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Variability analysis on the structural elastic properties of adhesively joined cylinders

K Van Massenhove[1,3], S Debruyne[1] and D Vandepitte[2]

[1] KU Leuven Department Mechanical Engineering Technology TC, Technology Campus Ostend, Zeedijk 101, B-8400 Oostende, Belgium
[2] KU Leuven Department of Mechanical Engineering, Campus Arenberg, Kasteelpark Arenberg 41, B-3001 Leuven, Belgium

E-mail: korneel.vanmassenhove@kuleuven.be

Abstract. Elastic structural adhesives have very attractive mechanical properties compared to brittle ones, especially in dynamically loaded structures and applications. They often combine an acceptable stiffness and bonding strength with excellent impact and vibration damping properties. Their viscoelastic nature involves some complexities however. For these adhesive types the apparent stiffness changes with time, temperature, frequency and amplitude of the applied mechanical load. Moreover, each bonding process involves variability that reflects on the (dynamic) mechanical behaviour of completed adhesively joined structures.
This paper discusses part of an extensive research project on the uncertainty assessment of adhesive joint lifetime in case of fatigue loads.
A first part of this paper deals with uniaxial quasi-static cyclic tests on nominally identical adhesively bonded samples, with a simple cylindrical geometry.
The second part discusses dynamic measurements of a similar sample and identical load case, and identifies the effect of different load amplitudes. It also links the quasi-static measurements to the results of the dynamic measurements.
Finally the paper concludes the research results and highlights the ongoing and planned activities.

1. Introduction

Elastic structural adhesives have many advantages in industrial applications that are characterized by (highly) dynamic loads. Where shocks or vibrations must be insulated, the low modulus and high damping of these adhesives provide an excellent alternative to discrete shock absorbing fastening systems. However, the viscoelastic properties of these adhesives involve many challenges to design engineers that incorporate these elastic structural adhesives in their structural designs.

In contrast to stiff and brittle adhesives, structural elastic ones show a highly nonlinear stress-strain behavior that is very sensitive to environmental conditions, such as temperature and frequency of the applied mechanical load. The quality of the bond also dependst on several production parameters [1], such as surface preparation [2,3], adhesive thickness [3–6]. These cannot be easily and uniformly related to the behavior of a complete joint, but need to be considered as sources of variability of the joint's properties. A thorough quantitative and qualitative analysis of this variability requires a profound approach in which advanced numerical modelling of a joint design is validated through various adequate experiments.

This paper links the observed variability in the dynamic properties of cylindrical butt adhesive joints, to changes in the joint dimensions. The adhesive that is used is a MS-polymer adhesive produced by Novatech, TEC7. Quasi-static tensile tests on dogbone samples have shown that elastic modulus of this adhesive is 7MPa for low strains and strain rates, and that it behaves nearly incompressible.

2. Joint geometry

To characterise adhesives, single lap shear joints are traditionally used. The advantage of these is that the adhesive is mainly loaded in shear, but the joint is asymmetric. This causes a deflection of the substrates due to bending moments. For adhesives that require thin bond lines, such as epoxies[7], this is not as much as a problem if thin substrates are used. However, in the context of joint designs which are conceived for vibration damping performance, a thick adhesive layer is required. Moreover, the adhesive layer thickness specified for TEC7 is 3mm. This results in large bending moments in single lap shear joints and a highly nonlinear behaviour. A double lap shear joint greatly limits these effects, but requires two adhesive layers. Hence the geometrical complexity increases, which is not desirable in this variability study.

Cylindrical butt joints do not show the geometrical nonlinearity as single lap shear joints do and only have one adhesive joint layer. The behaviour of these cylindrical joints for linear elastic adhesives and static loads has been described by Sawa [8]. The dimensions of the coupons that will be used are shown in figure 1 below. The nominal diameter of the samples is 20mm, while the length of the steel substrates vary due to the substrate surface mechanical treatments. The exact thickness of the adhesive layer, *t*, is measured after production. There are threaded holes in the substrates to mount them to the devices used for the various validation tests.

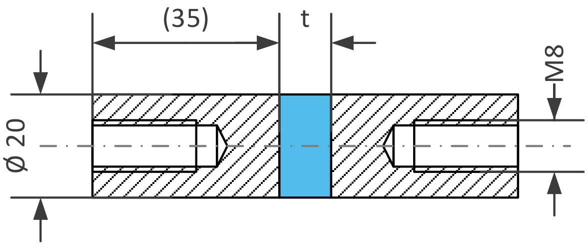


Figure 1. dimensions of the butted joint

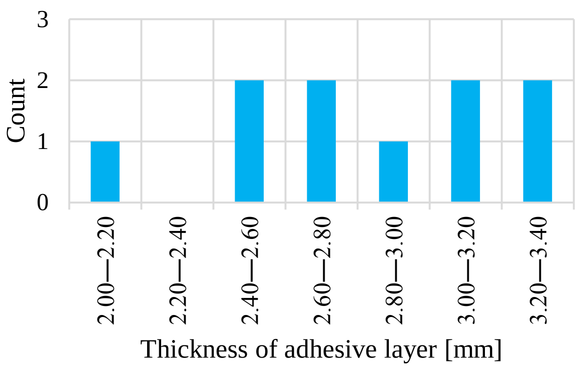


Figure 2. histogram of the adhesive layer thickness of the applied samples.

Ten of these samples are produced and their geometry is measured using a 3D coordinate measuring machine. The thickness of the joints is varied between 2.01mm and 3.40mm, distributed according to the histogram shown by figure 2.

3. Quasi-static cyclic tests

3.1. Initial tests

The samples were mounted on an Instron 3345 universal tensile testing machine as shown in figure3. A triangular, cyclic extension profile with an amplitude of 0.015mm and a deformation rate of 0.0025mm/s is applied, resulting in a test frequency of about 0.1Hz. The applied deformation pattern is repeated for a 100 cycles on each sample. The resulting stress-strain data is filtered to remove any noise and creep, as neither are currently relevant in the scope of this research. To remove any transition effects, the first two hysteresis loops are not interpreted.

Figure 3. test setup for the quasi-static tests.

The data for one sample is shown in figure 4. An average modulus of elasticity for the sample is determined, as well as the loss factor and angle. The data on figure 4 also show four points that are used to calculate each hysteresis loop surface. These are the points of maximum and minimum strain in each loop and the zero-crossing of the measured strain, as used by Carfagni [9]. The dotted line represents the average modulus of the (undamped) material.

The observed variability on the amplitude of the apparent complex modulus of the bonded joint is limited to 11%. On the other hand, the calculated values for the loss angle of the adhesive layer show a large variability of about 80%. The average loss factor is of the joint is 8%, indicating that the energy dissipation of the cyclically loaded sample is only a fraction of the total deformation energy, so small numeric errors may result in sizable errors of the estimated vibration damping.

Comparing the observed apparent complex modulus of 38MPa to the modulus of the bulk adhesive of 7MPa indicates that the difference is not merely due to experimental error. Contrary to tensile loading of a bulk material, the jointed structure constraints the perpendicular deformation of the adhesive. The core of the adhesive is no longer loaded in tension or compression, but by a volumetric change. As the material is nearly incompressible, the resulting apparent stiffness is much larger than expected.

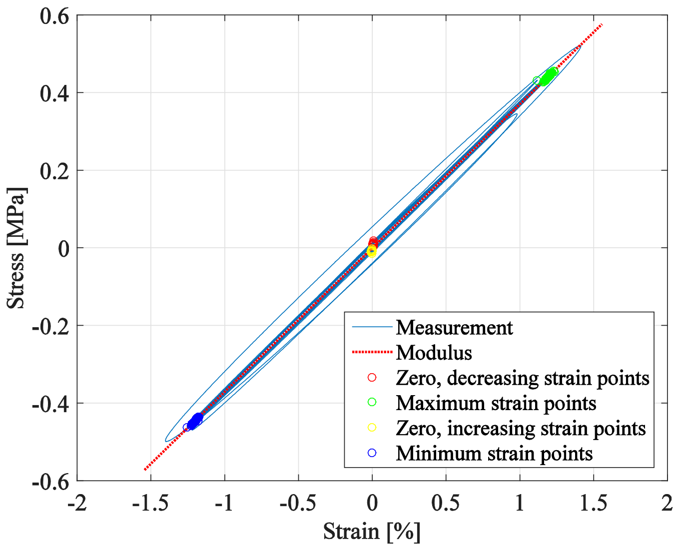


Figure 4. stress-strain data of low-frequency loading of a typical butt joint ($t = 2.01$mm, $E = 37$ MPa, $\tan\delta = 0.05$).

Table 1. averaged modulus of the butt joint, measured with 10 samples

Load frequency (Hz)	Complex modulus (MPa)	Loss angle (°)	RMS Load amplitude (N)
(0.111 ± 0.003)	(38 ± 4)	(5 ± 4)	(35 ± 8)

3.2. Effect of load rate and amplitude

As the adhesive stress-strain behavior is nonlinear, it is advisable to identify if there is any effect of the load rate and amplitude on the apparent stiffness of the sample. The sample with the lowest adhesive thickness is used, as this will result in the highest applied strains. A test with half the deformation is performed, followed by another test with a halved deformation rate. Table 2 gives an overview of the obtained results.

Table 2. effect of strain rate and strain amplitude on the apparent stiffness of a sample

Strain amplitude (%)	Strain rate ($\%s^{-1}$)	Frequency (Hz)	Modulus (MPa)	Loss factor (%)
1.2	0.13	0,11	37	5
0.74	0.04	0,057	35	12
0.74	0.074	0,10	39	1

It is clear that the effect of strain amplitude, strain rate and frequency of the applied load on the apparent modulus is low, yet the effect on the loss factor is high. However, the change of measurement frequency is very low compared to that of many dynamic applications. Therefore, a separate high frequency setup is used to characterize the dynamic adhesive properties.

4. Dynamic properties

4.1. Test setup

The quasi static, cyclic test results are only valid for low frequencies. Higher frequency measurements cannot be conducted with the measurement setup shown in figure 3. A different, customized setup is constructed, using an electrodynamic shaker and a universal testing machine frame, based on a paper by Gade et al [10]. As shown in figure 5, the shaker excites the adhesive that is rigidly mounted to the solid frame. To decrease the effect of local resonances on the measurements, both the frame and shaker head accelerations are measured. The applied load is measured with a separate load cell.

The system is then excited with a swept sine signal and a fixed load amplitude. The excitation frequencies lie between 5Hz and 200Hz with a sweep rate of 2.5Hz/s. The frequency response function of both accelerations to the excitation force are recorded and averaged over 1000 measurement slices of two seconds each.

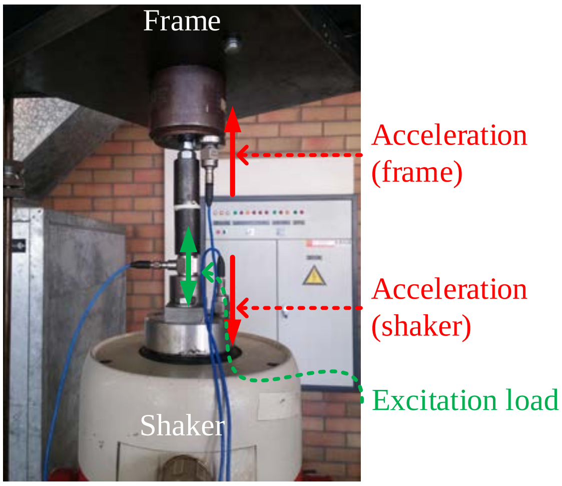


Figure 5. Test setup for high-frequency tensile tests

4.2. Measuring dynamic stiffness

The frequency response functions (FRFs) $\boldsymbol{H}_{\mathbf{s,a}}$ and $\boldsymbol{H}_{\mathbf{f,a}}$ compare the measured accelerations to the force $\boldsymbol{F}_{\mathbf{s}}$, applied by the shaker. These acceleration based FRFs need to be converted to displacement based FRFs by dividing with the square of the pulsation $\boldsymbol{\omega}$. It is advisable to correct the measured displacement of the shaker head $\boldsymbol{X}_{\mathbf{s}}$ with the displacement of the frame $\boldsymbol{X}_{\mathbf{f}}$ and to take the mass of the moving substrate m_{s_1} into account. This results in the frequency response function of the displacement of the adhesive layer $\boldsymbol{H}_{\mathbf{a,d}}$, as shown in expression (1):

$$\boldsymbol{H}_{\mathbf{a,d}} = \frac{\boldsymbol{X}_{\mathbf{a}}}{\boldsymbol{F}_{\mathbf{a}}} = \frac{\boldsymbol{X}_{\mathbf{s}} + \boldsymbol{X}_{\mathbf{f}}}{-\boldsymbol{F}_{\mathbf{s}} - m_{s_1} \cdot \ddot{\boldsymbol{X}}_{\mathbf{s}}} = \frac{\boldsymbol{H}_{\mathbf{s,a}} + \boldsymbol{H}_{\mathbf{f,a}}}{\boldsymbol{\omega}^2 \cdot \left(1 + m_{s_1} \cdot \boldsymbol{H}_{\mathbf{s,a}}\right)} \tag{1}$$

This calculated frequency response function describes the stiffness of the adhesive as a function of the load frequency. The apparent complex modulus can now be determined by using the dimensions of the adhesive layer, namely its thickness t and area A:

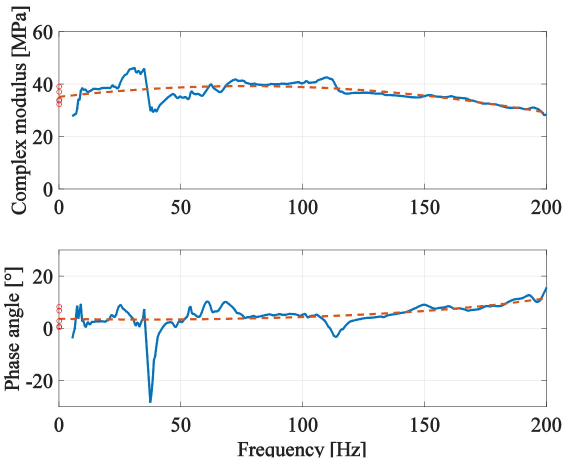
$$\boldsymbol{E} = \frac{1}{\boldsymbol{H}_{\mathbf{a}}} \cdot \frac{t}{A} \tag{2}$$

4.3. Experimental data

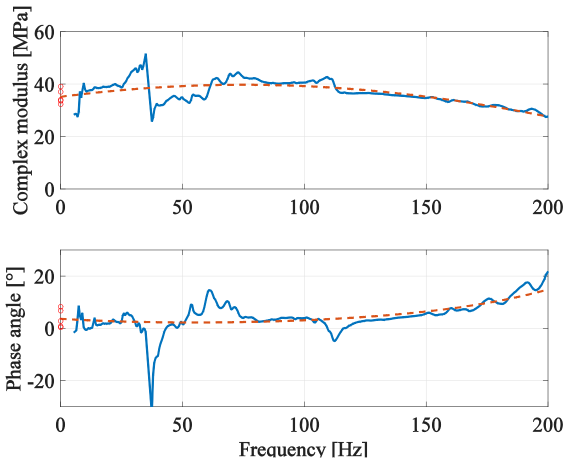
The setup described above is used to determine the apparent modulus of the bonded sample used for the experiments shown in table 2. An RMS excitation load of 10N, 15N and 20N is set. The result is fitted with a second order complex polynomial function, which is extrapolated to the quasi static frequencies. The results are offset with the difference between both measurements, as it is assumed that the measured stiffness is not as exact as measured quasi-statically. The results are shown in figure 6.

The adhesives stiffness is similar at lower frequencies, despite the difference in load amplitude. At first it increases to a maximum of 45MPa at 95Hz. At higher frequencies, the stiffness reduces, at a rate that changes proportionally to the applied load amplitude.

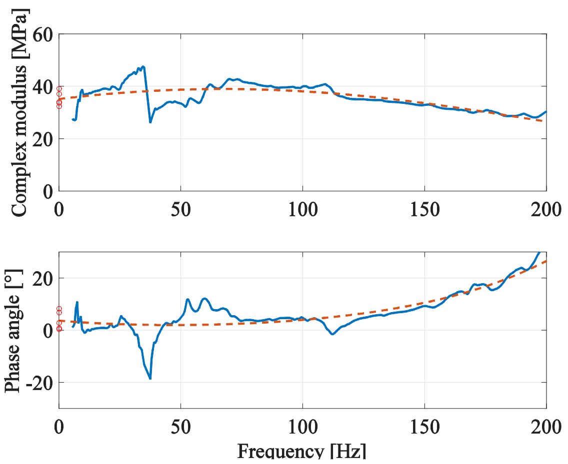
At a load amplitude of 10N, the loss angle increases almost linearly with increasing load frequency. However, the loss angle shows increasing higher-order dependence on load frequency at higher load levels.



(a)



(b)



(c)

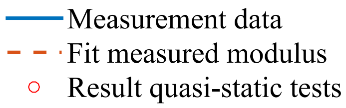


Figure 6. dynamic apparent complex modulus of the adhesive sample.

(a): 10N Excitation load, $R^2 = 0.433$

(b): 15N Excitation load, $R^2 = 0.489$

(c): 20N Excitation load, $R^2 = 0.655$

The dynamic stiffness curves on figure 6 show resonance peaks that originate from structural resonances from the test setup hardware. There is a clear resonance at 70Hz, of which the effect increases with increasing load levels. These structural resonances can be eliminated numerically for further analysis.

5. Conclusion

Both methods to measure the complex modulus of the adhesive joint in a cylindrical butt joint show promise, but must be optimized if any realistic and repetitive loss factor measurements must be conducted. This is especially the case for the quasi-static measurement method.

There is a large discrepancy between the apparent complex modulus of the joint and the modulus of the bulk adhesive. This is due to geometrical effects of the joint design, as the deformation of the adhesive is radially constrained by the steel substrates. When loading the samples, the core of the sample does not undergo simple tensile deformation, but rather a forced volumetric change. While the tensile modulus of the adhesive is relatively low, its bulk modulus is quite high. This results in a much larger apparent moduli. Future work will describe this geometric dependence by numerical simulation and experimental analysis.

6. Future work

The variation of the adhesive thickness is quite large for the small sample set demonstrated here and may explain some observed variability. In future work, more samples will be constructed. This will increase the possibility to link the adhesive thickness to the modulus, and to take other parameters into account. These may be the sample temperature, eccentricity and skewness of the joint and possibly others.

When the initial variability of this kind of adhesive joint is estimated, a set can be aged artificially following a number of industrially commonly used patterns. The resulting properties and their variability can then be linked to the aging effects and initial joint dimensions. This way, accurate lifetime predictions of similar joints may be conducted.

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