International Journal of Adhesion & Adhesives 37 (2012) 11–18

Contents lists available at SciVerse ScienceDirect

International Journal of Adhesion & Adhesives

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

On the thermomechanical behavior of two-dimensional foam/metal joints with shear-deformable adherends: Model validation with FE analysis

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ARTICLE INFO

Available online 21 January 2012

Keywords:
Epoxy adhesive
Aluminum and foams
Finite element stress analysis
Stress distribution

ABSTRACT

The stress distributions in metal/adhesive/foam planar joints subjected to biaxial tensile load and thermal load was investigated through a semi-analytical model. The shear deformation of adherends was accounted for according to a linear law in order to obtain closed-form solutions. For the model validation, a comparative study with a finite element (FE) simulation was carried out. A 2D behavior of stress fields is observed due especially to the Poisson's ratio effects and the biaxial nature of loads. The through thickness shear stresses are comparable to normal stresses; therefore, the adherend shear deformation must be accounted for correct failure prediction. According to the comparison with FE results, the normal stress distributions at any location in the foam and the shear stresses in the foam regions close to the adhesive surface can be well predicted by the proposed model. The through thickness shear stresses, however, showed to vary according to a cubic law rather than a linear law.

1. Introduction

For space launch vehicles, the need to develop light structures has led to foam as insulating material while the structural function is carried out by a metallic shell. A typical example, which is studied here, is the cryogenic tanks of launchers. In these structures, the insulation system consists of polymer foam panels glued on the metallic shell. In this work, the main concern is to study the stress distributions within the insulation/metallic shell assembly. Such analysis is useful for predicting the assembly strength through stress based criteria.

The combination foam and metal is very critical due to the incompatibility between their thermal dilatation and this situation may lead to failure either within the foam or the adhesive layer. In addition, the reservoir is often under pressure so that the mechanical loading of the foam–metal bilayer is a complex mixture of biaxial and shear loading. As discussed in the our recent study [1], the thermomechanical problem of insulation of a large cryogenic reservoir (half-illustrated in Fig. 1(a)) can be reduced to the problem of a single insulating panel glued on the metallic plate and subjected to thermal stresses due to the thermal expansion incompatibility of components, and axial and hoop stresses due to reservoir pressure effects (see in Fig. 1(b)). On the first hand, a finite element (FE) solution of this reduced problem is possible but it is not necessarily the best strategy when the ultimate goal is to provide an optimization of the material choice and the component dimensions. On the other hand, the simple formula often used for dimensioning tank insulation [2] is very useful but is questionable in some situations since it misses some important mechanics. There is thus a need to develop an effortless and less time-consuming approach enabling us to provide a transparent analysis of the influence of the variables of the problem (material properties and component dimensions).

In the literature, adhesively bonded bi-materials are usually treated using the shear-lag theory. The recent literature review, conducted by da Silva et al. [3], gives an overview of adhesively bonded joints and the proposed solution approaches. The most studied joints are the single-lap and double-lap joints [4–7]. There are also some studies concerning stiffened joints [8], which seem close to the current configuration. It is interesting to note that almost all existing closed-form solutions neglect (*i*) the stresses in the normal direction to the loads caused by Poisson's ratio strains in the adherends; and (*ii*) the through thickness shear adherend deformations.

In many situation encountered in practice (such as structures repaired or reinforced by patches [9–11] and reservoirs insulated with glued panels as in the current problem), the systems are two-dimensional (2D) and the loading is more complex. Attempts to include these complexities have been initiated by Adams and Pappiatt [12] through a simplified 2D stress model. A 2D strain–stress relationship, allowing the connection between the in-plane stresses due to the Poisson's ratio effects, was considered. It has been, however, shown that this simplified model provides only accurate prediction for joints subjected to uniaxial loading [10,12]. Later, Mathias et al. [10] improved the Adams and Pappiatt's works

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0143-7496/$ - see front matter
doi:10.1016/j.ijadhadh.2012.01.006

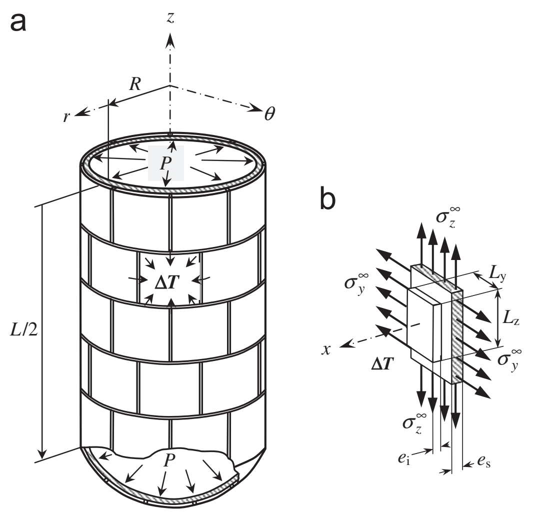

Fig. 1. Illustration of the studied configurations. (a) Lower-half part of cryogenic tank recovered with foam panels and subjected to internal pressure P and temperature drop ΔT; (b) plane geometry approximation of an elementary unit.

by taking into account correctly the coupling between in-plane stresses and the effects of the Poisson's ratio strains. Cases of joints subjected to biaxial tension or plane shear loadings were investigated. Deheeger et al. [11] extended the Mathias et al.' model to study the problem of reinforcement of metallic structures with composite patches subjected to thermal stresses due to the difference of thermal expansion of adherends.

In all the above theoretical models, the shear deformations of adherends have been neglected. However, when the shear stiffnesses of adherends are much lower than that of the adhesive, large shear deformations will also be present at the adherend surfaces adjacent to the adhesive layer for shear stress equilibrium at the interface. It is the case of some laminated composite adherends [13–15] and probably of polymer foam layer glued on metallic plate as studied here. Thus, the adherend shear deformations must be included in the theoretical models. In our recent works [1], a semi-analytical model enabling to take into account the adherend shear deformations, the Poisson's ratio effects, and the 2D nature of loadings was developed and was applied to explore the influence of material mechanical properties and component dimensions on the foam/metallic plate behavior. To get an idea about the validity limits of this model, a comparative study with a reference approach is necessary. In the current study, a comparative study of the semi-analytical model against FE simulation is conducted. The effects of type of loading (biaxial stresses or thermal stresses) are explored independently. Also, the case of joints made of isotropic and orthotropic polymer foam adherends is considered.

The paper is structured as follows. First, the semi-analytical model is recalled after evoking briefly the major simplifying hypotheses. Then, the comparative study of the current model against FE simulation is presented. The appropriateness of each simplification is then discussed.

2. Theoretical model

2.1. Hypothesis

In the following, the indexes i, s, and a refer respectively to insulating plate, metallic shell, and adhesive layer.

- As illustrated in Fig. 1(b), a parallelepipedic configuration was considered (length, L_z, width, L_y, and the thicknesses e_i (for the insulating plate), e_a (for the adhesive) and e_s (for the substrate).
- The adherends were assumed to be subjected only to in-plane stresses (classical assumption of problems of thin reservoirs [16]).
- The adhesive layer was considered to be a shear spring allowing transferring the in-plane forces from an adherend to the other. The shear stresses in the adhesive layer were assumed constant through the thickness.
- The three materials involved were assumed to be linear elastic until they fail by brittle fracture (at least at the temperature level 20 K that we are interested here).
- The substrate and the adhesive are isotropic whereas the insulating foam may be considered as orthotropic. This orthotropic behavior of the insulation is inherited from the foaming process discussed in Section 3.2. The involved material parameters are thus the following: E^s, G^s, υ^s and α^s for the substrate; E^i_y, E^i_z, G^i_{yx}, G^i_{zx}, υ^i_{yz}, α^i_y, and α^i_z for the insulating material (ignoring the x-components); and G^a for the adhesive. E, G, υ, and α refer to the Young's modulus, shear modulus, Poisson's ratio, and thermal expansion coefficient, respectively.
- The effects of bending moments and peeling due to load-path eccentricity were neglected.
- The shear stresses vary linearly through the adherend thicknesses. This simplification is essential to obtain a semi-analytical solution of the current problem. Note that this simplification fulfils the boundary and continuity conditions (in terms of shear stresses and strains), i.e., the adherend shear stresses are zero at the outer insulation and inner substrate surfaces; and the adherend and adhesive shear stresses/strains are identical at interfaces.

2.2. Semi-analytical model

According to the assumptions listed in Section 2.1, the unknowns of the insulation/adhesive/metallic plate bonded joint problem are the following stress components.

$$\begin{bmatrix} 0 & \sigma^j_{yx} & \sigma^j_{zx} \\ \sigma^j_{yx} & \sigma^j_y & 0 \\ \sigma^j_{zx} & 0 & \sigma^j_z \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 0 & \sigma^a_{yx} & \sigma^a_{zx} \\ \sigma^a_{yx} & 0 & 0 \\ \sigma^a_{zx} & 0 & 0 \end{bmatrix} \tag{1}$$

The left equation refers to the stress states in the adherends with $j=i$ for the insulating material, and $j=s$ for the substrate whereas the right equation refers to the stresses in the adhesive layer, which are only function of y and z.

Fig. 2(a) depicts the x–z plane view of the joint. The inner substrate surface is at abscissa $x=0$, the adhesive/substrate interface is at abscissa x_s, the insulation/adhesive interface is at abscissa x_a, and the outer insulation surface is at abscissa x_i. The equilibrium equations schematically shown in Fig. 2(b), the stress–strain relationship, the kinematic equations, the continuity of internal forces, and the through-thickness linear shear stress assumption enable us to derive the equations governing the stress distributions in Eq.(1). For the details of derivation, the readers are recommended to refer to reference [1]. It is shown that the normal stresses in the in-plane directions in the insulating material satisfy the second order differential Eqs. (2) and (3):

$$\frac{\partial^2 \sigma^i_z}{\partial z^2} = a_z \sigma^i_z + b_z \sigma^i_y + c_z \tag{2}$$

$$\frac{\partial^2 \sigma^i_y}{\partial y^2} = a_y \sigma^i_y + b_y \sigma^i_z + c_y \tag{3}$$