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A strain-hardening microplane damage model for thin-walled textile-reinforced concrete shells, calibration procedure, and experimental validation

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ABSTRACT

Thin-walled shell structures made of textile-reinforced concrete (TRC) exhibit a high load-bearing capacity and considerable ductility. However, the material behavior exhibits several interacting mechanisms of material disintegration that result in a complex, highly nonlinear structural response. In this paper, an anisotropic material model for TRC will be discussed that is able to capture those effects. The calibration of the material model is performed based on an inverse analysis using the strain-hardening response measured in a uniaxial tensile test. Finally, we validate the material model through a finite-element simulation of three-point bending tests as well as the complex biaxial load-bearing behavior as observed in slab tests with central loading. In this context, further issues such as the influence of large deflections and geometrical nonlinearity will be investigated. The calibrated model provides a valuable tool for an in-depth analysis of the structural behavior of thin-walled TRC shell structures. This is especially important for a realistic prediction of the deflections in the cracked state as well as load-bearing reserves resulting from stress redistributions.

1. Introduction

Textile-reinforced concrete (TRC) consists of a fine-grained concrete matrix and high-strength textile fabric reinforcement made of carbon or alkali-resistant glass fibers. Owing to the noncorrosiveness of the textile reinforcement, the composite material exhibits long durability even for very small concrete covers. As a consequence, the material performance can be most effectively exploited in thin cross sections, e.g., slender TRC precast elements or strengthening layers of existing structures. Because of the high form flexibility of the textile reinforcement, TRC lends itself for the construction of thin-walled shells. Examples of TRC shell structures recently constructed at the campus of RWTH Aachen University [1,2] are shown in Fig. 1. The related development of TRC sandwich elements applicable as wall panels, slabs, or shells has been recently reported by several authors [3–5].

Textile-reinforced concrete shells exhibit a complex nonlinear and anisotropic behavior. Given a uniform loading of a cross section in tension, the nonlinearity of the response is due to the matrix cracking and subsequent debonding of the fabrics from the matrix. The material response with the corresponding shape of the stress–strain curve with large initial stiffness and high deformation capacity at the later stages of loading is referred to as strain hardening. Understanding the link between the elementary damage effects in the material structure (matrix cracks, debonding, statistical effects resulting from the heterogeneity of the bond microstructure, etc.) and the corresponding shape of the stress–strain curve is essential for targeted design of the composite material structure. Modeling approaches capturing the elementary effects within the material structure were published recently by several authors using multiscale approaches [6–10]. Finite-element models focused on the tensile behavior of TRC with explicit representation of the multiple cracking of the matrix in association with debonding were presented in [7,11,12].

As an alternative to the cited modeling approaches focused on detailed description of the disintegration process of the material structure, in this paper we propose a phenomenological material model of the strain-hardening material behavior in a two-dimensional stress state within a thin cross section with the goal to predict and study the behavior of large-scale shell structures. The reinforcement is not explicitly distinguished in the finite-element discretization of a cross section but the material is regarded as a homogeneous unit. The material disintegration process resulting from cracking and debonding is represented by

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Fig. 1. Examples of TRC shell structures at RWTH Aachen University: (a) load-bearing structure of the T3 pavilion consisting of four doubly curved shell elements; (b) bicycle stand consisting of five singly curved barrel vault shells.

a damage function valid only for a considered cross-sectional layout. An alternative microplane formulation with explicit representation of the reinforcement layer has been proposed for conventional reinforced concrete by Wang et al. [13] using the criteria of strain compatibility and energetic equivalence to incorporate the effect of reinforcement.

In the context of the two-dimensional stress state, multiple cracking of the matrix in the direction of principal tensile stress induces anisotropy. The stiffness of a zone with a fine crack pattern then depends on the direction of further loading. The lowest stiffness is provided for the direction perpendicular to the orientation of the cracks, i.e., loading aligned with the original principal stress direction, while higher values of stiffness are available for non-aligned loading. This type of anisotropy will be further referred to as *damage-induced*.

An additional source of anisotropy is provided by the orientation of the textile fabrics within the structure. The composite may respond differently to loading depending on the alignment of the loading direction with the orientation of the textile fabric within the composite. This can be referred to as the *initial* anisotropy of the material. To capture the complex behavior of TRC in a numerical model representing the strain-hardening response and both *initial* and *damage-induced* anisotropy we have established a modeling framework based on the microplane damage model with a meso-macroscopic representation of the damage process that was briefly introduced in [14]. In the present paper, the model formulation is set into the context of general development of microplane models and its utilization for shells and strain-hardening behavior is described in a more detail. Furthermore, systematic framework for calibration and validation is provided for thin shell cross sections.

The key idea of the microplane concept is to provide a directional interpretation of the damage state in a material point by a spherical (three-dimensional) or polar (two-dimensional) decomposition of the stress/strain state into a set of microplane directions (Fig. 2a). An overview and a classification of existing microplane models are presented in Section 2. Subsequently, the formulation of the *microplane damage model* originally formulated by Jirásek [15,16] is described in detail in Section 3. Based on this formulation, utilization of the model for strain-hardening composites is presented.

The calibration of the strain-hardening microplane damage model is performed based on the experimentally obtained uniaxial tensile response of the composite cross section using an inverse analysis to determine the underlying damage function of the microplane model [2]. The usage of a tensile test for calibration was motivated by the fact that only a single material point is needed to reproduce the uniform stress state within the tensile specimen, as indicated in Fig. 2b. It must be emphasized that the validity of the calibrated model is limited to a particular cross-sectional layout and reinforcement ratio. A detailed explanation of the calibration procedure is described in Section 6.

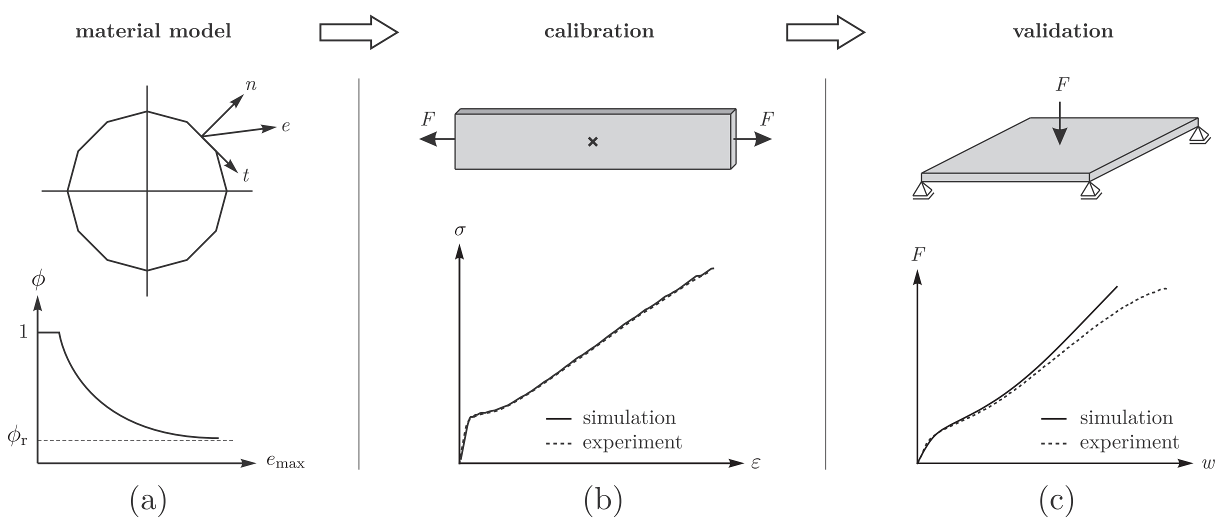

Fig. 2. (a) Model formulation. (b) Calibration process. (c) Validation using test results.