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NUMERICAL SIMULATIONS OF EFFECTS OF SPECIMEN PREPARATION METHOD ON PROPERTIES OF FIBER COMPOSITES

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Abstract: *The correct determination of mechanical properties of construction materials has a major impact on the design and reliability of structures. Strength and deformation characteristics are evaluated based on data from experiments. The determined parameters can be largely affected also by fabrication of experimental specimens. Either by nature of production, storage conditions before experiment itself, or by testing set-up (equipment, boundary conditions, etc.). This article deals with influence of specimen preparation method on the strength of reinforcement in fiber composites. To clarify this phenomenon we performed numerical calculation based on randomly generated fibers.*

Keywords: ***fiber-reinforced composites, fiber bridging, cohesive law, specimen preparation method***

1. Introduction

In our research, we are developing new high performance mortar for restoration works on historical structures. It is a composite material made from fine-grained lime matrix, which is reinforced with short randomly oriented fibers in a small volume fraction ($V_f \leq 2\%$). For the material design we use a methodology, which has been developed for design of quasi-brittle composites reinforced with short fibers (Li, 2003). We expect that this mortar will exhibit unique properties that lead in particular to improve the durability of restoration works and to reduce the amount of interventions required to maintain historical monuments. The main feature of this material is pseudo-ductile and strain-hardening behavior when undergoing tensile strains. Therefore the failure during cracking doesn't localize into one crack, like in brittle material. The strength of fiber reinforcement bridging the crack is higher than the tensile strength of the matrix and therefore external loading can increase while large number of parallel fine cracks forms in the matrix and material retains macroscopic integrity. This process is called multiple-cracking (Li, 1992). Controlled crack width may prevent the penetration of water and contaminants into the masonry, which can improve the durability of structures. This methodology was successfully used, for example, for design of Engineered Cementitious Composites – ECC (Li, 2003).

As part of the research of cementitious composites, several comparative tests were carried out. A comprehensive round-robin study was performed to compare the experimental data from tensile and bending tests on specimens with different shape and size (Kanakubo, 2006). Another comparative study was organized by RILEM Technical Committee 208 – HFC in 2007 (not published yet) and involved only tensile experiments. All specimens were prepared from identical commercially available dry mix (ECC-crete, produced by Kajima corp. and Futase corp., Japan), but in different laboratories according to local convention with different equipment. The results of these studies indicate that obtained material characteristics are largely influenced by the particular set up of the experiments, such as boundary conditions, size of a specimen and the method of specimen preparation. The aim of our work is to clarify some differences in behavior between experimental specimens that were prepared either by casting into appropriate mold or by cutting from a large body of material. For the purpose of this work we performed numerical simulations to predict cohesive behavior of a single crack for specimens prepared by different methods.

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2. Numerical simulations

Numerical simulations were performed for lime mortar reinforced with polyvinyl-alcohol fibers (PVA – type REC 15, made by Kuraray Company) in volume fraction 2% with variable length (4 ÷ 12 mm) to predict cohesive behavior of a single crack (cohesive law) – relation between crack opening displacement δ and bridging stress σ_b. From calculated relations the most important is maximum bridging stress σ_{mb} at each point of the cross-sectional area of the specimen.

Simulations were performed so that, first of all, fibers with uniform diameter and length were randomly generated in a prismatic volume. The size 40×40×160 mm corresponds to the standard beam, which we use for experiments. Secondly, at least ten fictional crack planes, perpendicular to the longitudinal axis, were inserted into each specimen with minimal mutual distance corresponding to the length of fiber L_f. For incrementally increasing prescribed crack opening displacement δ the bridging stress σ_b was calculated as the sum of all forces P in fibers bridging a crack divided by the crack area A_c (Přinosil, 2012):

$$\sigma_b(\delta) = \frac{\sum P_i(\delta)}{A_c} \quad (1)$$

For behavior of individual fiber we used two-stage description and the force in fiber corresponds to the equations in (Li & Leung, 1992) and (Yang et al., 2008). Micromechanical parameters used in these relations have been previously observed experimentally (Přinosil & Kabele, 2012). Typical examples of cohesive law are illustrated in Figure 4.

Furthermore, the cross section was divided into a regular grid (Fig. 2) with dimension d_x (1 ÷ 40 mm) and the bridging stress σ_b^{kl} in every part (row k and column l) was:

$$\sigma_b^{kl}(\delta) = \frac{\sum P_i^{kl}(\delta)}{d_x^2} \quad (2)$$

and maximum bridging stress in part kl was:

$$\sigma_{mb}^{kl} = \max\left(\sigma_b^{kl}(\delta)\right) \quad (3)$$

For every specimen, the results from all crack planes were averaged.

2.1. Generating of fiber reinforcement

Random parameters X_c, Y_c, Z_c determine the position of the fiber's center of gravity, random spherical coordinates φ and θ determine its orientation (Fig. 1). Rectangular distribution of all random variables ensures uniform distribution of fibers in a specimen. From these five random parameters, the coordinates of both ends of the fiber are calculated and it is considered that the fiber is direct.

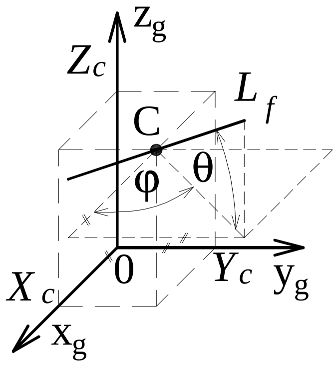

Fig. 1: Position and orientation of a fiber determined by the random parameters

To reproduce the casted specimen, all fibers were generated in its volume. If any part of any fiber reached outside, coordinates of center of gravity remained fixed and only spherical coordinates were generated again until the condition was fulfilled. Therefore fibers in the surface layer tended to align with specimen surface. To reproduce the sawed specimen, fibers were generated in volume expanded on each side by one half of fiber's length (total amount of fibers was higher than in the casted specimen). Subsequently, parts of fibers in original volume (not expanded) were selected. Therefore fibers in the surface layer of the specimen could be shortened (Fig. 3).

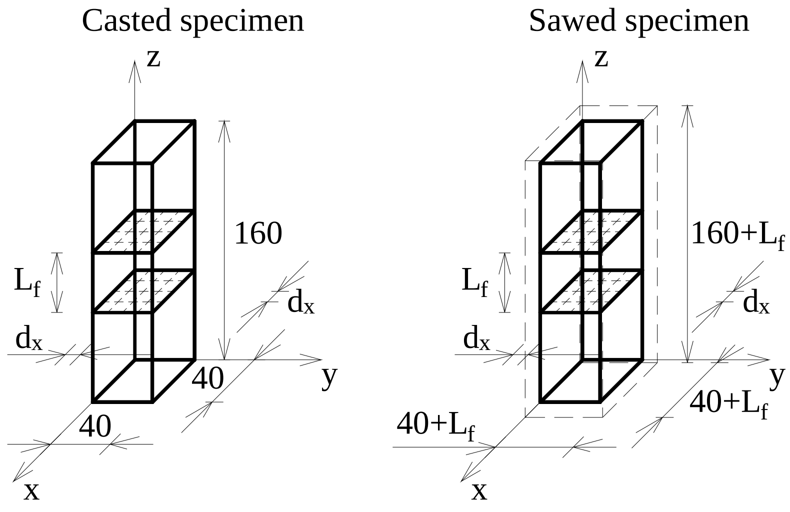

Fig. 2: Schematic drawings of casted and sawed specimen

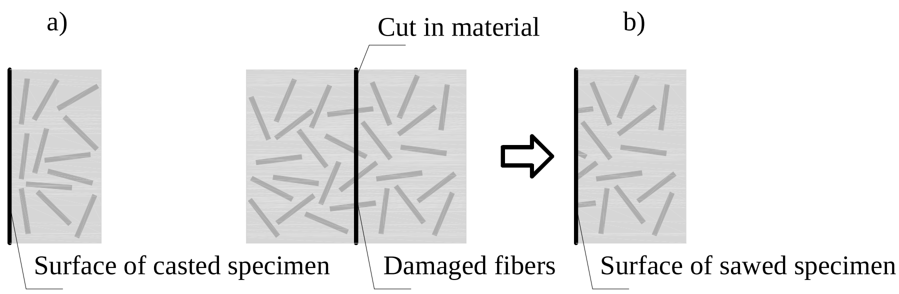

Fig. 3: Surface layer in casted (a) and sawed (b) specimen

3. Effects of specimens preparation method

Typical examples of calculated cohesive relations σ_b-δ over the whole cross-sectional area (d_x = 40 mm) of fine grained lime mortar reinforced with 2% PVA fibers with length 12 mm are illustrated in the Figure 4.

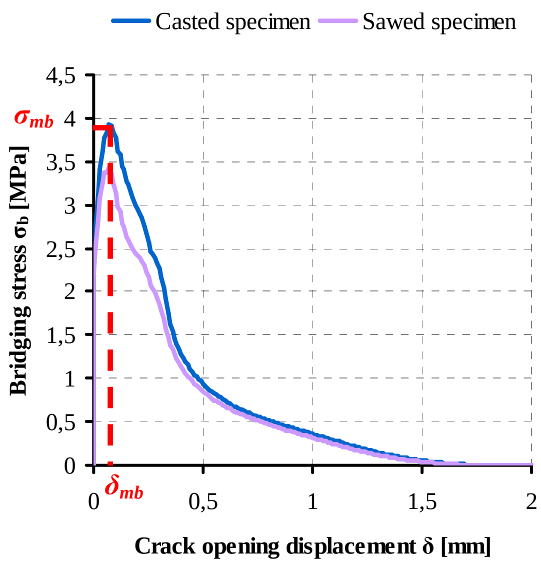

Fig. 4: Typical σ_b-δ relations for casted and sawed specimen reinforced with fibers with L_f = 12 mm and d_x = 40 mm

Figure 5 shows the maximum bridging stress σ_{mb} for specimens with L_f = 12 mm and d_x = 4 mm. In the case of casted specimen, surface layer has a higher maximum bridging stress than the inner part. The highest strength is calculated in corner sections where the fibers are aligned with two surfaces and their direction nearly corresponds to the longitudinal axis. In the case of sawed specimen, it is just the opposite. Damaged fibers are able to transfer reduced force and therefore the surface layer is weakened. It is particularly evident in the corners where the fibers are sawed by two surfaces. Therefore the maximum bridging stress from the whole cross-section (d_x = 40 mm) is higher for casted specimen than for sawed specimen (Fig. 4). The difference in values is more obvious for specimen with small cross-sectional area, whereas for large cross-sectional area it disappears because thickness of affected layer does not change for a different size of the specimen.

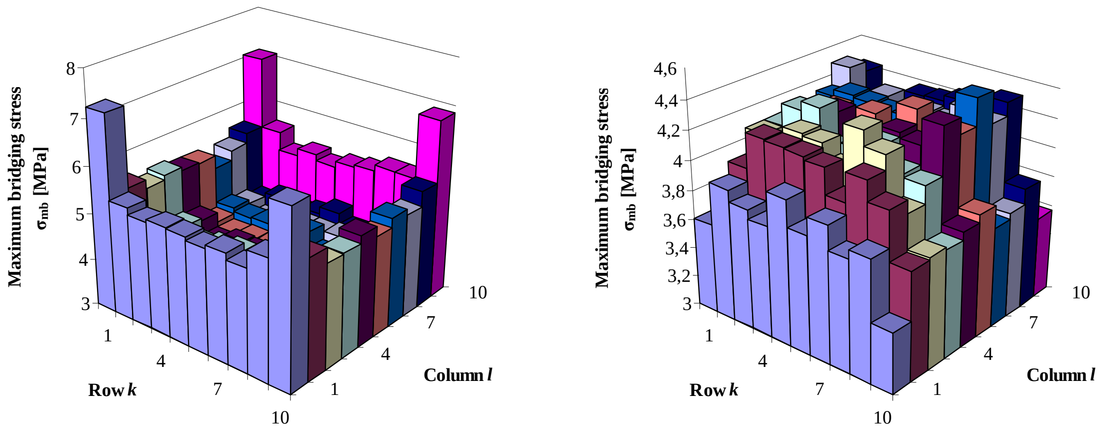

Fig. 5: Maximum bridging stress σ_{mb} at particular points of the cross-section (d_x = 4 mm) of casted (left) and sawed (right) specimen

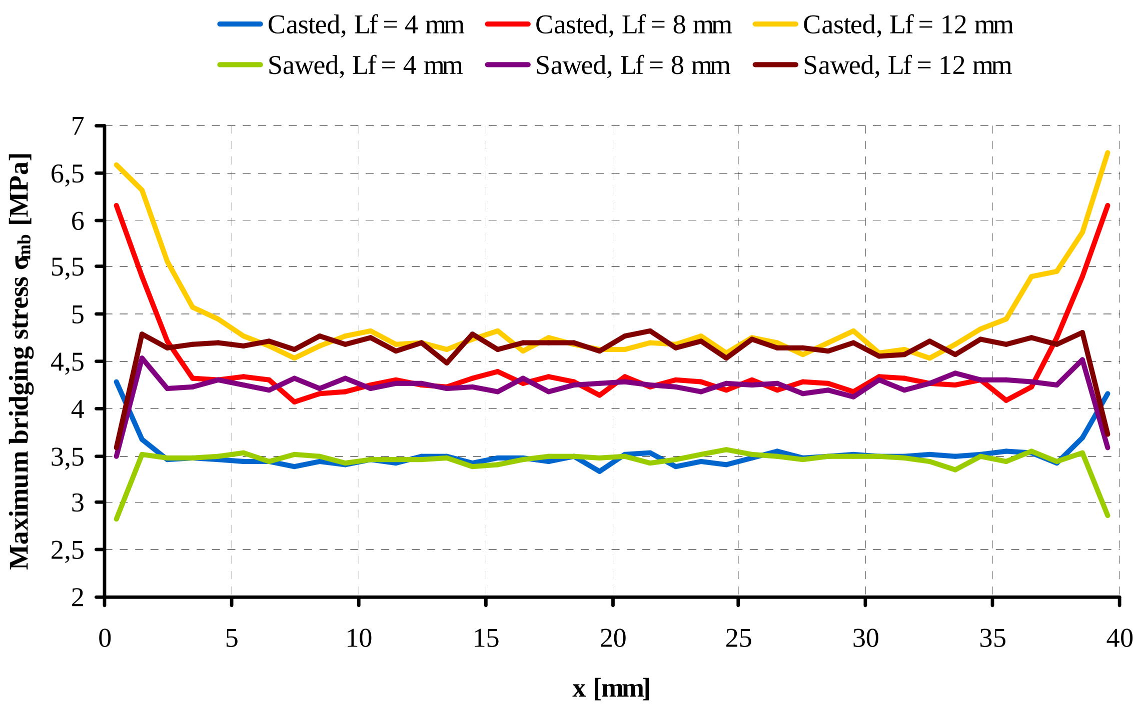

Fig. 6: Average maximum bridging stress σ_{mb} at particular points of the cross-section (d_x = 1 mm) of specimens with different preparation method and length of fibers

For a detailed overview, the cross-sectional area was divided into finer grid with $d_x = 1$ mm. Figure 6 shows the average maximum bridging stress σ_{mb} (within columns 10 and 30) of specimens with different preparation methods and length of fibers. In all cases, inner part of specimen has the same maximum bridging stress for both preparation methods. In the case of sawed specimens the weakened surface layer has similar depth about 1 ÷ 2 mm, while in the case of casted specimens the depth of affected layer depends on the length of the fiber and corresponds approximately to the half of fiber's length. Weakened layer has smaller depth because broken fibers with increasing distance from the surface deflect more from the longitudinal axis and thus contribute less to the overall bridging stress (force in the fiber depends on an inclination from the crack plane, Li & Leung, 1992).

4. Reproduction of an experiment using numerical simulations

In the introduction we have mentioned a study organized by RILEM. Series from this study were numerically simulated using finite element method with stochastic fields, which represented the inhomogeneities in material (Přinosil, 2010). A parametric study of characteristics of stochastic fields (crack spacing, correlation length and coefficient of variation) was performed on two series, which were produced from the same batch of fresh mix. Therefore it could be assumed that the influences appeared during preparing of mixture were eliminated. Specimens in the first series were prepared by casting, but in the second one by sawing along three sides (Fig. 7). In order to reach agreement in the results from numerical simulations and from experiment for both series, the preparation method had to be taken into account. Since the analyses were conducted in 2D, the effect of damaged fibers was averaged through the specimen thickness, assuming that strength of fiber reinforcement linearly decreased towards cut surface up to distance corresponding to half of fiber length. This assumption caused reduction of bridging stress in cohesive law to the 70% of the original value.

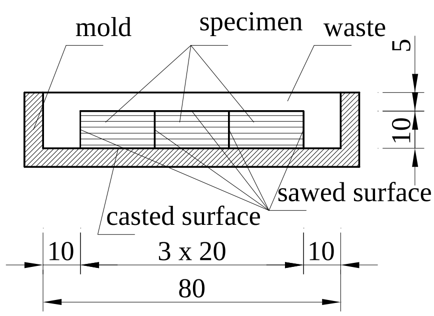

Fig. 7: Schematic drawing of the experimental specimen

If we consider correct distribution and damage of fibers in specimens from second series using our simulation, we can calculate the maximum bridging stress σ_{mb} = 5,81 MPa for casted case. In the case of one casted surface and three sawed surfaces (Fig. 7) we obtain σ_{mb} = 4,22 MPa. That is reduction approximately to 72% of the original value and it is in very good agreement with the original assumption. It should be noted that the values of maximum bridging stress correspond to the lime matrix reinforced with PVA fibers. We assume that for cementitious composites the ratio of values would be the same.

5. Conclusion

The results of numerical calculations confirmed the assumption that material parameters of fiber composites evaluated from experiments depend on the preparation method of the specimen. It has been demonstrated that in the case of sawed specimens, the fibers in surface layer are damaged and thus their ability to transfer the load is reduced. In the case of casted specimens, fibers tended to align with mold surface and thus the maximum bridging stress in surface layer increases. According to the results, the depth of weakened surface layer doesn't depend on the fiber length compared to the depth of the reinforced layer in the case of casted specimens.

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