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A numerical model for delamination growth simulation in non-crimp fabric composites

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Abstract

In this paper, a novel finite-element tool, for the simulation of delamination growth in non-crimp fabric (NCF) composite materials, is presented. The proposed finite-element tool is based on the stiffness averaging method (SAM), on the modified virtual crack closure technique (MVCCT) and on the penalty method (PM); all these methods have been implemented in the research oriented B2000 finite-element code. The stiffness averaging method allows taking into account the effects of the processing variables, which characterize the representative volume element (RVE) of the non-crimp fiber composites (NCF) on their mechanical performances; while the modified virtual crack closure technique is used to determine the strain energy release rate (SERR) for the delamination growth. Already available experimental data on Mode I fracture toughness, obtained by using double cantilever beam (DCB) tests have been employed for validation purpose of numerical procedure. The modeling of DCB tests, considering different geometrical cases, has been performed by means of non-linear analyses. Excellent results in terms of deformed shapes and load–displacement curve, compared with experimental data, are reported to support the validity and the accuracy of the presented computational procedure. Moreover, the ability of the developed tool to take account for the NCF performances variability with processing parameters along with the delamination growth has been assessed and critically discussed.

Keywords: A. Textile composite; B. Modeling; C. Delamination; C. Finite-element analysis

1. Introduction

Composite materials are rapidly evolving from secondary non-load bearing applications to primary load bearing structural applications. In order to meet the consequent increased requirements, a significant improvement in the damage tolerance and reliability of these materials is needed as well as a reduction in the costs related to their manufacturing. Traditional aerospace high-performance composites, based on unidirectional pre-preg tape, generally provide unsurpassed in-plane specific properties, but their manufacturing costs are still very high. Indeed, the material itself is expensive, as well as the time consuming lay-up process and the equipment needed for storage and cure. Moreover, the out-of-plane properties of traditional composites are usually low due to the lack of through-thickness reinforcements.

On the other hand, textile technology, in combination with liquid molding technique (RTM, RFI, etc.) offers economically attractive alternatives to the traditional pre-preg composites. Several different types of preforms are available, such as weaves, braided and knitted fabric. However, the amount of crimp present in the fiber yarns, although gains the integrity of the fabric, can cause a reduction of the in-plane material properties and can also induce dangerous failure mechanism (as kinkband formation). As a result, the non-crimp fabrics based composites have attracted the attention of many researchers and industries, offering lower operating costs and improved

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through-thickness properties with no significant drop in the in-plane performances (indeed, the presence of the stitching threads between the fibre tows may give a benefit in terms of out-of-plane properties). Due to the complex architecture of NCF materials, the local geometrical and material characteristics can significantly influence the global mechanical properties. Thus, according to most of bibliographic sources, the preferred way to obtain an accurate global model is to first undertake the development of an accurate local model based on experimental and analytical consideration taking into account the micro-structure and the meso-structure of these innovative materials. An experimental investigation on the NCF composites is performed in [1] where a comparison with standard tape composites is carried out highlighting the improved performances of NCFs in terms of compression after impact strength and the limited loss in terms of compression and tension strength with respect to tape laminates.

The influence of stacking sequence on the NCF elastic properties has been experimentally investigated in [2] where the results of tension tests on multilayered warp-knit fabric reinforced epoxy composites with different material lay-ups are presented and discussed. In [3], a review of the main analytical models for the prediction of thermo elastic properties of two- and three-dimensional fabrics is presented. Several analytical models can be found in literature, which are based on assumptions on the geometric and mechanics characteristics of NCF composites constituents. In [4] the stiffness averaging method is introduced and applied to multi-axial warp-knit fabrics; a relevant improvement in the industrial design process involving such materials is demonstrated. References [5,6] present two-dimensional models for biaxial fabrics able to relate, respectively, the NCF compressive and shear properties to the geometrical and mechanics characteristics of the constituents; however the validity of these models is limited to specific loading conditions. In [7], a basic analytical model based on the rule of mixture for determining the tensile elastic modulus of knitted-fabric reinforced epoxy laminates is introduced; the validation of this model is justified in [8] where a relevant experimental campaign on NCFs is reported and discussed. In [9], the "cross over model" is presented underlining its ability to determine the elastic properties of the NCF composites by averaging the properties of the constituent curved yarns and its limitation for composites with high volumetric fraction of fibers. In [10] three analytical simplified models: the "mosaic model" the "fiber undulation model" and the "bridging model" for determining the stiffness and the strength behavior of woven fabrics are presented; these models are shown to be effective only for non-braided composites. Ref. [11] introduces an approximated analytical model for NCF composites elastic properties evaluation based on the Timoshenko beam theory; the model validation by comparisons with experimental results, is carried out for cross-ply laminates under tensile load. In [12], the "fabric geometric model" able to relate the fibre architecture and the material properties to the global stiffens properties of textile reinforced composites is analyzed and its limitations in terms of matrices transformations and yarn modeling are discussed. Indeed, at micro-scale level the fibre–matrix structure within the tows needs to be taken into account by means of a micro-mechanical approach in order to correctly consider the load transfer between fibres and matrix. At meso-scale level (preform level) the defects in the NCFs (as, for example, the waviness of the tows) need to be considered in order to set up a realistic three-dimensional effective model for the determination of the mechanical performances of the NCFs. The failure mechanisms and the fracture toughness properties are also influenced by the micro-structure and the meso-structure of the NCFs as shown in [13,14], where the formation of damage and its progression are investigated by fractography and the influence of stitching on NCFs toughness properties is assessed by experimental tests [15,16]. Very few examples of failure analytical models can be found in literature. In [17] an analytical model based on the "fracture surface approach" is introduced to simulate the failure behavior of NCFs. A good agreement has been found with experimental data but only for plain stitch fabric composites. Hence new analytical more general failure models able to take into account the important aspects related to micro-structure and meso-structure of the NCFs are needed in order to correctly predict the damage propagation and in particular the delamination growth under generic loading conditions.

This paper presents a novel finite-element based approach able to represent the complex architecture of the non-crimp fabric composite materials and to simulate their mechanical behavior. By means of the stiffness averaging method [4,12], the proposed model, derived by a previously developed method [18], takes into account the processing variables (fibres and matrix components, type of stitching, type of dry preform, fibre waviness, stitching parameters, etc.) affecting the mechanical performances within a defined representative volume element. The damage progression in terms of delamination growth has been simulated by interface elements based on the modified virtual crack closure technique [19] for the evaluation of the strain energy release rate contributions. The proposed FEM approach has been implemented in the finite-element code "research oriented" B2000 and validated by means of comparisons with experimental data on delaminated double cantilever beam coupons. Different coupons configurations characterized by different geometrical parameters (stitch length, stitch gauge) and different processing technique (resin film infusion – RFI and resin infusion under flexible tooling – RIFT) have been analyzed, in order to investigate the capability of the developed tool to take into account the relative changes in mechanical performances including delamination growth. In the following sections, the theoretical background of the implemented approach and the numerical applications will be described. First of all, the theory behind the representative volume evaluation approach and the stiffness averaging method implementation is introduced. The