

Contact stresses in adhesive joints due to differential thermal expansion with the adherends

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ABSTRACT

The contact stresses in a bonded joint due to differential thermal expansions are calculated by considering the adhesive as an elastic rectangle confined by plates representing the adherends. The interface is cohesive in type, so that the contact area is a perfectly adherent region surrounded by cohesive areas where slip occurs at constant shear-stress. The problem is formulated in terms of Papkovitch–Fadle eigenfunctions, which satisfy the boundary conditions on the stress free edges. The resulting integral equations are solved with the Jacobi integration formula. The size of the cohesive zone, which is determined by imposing the finiteness of the contact stresses at the frontier with the bonded region, depends upon the length and height of the joint. In very long joints the result tends to the technical rule of thumb traditionally employed to design such joints, but for intermediate lengths the elastic solution is quite different.

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1. Introduction

Adhesive bonded joints play a significant role in the development and production of different-in-type structures, in the aerospace and automotive industries as well as in the electronic technology. In the building industry, structural façades make use of high performance adhesives to fix glass, or other materials, to a rear frame *in lieu* of gaskets or other mechanical attachments. Indeed, metal and glass are frequently glued together in order to avoid the high stress concentrations associated with bolt holes. Apart from the effects of the dead and service loads, the state of stress in the adhesive joints may become critical because of the differential thermal expansion of the adherends and of the adhesive itself.

Since the adherends may present different coefficients of thermal expansion, in the design phase a great attention is paid to their repeated expansions and contractions due to cyclic temperature variations. Consequently, the adhesive thickness is sized to accommodate these movements, as well as to compensate for flatness tolerances between the adherends. However, quite surprisingly, the thermal straining of the adhesive layer itself is most of the time neglected, although its coefficient of thermal expansion can be orders of magnitude greater than that of the adherends.

Just to illustrate, reference can be made to the case of united cells for structural glazing, obtained by bonding glass panels to a metallic frame with structural silicone. Technical guidelines and datasheets for adhesives (3M, 2015; ASTM C1401-14, 2014; Dow-Corning®, 2015; ETAG 002, 2012) prescribe for the adhesive joint a minimum thickness (in general 6 mm), or a maximum strain of 10%–15%. Such a limit has to comply with the relative movement of the metallic frame (typically made of steel or aluminum) with respect to the glass panel, due to their different thermal expansion.¹ However, the aforementioned guidelines never mention the thermal dilatation of the structural silicone, although its coefficient of thermal expansion is much greater than that of the adherends.²

The aim of this article is to accurately characterize the role of the adhesive when the joint undergoes a temperature variation. The model problem is that of an elastic rectangle (the adhesive) in plain strain, confined by two plates (the adherends), under a uniform thermal variation ΔT . If one refers to a typical situation, the confining layers are made of, say, steel and glass, whereas the elastic rectangle represents the structural silicone. Since the adherends have quite similar coefficients of thermal expansion, one can neglect their difference with respect to the much higher thermal deformation of the adhesive, and assume the same thermal strain $\varepsilon_p = \alpha_p \Delta T$ in the confining plates for any temperature variation.

¹ Typical coefficients of thermal expansion are $\alpha_{st} = 10.5 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ (ferritic stainless steel), $\alpha_{al} = 23.2 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ (aluminum), $\alpha_{gl} = 9 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ (glass).

² A typical coefficient of thermal expansion for a commercial type of structural silicone is $\alpha_{si} \approx 290 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$.

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Nomenclature

λ_n	Non zero complex roots of the equation $\sin 2\lambda_n + 2\lambda_n = 0$
ν	Poisson's ratio
$\sigma_{xx}, \sigma_{xz}, \sigma_{zz}$	Stresses
ε_T	Thermal deformation
ε_r	Thermal deformation in the rectangular domain
ε_p	Thermal deformation in the plate
θ	Shear function
α_p, α_r	Coefficient of thermal expansion of plates and rectangle.
$\alpha_{st}, \alpha_{gl}, \alpha_{al}, \alpha_{si}$	Coefficient of thermal expansion of steel, glass, aluminum and silicone.
δ	Cohesive length in the simple model
Ω, Ψ	Stress functions
Δ	Uniform displacement
a	Aspect ratio
f_{1n}, f_{2n}	Papkovich–Fadle eigenfunctions
u_x, u_y	Displacements
c	Half length of the adhesive portion
b	Width of the elastic rectangle
h	Half width of the elastic rectangle
p_T	Uniform pressure
q	Constant shear stress
$w_i^{\alpha, \beta}$	Weights of the Jacobi integration formula ($i = 1, \dots, n_1$)
n_1	Number of equations approximating the integral equation
A_n	Unknown complex constants ($n = -\infty, \dots, -1, 1, \dots, \infty$)
D	Real constant
G	Shear modulus
Q_1, Q_2	Shear functions
J_0	Bessel functions
I_0, I_1	Modified Bessel functions
H	Height of the elastic rectangle
E	Young's Modulus of the rectangle
K_{II}	Mode II stress intensity factor
$p_n^{\alpha, \beta}$	Jacobi polynomial of the first kind
L^0, L^1, L^2	Kernels
K	Kernel
M^0	Kernel
F	Kernel
N	Kernel
$H(y, z)$	Kernel

On the other hand, the thermal strain $\varepsilon_r = \alpha_r \Delta T$ in the adhesive is much higher. With an elementary argument based upon superposition of effects, schematically illustrated in Fig. 1, one can

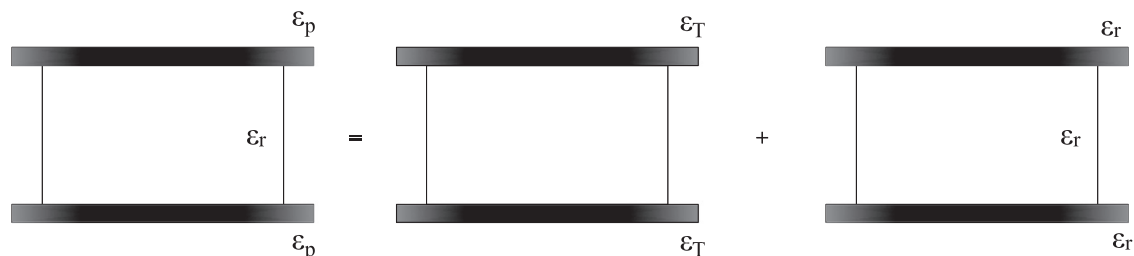


Fig. 1. A bonded joint subject to a thermal mismatch. Superposition of the effects of an elastic rectangle confined by two deforming layers, and of the condition in which all the constituents undergo the same thermal deformation.

consider the case of an elastic rectangle in contact with two layers undergoing the same thermal strain $\varepsilon_T = \varepsilon_p - \varepsilon_r = (\alpha_p - \alpha_r) \Delta T$, in addition to the case in which all the constituents undergo the same thermal deformation ε_r . Clearly, only the first case is of importance, because the second condition is stress-free.

An expansion (or contraction) of the external layers causes the adhesive interlayer to undergo a state of stress at the interface that can produce partial debonding. Such process is governed by the interfacial bond strength, which is in general correlated with the relative displacement between the adhesive and the adherend.

While investigating the adhesion properties between glass and polymers through TCT (Through-Cracked-Tensile) tests, Ferretti et al. (2012) observed that the force–displacement diagram showed a peak followed by a horizontal plateau associated with progressive delamination. Analysis of these tests has shown that during the delamination process, the glass-polymer relative displacement increases while the corresponding shear stress remains almost constant. This steady state regime has also been observed by other authors, for other types of polymeric interlayer (Delincé et al., 2008; Muralidhar et al., 2000). There is a general agreement that the strength of an adhesive joint can be characterized through a bond-stress vs. relative-displacement constitutive law. Many models for adhesive interfaces have been developed since the 1960s and a list of relevant references can be found in Raous (2011). Most of them have focused on the cohesive zone models in the context of fracture mechanics, following the seminal works by Dugdale (1960), Barenblatt (1962), Needleman (1987, 1990, 1992), for normal-loading conditions, and Tvergaard and Hutchinson (1993, 1994), Xu and Needleman (1994), for mixed-mode loading.

One of the most used model is that by Tvergaard and Hutchinson (1993), who assumed a trapezoidal shear-stress vs. relative-slip constitutive law at the interface, articulated in three phases: a linear ascending branch up to the peak stress, a plateau where displacement increases at constant stress and, finally, a linear strain-softening phase approaching the fracture displacement where the stress is null. In certain cases, since the ascending and descending branches can be considered negligible if compared with the width of the intermediate plateau, it is reputed to be sufficient to consider the simplest step-wise law to interpret the gradual debonding process (Franco and Royer-Carfagni, 2014a, 2014b).

Other authors have considered the imperfect bonding of two elastic solids through a thin elastic layer, to rigorously derive interface conditions by letting the thickness of the interlayer go to zero. In general, one obtains constitutive relations more complex than the classical ones, in which the local stress is supposed to be a linear function of the relative displacement between the adherends. These methods rely in general on asymptotic expansions, under some basic assumptions about the rescaling of the elastic moduli and the type of strain inside the interlayer. For example, Klarbring (1991) made the hypothesis that the displacement varies linearly and the stress is constant through the interface. The solution was shown to be unique also in the limit of vanishing thick-

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