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The role of transverse stretching in the delamination fracture of softcore sandwich plates

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ABSTRACT

This paper presents the semi-layerwise analysis of structural sandwich plates with through-width delamination. The mechanical model of rectangular plates is based on the method of four equivalent single layers and the system of exact kinematic conditions. An important improvement compared to a previous formulation is the consideration of linear and quadratic stretching term in the transverse displacement component. Three different delamination scenarios are investigated: core-core failure, face-core delamination and the face-face failure. By applying the first- and second-order laminated plate theories and the principle of virtual work the governing equations are derived. The equilibrium equations are solved under Lévy type boundary conditions using the state-space approach. Solutions for the mechanical fields are provided and compared to 3D finite element results. The energy release rate distributions along the delamination front are also determined using the J-integral. Although the stress resultants by transverse stretching do not influence directly the J-integral, the results indicate that this effect improves the accuracy of the model in general, and substantially influences the results of the first-order plate theory in the case of the face-face delamination.

1. Introduction

Sandwich plates play important role in the industrial applications, such as airplanes, spaceships and satellites. The high stiffness and strength is an essential requirement to maintain the lifetime and durability of these structures. Sandwich plates are composed of facesheets and core [1]. Generally, facesheets are made either by advanced composite (e.g.:[2–5]) or metal plates [6]. The core of the sandwich structure might be constructed by honeycomb or other patterns made out of metals or plastics [7–10]. However, the simplest solution is the application of a some kind of foam [11–13]. Also, functionally graded materials are effectively used to construct sandwich beams and plates [14,15]. Delamination and cracking is a typical failure mode of laminated composite (e.g.:[16–18]) and sandwich structures [6]. This type of damage may be induced by low velocity impact [11,12,19–26], blast loading [27], drilling and perforation [28,29], indentations [30–32], manufacturing technology or other special loads [17,18,33,34]. The delamination or interlaminar fracture can be initiated or propagated under mode-I [35], mode-II [36], mode-III [37–39] and combined modes [40–43]. Moreover, for sandwich structures there are three possible scenarios of delamination position shown by Fig. 1: core-core (Scenario I.) means that the crack takes place in the core material, the face-core scenario (Scenario II.) refers to the delamination between any of two facesheets and the core material. Finally, the crack can appear within the facesheet providing the face-face scenario (Scenario III.) [6].

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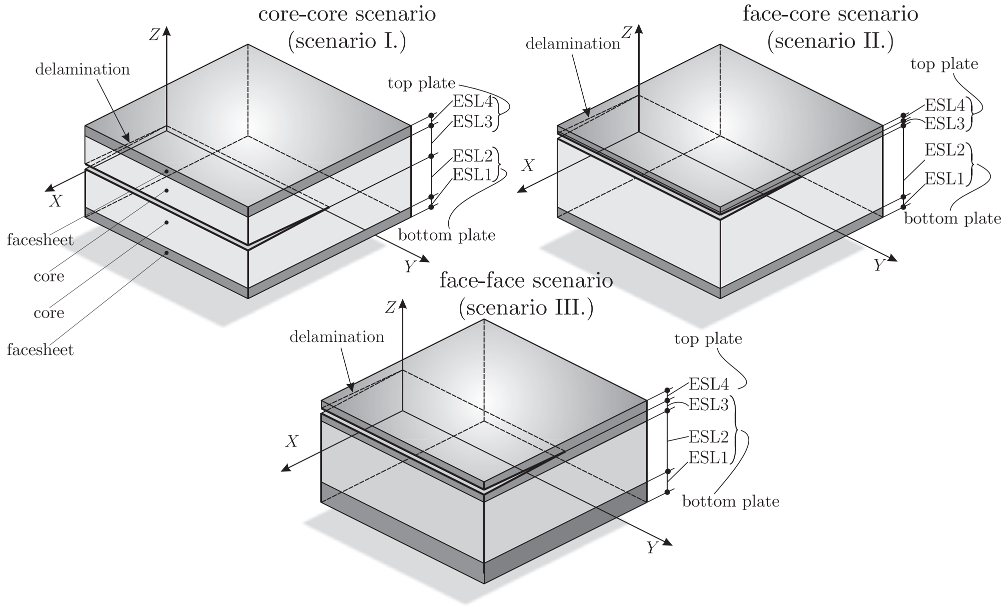

Fig. 1. Sandwich plate elements with orthotropic core and facesheets and the position of delamination over the thickness.

The literature offers numerous plate theories to create mechanical models for such structures. The classical laminated plate theory (CLPT or Kirchhoff plate theory) [6,44] *can be applied* only to sandwich plates *undergoing* membrane stress state. The first-order shear deformable (FSDT) plate theory is based on the independent rotation and deflection functions providing a piecewise constant shear stress distribution over the plate thickness [45–47]. In the past numerous higher-order models have been developed for composite and sandwich plates including the elasticity solution [6,48], higher-order and layerwise theories [49–54] and zig-zag theories [55–58]. These theories are also applicable to free vibration and buckling problems [29,55,59–72], to develop finite element (FE) models and types [73–78] moreover to solve issues related to non-linear effects [79–81], transient dynamic analysis [82–85], dynamic stability [86], deformation analysis of test specimens [87] and functionally graded core materials [88–96].

The papers and works mentioned so far deal with perfect sandwich structures without material defects. Alternatively, if delamination is considered, then only its global effect on the stiffness reduction was considered [97–99]. The cracks and delaminations induce significant perturbations in the mechanical fields. Apparently this is a case when higher-order plate theories are required to obtain accurate results locally in the vicinity of the delamination front. In some previous works the layerwise models have been developed for delaminated composite plates using the FSDT [100], second-order shear deformation plate theory (SSDT) [101,102], third-order shear deformation plate theory (TSDT) [103] and Reddy TSDT [104,105]. First, the plates were divided into two halves in the delamination plane and the equilibrium equations were developed separately for the top and bottom halves. This solution is called the method of 2ESLs. Later the model was refined and four ESLs were created over the plate thickness [106,107]. The method of 4ESLs (or the semi-layerwise model) results in a significantly better accuracy of the stresses and energy release rates than the method of 2ESLs if the delamination takes place near the boundary surface of the plate.

The aim of the present work is develop an improved semi-layerwise (method of four ESLs) model for delaminated soft-core sandwich structures using the first and second-order shear deformation theories (FSDT and SSDT). In a previous paper the FSDT, SSDT and TSDT theories were applied to analyze delaminated sandwich plates [108], however the transverse stretching was not taken into account. Three different scenarios were considered in accordance with Fig. 1. Scenario I.: core-core failure, Scenario II.: face-core failure and Scenario III.: face-face failure. It was shown that the SSDT and TSDT theories perform with good accuracy for all scenarios [108]. On the other hand the FSDT solution is able to produce reasonably accurate results for Scenarios I. and II., but fails in Scenario III. The failure of FSDT is devoted to the lack of transverse stretching effect.

The novelty of this paper is that the transverse normal strain is captured by linear and quadratic stretching terms in the assumed displacement field *of the first and second-order plate theories*. This effect is considered to be important in softcore sandwich structures.

2. Semi-layerwise laminated plate theory - the method of four ESLs

Fig. 2 shows the deformation of cross sections in the $X-Z$ plane of the delaminated sandwich plate if the core-core scenario is considered. The cross sections in the $Y-Z$ plane are represented in Fig. 3. The whole sandwich plate is modeled by