Materials and Design 64 (2014) 520–526

Contents lists available at ScienceDirect

Materials and Design

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

Parametric study of the creep failure of double lap adhesively bonded joints

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A R T I C L E   I N F O

Article history:
Received 1 June 2014
Accepted 1 August 2014
Available online 13 August 2014

Keywords:
Adhesive
Developed rheological model
Creep failure
Finite element

A B S T R A C T

In this paper the influence of adhesive thickness and adhesive fillet on the creep deformation and creep life time of the adhesively bonded double lap joint have been studied experimentally. Also finite element modeling was used to simulate creep behavior of bonded joints and the results are compared with those obtained from experimental tests. The adhesive used in this research was Araldite 2015 which is an epoxy based adhesive. Research procedure is carried out in two major stages. Firstly, uniaxial creep tests were conducted in 63 °C to obtain the creep characteristics and constitutive equation parameters of the adhesive at 63 °C. An empirical based rheological model based on Maxwell and Zener's model is proposed to simulate the creep behavior of the adhesive and it is used to predict the creep behavior of the bonded joint using finite element method. Numerical results show good agreement with experimental data. It was observed that applying fillet increases creep life and decreases joint creep deformation, however increasing adhesive thickness has slight effect on the creep life time of the joint.

1. Introduction

Nowadays adhesively bonded joints are increasingly being used to design lightweight structures such as aircrafts and vehicle body frames. In addition, different components with dissimilar materials can be joined using adhesives. Knowledge of the stress and strain distribution in the adhesive is required to design and for proper use of adhesively bonding joints. Therefore using models which accurately predict the deformation behavior of adhesives are required. Like most polymers the behavior of adhesives, is time-dependent. Adhesives show viscoelastic and viscoplastic behavior when subjected to relatively high stress and temperature levels. Therefore, to increase durability and reliability of the adhesive, close attention needs to be paid to the creep behavior of the adhesive joints in structural applications [1].

Experimental studies show that, epoxies deform approximately linear below moderate stress levels; however, the stiffness of material decreases with increasing time under load and it exhibits nonlinear behavior [2]. Thus wide experimental and numerical studies were carried out to simulate the nonlinear behavior of adhesives. In literature, several viscoelastic and viscoplastic models have been developed to perform stress analysis of adhesively bonded structures. Voigt and Maxwell have developed the simplest viscoelastic models [3]. Also, improved viscoelastic and viscoplastic models are available in the literature [4,5]. Feng et al. [6] based on series of short term accelerated tests established a method to study the long term creep behavior of epoxy adhesives. They investigated the temperature and moisture effects by means of mechanical response and they used a coupling model to analyze creep behavior in epoxies. An important attribute of this model is its ability to physically describe the characteristics of the molecular mobility by means of coupling parameters. Dean [7] modeled the creep behavior of polypropylene using exponential function with four spring and damper elements. He used the parameters which called relaxation time to model the nonlinear behavior. Yu et al. [8] used Bailey-Norton model, unified theory and viscoelastic models to simulate the creep behavior of epoxy adhesives. They have presented a complete range of exponential data for a typical adhesive system including constant strain rate, creep and recovery in tension and compression. Majda and Skrodzewicz [9] have modified burgers mechanical model which is composed of Maxwell and Kelvin-Voight elements to simulate nonlinear behavior of the epoxy adhesives in ambient temperature. Yu et al. [10] determined properties like time dependent creep compliance function of viscoelastic adhesive contact models using an empirical method. Roseley et al. [11] have investigated the creep response of three less heavily cross linked epoxy based adhesives, which posse transition temperature values between 30 °C and 60 °C. They showed Kelvin-Voight equation is not successful in modeling the adhesive creep behavior in temperature range above transition temperature.

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http://dx.doi.org/10.1016/j.matdes.2014.08.003

Therefore, they have used a series of two Kelvin-Voight models to improve the simulation over the complete range of temperature. Nguyen et al. [12] studied rheological characterization of a novel isotropic conductive adhesive (ICA). They have studied the rheology of an epoxy filled with monodisperse polymer spheres with or without Ag coating. They have shown that the rheological properties of the ICA with 45 vol% Ag-coated spheres were found to be suitable for stencil/screen printing and dispensing processes.

Literature review reveal that various analytical and finite element techniques have been employed to study viscoelastic behavior of adhesively bonded joints [13–17]. In addition several papers deal with creep constitutive modeling of the bulk adhesive. Pandey and Narasimhan [18] have evaluated the creep behavior of the adhesively bonded joints by modeling the adhesive layer with elasto-viscoplastic behavior. They have assumed that the adherend behaves linearly. kalili et al. [19] experimentally have showed that at a temperature above the glass transition temperature of the adhesive, the failure time and initial strain for all specimens which have been fiber reinforced were elevated compared to unreinforced adhesive joints. Ferrier et al. [20] studied the creep behavior of epoxy adhesives, used to strengthen steel-reinforced concrete structures. The durability and performance of these reinforcements which are depended on the rheological behavior were investigated and permissible shear stress of the interface taking into account the effects of time and temperature was evaluated. Choi [21] studied the rheological modeling and finite element simulation of epoxy adhesive creep in fiber-reinforced polymers in reinforced concrete beam. They have shown that significant creep occurs at the concrete-fiber reinforced polymers. Hamed and Chang [22] investigated the influence of creep on the edge de-bonding failure of fiber reinforced beams and showed creep can increase or decrease the maximum load which leads to edge de-bonding, depending on the material properties.

This paper intends to study the creep behavior of the adhesively bonded joint at elevated temperature. The aim is to firstly propose a creep constitutive model which is able to simulate the creep characteristics of the adhesive at different stress levels. The model is developed based on uniaxial creep test results. In the second step, the creep behavior of the bonded joint is simulated using the Finite element numerical softwares in which the proposed model is implemented. The results are compared with experimental data. Finally the effect of adhesive thickness and fillet is investigated on creep life time.

2. Materials and creep tests

2.1. Bulk specimen Uniaxial creep test

In the present research, the Araldite 2015 (Huntsman Advanced Materials) which is a two component epoxy adhesives has been used to investigate the creep behavior of the double lap joint. Table 1 shows the mechanical properties and curing conditions of the adhesive provided by its manufacturer.

Table 1
Mechanical properties and curing temperature given by adhesive manufacturer (data provided by manufacturer).

Properties	Araldite 2015
Young's modulus, E (GPa)	1.85 ± 0.21
Poissons ratio, υ	0.33
Lap shear yield strength at 63 °C, τ_f (MPa)	15
Yield stress at 63 °C (MPa)	10
Curing temperature/time (°C/min)	60/35
Glass transition temperature (°C)	68
Thermal expansion coefficient (1/°C)	8.5e − 5

In order to obtain creep characteristics of the adhesive, bulk specimens with the dimensions as shown in the Fig. 1 and thickness 3.2 mm have been used. This specimen has been prepared based on ASTM: D638. The uniaxial creep tests have been carried out using Amsler testing machine (Fig. 2). The force is applied through the weights located on the arm of the machine. To obtain more accuracy in controlling the applied load on the specimen, a load cell device is used which measures the applied load with accuracy of ±0.1 kg. The specimen elongation measurements have been carried out using contact extensometers and a micrometer with the accuracy of ±0.0001 in. An interface system is used to record all data including applied load, displacement and temperature which saves data in a computer file every 1 s. A PLC controller system is employed to maintain a constant temperature within the furnace with the accuracy of ±0.5 °C. The specimens were tested at 63 °C. The maximum stress applied to the specimen is about 45% of the lap shear strength of the adhesive at the testing temperature. This stress level is also lower than the adhesive tensile yield strength therefore no initial plastic strain occurs in loading.

2.2. The experiment results and modeling

Uniaxial creep tests on bulk specimens of the adhesive have been conducted at 63 °C. The elongation of specimens was recorded and the true strain of the specimen was calculated. The maximum applied stress on the specimens was lower than the yield stress; hence, the total strain is sum of the elastic and creep strains. Creep strain is calculated using Eq. (1).

$$\varepsilon_c(t) = \varepsilon_{\text{total}}(t) - \varepsilon_e \tag{1}$$

where ε_c is creep strain, ε_e is initial elastic strain and $\varepsilon_{\text{total}}$ is total strain.

2.3. Rheological modeling of the material

Different models have been proposed to explain the creep behavior of adhesives [3,4]. These research studies have shown that classic Bailley-Norton model is not capable of predicting the creep behavior of adhesives accurately [8,9]. Also it has been shown that the viscoelastic behavior of the polymers can be modeled more accurately by using appropriate number/combination of the elastic and damping elements [2,7–9,20,21]. The layout and combination of the model depends on the properties of the material and appropriate model is usually determined based on the experimental data. Hence, the model shown in Fig. 3 which is a series combination of two Zener and one Maxwell models is proposed in this research study.

In this model, the compliance was obtained using the usual solution method for solving ordinary linear differential equations with constant coefficients by Laplas transformation technique. Therefore the adhesive strain ($\varepsilon_{\text{total}}(t)$) could be determined as a function of time (t), and average tensile stress (σ_0):

$$\varepsilon_{total}(t) = \sigma_0\left[\frac{1}{E_1} + \frac{t}{\eta_1} + \frac{2}{E_\infty} - \frac{E_0 - E_\infty}{E_0}e^{-\frac{t}{\theta_1}} - \frac{E_0 - E_\infty}{E_0}e^{-\frac{t}{\theta_2}}\right] \tag{2}$$

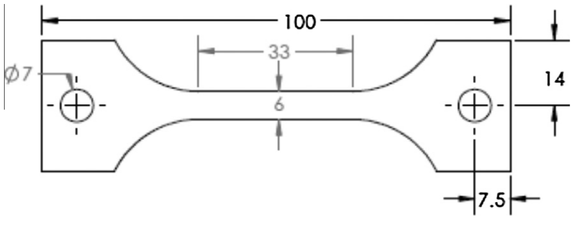

Fig. 1. Adhesive bulk sample dimensions.