Composite Structures 94 (2012) 3327–3335

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Vibration damping properties of steel/rubber/composite hybrid structures

E. Sarlin [a,*], Y. Liu [b], M. Vippola [a], M. Zogg [b], P. Ermanni [b], J. Vuorinen [a], T. Lepistö [a]

[a] Department of Materials Science, Tampere University of Technology, P.O. Box 589, 33101 Tampere, Finland
[b] Centre of Structure Technologies, ETH Zurich, Switzerland

ARTICLE INFO

Article history:
Available online 19 May 2012

Keywords:
Hybrid structures
Vibration damping
Loss factor
Rule of mixtures

ABSTRACT

By using hybrid structures, attractive and advantageous combinations of material properties can be achieved. In addition to the combination of good mechanical properties and low weight, also dynamical properties can be enhanced by suitable materials selection. However, the hybrid structure properties depend on the properties of the constituent materials as well as on the interfacial properties.

In the present study, the damping properties of laminated structures consisting of steel, rubber or epoxy adhesive and glass fibre reinforced epoxy composite were studied. Damping properties of the structures were investigated through the loss factors. The loss factors of the hybrid structures and the constituent materials were determined by frequency and time domain test methods. By using the loss factor results of the constituent materials, the loss factor of the hybrid structures were estimated by the rule of mixtures and the results were compared with the experimental results. It was observed, that the use of weight fractions instead of volume fractions in the rule of mixtures provides a good average estimation of the damping behaviour of the hybrid structure and the results of rule of mixtures method can be used as rough estimates during the design phase of hybrids of this kind.

1. Introduction

Hybrid structures enable the utilisation of the most advantageous material properties of different material grades and incorporation of them into one structure. A typical desired material property combination of hybrid structures is low weight combined with good mechanical properties. The number of beneficial property combinations is numerous, since the constituent materials of a hybrid structure may have substantially different material properties.

The manufacturing stage of a hybrid structure is usually challenging. Especially in laminated hybrid structures, in which macroscopic mechanical interlocking between the layers is unfeasible, the attainable adhesion level between the constituent materials may be insufficient. Since the interface quality often determines the service performance of the structure, additional surface treatments or adhesion layers are generally applied in hybrid laminates. Within steel/polymer hybrids, chemical surface treatments such as etching and anodizing [1–3], or additional interface layers such as coupling agents, adhesives, or coatings [2–4] are used to achieve good adhesion level. In addition, surface roughness of steel is often increased by grit blasting to enhance the interfacial strength. The use of chemical surface treatments usually highlights the issue of noxious chemicals and thus the use of additional interface layer may be favoured. However, the drawbacks of the surface treatments are increasing manufacturing time and costs and thus it would be beneficial if they would not be needed.

Rubbers can be modified with additives to achieve good bond strength with steel as well as with polymers without surface pretreatment [5,6] and thus it is a potential adhesive material. In addition to good adhesion properties, the viscoelastic nature of rubbers can be utilised in hybrid structures: the elasticity can equalise the internal stress concentrations at the interfaces and the good energy absorption properties can improve the dynamic properties of the structure. Further, the rubber can be vulcanized directly between steel and composite layers, which ensures a simple manufacturing process. However, in spite of its potential, rubber has not yet been widely used as adhesive in metal/polymer hybrids.

In an engineering system, a structure should stay stable and undamaged despite of the internal and external vibrations. The stability of a system depends on its damping ability, which can be affected by design. Damping is defined as the energy dissipation of a system in vibration and it can be presented by various parameters, one of which is the loss factor. Loss factor η is defined as the specific damping capacity D per radian of the damping cycle [7]:

$$\eta = \frac{D}{2\pi} = \frac{\Delta U}{2\pi U_{max}}, \quad (1)$$

where ΔU is the energy loss per cycle and U_{max} is the total stored reversible energy of the system. Parameters ΔU and U_{max} can be measured through the area and the shape of the hysteresis loop

* Corresponding author. Tel.: +358 408490146.
E-mail address: essi.sarlin@tut.fi (E. Sarlin).

0263-8223/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2012.04.035

in a stress–strain diagram of the damping cycle. The loss factor corresponds to the phase angle between strain and stress (tan δ) in Dynamical Mechanical Analysis (DMA):

$$\eta = \tan\delta. \quad (2)$$

In addition, the loss factor can be defined as the ratio of loss and storage moduli:

$$\eta = \frac{E''}{E'}. \quad (3)$$

Loss factor can be determined by several different methods, which are divided in two categories: frequency domain and time domain tests. Examples of the frequency domain methods are the half-power point and the magnification-factor methods, and examples of the time domain methods are logarithmic decrement and hysteresis loop methods [7,8].

The estimation of the dynamical properties with an effective method would be beneficial during the design phase of a hybrid structure. Since 1970s, there has been an attempt to derive an expression for the loss factor of a reinforced composite [9], but it has been found to be highly sensitive to fibre architecture [10,11]. Instead, as a simpler approach to estimate the dynamic properties of composites, rule of mixtures could be used. Hashemi et al. [12] have studied the impact strength values of glass fibre/glass bead reinforced hybrid composites and found a positive deviation for the rule of mixtures behaviour when compared to the experimental data. However, if research is focused on hybrid structures where composite is one of the constituents, the composite component can be represented with homogenous equivalent component and the rule of mixtures can be applied for the hybrid structure. For example, Botelho et al. [13] have used the rule of mixtures for aluminium based fibre metal laminates and found, similarly to the Hashemis results, a positive deviation for the estimated loss factor values when compared to experimental results. However, in [13], the effect of the aluminium/composite interface was not taken into account.

In the present study, the damping properties of hybrid structures based on alloy steel sheets and glass fibre reinforced plastic composite layers were studied. Both cold rolled and stainless steel grades were used. A thin EPDM based rubber layer or a commercial epoxy adhesive was used as an adhesive leading to four different hybrid structure types. The loss factors of the hybrid structures and the constituent materials were determined by two methods, based on frequency and time domain testing. The loss factor of the plain rubber was determined with dynamical mechanical analysis. By using the loss factor results of the constituent materials, the loss factor of the hybrid structures were estimated by the rule of mixtures and the results were compared with the experimental results.

Table 1
The samples used in the damping tests and the nominal thicknesses of the components.

Sample	Metal	Adhesive	GFRP
1	Cold rolled steel 0.5 mm	EPDM grade A 0.5 mm	GFRP 1.3 mm
2	Cold rolled steel 0.5 mm	EPDM grade A 1.0 mm	GFRP 1.3 mm
3	Cold rolled steel 0.5 mm	EPDM grade A 1.5 mm	GFRP 1.3 mm
4	Stainless steel 0.5 mm	EPDM grade B 0.5 mm	GFRP 1.3 mm
5	Stainless steel 0.5 mm	EPDM grade B 1.0 mm	GFRP 1.3 mm
6	Stainless steel 0.5 mm	EPDM grade B 1.5 mm	GFRP 1.3 mm
7	Cold rolled steel 0.5 mm	Epoxy adhesive 0.14 mm	GFRP 1.3 mm
8	Stainless steel 0.5 mm	Epoxy adhesive 0.19 mm	GFRP 1.3 mm
9	Cold rolled steel 0.5 mm	–	–
10	Stainless steel 0.5 mm	–	–
11	–	–	GFRP 1.3 mm

2. Materials and methods

2.1. The samples

In this study, laminated structures of steel and glass fibre reinforced plastic (GFRP) composites were studied. As an adhesive between the steel and GFRP layers, an EPDM based rubber or an epoxy adhesive was used. Two kinds of steels were used: cold rolled steel EN 10130 DC01 (Ruukki Oy, Finland) and stainless steel AISI 304 (Outokumpu Stainless Oy, Finland). The surface of the cold rolled steel has been passivation treated and the stainless steel surface finish is one of the most widely used grade 2B (cold rolled, heat treated, pickled and skin passed). The GFRP layers were manufactured by vacuum infusion from 0/90 E-glass fibre mats (682 g/m^2) and Sicomin SR 1660/SD 7820 epoxy. The fibre content of the GFRP was 46%. The heat resistant epoxy was chosen to provide the

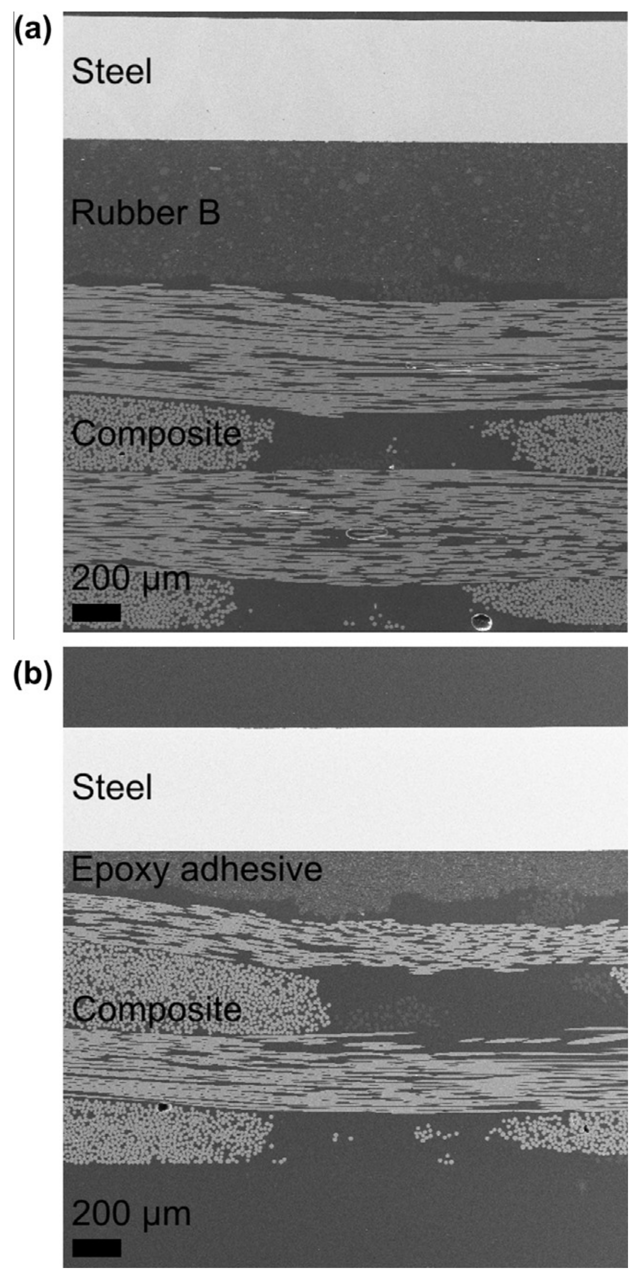

Fig. 1. Cross-sections of (a) the stainless steel/rubber/GFRP hybrid and (b) the stainless steel/epoxy adhesive/GFRP hybrid.