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LOCALIZATION OF PROPAGATION OF FAILURE IN CONCRETE SPECIMENS ASSESSED BY MEANS OF ACOUSTIC AND ELECTROMAGNETIC EMISSION AND NUMERICAL SIMULATIONS

LOKALIZACE PRŮBĚHU PORUŠOVÁNÍ V BETONOVÝCH VZORCÍCH STANOVENÁ POMOCÍ AKUSTICKÉ A ELEKTROMAGNETICKÉ EMISE A NUMERICKÝCH SIMULACÍ

Abstract

This paper presents a numerical analysis aimed at verification of the monitoring of failure – its propagation and the locations of the individual failure events – in quasi-brittle cement-based materials. The failure monitoring methodology in question is performed using a technique based on utilization of (a combination of) acoustic emission (AE) and electromagnetic emission (EME) phenomena. The analysis is conducted on concrete laboratory specimens and aims to reveal the type and intensity of failure which can be captured by this experimental technique. The computational tools ATENA and FyDiK are employed in the numerical analysis, the first being based on continuum mechanics with an implemented cohesive crack model while the second utilizes the physical discretization of continuum, again with a material model that takes account of the cohesive nature of quasi-brittle fracture.

Keywords

Cementitious composites, quasi-brittle failure, acoustic emission, electromagnetic emission, numerical simulation, cohesive crack model, physical discretization of continuum.

Abstrakt

V článku jsou prezentovány výsledky numerické analýzy zaměřené na verifikaci záznamu průběhu porušování – jeho postup a lokalizaci jednotlivých událostí – odehrávajícího se ve kvazikřehkých materiálech na bázi cementu. Experimentální metodika pro sledování porušení, která je zde zkoumána a verifikována, vychází z (kombinace) akustické a elektromagnetické emise (AE, resp. EME). Analýza je prováděna na zkušebních tělesech z betonu s cílem odhalit typ a intenzitu porušení, jež je schopna použitá technika zachytit. Pro zde prezentovanou numerickou analýzu jsou použity výpočetní nástroje ATENA, resp. FyDiK, založené na mechanice kontinua se zahrnutím modelu kohezivní trhliny, resp. na metodě fyzikální diskretizace kontinua, rovněž využívající materiálový model zohledňující kohezivní povahu kvazikřehkého lomu.

Klíčová slova

Cementové kompozity, kvazikřehké porušení, akustická emise, elektromagnetická emise, numerické simulace, model kohezivní trhliny, fyzikální diskretizace kontinua.

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1 INTRODUCTION

The initiation and propagation of failure in solids can be detected by means of acoustic and electromagnetic phenomena (for materials in the building industry see e.g. [8], [14], [23]). These phenomena are referred to as acoustic/electromagnetic emission (AE/EME). The development of a methodology for crack initiation and propagation monitoring and evaluation can be conveniently assisted by the use of computational tools enabling the simulation of the progress of material failures. This paper is devoted to simulations of tensile failure in selected building materials, particularly cementitious composites, during fracture tests. The majority of attention is focused on the investigation of the distribution of failure events and the corresponding energy dissipation over the test specimen volume, which results in (not only) acoustic and electromagnetic emission in the case of cementitious composites. Use is made of computational tools based on the finite element method (FEM) with implementation of the cohesive crack model (ATENA commercial software [3]), or based on the physical discretization of continuum (the FyDiK program [5], this being the authors' own lattice/particle model formulated as a nonlinear dynamical system).

2 NUMERICAL SIMULATIONS

2.1 Modelling via the finite element method: ATENA software

Previous works by the present authors that deal with related issues report on numerical studies of the stress/deformations and progress of failure in specimens subjected to tests in selected configurations conducted using ATENA FEM software. The paper [19] was focused on the proper choice of the specimen shape and the test boundary conditions (for compressive loading in a testing machine) which would be suitable for research on the failure of quasi-brittle materials by means of EME (a combination of AE and EME, respectively). The study was performed as a plane problem; various material models for concrete were employed. Subsequent analyses by the authors [20], [11], [12] were conducted in the 3D version of the used software and were focused on two shapes of the test specimen (sets A and B, i.e. slender and thick specimens, respectively, see Fig. 1) and two load configurations (or geometries; I involved the plain compression of the specimen while configuration II featured compression through centrally situated slim steel prisms resulting in a stress state leading to the failure of the specimen due to lateral tension; see Fig. 1) selected from a previous study.

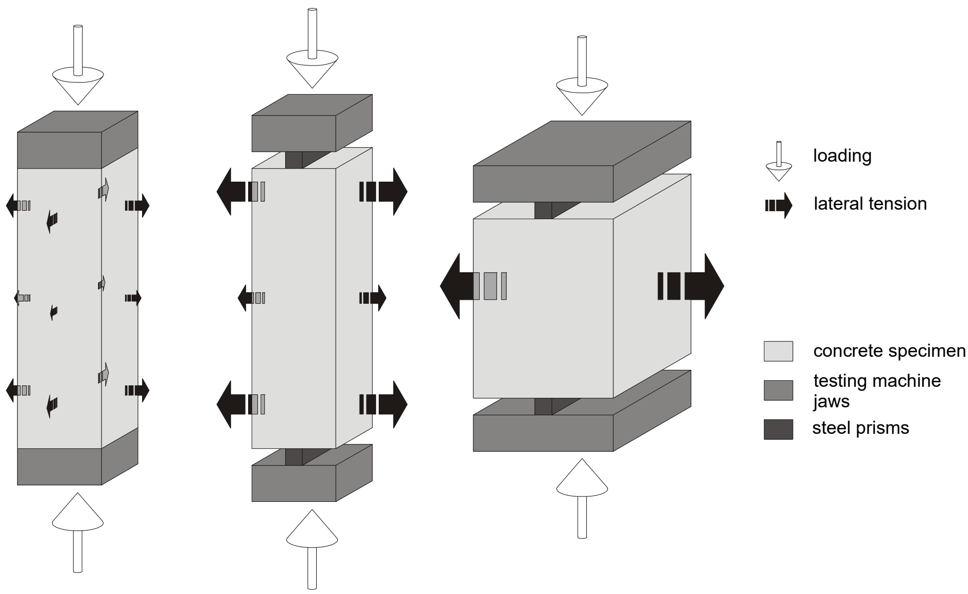


Fig. 1: Scheme of the test specimens (set A – left and middle, set B – right) in the considered loading configurations (configuration I – left, configuration II – middle and right) [12]

The conducted simulations verified the abilities of the computational tools to model the failure process in the specimens subjected to tests in the selected test geometries. In relation to the investigated experimental technique utilizing the AE and EME phenomena, a need for more detailed analysis of the characteristics of the simulated failure, e.g. the size (opening) and the orientation of the arising cracks or the corresponding inelastic strains, emerged. Based on the comparison of these characteristics with those of the AE/EME records it might appear possible to identify the abilities/sensitivity of the investigated experimental technique in the field of monitoring the failure of quasi-brittle materials in civil engineering (particularly with application to silicate composites and rocks).

Model

3D models from a previous study [12] were used for the above-described detailed analysis. A procedure was developed for this analysis and and its pilot simplified tests were performed on the corresponding 2D models. 3D versions of the models, including the FE mesh for tests AI, AII and BII (i.e. the specimen of shape A in loading geometry I, the same specimen in geometry II and finally the specimen of shape B in loading configuration II), are shown in Fig. 2.

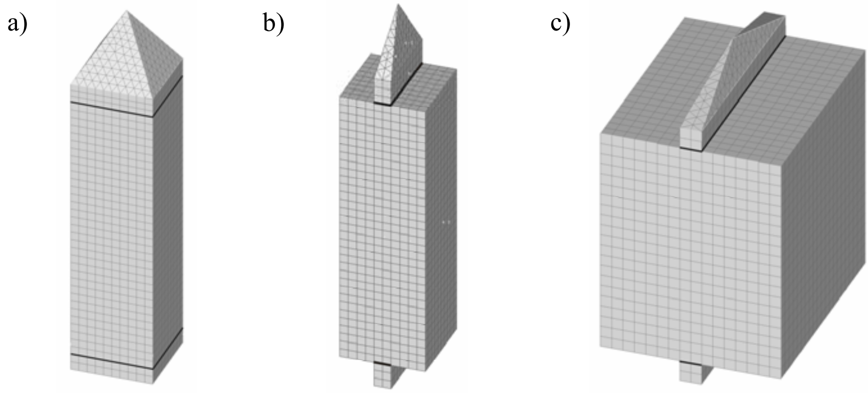


Fig. 2: 3D models of tests AI (a), AII (b) and BII (c), including a depiction of the loading fixtures determining the boundary conditions of the test

The modelled boundary conditions of the test are sketched out in Fig. 1; the bottom jaw of the testing machine was considered as stationary (all FE mesh nodes on the bottom side of the modelled steel pad were fixed); the upper jaw loaded the specimen (via steel platens or narrow steel prisms) by an increment of the vertical displacement. As is evident from Fig. 2, the displacement-controlled loading was applied in one point only, i.e. the vertex of the pyramid attached to either the loading platen or the prism in order to facilitate the monitoring of the loading force (i.e. the reaction against the displacement increment). The Young's modulus value assigned to the loading pyramid was set 3 orders of magnitude higher than for the loading platens or prisms.

Both the 2D and 3D models were created in several FE mesh density variants. The three-dimensional analyses were conducted with the fracture-plastic material model for concrete (3D Non-Linear Cementitious 2, see [3]); for the 2D pilot simulations the SBETA material model [3] was used as well. The parameters of the material models were set to values corresponding to concrete of a cubic compressive strength equal to 20 MPa, which was the strength of the material used for the specimens subjected to the experimental tests [10].

Results

For a comparison of the responses of the virtual tests – the results of the performed numerical simulations – with those of the real tests, loading curves are typically used, i.e. the dependences of loading force and introduced displacement (so-called *load–displacement*, or *P–d* diagrams). According to these diagrams, it is possible to distinguish several stages of specimen failure in quasi-brittle materials (structures): early linear behaviour; nonlinearity before reaching the maximal loading caused by formation and the coalescence of microcracks; peak load and the beginning of the descending branch of the diagram corresponding to the localization of failure; and the descending branch characteristic for the propagation/opening of formed macrocracks [1], [9], [15], [16].

Another important group of results is represented by the displaying (of the progress) of stress and deformations, and particularly the extent of failure. This is done with the help of a variety of parameters of different types (stress, deformation, energetic) that are offered by computational programs of the kind used. Here we restrict ourselves only to the presentation of selected examples of crack patterns at the stage at/after the reaching of maximal load (from 3D analysis) and their comparison with corresponding experimental results [10], [12].

For selected specimens of experimental sets AI, AII and BII, histograms of the frequency of emission event occurrence vs. the distance of such events from the acoustic sensor are shown in Fig. 5. It is apparent from this figure that there is an uneven and in principle inappropriately localized rupture for set AI and contrariwise a relatively narrow localized rupture for set BII (the histograms correspond very well to the representation of rupture in Fig. 3 in this respect – the rupture spread out over the volume for AI contrasts with the localized rupture in the central plane for BII).

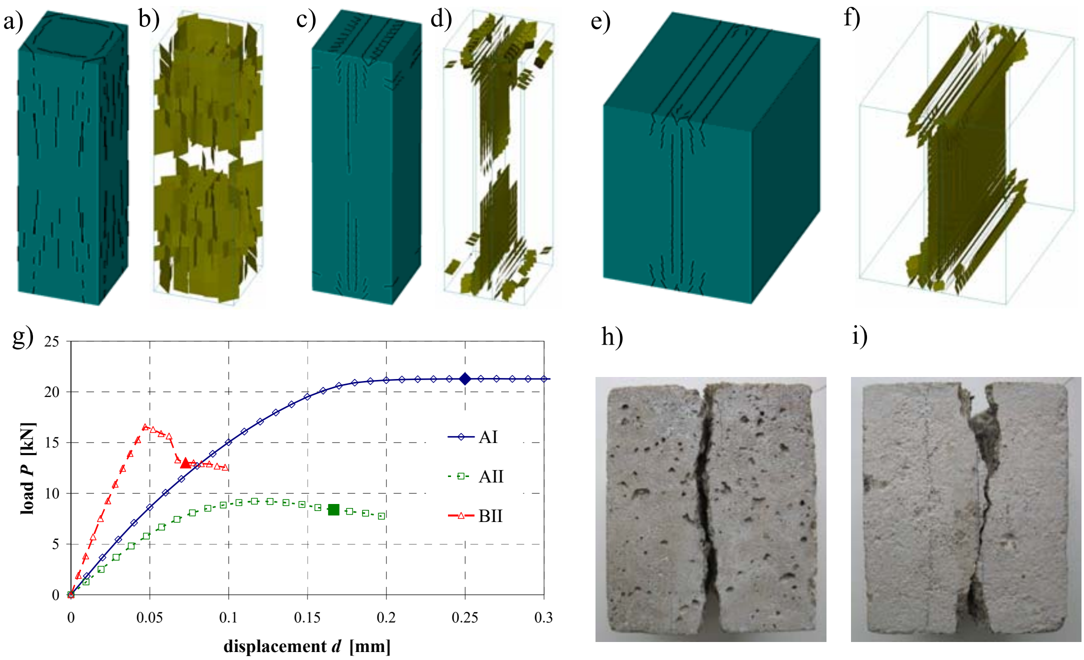


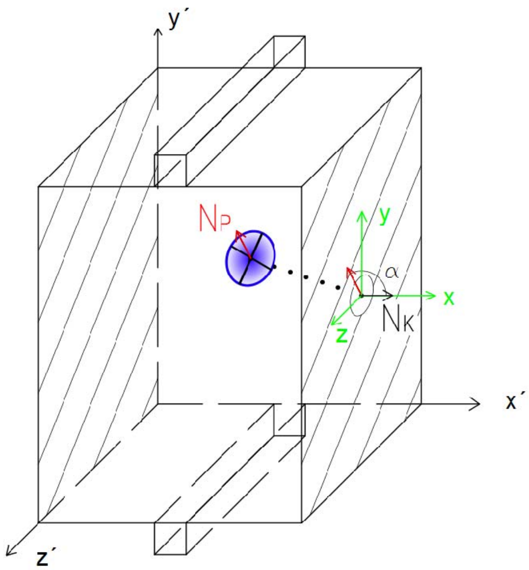
Fig. 3: Distribution of failure over the specimen volume predicted by the ATENA 3D software for tests AI (a, b) AII (c, d) and BII (e, f) – the surface crack pattern and the crack distribution within the specimen body are displayed; the corresponding simulated load–displacement diagrams (g); pictures of two failed specimens from the BII set (h, i)

Processing of simulation results, additional post-processing

As was mentioned above, the selected parameters of simulated failure were further processed for the purpose of e.g. ascertainment of the applicability limits of the experimental technique for the monitoring of quasi-brittle material/construction failure in the building industry, this monitoring being based on EME/AE, understanding and proper interpretation of recorded data, etc.

One of the goals was to process the simulation results into a form that allows their comparison with experimentally recorded histograms describing the frequency of the occurrence of events causing the EME/AE (the failure processes) depending on the distance from the acoustic probe placed on the specimen surface (Fig. 4). We note that for the experimental measurements, whose results were published in [10] and [12] and with which the conducted simulations should be in agreement, (only) a dual channel apparatus (1 channel for AE, one for EME) was used. The spatial failure distribution was thus, after projection into 1D, only examined via the abovementioned histograms. The main authors of papers [10] and [11] have recently developed and are testing a multi channel measuring apparatus (5 to 7 AE probes) that will be able to capture the failure distribution in 3D. The results of presently prepared experiments monitored with help of this apparatus are going to be analysed via the numerical simulations presented herein.

Supplementary post-processing was carried out by taking the text outputs of numerical simulations performed in ATENA 3D and loading and processing them in MS Excel. The calculated values of the inelastic part of the principal fracture strain ($\varepsilon_{\mathrm{fract},1}$ – see [3]) at all integration points of the FEM model were multiplied by a coefficient whose value is dependent on the mutual spatial orientation of the monitored inelastic fracture strain and the plates of the capacitor placed on the sides of the specimen (angle α, see Fig. 4). The value of this coefficient is determined by the value of the cosine of the α angle, i.e. if the normal vector of the fracture strain (N_P, herein it is a normal component of the unit vector that is used in the ATENA software to describe the direction of the deformation) forms a zero degree angle with the normal vector of the capacitor's plate (N_K), the coefficient value is equal to one; in the case of a 90° angle it is equal to zero. The thus-calculated results of the projection of the principal fracture strain $\tilde{\varepsilon}_{\mathrm{fract}}$ at each integration point (of the concrete part) of the FEM model were subsequently filtered (with different threshold filter values, from 1e–3 up to 1e–7) in order to investigate the sensitivity of the examined experimental method. If the $\tilde{\varepsilon}_{\mathrm{fract}}$ value at a given integration point exceeded the set filter value then the existence of failure was considered; i.e. the formation of a fracture. The coordinates of the integration points chosen in the above manner were used to determine the distance l of the localized rupture to the acoustic probe on the specimen surface (see Fig. 4).



Projection of the inelastic part of the principal tensile fracture strain on the plane perpendicular to the capacitor's plate plane is determined as:

$$\tilde{\varepsilon}_{\mathrm{fract}} = \varepsilon_{\mathrm{fract},1} \cos\alpha \,, \qquad (1)$$

where:

$\varepsilon_{\mathrm{fract},1}$ – is the inelastic part of the principal tensile strain, and

α – is the spatial angle between the direction of the principal fracture strain and the normal vector of the capacitor's plate.

The distance between an integration point and the AE probe is calculated according to the relation:

$$l = \sqrt{x^2 + y^2 + z^2} \,, \qquad (2)$$

where:

x, y, z – are the coordinates of the integration point.

Fig. 4: Scheme showing the determination of the spatial angle between the normal vector of a plane of a forming crack and the normal vector of the capacitor's plate, and distances between the forming crack and the acoustic probe; also, relations for computation of the processed parameters of the forming failure are shown

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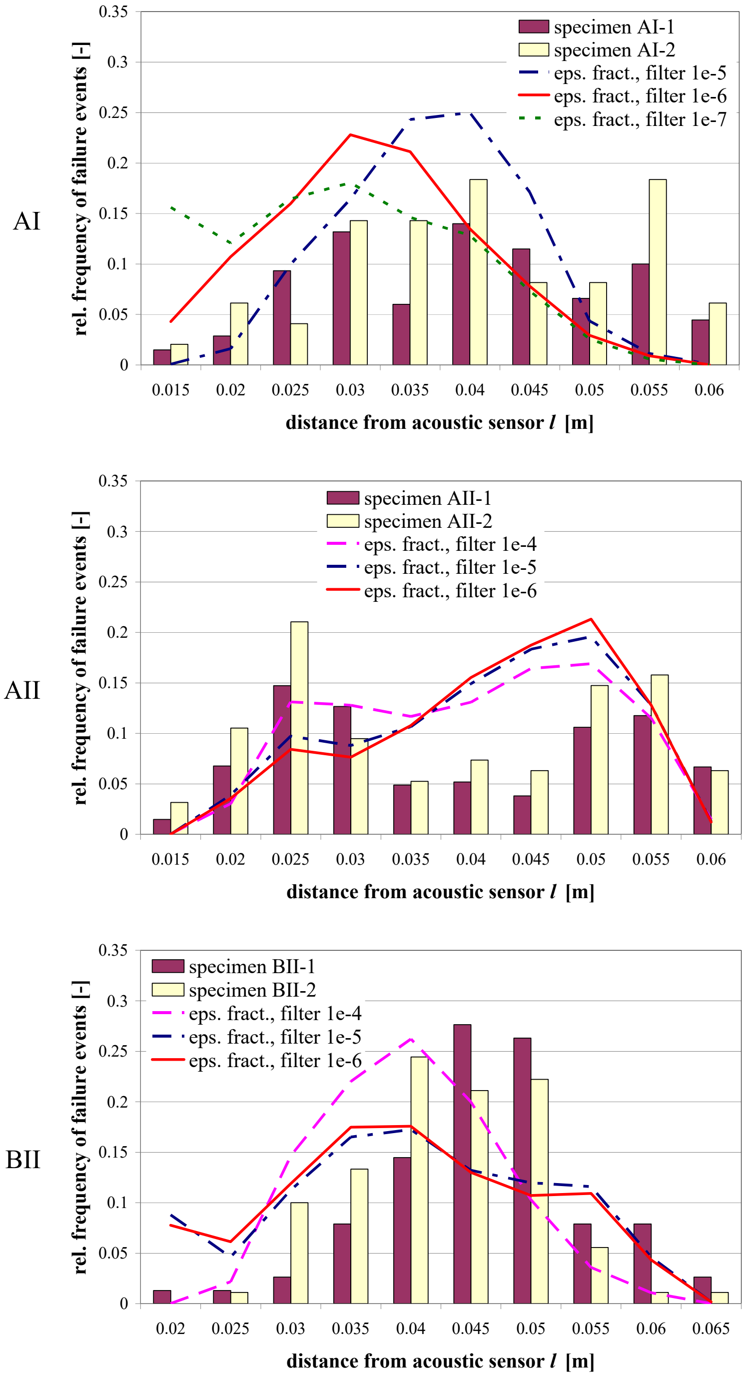


Fig. 5: Experimentally determined histograms of the frequency of AE events with a dependence on the distance between the locations of the failure event and the acoustic sensor for two selected specimens from sets AI, AII and BII [12]; the graphs also include the results of ATENA numerical simulations for several adjustments of the filter on the inelastic strain values (the projection of the strain in the plane perpendicular to the planes of the capacitor considered in the analysis); the corresponding loading stage is emphasized in the load−displacement diagrams in Fig. 3 by solid marks

The achieved fracture occurrences were then classified according to their spatial distance l to the acoustic probe (classes from 0.02 m to 0.065 m with steps of 0.005 m). Quantities of fracture occurrences in the individual classes were subsequently divided by the total quantity of occurrences in order to gain a relative frequency of failure events, which is suitable for comparison with the experimental histograms in Fig. 5. From the conducted analysis it can be concluded that the used experimental method utilizing EME/AE detects the forming of a crack corresponding to a fracture strain value greater than 1e–5; roughly 1e–4. It is expected that a comparison of the results of the presented simulations with the results of upcoming experiments using multi channel measuring apparatus will be able to add greater precision to this estimate.

2.2 Simulations using physical discretization of continuum: the FyDiK program

Another method which can be utilized for the investigation of the character of the failure processes triggering acoustic emission is a method based on the physical discretization of continuum. The hypothetical continuum is substituted by a set of mass points mutually connected by a network of simple translational springs. This method enables the solution of nonlinear problems without involving unduly complex models of material failure. However, the relatively large computational cost when very fine mesh is required can be viewed as a crucial disadvantage. This drawback can be to some extent effectively eliminated via parallelization, which can be easily implemented for such types of models [7]. The presented model is implemented in the FyDiK application [5].

The capabilities of the method were tested via simulations of fragmentation at impact and fracture experiments from the literature ([13]; some of the results gained from the simulations have already been reported in [7]). The latter of the above-mentioned group of simulations involved the performance of the wedge-splitting test (WST) on relatively large-sized specimens (see Fig. 6a) made of two mixes of concrete (differing in maximal aggregate size) and a mortar. The records of the AE scanning during loading were reported, however, without indication of the energy requirements of the individual emission events.

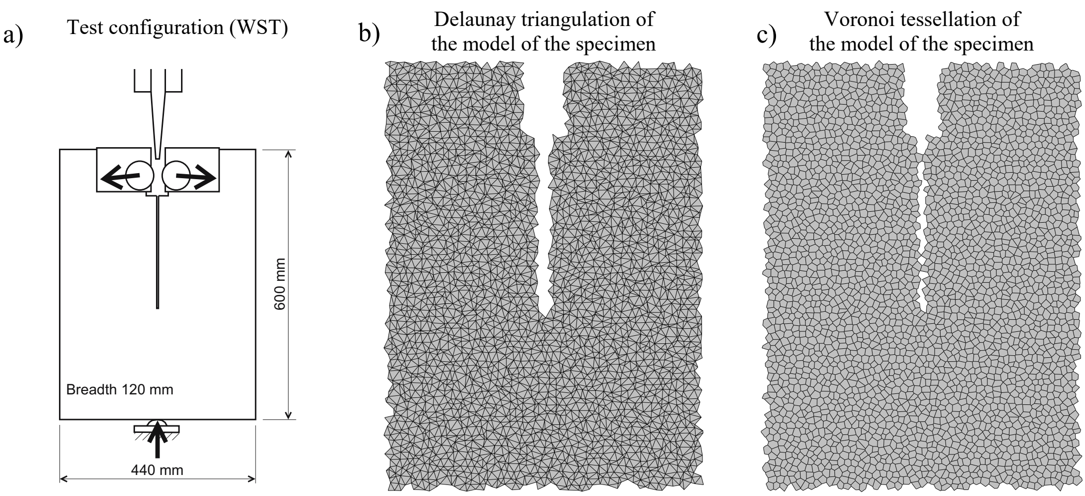
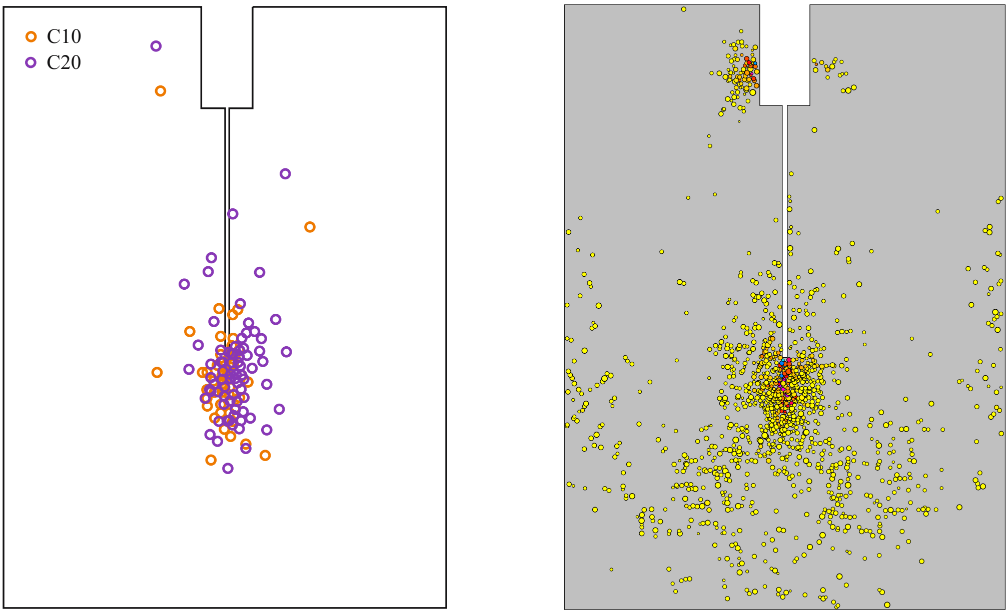


Fig. 6: a) Sketch of the test configuration from [13]; b) and c) illustration of the assembling of the model via a method developed for RBSN [2], [4] (the depicted mesh is substantially sparser than that used for the simulations whose results are presented)

Stage of the test corresponding to the maximal load (peak of the load–displacement diagram)



Stage of the test close to the end of the fracture process (end of the descending branch of the diagram)

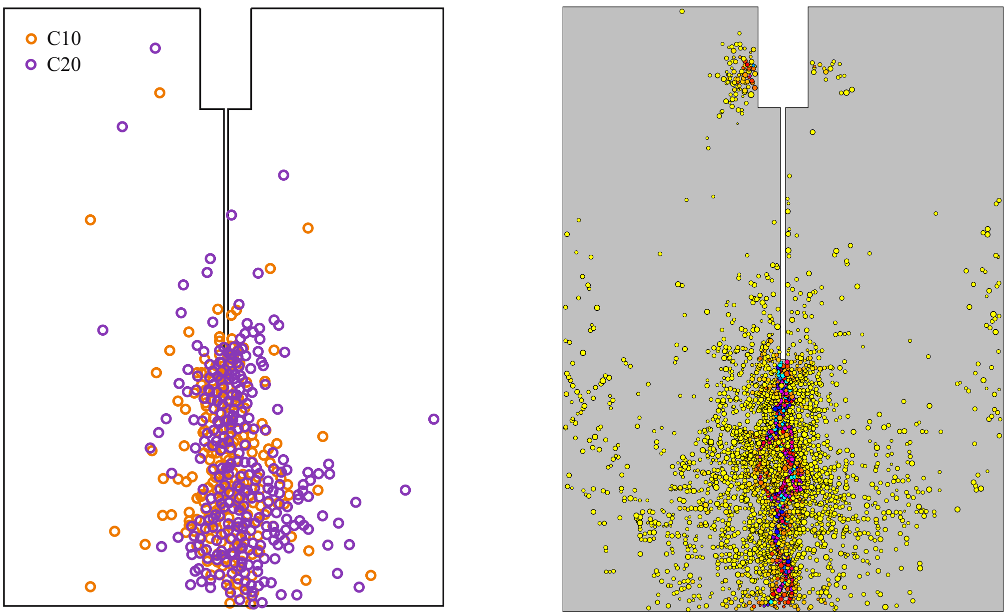


Fig. 7: Comparison of the AE record for two specimens (marked as C10 and C20, see [13]) – left – and the results of the dynamic simulation using the FyDiK model – right – for two loading stages

The model

The mass of the material is discretized by a set of mass points whose locations are generated in a hexagonal lattice with some degree of random noise. A Delaunay triangulation and subsequently a Voronoi tessellation are created for this set of mass points; see Fig. 6b and c. The triangulation determines the geometry of the spring network; the tessellation defines the properties of the springs. This procedure is adopted from a technique developed for what are termed Rigid Body Spring Networks (RBSN), see [2], [4]. The springs are modelled as quasi-brittle with bi-linear material law (linear elastic part, linear softening). Details about the construction of the lattice shape and specification of the characteristics of the springs can be found in [7].

Results

During the course of the simulation, the amount of energy dissipated via the failure of the springs was recorded. The location of the failure event, i.e. the progressive breakage of a spring, with an indication of the corresponding intensity of this energy dissipation in individual springs, is displayed in Fig. 7; the event location is marked with dots. The size of the dot corresponds with the length of the spring, while the colour (from yellow to blue) represents the intensity of the dissipated energy. A considerably dense mesh was used for the presented FyDiK simulations. The quantity of the simulated failure events is much higher. It is evident, however, that the estimation of the extent of failure within the specimen agrees well with experimental measurements published in [13]. It is intended that the FyDiK model will also be used for simulations of the tests described in section 2.1. It is planned that the spatial distribution of the failure (including its detailed aspects such as e.g. the energy released, etc.) will be scanned using a multichannel measuring device.

3 CONCLUSIONS

The paper presents two approaches to the modelling of failure processes in bodies/structures made of cementitious composites which can be detected using experimental techniques based on acoustic and electromagnetic emission, or its combination. A detailed analysis of the failure of a given material using numerical tools can be helpful with understanding and the proper interpretation of the results of such measuring techniques. Some of the features of the available computational tools were described in this paper.

Experimental techniques utilizing EME/AE have a great potential to answer the key questions related to the initiation and propagation of failure in quasi-brittle materials, which is connected with the evolution of what is termed the fracture process zone at the tip of the propagating macroscopic crack. The authors of the present paper have long been involved in research on related topics [7], [17], [18], [21], [22].

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REFERENCES

[1] BAŽANT, Z.P., PLANAS, J. 1998. *Fracture and size effect in concrete and other quasi-brittle materials*. Boca Raton: CRC Press, 1998.

[2] BOLANDER, J. E., YOSHITAKE, K., THOMURE, J. 1999. Stress analysis using elastically uniform rigid-body-spring network. *J. Struct. Mech. Earthquake Eng.*, 633, 125–132, 1999.

[3] ČERVENKA, V. et al. 2005. *ATENA Program Documentation, Theory and User Manual*. Prague: Cervenka Consulting, 2005.

[4] ELIÁŠ, J. 2009. *Discrete simulation of fracture processes of disordered materials*. Ph.D. thesis, Brno University of Technology, Brno, Czech Republic, 2009.

[5] FRANTÍK, P. FyDiK application, http://www.kitnarf.cz/fydik, 2007–2011.

[6] FRANTÍK, P., KERŠNER, Z., VESELÝ, V., ŘOUTIL, L. 2009. Fractality of simulated fracture. *Key Engineering Materials*, Vol. 409, 154–160, 2009.

[7] FRANTÍK, P., VESELÝ, V., KERŠNER, Z. 2011. Efficient lattice modelling of the fracture process zone extent in cementitious composites. In: *2nd Int. Conf. on Parallel, Distributed, Grid and Cloud Computing for Engineering – PARENG 2011.* Ajaccio, France. Civil-Comp Press, Stirlingshire, 2011

[8] GORDEEV, V. F. et al. 1994. Electromagnetic emission of dielectric materials due to the static and dynamic loading. *Journ. Tech. Phys*. 64 (4), 57–67, 1994.

[9] KARIHALOO, B. L. 1995. *Fracture mechanics and structural concrete*. New York: Longman Scientific & Technical, 1995.

[10] KOKTAVÝ, B., KOKTAVÝ, P., ŠTEFKOVÁ, M. 2007. On the effect of mechanical loading method on rectangular concrete specimen electromagnetic and acoustic emission signals (in Czech). In: *Experiment 2007*, FCE BUT Brno, CERM, s.r.o. Brno, 211–216, 2007.

[11] KOKTAVÝ, B., KOKTAVÝ, P., VESELÝ, V., FRANTÍK, P., KERŠNER, Z. 2008. Utilization of electromagnetic and acoustic emission in monitoring the tensile failure of cementitious composites. In: *Mechanics of Composite Materials – MCM 2008*, Riga,. V. Tamužs, K. Cīrule and A. Lagzdiņš (Eds.). Institute of Polymer Mechanics, University of Latvia, 138–139, 2008.

[12] KOKTAVÝ, P., VESELÝ, V., KERŠNER, Z., FRANTÍK, P., KOKTAVÝ, B. 2011. Utilization of electromagnetic and acoustic emission in monitoring of fracture of cementitious composites. *Key Engineering Materials*, vol. 465, 503–506, 2011.

[13] MIHASHI, H., NOMURA, N. 1996. Correlation between characteristics of fracture process zone and tension-softening properties of concrete. *Nuclear Engineering and Design*, 165, 359–376, 1996.

[14] SKLARCZYK, CH., ALPETR, I. 2001. The electric emission from mortar and concrete subjected to mechanical impact. *Scripta mater*., Vol. 44, 2537–2541, 2001.

[15] SHAH, S. P., SWARTZ, S. E., OUYANG, C. 1995. *Fracture mechanics of structural concrete: applications of fracture mechanics to concrete, rock, and other quasi-brittle materials.* New York: John Wiley & Sons, 1995.

[16] VAN MIER, J. G. M. 1997. *Fracture Processes of Concrete: Assessment of Material Parameters for Fracture Models*. Boca Raton: CRC Press, 1997.

[17] VESELÝ, V., FRANTÍK, P. ReFraPro – Reconstruction of Fracture Process, Java application, 2008–2011.

[18] VESELÝ, V., FRANTÍK, P. 2011. Reconstruction of a fracture process zone during tensile failure of quasi-brittle materials. *Applied and Computational Mechanics*, 2010, 4, 237–250.

[19] VESELÝ, V., FRANTÍK, P., KERŠNER, Z. 2007. Analysis of stress state and crack propagation in specimens used for quasi-brittle material failure measurement by electromagnetic emission (in Czech). In: *Modelování v mechnice 2007*, Ostrava, 14.–15. 2. 2007. Ostrava: Faculty of Civil Engineering, VŠB-TU Ostrava, 11–12 + CD 21 s, 2007.

[20] VESELÝ, V., KERŠNER, Z., KOKTAVÝ, P., KOKTAVÝ, B. 2007. Study of crack propagation in concrete specimens loaded by lateral tension (in Czech). In: *Experiment 2007*, FCE BUT Brno. CERM, s.r.o. Brno, 511–516, 2007.

[21] VESELÝ, V., FRANTÍK, P., KERŠNER, Z. 2009. Cracked volume specified work of fracture. In: *12th Int. Conf. on Civil, Structural and Environmental Engineering Computing*, B.H.V. Topping, L.F. Costa Neves and R.C. Barros (Eds.), Funchal, Civil-Comp Press, 2009.

10.2478/v10160-011-0036-5

[22] VESELÝ, V., KERŠNER, Z., NĚMEČEK, J., FRANTÍK, P., ŘOUTIL, L., KUCHARCZY-KOVÁ, B. 2010. Estimation of fracture process zone extent in cementitious composites. *Chem. Listy*, 104, 382–385, 2010.

[23] YAMADA, I., MASUDA, K., MIZUTANI, H. 1989. Electromagnetic and acoustic emission associated with rock fracture. *Phys. of the Earth and Plan. Inter*., Vol. 57, 157–168, 1989.

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