HIGH STRAIN RATE MODELING OF WOVEN COMPOSITE USING STACK SHELL METHOD

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Abstract

The mechanics of damage in woven composites during impact is complex and understanding them requires intense effort both experimentally and numerically. Majority of the research uses material models developed to aggregate properties and study the behavior under impact loading. In the present work, a novel stacked shell approach is used to represent a 5HS weave composite. The woven structure is modelled using MAT 58 material model from LS-DYNA material directory and the response is recorded at high strain rate under uniaxial compression performed on a Split Hopkinson Pressure Bar (SHPB) apparatus. The computed SHPB pulses, strain rates and stress-strain curves are successfully compared to the respective experimental pulses.

1. Introduction

The first experimental observations related to high strain rate testing were observed in early twenties from the pioneering work of Hopkinsons and Quinney [1-2]. The researchers used a pressurized container to create an impact on specimens using steel bars. The tests led to the development of Split Hopkinsons Pressure Bar Setup often referred as SHPB or SPB. [3-4]. Since then, the setup has been used to test metallic materials and later employed for testing of composites when these novel materials were proven adequate in high impact energy applications. The pressure bars can be used to test materials at strain rates ranging between 100/s to 10^4/s. [5] Complementary fixtures can be used to convert the traditional compressive loading to tension and shear loading. [6-7]

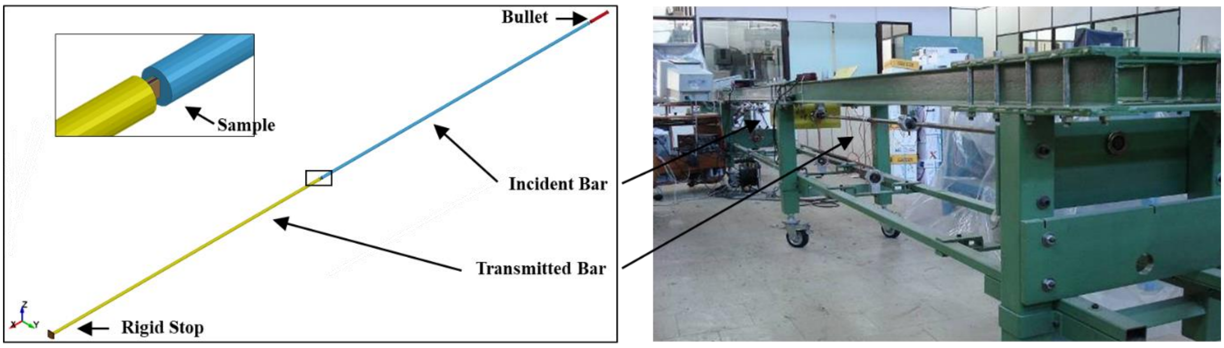

Figure 1(a) FE Model of SHPB apparatus, (b) SHPB testing facility at LTSM, University of Patras.

A conventional SHPB test facility consists of 3 components including: a bullet impactor, an incident bar and a transmitted bar. A rubber or spring attachment can be used to cease the movement of the transmission beyond the test setup. The test setup installed at the Laboratory of Technology and Strength of Materials of University of Patras is shown in Figure 1(a), while the numerical model of the test setup is shown in Figure 1(b). The specimen is kept between the incident and the transmitted bar and strain gauges are mounted on external surfaces to record the elastic waves propagating and the strain histories during the test. This data is sent to the data acquisition system for further processing. The impact event also referred as a strike is recorded as a “pulse” when an elastic compressional longitudinal stress propagates along the input bar and towards the specimen. When the pulse reaches the specimen-incident bar interface a part of it is reflected as tensile pulse and the remaining is transmitted through the specimen-transmission bar interface. These pulses are hence required as an input to calculate the stress, strain and the strain rate during the experiment using the equation derived from 1D (one-dimensional) wave theory. [3], according to equations 1 to 3:

$$\sigma_s(t) = E_0 \frac{A_0}{A_s} \varepsilon_0(t) \tag{1}$$

$$\varepsilon_s(t) = -2 \frac{C_0}{L_s} \int_0^t \varepsilon_i(t) dt \tag{2}$$

$$\frac{d\varepsilon_s(t)}{dt} = -2 \frac{C_0}{L_s} \varepsilon_i(t) \tag{3}$$

In equations (1) to (3), the parameters A_i, E_i, C_i denote the bar characteristics, A_0 being the cross-section area of the input and output bars, E_0 the elastic modulus of the impactor and bars and C_0 the wave velocity at both the bars. A_s and L_s define the cross-section and length of the specimen respectively. The strain pulses recorded from the strain gauges are represented by ε_i and ε_0 for the incident and transmitted bar respectively.

2.Stacked Shell Method

Interlaminar stresses play an important role in the failure initiation and propagation of damage in laminated structures as they lead to delamination which is one of the most significant modes of failure in composites. Hence, it is important to estimate out-of-plane stresses of the laminated structure. Numerous theories and approaches have been developed till now to calculate the interlaminar normal and shear stresses. Higher order theories (HOT) is a modification of First Order Shear Deformation Theory (FSDT) based on the displacement field given by equation: [10]

$$u_i(x,y,z) = u_1^0 + z u_{i1} + z^2 u_{i2} + \ldots\ldots\ldots\ldots\ldots\; z^{Ni} u_{iN} \tag{4}$$

This theory expresses higher order variation of the stresses, compared to the classical theories. The interlaminar stresses and kinematic behavior of laminates has also been accurately measured with considerably lower computational efforts. [12]

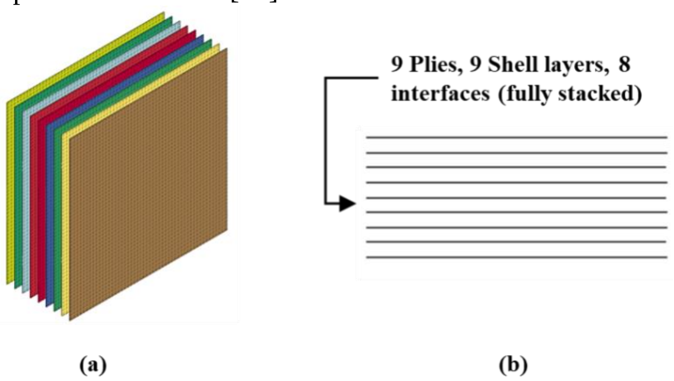

Figure 2: (a) Isometric (b) Side view of fully stack shell finite element model of a woven composite system

This innovative simulation approach which involves the use of "stacked shell" or "2.5D" is presently applied in the modeling of woven material systems as illustrated in Figure 2. The stacked shell method is based on modified FSDT to approximate the behavior of each discrete sub-laminate of the composite structure. Thus, the behavior of the complete composite can be broken down into an interactive set of sub-laminates, each of which exhibits constant through the thickness normal and shear strains. The stacked shell approach has been widely investigated for static loading conditions. [10] In order to enable an efficient implementation in dynamic, non-linear problems, an explicit FE code (LS-DYNA) is applied for model development and solution. However, a systematic investigation of stacked shell method is not available in literature, the approach has demonstrated very good agreement with numerical and analytical solutions for interlaminar stress prediction. [10]

2.1 Contact Modeling in Stack Shell Method

One of the most important aspect of the stacked shell approach is selecting an appropriate contact interface modeling technique. The interfaces of the sub-laminates can separate due to normal and shear stresses developing in the composite laminate. The most commonly used modeling method is based on the fracture mechanics approach in the form of cohesive zone modeling which uses the interface between the laminates as a medium through which the crack propagates leading to a delamination. One of the advantages of CZM over other methods is the capability to predict failure without introduction of a pre-crack in the model. In this study, a "contact_automatic_surface_to_surface_tiebreak" is chosen to model interface delamination between the discrete laminates. A bilinear cohesive law is defined in LS-DYNA contact interface by selecting "OPTION 8" [11]. This tiebreak is active for all the nodes which are in contact. When the critical distance "PARAM" is reached the tiebreak is released and interface delamination occurs. After failure, the tiebreak behaves like a normal "surface_to_surface" contact. The failure criteria is as follows:

$$\left(\frac{|\sigma_n|}{\mathrm{NFLS}}\right)^2+\left(\frac{|\sigma_s|}{\mathrm{SFLS}}\right)^2 \geq 1 \qquad (5)$$

The contact instabilities can be eliminated by selecting "CONTROL_TIMESTEP" for the solution when the time-step is larger than the critical time-step controlled by the interfaces in contact.

3. Setup of the SHPB Numerical Model

In order to simulate the SHPB setup a 5 harness-satin weave composite specimen was selected. The specimens were prepared at Ulster University and then prepared for testing in Patras. The FE model was prepared fully in non-linear explicit FE code LS-DYNA. The dimensions of the apparatus are tabulated in Table 1. The impactor, incident bar and transmitted bar of the SHPB apparatus were modeled using solid elements and the woven composite specimen was modeled with fully integrated stacked shell elements. The impact velocity is set to 18 m/s to obtain strain rates close to 3000 s^{-1}.

Table 1.SHPB finite element model details.

Component	E_i (GPa)	Dimensions (mm)	T_i (°C)	Number of Element (×10^3)
Incident Bar	200	Ø20 × 2400	28	5.2
Transmitted Bar	200	Ø20 × 2400	28	5.2
Bullet	200	Ø20 ×150	28	1.05

3.1 Material Modeling

MAT 58 is a continuum damage mechanics model based on the Matzenmiller-Lubliner-Taylor theory and is only compatible with shell elements used to simulate composite fabrics [10]. The model requires material properties in tension, compression and shear to define stress-strain behavior of the laminate. The maximum strength values in all the above modes is also provided. For tensile loading, the modulus E_A is initially assumed linearly elastic. The stress increment is nonlinear until X_T, the maximum strength and then reduced based on the SLIMT1 factor which is called as the limiting factor. Similar stress-strain response is also observed for compression and shear in MAT 58 material model. The classical material parameters like the modulus, strength and Poisson ratio are material properties directly obtained from tests. Table 2 provides the values of the material and non-physical numerical parameter used in this work.

Table 2. Constitutive parameter summary table

Type	Var Name	Description	Value	Var Name	Description	Value
Material Parameters	E_A	Longitudinal Young's modulus	74000 MPa	Y_T	Transverse tensile strength	880 MPa
	E_B	Transverse Young's modulus	74300 MPa	SC	Shear strength	110 MPa
	X_C	Longitudinal compressive strength	660 MPa	TAU	Stress limit for non-linear part	70 MPa
	X_T	Longitudinal tensile strength	800 MPa	GAB	Shear modulus	9500 MPa
	Y_C	Transverse compressive strength	750 MPa	ERODS	Maximum effective strain for element failure	0.02

4. Preliminary Numerical Results

For initial validation of the model, the output of the model is plotted as a function of axial strain-time histories which are recorded from the strain gauges placed on the bars of the SHPB apparatus. As shown in Figure 3 (a), the numerical and the experimental curve shows a good match. The maximum observed strain in experiment is ≈ 3100 milli-strain in both the incident and reflected pulse. The maximum strain obtained from the FE model is ≈ 3130-3250 mill-strain in incident and reflected pulse respectively.

For the calculation of evolution of strain rate with time, mean strain rate was extracted from every stack shell and averaged. Figure 3 (b) shows the results from experimental and FE model. It is found that the maximum strain rate obtained from experimental and FE model are in good agreement, despite that the decrease in strain rate of the experimental curve is more progressive compared to the FE results which decreases suddenly after impact.

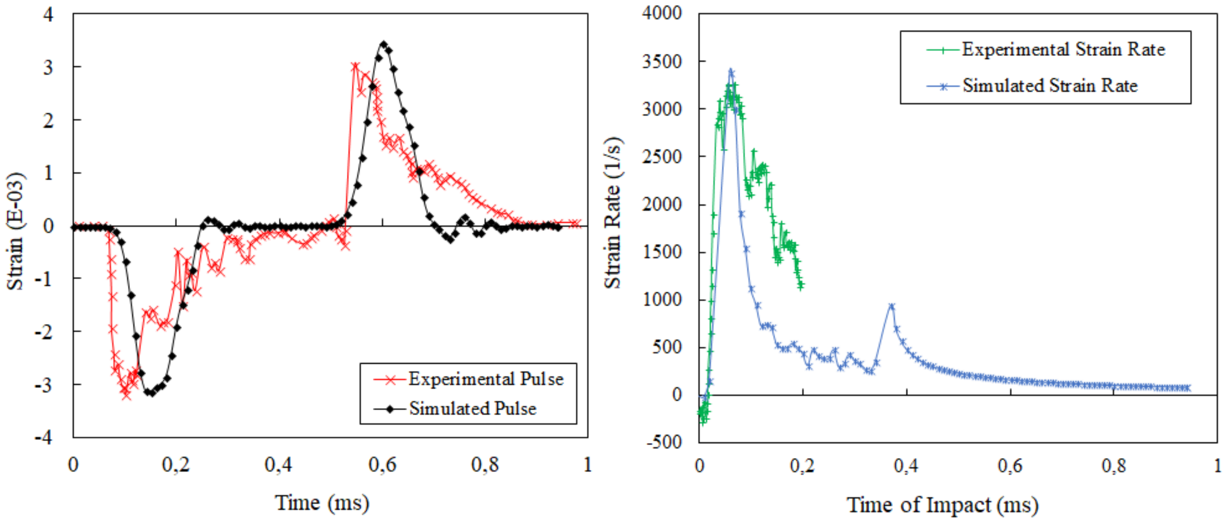

Figure 3: (a) Comparison of incident and transmitted pulse from experiment and FE model (b) Strain rate obtained from experiment and FE Model.

4. Conclusions

SHPB tests of compressively loaded woven composite specimen were modelled using explicit dynamics non-linear Finite Element analysis using the stacked shell method. The obtained strain vs time pulses in the SHPB bars and the strain rate obtained are in good agreement to the experimental results.

5. Acknowledgement

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