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Indentation of sandwiches using a plate model with variable kinematics and fixed degrees of freedom

Icardi U.*, Sola F.

Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

A recent 3-D, 5 degrees of freedom, variable kinematics zig-zag homogenised model is used for studying sandwich indentation. This model cannot describe in a point-wise sense cells collapse, buckling, debonding failure, plastic yielding, or brittle fracture. Therefore, the progressive folding followed by densification of the core is described through mechanical properties variable with loading, which are computed apart once at a time through a 3D FEA discretisation of the core structure. Onset of damage is determined using stress-based criteria; degraded properties of failed regions are obtained from a mesoscale damage model. The results show efficiency and accuracy of this approach.

1. Introduction

Composites are finding use in many structural applications, owing to low weight, excellent strength, stiffness, energy absorption, thermoelastic and fatigue properties. However, since they cannot yield and dissipate a large amount of energy via plasticity, they mainly absorb energy through local damage rise and growth in service, as discussed in the review paper by Garnich and Akula [1], in the book by Liu and Zheng [2] and in the papers by de Borst and Remmers [3] and Ajdari et al. [4].

Damage of laminates initiates as matrix cracking, fibres breakage and local puncture. Nature, position and extent of the damage depend upon distribution, magnitude and duration of stresses, stacking sequence, pre-existing defects, strengths and load history. Instead, sandwiches exhibit the crushing of core followed by tearing of the loaded face. The topology of cells, their relative density and the thickness of the foil have considerable influence on this behaviour.

Matrix cracking and delamination can be simulated with the maximal accuracy using fracture mechanic models, which efficiently evaluate the strain energy release rates through modified versions of the crack closure integral (see, e.g., [5] and [6]), as well as using cohesive zone models based on a traction-separation law (see, e.g., [7,8,9]). Often, three-dimensional finite elements are used as structural models, but recently developed high-order layerwise plate (HLW) models based on a combination of global higher-order terms and local layerwise functions have been proven to be equally accurate with a much lower number of unknowns. The recent papers by Frostig [10], Plagianakos and Saravanos [11], Zhen and Wanji [12], Elmalich and Rabinovitch [13] and Giunta et al. [14] are cited as examples, which demonstrate accuracy and efficiency of HLW models. A thorough discussion of the techniques employed to account for the layerwise requirements, extensive assessments of the structural performances of HLW models and of related finite element counterparts are given among many others in the recent papers by Matsunaga [15] and Chakrabarti et al. [16]. The distinctive feature is whether HLW models have a number of unknowns that depends or not on the number of physical or computational layers, as this determines accuracy and computational costs.

The behaviour of sandwiches is often described through a detailed finite element simulation of the cellular structure of honeycomb (Aminanda et al. [17]), or using solid elements for foam core (Mamalis et al. [18]), despite this may result in too high computational costs. However, many studies also consider sandwiches as multilayered composites where the core is treated as a homogeneous material (see, e.g., [13,14]). This latter approach may be unsuitable for simulating localised phenomena, like the buckling of cell walls, but it is more attractive in an industrial environment due to its much lower computational costs.

Low-velocity/low-energy impact studies, also called indentation studies, follow the same path. They are often carried out through three-dimensional (3-D) finite element analyses (FEA) and fracture mechanics or cohesive zone models (see, e.g., [19,20]).

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* Corresponding author. Tel.: +39 0110906872; fax: +39 0110906899.
E-mail addresses: ugo.icardi@polito.it (U. Icardi), federico.sola@polito.it (F. Sola).

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But studies have also shown that simulations can be successfully carried out using HLW or even less sophisticated plate models as structural models. In these cases, stress-based failure criteria can be employed for locating the onset of damage. Then the damage growth can be simulated by degrading the elastic properties of the failed regions with appropriate multiplication factors, as shown e.g. in the papers by Icardi and Ferrero [21], Yokoyama et al. [22] and Khalili et al. [23]. The importance of indentation studies lies on the relevant amount of internal damage they can generate without leaving any visible evidence on the surface.

As far as HLW models are concerned, those called zig-zag models (ZZ) that *a priori* fulfil the continuity of out-of-plane stresses at the layer interfaces with a number of functional degrees of freedom (d.o.f.), independent of the number of layers have been proven to be accurate with the lowest costs. In the early developed ZZ, just piecewise in-plane displacements were considered, while the transverse displacement was assumed constant. Since in many problems of practical interest the transverse normal stress has a significant bearing for keeping equilibrium, later full 3D ZZ were developed. Usually, ZZ require integration of local differential equilibrium equations to provide accurate stress predictions, but, since cases exist for which the predictions still remain inaccurate, as shown by Cho et al. [24], researchers developed ZZ that can be accurate from constitutive equations.

Sublaminate models that conjugate the concepts of ZZ and discrete-layer models (DL), giving a separate representation for each constituent layer, have been developed to this purpose. Other researchers, like the authors [25], Li and Liu [26] and Zhen and Wanji [12], developed ZZ that are based on different approaches, trying to keep the number of unknowns independent from the number of layers with the aim of saving costs.

The model VK-ZZ by the authors [25] is used in this paper as structural model to study indentation of sandwich panels.

This model is chosen because it has the merit of solving the structural problems with the minimal number of unknowns and of efficiently treating problems with different length and elastic scales with a low computational cost. As it offers a variable representation across the thickness, it achieves a great accuracy without a considerably larger computational effort [27] than equivalent single-layer models, to date still the cheapest ones.

Differently to other indentation studies of sandwiches that, relying on homogenised multi-layered plate models as structural models, cannot properly treat the core crushing behaviour, the present simulation procedure can treat this phenomenon. Indeed, a detailed 3-D finite element simulation of the behaviour of core structure, which is described as it is in the reality, is carried apart once at a time to compute the variable, apparent elastic properties of core (tangent moduli) under variation of the transverse load, so to describe the most relevant local phenomena in the core structure. In this preliminary FEA, plate elements are used to discretise the face sheets and the cellular structure of honeycomb, while foam core is discretised by solid elements with non-linear material behaviour. As microbuckling and local failure of core are highly mesh sensitive, a very refined meshing is required. In fact, a too coarse meshing could provide an incorrect initial load peak and an incorrect load in the densification regime could be obtained. Accordingly, whether reference results for the core behaviour are not available to help in understanding when meshing is acceptable, a convergence analysis should be carried out considering progressively refined meshing till results repeat.

The real properties of core are determined in a tabular form according to the results of the detailed FEA, and then they are provided to VK-ZZ model, so that they are those suited at each load step and at each point location, instead of being the initial one of the health material. Using these variable core properties at each load step and from a point to a neighbouring one over the contact area, the analysis is carried out with a degree of accuracy comparable to that of three-dimensional models, as shown by numerical results, with a much lower computational effort. In fact, the most expensive iterative computations for determining the damage at each load and time step are carried out using the low cost VK-ZZ model instead of a 3-D finite element meshing. Since the computational burden is kept as low as possible because 3-D modelling is limited to the computation of the apparent elastic properties of core, this simulation procedure saves costs.

Nevertheless many authors agree that just static simulations can be used to study indentation because there is equivalence between static and dynamic results for low velocity impacts, a dynamic solver is developed for future solution of transient dynamic problems and applied to study the present topic. Newmark's implicit time integration scheme is employed to solve the transient dynamic equations, because it does not need extremely small time steps to be stable and to limit convergence and rounding errors. As customary, the indentation depth and the contact area are computed assuming the distribution of the contact force to be Hertzian and the projectile as a rigid body. The contact area is evaluated at any time step using the iterative algorithm by Palazotto et al. [28] that forces the surface of the target to conform the shape of the impactor, as required by soft media. Failure of fibres, fibre-matrix debonding, transverse matrix cracking, onset of delamination and crushing of core are predicted using stress-based criteria, as customary. But instead of considering a healthy material, a damaged material is considered at each time step because the continuum damage mesomechanic model by Ladevèze et al. [29], [30] is used inside the VK-ZZ model, along with the properties of core provided by the preliminary FEA carried apart. A mesoscale model was chosen because, as claimed in [31], this kind of models is more accurate and computationally advantageous than structural scale ones, which consider cracks as hard discontinuities. The mesoscale model provides a modified expression of the strain energy that accounts for the effects of the damage on the microscale. The failure analysis is still carried out using failure criteria, as customary, but stresses are computed taking into consideration the effects of local damage. The progressive failure analysis is performed extending a pre-existing delamination to the points where the ultimate condition is reached, as predicted by the criteria.

Hereafter, the technique used to simulate the core crushing behaviour, the main features and assumptions of the VK-ZZ structural model and how they reflect into its accuracy and computational costs are overviewed. Next, the procedures for computing the damage indicators and the contact force are briefly reviewed. Finally, applications are presented.

2. The structural model

2.1. Modelling of the core crushing behaviour

The behaviour of the “soft” material constituting the core needs to be accurately described, because a large amount of energy is absorbed through various folds and failure modes of the core structure. Thus, a discrete modelling is required for simulating with the due accuracy the effects that local phenomena have upon energy absorption mechanisms, which are strongly affected by the through-the-thickness properties.

As shown in many works taken from literature (see, e.g. [17] and [32]), honeycomb core behaves linearly at low strains, buckles and then undergoes progressive folding, finally followed by densification. Indeed, depending on the nature of the wall material, cells collapse by elastic buckling, plastic yielding, creep or