An effective modeling strategy for drop test analysis of composite curved beam

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Recent studies on the drop test analysis of composite structures mainly focus on the unidirectional or quasi-isotropic composite plates. Impact studies on the three-dimensional curved structures with woven fabric composite materials have received much less attention in the literature. This paper presents detailed experimental and computational investigations of the impact behavior of woven fabric Eglass E722-8HS composite curved beam. Experimental drop tests of the curved beam are performed from the drop test tower to obtain the impact forces and deformation at various locations of the beam. Quantitatively experimental observation reveals a discrepancy in the time-dependent reaction forces obtained between two legs of the beam and in the strains measured at correspondingly symmetric positions. To correctly rationalize the mechanical behavior as observed in the experiment, an effective drop test modeling strategy is proposed and implemented by Python script allowing the nonlinear time-dependent response of each leg of the beam to be effectively computed. The predicted results by the drop test model are compared to the experimental data and reasonably good correlations between experimental and numerical results are achieved.

Nomenclature

\( t_n \) = Normal traction
\( t_s \) = Shear traction
\( t_t \) = Shear traction
\( N \) = Normal interlaminar strength
\( S \) = Shear interlaminar strength
\( T \) = Shear interlaminar strength
\( G_I \) = Mode I Strain Energy Release Rate
\( G_{II} \) = Mode II Strain Energy Release Rate
\( G_{III} \) = Mode III Strain Energy Release Rate
\( G_{IC} \) = Mode I Critical Strain Energy Release Rate
\( G_{HII} \) = Mode II Critical Strain Energy Release Rate
\( G_{HIII} \) = Mode III Critical Strain Energy Release Rate

I. Introduction

Composite materials are extensively used in aerospace and automotive applications due to their light weight, high strength and stiffness, excellent fatigue properties and good impact resistance. Impact of composite materials has been the topic of several studies in the literature where the impact response of structures and effects of impact-induced damage were analyzed. Studies on composite structures in the past decades have shown significant benefits of woven-fabric composite materials in enhancing the impact resistance of composite structures. Most of the experimental and numerical impact analyses, however, have been focused on two-dimensional composite plates either with unidirectional or woven fabric materials \([1-17]\) and little efforts are made for three-dimensional curved structures. To help contribute to a better understanding of the impact behavior of three-dimensional composite

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structures in general, this work provides experimental and computational drop test analyses of a woven fabric E-glass/E722 8HS composite curved beam. The size of the curved beam is representative of that of a small aircraft landing gear structure. Two experimental impact tests of the composite curved beam are carried out under a drop test tower to measure the time-dependent reaction forces and strain magnitudes at various locations of the beam. A fixture is designed to fully grip the specimen for the impact test. Non-linear impact behavior of each leg of the curved beam is experimentally analyzed and numerically simulated by drop test finite element (FE) models using Abaqus solvers. An effective drop test modeling is proposed and implemented by Python script under the Abaqus environment to help correctly capture the time-dependent reaction forces and deformation at different positions of the curved beam under impact.

II. Experimental drop test of woven fabric Eglass/E722-8HS composite curved beam

A. Description

The curved beams specimens for the impact test are made of woven-fabric Eglass/E722-8HS composite material. The composite beam under testing consists of 18 composite layers with a layer thickness of 0.75 mm. The beam specimen has an overall length of 0.792 m and a height of 0.189 m. Details on the dimensions of the specimen are illustrated in Fig. 1. For the specimen preparation, various strain gauges are symmetrically mounted on two sides of the specimen, as shown in Fig. 2. The drop tests of the curved composite beam are conducted from a drop test tower. The setup of the drop test tower is shown in Fig. 3. The drop tower is six meter high and its max weight allowable is 400 kg. It consists of two vertical steel rods mounted in a heavy steel base. Two aluminum blocks are placed at the base to serve as impact grounds. Underneath these blocks are two load cells used to measure the reaction forces during the impact test. A jig fixture is designed and fabricated to fully grip the curved beam at 30° angle with horizontal plane. The fixture assembly is shown in Fig. 4 with its total weight of 40 kg. Two experimental drop tests are conducted from a drop height of 1.5 m above the aluminum grounds. All strain gauges and load cell are carefully calibrated before the test. They are connected to strain and load reading modules which record strain and load-time histories during the impact event.

B. Results

Since the impact responses of the two legs of the beam are similar, only the behavior and response of the Leg 1 are shown and demonstrated in Fig. 5. The Leg 1 is observed to experience the biggest reaction force at its very early impact with the ground (Fig. 5b). After the beam touches the aluminum grounds, the large kinetic energy of the beam from the 1.5 m drop height is quickly transferred to the internal energy of the beam. Consequently, the two legs of the beam stretch out and slide on aluminum surfaces in opposite directions (Fig. 5c). These two legs continue to slip on aluminum surfaces until a balance in internal and kinetic energies is achieved (Fig. 5d). After that, the legs slip back to their originals (Fig. 5e). Stick-slip behaviour is observed during the impact process resulted from a complicated contact between the composite material and aluminum grounds. The remaining kinetic energy then causes the whole beam to bounce back from the impact surfaces (Fig. 5f). The afore-mentioned sliding mechanisms observed between the composite legs and aluminum surfaces during the impact event primarily cause the failure at the edges/tips of specimen. Matrix and fiber failures have been observed at the tips whereas no delamination is detected in the beam specimen.

Details of the time force histories obtained for the Leg 1 (read by load cell 1) and the Leg 2 (read by load cell 2) from two drop tests are presented in Fig. 6. Maximum forces recorded for the two tests are summarized in Table 1. The peak forces derived for the Leg 1 and Leg 2 from the first test are 14.75 KN and 9.45 KN, respectively while those from the second test are 13.53 KN and 15.2 KN, respectively. The load differences between the two legs are about 35.9% for the first test and 11.01% for the second test. The load discrepancy significantly reveals that the two legs of the beam may hit the aluminum blocks at the same time. One leg of the specimen may strike one aluminum block first before the other leg comes to hit the other block shortly thereafter. This is true for realistic testing of a relatively big curved beam specimen since simultaneous impacts of both legs are difficult to happen. The small load difference percentage for the second test (11.01%) indicates that the time delay between the two subsequent impacts of the legs in the second test is shorter than that in the first test.

Table 2 summarizes the peak strains obtained at the positions 1, 2, 3, 4, 6, 7, 8 of the Leg 2 and their correspondingly symmetric positions 22, 20, 21, 17, 19, 15, 16 of the Leg 1 from the first drop test. Overall, the peak strain magnitudes obtained for the Leg 1 are greater than those for the Leg 2 since the Leg 1 exhibits higher impact...
force. These strain differences are attributed to the fact that impact of the two legs of the beam does not happen concurrently. The peak strains at the positions 1, 22, 2, 20, 3, 21 are found at the beginning of the impact event whereas those at the positions 4, 7, 6, 19, 7, 15 are observed in the middle of the impact when the two legs of the beam might have extensively stretched out.

Figure 1. Dimensions of the woven-fabric composite curved beam

Figure 2. Strain gauges numbering from the front view (a), the top view of the Leg 2 (b), and the top view of the Leg 1 (c)

Figure 3. Drop test tower set up for impact test
Figure 4. a) Detail of the jig fixture assembly and b) attachment of the fixture on the specimen

Figure 5. Impact response of the Leg 1 of the curved beam during the impact event

Figure 6. Time - reaction force histories measured for the legs in the first test (a) and in the second test (b)
Table 1. Maximum reaction forces obtained from two experimental drop tests

|                  | Maximum reaction force for the Leg 1 (KN) | Maximum reaction force for the Leg 2 (KN) | Percentage of Load difference (%) |
|------------------|------------------------------------------|------------------------------------------|-----------------------------------|
| Test 1           | 14.75                                    | 9.45                                     | 35.9                              |
| Test 2           | 13.53                                    | 15.2                                     | 11.01                             |

Table 2. Summary on the peak strains at the positions 1 – 8 (SG #1 – SG #8) and their correspondingly symmetric positions 16 – 22 (peak SG16 – peak SG22) obtained from the first drop test

|          | SG #1   | SG #2   | SG #3   | SG #4   | SG #6   | SG #7   | SG #8   |
|----------|---------|---------|---------|---------|---------|---------|---------|
| Test 1   | -3.82E-04 | -2.57E-03 | 1.64E-03 | -4.53E-03 | -4.82E-04 | -1.36E-03 | -8.68E-04 |

|          | SG #22  | SG #20  | SG #21  | SG #17  | SG #19  | SG 15  | SG #16  |
|----------|---------|---------|---------|---------|---------|--------|---------|
| Test 1   | -3.94E-04 | -2.84E-03 | 2.07E-03 | -4.78E-03 | -6.06E-04 | -1.38E-03 | -6.36E-04 |

III. FE drop test model of the woven fabric composite curved beam

Three-dimensional FE drop test models for the woven-fabric curved beam and aluminum blocks are constructed, as shown in Fig. 7, to predict the non-linear dynamic impact of the curved beam. Both the curved beam and aluminum blocks are modeled as deformable bodies and with explicitly three-dimensional 8-node brick elements (C3D8). Additionally, one interface layer of cohesive elements (COH3D8) is inserted at the middle plane (neutral plane) of the beam specimen to allow for delamination modeling during the impact. The composite curved beam is built with fine mesh whereas the aluminum blocks are meshed by a rather coarse mesh. The FE mesh of the beam model consists of 140250 hexahedral elements and 5610 cohesive elements. The woven fabric composite with material properties reported in Table 3 is assigned for the beam model while standard aluminum material with Young modulus of 68GPa and Poisson’s ratio of 0.36 are used for aluminum blocks [19]. As seen in Fig. 7a, different local coordinates are used to correctly define the fiber orientations for different parts of the beam. Cartesian coordinate is specified for the middle part or the straight part of the beam whereas cylindrical coordinates are defined for the legs (the curved parts) of the beam. The curved beam model is tilted at 30° degree as similar to the experiment setup.

Additionally, a stress-based quadratic criterion is employed for the cohesive elements to identify the interlaminar damage onset. The stress quadratic criterion is controlled by one normal interface stress $t_n$ and two shear interface stresses $t_s$ and $t_t$ at the ply interfaces and has been proved to successfully predict the delamination in different composite laminates and material systems by Pham et al. [20-22]. A detailed review of different delamination criteria and the cohesive element method is available in Tay et al. [23]. The stress-based quadratic criterion for delamination initiation prediction is expressed as:

$$\left(\frac{t_n}{N}\right)^2 + \left(\frac{t_s}{S}\right)^2 + \left(\frac{t_t}{T}\right)^2 = 1 \quad (1)$$

where $N$, $S$ and $T$ are the cohesive strengths and approximated to be equal to the out-of-plane composite strength $Z_i$ derived from the material coupon tests (Table 3).

Besides, a linear energy-based criterion is used for modeling of delamination propagation:

$$\frac{G_{II}}{G_{Ic}} + \frac{G_{III}}{G_{IIc}} + \frac{G_{III}}{G_{IIc}} = 1 \quad (2)$$

where $G_{II}$, $G_{III}$ and $G_{III}$ are computed work done by the tractions and their relative displacements in the normal and shear directions, respectively and $G_{Ic}$, $G_{IIc}$, $G_{IIIc}$ are the critical strain energy release rates (SERRs) corresponding to
mode I, mode II and mode III fractures, respectively. The values of SERRs such that $G_{IIc} = G_{IIIc} = 822 \text{ J/m}^2$ are assumed and referred to the work by Asgari Mehrabadi [24] in which mode III and mixed mode delamination behavior of glass woven-fabric laminates with various crack lengths were analyzed. Additionally, the SERR $G_{Ic} = 600 \text{ J/m}^2$ is estimated from a study by Pereira et al. [25] in which the mode I fracture of woven glass multidirectional laminates was presented.

Conventionally, the drop test analysis is performed by assigning an initial velocity to the FE curved beam model to initiate the impact analysis from which the non-linear impact response of the structure can be analyzed. When the same strategy is applied for the curved beam structure with two impact surfaces, it is contended that the impacts of the two legs would happen simultaneously and that the resulted reaction forces and strains at symmetric positions of the beam would be similar. However, the experimental results significantly showed a discrepancy in the reaction forces and strains at symmetric positions. Hence, employing the traditional drop test modeling strategies may not be consistent for this case.

Efficient drop test models have been developed to better account for the reaction force and strain differences between two sides of the curved beam. Instead of assigning an impact velocity to trigger the impact, the proposed strategy effectively use the experimental time-dependent force histories (Fig. 6) as the prescribed loadings for the FE model to predict the resulted strain at different positions of the beam. Using this strategy, modeling of aluminum blocks can be neglected since the experimental force-time histories are directly applied on the edges of two legs. The new boundary condition for the proposed modeling strategy is illustrated in Fig. 7b.

The impact analysis of the curved beam by the afore-mentioned strategy is carried out using Abaqus 6.13 [26]. It should be noted that the data set of reaction force-time histories obtained from the experiment are very large consisting of 450,650 data in total, thus making it impossible for the loads to be directly prescribed in Abaqus. Instead, a Python script is implemented to define the drop test model and carry out the drop test simulation using the Abaqus solvers. Python script is coded to correctly assign composite material properties, fiber material orientations and new boundary conditions for the FE drop test models. Separate sets of time-dependent reaction forces are applied for the legs of the beam to simulate non-linear behavior of each leg during impact. Upon successful application of the load histories for the two legs, the strains at various locations of the beam are then computed and validated against the experimental drop test data.

![Figure 7. Conventional boundary conditions for drop test model with aluminum blocks (a), and modified boundary conditions for the drop test model (b)]
Table 3. Material properties for E-glass/Epoxy 7781 woven fabric composite [18]

| Description                        | Woven Fabric E-Glass/Epoxy 7781 |
|------------------------------------|----------------------------------|
| Longitudinal modulus               | $E_1$ (GPa)                      |
| Transverse in-plane modulus        | $E_2$ (GPa)                      |
| Transverse out-of-plane modulus    | $E_3$ (GPa)                      |
| In-plane shear modulus             | $G_{12}$ (GPa)                   |
| Out-of-plane shear modulus         | $G_{23}$ (GPa)                   |
| Out-of-plane shear modulus         | $G_{13}$ (GPa)                   |
| In-plane Poisson’s ratio           | $\nu_{12}$                       |
| Out-of-plane Poisson’s ratio       | $\nu_{23}$                       |
| Longitudinal tensile strength      | $X_t$ (MPa)                      |
| Transverse tensile strength        | $Y_t$ (MPa)                      |
| Out-of-plane tensile strength      | $Z_t$ (MPa)                      |
| Longitudinal compressive strength  | $X_c$ (MPa)                      |
| Transverse compressive strength    | $Y_c$ (MPa)                      |
| In-plane shear strength            | $S_{12}$ (MPa)                   |

IV. Results and Discussions

The experimental force time history profiles, as shown in Fig. 6a, are applied on the edge nodes of the FE model allowing for strains at different locations of the beam to be computed during the load application period. For validation purpose, only the loads for the first test are considered. The predicted strain-time histories at symmetric positions of the beam are shown in Fig. 8 and plotted in comparison, i.e. SG 1 vs. SG 22, SG 2 vs. SG 20, SG 3 vs. SG 21, SG 6 vs. SG 19, SG 7 vs. SG 15, SG 8 vs. SG 16. The estimated strains at the symmetric positions are not necessarily the same since the loading inputs prescribed for each leg of the beam are different. As observed in Fig. 8, the strains in the forward direction obtained at the positions 1, 22 and those in the longitudinal direction at the positions 2, 20, 3, 21 gain their maximum magnitudes at the very early impact. These positions are very close to the load application regions or the impact regions. Besides, the computed strains in the longitudinal direction of the beam at the positions 4, 17, 7, 15 and those in the thickness direction at the positions 6, 19, 8, 16 attain their peaks in the middle of impact event when the curved beam might have extensively stretched. Most of the predicted strains are close to the experimental measures. The proposed drop test modeling strategy, therefore, is able to reasonably capture the impact response of the three-dimensional woven fabric curved beam.
Figure 8: Comparison between the predicted strains (FEM) and experimental strains (SG) at symmetric positions: a) Position 1 vs. position 22; b) Position 2 vs. position 20; c) Position 3 vs. position 21; d) Position 4 vs. position 17; e) Position 6 vs. position 19; f) Position 7 vs. position 15; g) Position 8 vs. position 16.
V. Conclusions

The impact behavior of the woven-fabric Eglass E722-8HS composite curved beam has been experimentally and computationally studied. The experimental drop tests suggested that there are discrepancies in the force and strain history measurements at symmetrical positions of the beam, reflecting an actual drop test case where concurrent impacts of the two legs of the curved beam are hardly obtained. Effective drop test models have been developed, prescribing the time-dependent impact force histories obtained from the experiment as the dynamic load inputs for the FE model through the implementation of Python script. The predicted time-dependent strains at various locations of the beams have been successfully validated against experimental data. It is shown that the developed drop test model is capable of effectively capturing the non-linear impact response of each leg of the composite curved beam.

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