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Material modeling for the simulation of quasi-continuous mode conversion during Lamb wave propagation in CFRP-layers

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ABSTRACT

The homogenization of material parameters layer by layer is a mostly sufficient method for the simulation of Lamb wave propagation in carbon fiber reinforced plastics. But since current experimental investigations of the wave behavior in undamaged CFRP structures reveal an effect called "quasi-continuous mode conversion", which can not be reproduced with this layer-wise homogenization procedure, an improved material model for the finite element analysis of the Lamb wave propagation is presented in this work. The used 2D plane strain state model considers the random distribution of fibers in the matrix material on the microscale by homogenized subdomains and thereby properly capture the "quasi-continuous mode conversion" effect. Numerical investigations of the influence of the material model on the developing wave modes in a unidirectional layer will complete the work.

1. Introduction

Modern infrastructure includes a vast variety of structural systems which have to be kept under surveillance in order to avoid malfunction and accidents. Typical examples are steel and concrete bridges, pressure vessels, railway tracks, and transmission lines, to name just a few. Especially aerospace structures are in the focus of improved inspection techniques since a considerably amount of life cycle costs is due to inspection and repair and since damage can lead to catastrophic failure. A reliable monitoring technique would allow for adjusted maintenance intervals in accordance to the real requirements so that a reduction of the operating costs can be expected.

Because of the reasons above mentioned, current research on structural health monitoring methods and non-destructive testing techniques aims at the fast, efficient, and reliable detection of visible and hidden structural damages in engineering structures.

The difficulty in identifying the damage is often caused by the complex phenomena of damage initiation and evolution including various failure modes which have to be detected reliably. Among others, techniques based on elastic waves play an important role for damage detection. In plate and shell structures, especially high frequency waves, i.e. guided waves or Lamb waves, cf. Graff [4], and their possible contributions to structural health monitoring methods are in the focus of current research, cf. Giurgiutiu [3]. Reflections, refractions or mode conversions are distinct indications of faults or defects and are often instantaneous visible in the pattern of an otherwise undisturbed propagating wave.

Beyond that, the increasing application of fiber reinforced plastics for application in lightweight structures is currently demanding for advanced monitoring techniques. Thus Lamb wave based techniques are investigated for potential use in carbon fiber reinforced plastic structures. However, with the anisotropic behavior of this class of materials and their layered structure in mind, the arising physical phenomena are more complicated and the interpretation of the observed Lamb wave behavior becomes more challenging, cf. Rose [9].

This work deals with the observation of a phenomenon which is called "quasi-continuous mode conversion", cf. Neumann et al. [8] and Willberg et al. [10]. It appears after the fastest guided wave (S_0-wave in isotropic solids) has passed the observed area and before the second-fastest wave (A_0-wave in isotropic solids) arrives. In this time period, regular patterns occur which are not seen in isotropic solids. This phenomenon is observed in thin-walled fiber reinforced plastic material with arbitrary fiber orientation and lay-up or with woven fabrics.

The manuscript is structured as follows: First, the experimentally observed quasi-continuous mode conversion is described in detail. In a next step, possible reasons of the quasi-continuous mode conversion are discussed and the material inhomogeneity

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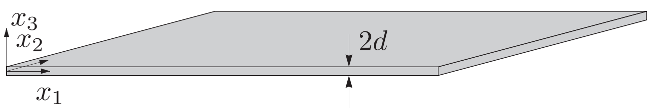

Fig. 1. Infinitely extended plate (in $x_1 - x_2$-plane) with coordinate system.

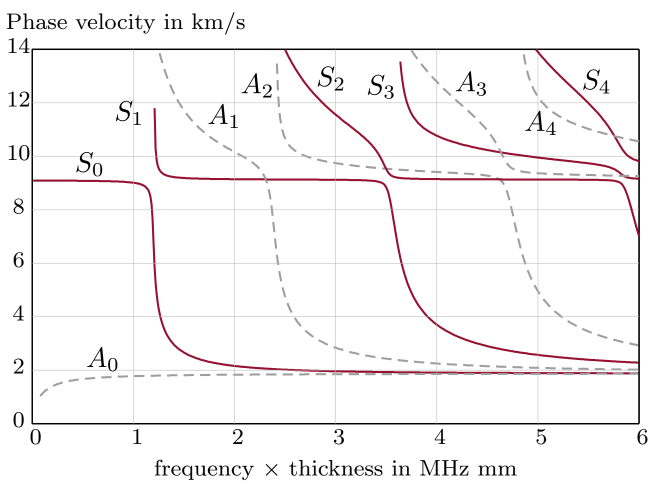

Fig. 2. Dispersion diagram of a single unidirectional layer in fiber orientation (0°-layer).

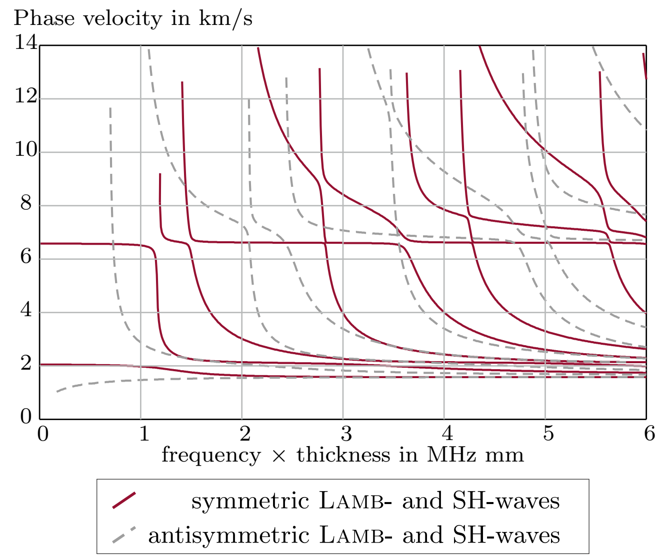

Fig. 3. Dispersion diagram of a single unidirectional layer in fiber orientation (45°-layer).

is identified as the source. Then, a stochastic inhomogeneity is implemented into the material law, cf. Hennings [5]. Subsequently, numerical investigations show that this phenomenon can be captured in this way.

2. Theoretical foundations

2.1. Waves in elastic plates

Based on the linearized strain–displacement-relation (linear Green–Lagrangian strain tensor **E**)

$$\mathbf{E} = \frac{1}{2}\left(\text{grad } \mathbf{u} + \text{grad}^T \mathbf{u}\right), \tag{1}$$

generalized Hooke's law

$$\boldsymbol{\sigma} = \mathbb{C} : \mathbf{E} \tag{2}$$

and the balance of momentum

$$\text{div } \boldsymbol{\sigma} + \rho \mathbf{b} = \rho \ddot{\mathbf{u}}, \tag{3}$$

the general formulation of the wave equation is obtained by combining those equations and disregarding the body forces **b**, cf. Eq. (3)

$$\text{div}(\mathbb{C} : \text{grad } \mathbf{u}) = \rho \ddot{\mathbf{u}}. \tag{4}$$

In Eqs. (1)–(4), **E** denotes Green's strain tensor and $\boldsymbol{\sigma}$ marks the Cauchy stress tensor. Variable **u** represents the displacement field, **b** – as noted above – the distributed volume specific body forces and ρ is the mass density. The differential operator grad(.) resp. div(.) identifies the gradient resp. divergence of a tensor field (.) and a superimposed dot indicates differentiation with respect to time.

In the case of isotropic material Hooke's law can be expressed by the Lamé-constants λ and μ and Eq. (4) may be rewritten as

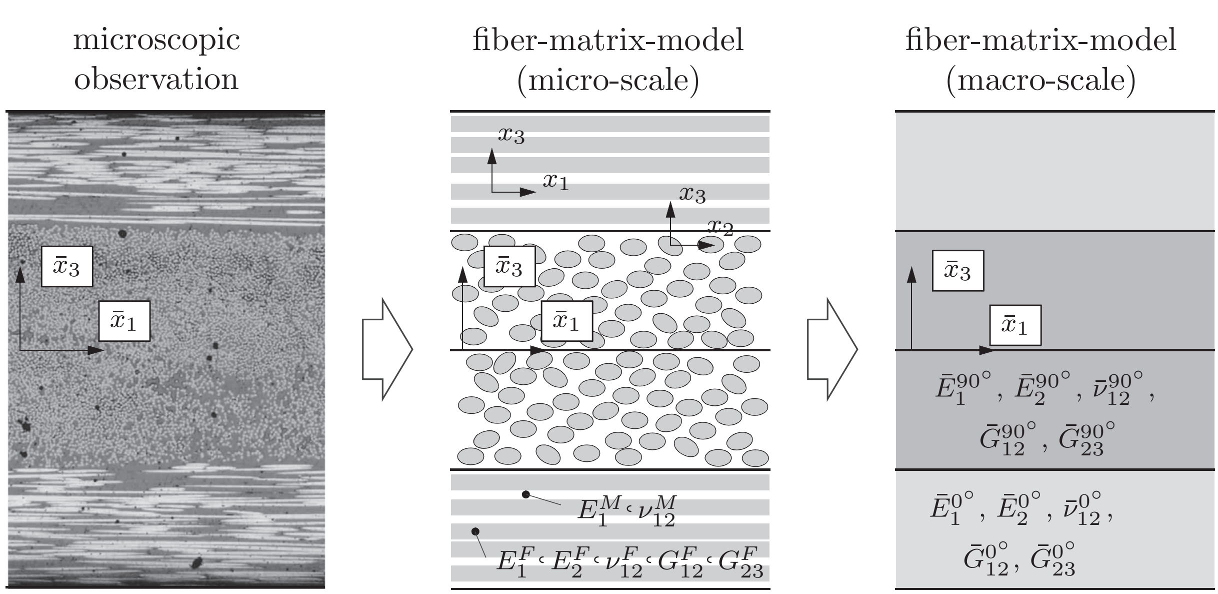

Fig. 4. Material modeling: from microscopy to fiber-matrix-model.