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Simulating drop-weight impact and compression after impact tests on composite laminates using conventional shell finite elements

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ABSTRACT

Simulating polymer-based composite structures under low-velocity impact and sequencing compression after impact loading, is a complex problem that requires using well-suited constitutive models and defining advanced finite element capabilities. Therefore, developing simplified and efficient, but sufficiently accurate finite element models to solve such problems, is of interest. Here, a finite element modelling strategy is presented for simulating low-velocity impact and compression after impact tests on composite laminates using Abaqus/Explicit software. The strategy is based on using conventional shell elements and cohesive surfaces. The proper out-of-plane structural response is solved by considering surface elements located on the bottom and top faces of the layers. The key parameters requested for defining the models are concisely described and the values selected are well justified. The accuracy of the modelling strategy is proved by simulating monolithic and rectangular laboratory coupons. The results of the simulations reveal good agreement with most of the experimental data reported.

1. Introduction

In order to assess the damage resistance and tolerance of a polymer-based composite structure, the Low-Velocity Impact (LVI) and sequenced Compression After Impact (CAI) tests are typically performed. The large number of publications available in the literature evidences an intensive research dealing with the experimental analysis of these tests, with the aim of knowing the complex progressive degradation of the material at different interacting failure mechanisms (e.g. Chai et al., 1983; Byers, 1980).

The structural response in a LVI test is a function of the structure parameters (thickness, in-plane size, lamina type, elastic and fracture properties, density, stacking sequence, and boundary conditions), impactor parameters (shape, size, elastic properties, mass, velocity, and incidence angle), and the environmental conditions (Davies and Olsson, 2004). Reviews of studies addressing the analysis of composite structures under impact tests can be found (Cantwell and Morton, 1991; Richardson and Wisheart, 1996; Abrate, 1998). In a LVI event, the damage may not be clearly visible and the criteria for damage assessment may include measurement of the visually apparent damage area, measurement of dent depth, and non-destructive evaluation, such as C-Scan, for the internal damage area (MIL-HDBK-17-3F, Military Handbook). Typically, matrix cracking is the first failure to occur at early stages of the impact load. The matrix cracking induce delaminations which grow as the load increases. Often, the appearance of notable delaminations can be detected by a noticeable drop in load (ASTM D 7136/D 7136M-12, 2012a). Following the growth of the delamination, perceptible fibre breakage may occur depending on the level of impact energy. After a LVI test, permanent indentation may appear due to matrix plasticity and the disorder of broken fibres, and it is used as an indication of the severity of the internal damage induced by impact.

LVIs caused by large-mass impactors yield a type of response which can be approximated as quasi-static (Olsson, 2000). In this sense, the impact event can be analyzed as a static indentation problem and these tests can provide a meaningful indication on the damage mechanisms occurring during LVIs at different displacement values (Wagih et al., 2016a; 2016b).

Concerning the CAI test, the residual strength is function of the local buckling of sublaminates, and propagation of impact-induced matrix cracks, delaminations and fibre breakage. As noted in the recent review found in Liv (2017), there is still a lot to do to understand the sequence of failure modes that leads to the final failure,

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because there exist a dependence on the interaction among different failure mechanisms, including local buckling, resulted from both material and structural properties of laminated composites.

The phenomenon of impact damage in laminated composite structures is very complex and difficult to model analytically. Alternatively, the numerical models based on the Finite Element (FE) method represent a power tool for the prediction of the physical processes. The FE models allow the analysis of a large number of impact configurations and structures, specially in cases that are too complex or expensive to analyze by purely empirical methods. Nonetheless, the more rigorous the model becomes, the more demanding the computational power becomes. Therefore, an effort must be done to develop FE models which are also time efficient.

Simulating LVI and CAI tests on polymer-based laminated composite structures is a complex problem since contact and progressive degradation of the material occur. Accordingly, the interlaminar (delamination) and the intralaminar failure mechanisms should be suitably modelled in a 3D FE analysis, together with the concise definition of several key parameters that can play a role in the quality of the numerical predictions, i.e. material properties, FE types and sizes, and model assembly and boundary conditions.

Modelling at the mesoscale level is a reasonable idealization of the structure to capture the complexity of the problem and is the scale commonly used in related work found in the literature. The mesoscale describes each ply as a homogenised material, which are separated from each other by the interfaces susceptible to delamination, i.e. interfaces with mismatch fibre orientation of the surrounding plies. Certainly, on this scale there are different alternatives for modelling the laminate depending on the FE type and the cohesive connection between plies and, in accordance with the modelling approach selected, well-suited interlaminar and intralaminar constitutive models should be formulated and implemented.

A large number of recent investigations dealing with the simulation of LVI tests on laminated and monolithic specimens can be found in the literature (Lopes et al., 2009; Bouvet et al., 2009; 2012; Hongkarnjanakul et al., 2013; Feng and Aymerich, 2014; Shi et al., 2014; Schwab et al., 2016; Liu et al., 2016; Lopes et al., 2016). Others dealing with the CAI test by assuming a damage pattern (normally delamination), which may be based on experimental inspections of impacted specimens in question, can also be found (Pavier and Clarke, 1996; Suemasu et al., 2008; 2009; Craven et al., 2010; Yan et al., 2010; Obdržálek and Vrbka, 2011). Moreover, there are a significant number of studies published in the last five years that report on the sequential simulation of both LVI and CAI tests (González et al., 2012; Dang and Hallett, 2013; Rivallant et al., 2013; Mendes and Donadon, 2014; Caputo et al., 2014; Tan et al., 2015; Abdulhamid et al., 2016; Perillo et al., 2017; Abir et al., 2017). These are the most interesting since neither LVI nor CAI have to be tested experimentally. It is worth mentioning that most of these numerical models are focused on simulating common laboratory coupons, however, some other work focused on predicting the LVI test on large composite structures has also been developed (Johnson and Holzapfel, 2006; Faggiani and Falzon, 2010; Riccio et al., 2016; Schwab and Pettermann, 2016; Sun and Hallett, 2017). Certainly, the simulation of large structures is more interesting from an industrial point of view, but even more so if both LVI and CAI tests are simulated in order to assess a structure's damage resistance and tolerance (Soto et al., 2017).

Within the studies cited above, there are different FE modelling technologies able to model the plies and delaminations: 3D solid FEs for plies, together with non-zero thickness cohesive elements (Lopes et al., 2009; González et al., 2012; Dang and Hallett, 2013; Lopes et al., 2016; Perillo et al., 2017; Sun and Hallett, 2017), zero thickness cohesive elements (Bouvet et al., 2009; 2012; Rivallant et al., 2013; Hongkarnjanakul et al., 2013; Feng and Aymerich, 2014; Shi et al., 2014; Liu et al., 2016; Abdulhamid et al., 2016) or cohesive surfaces (Tan et al., 2015; Lopes et al., 2016); continuum shell FEs for plies, together with non-zero thickness (Faggiani and Falzon, 2010; Caputo et al., 2014; Riccio et al., 2016) or zero thickness (Abir et al., 2017) cohesive elements; and finally, conventional shell FEs for ply modelling together with non-zero thickness cohesive elements (Mendes and Donadon, 2014; Schwab et al., 2016; Schwab and Pettermann, 2016), zero thickness cohesive elements (Soto et al., 2018) or cohesive surfaces (Johnson and Holzapfel, 2006). In some studies, different FE technologies are combined to simulate intralaminar failure mechanisms, as in the work of Bouvet et al. (2009, 2012), where spring-based interface and volumetric elements are used for matrix cracking and fibre breakage modelling, respectively.

When modelling LVI and CAI events for laminated composite materials, using small size FEs is recommended to adequately computate the energy dissipation for each failure mechanism (Abir et al., 2017). Moreover, if the option to model most of the interfaces susceptible for delamination is considered (Johnson et al., 2001), together with the fact that composite materials have high specific stiffness values, these features may lead to large FE models which require long computational analysis, especially when using explicit FE codes. Therefore, there is a need to develop accurate FE modelling strategies to improve computational efficiency. Because of their kinematic simplicity and their useful capability to model a certain number of plies using a single shell element, the use of conventional shell elements is an interesting modelling approach. Johnson et al. (2001) used conventional shell elements together with contact interface conditions in the PAM-CRASH FE software (PAM-CRASH FE Code, 2004). The accuracy of the FE models was proved by simulating LVI on carbon fabric reinforced epoxy plates for two impact velocities. A remarkable result of this work is how different number of interfaces for delamination are modelled, something which Soto et al. (2018) also considered for thin-ply based laminates. Similarly, Mendes and Donadon (2014) simulated woven composite laminates, but in this case they used Abaqus/Explicit FE code and simulated both the LVI and CAI tests using two FE approaches. The first uses a single shell element in which the whole laminate thickness is considered and the second approach uses two shell layers with half of the laminate thickness, so that the laminate is divided into two sub-laminates related by means of a thin layer of cohesive elements. They reported predictions for two laminate thickness and different impact energy levels. More recently, Schwab et al. (2016) presented another modelling approach in Abaqus/Explicit which used shell elements for ply modelling and cohesive elements formulated with zero-thickness but with a physical volume to join the separated surrounding shell plies. The accuracy of the model was checked only by simulating a fabric reinforced composite laminate under a high impact energy, at which the structure response was highly localized at the impact site and, therefore, the bending response was not important as it is for LVI tests. In this last work, all interfaces for the delamination of a laminate with eight plies were modelled.

Due to industrial interest in having predictive tools to deal with analyzing advanced structures in reasonable calculation times, for instance simulating both LVI and CAI tests on polymer-based laminated structures, this present work purposes an efficient and accurate modelling strategy to be used in Abaqus/Explicit FE code. This strategy is based on using conventional shell elements together with cohesive surfaces, where the out-of-plane structural response is checked and solved by considering surface elements placed on the bottom and top faces of the layers and tied to the shell elements. This modelling strategy and its validation are set out as follows. In Section 2, the proposed modelling strategy is described in detail. Section 3 details the materials, laminates and test set-ups considered for the LVI and CAI experimental test campaign

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