Combined FEM/Meshfree SPH Method for Impact Damage Prediction of Composite Sandwich Panels

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Abstract: *In this work, impact simulations using both meshfree Smoothed Particle Hydrodynamics (SPH) and combined FEM/SPH Method were carried out for a sandwich composite panel with carbon fibre fabric/epoxy face skins and polyetherimide (PEI) foam core. A numerical model was developed using the dynamic explicit finite element (FE) structure analysis program PAM-CRASH. The carbon fibre/epoxy facings were modelled with standard layered shell elements, whilst SPH particles were positioned for the PEI core. We demonstrate the efficiency and the advantages of pure meshfree SPH and combined FEM/SPH Method by comparing the core deformation modes and impact force pulses measured in the experiments to predict structural impact response.*

Keywords: Impact damage, composite material, sandwich structure concept, Finite Element Method (FEM), meshfree method, Smoothed Particle Hydrodynamics (SPH)

1 Introduction

Modelling of high velocity impact (HVI) and crash scenarios involving material failure and large deformation using classical FEM is complex. Although the most popular numerical method FEM is still an effective tool in predicting the structural behaviour in different loading conditions, FEM suffers from large deformation leading problems causing considerable accuracy lost. Additionally it is very difficult to simulate the structural behaviour containing the breakage of material into large number of fragments since FEM is initially based on continuum mechanics requiring critical element connectivity. The enhancement of existing numerical methods based on FEM is always current theme. Proposed adaptive remeshing method seems very promising method, however it is computationally very expensive since the procedure determining the error estimation for remeshing criteria takes

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time. To overwhelm the numerical problems due to remeshing, Extended Finite Element Method (X-FEM) has been proposed [1]. However the implementation of X-FEM is difficult since it is necessary to add global degrees of freedom during the simulation leading to the enlargement of the stiffness matrices, especially for the multi-crack problems. As an alternative to FEM, meshfree methods have been developed and applied to numerical simulations involving material failure and damage. Meshfree methods replace finite elements by a set of nodes or particles within the problems domain and its boundaries. This feature makes meshfree methods very effective since mesh connectivity is not as critical as in FEM. There are several meshfree methods and new meshfree methods are taking part in research[2]. Among them SPH is one of the earliest particle methods in computational mechanics. SPH was developed by Lucy [3] to solve astrophysical problems in 3D open space. Since its invention SPH has been extensively studied and extended to dynamic response with material strength, fracture and impact simulations, failure of brittle solids and metal forming simulations. The study presented here proposes SPH method and its combination with FEM to overcome the classical limitations of explicit FEM such as too small time steps, hour-glassing, mesh size dependency and element distortion during impact simulations of composite structures.

2 Theoretical Fundamentals

SPH is based on two interpolation approximations: Kernel approximation and particle approximation. Considering the function $f(x)$ in Eq (1), value at a point of $f(x)$ over domain Ω could be extracted from its integral using the delta function (δ) as a filter,

$$\langle f(\overline{x})\rangle = \int_{\Omega} f(\overline{x'})\delta(\overline{x}-\overline{x'})d\overline{x'}. \tag{1}$$

One can define delta function as follows:

$$\int_{\Omega} \delta(\overline{x}-\overline{x'})d\overline{x'} = 1. \tag{2}$$

As $h \rightarrow 0$, $\delta(\overline{x}-\overline{x'})$ can be replaced by with a kernel function $W(\overline{x}-\overline{x'},h)$ which has a support domain determined by the parameter h,

$$\lim_{h\rightarrow 0} W(\overline{x}-\overline{x'},h) = \delta(\overline{x}-\overline{x'}). \tag{3}$$

Therefore Eq (3) yields to following:

$$\langle f(\overline{x})\rangle = \int_{\Omega} f(\overline{x'})W(\overline{x}-\overline{x'},h)d\overline{x'}. \tag{4}$$

Since domain is represented by discrete particles, the summation of the contributions of each discrete particle within the kernel approximation range results the smoothed value of $f(x)$ at a point (particle approximation), as

$$\langle f(\overline{x})\rangle = \sum_{j=1}^{N} \left(\frac{m_j}{\rho_j}\right) f_j W(|\overline{x}-\overline{x'}|,h) \tag{5}$$

in which N represents the number of discrete particles, m_j and ρ_j stand for mass and the density of the particle j, respectively.

3 Material Modelling

It was considered that a homogeneous orthotropic elastic damaging material was an appropriate model for UD and fabric laminates, as this is applicable to brittle materials whose properties are degraded by micro cracking. Constitutive laws for orthotropic elastic materials with internal damage parameters are described in [4], and take the general form

$$\varepsilon = \mathbf{S}\sigma \tag{6}$$

where σ and ε are vectors of stress and strain and $\mathbf{S}$ is the elastic compliance matrix. In the plane stress case required here to characterise the properties of composite plies or shell elements with orthotropic symmetry axes (x_1, x_2), the in-plane stress and strain components are

$$\sigma = \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \qquad \varepsilon = \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ 2\varepsilon_{12} \end{bmatrix}. \tag{7}$$

Using a strain equivalent damage mechanics formulation, the elastic compliance matrix $\mathbf{S}$ may then be written :

$$\mathbf{S} = \begin{bmatrix} \frac{1}{E_1(1-d_1)} & \frac{-\nu_{12}}{E_1} & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2(1-d_2)} & 0 \\ 0 & 0 & \frac{1}{G_{12}(1-d_{12})} \end{bmatrix} \tag{8}$$

where ν_{12} is the principal Poisson's ratio, which for simplicity is assumed not to be degraded. The elastic damaging materials law for fabric reinforcements may be modelled in PAM-CRASH as a 'degenerate bi-phase' model in which the UD fibre phase is omitted, and the 'matrix' phase is assumed to be orthotropic. If the simplifying assumption is made that $d_1 = d_2 = d_{12} = d$, the composite fabric ply has orthotropic stiffness properties, but a single 'isotropic' damage function d which degrades all the stiffness constants equally. The code does however allow different damage functions in tension and compression. This model has been found to be easy to apply and appropriate for quasi-isotropic laminates, which are commonly used in aircraft structures.

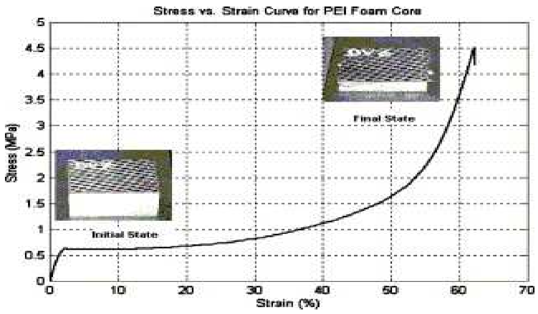

Figure 1: Stress-strain plot of PEI foam core

The DLR conducted a compression test on PEI foam core material and an elastic-plastic material response can be seen in Figure 1. To model this behavior, a crushable foam solid material model has been assigned to foam core. The elastic behavior response is described by its initial tangent and shear modulus. The inelastic behavior consists of coupling between volumetric (bulk) and deviatoric (shear) plasticity. This coupling between both parts of the inelastic material response is accomplished via a pressure dependent von Mises (J_2 plasticity) yield surface which is formulated as follows:

$$\phi_s = J_2 - (a_0 + a_1 p + a_2 p^2) = 0 \qquad \textit{where} \qquad J_2 = \frac{1}{2} S_{ij} S_{ij} = \frac{1}{3} \sigma_Y{}^2. \tag{9}$$

Here, J_2 is the second invariant of the deviatoric stress tensor on the von Mises yield surface, a_0, a_1, a_2 are user specified material parameters, p and σ_Y stand for pressure and effective yield stress, respectively. In order to overcome the high mesh distortion which causes numerical problems with the timestep assignment in explicit codes, the FE meshes in highly distorted local damage zone has been replaced by interacting particles. The material response assigned for discrete SPH particles is an isotropic-elastic-plastic-hydrodynamics solid material model in which the pressure-volume relation is modelled by an equation of state (EOS). This material model was originally developed for ballistic impact in metals and describes an isotropic elastic-plastic material at low pressure, whose properties are defined by the shear modulus and tangent modulus or effective plastic stresses and effective plastic strains. Additionally with EOS describes the "hydrodynamic" pressure-volume behavior at high pressures. In this case it is given as following:

$$p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 \qquad \textit{where} \qquad \mu = \frac{\rho}{\rho_0} - 1. \tag{10}$$

C_0, C_1, C_2, C_3 are material constants, μ is a dimensionless compressibility parameter defined in terms of the ratio current density, ρ, to initial density, ρ_0. The polynomial form is an established approximation of the observed EOS for many materials, see for examples [5], with the feature that it reduces to a dilatational elastic materials law with bulk modulus C_1 when C_0=C_2=C_3=0.

4 Numerical Analysis using combined FEM/SPH Method

The proposed finite element mesh based model, described in [6], can be used for accurate prediction of failure modes in sandwich panels. However topological element connectivity in FEM can lead to numerical instabilities (for higher velocities) and further enhancement is needed for better quantitative correlations. Following this idea, carbon fibre/epoxy facings were modelled with standard layered shell elements, whilst SPH particles are used for the PEI core where extensive crushing and fracture by the rigid impactor occur. Use of solid elements here leads to aforementioned difficulties with excessive distortion. Beside the advantages of its meshfree nature, as a result of the dynamic neighbouring search algorithm, the SPH Method is computationally expensive. One alternative numerical solution technique that is commonly used is coupling. Since SPH uses Lagrangian framework, a possible coupling between SPH and standard Lagrangian FEM is straightforward. This means (for impact problems) a coupling between discrete smoothed particles for the parts where large deformation occurs and finite elements for the parts where small deformation takes place is possible. Such coupling would exploit the potential of each method while avoiding their deficiencies. In this work, coupling was applied through a sliding interface condition. The mesh patterns or both discretizations can be combined with a tied kinematic constraint type contact that connects two contact interfaces defined on two meshed parts of a structure that are close to each other but whose respective discretization grids are not necessarily matching. Discrete SPH particles are generated with a simple transformation of finite element mesh into mass points.

To make a qualitative comparison between FEM, SPH and FEM/SPH, impact simulations were carried out for a sandwich composite panel mounted on a ring load cell and impact at the centre by a concrete impactor, Figure 2. Normal impact from a rigid impactor was considered at nominal impact velocity of 60m/s, which corresponds to the typical impact speed of runway debris on an aircraft structure during start and landing. Contact force history comparison between experimental analysis and FEM simulation in Figure 4 shows that the proposed FEM model provides reasonable accurate contact force history of HVI on sandwich panel. As one can observe from experimental curve, the first peak load is about 7kN and the second peak is about 4kN. Depending on the energy absorption mechanism of the sandwich plate, projectile loses its kinetic energy and this results in a lower second peak. Proposed FEM model estimates especially the first peak value accurately, which is very critical value for impact scenarios. However as Figure 3 shows, FEM model produces very severe deformation on core which can lead numerical errors, inaccurate results and numerical instabilities for higher velocities. Since mesh connectivity is not as critical as in FEM, in SPH Method depending on the deformation mechanism discrete particles can split and as Figure 3 illustrates core deformation is much more realistic than that of FEM. However, additional to expensive computation, contact history obtained using SPH Method is not as accurate as that of using FEM, Figure 4. Since in SPH the number of discrete particles itself and the extent of each particle's domain of influence are decisive for the CPU consumption , combined FEM/SPH Method, which combines the faster computation nature of FEM and accuracy of SPH, is proposed. Although both SPH and combined FEM/SPH Method use same number of particles in damage zone, combined FEM/SPH Method estimates first peak value more accurately than SPH Method with a realistic core deformation pattern, Figure 3. However as Figure 5 shows the second peak value is higher than both experimental and FEM results.

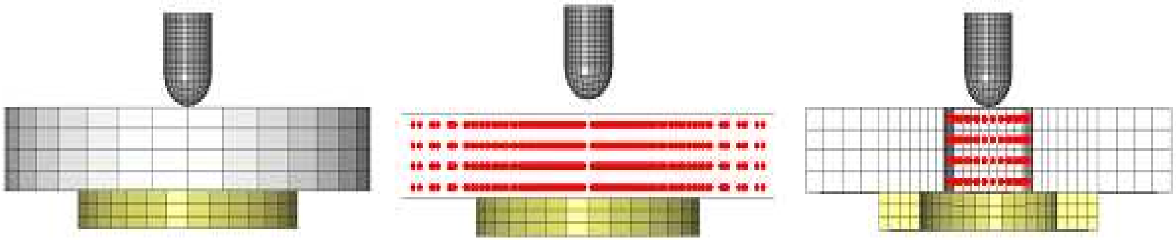

Figure 2: Numerical impact models using FEM, SPH and combined FEM/SPH

5 Conclusion

In this work the results of impact simulations carried out for a sandwich composite plate with carbon fibre fabric/epoxy face skins and PEI foam core using SPH and FEM/SPH Method have been presented. We demonstrated the capability of meshfree SPH Method to be an effective candidate to overcome the drawbacks of FEM, such as large core defor-

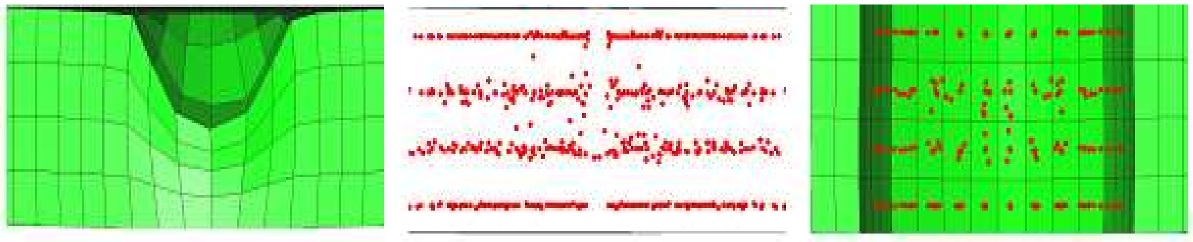

Figure 3: Severe element distortion using FEM and damage zone core deformation using SPH and combined FEM/SPH Method

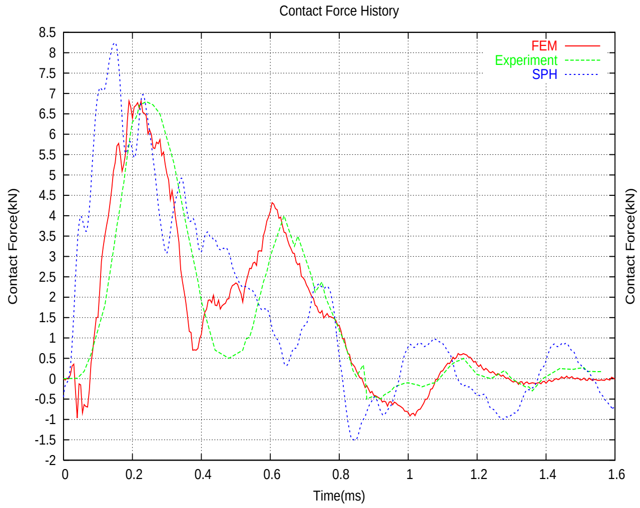

Figure 4: Contact force history plots

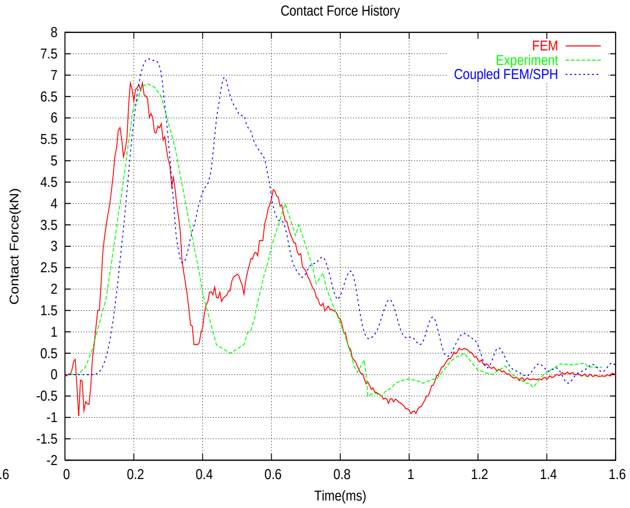

Figure 5: Contact force history plots

mation with numerical simulations. Consequently, since SPH Method is computationally expensive, it has been confirmed to be a good alternative in combination with FEM for the numerical simulations where large deformation and element distortion are critical.

6 References

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