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A FEM SUB-LAMINATES APPROACH FOR PROGRESSIVE FAILURE ANALYSIS OF MULTILAYERED BEAMS

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ABSTRACT

The response of damaged multilayered structures is a topic of main importance because defects may lead to an abrupt reduction of their load carrying capacity. Delamination onset and growth are studied both using stress analysis and fracture mechanics; Virtual Crack Closure Techniques (VCCT) [1] and interfacial decohesion elements [2] (based on the Cohesive Zone theory, CZ) are the numerical approaches widely used nowadays. Structural models coupled with these techniques are based on “sub-laminates” (each thickness sub-domain due to interfacial damage); the interaction between upper and lower sub-laminates may be described adding very thin and weak layers (compliant layer), virtual spring elements or additional b.c.’s in the delamination front.

Among the approaches used to take into account these and other modelling issues (transverse anisotropy, high transverse deformability), a good compromise between accuracy and complexity is represented by layer-wise approaches with the number of unknowns not depending on the number of layers, as happens for zig-zag theories pioneered by Di Sciuva. A recent development of this approach is the Hermitian Zig-Zag (HZZ) plate theory [3], characterised by: (i) cubic in-plane and linear transverse displacements, (ii) transverse shear stresses continuity, (iii) satisfaction of traction equilibrium conditions on external faces, (iv) transverse normal deformability, (v) use, as degrees of freedom, of displacements and transverse shear stresses of external faces. This last property, applied to beam and plate finite elements, allows using the sub-laminates strategy and the modelling of different damage kinds [3]; in this work the coupling of the HZZ FEM approach for beams (Fig. 1) with the CZ theory is tested [4].

Let us imagine, for example, to consider a beam and to study the pure shear mode (II); the interfacial constitutive equations of the CZ theory describe the path 0-1-2-3-4-5 in the axial displacement jump (Δu) - interlaminar shear stress (τ) plane (Fig. 2). We briefly describe the different phases of the delamination process and how it is possible to model them into the HZZ FEM approach; we imagine to use two-sub-laminates and to focus our attention on the mid node shared by elements η and φ (Fig. 3). In the 0-1-2 segment (i) the delamination is not present; there is no axial displacement jump ($\Delta u = u_\varphi - u_\eta = 0$) and the shear stress may rise up to the corresponding limit (τ_{LIM}). The onset of delamination occurs at point 2; in the 2-3-4 segment (ii) a linear relation links the shear stress and the displacement jump ($\Delta u = f(\tau)$). When reaching point 4, (iii) total

debonding occurs ($\Delta u\neq 0$, $\tau=0$). The CZ theory may be related to Griffith's theory of fracture considering that the area under the shear stress – displacement jump relation is equal to the corresponding fracture toughness G_{IIC} [2]. In all the phases of the delamination process (i, ii and iii), the interface constitutive equations are linear relations among the nodal degrees of freedom of the HZZ FEM model; thus, there is no need of interface elements as in other approaches [2] to allow the interface constitutive equation being introduced in the analysis.

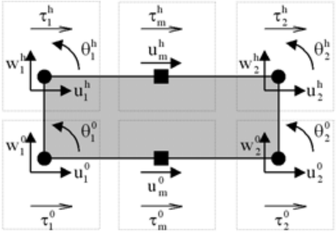

Fig. 1: HZZ beam finite element

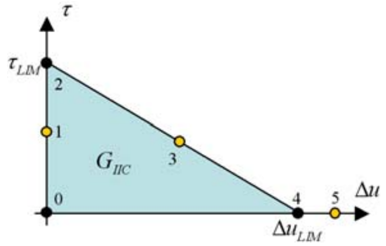

Fig. 2: Interface constitutive equations

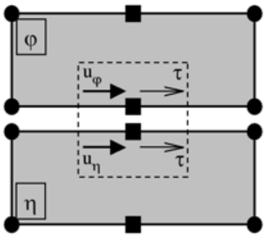

Fig. 3: Damaged mid-node

Some results of beam progressive failure analysis performed with the HZZ FEM model and the CZ procedure show the approach performances (Figs. 4 and 5). A comparison with analytic reference results is also considered [5]. The specimen is 102 mm-long, 25.4 mm-wide, with two 1.56 mm-thick 0° plies and initial delamination of length a_0=40 mm (two sub-laminates are used). Three models have been used to simulate the different tests: A - 61 el., 2 mm long, B - 102 el., 1 mm long, C - 204 el., 0.5 mm long. The material properties are E_1=123 GPa, E_2=E_3=10 GPa, G_{12}=G_{13}=5.5 GPa, G_{23}=3.7 GPa, ν_{12}=ν_{13}=0.25, ν_{23}=0.45, G_{IIC}=1.72 KJ/m^2, τ_{LIM}=105 MPa.

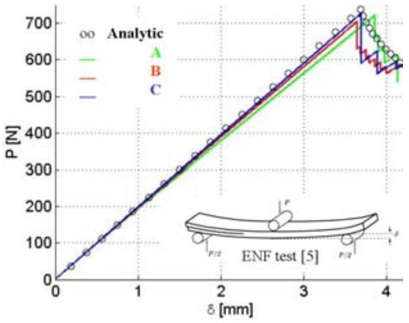

Fig. 4: ENF test numerical simulation

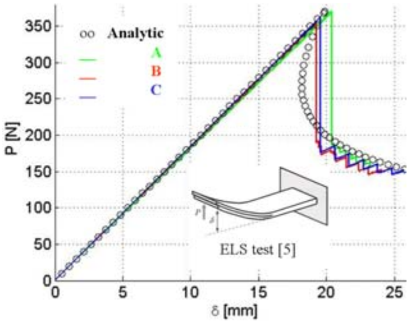

Fig. 5: ELS test numerical simulation

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