12th International Conference on Sandwich Structures (ICSS-12)
DOI: 10.5075/epfl-ICSS12-2018-198-200 Lausanne - Switzerland, 19–22 August 2018

MODELLING AND DESIGN OF COMPOSITE SANDWICH PANELS UNDER IN-PLANE COMPRESSION CRUSHING

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1. INTRODUCTION

This study aims to simulate in-plane compressive crushing behaviour of a composite sandwich panel using the finite element analysis (FEA) and to maximise its in-plane crushing energy absorption by optimising some geometrical variables. The proposed model describes a number of damage mechanisms and deformation behaviours of the composite sandwich panel during in-plane compression. Subsequently, the FEA results are validated by experiments. Further, some geometrical variables of the composite sandwich panel are assessed for optimal design with the maximum in-plane crushing energy absorption.

2. EXPERIMENT

In the experiment, the face sheets were fabricated in a quasi-isotropic configuration with T300 carbon fibre plain woven fabric - epoxy prepreg (CF/EP), and the core material was honeycomb from Nomex series. A 1515-3 film adhesive was utilised to bond the face sheets and the core tightly. Finally, the manufactured panel was cut into specimens with a constant $W = 60$ mm, and an initial $H = 50$ mm after set-up, as shown in Fig. 1. In addition, different bevel angles θ were introduced according to the design requirement, and chamfers were machined on the crushing edges for all specimens.

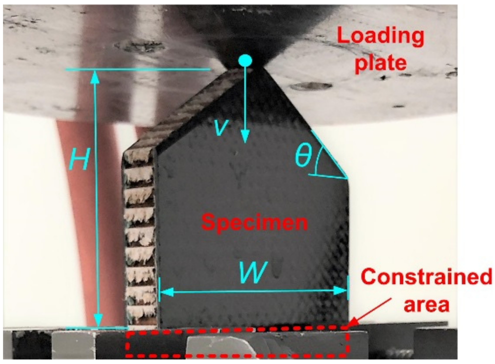

Fig. 1: Experimental set-up.

The quasi-static compression crushing tests were conducted on a MTS 810 material test system with a constant crushing rate of v=2 mm/min, as presented in Fig. 1. During compression, the load-displacement curve was recorded by a computer-instrumented data acquisition system, and the total absorbed energy (*TAE*) can be defined by integration of the load-displacement curve as

$$TAE = \int_0^S F(x)dx \tag{1}$$

where $F(x)$ is the crushing load as function of the displacement of x, S is the maximum crushing displacement. Additionally, the specific energy absorption (*SEA*) is defined by

$$SEA = \frac{TAE}{m} \tag{2}$$

where, m is the mass of crushed section.

3. FINITE ELEMENT ANALYSIS

The finite element analysis is integrated with a few mechanistic models that describe the damage and failure in the composite sandwich panels, including the continuum damage mechanics (CDM) model for the in-plane failure of composite face sheets, cohesive zone model (CZM) for interlaminar fracture in the composite face sheets and debonding between the face sheets and sandwich core, and elastic-plastic model for the sandwich core [1-4].

Continuum Damage Mechanics

CDM model expresses the damage defined by the degradation of the stiffness matrix of a composite with plain fabric of reinforcing fibres. The constitutive stress-strain relations are formulated as [1]:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{12}\end{Bmatrix}=\frac{1}{D}\begin{bmatrix}(1-d_1)E_1 & (1-d_1)(1-d_2)E_1v_{21} & 0\\ (1-d_1)(1-d_2)E_2v_{12} & (1-d_2)E_2 & 0\\ 0 & 0 & 2(1-d_{12})DG_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{12}^{el}\end{Bmatrix}\tag{3}$$

In the equation, σ_{11}, σ_{22} and σ_{12} are the stresses, and ε_{11}, ε_{22} and ε_{12}^{el} are the elastic strains, respectively. $D=1-(1-d_1)(1-d_2)v_{12}v_{21}$, d_1 and d_2 are the damage variables in the two main fibre directions, d_{12} denotes the current shear damage state; E_1 and E_2 are Young's moduli in the two fibre directions, respectively, G_{12} is the in-plane shear modulus, and v_{12} and v_{21} are Poisson ratios. In this work, the damage variables were calculated based on the stress state in the fibre directions as

$$d_i=d_{i+}\frac{\langle\sigma_{ii}\rangle}{|\sigma_{ii}|}+d_{i-}\frac{\langle-\sigma_{ii}\rangle}{|\sigma_{ii}|},\ i=1,2\tag{4}$$

where d_{i+}, d_{i-} and d_{12} are the damage variables that are assumed as a function of the corresponding effective stress. As for the initiation failure criteria, it is based on the ultimate strength. After the initiation failure criteria has been met, the damage evaluation will be implemented according to [4]. In the shear direction, plasticity is also considered using a classical plastic model [3].

Cohesive Zone Model

In terms of the interface damage and failure, a cohesive zone model (CZM) was utilised taking into account a damage initiation criterion and a damage evaluation law [3, 4].

Damage initiation criterion

$$\left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2+\left\{\frac{\langle t_s\rangle}{t_s^0}\right\}^2+\left\{\frac{\langle t_t\rangle}{t_t^0}\right\}^2=1\tag{5}$$

Damage evaluation law

$$G_n^C+(G_s^C-G_n^C)\left\{\frac{G_S}{G_T}\right\}^{\eta}=G^C\tag{6}$$

where t_i ($i=n, s, t$) is the traction stress vector and t_i^0 ($i=n, s, t$) is the strength vector. $G_S=G_s+G_t$, $G_T=G_n+G_S$, G_i ($i=n, s, t$) is the total strain energy release rate; G^C is the corresponding fracture toughness. η is the cohesive property coefficient.

Elastic-plastic Model

With regards to the honeycomb core, there are also a number of studies that could be referred to establish the numerical model [5, 6]. The geometric parameters and modelling detail of aramid paper and phenolic resin were proposed and discussed in previous work [3].

4. DESIGN METHOD

After the analysis of the numerical and experimental results, important geometric factors (including the bevel angle θ and the height H) were selected as the variables for optimisation design. The mass and energy absorption were defined as the objectives. To acquire mathematic surrogate model for approximating the variables and objectives, an optimal surrogate modelling technique on the basis of a radius basis function (RBF) was utilised [7]. The form of the RBF to construct the approximation by $\tilde{f}(x)$ can be formulated as:

$$\tilde{f}(x)=\sum_{i=1}^{n}\lambda_i\phi(r_i)\tag{7}$$

where n is the number of the sampling points, $\phi(r_i)$ is the basis function, r_i is the Euclidean distance and λ_i is the coefficient. After the model has been built, non-dominated sorting genetic algorithm (NSGA-II) was carried out to solve such a multi-objective optimisation problem and acquire the optimal solutions. The specific design methods can be referred in [7].

5. RESULTS AND DISCUSSION

The numerical model was validated by experiments for specimens with different bevel angles, and the results for the specimens of 30° bevel and 50 mm height are shown in Fig. 2. It can be seen that the forces gradually climb to the peak ahead of a devastating drop, which indicates that there was sustained damage propagation when the composite panel failed progressively under in-plane crushing. Further, it implies that there must be an optimal bevel angle with a specific height that can perform optimally in mass reduction but enhanced energy-absorption.

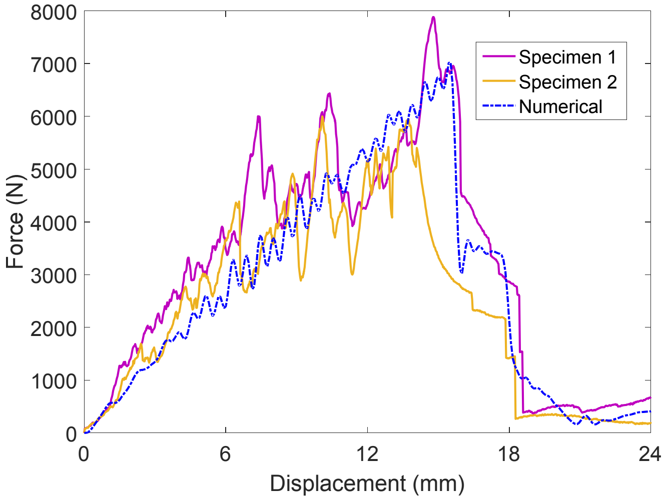

Fig. 2: Force-displacement plots of experimental and numerical results.

To acquire the optimal structural parameters, optimisation calculation was conducted as described before. Afterwards, with the aid of surrogate model, the optimal result was achieved, which was input into the numerical model for validation and analysis. It is found that the error of the objective responses between the surrogate model and numerical calculation were all below 10 %, indicating the effectiveness and reliability of the constructed model. To compare the performance of optimised result with other specimens within the design scope, the diagram of *SEA* versus crushed mass is depicted in Fig. 3. Clearly, the optimal composite sandwich panel, when the bevel angle is 36.5° and the height is 27 mm, can achieve the highest energy absorption by consuming comparatively less mass.

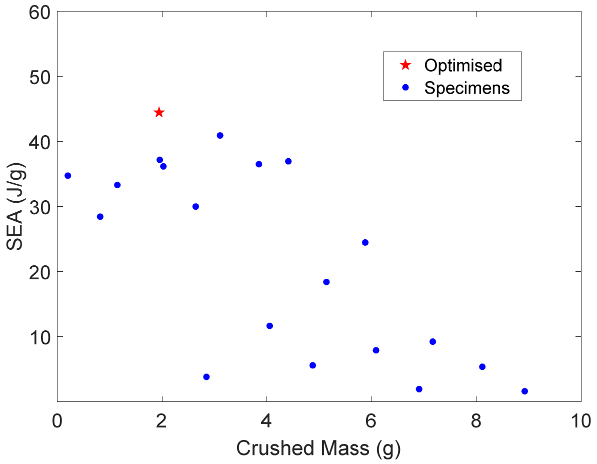

Fig. 3: SEA versus crushed mass of the optimised and other specimens.

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