Dynamics and fracture of impacted sandwich composites under time varying loads: Numerical modelling and simulations

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Summary. In this study, the dynamics and fracture of sandwich plates containing a pre-existing skin-to-core interfacial damage and sub-interfacial core damage induced by an incident impact is examined. The dynamic response of sandwich plates with debonding that is allowed to be growing with a time, is simulated by using the finite element method within the ABAQUS code. The forced vibration analysis of impact-damaged sandwich plates is carried out accounting for contact and friction conditions within the debonded region in the simulations with ABAQUS. The damage mechanics approach implemented into ABAQUS via cohesive elements is used for modelling the debonding propagation under impulsive and harmonic loading. The influence of the skin-to-core debonding growth on the global nonlinear dynamics and strength of the sandwich plates is studied in detail.

Introduction

Applications of composite sandwich materials has already demonstrated a continuing increase in various industries [1]. The extensive employment of sandwich composites in aerospace, wind energy, transportation, and naval structures as well as in sport equipment has escalated a need for improved understanding of dynamics and strength of these composites since such components and structures are exposed in service to not only quasi-static loading conditions, but various types of dynamic loads and regimes are widened significantly.

Sandwich composite structural components often suffer from skin-to-core interfacial debonding caused by impact-like reasons such as dropped tools, hail, a bird strike or runway debris. This damage, in fact, significantly reduces the load bearing capacity of sandwich structures and controls their overall behavior. Dynamic loading, being typically applied to sandwich structural elements in most their engineering applications, can promote the onset and evolution of debonding growth along the skin-to-core interface and into the core [2]. In this respect, numerical simulations are superior over costly and time consuming experimental studies. The numerical study on the dynamics and fracture of a sandwich plate subjected to time varying loading is presented in this work. The dynamics and the dynamic fracture in the sandwich plate with a pre-existing penny-shaped impact-damaged region is examined numerically by means of a number of predictions performed with the ABAQUS code [3].

Finite element modelling

From a mathematical point of view, the problem on a sandwich panel with interfacial skin-to-core and sub-interfacial core damages subjected to dynamic loads fails into a class of mechanical tasks for which a discrete change in the geometry and stiffness should be defined. The dynamics of a sandwich plate with a prescribed debonging interface and a locally damaged core is modelled by using impact-contact models, where contact and friction conditions are assigned in the impacted region. On the other hand, to allow the propagation of debonding into the skin-to-core interface and/or spreading damage into the core, crack initiation and crack evolution criteria are additionally defined.

In this work the finite element modelling is based on the classical displacement-based approximation within the framework of elastodynamics accompanied by contact-friction constrains and dynamic fracture constitutive laws. The FE statement of the elastodynamics problem of debonded sandwich plates accounting for contact and friction have been done in [4,5], while this problem with deboning propagation conditions have been considered in [6,7]. Here, we follow the mentioned formulations to develop a finite element model of a sandwich plate containing a pre-existing penny-shaped impact-induced interfacial skin-to-core and sub-interfacial core damages that are allowed to be growing with a time under external dynamic loads. Thereby, the unilateral contact conditions are implemented by imposing a 'hard contact' Signorini's law. The latter implies that the interacting surfaces transmit no contact pressure unless the nodes of the slave surface contact the master surface and no penetration is allowed at each constraint location. At the same time, a Coulomb's model describes the friction phenomenon. The dynamic debonding in the sandwich plate is modelled based on an idea of cohesive finite elements [8]. A traction-separation constitutive behaviour of the element allows predictions of both the onset of a softening process at the crack tip, as a result a strength-based analysis and the crack propagation conditions rely on fracture mechanics criteria. Herein, the quadratic stress crack initiation and the energy-based B-K crack evolution criteria are used throughout this numerical study. Damage imparted into the core due to an impact event is simulated by reducing its elastic properties with appropriate reduction coefficients. A rate-dependent crushable foam model with a volumetric hardening effect is used to model core fracturing.

Finite element simulations

The ABAQUS code is used to perform dynamic and fracture finite element analyses of the developed models of sandwich plates with impact-induced interfacial and sub-interfacial damages. In doing so, the FE geometry of the

impacted sandwich plate consists of different zones such as the face sheet with a residual indentation of known diameter and depth, and the crushed core, located beneath the face sheet indentation zone and including both the residual core indentation and the core stiffness degradation.
In the FE model, the face sheets are discretized with 8-node reduced integrated continuum shell elements, SC8R and the core is modelled by using 8-node reduced integrated linear solid elements, C3D8R. Because, such elements have only translation degrees of freedom they can be connected directly to each other without any kinematic transition. A layer of 3-D cohesive elements COH3D8 in conjunction with the fracture criteria utilized for simulating skin-to-core debonding is inserted between the elements of the face sheets and core.
The dynamic governing finite element equation, including the dynamic external, cohesive and contact forces in accordance with the developed FE model in the right-hand side, is solved using an implicit time marching algorithm based on the Hilber–Hughes–Taylor temporal integrator in the case of harmonic external loads, while the explicit solution scheme is more effective for obtaining the results in the case of transient loads. Hence, in the latter time integration a kinematic prediction-correction algorithm is used to resolve contact-friction constrains, while the penalty method and return-mapping scheme are applied to contact and friction problems, respectively, in the former one.

Results and discussions

The results obtained in the simulations showed that the dynamics of debonded sandwich plates subjected to both impulse and harmonic loads is considerably affected by the pre-existing impact-induced damage. It was found out that contacts arising in the debonded zone are responsible for the extent of nonlinearity of the plate's structural response. Due to contacts, the frequency spectra extracted from the transient vibrations reveal additional peaks in the frequency domain. And a redistribution of the vibrational energy to the sub- and super-harmonics seems the main signature of the dynamics of debonded sandwich plates.
Moreover, the typical assumption that if excitations are harmonic, then the response is also harmonic, commonly used in linear system is no longer valid for the response of debonded sandwich plates. Instead, a steady-state response of them should be studied based on the general dynamic analysis. Also, it was proven that the driving frequency is a dominant factor which governs the dynamics of debonded sandwich plates under harmonic loading. The numerical studies showed a wide range of motions such as harmonic with the frequency equal to the excitation frequency, periodic with period-one and period-two, quasi-harmonic, and even chaotic. Super-harmonics were always observed in the frequency spectrum of the debonded plates, sometimes they were even the strongest harmonics in the spectrum. The appearance of period-two, quasi-harmonic and chaotic motions was explained by intermittent contact between the detached segments, it enables to produce new frequencies.
The fracture analysis illustrated that the interfacial debonding propagates in a stick-slip manner. It jump from one arrest position to another one depending on the existing dynamic stress state at the current instant of time. Herewith, the dynamic stress state combines incident and reflecting stress waves that were generated by both the external loads and due to intermittent contact between the detached skin and core. Moreover, the study demonstrated differences between transient and harmonically loading events that are evident in variation of interfacial crack-initiation and crack-propagation processes. It was found that these features are dependent on the stress distribution within the sandwich plate at different moments of time caused by the nonlinear dynamic response of the plate. Importantly, a loading rate plays not merely a parametric part in dynamics and failure of sandwich composites, but its increase is accompanied by a significant change in a character of evolution of damage modes and their interaction.

Conclusions

The study contains contributions related to dynamics and fracture of composite sandwich plates. It is important to notice that a transition from quasi-static loading regimes to dynamic ones in heterogeneous materials like sandwich composites is much more complex than in traditional metals or alloys. A presence of phases with various mechanical properties and interfaces affects the character of stress-wave propagation, resulting in complex spatiotemporal scenarios of damage and failure evolution.

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