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# Stress redistributions in adhesively bonded double-lap joints, with elastic–perfectly plastic adhesive behavior, subjected to axial lap-shear cyclic loading

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ABSTRACT

A shear-lag model is developed in order to evaluate stress redistributions in double-lap joints under axial (tensile) lap-shear cyclic loading. The adherend materials exhibit linear elastic behavior, whereas the material of the adhesive layer satisfies the elastic–perfectly plastic shear stress–strain constitutive relation. The reference state (from which the stresses are redistributed) is based on the standard elastic–perfectly plastic shear-lag analysis for double-lap joints. The main conclusion of the current analysis is that, during unloading, shear stresses of opposite sign may develop in the plastic zones of the adhesive layer, at the ends of the overlap, without reversing the direction of the applied load. A simple model for evaluating the variation of the maximum peel stress in the adhesive layer, based on the variation of the peak shear stress, demonstrates that the sign of peel stresses may alternate, as well. Under cyclic (fatigue) loading, the range of the peak stresses in the adhesive layer is the basic parameter for the evaluation of the variation of the energy release rate and the associated crack growth rate in the overlap. In this framework, the current simplified analysis may provide a reference model for comparisons with experimental data or with results which are based on more complex numerical models. The current model can be readily extended to cover the cases of development of plastic zones in the adhesive layer with shear stresses and plastic strains of opposite sign (during unloading or during load direction change).

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## 1. Introduction

During the recent years considerable interest has been shown in the use of adhesive-bonded joints as load-bearing structures. The use of adhesive bonding offers certain advantages over traditional jointing techniques, like corrosion and fatigue resistance, crack retardation, good dumping characteristics, cost saving, lighter weight structural components, etc. [1,2]. Another advantage of adhesive bonding is the ability to join dissimilar materials more efficiently than conventional jointing techniques [3,4].

The purpose of the current work is the development of a simplified model to evaluate the redistribution of stresses in the adhesive layer of a symmetric, stiffness imbalanced, double-lap joint (DLJ), subjected to a cyclic (fatigue) tensile lap-shear loading [5–8]. It is assumed that the adhesive material follows the standard elastic–perfectly plastic shear stress–strain constitutive relation [1,4,9,10]. The adherend materials exhibit linear elastic behavior, including thermal stress effects. Moreover, the maximum level of the applied load is such that plastic zones are developed in the adhesive layer at the ends of the overlap (where the stresses reach their extreme values).

The main result of the current analysis is that, during unloading, shear stresses of opposite sign may develop in the adhesive plastic zones. This phenomenon is observed even without changing the direction of the applied axial load. Multi-dimensional finite element models, based on elastic–plastic analysis, also verify the fact that, during unloading, the sign of the peak shear stresses, at the overlap ends, changes without reversing the loading direction, see [7] for single-lap joints.

A simple model for the evaluation of the variation of the maximum peel stresses in the adhesive layer [4,5], demonstrates that the sign of the peel stresses may alternate, as well, (see Section 2). Under cyclic (fatigue) loading, the accumulated plastic strains, as well as, the ranges of the peak shear and peel stresses in the adhesive layer, determine the variation of the *energy release rate* and the associated *crack growth rate* in the overlap [5,7,11–15]. Since, more or less, all adhesives exhibit a certain degree of plastification [4,16], the current simplified analysis may provide a reference model for comparisons with experimental data or with results which are based on more complex numerical models [7,17]. The current model can be

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extended to cover the case of plastic zones development in the adhesive layer with shear stresses and plastic strains of opposite sign (during unloading or during load direction change).

Resuming, the paper is organized into the following parts: Section 2 provides the basic nomenclature and contains a brief summary of the elastic–plastic shear-lag analysis for double-lap joints. This is the reference state from which the stresses are redistributed. The current model for the redistribution of stresses in the adhesive layer of a DLJ, subjected to axial lap-shear cyclic loading, is developed in Section 3. Section 4 contains numerical results for Aluminum-to-Aluminum (stiffness balanced) DLJ and high strength Graphite epoxy-to-Aluminum (stiffness imbalanced) DLJ (with and without effects of the thermal mismatch between the adherends). Finally, Section 5 provides concluding remarks and possible future research directions, based on the proposed model.

## 2. Nomenclature and brief summary of the elastic–plastic shear-lag analysis for double-lap joints

The scope of the current section is to introduce the necessary nomenclature and to recall some results which are deduced based on the standard *shear-lag analysis*, using the elastic–perfectly plastic model for the adhesive layer [4]. The geometry of a typical symmetric double-lap joint is depicted in Fig. 1. To avoid further technicalities, only tensile (axial lap-shear) loads are assumed to be transferred. Compressive loads are not considered in this work. Nevertheless, the analysis of Section 3 may be extended to cover compressive lap-shear loads. Due to symmetry, the analysis refers only to the upper part of the joint configuration (see Fig. 1).

The adherend deformations lie within the linear elastic range, while the adhesive layer is assumed to be relatively *ductile*. The shear deformation of the adhesive is described by an elastic–perfectly plastic shear stress–strain curve, see Fig. 2 and [1,4,9]. The load eccentricity in the outer adherends (with respect to the adhesive bond line) is neglected in the evaluation of the adhesive layer shear stress. The peel stresses in the adhesive may be approximated separately, based on appropriate assumptions, see [4,5,7] and below.

We assume in the following that either one or two plastic zones have developed at the ends of the overlap. The plastic-to-elastic zone interfaces are located at $x = a$ for the left plastic zone and at $x = b$ for the right plastic zone, $0 < a < b \leq L$. Without loss of generality, it is assumed that in the case of one plastic zone, this zone appears at the left end of the overlap.

The longitudinal force equilibrium of adherend differential elements at a typical location $x$ gives (see Fig. 1),

$$\frac{dT_1}{dx} = -\tau, \quad \frac{dT_2}{dx} = +\tau \tag{2.1}$$

where $T_1$, $T_2$ are the axial resultant forces (per unit width) in the adherends and $\tau(x)$ represents the shear stress distribution in the adhesive layer.

The shear strain in the adhesive layer is approximated by the bond line differential displacements (neglecting the rotations of the outer adherends due to possible bending),

$$\gamma = \frac{u_2 - u_1}{n} \tag{2.2}$$

where $u_1$, $u_2$ are the longitudinal displacements of the adherends and $n$ is the thickness of the adhesive layer.

The shear stress–strain relations for the adhesive layer are stated as follows:

$$\tau = G\gamma \quad \text{(adhesive layer's elastic region)} \tag{2.3a}$$

$$\tau = \tau_P \quad \text{(adhesive layer's plastic regions)} \tag{2.3b}$$

where $G$ is the effective elastic shear modulus of the adhesive layer and $\tau_P$ is the ultimate plastic stress of the adhesive layer, see Fig. 1.

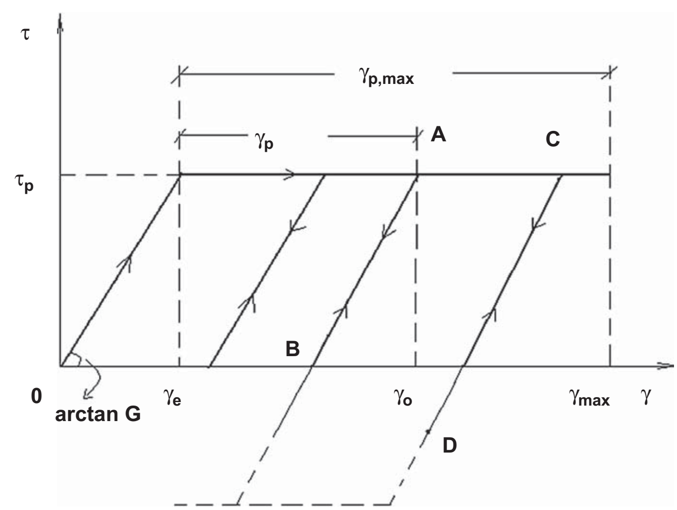


**Fig. 2.** Idealized elastic–perfectly plastic shear stress–strain curve for the adhesive layer, including unloading paths.

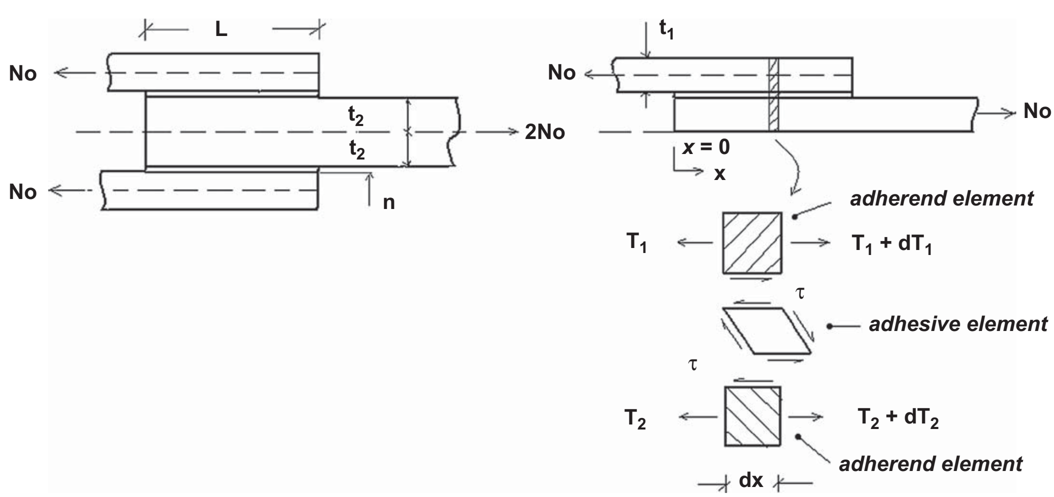


**Fig. 1.** Geometry and nomenclature for a symmetric double-lap joint.

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