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Progressive damage modeling of plain weave E-glass/phenolic composites

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ABSTRACT

An optimized set of material properties and parameters for E-glass/phenolic composites is determined for use in the rate dependent composite damage model MAT162 in LS-DYNA. The model requires 39 material properties and parameters, and is able to capture the seven different damage modes and post damage softening behavior of composites. The unknown MAT162 parameters were determined by conducting parametric simulations of low velocity impact (LVI), depth of penetration (DOP), and ballistic impacts. The modulus reduction parameter OMGMX is found by simulating LVI tests and varying the values of OMGMX to find the best agreement with LVI experimental data. The limit of compressive volume strain for element eroding was found by simulating DOP experiments and comparing the results to the experimental data. Then the element eroding axial strain E_LIMT and EEXPN were determined by simulating ballistic impact experiments. When the optimized values were determined, analysis of ballistic experiments were conducted and compared to the experimental impact versus residual velocity curve. The results of the simulations were in excellent agreement with the experimental data.

1. Introduction

Glass-fiber-reinforced plastic (GFRP) composites, such as E-glass, R-glass and S2-glass are considered cost effective solutions for mitigating ballistic impact energy. This investigation is focused on the E-glass/phenolic since it is the least expensive of the GFRP materials. The objective of this investigation is to determine the modeling parameters required for LS-DYNA MAT162 [1,2]. The rate dependent material model MAT162 has the capability to model the seven failure modes of the plain weave GFRP composites. Yen discusses the newly developed material failure model MAT 161/162 which had been implemented in LS-DYNA for unidirectional composites [3,4]. The failure model was developed by generalizing the Hashin failure criteria [5] to include the effects of high strain rate and high pressure which occur under ballistic and blast loadings [6]. The MAT161/162 model was expanded [3,4] to include the seven failure modes for plain weave composite materials; tensile and compressive fiber failure in the warp and fill directions, fiber crushing, in-plane matrix failure (in-plane shear), and through thickness matrix failure (delamination). The basic layer failure model is MAT161 and the damage model is MAT162. The plain weave fabric failure criteria are expressed in terms of ply (lamina) level engineering strains (ε_x, ε_y, ε_z, ε_{xy}, ε_{yz}, ε_{zx}) with x, y, z indicating the in-plane warp (longitudinal), in-plane fill (transverse), and out-of-plane (through thickness) directions, respectively, with the associated elastic moduli being (E_x, E_y, E_z, G_{xy}, G_{yz}, G_{zx}) [1,2,4]. The equations developed and implemented into LS-DYNA can be found in the LS-DYNA Keyword User's Manual [1] and the Progressive Composite Damage Model for Unidirectional and Woven Fabric Composites User Manual [2]. Yen et al. used [6] quasi-static punch shear (QS-PST) to determine the crush strength and punch shear strength for the composite material. A detailed discussion of the QS-PST approach is given in [7]. Brown used a quasi-static material calibration and numerical simulation validation to investigate Twinex [8]. This calibration/validation was followed by a dynamic impact damage simulation to improve the accuracy of the model parameters under low-velocity impact. Gama et al. [9] introduced a single element approach to determining the modeling parameters for MAT 162. Gamma and Gillespie [10] used numerical simulations of QS-PST experiments to determine the softening parameters and the element erosion parameters for MAT 162. Haque et al. [11,12] used the QS-PST, low-velocity impact (LVI), and depth of penetration to determine the modeling parameters, and this approach will be used with this paper and is outlined below.

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The MAT 162 constitutive material model requires 39 material properties and parameters. Numerical simulations will be used to determine the damage softening parameters AM, OMGMX, ECRSH, E_LIMT, and EEXPN. Post damage softening parameters AM1–AM4 and the modulus reduction factor OMGMX are determined by simulating low-velocity impact experiments. The damage parameters AM are the coefficients for strain softening property for; fiber damage in 1-direction (AM1), fiber damage in 2-direction (AM2), fiber crush and punch shear damage (AM3), and matrix failure and delamination damage (AM4). The penetration erosion parameter ECRSH is found by simulating depth of penetration experiments; while the penetration erosion parameters E_LIMT and EEXPN are determined by simulating ballistic impact experiments. Both ECRSH and EEXPN erode elements based on the ratio of the initial volume of the element to the current volume of the element. In the compression case the element is eroded if the volume ratio is smaller than the limit value shown in ECRSH. For element expansion, the element is eroded if the volume ratio is larger than the EEXPN value. E_LIMT is controlled by the fiber tension in both in-plane directions. When tension in both in-plane directions exceeds the value of E_LIMT the element is eroded. Since these computational model parameters cannot be determined experimentally, parametric simulations of LVI, DOP and ballistic experiments will be conducted to determine these parameters.

2. Experiments and experimental results

2.1. E-glass/phenolic material

The [0/0] E-glass/phenolic panels were fabricated using a (5 × 5) plain weave prepreg comprised of OCV Advantex 3011 E-glass and Hexicon SC-1008 phenolic resin. Three nominal thicknesses (4 mm, 14 mm, and 50 mm) of composite panels were used in this investigation. The 4 mm thick panel was comprised of 8 plies, the 14 mm thick panel was comprised of 28 plies, and the 50 mm thick panel was comprised of 100 plies. All panels were manufactured in accordance with MIL-DTL-6415B [13].

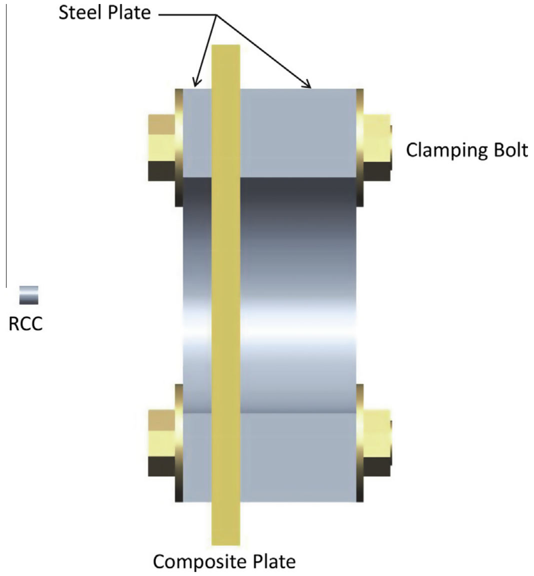

Fig. 2. Cross-section of V_{50} ballistic test fixture.

2.2. Material properties

The panel specimens were subjected to tensile, compressive and shear tests [14,15] to obtain the material properties of the composite material. The material properties required for MAT162

Table 1
Material properties.

Elastic moduli	MPa	Shear moduli	MPa	Compressive strengths	MPa
E_1	29,151	G_{12}	1,540	F_1^{cu}	131
E_2	29,151	G_{23}	1,671	F_2^{cu}	131
E_3	11,000	G_{13}	1,671		
Poisson's ratios		Tensile strengths	MPa	Shear strengths	MPa
$\nu_{12} = \nu_{21}$	0.078	F_1^{tu}	531	F_{12}^{su}	35
$\nu_{31} = \nu_{32}$	0.109	F_2^{tu}	531	F_{23}^{su}	27
$\nu_{13} = \nu_{23}$	0.288	F_3^{tu}	50	F_{13}^{su}	27
Density	kg/m^3				
$\underline{P}$	2,107				

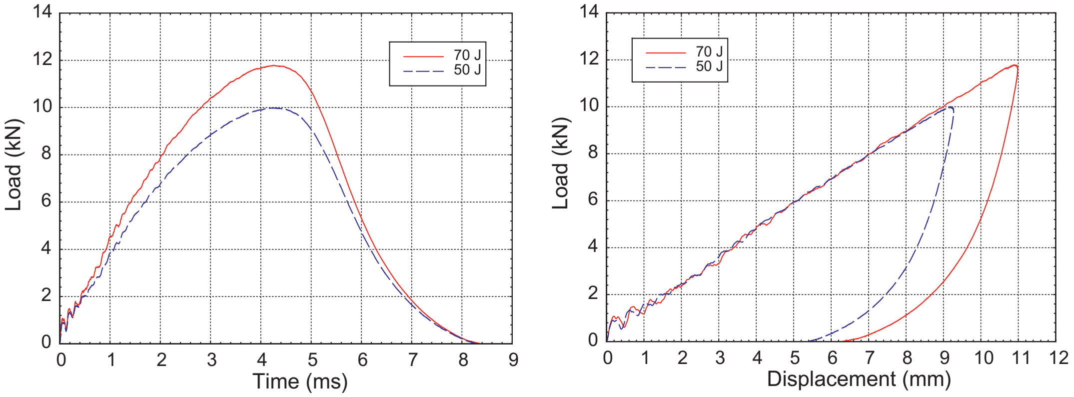

Fig. 1. Force–time and force–displacement curves for LVI.