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Research paper

Fuzzy modeling of wave-shielding under consideration of cost-effectiveness for an efficient reduction of uncertainty

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A B S T R A C T

The shielding of waves is an appropriate method to protect human beings, livestock, as well as structures and commercial goods from the harmful effects of dynamic loads. Areas of application of the concept of shielding range from ocean and coastal engineering, acoustics, to civil as well as mechanical engineering. Materials that can be effective in constructing shielding structural components and facilities are primarily cementitious composites as well as various categories of non-cementitious composites. However, the planning and production processes behind these low-cost materials is often characterized by uncertain information regarding their mechanical properties and even their dimensions. This leads to uncertainty in the forecasting of their overall performance, as well as their effectiveness in shielding incoming elastic, acoustic and water waves. In this paper, a new approach is presented which allows for improving these performance forecasts. In the proposed interdisciplinary procedure used here, the cost-effectiveness fuzzy analysis is connected to an appropriate mechanical model describing the shielding of elastic waves. This analysis procedure leads to a reduction of epistemic uncertainty. This can be achieved provided additional monetary investment is made, as proposed for the first time here, in order to improve the production quality of these shielding materials.

1. Introduction

In many fields of engineering application dynamic loads occur. These fields cover e. g. coastal and ocean engineering, civil engineering, environmental engineering, and mechanical engineering. These dynamic loads lead to e. g. water waves, acoustic waves, and elastic waves within the respective material. In order to protect human beings, livestock, as well as structures and commercial goods from the harmful effects of dynamic loads appropriate methods for reducing these dynamic loads are sought. For example, harbours and the ships within are sheltered from water waves by arrangements of breakwaters. The same holds for humans living nearby railway tracks or roads, who are secured against traffic noise by sound protection walls. As a last example, the shielding of elastic waves by composite materials is mentioned. These structures or materials consist of (numerous) scatterers which ideally hinder the respective incoming harmful waves or wavelengths from propagating through the shielding structures.

The effectiveness of such shielding structures is driven by amongst others (i) the number and arrangement of the single scatterers, (ii) the transition condition between these scatterers and the surrounding medium, and iii) if existent, the inner (inhomogeneous) structure of these scatterers. It is emphasized that not only dynamic loads leading to immediate failure or damage are of concern. As can readily be seen from the example of traffic over a bridge, also dynamic loads leading to exposures below a certain critical value (e. g. the elastic limit) have enormous practical relevance. Thus, within this contribution elastic waves are presupposed which propagate through composite materials made from constituents whose material behaviour is modelled as linear elastic and isotropic.

However, in practical applications the designing engineer has to deal with uncertain input data (e. g. the material configuration) which result in uncertain output data (in the present case the forecast variable “wave-shielding degree”). But reducing this uncertainty needs monetary investments. Thus often the question arises whether a doubled effort results in a doubling in preciseness of the forecast variable. The cost-effectiveness fuzzy analysis is an appropriate method to answer this question and to evaluate how effective (additional) monetary investments reduce the uncertainty

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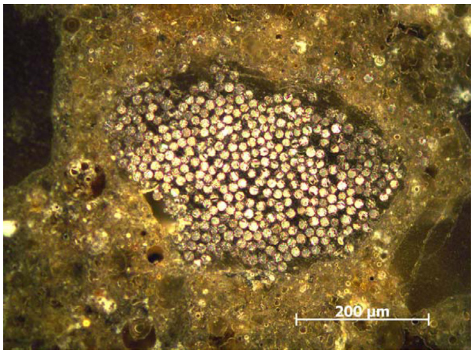

Fig. 1. Typical cross-section of a fibre, by courtesy of Institute of Construction Materials, Technische Universität Dresden.

in the forecast variable. Within this contribution a new interdisciplinary approach is presented which allows for an efficient reduction of uncertainty of the wave-shielding degree by means of an appropriate mechanical model which is solved semi-numerically and by means of cost-effectiveness fuzzy analysis. For the best knowledge of the authors this is the first work where such an interdisciplinary procedure is performed.

To cope with the motivated task an overview over parameters influencing the wave scattering behaviour is given in Section 2. Within Section 3 the deterministic model of the wave-shielding problem for elastic waves is sketched and solved for an exemplary configuration. After the example is introduced, the necessary theoretical background of the cost-effectiveness fuzzy analysis as well as of the fuzzy analysis is discussed in Section 4. Based on these findings the cost-effectiveness fuzzy analysis is performed for the mentioned example of wave-shielding. Finally, major conclusions and a summary are given in Section 5.

2. Parameters influencing the wave scattering behaviour

If waves are to be shielded by structures made of composite materials, the respective material has to be investigated more precisely. In civil engineering, cementitious composite materials are used. One example is textile reinforced concrete (TRC). An overview over some characteristics is given in e. g. [4]. In general, cementitious composite materials consists of a cementitious matrix in which strengthening fibres made of steel, glass, or carbon are embedded. Concerning these fibres, both monofilament fibres and fibres with a layered structure exist. An example of the former are steel fibres used in conventional fibre-reinforced concrete; examples of the latter are integral glass, carbon or steel fibres consisting of numerous filaments such as those used in TRC. Herein, each fibre consists of up to 3 000 filaments as shown in Fig. 1 for the case of a glass fibre. Also fabrics consisting of such fibres are used as reinforcement elements, see e. g. [8]. The material behaviour of TRC and other cementitious composite materials under static loads is quite well understood. Basically, it is influenced by 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, see e. g. [26]. For experimental investigations covering the matrix material it is referred to [2]. Concerning the bonds between matrix and embedded fibres, mainly two phenomena are dealt within scientific literature: Larner et al. [12] investigated the chemical interaction between the fibre and the matrix, whereas the enhancement of the bonding behaviour by means of an additional fibre coating was subject of the works of Scheffler et al. [24]. More recently, the material behaviour also under low-cycle, repeated loading was investigated in [9,10]. It should be noted that the "bonds" between the fibres and the matrix do not possess a singular character but physical dimensions. Thus, the term (interfacial) transition zone or interphase is used in what follows, see also [30]. What is still missing is a deep understanding of the material behaviour under dynamic loads. To close this gap, first experimental studies were performed. However, the focus of these studies is on exposures far beyond the elastic limit. This is due to the need for impact- and blast-resistant structures, see Fig. 2. However, these studies are restricted to pull-out experiments of single fibres, [15] or to experiments at the macro-scale [8] which do merely allow to draw conclusions concerning the material behaviour at the micro- or meso-scale. But also dynamic loads below a certain critical value – for example the elastic limit – may lead to the deterioration of the respective material. This is due to the focusing of (stress-)waves propagating through the material. This was exemplarily shown in [20] for a time-harmonic load and in [29] for a transient load. A deep understanding of the effects taking place within the affected material directly before failure from impact or blast loads is sought. Hence, the underlying model of the present contribution is on elastic waves propagating through a composite material made from constituents whose material behaviour is modelled as linear elastic and isotropic.

Several amouring concepts are used in engineering practice: (i) dispersed armouring, (ii) armouring by means of directed reinforcing elements, and (iii) combined forms. Within this contribution we restrict ourselves to concept (ii). For taking into account both the inner structure of the reinforcement elements – each fibre consists of approximately 500 to 3 000 filaments – and the surrounding interfacial transition zone, the mechanical model should allow a layered structure of each fibre. Thus, treating the

(a) without near-surface steel fabric reinforcement (b) with near-surface steel fabric reinforcement

Fig. 2. Illustration of the influence of near-surface steel fabric reinforcement on the impact resistance of high-performance concrete slabs, taken from Hummeltenberg et al. [8]. The underlying mechanical model of the present contribution is on elastic waves.