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Delamination onset and growth in composite shells

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ABSTRACT

In this paper an efficient numerical tool is proposed to investigate delamination type failure in multi-layered composite shells. In the current contribution the extended finite element method (XFEM), the mixed-mode cohesive zone model, the contact formulation, and the damage criterion are incorporated into a new algorithm to study the interfacial delamination initiation and growth with less computational effort. A flat-shell formulation is developed in the geometrically non-linear regime to study the response of shells in small strains and moderate rotations. In addition, the equivalent single layer theory (ESLT) is applied to simulate the multi-layered laminates. This formulation is enhanced through the XFEM topology to be able to model discontinuous domains and a mixed-mode bilinear cohesive formulation to track the delamination growth. In the current study, the simulation can be initiated in an intact laminate. Thus, unlike formulations in existing finite element models, incorporating cohesive zone model at all available interfaces is not necessary. The interlaminar stresses are calculated during post-processing and they are being used in the delamination onset criterion. As soon as the criterion is satisfied at a specific layer and location, the formulation of that corresponding element is locally changed to XFEM and the cohesive behaviour. Consequently, the possibility to track delamination growth is locally provided; and hence, the computational cost is reduced.

1. Introduction

In order to be able to predict failure phenomena at the process zone of damaged areas in composite laminates in an efficient way, many attempts were made in the last decades to develop appropriate tools for the simulation of failure. The difficulty in the simulation process of these materials lies in two main aspects: the complex behaviour of composite materials itself and numerical deficiencies. The failure in composite materials is followed at different scales. For example, micro cracks initially occur in the matrix-rich areas that substantially have influence on the interfacial weakness of the structure in the corresponding scale. At macroscale, laminated plate and shell models are appropriate when the structure is subjected to in-plane, bending, or combined loading conditions. However, the load-carrying capacity of these structures in transverse direction is limited. This issue arises once they are manufactured using orthotropic materials. Due to this fact, damage in composite materials is categorised by two distinct types of failure: intralaminar and interlaminar failure. The intralaminar failure is related to the strength of components, being fibre and matrix while interlaminar failure occurs due to interfacial damage. The former is generally modelled based on the ply discontinuing method using knock down factors of material properties or by means of a continuum damage approach. The latter needs advanced tools that combine damage and fracture mechanics, such as a cohesive zone model. In both methodologies, a gradual reduction of the material properties should be assumed to represent damage of the interface region in the experimental analysis and to avoid numerical problems when simulation methods based on knock down factors are used. Nevertheless, instant reduction of stiffnesses can also be provided by incorporating several damage parameters for each individual mode of failure [1].

In general, due to the sophisticated nature of damage in laminated composites, each failure category has been independently investigated. Hu et al. [2] decomposed the in-plane and out-of-plane damages. For the in-plane damage, the stiffness components of the corresponding mode are reduced and to track the out-of-plane failure cohesive elements are arbitrary inserted at one interface in the middle of thickness. However, their interactions are also of importance and should be taken into account [3]. For example, E. D. Reedy et al. [4] detected the occurrence of several modes of failure during the numerical analysis of a ring subjected to transverse loading condition; nonetheless, the delamination failure was

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reported as an important mode in the damage analysis. Furthermore, several drops in the load-displacement diagram of composite laminates are observed that indicate the existence of numerous modes of failure during the loading process. At macroscale, depending on the stacking sequence or the type of structure, primary failure is related to the first ply failure or the delamination. Next, the structure sustains further loads but can undergo several local failures as well. Therefore, the first ply failure should not be assumed as the final failure in the loading history [5].

Methods that are applied to detect the onset of damage are based on strength of material or on fracture mechanics. Recently, a mixture of these approaches is applied to follow initiation and propagation of failure mechanisms. It is worth mentioning that the available criteria for the damage onset in composite materials were developed based on the experimental observations using curve fitting, leading to almost the same results [6]. Despite that, looking for singularities in the stiffness matrix of the problem can also be an indicator of damage occurrence. The buckling phenomenon in shell structures affects the transverse properties and this might be followed by the nucleation of delamination. Thus, accounting the geometrically non-linear terms is important. Apart from this fact, the effect of geometrical non-linearity on the accurate prediction of failure in composite laminates was already proven in [7]. Taking into account the geometrical non-linear terms, the maximum predicted load is being reduced. Once delamination is initiated, a fracture mechanics-based technique should be incorporated to simulate the propagation of delamination. Virtual crack closure technique (VCCT) and cohesive zone model are widely used to simulate the delamination propagation. VCCT is based on calculating the energy release rate of a pre-delaminated area and comparing it with the fracture toughness of material. However, the cohesive zone model is based on relating the interfacial tractions to the displacement jump at the discontinued region. Dávila et al. utilized cohesive elements based on a bilinear traction-separation law to simulate the delamination onset and growth in shell structures in [8]. Qiu et al. investigated the combination of delamination and buckling phenomenon in plates by developing a bilinear cohesive formulation in a corotational framework in [9]. Reinoso et al. studied the delamination analysis in geometrically non-linear regime by incorporating exponential-based and polynomial-based cohesive models with the degenerated solid-shell formulation in [10].

The delamination can either be modelled by double-node technique through defining specific elements at the plane of discontinuity or by using a regularized description of discontinuities through an additional phase-field variable [11]. The standard finite element method is used in the double node technique and simulating the propagation of delamination requires further re-meshing process to align the mesh to the updated geometry of the crack. In the phase-field approach the location of discontinuity is not explicitly followed and instead a diffusive crack modelling based on introducing of a crack phase-field is traced and it requires a very fine mesh.

The sequence of damage in composite materials under compression was reported by Goyal et al. as buckling, intralaminar failure, and delamination [3]. It was concluded that the intralaminar failure plays an important role to induce the delamination phenomenon. Since the nature of delamination primarily corresponds to the stacking sequences, type of load, and growing interlaminar stresses; most of the current research is devoted to this phenomenon in particular. Delamination can be initiated by the occurrence of matrix cracking. Generally, this type of failure is observed in the laminate under bending or transverse load. Since the phenomenon is pretty complex and the fracture mode mixing at the delamination front is non-avoidable, the simulation tools using the finite element method can be exploited to precisely follow the corresponding fracture mode involved in the fracture process zone [12]. In case of flat plates under tensile loading condition, the interlaminar stresses suddenly grow at the free edges, owing to the mismatch of engineering properties and Poisson's ratio or mutual effects. In addition, inclusion of a notch, ply drop, bolted joint, and cracked surface in laminates are other reasons of growing interlaminar stresses in a plate under tension. In contrary, local buckling induces interlaminar stresses at the edge of the buckled region in plates under compression [13].

In this paper, we focus our attention on the interlaminar failure and the delamination of laminates within shells. Thus, a flat-shell formulation is developed based on a first-order shear deformation theory (FSDT). In addition, the equivalent single layer theory (ESLT) is incorporated to include multi-layered composite laminates. In order to simulate the de-bonded region, the formulation, itself, is enhanced by the extended finite element method (XFEM). Therefore, the same mesh scheme can be applied for the delaminated interfaces and the necessity of the simulation of subdomains using double-nodes is avoided. The developed formulation can predict the response of intact or delaminated composite shells in the linear and geometrically non-linear regime. Since XFEM can model displacement jumps at the de-bonded interface, the implementation of traction-separation law is also facilitated. Since the delamination can be initiated at any arbitrary interface, the simulation model should be efficient enough to monitor any potential location of delamination. Therefore, the most common approach is to simulate the multi-layered laminate in such a way that all plies are discontinuous whilst they are modelled as separate laminates. Afterwards, the cohesive elements with zero or negligible thickness are inserted at all interfaces to predict the damage and fracture process. This method is numerically expensive, especially when the geometrically non-linear response of the shell structure is contributed. Moreover, the artificial geometry of the cohesive elements can influence the accuracy of results. In this paper we propose a novel algorithm to overcome the aforementioned deficiencies. In the present approach, the cohesive formulation is provided through the availability of enhanced degrees of freedom (DOFs) in the formulation of XFEM; therefore, no effort is needed to adjust the corresponding finite element meshes and the physical geometry of the cohesive elements is not modelled. Furthermore, taking into account a proper criterion for the delamination onset, the XFEM and cohesive formulations can be activated locally at the critical interface or locations within the plane of the shell. By doing so, the simulation can be carried out automatically using four-node elements and the computational cost and effort is decreased.

2. Formulation

The proposed formulations are categorised into four unified theories: the theory of a flat shell, the damage model, the cohesive zone approach, and the contact formulation. The developed formulations are discussed in details in the following sections. Next, a novel algorithm is proposed – integrating the aforementioned theories – in order to perform delamination analysis in an efficient way.

2.1. Discontinuous flat-shell element

Shell formulations are categorised into three general classes: axisymmetric shell formulations, general shell formulations, and flat-shell formulations. The formulation of general shell element is mathematically complex since one has to generate a singly or doubly curved middle surface to handle any shape of curvature. In this paper, the method will be used which is based on the