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The influence of adhesion defects on the collapse of FRP adhesive joints

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ABSTRACT

In this paper, the debonding of adhesive double-lap joints between FRP adherents is analyzed with regard to the influence of an initial adhesion defect on their ultimate capacity. The analysis is carried out by using the interface cohesive models proposed by Hutchinson & Suo, Xu & Needleman, and Camacho & Ortiz.

The mechanical model utilized takes into account the shear deformability of the adherents and the coupling effects between axial and shear/flexure behavior. The model is non-linear due to the hypothesis of a cohesive interface adopted for the adhesive layer. The numerical results, obtained via finite element analysis, have highlighted that the model of Hutchinson and Suo is less conservative than the other two and that joints subjected to axial forces are less sensitive to initial adhesion defects than ones loaded by both axial and shear forces.

1. Introduction

Thanks to advances in the chemical industry that make it a valid solution for structural joining applications, the adhesive bonding technique is now used in a wide variety of industries, such as the automotive, electronics, aerospace, and naval industries, as well as in the field of civil engineering, especially in full-composite structures. All of the famous examples of them, such as the Eyecatcher Building in Basel (1998) and Lleida bridge in Barcelona (2001), are a combination of bolted and adhesive joints between Glass Fiber Reinforced Polymer GFRP profiles and/or plates.

Adhesive joints present some significant advantages: they are fast, cheap, and light to manufacture. Their disadvantage is their sensitivity to bonding defects such as voids and bubbles. Historically, the study of adhesive joint behavior is generally based on two different approaches: stress/strain analysis in linear elasticity [1–3] and fracture mechanics [4–9]. The second, more recent approach is today based on the mixed mode of fracture. In fact, as is well known in the literature, the co-presence of shear and flexural stresses along with normal ones is possible [10–12]. There are a large number of works conducted by various researchers around the world that are focused on the study of adhesive joint behavior under static loadings [13–15] as well as dynamic ones [16,17] from both a numerical and an experimental point of view. However, further researches concerning the mechanical modeling of the components, the formulation of efficient criteria of debonding, and the understanding of the failure mechanisms are necessary. The present paper deals with the last two subjects listed above: more precisely, it concerns a defect sensitivity analysis, which represents a relevant topic, mainly for civil applications. In particular, the influence of an adhesion defect on the ultimate capacity of an adhesive double lap joint is examined: the case of an internal joint of a beam truss is analyzed.

The numerical results presented here have been obtained by using a mechanical model previously developed by the author in Ref. [18], in which the adherents are modeled according to the Timoshenko beam theory, while the adhesive interfaces are modeled by continuous distributions of springs, arranged along both the normal and axial directions. The above cited model takes into account the most popular cohesive interface laws and related fracture criteria available in the literature such as Hutchinson and Suo (HS) [19], Xu and Needleman (XN) [20], and Camacho and Ortiz (CO) [21,22]. The results are summarized in graphs showing the sensitivity curves with respect to an initial adhesion defect for different values of adhesive toughness according to the market.

2. Cohesive laws

In this section, the three cohesive laws introduced above are presented and discussed.

The first criterion, recently applied by the author to FRP adhesive lap joints under axial monotone loads [18], is based on two uncoupled cohesive laws, as shown in Fig. 1: the normal interaction,

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σ, versus the transverse relative displacement, δ, and the tangential interaction, τ, versus the axial relative displacement, s, evaluated at the interface. The toughnesses relative to mode I (*opening*), $\Phi_{\mathrm{I}}^{(\mathrm{HS})}$, and mode II (*sliding*), $\Phi_{\mathrm{II}}^{(\mathrm{HS})}$, are activated by the displacements δ_u and s_u, respectively.

While crack initiation is obviously stress-based, full separation is achieved when the following condition occurs:

$$\frac{G_{\mathrm{I}}^{(\mathrm{HS})}}{\Phi_{\mathrm{I}}^{(\mathrm{HS})}}+\frac{G_{\mathrm{II}}^{(\mathrm{HS})}}{\Phi_{\mathrm{II}}^{(\mathrm{HS})}}=1. \tag{1}$$

The terms in Eq. (1) assume the following meanings:

$$G_{\mathrm{I}}^{(\mathrm{HS})}=\oint_l \sigma(\delta)d\delta \quad G_{\mathrm{II}}^{(\mathrm{HS})}=\oint_l \tau(s)ds \tag{2a,b}$$

$$\Phi_{\mathrm{I}}^{(\mathrm{HS})}=\int_0^{\delta_u}\sigma(\delta)d\delta, \quad \Phi_{\mathrm{II}}^{(\mathrm{HS})}=\int_0^{s_u}\tau(s)ds. \tag{2c,d}$$

It is important to remark that the symbol "*l*" in Eq. 2a,b denotes the complete path followed, which includes loading, softening, and unloading/reloading of parts, while the symbols "$\bar{\delta}$" and "$\bar{s}$" in Fig. 1 indicate, respectively, the current values of displacements δ and s.

The criterion proposed by Xu and Needleman in Ref. [20] is based on two coupled cohesive laws which can be derived from the following potential:

$$G^{(\mathrm{XN})}(\delta,s)=\Phi_{\mathrm{I}}^{(\mathrm{XN})}+\Phi_{\mathrm{I}}^{(\mathrm{XN})}e^{-(\delta/\delta_c)}\left[(1-r+\delta/\delta_c)\frac{1-q}{r-1} - \left(q+\frac{r-q}{r-1}\,\frac{\delta}{\delta_c}\right)e^{-(s/s_c)^2}\right]. \tag{3}$$

In Eq. (3) the term $\Phi_{\mathrm{I}}^{(\mathrm{XN})}$ still represents the mode I fracture energy (toughness), the term q denotes the ratio of mode II ($\Phi_{\mathrm{II}}^{(\mathrm{XN})}$) to mode I ($\Phi_{\mathrm{I}}^{(\mathrm{XN})}$) fracture energies, while the quantities δ_c and s_c represent, respectively, two cohesive parameters relating the energies $\Phi_{\mathrm{I}}^{(\mathrm{XN})}$ or $\Phi_{\mathrm{II}}^{(\mathrm{XN})}$ to maximum stresses σ_c and τ_c, respectively (Eq. 4a,b). Furthermore, the parameter r is set equal to $r=\delta^*/\delta_c$, where δ^* is the value of δ after complete shear separation under the condition of zero normal interaction ($\sigma=0$) and e is the Neper number. The terms introduced above assume the following expressions:

$$\Phi_{\mathrm{I}}^{(\mathrm{XN})}=\sigma_c\, e\, \delta_c, \tag{4a}$$

$$\Phi_{\mathrm{II}}^{(\mathrm{XN})}=\tau_c\sqrt{e/2}\, s_c, \tag{4b}$$

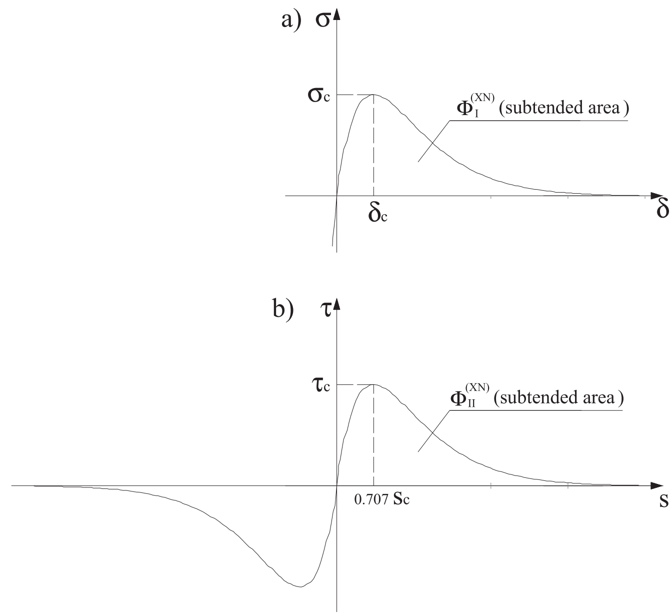

Fig. 2. Coupled interfacial cohesive laws, XN criterion: a) $\sigma(\delta, s=0)$; b) $\tau(\delta=0, s)$.

$$q=\frac{\Phi_{\mathrm{II}}^{(\mathrm{XN})}}{\Phi_{\mathrm{I}}^{(\mathrm{XN})}}. \tag{4c}$$

Fig. 2a shows the normal interaction, σ, versus the transverse relative displacement, δ, when zero sliding displacements occur ($s=0$). Analogously, Fig. 2b exhibits the tangential interaction, τ, versus the longitudinal relative displacement, s, when zero transverse displacements occur ($\delta=0$).

Finally, the third criterion consists of a generalization of the failure criterion proposed by Camacho and Ortiz [21,22]. As is well-known, this criterion consists of a unique cohesive law, accounting for both modes I and II. It can be derived from the following potential:

$$G^{(\mathrm{CO})}(d)=\Phi_U^{(\mathrm{CO})}\left[1-\left(1+\frac{d}{d_c}\right)e^{-(d/d_c)}\right]. \tag{5}$$

In Eq. (5), the term d represents the norm of the following equivalent relative displacement:

$$\vec{d}=\lambda_{\mathrm{I}}\delta\,\vec{n}+\lambda_{\mathrm{II}}\,s\,\vec{t}, \tag{6}$$

where $\vec{n}$ and $\vec{t}$ denote the normal and longitudinal unit vectors, respectively, while $\lambda_{\mathrm{I}}>0$ and $\lambda_{\mathrm{II}}>0$ represent coupling coefficients between modes I and II. The introduction of parameters λ_{I} and λ_{II},

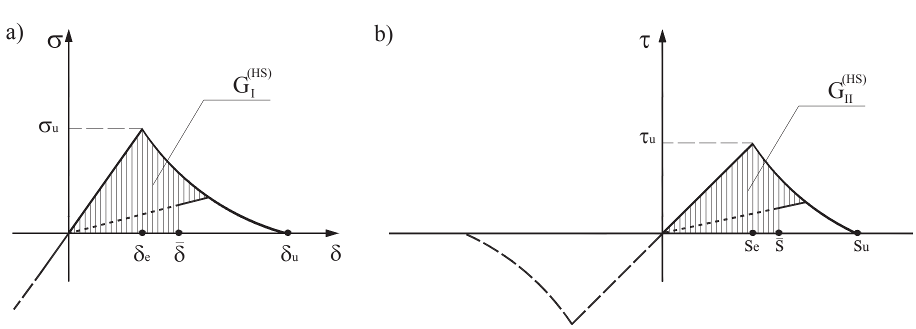

Fig. 1. Uncoupled interfacial cohesive law, HS criterion: a) $\sigma(\delta)$; b) $\tau(s)$.