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Research paper

Nonlinear viscoelastic constitutive model identification for a polyurethane adhesive in a bonded joint using structural dynamic model updating

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In this study, a nonlinear viscoelastic constitutive model was identified to characterize the mechanical properties of an industrial adhesive in a bonded joint. A model updating method based on Frequency Response Function (FRF), referred to as the Response Function Method (RFM), was modified for identification of the parameters of the constitutive model. A test setup was utilized which comprises of a steel beam that is bonded to a heavy rigid steel block by a layer of Sikaflex-252 polyurethane adhesive. The accelerance FRFs at different excitation levels were measured experimentally, using the concept of Optimum Equivalent Linear FRF (OELF) and the parameters of the nonlinear viscoelastic constitutive model were identified. Then applying the identified model, the correlations between the FRFs of the FE models and the experimental ones were tested and high level of correlation was observed. Also, it has been shown that, as the strain level increases, the storage modulus of the adhesive decreases.

1. Introduction

Continually growing trends toward application of elastic bonding in various industries, most notably in the wind turbines and air, road and rail vehicles can be explained by advantages of adhesive bonding in comparison with traditional joining methods like welding, bolting or riveting. Some of these advantages are uniformly distributed stresses along the bond line, sealing, shock-absorbing, noise and vibration damping, insulating properties, improving external appearance and compensation of the effects of thermal expansion coefficients mismatch.

Therefore, there is always need to develop methods for establishing exact and reliable models which represent static and dynamic behavior of adhesively bonded structures. Amongst different methods, the most commonly used are the Finite Element (FE) models that are widely used in design and analysis of structures (He, 2011).

One of the main prerequisites that influences the accuracy of the FE model is the definition of constitutive or stress-strain model. Most of adhesive materials exhibit elastic and energy dissipation (damping) behavior simultaneously that is referred to as viscoelastic property. Both the elastic and damping properties may depend on temperature, excitation frequency, excitation amplitude, pre-stress and relative humidity. Manufacturers usually provide minimal mechanical properties which are related to static, linear behavior of adhesives. These data can be useful only for static modelling of thin adhesive layers. So, establishing constitutive models for viscoelastic adhesives causes challenging issues in dynamic FE modelling of adhesive joints.

As can be found in literature, numerous methods have been employed for characterization of viscoelastic properties of materials through experiments. Generally speaking, these methods can be classified into two categories, namely, direct and inverse identification methods.

In the direct methods, for a prepared test specimen, dynamic test data are obtained using a selected experimental procedure, for instances, resonance testing (Maheri and Adams, 2002), dynamic mechanical thermal analysis (DMTA) (Barruetabena et al., 2011), dynamic mechanical analysis (DMA) (Martinez-Agirre et al., 2015; Zhang et al., 2015), and high strain rate tensile tests (Mohotti et al., 2014; Zhang et al., 2015). These dynamic data can be con-

Abbreviations: ACC, Amplitude Correlation Coefficient; EMA, Experimental Modal Analysis; FE, Finite Element; FRAC, Frequency Response Assurance Criterion; FRF, Frequency Response Function; IEM, Inverse Eigen-sensitivity Method; OELF, Optimum Equivalent Linear FRF; RFM, Response Function Method; SCC, Shape Correlation Coefficient; SLS, Standard Linear Solid model.

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verted directly to the dynamic stress-strain data or equivalently to the dynamic modulus at a specific frequency or strain rate. Over a frequency range, the parameters of a viscoelastic model can be obtained by means of curve fitting. In continuation the referred studies in this category are explained briefly.

Maheri and Adams (2002), using a standard Thick Adherend Shear Test (TAST) specimen introduced two empirical expressions for the adhesive shear modulus based on the adhesive layer thickness and the resonance frequency of the lateral and axial modes of vibration.

Barruetabena et al. (2011) characterized the nonlinear viscoelastic properties of a flexible industrial adhesive, under tension strains, using DMTA. They prepared master curves for relaxation and dynamic moduli by means of the time–temperature superposition principle. They obtained the parameters of a generalized Maxwell model (Prony series) and a fractional derivative model by means of curve fitting. It was shown that the models are able to simulate the influence of time, temperature and strain level.

Mohotti et al. (2014) proposed a strain rate dependent constitutive material model to predict the high strain rate behavior of polyurea. They introduced a rate dependent term into the original well-known nine parameter Mooney–Rivlin model and validated their model using high strain material data for polyurea.

Using a single lap joint configuration and DMA technique, Martinez-Agirre et al. (2015) analyzed the effects of static pre-strain on the elastic and dissipative properties of adhesives. Their results showed that for the investigated adhesive material, the shear modulus increases with the static pre-strain level, whereas the loss factor decreases. They also proposed and validated a new material model based on the four-parameter fractional derivative model to characterize the frequency-pre-strain dependence of the constrained viscoelastic layer.

Zhang et al. (2015) performed experimental studies on dynamic tensile response of a transparent polyurethane interlayer using DMA, INSTRON testing system and low impedance Split Hopkinson Tension Bar (SHTB), under wide ranges of strain rates and temperatures. They introduced a thermal-viscoelastic constitutive model, referred to as Zhu–Wang–Tang (ZWT) model and obtained its parameters. They unified the effects of strain rate and temperature in a single parameter by introducing a dimensionless parameter, and obtained a unified curve reflecting the time–temperature equivalence relation.

The direct methods used for the measurement of the dynamic mechanical properties of adhesives suffer from the problem that if adherents are used in the test setup, like using a lap joint, then it would be very difficult to separate between elastic effects of the adherents and adhesive, especially, if the adherents and adhesive have the same order of stiffness at the interface.

In the category of inverse methods the main point is that the measured dynamic data cannot be converted directly to the dynamic stress-strain data in the adhesive region of the specimen. So, an inverse problem solving is preferable, even inevitable. There are many instances of inverse methods in the literature for the identification of viscoelastic material properties. In the present article the focus is on the methods based on the FE model updating. Some instances are as follows:

Jahani and Nobari (2008) identified dynamic Young's and shear moduli of an adhesive using modal based direct model updating method and experimental modal analysis and showed that both Young's and shear moduli are frequency dependent. Also, the same authors, Nobari and Jahani (2009) introduced a modification to the modal based direct model updating method to indentify damping characteristics of the same adhesive in bending and shear modes of vibration. Recently, Naraghi and Nobari (2015) have identified the mechanical characteristics of an adhesive using eigenvalues of the system and Inverse Eigen-sensitivity Method (IEM) and experimental data. They illustrated the stiffness softening characteristic of the adhesive and tuned the Standard Linear Solid model (SLS) to represent the adhesive viscoelastic behavior.

Model updating methods are generally classified into modal-based and FRF-based methods (Friswell and Motiershead, 1996). In Modal-based methods the modal properties obtained through experimental modal analysis of measured FRFs are used to identify erroneous design parameters. Experimental modal analysis inherently introduces errors and inaccuracies over and above those already present in the measured data. In contrast, in FRF-based model updating techniques the measured FRFs are directly utilized for updating procedure. In FRF-based methods updating equations can be obtained at any measured frequency points and are not limited to the natural frequencies. In addition, having measured FRFs for a limited frequency range, the effect of out-of-range modes is already reflected in the measured data. Besides, the damping problem can be handled relatively easier than modal-based methods (Imregun et al., 1995). The RFM proposed by Lin and Ewins (1990) is a representative example of FRF-based model updating methods.

In this paper, the RFM method will be modified to make it suitable for identification of material constitutive models. This method minimizes the differences between the theoretical and experimental FRFs at selected frequencies. With the proposed method the parameters of the considered viscoelastic constitutive model are identified and therefore, the material properties can be determined in the whole measurement bandwidth.

Compared with the direct methods, the proposed technique can be accomplished without the need to use complex test equipment and complicated test setups and in comparison with the modal-based FE model updating methods, in the proposed method the identification is not limited to the resonance points and the material properties can be obtained from any set of frequency points. On the other hand, as in the proposed method there is no need for experimental modal analysis, inaccuracies such as the effect of out-of-range modes and difficulties arising from close modes are avoided. More importantly, in the proposed method, the effects of adherents and adhesive are completely separated and adherents' behavior cannot contaminate those of adhesive.

The experimentally measured FRFs of a beam connected to a rigid support via a layer of elastic adhesive will be used to update the FE model of the bonded beam. The parameters of a nonlinear viscoelastic constitutive model will be identified and examined through correlation tests between experimental FRFs and those from updated FE model. Also, the effects of strain level on the identified static modulus will be examined.

2. Formulation of RFM

The formulation of RFM proposed by Lin and Ewins (1990) is presented here briefly and the reader is referred to (Grafe, 1998; Imregun et al., 1995) for more details and computational aspects.

Consider the following mathematical identity that is valid for two complex matrices $\mathbf{A}$ and $\mathbf{B}$, satisfying the condition that both $\mathbf{A}$ and $(\mathbf{A}+\mathbf{B})$ are nonsingular:

$$(\mathbf{A}+\mathbf{B})^{-1} = \mathbf{A}^{-1} - (\mathbf{A}+\mathbf{B})^{-1}\mathbf{B}\mathbf{A}^{-1} \tag{1}$$

Assuming

$$\mathbf{A} = \mathbf{Z}_A(\omega)$$
$$\mathbf{B} = \mathbf{\Delta Z}(\omega)$$
$$\mathbf{A}+\mathbf{B} = \mathbf{Z}_A(\omega) + \mathbf{\Delta Z}(\omega) = \mathbf{Z}_X(\omega) \tag{2}$$

where $\mathbf{Z}_A(\omega)$ and $\mathbf{Z}_X(\omega)$ are the dynamic stiffness matrices of the analytical and experimental models of structure, respectively and $\Delta Z(\omega)$ is the dynamic stiffness error matrix,

$$\mathbf{\Delta Z}(\omega) = \mathbf{Z}_X(\omega) - \mathbf{Z}_A(\omega) \tag{3}$$