Composite Structures 203 (2018) 85–100

Contents lists available at ScienceDirect

Composite Structures

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

Simplified stress analysis of functionally graded single-lap joints subjected to combined thermal and mechanical loads

Eric Paroissien[a,*], Lucas F.M. da Silva[b], Frédéric Lachaud[a]

[a] Institut Clément Ader (ICA), Université de Toulouse, ISAE-SUPAERO, INSA, IMT MINES ALBI, UTIII, CNRS, 3 Rue Caroline Aigle, 31400 Toulouse, France
[b] Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Portugal

A R T I C L E I N F O

Keywords:
Functionally graded adhesive
Single-lap bonded joint
Stress analysis
Macro-element
Thermoelasticity
Dissimilar adherend

A B S T R A C T

Functionally graded adhesive (FGA) joints involve a continuous variation of the adhesive properties along the overlap allowing for the homogenization of the stress distribution and load transfer, in order to increase the joint strength. The use of FGA joints made of dissimilar adherends under combined mechanical and thermal loads could then be an attractive solution. This paper aims at presenting a 1D-bar and a 1D-beam simplified stress analyses of such multimaterial joints, in order to predict the adhesive stress distribution along the overlap, as a function of the adhesive graduation. The graduation of the adhesive properties leads to differential equations which coefficients can vary the overlap length. For the 1D-bar analyses, two different resolution schemes are employed. The first one makes use of Taylor expansion power series (TEPS) as already published under pure mechanical load. The second one is based on the macro-element (ME) technique. For the 1D-beam analysis, the solution is only based on the ME technique. A comparative study against balanced and unbalanced joint configurations under pure mechanical and/or thermal loads involving constant or graduated adhesive properties are provided to assess the presented stress analyses. The mathematical description of the analyses is provided.

1. Introduction

In the frame of structural design, the proper choice of joining technology is decisive for the integrity of the manufactured structure. Mechanical fastening, such as riveting or screwing, appears to be a reliable solution for the designers. Nevertheless, alone or in combination with mechanical fastening, the adhesive bonding technology may offer significantly improved mechanical performance in terms of stiffness, static strength and fatigue strength [1–3]. Indeed, unlike the discrete load transfer of mechanical fasteners, the load transfer between structural bonded components is continuous all along the overlap. This higher level of mechanical performance allows for lighter joints. In other words, adhesive bonding offers the possibility to reduce the structural mass while ensuring the mechanical strength. The optimization of the strength-to-weight ratio is a challenge for several industrial sectors, such as aerospace, automotive, rail or naval transport industries.

Nevertheless, stress gradients at both overlap ends appear in bonded joints, due to the relative deformation of the adhesive layer with regards to the adherends. It leads to a load transfer restricted on a small length at the overlap ends. In order to increase the load capability of bonded joints, the reduction of adhesive peak stresses is wanted. The specimen design for the thick adherend shear test [4] leads to both a homogenization of the adhesive shear stress and a drastic reduction the adhesive peel stress, all the more when care is taken to reduce the edge effects [5]. Another approach is to make the material and/or geometrical properties of the adherends and/or the adhesive layer vary along the overlap. Several design solutions have been published [3]. For example, a solution is the tapering of adherends at overlap ends, which allows for a progressive increase of the neutral line lag and a reduction of adhesive peel stress [6,7]. A more local solution is the rounding of adherend corner associated with adhesive spew fillets [8,9]. The mixed adhesive solution which is a rough version of a graded joint consists in the use of various different adhesives along the overlap to increase the joint strength [10–13]. In recent past years, functionally graded adhesive (FGA) have been more and more considered [14,15]. FGA joints involve a continuous variation of the adhesive properties along the overlap allowing for the homogenization of the stress distribution and load transfer. When dissimilar adherends have to be bonded, the adhesive stress distribution is asymmetrical, so that one of the overlap ends is overstressed. Moreover, this overstressing is magnified under thermal loads due to the mismatch in coefficient of thermal expansion (CTE) of adherends. The capability of a local graduation of the adhesive stiffness is a promising solution to optimize the strength of

* Corresponding author.
E-mail address: eric.paroissien@isae-supaero.fr (E. Paroissien).

https://doi.org/10.1016/j.compstruct.2018.07.015
Received 9 May 2018; Accepted 3 July 2018
Available online 05 July 2018

Nomenclature and units

A_j	extensional stiffness (N) of adherend j
B_j	extensional and bending coupling stiffness (N mm) of adherend j
D_j	bending stiffness (N mm^2) of adherend j
E_a	adhesive peel modulus (MPa)
$E_{a,\min}$	adhesive shear modulus (MPa)
$E_{a,\max}$	adhesive shear modulus (MPa)
E_j	adherend Young's modulus (MPa) of adherend j
F	magnitude of applied force (N)
F_e	element nodal force vector
$F_{e,therm}$	element nodal force vector equivalent to thermal load
G_a	adhesive shear modulus (MPa)
$G_{a,\max}$	maximal adhesive shear modulus (MPa)
$G_{a,\min}$	minimal adhesive shear modulus (MPa)
K_{BBa}	elementary stiffness matrix of a bonded-bars element
K_{BBe}	elementary stiffness matrix of a bonded-beams element
$K_{bar,j}$	elementary stiffness matrix of a bar for the adherend j
L	length (mm) of bonded overlap
M_e	element matrix linking the element nodal displacement to the constant integration vector
M_j	bending moment (N mm) in adherend j around the z direction
M_e	element matrix linking the element nodal force to the constant integration vector
$M_j^{\Delta T}$	thermal bending moment (N mm) in adherend j around the z direction
N_j	normal force (N) in adherend j in the x direction
$N_j^{\Delta T}$	thermal normal force (N) in adherend j in the x direction
S	adhesive peel stress (MPa)
T	adhesive shear stress (MPa)
T_{max}	maximal adhesive shear stress (MPa)
U_e	element nodal displacement vector
V_j	shear force (N) in adherend j in the y direction
b	width (mm) of the adherends
c	half-length (mm) of bonded overlap
e_a	thickness (mm) of the adhesive layer
h_j	half thickness (mm) of adherend j
k_I	adhesive elastic stiffness (MPa/mm) in peel
k_{II}	adhesive elastic stiffness (MPa/mm) in shear
n_max	order of truncation
n_ME	number of macro-elements
p	power of the graduation law
u_j	displacement (mm) of adherend j in the x direction
v_j	displacement (mm) of adherend j in the y direction
Δ	overlap length (mm) of a macro-element
Δ_T	variation of temperature (K)
Δu	slipping displacement (mm)
Δ_j	characteristic parameter (N^2 mm^2) of adherend j
α_j	coefficient of thermal expansion (K^{-1}) of adherend j
θ_j	bending angle (rad) of the adherend j around the z direction
χ_A	adherend stiffness unbalance parameter (–)
χ_α	adherend thermal unbalance parameter (–)
(X,Y,Z)	element reference system of axes
(x,y,z)	global reference system of axes
BBa	Bonded-bars
BBE	Bonded-beams
CTE	coefficient of thermal expansion
FE	finite element
FGA	functionally graded adhesive
GM	general model
ISLM	improved shear-lap model
JE	joint element
ME	macro-element
ODE	ordinary differential equation
TC	test case
TEPS	Taylor expansion in power series

multimaterial joints under severe loads, such as combined thermal and mechanical. This situation occurs very often in multi-material structures found in the transport industry. That is why the development of dedicated stress analyses to predict the stress distribution is fundamental. The Finite Element (FE) method is able to address the stress analysis of FGA joints [12,14]. Nevertheless, since analyses based on FE models are computationally costly, it would be profitable both to restrict them to refined analyses and to develop simplified approaches, enabling extensive parametric studies and optimization processes. Moreover, numerous simplified stress analyses of bonded joints are available and provide accurate predictions [16–18]. In 2014, Carbas et al. published a first analytical approach for 1D-bar stress analysis of FGA joints [19]. This stress analysis is based on the shear-lag approach by Volkersen [20] associated with a resolution scheme making use of Taylor expansion in power series (TEPS) to solve the involved differential equations. This stress analysis is restricted to half of the overlap length of balanced joints with a linear graduation of the adhesive shear modulus. Stein et al. presented a 1D-bar analysis using TEPS resolution able to address unbalanced bonded joints under any adhesive properties graduations [21,22]. This analysis is called by the authors Improved Shear Lag Model (ISLM). Moreover, Stein et al. provided a sandwich-type analysis using TEPS resolution, taking into accounts both in-plane and out-of-plane load, termed General Model (GM). The sandwich-type analysis concept comes from the analysis methodology by Goland and Reissner [23] who provided the first closed-form solution for the adhesive stress distribution for simply supported balanced joint made of adherends undergoing cylindrically bending. Goland and Reissner took into account the geometrical non linearity due to the lag of neutral line to assess the bending moment at both overlap ends through a bending moment factor. This methodology was then employed by other researchers to improve the initial model [24–32] leading to various forms of the bending moment factor [33]. In 2017, Stapleton et al. used a joint element (JE) for the stress analysis of FGA joints under various geometrical configurations, including in-plane and out-of-plane load as well as non-linear material behavior [34]. A JE is a 4-nodes brick element allowing for the modelling of two bonded adherends [34,35]. Over a similar period of time, the first and third authors of the present papers and co-workers have been working on the development of the macro-element (ME) technique for the simplified stress analysis of bonded, bolted and hybrid (bonded/bolted) joints [36–43]. Dedicated 4-nodes Bonded-bars (BBa) and Bonded-beams (BBe) have been formulated. As for the JE model, only one BBa or BBe, depending on the chosen kinematics, is sufficient to be representative for an entire bonded overlap in the frame of a linear elastic analysis (see Fig. 1).

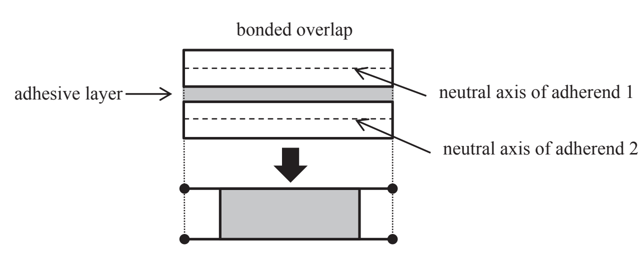

Fig. 1. Modelling of a bonded overlap by a macro-element.