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Determination of elastic constants of glass/epoxy unidirectional laminates by the vibration testing of plates

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Abstract

Identification of elastic properties of unidirectional glass/epoxy laminates from the measured eigenfrequencies has been performed. The stiffness of the laminates has been investigated by a mixed numerical/experimental method employing the vibration test of plates. Elastic constants of laminates have been determined by using an identification procedure based on experiment design, the finite-element method and the response-surface approach. Elastic properties of laminates with two different fibre-surface treatments have been compared. It was found that only for the transverse elastic modulus is there a statistically significant difference between the composites with good and poor fibre/matrix adhesion. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The transverse properties of unidirectional composite laminates such as stiffness, strength, delamination fracture toughness, etc., depend on the fibre/matrix adhesion quality. The influence of interfacial effects on the mechanical properties have been studied in Refs. [1–6] and others. Different experimental, analytical and numerical methods have been used in order to model the interface behaviour. Among the experimental methods mainly are used such as fibre pull-out, fragmentation, transverse tension and shear and other destructive methods. Some non-destructive methods are discussed in [5] and other papers. One non-destructive method for studying the elastic properties of laminates is the vibration test [4,7], which is based on identification of elastic constants from the measured natural frequencies.

During recent years investigations for developing a new technique for material identification, the so-called mixed numerical–experimental technique, have started [8–19]. The determination of stiffness parameters for complex materials such as fibre-reinforced composites is much more complicated than for isotropic materials since composites are anisotropic and non-homogeneous. Conventional methods for determining stiffness parameters of the composite materials are based on direct measurement of strain fields. Boundary effects, sample-size dependencies and difficulties in obtaining homogeneous stress and strain fields are some of the most serious problems. Because of this, indirect methods have recently received increasing attention. One such indirect method is based on measurements of the structure response and application of the numerical–experimental identification technique.

Mixed numerical–experimental methods are sensitive for model errors because the numerical model is always based on a series of hypotheses. If the real structure does not satisfy one or more of these hypotheses, the model of the structure is evidently not appropriate. Since the development of mixed numerical–experimental techniques for material identification is aimed at obtaining a practical method which yields quick and reliable results, much research has been done in order to minimise these model errors [8,20,21].

In the meantime many different approaches were produced for identification of the physical parameters directly characterising structural behaviour (i.e. Young's modulus and density of the material). In [11] appropriate comparisons were made between actual eigenfrequencies of an existing structure and those obtained through the finite-element analysis. This led to

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the identification of parameters which can be used for the model calibration as well as for the detection of damaged zones in the structure.

Numerical–experimental identification methods are mainly used in structural applications [8–19]. For example, in [8] elastic properties of laminated composites have been identified by using experimental eigenfrequencies. The stiffness parameters were identified from the measured natural frequencies of the laminated composite plate by direct minimisation of the identification functional. A similar approach to identifying the stiffness properties of the laminated composites was used in [18,19,22]. In [20] an improved plate model was used for identification of elastic constants of the laminate. In [23] it was shown that the mixed numerical–experimental method can also be used for identification of damping properties of polymeric composites.

In the present study the numerical–experimental method for identification of mechanical properties of laminated polymeric composites from the experimental results of the structure response has been further developed. The difference between the conventional [8,20] and the present approach is that, instead of direct minimisation of the identification function, experimental design is used, by which response surfaces of the function to be minimised are obtained. The response surface approximations are obtained by using information on the behaviour of a structure in the reference points of the experiment design. Note that finite-element modelling of the structure is performed only in the reference points. The function to be minimised describes the difference between the measured and numerically calculated parameters of the response of structure. By minimising the function the identification parameters were obtained. The method was employed to identify the elastic properties of the laminates from the measured eigenfrequencies of the plates. The main advantage of the present method is a significant reduction of the computational effort. Previously this method was used for the solution of the optimum design problems [24–27].

In the present study the numerical–experimental method has been applied for identification of elastic properties of glass/epoxy laminates with two different fibre-surface treatments. Experiments were performed on laminated plates and about 16 natural frequencies were measured. Elastic properties obtained from vibration tests have been compared with those from the transverse tensile test.

2. Experimental

2.1. Material

Unidirectionally reinforced laminates were produced from E-glass fibres (12 μm, 63 tex) with two different types of surface treatments. The first type was treated by epoxy dispersion with aminosilane to promote good fibre/matrix adhesion. More details about this fibre treatment can be found in [28,29]. For this composite the notation EP is used. The second type was sized with polyethylene to prevent fibre/matrix adhesion. For this composite the notation PE is used. A Ciba Geigy Ltd. Araldite epoxy system (LY556/917/DY070) with an ultimate tensile strain of 3.3% was used as the matrix material.

Unidirectionally reinforced test samples were produced on a winding machine. The content of micropores was below 0.75% by volume. The glass fibre-reinforced plates (see Fig. 1) were prepared with given geometric parameters. The total number of plies was eight in order to get a plate thickness of approximately 2 mm. The EP and PE laminates were produced by following the standard cure cycle recommended by Ciba Geigy Ltd. To improve the quality of the plates and to reduce the void content, the plates were placed in a vacuum before curing. Specimens were cut out with a diamond wheel and kept under standard conditions (23°C and 50% of relative humidity) until testing. All tests were performed in the same conditions. The fibre content of the specimens was about 50 ± 1.5 vol%. The density was measured for each specimen. The specimen geometric parameters and density ρ for the unidirectionally (UD) reinforced PE composite plates are presented in Table 1. Similar data for the EP composite plates were given in [7].

2.2. Vibration tests

The eigenfrequencies of the test plates were measured by a real-time television (TV) holography. The samples having mean dimensions of 140 mm×140 mm×2 mm were hung upon two threads in order to simulate free–free boundary conditions. The sample was located in front of the holographic testing device. A piezoelectric resonator (sensor) was glued on one corner to excite the sample plate at increasing frequencies. The sensor is of

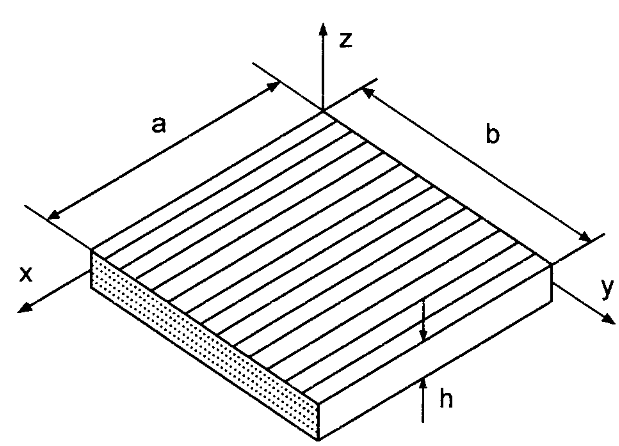

Fig. 1. Geometry of the unidirectionally reinforced plate.