ON THE DESIGN AND ANALYSIS OF INTERLAMINAR FRACTURE TOUGHNESS TESTS ON DISSIMILAR METAL-COMPOSITE ADHESIVE JOINTS WITH RESIDUAL THERMAL STRESSES

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Abstract

The present work focuses on the design and analysis of interlaminar fracture toughness tests for dissimilar (metal-composite) adhesive joints in the presence of residual thermal stresses. A generic joint configuration is studied; the thin metal and composite adherents have different thicknesses, while also two metallic stiffening beams of different thicknesses are applied in both sides of the joint to increase the strength of the joint and prevent undesirable failures during the tests. Also, residual thermal stresses are considered to account for high-temperature curing cases. Special attention was paid to the double cantilever beam (DCB) and end-notched flexure (ENF) tests. Firstly, a methodology was provided for the preliminary design of the specimens for these tests. Subsequently, an analytical model that is currently being extended by the authors was utilized to determine the mode I and II strain energy release rates (SERR) of the interface crack between the metal and composite components. It was shown that non-constant mode mixity is introduced during both pure mode fracture tests due to the dissimilar materials/geometries of the adherents in combination with the residual thermal stresses. Also, in DCB analyses, the SERR without considering residual thermal stresses are lower than those that take into account this effect. Finally, in ENF tests, specimen placement plays crucial role in the SERR results, something that is not the case with the DCB tests.

1. Introduction

Adhesive joints consisting of dissimilar materials, i.e. materials with different mechanical and physical properties, are finding increasing usage in many high-performance structural applications in several industries (e.g. aerospace, automotive, wind energy etc). Typical examples are the Fiber Metal

Laminates (FML) [1] and metal-composite structural adhesive joints [2]. The joining usually takes place after curing in elevated temperatures, at least in the high-performance cases, and this results in residual thermal stresses along the interface(s). Also, humidity uptake during service life has a similar effect, it gives rise to hygroscopic stresses. Delamination or interfacial disbonding studies in the presence of hygrothermal stresses need special attention and maybe new data reduction schemes. In fact, these failure modes are critical for the structural integrity of structural adhesive joints as they typically propagate in the interface between two layers or adherents compromising the structural performance of the joint. As a result, a huge number of experimental, analytical and numerical studies has been devoted to this problem during the last decades, mainly for similar adhesive joints. The literature concerning dissimilar adherents is much more limited [3-7], with the main volume being devoted to studies regarding FML characterization and performance [8].

Residual thermal stresses, which typically exist in multi-layered structures due to the mismatch of the coefficients of thermal expansion of different layers, are not considered in these solutions and are frequently ignored in many experimental delamination or disbonding studies in the literature. It is crucial though to evaluate the effect of residual thermal stresses on the interface fracture toughness [9, 10]. It is obvious that effects of residual thermal stresses should be incorporated when evaluating the fracture toughness of generally layered specimens subjected to temperature change from the curing temperature. For an interlaminar fracture specimen with dissimilar adherents, because of temperature change, bending moments and deformations are induced in the interface and thus non-zero SERR exists in the specimen without any externally applied load [9, 10]. Nevertheless, no established standardized test method exists to consider the effects of residual hygrothermal stresses on the evaluation of the SERR and its mode components.

The current work approaches the problem of design and analysis of interlaminar fracture toughness tests for adhesive joints between dissimilar materials with residual thermal stresses. The generic adhesive joint to be designed is schematically shown in Fig. 1(c). It consists of two dissimilar (metal and composite) components to be joined. Also, backing beams of different materials are backed in both sides of the joint in order pre-mature undesirable failures to be avoided. Section 2 presents the configuration of the joint under design and analysis, an approach for the preliminary design of the interlaminar fracture tests and the analytical model utilized for the analysis (data reduction) of the tests. In Section 3, results for the SERR and mode mixity of the DCB and ENF tests with and without considering the effect of residual thermal stresses are presented and discussed. Finally, in Section 4, the summary and conclusions drawn from the current paper are presented.

2. Problem description and analysis methods

2.1. The metal-composite adhesive joint under design and analysis

Let us focus on the design of a metal-composite structural adhesive joint, both adherents of which are very thin. Such joints are applied to a variety of engineering structures, including the hybrid laminar flow control (HLFC) systems of modern aircrafts [11] (Fig. 1(a)). Interface strength is an important property to be studied during the course of designing the joint. This property is typically measured by interlaminar fracture toughness tests that require the adherents to be stiff enough, in order to avoid large deformations during the test. On the contrary, preliminary tests on a representative metal-composite adhesive joint showed, as expected, excessive plastic deformation of the adherent (Fig. 1(b)). A common mitigation option to avoid pre-mature failure phenomena is to use backing materials [12]. In fact, in this study the initial metal-composite joint is backed from both sides with two stiffening beams of different thicknesses, as shown in Fig. 1(c). Before backing, it is hypothesized that the initial (metal-composite) joint is co-cured in high temperature, which induces high residual thermal stresses after curing. Subsequently, the “full” (backed) joint with residual thermal stresses will be studied under DCB and ENF tests (Fig. 1(d)).

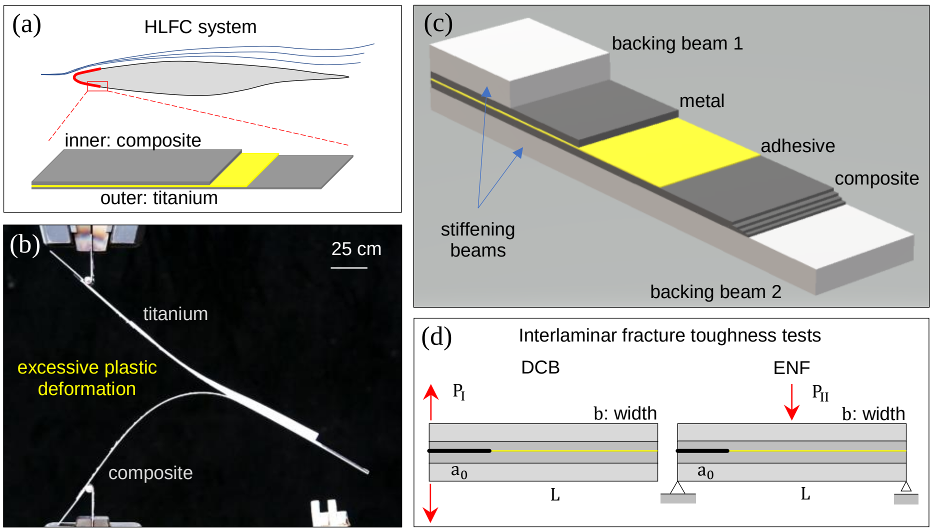

Figure 1. (a) A representative paradigm of application of thin metal-composite adhesive joints: Hybrid laminar flow control (HLFC) system. (b) Excessive plastic deformation during double cantilever beam (DCB) testing of a typical metal-composite adhesive joint with thin adherents. (c) Generic metal-composite adhesive joint (with stiffening materials) under design and analysis. (d) Configuration of the interlaminar fracture toughness tests (not in scale); DCB and end-notched flexure (ENF).

2.2. Preliminary design of the interlaminar fracture toughness tests

In this paragraph, some preliminary design requirements are set in order to estimate the critical design parameters, such as the thicknesses or Young's moduli of the backing materials. First of all, it is underlined that pure mode conditions during pure mode fracture testing (e.g. DCB, ENF) of the current adhesive joint cannot be achieved, as it will be discussed in Paragraph 3.1. Thus, the requirement for matching the stiffnesses of the two dissimilar adherents in order to achieve pure mode, which is commonly reported in literature for specimens without residual thermal stresses [3-7, 12], is not applicable in our case. On the other hand, the unknown design parameters can be estimated by requiring the two preliminary design criteria outlined in Fig. 2 to be fulfilled simultaneously. These criteria are simply extracted using Elementary Mechanics of Materials (design requirement 1, Fig. 2(a)) and Classical Lamination Theory (design requirement 2, Fig. 2(b)). They have been set in order to prevent unacceptable failures (yielding, first-ply failure) in each of the two sub-laminates. For the second design requirement, analytical equations are not given in this paper for the sake of brevity. The maximum loads during DCB and ENF tests ($P_{c,i}$, i = I, II) were estimated based on Linear Elastic Fracture Mechanics (Fig. 2(c)). It is obvious that these criteria can be used only for preliminary design of the full joint, as they utilize some simplifying assumptions, such as that the specimens behave as Euler's/classical beams up to crack initiation. Finally, the inevitable mode mixity effects during pure mode tests will be estimated using an analytical model originally proposed in [10] and currently being extended by the authors [13], as it will be presented in Paragraph 2.3.

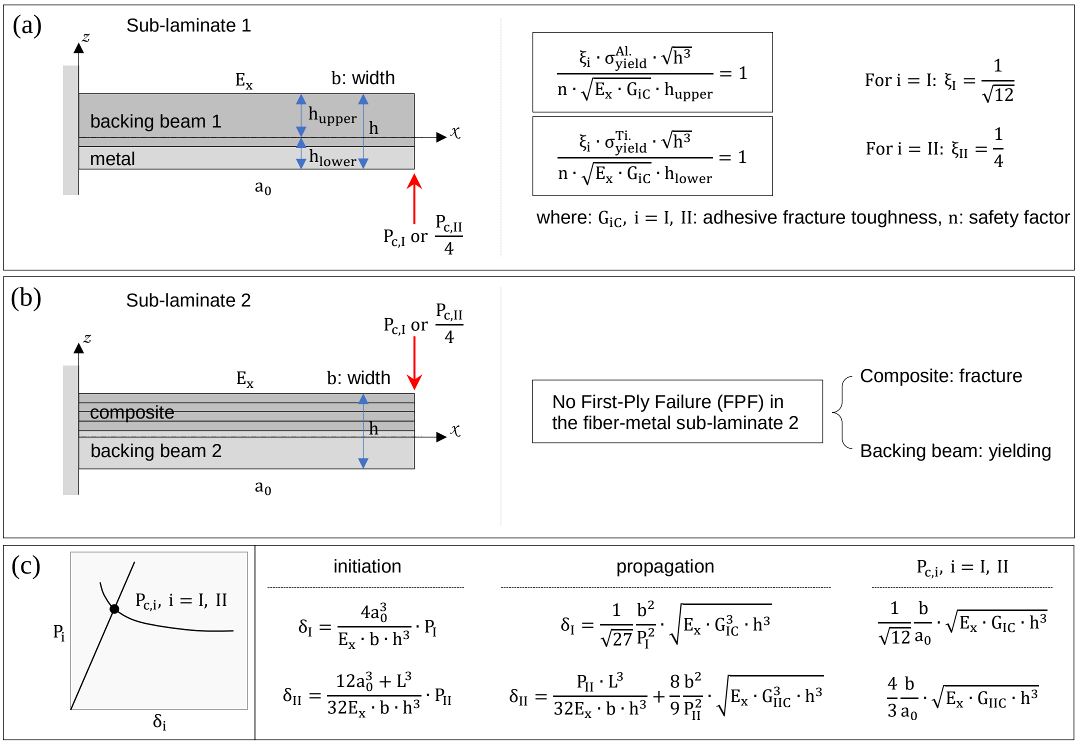

Figure 2. Preliminary design requirements for specimens subjected to double cantilever beam (DCB) and end-notched flexure (ENF) tests. (a) Design requirement for the sub-laminate 1. (b) Design requirement for the sub-laminate 2. (c) An estimation of the maximum loading during DCB and ENF tests based on Linear Elastic Fracture Mechanics (LEFM).

2.3. Analytical modeling

The analytical model presented in [13] is utilized in this work in order to estimate the “parasitic” mode mixity that is inevitably introduced during pure mode I and II testing of the current adhesive joint. This model is capable of calculating the SERR and its mode I and II components for beam-type interlaminar fracture specimens with generic (non-symmetric and unbalanced) sub-laminates, under concentrated mechanical loads and hygrothermal residual stresses. Fig. 3 outlines the model. Each sub-laminate is modeled as first-order shear deformable beam (Timoshenko beam) while the crack-tip kinematic assumptions were provided by the well-known in literature “semi-rigid interface joint model” [14]. Subsequently, Irwin’s approach [15] is adopted in order to obtain the partitioning of the total SERR of the interface crack using the equations shown in Fig. 3, where δ_I and δ_{II} are two coefficients that constitute measures of the elastic deformability of the crack-tip element (CTE). The analytical expressions for the calculation of the SERR are lengthy and are not given in this paper.

2.4. Application

As an application, a structural adhesive joint consisting of a titanium-CFRP joint, backed from both sides with two thick aluminum beams is studied. Also, an aerospace-grade adhesive film is used. Firstly, the initial joint is co-cured in high temperature, followed by secondary bonding of the aluminum backings. The material and geometric properties of the exemplary joint are presented in Table 1 and are consistent with the design requirements of Paragraph 2.2. In Section 3, analytical calculations of the SERR for this joint will be presented.

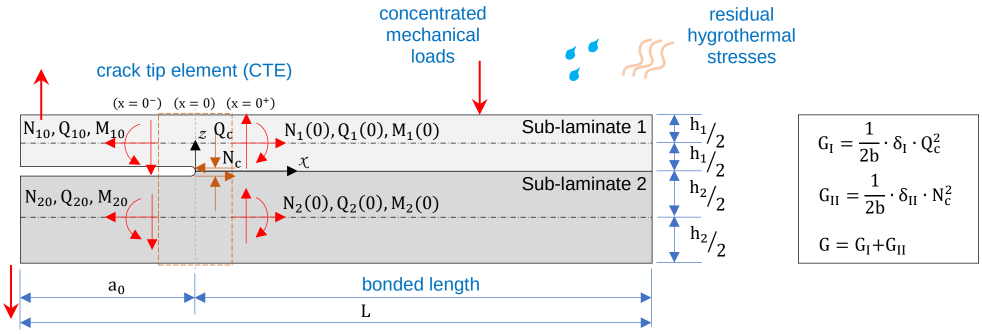

Figure 3. Outline of the analytical model used in this work: Timoshenko beam model, crack-tip element (CTE) approach, semi-rigid interface joint model.

3. Results and discussion

3.1. Pure fracture mode of dissimilar joints with residual thermal stresses: discussion

The residual thermal stresses play a crucial role in the mode mixity during pure mode fracture tests of dissimilar joints; they induce an ever-changing mode mixity to the test specimen at all times [10]. Thus, in DCB and ENF tests of dissimilar specimens with residual thermal stresses we cannot secure pure mode I and II, respectively, conditions. As a result, the stiffness matching criterion usually called in literature for specimens without any residual stresses, e.g. [3-7, 12], is relaxed. Obviously, if there were no residual thermal stresses, the mode mixity of a given dissimilar specimen would remain constant during the test [10]. Also, for such a specimen one can match the strains and/or rotations in the bi-material interface and secure pure mode I [4] or pure mode II [3] conditions. Fig. 4 is reviewing on this topic.

3.2. Effect of residual thermal stresses on the total strain energy release rate (SERR)

The increase of the total SERR (*G*) with increasing the applied load (*P*) is presented in Fig. 5(a) for the DCB and ENF tests, with and without considering the effect of residual thermal stresses. Also, the effect of the length of the initial crack (a_0) on the total SERR for the same tests is presented in Fig. 5(b). It is shown that the residual thermal stresses account for a significant percentage of the total SERR for both test types. The results for the DCB (Fig. 5(a)-i) and ENF (Fig. 5(a)-ii) tests are consistent with those in [9].

Table 1. Material and geometric properties of the adhesive joint under study – input data for the calculations presented in Section 3.

Material	E_x (GPa)	G_{12} (GPa)	ν_{12} (-)	σ_{yield} (MPa)	CTE α_i ($\cdot 10^{-6}$/°C)	G_{IC}, G_{IIC} (N/m)	thickness (mm)	*b*, *L*, a_0 (mm)	ΔT (°C)
Composite	66	4.5	0.035	-	3.0	-	1.4	*b*: 25	-155
Titanium	105	45	0.34	368	9.0	-	0.8	*L*: 250	-155
Aluminum	73	28	0.33	345	-	-	5.0	DCB: a_0: 50	-
Adhesive	-	-	-	-	-	1000, 1400	-	ENF: a_0: 35	-

CTE: Coefficient of thermal expansion, DCB: Double cantilever beam, ENF: End-notched flexure

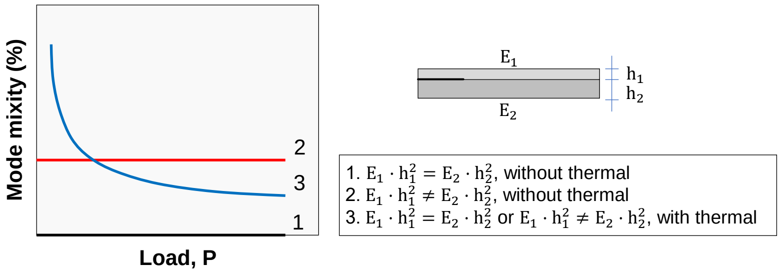

Figure 4. Mode mixity with increasing applied load (*P*) for double cantilever beam (DCB) or end-notched flexure (ENF) tests with/without stiffness matched adherents and with/without considering the effect of residual thermal stresses.

3.3. Effect of residual thermal stresses on the mode mixity

The effect of residual thermal stresses on the mode mixity (i.e. G_{II}/G) during pure mode I fracture tests (i.e. DCB tests) and mode mixity (G_I/G) during pure mode II fracture tests (ENF tests) is presented in Fig. 6(a) and 6(b), respectively. For the DCB tests, the results are similar with those in [10]. ENF results, although seemingly not so obvious, they can be fully understood if the interlaminar fracture behaviour of the reversed joint is also studied. This study will be presented in a next paper. Finally, if the effect of residual thermal stresses is not taken into account, the mode mixities in both tests remain constant and almost zero.

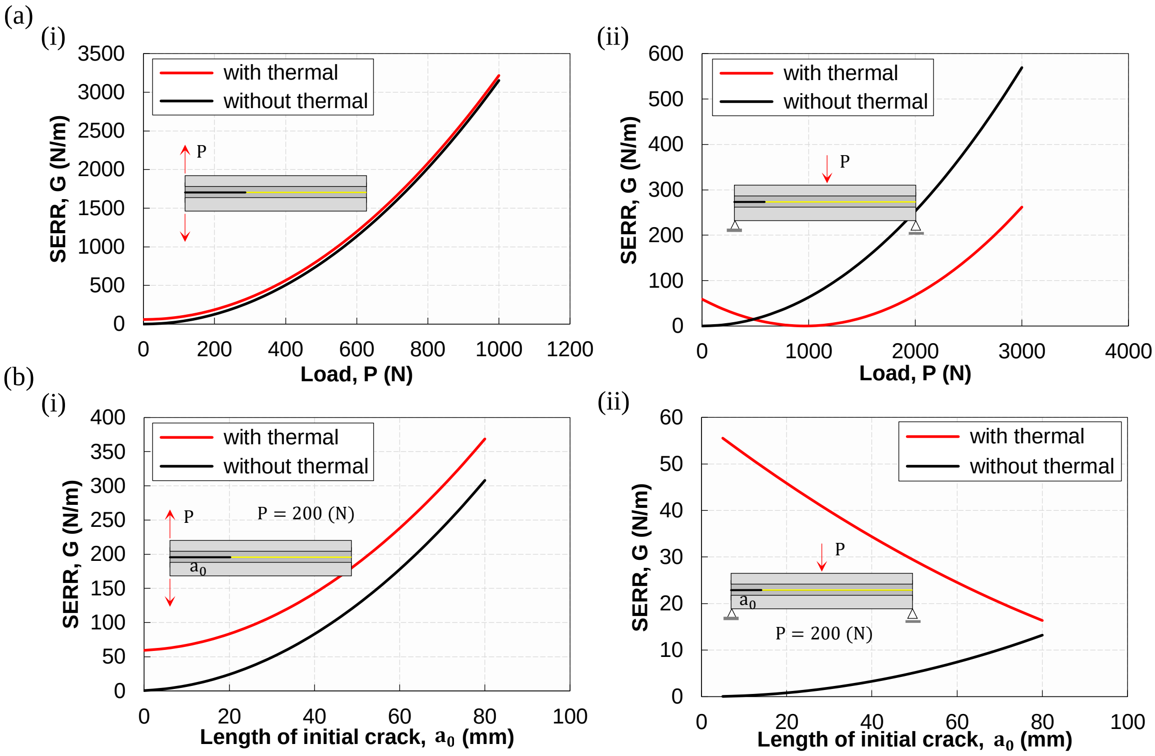

Figure 5. (a) Total strain energy release rate (SERR) (*G*) with increasing applied load (*P*), with and without considering the effect of residual thermal stresses; (i) Double cantilever beam (DCB) test. (ii) End-notched flexure (ENF) test. (b) Total SERR (*G*) as a function of the initial crack length (a_0), with and without considering the effect of residual thermal stresses; (i) DCB test. (ii) ENF test.

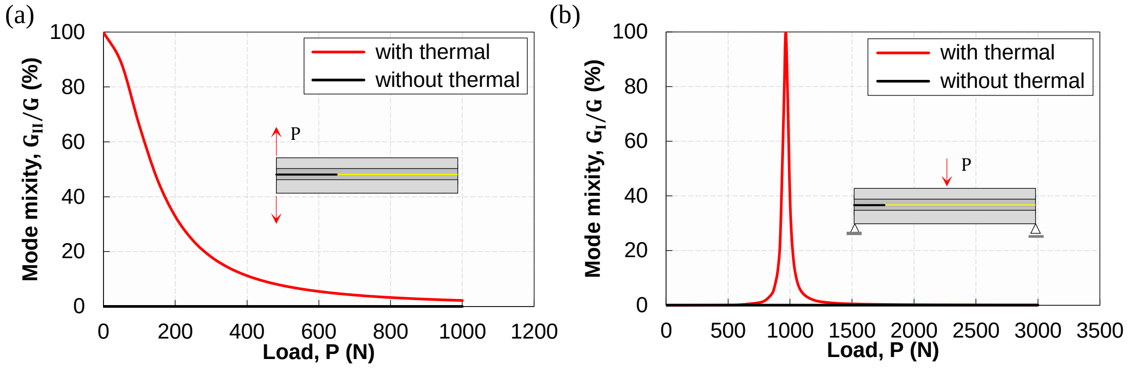

Figure 6. Mode mixities (G_I/G (%) and G_{II}/G (%)) with increasing applied load (P), with and without considering the effect of residual thermal stresses. (a) Double cantilever beam (DCB) test. (b) End-notched flexure (ENF) test.

3.4. Discussion

Some interesting points to be discussed emerge from this study. Firstly, in almost all the results presented above, the SERR without considering residual thermal stresses are lower than those that take into account this effect, which indicates that the fracture toughness without consideration of residual thermal stresses will be underestimated compared to the true fracture toughness. Also, when the residual thermal stresses are considered, the mode mixities depend not only on the material properties, test geometry and initial crack length, but also the applied load. In addition, the effect of the positions of the metal and composite adherents on the reported ENF results must be underlined; significantly different results would be observed if the joint configuration was reversed. In other words, the effect of residual thermal stresses may be either detrimental or beneficial to the total SERR but need definitely to be taken into account, especially in applications with high temperature difference from the stress-free temperature.

4. Summary and conclusions

The present paper focused on the problem of design and data reduction of interlaminar fracture toughness tests for adhesive joints between dissimilar materials (metal-composite) with residual thermal stresses. A generic joint configuration was studied; the thin metal and composite adherents had different thicknesses, while also the metal-composite joint was sandwiched between two aluminum backing materials to obtain the required strength. Two criteria for the preliminary design of the backed joint were set based on Elementary Mechanics of Materials, Classical Lamination Theory and Linear Elastic Fracture Mechanics. Subsequently, an analytical model that is currently being updated by the authors was utilized to extract the SERR.

Firstly, it was shown that “parasitic” mode mixity is introduced in both pure mode fracture tests (DCB and ENF) due to the dissimilar adherents of the joint in combination with the residual thermal stresses. Also, the evolution of mode mixity with increasing applied load was derived. It is believed that the design and data reduction approach discussed in this paper may be adoptable for the analysis of adhesive joints between dissimilar materials with residual thermal stresses, without any restriction for homogeneity of elastic properties and zero bending-extension coupling. Finally, ongoing work on the numerical verification of the present results will be presented in next paper.

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