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Efficient modelling of forces and local strain evolution during delamination of composite laminates

Alessandro Airoldi *, Andrea Baldi, Paolo Bettini, Giuseppe Sala

Dept. of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156 Milano, Italy

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ABSTRACT

FEM analyses based on cohesive zone models are a well-assessed methodology to predict onset and propagation of delamination in composites. In this work, a specific modelling technique based on a cohesive zone model is applied to analyse Double Cantilever Beam (DCB) and 4-point bending End Notched Flexure (4-ENF) tests, focusing on the evolution of forces as well as of internal local strains, which have been monitored by Fibre Bragg Grating sensors embedded in the specimens. The numerical approach is based on explicit FEM computations and presents some appealing advantages with respect to conventional models, since it does not use zero-thickness cohesive elements and does not require a non-physical penalty stiffness to be introduced between adjacent plies. In the cases presented, such approach is applied to model both force response and local strain evolution during the stable propagation of delamination in mode I and mode II, in the presence of fibre bridging phenomena and taking into account frictional effects between crack faces. The paper presents the experimental results and analyses the data acquired by the sensors embedded in the specimens. Then, the general accuracy and the computational advantages of the numerical approach proposed are evaluated considering numerical benchmarks. Models of the tests are developed at different levels of through-the-thickness mesh refinement and sensitivity analyses are performed to point out the effects on the overall and local response of significant model parameters, such as the length attributed to the process zone in the cohesive zone model and the friction coefficient in the contact interaction between crack faces. Numerical results and numerical–experimental correlation prove that the modelling technique and the methodologies applied to represent fibre bridging and frictional effects represent efficient tools to reliably model complex delamination processes.

1. Introduction

The development of approaches to the analysis of delamination in composite laminates is of a paramount importance for application of composite materials. Delamination can be promoted by technological processes, foreign object impact or by highly concentrated loads and can be regarded as one of the major threats to structural integrity of a composite structure [1]. Numerical analyses of delamination may reduce the large amount of testing required in design methodologies based on damage tolerance, which take into account the existence of a certain amount of damage in a composite structure, often represented by delamination scenarios. Nowadays, the prediction of the effects of delamination on the structural response is also important for the development of Structural Health Monitoring (SHM) systems. In particular, the design of systems based on the application of strain sensors, such as embedded Fibre Bragg Grating (FBG) sensors, requires an accurate prediction of the local strain field close to delaminated zones [2,3].

The introduction of cohesive zone models in finite element analyses has proved to be a successful approach to model delamination. A large number of results [4] proves that cohesive zone approach is particularly suited to model fracture in the interfaces between adjacent plies of a laminates, where the plane of crack propagation is known in advance. In Finite Element (FE) analyses, the cohesive zone model is implemented in a traction-displacement constitutive law, which is typically attributed to a layer of zero-thickness or infinitesimal thickness interface elements, introduced between the elements modelling single plies or sub-laminates. Cohesive elements have been also successfully applied to model the local strain evolution during crack propagation, which was acquired by FBG sensors embedded in the structure for the design of SHM systems [2,3] and for the identification of

* Corresponding author. Tel.: +39 02 23998363; fax: +39 02 23998334.
E-mail address: alessandro.airoldi@polimi.it (A. Airoldi).

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traction-displacement laws in the presence of fibre bridging phenomena [5,6].

Indeed, one of the major drawbacks of cohesive elements derives from the representation of fracture processes by means of displacement discontinuities, which requires, in a FE model, the introduction of degrees of freedom that are inactive until the onset of a crack. Hence, before delamination, relative displacements at the interface must be inhibited to avoid the introduction of undesirable compliance. This is done by using high penalty stiffness levels in cohesive elements, but such solution can introduce several numerical problems [7–9]. Therefore, calibration of penalty stiffness is an important issue in cohesive zone approach and guidelines have been provided to obtain the best trade-off between computation effectiveness and accuracy [9]. Another issue for the effective application of cohesive zone models to design and analysis of real-world structural components is represented by convergence problems, which often arise in the presence of unstable crack propagations and involve difficulties in the accomplishment of analyses. Such problems complicates the application of cohesive zone models, in particular when the location of interlaminar damage is not known a priori and multiple damage scenarios have to be taken into account.

The modelling technique proposed in [10], which was applied to model complex delamination scenarios in different significant cases [10–12], overcomes the typical difficulties involved in the adoption of zero-thickness interface elements. Such technique was developed for quasi-static analyses performed by explicit FE codes, which eliminate convergence problems in dealing with delamination phenomena, but require a very small stable time-step, which depends on the stiffness of the elements [10,13]. Therefore, high penalty stiffness levels lead to additional problems in quasi-static explicit computations, due to the severe reduction of the stable time step required for the analysis. In the alternative method proposed in [10] composite laminates are represented by the superposition of a stack of bi-dimensional elements, which carry membrane stress components, and of finite-thickness three-dimensional connection elements, which model the average out-of-plane stress–strain state between the adjacent layers in the stack. No penalty stiffness is required and the stiffness parameters of three-dimensional connection elements are the physical transverse shear and thickness moduli of the composite material. Consequently, stable time step can be significantly higher than in explicit analyses carried out by using traditional cohesive elements.

In this work, such approach is applied to model the force response as well as the local strain evolution during crack propagation, acquired by FBG sensors carried by optical fibres embedded in glass–fibre reinforced composite specimens. Double Cantilever Beam tests (DCB) and four-point bending tests on End Notched Flexure specimens (4-ENF) are considered. In the tests performed, the overall and local responses of the laminates are influenced by fibre bridging and by the presence of friction between the crack faces. Hence, the development of a reliable model must also represent such phenomena.

A first objective of the paper is a quantitative assessment of accuracy and computational advantages of the modelling technique proposed by comparing the numerical results with reference models. Then, the overall response and the local strain evolution acquired by FBG sensors are considered to experimentally validate the predictions of numerical models and to discuss the influence of the model parameters used to represent fibre bridging in DCB tests and the friction between the crack faces in 4-ENF tests. Moreover, numerical correlation are carried out by using different through-the-thickness mesh refinements in order to provide some guidelines for the development of computationally effective and accurate FE models for the prediction of the force required to drive delamination and of the local strain states during delamination propagation.

The paper is organised into five sections, including this introduction. In the next section, the experimental activity is presented and the evolution of local strain field during delimitation propagation is analysed. In a third section, the modelling technique is discussed and numerical benchmarks for validation are introduced. The application of the modelling technique to the experimental tests is described and in a fourth section. The main findings are finally summarised in a conclusive section.

2. Experimental response and detection of local internal strains during stable delamination propagation

2.1. Manufacturing of glass fibre reinforced composite specimens with embedded optical fibres

The evolution of local strain fields during the development of an interlaminar damage depends on mode propagation of interlaminar fractures and on the overall response of the laminate under the applied loads. Composite laminates with embedded optical fibres (OF) carrying Fibre Bragg Gratings (FGB) were manufactured to carry out an experimental analysis of internal strain field evolution during delamination. The material used was a S2 Glass fibre reinforced composite with CYTEC 5216 epoxy matrix and the following in-plane elastic properties in material axis: E_{xx} = 47.5 GPa, E_{yy} = 13.5 GPa, ν_{xy} = 0.25, G_{xy} = 5.896 GPa [14]. Specimens were cut from laminates with a $[0]_{48}$ lay-up sequence and an average final cured thickness of 10.39 mm. In all the specimens, a 13 μm-thick film of Polytetrafluoroethylene (PTFE), with a length of 80 mm, was interposed at the mid-plane of each laminate to obtain a pre-crack.

Laminates were produced by means of a vacuum bag process, by using metallic mould and counter-mould and an elastomeric frame made of stiff non-silicon rubber (Airpad® Airtech). Optical fibres carrying 12 mm long FBG's were embedded in some of the specimens. The technology used to embed the fibres is shown in Fig. 1, which is referred to the manufacturing process. Optical fibres were protected by possible damages at the egress of the laminate by using a PTFE tubing, which was partially embedded at the border of the laminate and passed through the stiff elastomeric frame.

Specimens were cut from the laminates and used to perform Double Cantilever Beam (DCB) tests and End Notched Flexure tests in four-point bending configuration (4-ENF), represented in Fig. 2a and b, respectively. All specimens had a length of 300 mm and a

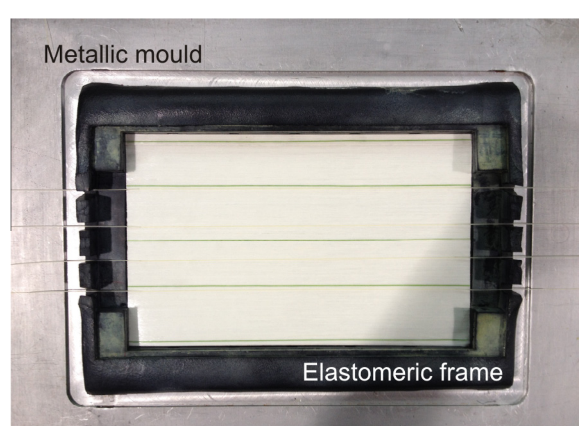

Fig. 1. Manufacturing of a laminate endowed with optical sensors.