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Creep analysis in smart single-strap adhesive joints reinforced by shape memory alloys—Experimental study

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ABSTRACT

The mechanical properties of adhesive joints are very sensitive to temperature and these types of joints which are subjected to high temperature, lose their strength. Therefore, the improvement of adhesive joints' thermal resistance is highly desired. In this study, creep phenomena in single-strap adhesive joints are considered and the effect of reinforcing the joints by shape memory alloy (SMA) on the creep behavior and the lifetime of the joints are studied experimentally. The effects of temperature and wires volume fraction on the joints creep behavior are also considered. For this purpose, several single-strap adhesive joints are reinforced by SMA in the shape of wires. The epoxy used in the adhesive joints is Araldite 2015 and NiTi shape memory wires with various volume fractions ranges from 0.5% to 2% are embedded into the adhesive. The creep tests are conducted at temperatures of 100 °C, 120 °C and 135 °C which all are above the glass transition temperature of the adhesive. By using SMA wires, a significant improvement in the adhesive joints creep properties could be achieved.

1. Introduction

Due to their great structural properties such as having more uniform distribution of loads, less stress concentrations and the edge factors, lighter weight and greater fatigue properties comparing to other traditional mechanical fastening and joints, the usage of adhesive joints is widely deployed in various industrial applications [1]. Adhesive joints are subjected to low or high temperature conditions in many applications and many researchers have tried to develop suitable models in order to describe the thermal and mechanical properties of adhesives at such temperatures [2–4]. Dean [5] worked on the creep behavior of an adhesive joint and studied the humidity effect on the adhesive model. Goland and Reissner [6] tried to predict the bending deflections in a single-lap joint according to Green's function. They considered a beam model and simulated the joint as two beams bonded with an adhesive layer and subsequently found equations representing the peel and shear stresses in the adhesive layer. They also showed the importance of the peel stress in the joint failure.

Oplinger [7] studied the Goland and Reissner analysis with a more realistic model in which the adhesive layer deflections are allowed to decouple the two halves of the joint in the bending deflection and stress analysis. He found that the substantial differences from the Goland–Reissner analysis can occur for relatively thin adherends and most of their analysis predictions are recovered in the limit of large adherend-to-adhesive layer thickness ratios.

Allman [8] analytically studied the elastic stress distributions in single-lap adhesive bonded joints with a higher-order theory which could simultaneously include the effects of bending, stretching and shearing of the adherends and accounts for the shearing and tearing actions in the adhesive layer. Tsai and Morton [9], worked on the mechanics of a single-lap joint subjected to tensile load theoretically, including the classic Goland and Reissner solution. Delale et al. [10] and Cornell [11] studied the stress distribution in the edges of the adhesive joints numerically and showed that a stress concentration existing in the adhesive layer is the main factor of the joint failure.

Alfano et al. [12] numerically studied the mode I fracture in bonded adhesive joints by considering a pre-cracked bonded Double Cantilever Beam (DCB) Specimen. Khalili et al. [13] reinforced a single-lap epoxy adhesive joint by carbon, aramid and glass fibers in different orientations and studied the creep behavior and lifetime of the adhesive joints experimentally. Feng et al. [14] investigated the long-term creep behavior of a neat epoxy resin and a commercial structural adhesive for bonding aluminum substrates experimentally and produced a master curve for the long-term creep compliance of the joints.

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Shape memory alloys (SMA) are materials with excellent thermo-mechanical behavior, which were first observed by the Naval Ordinance Laboratories in the form of a composition of Nickel–Titanium (NiTi) alloy in 1962. Although other materials with similar behavior have been discovered afterwards, NiTi shape memory alloys are still used in most applications, having characteristics such as very large recoverable inelastic strain, shape memory effect, pseudo elastic response, etc. Considerable work has also been carried out by other researchers on the reinforcement of the joints in order to improve joint strength [15,16]. Raghavan et al. [17] worked on a thermoset polymer matrix with 20% SMA fiber volume fraction and investigated the composite damping capacity, tensile and impact properties. Ivshin [18] studied the connection between complete transformation phenomena and arrested loading / unloading (outer loops vs. sub-loops) and the transition from isothermal to adiabatic loading via loading in a heat convective environment in a shape memory alloy by a thermo-mechanical model.

Khandelwal and Buravalla [19] presented an overview of SMA's behavior modeling approaches. Tanaka et al. [20,21] worked on the SMAs behavior considering the issues such as partial transformations, hysteresis sub-loop formation and transformation returning points. SMAs are often coupled with other structural materials to form a class of smart structures; and the usage of SMAs as actuators in different structures was also done by some researchers [22]. Lagoudas and Bo [23] considered a laminated plate with orthotropic piezoelectric layers, attached to SMA thin strips and theoretically studied the plate deformations by applying electro-mechanical loading. Khalili et al. [24] studied experimentally the mechanical properties of an edge notched steel plate repaired by polymer composites and smart patches reinforced with NiTi shape memory alloys in the shape of wires. They conducted tensile, bending and impact tests on the specimens.

Chen and Levy [25,26] using a mathematical model, studied the natural frequencies and vibration, and the effect of temperature on the frequencies, of a flexible beam covered with SMA layers used as actuators. Brinson et al. [27] studied the SMA active phenomena and used the SMA behavior to control the shape of a composite structure. Furthermore, an analytical analysis of single-strap adhesively bonded joint integrating SMAs was carried out by Cheng et al. [28]. John and Hariri [29] used analyses of strain energy perturbations on a polymeric composite plate and studied the alteration of the dynamic response and natural frequency of the plate by using Nitinol-based SMA wires analytically and numerically.

Although the creep behavior in adhesive joints and also in shape memory alloys has been investigated by a few researchers, the creep behavior of single-strap joints which are reinforced by shape memory alloys has not been investigated. In the present work, by considering the published research works, the creep phenomena of single-strap adhesive joints reinforced by NiTi shape memory wires at the temperatures higher than the adhesive glass transition temperature is studied experimentally and the effect of temperature and the SMA's volume fraction on the creep behavior such as the time to failure and the creep compliance of the reinforced joints are obtained.

2. Experimental procedure

2.1. Materials

The adherends material selected for manufacturing the specimens for the creep tests in the present work was steel S235. The minimum suggested thickness for the adherends according to ASTM D1002-10 standard [30] was 1.6 ± 0.1 mm. Therefore, in order to ensure that there would be no failure in the adherends during the tests, the thickness of the adherends was selected to be 3 mm. Detailed dimensions of adhesive joints reinforced by six SMA wires are shown in Fig. 1.

The epoxy adhesive used in the adhesive joints was Araldite 2015 (Huntsman Advanced Materials Co., Basel, Switzerland), a two components toughened epoxy adhesive with high thermo-mechanical properties such as mechanical stability, high viscosity paste, low shrinkage, good gap filling and fatigue properties, allowing resilient bond to metals, etc. The properties of the adhesive are shown in Table 1. These data are taken from the manufacturer data sheets. The adherends were cut by laser and a mechanical machining procedure at the adherends edges was applied in order to have the same geometrical dimensions as denoted in Fig. 1. In order to promote a good adhesion, the adherends surfaces were prepared for bonding according to the procedure indicated in ASTM D2651-01(2008) standard [31]. The procedure is described in detail in Section 2.2.

The reinforcing wires were made of NiTi SMA with the diameter of 0.3 mm and the wires were embedded into the adhesive along the longitudinal axis of the joint (loading direction). The NiTi SMA properties are listed in Table 2.

In Table 2, M_s, M_f, A_s and A_f are the starting and finishing transformation temperatures for martensite (M) and austenite (A) phases, respectively, E_A and E_M are the elastic moduli in austenite and martensite phases respectively, Ω is the transformation coefficient, ε_R is the maximum recoverable strain, C_M and C_A are the experimental constants for martensite and austenite phases, $\sigma_s^{\text{critical}}$ and $\sigma_f^{\text{critical}}$ are the critical stresses at the starting and finishing phase transformation and υ is the Poisson's ratio for SMA wire.

In order to prepare the lap shear specimens, the adhesives and also the wires were placed with exact gap distance between the wires, using a specific engineered fixture shown in Fig. 2, with the accuracy of 0.01 mm prior to bonding the adherends. The fixture includes two perforated rails jointed together by four adjustable threaded bars. The wires are fixed at the required locations and then tightened by screws and bolts from both the ends on the rails. In the cases, where the pre-strain is necessary in the wires, the four adjustable threaded bars are turned to adjust the distance between the rails, accordingly.

2.2. Preparation of the specimens for creep test

The machine used for the creep tests was a Torsee Creep and Rupture Testing machine (Tokyo, Japan). The machine has: three special heat elements with variable controllable heating power for adjusting the temperature; a loading mechanism in which variable mass units enable the loading; and a strain measuring system with an accuracy of 0.01 mm (Fig. 3). In the current work, the creep tests were performed according to the ASTM D1780-05 standard [33] and no heat shock or load shock was imposed on the specimens. The load was applied to the specimens by means of two specific gripping fixtures at the ends of the specimens and to allow the specimens to achieve the exact testing temperature, 15 min exposure time was given to the system before application of the load.

The adherends surfaces were roughened first by abrasive machine and then degreased by liquid acetone. The surfaces were then rinsed in a dilute NaOH solution and after that the adherends were etched by 27% concentration H_2SO_4 acid to ensure that there was no dirt on the surfaces and to obtain a good adhesion. After the adherends surface preparation, the two parts of the epoxy adhesive were mixed according to the manufacturer's instructions by specific volume fractions. The specimens were bonded in an engineered fixture after placing the SMA wires on the adherends at exact distances. The SMA wires were placed parallel to the