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Modeling the dynamic properties of fibre-reinforced concrete with different coating technologies of multifilament yarns

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ABSTRACT

The dynamic behaviour of fibre-reinforced, cementitious composite materials is gaining increasing interest. With respect to service life dynamic loading just under the elastic limit of the material at hand is relevant to practical applications, for the resulting (stress-)waves may be focused within regions of the heterogeneous composite material. This local overstraining of the material may lead to deterioration of the structural element. In this contribution, the effect of the set-up of the reinforcing fibres on the wave scattering behaviour is investigated. Special attention is paid to layered centric configurations of these fibres, as it occurs e. g. within textile-reinforced concrete (TRC). A mechanical model is developed and solved analytically providing an efficient and robust method to describe the dynamic behaviour of given fibre configurations. This method is needed for materials which have to be described mechanically before the manufacturing process – as it is the case for TRC. The proposed model also allows for planning experiments and thus is of additional value. It is shown that the inner structure of the fibres does influence the amplitude response spectra and consequently the proposed method also may be used for non-destructively detecting the inner structure of the multifilament yarns and other related objects.

1. Introduction

The dynamic behaviour of cementitious composite materials is the subject of increasing interest. But not only dynamic loads leading to immediate failure or damage are of concern. Also dynamic cyclic loads which bring about (slightly) subcritical conditions have enormous practical relevance, as can readily be seen from the example of traffic over a bridge. These dynamic loads may be transient or time-harmonic, depending on the field of application. The dynamic behaviour of the respective composite material depends on the mechanical properties of (i) the strengthening fibres, (ii) the bond between these fibres and the surrounding matrix, (iii) the matrix itself, and (iv) if existent, the bonds within layered fibres.

Major investigations have been conducted in order to clarify the main contributions to the mechanical behaviour of composite materials in the case of static loads. These investigations cover the influences of the fibre material, of the matrix [6], and of the bond between these two. Concerning this bond two phenomena are treated in the literature: (i) the chemical interaction between the fibre and the matrix as investigated e. g. in the early works of [16,18] and (ii) the enhanced bonding behaviour of an additional fibre coating; see as examples [11,31]. This applies both to monofilament fibres and fibres with a layered structure. An example of the former are steel fibres used in conventional fibre-reinforced concrete; examples of the latter are integral glass or carbon fibres consisting of numerous filaments such as those used in textile-reinforced concrete (TRC). Recently the durability of the bond, in particular between fibre and matrix, is investigated more intensely; see e. g. Refs. [4,5,6,26]. Furthermore, there is a good knowledge concerning the response of cementitious composite materials to static loads, which is at least partly applicable to low-cycle, repeated loading as

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well, [13,14].

Whereas the material behaviour of various cementitious composite materials under quasi-static loading has been investigated for several decades, there is little knowledge of the material's behaviour under dynamic loads. If dynamic loads are applied in experimental studies, the main interest at present is in exposures far beyond the elastic limit, [21–23,32,38]. The motivation for these experimental studies is given by the need for impact- and blast-resistant structures, see Fig. 1 for an example of high-performance concrete (HPC) slabs. However, investigations have shown that deterioration is also caused by time-harmonic exposures which are moderate with respect to the elastic limit. This is due to the focusing of waves which are induced by dynamic loading and propagate through the material as shown by, for example [27], for a time-harmonic load and by Ref. [37] for a transient load.

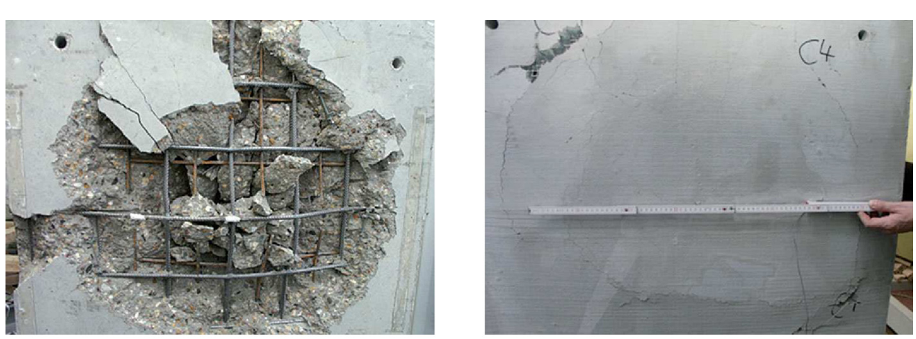
Additionally, the effects taking place within the affected material directly before and during failure from impact or blast loads currently are not completely understood. But this understanding is necessary for an efficient use of high-performance materials in strengthening existing structures, in increasing their impact and blast resistance, and for building new constructions as well. Thus, presently the dimensioning of near-surface strengthening is more or less driven by empirical approaches.

Concerning the reinforcement of the cementitious matrix, several concepts are of practical relevance: (a) dispersed reinforcing, (b) strengthening by means of directed "endless" fibres, and (c) combined forms; see also Fig. 2. As a first step in investigating the impact or blast resistance of reinforced structures from a theoretical point of view, the confinement to concept (b) has been chosen. That is, a directionally reinforced cementitious composite material is being looked at in this work.

Several models exist for describing the scattering behaviour of waves in cement based materials reinforced by monofilament fibres and by multifilament fibres (yarns or rovings). The respective investigations are performed with either electromagnetic, acoustic, or elastic waves. The solution procedure is either numerical or analytical. Both procedures currently project the complex 3*D*-nature of the problem into a so-called plane of observation and consequently solve a 2*D*-problem. In Ref. [8], for example, the propagation of an electromagnetic pulse through a concrete specimen with a single circular steel reinforcing bar was modeled by the finite difference-time domain method. However, the concrete specimen and the reinforcing bar were modeled by square grids. This results in sources of errors as the curved edge of the circular steel bar is thus approximated by squares. An analytical method involving electromagnetic and elastic waves propagating in a material of infinite extent was derived in Ref. [15]. For a computer model of a test specimen numerical investigations were performed to show that (i) the reinforcement influences the scattering behaviour of the applied wave types and (ii) from these wave scattering data the position of the reinforcement within the concrete specimen can be detected by means of an inverse procedure. A drawback of this analytical approach is its restriction to reinforcing having non-varying material properties all over the cross section. Thus, the method proposed in Ref. [15] works very well for conventional reinforced concrete. However, for the present case of reinforcings made of multifilament fibres the method is not applicable due to the inhomogeneous set-up of the reinforcing elements. Beside the analytical or numerical investigations also experimental studies took place. In Ref. [24] ultrasonic pulses were applied to concrete specimens without reinforcing. In this experimental study frequency-dependent velocities of longitudinal and transverse waves were determined by analysing measured data with the method of continuous wavelet transform.

Based on the literature review and the drawbacks of current methods, in this contribution is chosen another approach. Firstly, the complex 3*D*-structure of a multifilament fibre embedded in a cementitious matrix is also projected into a plane perpendicular to the axis of the reinforcing. Secondly, within this plane of observation the 2*D*-wave scattering problem is solved analytically, hence no discretization errors occur. Moreover, the shape of the reinforcings (or other inclusions as well as voids) is taken into account and appropriate ansatz functions are used to solve the wave equation. The method is applicable both to time-harmonic and transient loading conditions. Generally, in such numerical analyses the response of non-cementitious composite materials to time-harmonic loading is examined. Mostly, the scatterers are treated as voids or rigid inclusions; see Refs. [25,28]; respectively [9,39]. modeled a reinforcing as a homogeneous elastic inclusion within an elastic shell, which may be looked at as a monofilament fibre with a surrounding transition zone to the embedding matrix. In the present work, the influence of the inner structure of the reinforcing fibres on the dynamic behaviour of composite materials is investigated by means of an enhanced 2*D*-model of wave scattering. Special attention is paid to the layered centric configuration of these fibres, which is due to the numerous filaments each yarn consists of.

Concerning the composite material, focus is set on TRC, a recently developed composite material consisting of fine-grained concrete as matrix material reinforced by high performance multifilament yarns of glass, polymer or carbon filaments. Here each strand of yarn, or roving, consists of approximately 500 to 3000 filaments, see Fig. 3. As can be seen from Fig. 3, circular or elliptical shapes may be a first approximation of the cross section of



(a) without near-surface steel fabric reinforcement

(b) with near-surface steel fabric reinforcement

Fig. 1. Influence of near-surface steel fabric reinforcement on the impact resistance of HPC slabs, from Ref. [12].