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Cohesive interface behaviour and local shear strains in axially loaded composite annular tubes

Agostina Orefice, Geminiano Mancusi *, Luciano Feo, Fernando Fraternali

Department of Civil Engineering, University of Salerno, Italy

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ABSTRACT

The local behaviour of a composite profile with annular cross-section is studied in presence of interfacial cohesive forces at the ends, where the lateral surface may be involved in a bonding connection. Features include the possibility of warping displacements, nonlinear shear strains within the thickness of the annular wall originated by the bonding interactions. Numerical simulations are carried out in order to investigate the tube behaviour over the loading path up to the failure, thus underlining the relevance of the thickness on the magnitude of the shear strains.

1. Introduction

Thick-walled tubular composite profiles with annular cross-section represent the optimal solution for a number of applications (large truss covers, large bridge decks or spatial frames). Within this context, the possibility of connecting the composite tubes by means of co-axial nodal devices has been recently investigated with the aim of developing a standard, reliable, easy to make system for onsite assembling modality by using a structural glue.

Many factors affect the bonding behaviour at the ends of the tube, where the adhesive interface to the nodal device exists: the constitutive properties for the device (metal, composite) and the tube (GFRP, CFRP), the choice of the glue, the length and thickness of the bonding layer, the considered loading path.

A useful approach for modelling the mechanical response of the adhesive interface refers to the cohesive fracture mechanics. In this view, the interfacial interactions come from appropriate potentials thus allowing a simple mathematical formulation of the bonding problem.

The cohesive fracture mechanics literature includes many contributions over the recent years especially devoted to the bonding of composite adherents.

Almitani and Othman [1] investigated the harmonic response of single lap and double-lap joints including viscoelastic properties of the adhesive and the adherents. To this aim they assumed a viscous-elastic behaviour for the adhesive and the adherents, which is represented by a complex modulus written using the model of Kelvin-Voigt.

Xu and Qu [2] developed a model that incorporates the unloading behaviour varying from full plasticity to damage. They captured the irreversible deformation mechanisms resulting from the localized plastic deformation and damage accumulation due to the nonlinear separation of fibre–matrix interface under transverse loading and unloading conditions.

The last models are the most recent ones. However, for the specific scope of the present study, which is focused on the analysis of the local behaviour of the tube in presence of cohesive forces, we have chosen to start a discussion from two well-known papers by Rose et al. [3,4]. These works exhibit a great interest due to their universal binding energy law for studying the mode I crack propagation in metallic and bimetallic interfaces. Moreover, the work by Camacho and Ortiz [5] is also considered. They define, in fact, an effective opening displacement as a function of the opening (mode I) and sliding (mode II) interfacial displacements and introduce a coupling rule in order to account for both.

In a recent work [6] the mechanical behaviour of tubular composite profiles bonded to apposite nodal devices has been investigated in a combined manner which accounts for both the kinematics of the tube and the cohesive behaviour of the bonding interface. The effects of shear strains within the thickness of the tube are also considered. Although internal stresses essentially accord to the axial regime, it is observed that shear strains and stresses originated by the interfacial interactions are present within the composite tube over the adhesive bonding zones. As a

* Corresponding author.
E-mail addresses: aorefice@unisa.it (A. Orefice), g.mancusi@unisa.it (G. Mancusi), l.feo@unisa.it (L. Feo), f.fraternali@unisa.it (F. Fraternali).

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Notation

O	origin of the reference system
i_1, i_2, k	unit vectors (orthonormal)
r	radial coordinate
z	longitudinal coordinate (axial)
z_I	axial coordinate at the beginning of the cohesive zone
O_i	intersection between z-axis and the generic cross-section (i.e. O_1)
t_b	thickness of the bonding layer
L_b	length of cohesive zone
t	thickness of the composite tube
L	length of the composite tube
r_2	inner radius of the composite tube
r_3	outer radius of the composite tube
ζ	dimensionless axial coordinate over the cohesive zone : $\zeta = (z - z_I)/L_b$
ρ	dimensionless radial coordinate: $\rho = (r - r_2)/t$
$w(r,z)$	displacement field (axial)
$w_i(z)$	displacement field (axial) at a defined radial coordinate r_i
$f_i(r)$	polynomials of the radial coordinate
d_r	interfacial normal displacement
d_k	interfacial tangential displacement
λ_I, λ_{II}	coupling coefficients between the normal and tangential interfacial displacements
h	interfacial equivalent displacement
h_c	characteristic value of the interfacial displacement (related to a static fracture)
Φ_U	fracture energy (per unit surface)
$F(h)$	cohesive potential
t_{rk}	interfacial tangential traction (per unit surface)
t_{rr}	interfacial normal traction (per unit surface)
p	interfacial traction
p_c	strength of the cohesive interface
κ	secant slope of the cohesive interface law
$p_z(r)$	normal traction forces (per unit surface) applied at the loaded end of the system
T	resultant traction
T_{max}	failure load
γ_i	average shear strain over the inner half thickness of the composite tube
γ_o	average shear strain over the outer half thickness of the composite tube

consequence, the local behaviour of the composite profile is affected by them and the failure criterion should account for this.

In the present work a parametric numerical analysis has been carried out in order to investigate the strains and stresses within the tube accounting for the interfacial interactions distribution. Moreover, the load provoking the bonding failure is evaluated. The numerical model has been developed according to the mechanical model described in [6,7]. A preliminary assumption has been made: the nodal device stiffness has been considered extremely high in comparison with the tube stiffness, that is a condition which substantially occurs in practice. The considered parameters of the study include the thickness of the composite tube, the bonding lengths, the load entity over a monotonic loading path up to the failure (Fig. 1).

2. The mechanical model

The mechanical model considered in the present study is based on appropriate kinematic hypotheses [6,7] that allow to investigate how the shear strains can influence the system response in terms of displacements and failure load. The model, which is very general, is now proposed for studying the response of a pultruded tubular profile made of FRP when generic forces, for instance cohesive forces or active forces, act on the lateral surface of the tube. The main feature of this model is the simulation of the axial displacement field as a linear combination of generalised unknowns, $w_i(z)$, which assume the physical meaning of axial displacements at defined radial coordinates, r_i. Moreover, the combination coefficients are polynomials of the radial coordinate, $f_i(r)$, truncated at the second order terms:

$$w(r,z) = w_i(z) f_i(r) \quad (i = 1,2,3) \tag{1}$$

The geometry of the problem under consideration is shown in Figs. 2a and 2b, where symbols L,t,r_2 and r_3 denote the length, the thickness, the inner and the outer radius of the tube, while L_b is for the length over which the cohesive forces act.

Furthermore, $\mathbf{i}_1$, $\mathbf{i}_2$ and $\mathbf{k}$ represent the unit vectors of the orthonormal basis, with $\mathbf{k}$ aligned to the z-axis, while $\mathbf{i}_1$, $\mathbf{i}_2$ lying within the cross-section plane, as well as the point O is a global origin. The symbol O_1 denotes the intersection between the z-axis and the 1–1 cross section.

By virtue of axisymmetric geometry, it is possible to model the distribution of the cohesive forces (per unit of surface) acting over the bonding zone (i.e. the interfacial normal traction, t_{rr}, and the tangential interaction, t_{rk}) as a function of the conjugated displacements d_r and d_k (Fig. 3).

According to [6–7], the following potential is introduced:

$$F(h) = \Phi_U \left[1 - \left(1 + \frac{h}{h_c}\right) e^{-(h/h_c)}\right] \tag{2}$$

where h indicates the norm of the vector $\mathbf{h}$:

$$\mathbf{h} = \lambda_I d_r \mathbf{n} + \lambda_{II} d_k \mathbf{k} \tag{3}$$

with λ_I and λ_{II} the coupling coefficients between the normal and tangential interfacial displacements.

The corresponding interaction, $\mathbf{p}$, is assumed as follows:

$$\mathbf{p} = \frac{1}{\lambda_I} t_{rr}\ \mathbf{n} + \frac{1}{\lambda_{II}} t_{rk}\ \mathbf{k} = p \frac{\mathbf{h}}{h} \tag{4}$$

with the norm p being expressed by:

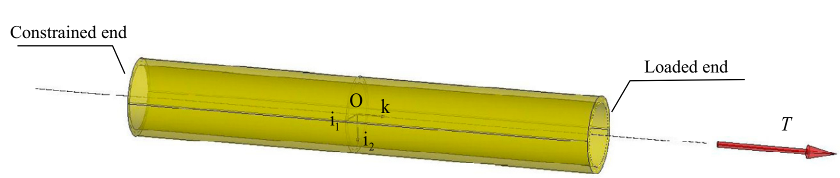

Fig. 1. Composite tube (axonometric view).