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Delamination modelling of GLARE using the extended finite element method

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A B S T R A C T

In this paper, an application of the Extended Finite Element Method (XFEM) for simulation of delamination in fibre metal laminates is presented. The study consider a double cantilever beam made of fibre metal laminate in which crack opening in mode I and crack propagation were studied. Comparison with the solution by standard Finite Element Method (FEM) as well as with experimental tests is provided. To the authors' knowledge, this is the first time that XFEM is used in the fracture analysis of fibre metal laminates such as GLARE. The results indicated that XFEM could be a promising technique for the failure analysis of composite structures.

1. Introduction

Fibre metal laminates (FMLs), such as glass fibre reinforced aluminium laminate (GLARE), are hybrid fibrous composite-metal layered materials used in the manufacturing of aerospace structures. In particular, GLARE is a FML made of alternating thin aluminium layers and plies of glass reinforced composite materials [1]. FMLs are designed to be a good damage-tolerant material (incl. slow crack propagation) due to fatigue in aerospace structures. GLARE is utilised in the aircraft upper fuselage and the leading edge surfaces of the vertical and horizontal tail planes in the Airbus^{TM} A380 [2]. In general, the FML analysis by means of computer-aided engineering software offers a substantial reduction of costs in comparison with experimentation what makes it highly attractive for practising engineers. From a computational point of view, the modelling of delamination in FML involves special features which make the task challenging as many of the necessary numerical strategies are still in development. For instance, modelling discontinuities [3], nonlinear interfaces [4], mixed damage modes [5], initiation and propagation of cracks [6], etc. These techniques cause often divergence of the numerical procedure.

Finite elements have been used extensively in many areas of engineering. However, modelling of cracks – or discontinuities, in general – with the standard Finite Element Method – FEM – is cumbersome because of the high computational cost associated to remeshing. Remeshing in Fracture Mechanics problems is necessary for matching the evolution of the crack in FEMs. The inclusion of crack propagation techniques on numerical methods has concentrated much attention in the last decade. Amongst them, the next ones could be highlighted,

- meshless methods and the application to composite fracture is still to be researched in depth. Nevertheless, some works have been reported using element-free Galerkin method [7], meshless cohesive segments method [8] or a meshfree penalty approach [9].
- standard FEM with adaptive remeshing to characterise the crack propagation is possibly the most used but to a high computational cost.
- cohesive elements are special finite elements for modelling discontinuities subjected to a crack initiation criteria and a crack propagation evolution. They have been used in the simulation of delamination extensively in last years. For instance, Pinho et al. [10] applied a cohesive element model in the framework of explicit FEM to replicate fracture in a composite laminate.
- XFEM is a relatively novel technique developed by Belytschko and Blacks in 1999 [11] that it is starting to be used in fracture of composites. For instance, Lua [12] has applied XFEM to analyse delamination in pi-joints through computation of strain energy release rates along the crack front on delaminated layers. Lua [12] provided an excellent analysis of convergence relating fracture energies in modes I and II along the crack front for different mesh sizes. Also, Miot and Pinho [14] have recently presented results for the interaction between matrix cracking and debonding using XFEM.

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In contrast to classical finite elements using cohesive elements, XFEM introduces the crack independently of the mesh which constitutes a great advantage from the computational perspective. In XFEM, the crack potentially develops and propagates on any location/zone within the finite element. Moreover, it is still possible to use all other features – solvers, library of finite elements, etc. normally present in classical FEM software packages. One of the special features of XFEM is the use of enrichment functions near the crack tip. These functions define the discontinuous fields to capture the singular asymptotic material response ahead of the crack tip and, to allow displacement jumps if the crack propagates, simulating in that case the opening or evolution of the crack. For Fracture Mechanics problems, these enrichment functions are chosen to span adequately the region close to the crack tip.

In this paper, we present an study using XFEM with orthotropic enrichment functions, particularly convenient for the treatment of discontinuities. This paper is organised as follows: firstly, aspects of XFEM are introduced to highlight the differences with standard FEMs; secondly, details of the double cantilever beam (DCB) specimen tested – based on ASTM standard – are described. Finally, the results for the DCB by means of XFEM is compared with the outputs provided in the literature by using FEM and, also, with experimental tests.

2. Extended Finite Element Method (XFEM)

The XFEM used here follows the works by Belytschko and Blacks [11] based on the partition of unity finite element method by Melenk and Babuska [15]. For further detailed information about XFEM, the interested reader is referred to those works. The scope in this study is the analysis of delamination in GLARE laminates by XFEM. In this section, the main differences between standard FEM and XFEM are highlighted. These are mainly related to the enrichment functions and the displacement field jump created. The enrichment functions are introduced in the finite element approximation of the displacement field. They are functions designed to describe the discontinuity by capturing the asymptotic fields in the neighbourhood of the crack tip and, to represent the jump in the displacement field across the crack faces. Following [11], the enrichment functions are expressed as,

$$\mathbf{q} = \sum_{i=1}^{nnodes} \mathbf{N}_i(\mathbf{x}) \left(\mathbf{q}_i + H(\mathbf{x})\mathbf{a}_i + \sum_{k=1}^{4} F_k(\mathbf{x})\mathbf{b}_i^k \right) \quad (1)$$

where *nnodes* are the number of nodes per element, $\mathbf{q}_i$ are the displacements of the nodes and, $\mathbf{N}_i(\mathbf{x})$ are standard FEM shape functions for interpolating from nodal values. The remaining terms are only computed for enriched nodes, i.e. in the neighbourhood of the crack. Thus, $H(\mathbf{x})$ is the Heaviside function considering the discontinuous jump across crack faces, $\mathbf{a}_i$ and $\mathbf{b}_i^k$ are nodal enriched degree of freedom vectors and $F_k(\mathbf{x})$ is accounting for the asymptotic response in the neighbourhood of the crack tip. $\mathbf{x}$ denotes the coordinates of a gauss point inside the finite element. The enrichment functions provided by [11] (two-dimensional) are as follows,

$$F_k(\mathbf{x}) = [\sqrt{r}\sin(\theta/2), \sqrt{r}\cos(\theta/2), \sqrt{r}\sin(\theta/2)\sin(\theta), \sqrt{r}\sin(\theta) \times \cos(\theta/2)] \quad (2)$$

where (r, θ) denotes a polar system of coordinates with origin at the crack tip. The enrichment functions in Eq. (2) are not enough for capturing the delamination asymptotic fields in composites as they are intended for isotropic elastic materials. Instead, we have used the functions proposed by Sukumar et al. [16] that circumvents this shortcoming adapting the functions for bimaterial interfaces more appropriate for dealing with delamination in composites,

$$\begin{aligned} F_k(\mathbf{x}) = [&\sqrt{r}\sin(\theta/2)\cos(\varepsilon\log(r))e^{-\varepsilon\theta}, \sqrt{r}\cos(\theta/2)\cos(\varepsilon\log(r))e^{-\varepsilon\theta},\\ &\sqrt{r}\sin(\theta/2)\cos(\varepsilon\log(r))e^{\varepsilon\theta}, \sqrt{r}\cos(\theta/2)\cos(\varepsilon\log(r))e^{\varepsilon\theta},\\ &\sqrt{r}\sin(\theta/2)\sin(\theta)\cos(\varepsilon\log(r))e^{\varepsilon\theta}, \sqrt{r}\sin(\theta)\cos(\theta/2)\cos(\varepsilon\log(r))e^{\varepsilon\theta},\\ &\sqrt{r}\sin(\theta/2)\sin(\varepsilon\log(r))e^{-\varepsilon\theta}, \sqrt{r}\cos(\theta/2)\sin(\varepsilon\log(r))e^{-\varepsilon\theta},\\ &\sqrt{r}\sin(\theta/2)\sin(\varepsilon\log(r))e^{\varepsilon\theta}, \sqrt{r}\cos(\theta/2)\sin(\varepsilon\log(r))e^{\varepsilon\theta},\\ &\sqrt{r}\sin(\theta/2)\sin(\theta)\sin(\varepsilon\log(r))e^{\varepsilon\theta}, \sqrt{r}\sin(\theta)\cos(\theta/2)\sin(\varepsilon\log(r))e^{\varepsilon\theta}] \end{aligned}$$

More recently, Ashari and Mohammadi [17] have proposed novel orthotropic interface enrichment functions for the use in composites. However, these have not been attempted in this work.

3. Delamination on GLARE DCB: numerical tests

3.1. DCB specimen

Values of fracture toughness of GLARE interfaces influences significantly the delamination propagation. As reported by Williams [18], the only irreversible mechanism relevant for measuring the fracture toughness in GLARE is the propagation of inter-laminar cracks. However, the aluminium layers of a conventionally layered DCB sample undergo plastic deformation, dissipating a significant energy and making cumbersome the measurement of energy dissipated due to delamination. The DCB sample for testing is designed with an outer thick aluminium layers (4.1 mm each) and, the central part of the DCB contains an appropriate GLARE laminate of relatively small thickness in comparison (1.25 mm) – specified in Fig. 1. Following ASTM specifications [13], the length of the DCB specimen must be at least 125 mm with a width ranging from 20–25 mm, Fig. 2, and a total laminate thickness of 3–5 mm.

This paper concentrates on estimation of crack opening displacement vs. force relationship using a DCB test procedure following ASTM standards [13]. It is noted that the aforementioned standard has been developed for unidirectional carbon fibre tape laminates with brittle and tough single-phase polymer matrices. The current model uses Aluminium 7075-T6 layers bonded to GLARE 3-2/1-0.4 (see Ref. [2] for an explanation of the GLARE codes). The material properties can be found in Tables 1–3.

The CAD modelling procedure consisted of generating a prism to form the outer profile of the specimen followed by partitioning in layers and with a pre-crack of 40 mm length along the width of the sample. Vlot and Gunnink [1] pointed out that the adhesive bonding across the aluminium/composite interface has a much higher ultimate interface strength than the transition zone between fibre rich and resin rich zones of the composite. Therefore, the delamination tendency is higher in such areas. They corroborated in experiments such a statement, i.e. delamination is more

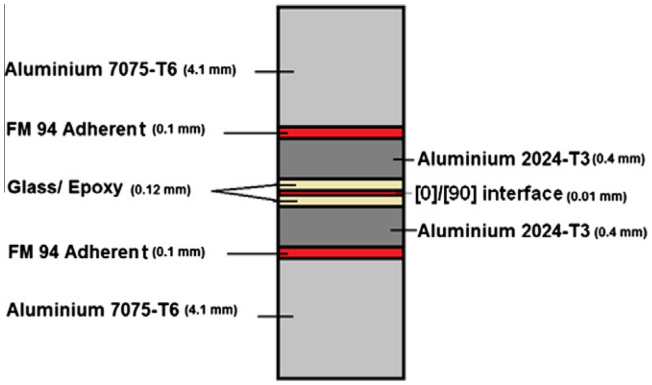

Fig. 1. Detail of the layers of the sample laminate – nonsymmetric – for analysing delamination following ASTM standards [13].

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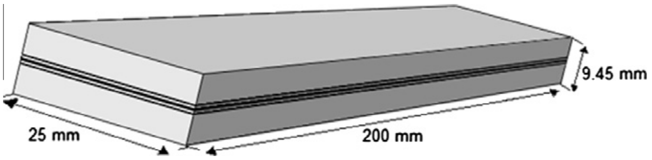

Fig. 2. Dimensions of the sample laminate.

Table 1
Material parameters for Aluminium and FM94 adherent. Values in N/mm^2 for Young's modulus and in N/mm$^{3/2}$ for fracture toughness.

Material	Young's modulus	Poisson ratio	Fracture toughness
Aluminium 2024-T3	73,800	0.33	–
Aluminium 7075-T6	71,700	0.33	–
FM94 adherent	1900	0.38	5

Table 2
Fracture toughness values of GLARE interfaces in mode I [19].

Interface	G_{Ic} (J/m^2)
Al/glass–epoxy	3067
Glass–epoxy [0]/[90]	3545

Table 3
Material properties of glass–epoxy layers. Values in N/mm^2 for Young's modulus E_i and shear modulus G_{ij} [2].

Parameter	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
Value	53980	9412	9412	0.33	0.33	0.33	5548	3000	5548

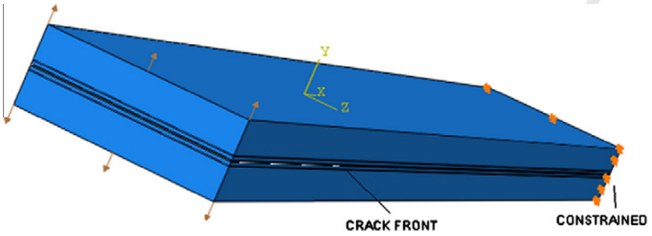

Fig. 3. Boundary conditions and nodal application of external loading on the specimen.

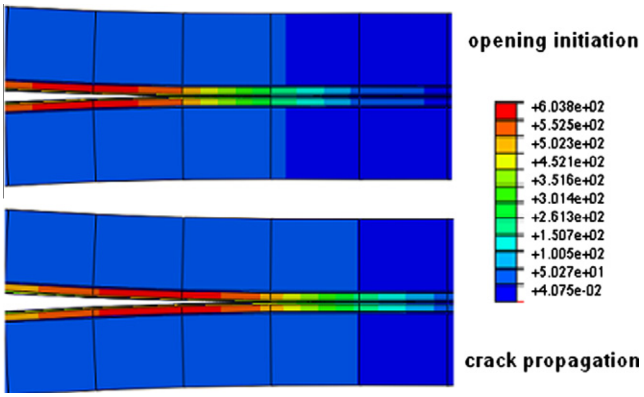

Fig. 4. Detail of Von-Mises stress fields at the initiation of the opening (top) and just after some delamination (crack propagation)(bottom figure).

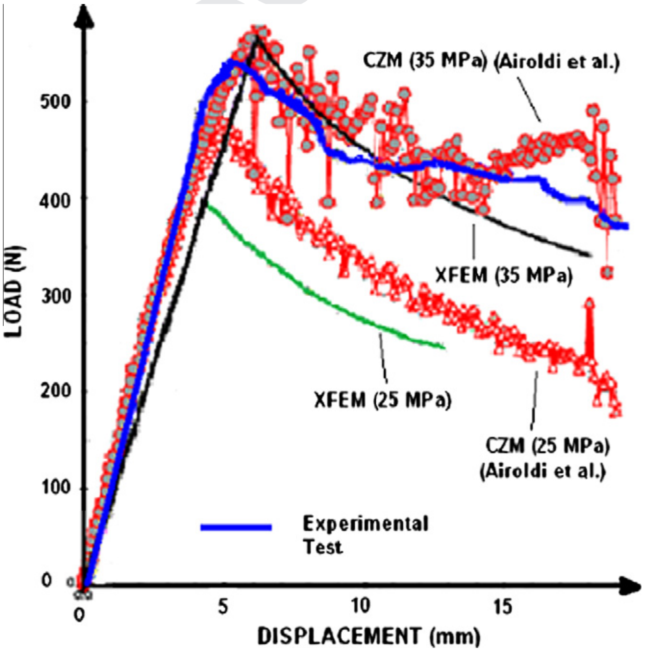

Fig. 5. Load (N) versus opening displacement (mm) of the DCB sample showing results from the literature, experimental tests (Airoldi et al. [19]) and the results from XFEM. The numerical results were obtained with two trial axial strength of the interface parameters 25 MPa and 35 MPa. It is clear from the results that the latter one is more appropriate for future modelling in GLARE.

likely to occur in the resin rich areas between the plies of the composite. The pre-crack required for Mode I testing [13] was modelled as a separate part by shell elements to account for the initial discontinuity in the centre of the specimen. With this set-up, delamination is potentially able to develop at any interface. The loading was simulated by applying a constant prescribed velocity to both edges of the DCB specimen. These nodal prescribed velocities were applied to three nodes on each edge allowing for straight measure of total external force, Fig. 3. The prescribed velocity applied at the edges of the specimen is set to 10 mm/s. The resulting load vs. opening displacement curve is shown in Fig. 5. In order to validate the XFEM simulation, the load–displacement curves were validated against experimental data available in the literature and against the simulation tests performed by Airoldi et al. [19] with the cohesive zone model (CZM) using standard FEM. Airoldi et al. [19] initially used 25 MPa as an interface strength parameter in the material model. They found out that 35 MPa provides a better match – for GLARE – to the experimental results. In our study, we took both values just as a comparison of how XFEM compares with cohesive zone method by [19] at both values. The results are depicted in Fig. 5 correlating in some detail those mentioned, although no procedure experimental or numerical is exempt of shortcomings. It can be noticed that the XFEM approach slightly underestimates the fracture energy, i.e. area beneath load-opening displacement curve, whereas the CZM approach slightly overestimates the values respect to the experimental ones. From a numerical point of view, XFEM provided an excellent match with a really coarse mesh. This was conducted in this manner to highlight the independence of XFEM upon the finite element mesh. Delamination propagated in the middle of the specimen between layers – in L. No through-thickness crack propagation was observed. Table 4 shows the values of delamination against opening displacement and loading. The Von-Mises stress is shown in Fig. 4 and the crack opening is depicted in Fig. 6.

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Table 4
Delamination related to opening displacement and loading. Opening displacement is measured between load application points, i.e. between edges of the sample. Note that the pre-crack length of 40 mm is not added on in the values of delamination, *a*.

Delamination, a (mm)	Displacement, δ(mm)	Load (N)	δ/a
0	6.1	567	0.1525
5	7.6	510	0.1689
10	9.3	460	0.1860
15	11.2	425	0.2036
20	13.3	392	0.2217
25	15.5	362	0.2385
30	18	340	0.2571

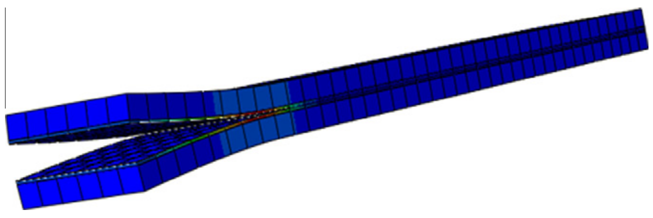

Fig. 6. Detail of the crack opening.

4. Conclusion

In this paper, an application of the extended finite element method to the solution of the delamination problem in double cantilever beam made of glass reinforced aluminium laminates is presented. Special orthotropic enrichment functions adapted to composites have been used to model the propagation of delamination. The comparison with results from the literature – experimental and by using FEM – showed a close agreement but with less computational cost as remeshing was not necessary. XFEM is able to replicate discontinuities such as delamination independently of the finite element size. Although XFEM was tried only for delamination on DCB, the results pointed out that this could be a promising technique for modelling failure in composites. Future research is potentially addressed towards the development of more specific enrichment functions for the fracture in composite materials, in particular for fibre metal laminates, that enhance the current results obtained with the few ones available yet.

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