FIBRE ORIENTATION PHENOMENON IN CONCRETE COMPOSITES: MEASURING AND THEORETICAL MODELLING

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Abstract

The paper highlights the constitutive modelling of the anisotropy created by the adding of short fibres to the concrete matrix to form the steel fibre reinforced concrete. In the constitutive model developed the anisotropy is based on the use of the alignment tensors and the orientation distribution function of fibres. Utilizing these characteristics it is possible to lay down the material symmetry and to estimate the direction dependent elastic properties of the composite.

Keywords: fibre orientation, constitutive mappings, orthotropic material

1. Introduction

Composite materials are partly replacing the traditional materials since the combination of various materials leads to improved physical and mechanical properties. One of the options to strengthen the base material (matrix) is to add fibres, which can be made of different materials such as glass, polypropylene, or steel. The investigation of the composite material where the properties of concrete (matrix) are reinforced by short hooked-end steel fibres (SFRC) is a subject of the present research. This composite has been used since the middle fifties of the 20th century, but the modelling of its mechanical properties still remains an open topic for research. One of the main challenges has been that the mixing of short fibres with the concrete matrix results in anisotropy, the nature of which depends on the orientation of fibres. The fibre orientation and, particularly, its stochastic nature is not taken into account by the existing material models for short fibre composites adequately [Chyba! Nenalezen zdroj odkazů., Chyba! Nenalezen zdroj odkazů., Chyba! Nenalezen zdroj odkazů.]. Although, only by knowing fibre orientations it is possible to determine the bearing capacity of SFRC. Thereby, a goal of the research is to develop an orthotropic material model, which would include the stochastic nature of fibre orientations objectively.

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2. Phenomenological assumptions for constitutive mappings for SFRC

The idea for the orthotropic model is based on comparison of the behaviour of reinforced concrete and SFRC beams. In a concrete beam, reinforcement bars are often located in orthogonal directions, which may also coincide with tensile stresses (Fig. 1). The arrangement of the reinforcement creates orthotropy.

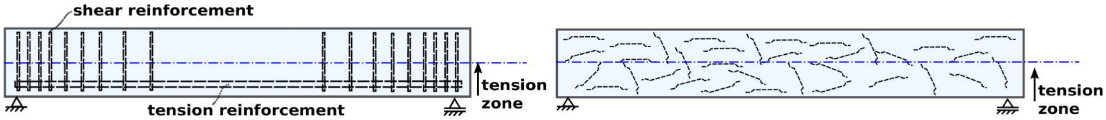

Fig. 1: The comparison of reinforced concrete versus SFRC beam. In SFRC beam the orientation distribution of fibres is not specified.

The optimal arrangement of fibres in SFRC beam is not random generally, as the some directions are more favourable against external loading. Thus, it is a reasonable assumption that the fibres may align along preferred directions and the research problem is their identification and modelling. The identification of fibre orientations can be made by different methods of which X-ray micro-tomography (µCT) is one modern example. Hence, during the research this method was chosen to investigate the orientation of fibres in sufficiently large specimens [Chyba! Nenalezen zdroj odkazů.]. The specimens—cylinders (H: 25 cm, d: 10 cm)—were drilled from full-size floor-slabs ($H\times W\times L$: 25 $cm\times 100\,cm\times 500\,cm$) and scanned by a µCT scanner (Fig. 2).

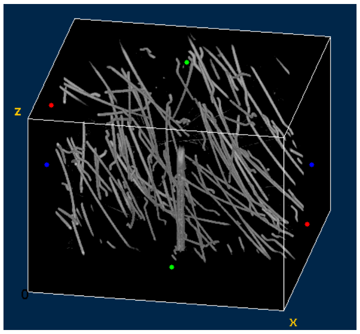

Fig. 2: Thresholded volume image of a cylinder sample scanned by µCT scanner: Nanotom 180 NF supplied by Phoenix| xray Systems + Services GmbH. The image is still showing an artefact in the middle.

These µCT investigations have shown, that the fibres may align along some directions, which can be different within the same structure. The modelling of these location-specific directions can be made by the eigenvectors of the 2nd order alignment tensor (AT), which are also able to consider the orthotropic symmetry of the composite (Fig. 3).

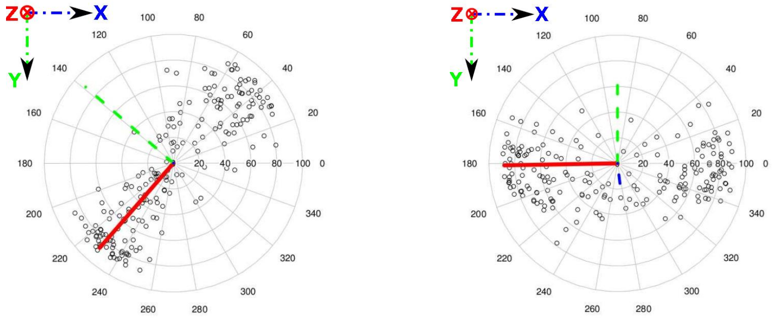

Fig. 3: Scatter plot of fibre orientations in cylinder samples 2A (left; side region of a slab) and 2B (right; centre region of a slab). The lines correspond to the directions of the eigenvectors of the 2nd order AT. The radius is the inclination angle in degrees, Z-axis points to the direction of principle stress in a floor-slab.

The infinite hierarchy of the ATs rebuilds the orientation distribution function, (ODF) [Chyba! Nenalezen zdroj odkazů., Chyba! Nenalezen zdroj odkazů.]. The ODF defines a probability of finding a fibre (rod-like particle) between the given angles on a unit sphere and can be measured experimentally, e.g. with μCT, using the scanned samples. Thus, the ODF may be used to give a probabilistic assessment of fibre contributions in material symmetry axes and this may result in the orientation-weighted 4th order elsticity tensor of fibres.

The brittle behaviour of the concrete matrix, an incomplete (minor) anchoring of steel fibres, and restricted deformation capacity of high strength steel used for fibres compared to ductile steel justify the assumption of linear-elastic dependence between stresses and deformations used in the constitutive mapping. The results of the bending tests performed during the research supported also the hypothesis of linear-elastic regime [Chyba! Nenalezen zdroj odkazů.].

3. Formulation of orthotropic linear-elastic material model for SFRC

The SFRC material model developed utilizes the full orientation information of a fibre, i.e. the inclination and azimuth (in-plane) angles of spherical coordinates, and uses tensor quantities, which satisfy the objectivity condition and the principle of material frame indifference [Chyba! Nenalezen zdroj odkazů.]. The constitutive mappings for SFRC are grounded on a hyperelastic material model. The assumed isotropic concrete matrix is modelled employing the representation of the strain-energy density as an isotropic tensor function of one argument and retaining only quadratic terms. This leads to the isotropic St. Venant-Kirchhoff model [Chyba! Nenalezen zdroj odkazů.]. The orthotropic influence of short fibres is characterised by the strain-energy function of arguments among which are the structural tensors [Chyba! Nenalezen zdroj odkazů.]. The structural tensors determine the material symmetry and thus may be specified by the eigenvectors of the 2nd order AT. Accordingly, the orthotropic St. Venant-Kirchhoff model is received as an isotropic tensor function of the mixed invariants. Thereby, the strain-energy function for SFRC is elaborated by the combination of the isotropic and orthotropic St. Venant-Kirchhoff models that are further being differentiated to give the relation between the stress and deformation. The developed linear-elastic and orthotropic material model has material symmetry axes the directions of which are connected to local fibre orientation distributions that can be described by statistically predefined ODFs of fibres.

4. Conclusion

The material model formulated gives a representative description of composite properties in a physical term since it is observer-independent and uses a tensorial description. Orientation order of fibres is quantified by the ATs, which can be used in the evolution equations for estimating the rheological properties of fibre suspensions. The constitutive model formulated, provides a groundwork for numerical applications since it establishes the relation between the stress and deformation of the composite through the orientation-weighted 4th order elasticity tensor. The material model postulated allows the manufactures to simulate and understand SFRC properties and thus may help in product development.

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