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A SOLID SHELL ELEMENT WITH ROTATIONAL DEGREES OF FREEDOM FOR SANDWICH ANALYSIS

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Sandwich laminates consist of two thin, stiff, and strong face sheets separated by a thick, soft, and weak core. Classical laminate and first order shear deformation plate theories (CLT and FSDT), respectively, both relying on the assumption that perpendicular cross-sections remain plane in turn of deformation, are able to reproduce the global deformation pattern as well as the stress resultants of loaded sandwich structures quantitatively. However, the through-the-thickness distribution of stress and strain components, free edge effects, and local instability phenomena are not displayed correctly by these theories. These deficiencies become most relevant for strength analyses and layup optimization.

A number of laminate beam, plate, and shell theories have been proposed which take into account a sort of cross-sectional warping (sometimes called 'zig-zag' [ZZ] effect) together with inter-laminar transverse shear stress continuity [1]. These theories provide a more realistic stress distribution compared to CLT and FSDT. In addition, specific sandwich theories have been developed to reproduce sandwich-type deformation pattern such as wrinkling or dimpling of the face sheets. They rely on the assumption that the face sheets deform according to the Kirchhoff-Love theory whereas the whole transverse shear and normal deformation is absorbed by the core. A substantial simplification of the theory is achieved by the assumption of negligible in-plane stiffness of the core compared to the stiffness of the face sheets [3], [2]. An extended theory doing without this restriction has been given recently [4].

Due to the presence of second derivative of the deflection, finite element implementations of these theories require either a C^1 continuous interpolation or a mixed formulation. Both approaches come along with specific difficulties which make them hardly applicable in the context of complex finite element models of industrial relevance and of commercial codes. The present contribution describes an alternative formulation which is fully compatible with the architecture of conventional shell elements and exhibits the required functionality for three-dimensional sandwich strength analysis.

The new approach is based on a linear third-order shear deformation theory [5] involving a ZZ displacement and linear thickness stretching of the core. This gives rise to a piecewise quadratic and linear through-the-thickness dependence of transverse shear and normal stress components, respectively. The assumption of negligible in-plane core stiffness leads to constant shear stress components through the thickness of the core. Together with the boundary conditions and the inter-laminar continuity requirements for the transverse stress components it is possible to express the quadratic and cubic terms of the in-plane displacement field as well as the curvatures of the face sheets in terms of displacement components $u_x^{(l,u)}$, $u_y^{(l,u)}$, $u_z^{(l,u)}$ and rotations $\varphi_x^{(l,u)}$, $\varphi_y^{(l,u)}$, $\varphi_z^{(l,u)}$ of the lower (l) and upper (u) face sheet. This finding suggests to introduce a finite element discretization involving nodes located at the mid-surface of each face sheet to obtain an eight-node brick element where each node is equipped with six degrees of freedom (DOFs). Note that the rotational DOFs corresponding to in-plane rotations of the face sheets, which are not present in FSDT theories, are naturally supported by the torsional rigidity of the core.

The resulting solid-shell sandwich element applies for non-symmetric layups. It can be directly linked with conventional 6-DOF shell elements. Accordingly, sandwich ramps at the interface of monolithic and sandwich components can be represented by two layers of conventional shell elements, one linked with the lower, one with the upper face sheet, and with a common edge linked with the elements of the monolithic structure. The element has been implemented as an Abaqus user subroutine (UEL). Its industrial applicability in the context of large-scale models involving sandwich and monolithic laminates, as well as metallic components has been proven in the course of the design phase of the Airbus A350 winglet and, in particular, in combination with our in-house layup optimization procedure [6].

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