EXPERIMENTAL DATA ON DAMPING OF ADHESIVELY BONDED SINGLE-LAP JOINTS

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Abstract

The paper provides experimental data on vibration damping of adhesively bonded single-lap joints with steel adherends. Modal testing has been performed with several joints, using different adhesive materials. Additionally, the adhesive materials mechanical and damping characteristics have been determined in a DMTA test. The mechanical properties of the adhesives have been measured also in a tensile test. Finally, the lap shear strength of the single-lap joints was measured.

Keywords

Vibration, Damping, Joints, Experiments

1. INTRODUCTION

Structural damping has become a more and more important property in many applications. For example, passenger comfort in many vehicles can be enhanced by increased structural damping. Also, fatigue life of machinery can be extended by increasing the structural damping of certain components.

The term ’damping’ as used here refers to the energy-dissipation of materials or structures under cyclic stress but excludes energy-transfer devices such as dynamic absorbers. With this definition, energy must be dissipated within the vibrating system. The energy of the vibration is dissipated into a non-recoverable form of energy, in most cases in heat.

As in many other structures, the damping of multimaterial products is composed of material damping and damping due to mechanical construction. A possible domination of the damping due to mechanical construction depends on the complexity of the structure and on the type, number and stress state of the joints.

There is a large number of mechanisms by which vibrational energy can be dissipated within the volume of a material element. These mechanisms are usually associated with internal reconstructions of the micro and macro structure, ranging from crystal lattice to molecular scale effects. The majority of published information on material damping is of empirical nature and the underlying physical effects are not fully understood.

The mechanisms of energy dissipation at structural joints and discontinuities are complex. Friction is involved in many mechanical joints (as in bolted and riveted joints). The stress concentrations near the joints and at the joint interfaces lead also to increased damping.

For analysis and testing purposes, several mathematical models are used to represent damping. It should be noted that these models do not necessarily imply a particular mechanism for energy dissipation:

- viscous damping (damping force proportional to the velocity)
- hysteretic damping (damping force proportional to the displacement)
- Coulomb damping (damping force is constant).

Various tests are used to quantify the damping of materials and structures and several measures are frequently used for damping:

ψ	specific damping capacity
η	loss factor
Δ	logarithmic decrement
ζ	damping ratio
Q	Q-factor
dW/W	ratio of dissipated and stored energy
$\tan\delta$	tangent of the phase angle.

Additional information about the corresponding test methods and definitions of these measures can be found in the literature [1].

The relationship between these measures is expressed in Formula 1, which is valid for harmonic vibration at resonance. [2].

$$\eta = \psi/2\pi = dW/2\pi W = 1/Q = 2\zeta = \Delta/\pi = \tan\delta \quad \text{..........................} \quad (1)$$

When comparing the results of different tests it is important to take into account the possible differences in stress level and stress distribution of the tested specimens as these have an influence on the quantity of damping.

2. DAMPING IN JOINTS

The damping due to mechanical construction (e.g. joints and discontinuities) in many complex metal structures is dominant compared to the low damping of the metallic material itself. Local and discontinuous joints (spot welds, short intermittent welds, rivets, bolts, screws) can effectively contribute to the damping behaviour of the whole structure. Friction, which dissipates energy during the vibration of a structure, is always present in mechanical joints. This vibrational damping occurs when small relative movements take place between the joint interfaces. However, the information available on the damping behaviour of structural joints is rather limited and not sufficient for optimising damping at the design stage of the product. Relatively few are also the studies that compare the damping behaviour of alternative joining methods.

Adhesive bonding also provides attractive solutions for achieving joints with high damping [3-5]. Tough structural adhesives (e.g. modified epoxies and polyurethanes) have excellent strength and good damping properties due to their viscoelastic behaviour.

Due to the shear and peeling stress peaks normally present at the edges of the adhesive bond line, local stresses are high, thus emphasising the damping properties of the adhesive joint.

Srivatsan et al. [3, 4] measured the damping of adhesively bonded steel-steel double-lap joints in flexural vibration at frequencies of around 250 Hz. A plasticised epoxy resin was used as adhesive. For joints without defects they achieved specific damping capacities (ψ) of 16%. Introducing defects (partly debonded joint area) the specific damping capacity increased significantly but, naturally, the strength of the joints decreased considerably.

There is hardly any literature about the damping behaviour of adhesively bonded joints between dissimilar materials. Nevertheless, the damping effects arising in adhesively bonded joints are fairly similar regardless of the adherends being of similar or dissimilar materials.

The presence of joints is essential in multimaterial products. Consequently, joints offer a major potential for passive vibration control.

3. PREDICTION METHODS OF STRUCTURAL DAMPING

Although structural damping has been the subject of many recent studies, it remains a relatively poorly understood phenomenon. The confidence of any analytical prediction method lies far below comparable structural analyses [6]. Theoretically the finite element method (FEM) allows to analyse the manifold damping features of structures as it is possible to include damping in the analysis in several manners. Damping effects can be introduced by using discrete damping elements, by introducing modal damping or through the material model (for instance using a viscoelastic material model). In practice, although some FEM-codes do allow to include damping in several ways into the model, there are many obstructions in the way towards a successful structural damping analysis.

Material input data which would be accurate enough for the damping models used in the analyses is not yet available. At present, damping materials, developed specifically for damping layers, are the only group of materials for which sufficient experimental values have been generated, i.e. damping has been measured as a function of frequency and temperature.

Often, much of the damping is due to joints and structural discontinuities. Thus, to achieve confidence in the analysis, these regions should be modelled very accurately, in practice with a considerably finer mesh than normally used in a structural analysis. Provided that the damping behaviour of the joints and discontinuities will become better understood, it is also possible in certain cases to use discrete dampers to model the damping behaviour of these regions.

In brief, a reliable analysis of structural damping requires not only a highly evolved FEM-program but also a better understanding of the damping properties of structural materials and joints, a very accurately meshed structural model and in most cases a non-linear analysis method.

In the next chapter, experimental vibration damping data is provided for adhesively bonded single-lap joints. This data can be used to compare, verify and further develop methods for assessing structural vibration damping in adhesively bonded joints.

4. TESTED MATERIAL

Adhesively bonded single lap joints have been manufactured with various adhesives. Additionally, some bolted, bolted/bonded and welded alternatives with similar geometries have been made for comparison.

The adherends are of steel (AISI304) and their size is 225×50×2 mm. Before bonding, the surfaces of the adherends have been cleaned with acetone, grit-blasted (aluminium oxide) and cleaned again. Then, the specimens have been adhesively bonded. The overlap length is 50 mm, resulting in a total length of the joint specimen of 400 mm. The thickness of the adhesive layer was controlled during the manufacturing of the joints, resulting in bond line thickness of 0.2, 0.5 or 2.5 mm.

Several adhesive materials have been used, as shown in Table 1.

Table 4. Adhesive materials used in the different specimens

Specimen	Adhesive type	
A	2K polyurethane	Henkel Makroplast 8202 + 5430
B	2K epoxy	Eurepox 710 + 140
C	2K epoxy	3M DP 110
D	2K epoxy	Ciba AV 138
E	2K epoxy	3M DP 460
F	2K polyurethane	Teopur 4012
G	2K polyurethane	Kiilto Kestopur PL 240
H	1K polyurethane	Sikaflex 360 HC (0.5 mm thickness)
I	1K polyurethane	Sikaflex 360 HC (2.5 mm thickness)
K	Hot Melt	Hot Melt Bostik 9951

5. EXPERIMENTS

The following experiments have been performed:

- Lap joint modal test

The experiments have been performed as follows:

Two additional steel masses (each 0.98 kg) have been attached to both ends of the specimens in order to decrease the eigenfrequencies of the specimens. The size of the steel masses was 80×40×40 mm.

During the modal testing the specimens were allowed to hang freely supported by one flexible rope attached to the steel mass on the other end of the specimen. The test was carried out by applying the impact hammer method in which the structure is excited into vibration by using a proper instrument hammer. Frequency Response Functions (FRF) in form of acceleration/excitation force [$m/s^2/N$] for the same seven response locations on each test specimen were measured using an 8-channel HP3566A/67A spectrum analyser. Seven accelerometers of types Brüel&Kjær 4393 and 4375 (each weighing about 2.5 grams) were used to measure vibration responses. A force transducer of type Brüel&Kjær 8200 was used to measure the impact force. Figure 1 illustrates the test arrangement.

Measured FRFs were analysed using SMS Star Strct modal analysis program to get the natural frequency and damping data for the first bending and torsional mode of each test specimen.

Figure 1. Arrangement of the modal test.

- Lap joint tensile test

The lap joint tensile test was performed on a universal testing machine at a speed of 2 mm/min. As a result, the mean shear strength of the joint has been obtained.

- Adhesive tensile strength

The tests were performed according to the standards ISO/DIS 527 at a loading rate of 2 mm/min. As a result, tangent modulus, maximum strength and elongation at break have been obtained. Additionally, the stress-strain curves are also shown.

- Adhesive DMTA

The dynamic mechanical thermal analysis (DMTA) has been made in the torsional mode. Modulus and loss factor are obtained as a result over a temperature range between -20 and 100°C (between -80 and 100°C for adhesive K). The testing frequency has been 10 Hz.

6. RESULTS

The experimental results are summarised in Table 2. Additionally, the DMTA and adhesive tensile test results are shown in Figures 2, 3 and 4.

Table 5. Summarised test results. All values at 20 °C. The joint modal, joint tensile test and adhesive tensile test results are mean values of three specimens. Damping values are given in percentage of critical damping (c/c_{cr}).

		Modal test				**Joint tensile test**	**Adhesive tensile test**			**DMTA**	
	adhesive layer thickness [mm]	damping (torsion) [%]	frequency (torsion) [Hz]	damping (flexure) [%]	frequency (flexure) [Hz]	Mean shear strength [MPa]	Tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Adhesive damping (tan δ) [-]	Adhesive torsional modulus [MPa]
A	0.2	0.112	53.9	0.262	33.7	13.1	13.9	341	50.9	0.085	1079
B	0.2	0.139	53.8	0.179	33.6	11.7	36.4	2570	1.5	0.013	1092
C	0.2	0.144	54.5	0.173	34.7	14.3	26.8	1470	11.5	0.060	921
D	0.2	0.088	54.0	0.151	34.1	12.2	24.5	3940	0.8	0.014	1654
E	0.2	0.114	54.2	0.133	34.1	15.0	38.1	2790	3.9	0.013	941
F	0.2	0.311	53.9	0.516	34.0	10.3	8.6	197	21.7	0.066	1202
G	0.2	0.345	53.7	0.466	33.5	9.94				0.096	1264
H	0.5	0.149	50.6	0.209	30.8	6.20	7.6	16	296	0.202	5.01
I	2.5	0.119	51.0	0.215	31.7	8.11	7.6	16	296	0.202	5.01
K	0.2	0.669	52.0	0.73	32.2	3.44					

The damping of the steel base material, tested correspondingly with a 400 mm long specimen without a joint is 0.048 and 0.095 in torsion and flexure, respectively.

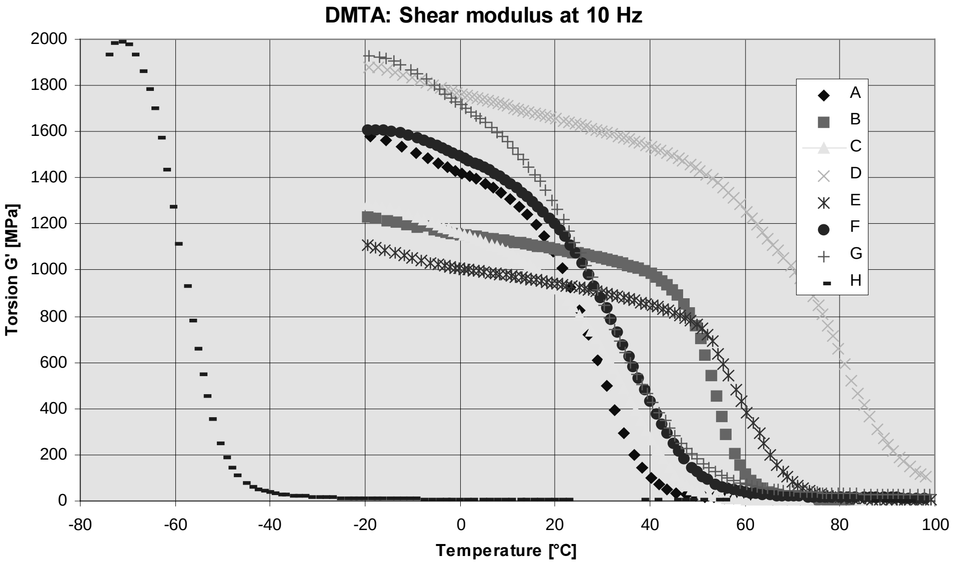

Figure 2. Shear moduli of the adhesives as a function of temperature as measured in the DMTA in torsion. Testing frequency is 10 Hz.

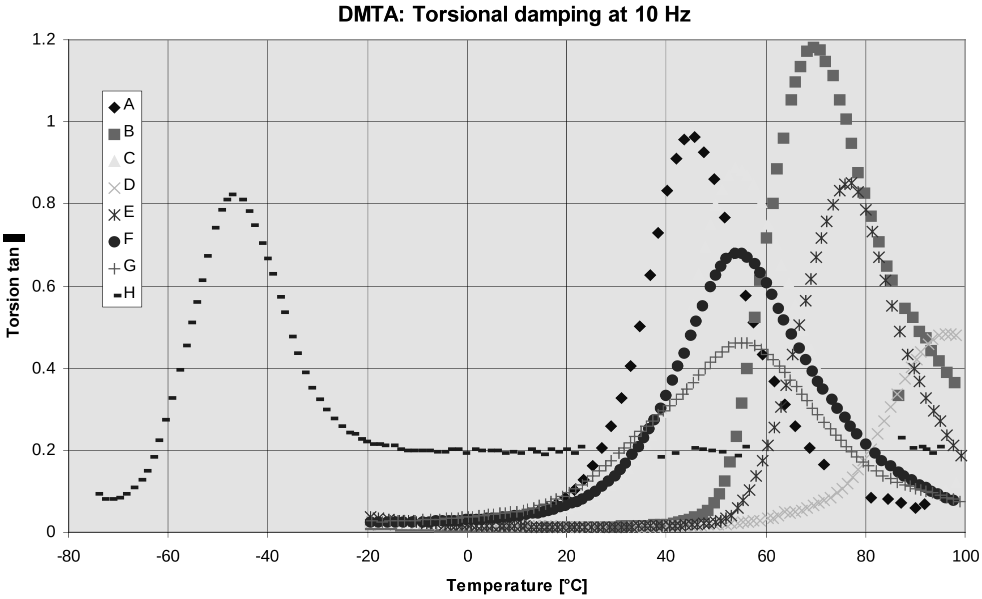

Figure 3. Damping of the adhesives as a function of temperature as measured in the DMTA in torsion. Testing frequency is 10 Hz.

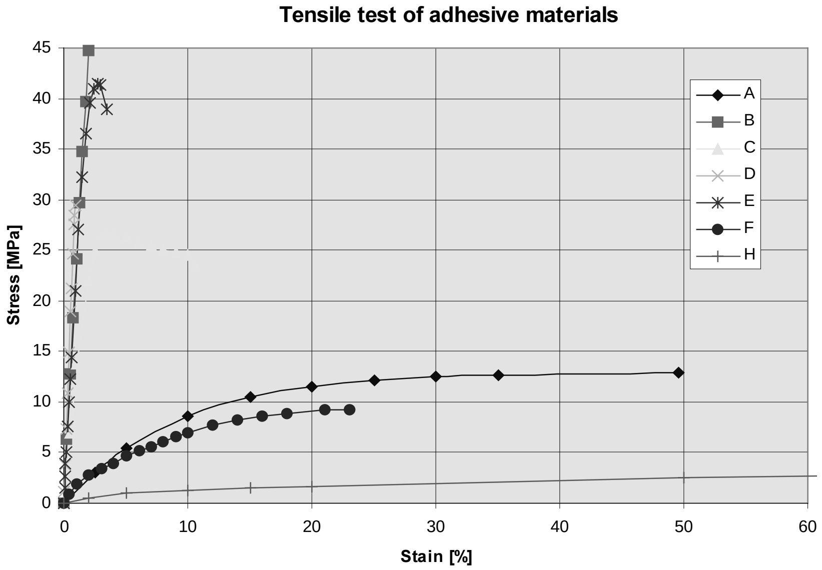

Figure 4. Tensile stress-strain curves of the adhesives. The speed of testing is 2 mm/min.

7. CONCLUSIONS

The experimental data provided in this paper is intended to serve analytical or numerical efforts for predicting structural vibration damping in structures with adhesively bonded joints.

It is interesting to note that the modal damping of the joint does not clearly correlate with the adhesive material damping capacity. This is shown in Figure 5. There are also other factors which determine the damping capacity of the joints, such as joint geometry and mechanical properties of the joint.

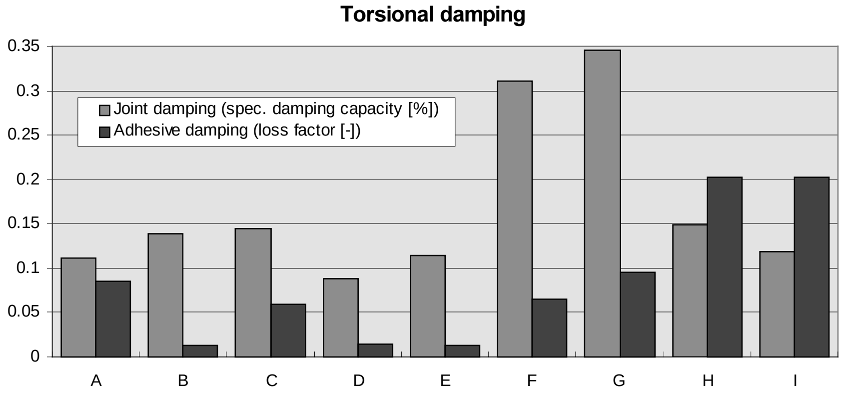

Figure 5. Comparison between torsional damping of the joints and the corresponding adhesive material.

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