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DETERMINATION OF STRESS INTENSITY FACTOR VALUE FOR CHEVRON-NOTCHED SPECIMENS – PILOT STUDY

Abstract

The description of material behavior is one of important information for its application in civil engineering. One area is covering fracture mechanical properties. For evaluation of the fracture toughness values, the knowledge of calibration curve is important. The paper is aimed on the numerical modelling of the test specimens with a chevron notch serving as an initiator of the stress distribution at the crack tip. The three-point bending test configuration with a chevron notch is used for the simulation given by plane model with different layer width of cross section part and output is given by the value of the stress intensity factor K_I for tension loading mode.

Keywords

Chevron notch, fracture test, stress intensity factor, three-point bending.

1 INTRODUCTION

Three-point bending (3PB [1]) destructive testing of quasi-brittle materials is established procedure of testing various building structures (and its parts). Fracture tests are upgraded by adding the so-called stress concentrators – initial notches, usually made in the horizontal direction at the bottom part of the normalized test specimen, which can be taken from the construction in the form of core drill. Originally, for the ductile materials, the initial notch in the form of chevron (V-shape) notch was designed (since 1964 [2,3,4]). It allows crack propagation to be directly in the central plane direction of the test specimen because the crack initiates from the sharp edge of the chevron notch (see Fig.1 and 2). This type of initial notch can be used both for oval shape and rectangular/cube

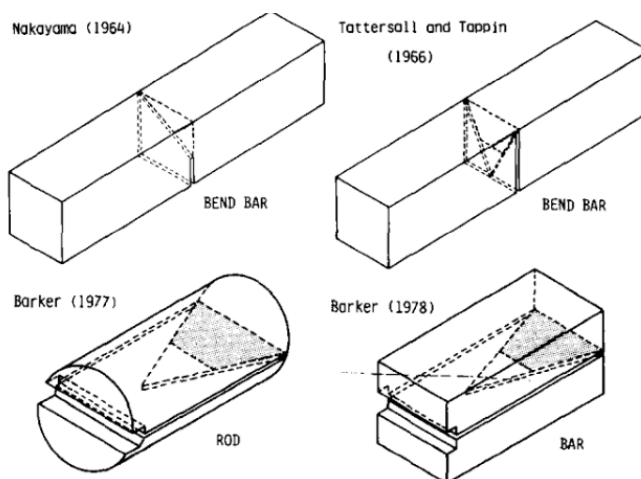


Fig. 1: Various configurations of a chevron notch usage on different types of test specimens, adopted from [3]

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shape test specimens. Later applications on rock materials made it to be suitable instrument for evaluation of fracture toughness K_{IC} [5,6]. The International Society for Rock Mechanics (ISRM) has proposed suggested method for testing rock fracture toughness K_{IC} using a core-based specimen with a chevron notch [7,8,9]. The pilot experimental campaign performed on concrete 3PB oval specimens with chevron notch is published in [10].

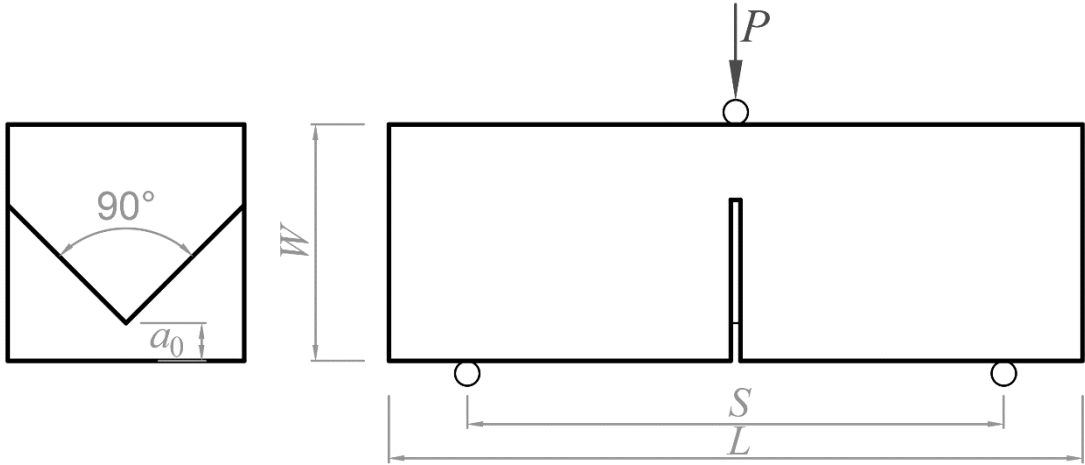


Fig. 2: Geometry of the 3PB test specimen configuration with initial chevron notch

The aim of this paper is to introduce the pilot study about evaluation of the values of stress intensity factor (SIF, K [5,6]) for test specimens subjected to 3PB with an initial chevron notch. The plane numerical model is used within the calculation by finite element (FE) computational tool.

2 THEORETICAL BACKGROUND

Bending stress in uncracked specimens could be determined exactly by applying the simple beam theory from:

$$\sigma = \frac{3SP}{2BW^2} \quad (1)$$

In eq. (1) σ is nominal bending stress, B is breadth/thickness, W is width, P is a force and S is a span, a_0 represents initial crack length. The presented linear elastic fracture mechanics concept consists in the idea that the stress field in the close vicinity of the crack tip is described by means of the Williams expansion [11]. Originally, the infinite power series was derived for a homogenous elastic isotropic cracked body with an arbitrary remote loading, in the case of normal mode I loading condition, it can be written in the form:

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(n, \theta) + O_{ij}(\sqrt{r}, \theta), \quad (2)$$

where σ_{ij} represents the stress tensor components, K_I is the stress intensity factor and r, θ symbolize the polar coordinates (provided in the centre of the coordinate system at the crack tip, where crack faces lie on the negative x -axis).

For finite specimen the stress intensity factor could be expressed in the following form

$$K_I = \sigma \sqrt{\pi a} f(a/W), \quad (3)$$

where σ represents applied load given by eq. (1), a represents the crack length and a/W represents the relative crack length. In case of chevron notch stress intensity factor could be influenced by missing portion of material.

3 NUMERICAL PROCEDURE

The pilot study was conducted by using FE software ANSYS [12]. The element type PLANE82 (8 nodes element) was used to consider the stress singularity at the crack tip (with the option KSCON [12,13,14]). The basic dimension for numerical model was created according the 3PB geometry with initial chevron notch geometry (see Fig. 2). The specimen's dimensions: length $L = 220$ mm, span of supports $S = 170$ mm, breadth $B = 75$ mm, width $W = 75$ mm, $S/W = 2.27$, initial crack length $a_0 = 12$ mm, $a_0/W = 0.16$, the angle of chevron notch is 90° [10]. Cross section area of the rectangular shape profile was formed by 75 mm sides.

Only the symmetrical half of the specimen's body was used with the plane stress condition [15] – the reason was the simulation of non-uniform thickness of the notch layer along the height of the cross section. Figs. 3 and 4 show the individual layers (in total amount of 11 layers) with the different real characteristic in FE code simulating thickness of the layer (forming the characteristic V-shape).

Material properties were used as: for quasi-brittle material (concrete, indicated by green color in Fig. 4) the Young's modulus is $E = 35$ GPa, Poisson's ratio is $\nu = 0.2$. For the ductile part (steel platen for load distribution, indicated by purple color / dark region on the top of specimen in Fig. 4) are the values given by $E_s = 210$ GPa and $\nu = 0.3$, respectively. The value of load is $P = 1000$ N.

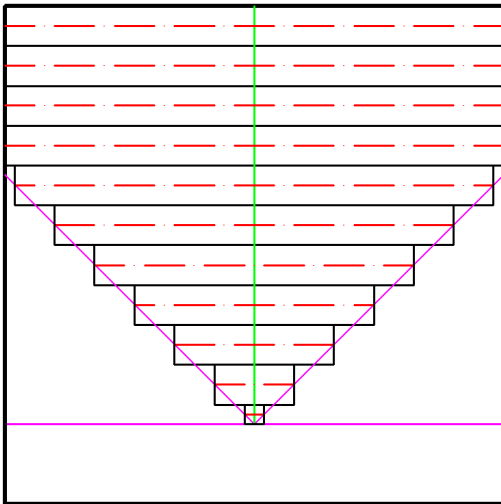


Fig. 3: Area division in cross section part – with diameter of each single layer (horizontal dashed line)

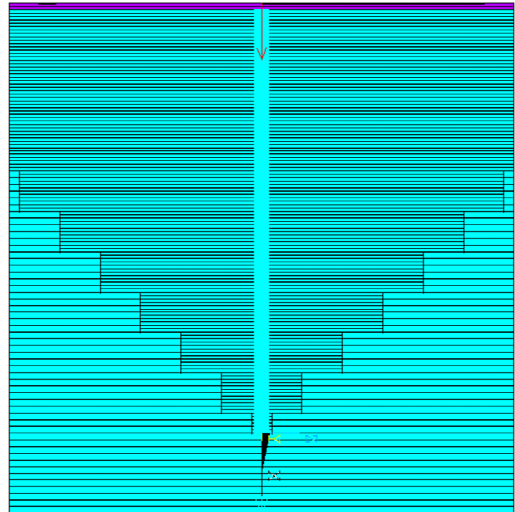


Fig. 4: Area division in cross section part – numerical model in ANSYS sw., including boundary conditions

Details of numerical modeling are displayed in the following figures. Fig. 5 represents central plane of numerical model – with the indication of areas before the assigning of the real characteristics (thicknesses of the layers). The crack-tip mesh is presented in Fig. 6 which shows the same central plane like in previous figure, but with the finite mesh (the real characteristics are assigned). The homogeneous part of the test specimen (numerical model) is represented by keeping the degrees of freedom of related nodes to be fixed. That is also way how the supports were simulated (symmetrical).

Whole model including thicknesses of all layers is displayed in Fig. 7 – axonometric. This model has almost 14 000 finite elements.

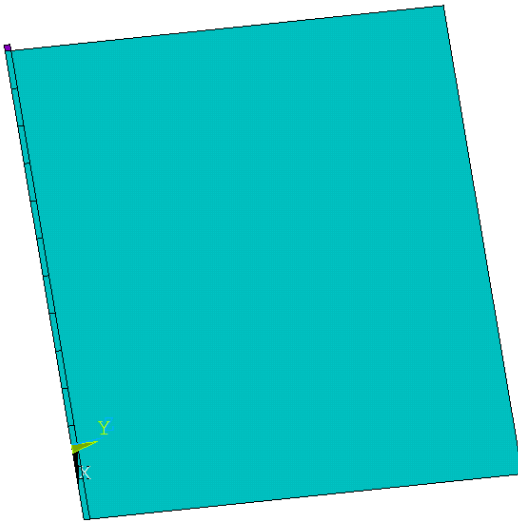


Fig. 5: Centerline area of numerical model – division of the areas (for different thickness of layers)

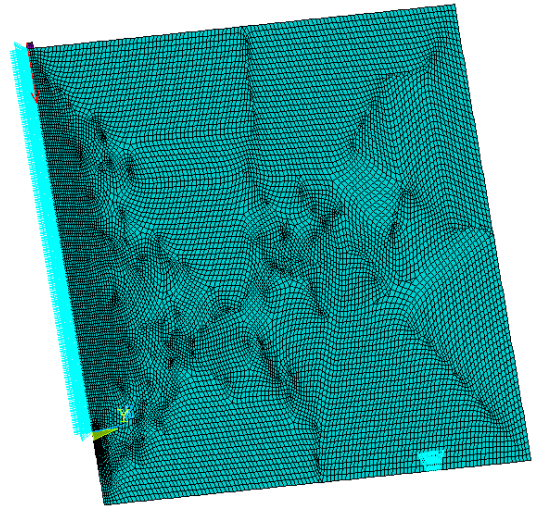


Fig. 6: Centerline area of numerical model – finite element division with boundary conditions

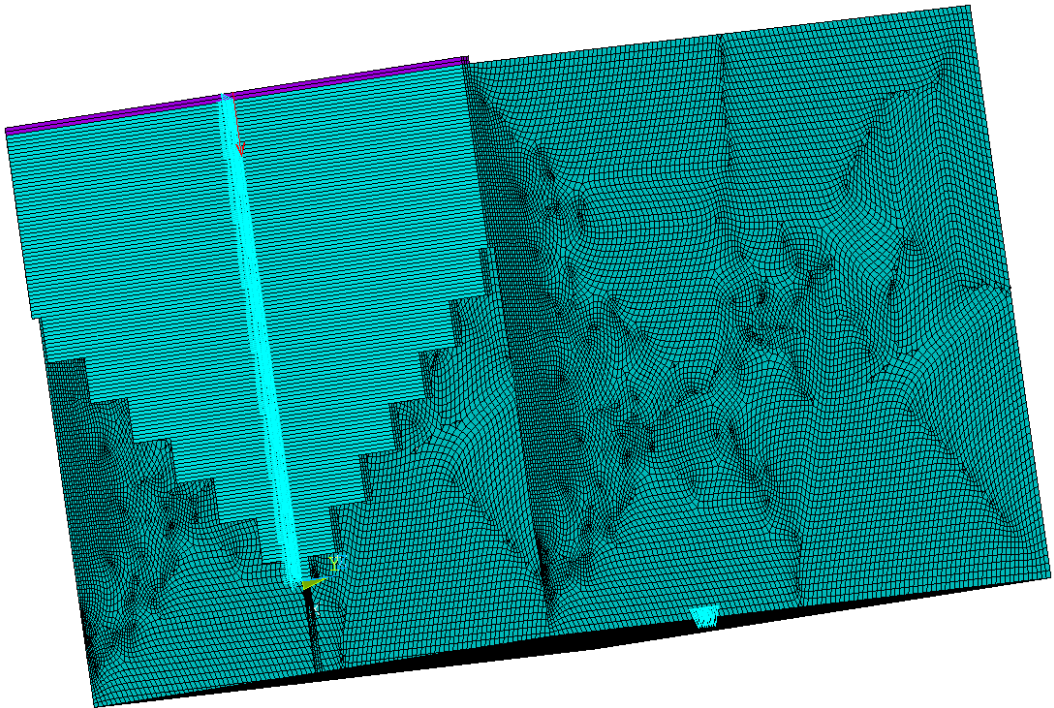


Fig. 7: Whole numerical model in ANSYS system (axonometric), including boundary conditions

Fig. 8 shows detail of the crack tip (red mark) in the plane problem. KSCON option was used to create the nodal ring around it. Fig. 9 shows the same situation but with the option to see the thicknesses of the layers – simplified 3D model (axonometric). But this issue is not relevant for the calculation itself. That is why the red arrow is displayed in many levels of thicknesses.

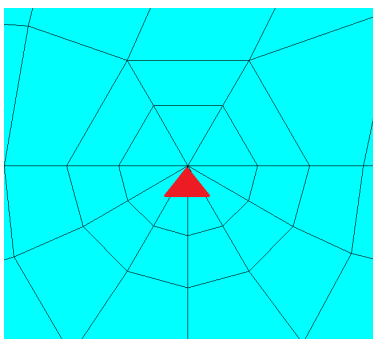


Fig. 8: Detail around the crack tip (red mark), plane view

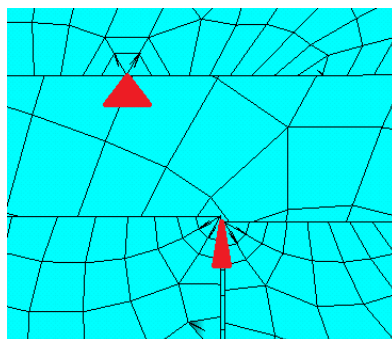


Fig. 9: Detail around the crack tip (red mark), axonometric view of each single layer – wide mark represents top part, thin is for bottom part

4 DISCUSSIONS OF RESULTS

Functionality of the numerical model was performed by linear calculation. The value of the stress intensity factor for tensile loading mode $K_I = 14.158 \text{ kPa}\cdot\text{m}^{1/2}$ was obtained by the tool KCALC (included in ANSYS FE software.) which uses the extrapolation of nodes' displacements around the crack tip. Its value is not so informative because usually it is accompanied with function of relative crack length (α) or normed into K_{IC} –fracture toughness; but it shows that the implementation of chevron notch into 2D (plane problem) was successful. For example, the 3PB configuration with regular initial notch (same relative crack length) is in the proper order of the magnitude [16,17]. Thickness of the “zero” layer (related to the empty space – initial notch, initial crack length) must be set by non-zero value (e.g. 10^{-10} m). Zero value inputted means that the calculation cannot be carried out. Dependence of the low value of the thickness on the value of K_I was investigated – ANSYS system keeps it by itself.

5 CONCLUSION

Successful implementation of the chevron initial notch of test specimens was shown. This pilot study opens new possibilities how to use chevron notch in fracture analysis (determination of the fracture parameters) to avoid the usage of 3D numerical model (where is necessity to use different ways how to obtain K values). Further analysis can provide possibilities of different geometries of chevron notch specimens like dependence of variable number of layers used, width and height of the initial crack (the different angle of V-notch); oval-shape specimens, etc. Last step should be modelling in 3D and comparison with experimental obtained data, see e.g. [18,19]. Application of multi-parameter elastic fracture mechanics [5,13,15] will provide determination of dimensionless shape functions for specimens with initial chevron notch for all configurations.

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LITERATURE

- [1] RILEM Technical Committee 50-FMC. Determination of the fracture energy of mortar and concrete by means of three-point bend test on notched beams. *Materials and Structures*. 1985, Vol. 18, Issue. 4, pp. 285–290.
- [2] NAKAYAMA, J. A Bending Method for Direct Measurement of Fracture Energy of Brittle Material. *Japan Journal of Applied Physics*. 1964, Vol. 3, pp. 422–423.

- [3] UNDERWOOD, J. H., FREIMAN, S. W. & BARATTA F. I. *Chevron-notched Specimens, Testing and Stress Analysis: A Symposium*. Baltimore, 1984. ISBN 0-8031-0401-4.
- [4] NEWMAN, Jr., J. C. *NASA TM-85797: A review of chevron-notched fracture specimens*. NASA Langley Research Center Hampton, 1984, 53 p.
- [5] ANDERSON, T. L. *Fracture mechanics. Fundamentals and Applications*. Boca Raton: CRC Press, 2005.
- [6] BAŽANT, Z. P. & PLANAS J. *Fracture and size effect in concrete and other quasi-brittle materials*. Boca Raton: CRC Press, 1998.
- [7] ISRM. Suggested methods for determining mode I fracture toughness using cracked chevron notched Brazilian disk (CCNBD) specimens, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, 1995, Nr. 32, pp. 57–64.
- [8] WEI, M-D., DAI, F., XU, N-W. & ZHAO T. Stress intensity factors and fracture process zones of ISRM-suggested chevron notched specimens for mode I fracture toughness testing of rocks. *Engineering Fracture Mechanics*. 2016, Vol. 168, pp. 174–189.
- [9] YUWEI CUI, F. & VINCI R. P. A chevron-notched bowtie micro-beam bend test for fracture toughness measurement of brittle materials. *Scripta Materialia*. 2017, Vol. 132, pp. 53–57.
- [10] ŠIMONOVÁ, H., DANĚK, P., FRANTÍK, P., KERŠNER, Z., & VESELÝ V. Tentative Characterization of Old Structural Concrete through Mechanical Fracture Parameters. *Procedia Engineering*. 2017 (in press).
- [11] WILLIAMS, M. L. On the stress distribution at the base of a stationary crack. *ASME J Appl Mech*. 1957, Nr. 24, pp. 109–114.
- [12] *ANSYS Documentation. Version 11.0.*, Swanson Analysis System, Inc., Houston, Pennsylvania, 2007.
- [13] SOBEK, J. Shape functions analysis of cracked specimens: plane problem variants. *Transaction of the VŠB-Technical University of Ostrava, Civil Engineering Series*. Vol. XIV, Issue 1., 2014, pp. 159–164. ISSN 1213-1962. 2014.
- [14] SEITL, S., VESELÝ, V. & ŘOUTIL L. Analysis of influence of cylindrical specimens proportions on fracture parameters from wedge splitting test. *Transaction of the VŠB-Technical University of Ostrava, Civil Engineering Series*. Vol. XI, Issue 1, pp. 299–308. ISSN 1213-1962. 2011.
- [15] SOBEK, J., VESELÝ, V. & ŠESTÁKOVÁ L. Accuracy of approximation of stress and displacement fields in cracked body for estimation of failure zone extent. *Transactions of the VŠB – Technical University of Ostrava: Construction Series*. Vol. 12, Issue 2, pp. 170–179 (10 p). ISSN 1804-4824 (Online); ISSN 1213-1962 (Print).
- [16] GUINEA, G. V., PASTOR, J. Y., PLANAS, J. & ELICES M. Stress intensity factor, compliance and CMOD for a general three-point-bend beam. *International Journal of Fracture*. 1998, Vol. 89, pp. 103–116.
- [17] KARIHALOO, B. L. & XIAO Q. Z. Higher order terms of the crack tip asymptotic field for a notched three-point bend beam. *International Journal of Fracture*. 2001, Vol. 112, pp. 111–128.
- [18] SOBEK, J., GONZÁLEZ MENÉNDEZ, S. & SEITL S. Numerical modelling of a chevron notched bend specimen – plane model. *Key Engineering Materials*. 2017, Vol. 754, pp. 198–201. ISSN:1667-9795. DOI: 10.4028/www.scientific.net/KEM.754.198.
- [19] SEITL, S., MIARKA, P., SOBEK, J. & KLUSÁK J. A numerical investigation of the stress intensity factor for a bent chevron notched specimen: Comparison of 2D and 3D solutions. *Procedia Structural Integrity*. 2017, Vol. 5, pp. 737–744, ISSN: 2452-3216. DOI: <https://doi.org/10.1016/j.prostr.2017.07.164>.