–9) for each considered variant of geometry, relative notch length (of values ranging from 0.1 to 0.4) and loading eccentricity. For Fig. 7 and 8, the displayed crack pattern corresponds to a stage at the peak of the loading diagram. Crack patterns from a stage near the end of the descending branch of the loading curve are displayed in Fig. 9 in addition to the peak load stages. It is clearly seen that the constraint is being reduced with the shift of the applied force resultant closer to the rear edge of the test specimen (i.e. with decrease of the tensile force eccentricity). The decrease in constraint is indicated by the increase in the width of the band of failure, thus enlarging the area (at least the width) of FPZ. "Inappropriate" variants (i.e. variants that are damaged outside the central area of the specimen, such as in the area around the loading pins and coupling bolts) are indicated by cross.

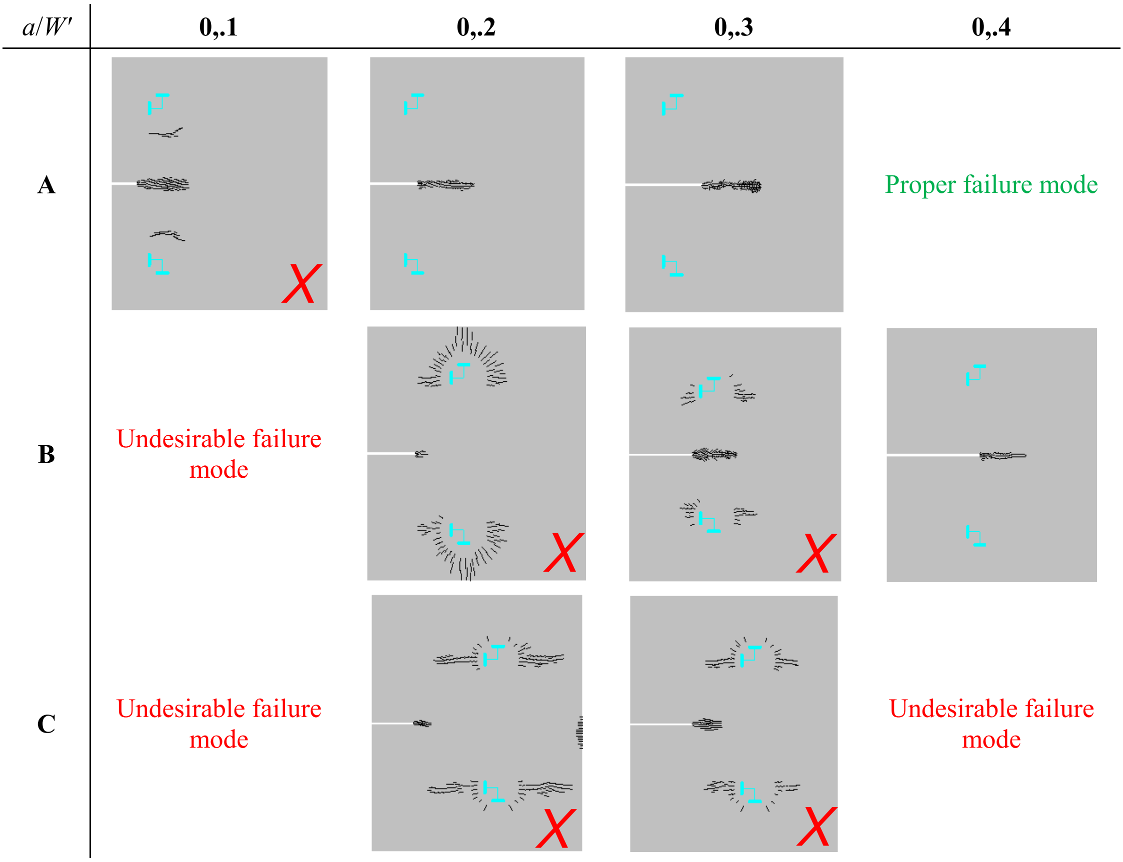

Fig. 7: Simulated fracture of variants from Fig. 2 for different notch lengths and loading position

4 CONCLUSION

For the purpose of the prepared experimental campaign it is necessary to select an economical and, at the same time, especially technically/technologically executable variant. From the preliminary evaluation of the results of the conducted study, the variant with the glued platens (typically using an epoxy glue), in which the openings for the loading pins are created, provided with cutting off on the side edges (see Fig. 4) appears to be the best option. Suitable test configuration will include specimens of sizes in a ratio of 4 : 2 : 1 (widths $W' = \{76, 38, 19\}$ mm), with the relative crack lengths $a/W' = \{0.2; 0.3; 0.4\}$ and eccentricity of the applied tensile force in variants A, B and C (except $a/W' = 0.2$ for the C variant). Detailed numerical study of the fracture test in this configuration for the whole set of specimen sizes and expected material parameters is before

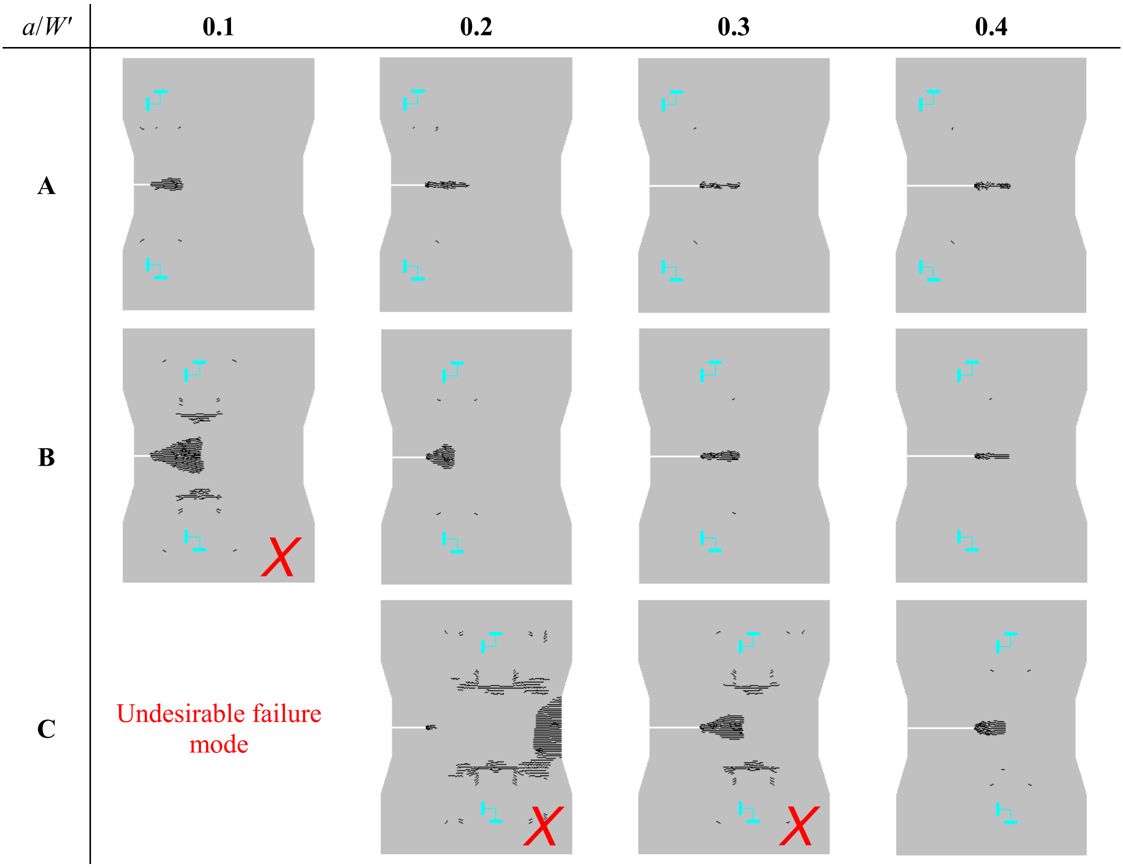

Fig. 8: Simulated fracture of variants from Fig. 3 with various notch lengths and loading position

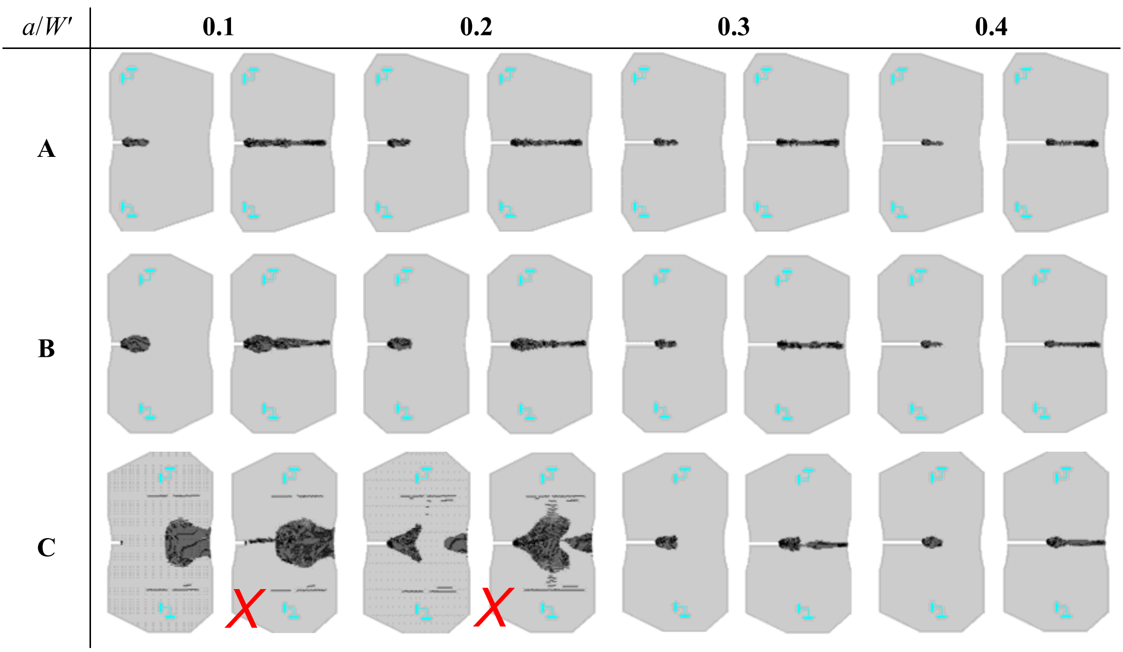

Fig. 9: Simulated fracture of variants from Fig. 4 with various notch lengths and loading position

completion, the results for L size are only presented here. Whether variants S and M behave similarly is being verified in subsequent studies. They are processed also with regard to the size effect and will be validated by the results of real experiments of the manufactured specimens.

Fig. 10 shows already finished moulds for casting of test specimens. It is planned that the modified CT specimens are accompanied by the traditional three-point bending of notched beams.

Fig. 10: Moulds designated for modCT specimens casting (accompanied with the three-point bending specimens moulds) *(photo © Keršner 2013*)

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