Localised Effects in Sandwich Structures – Load Response, Failure and Fatigue

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Abstract. The objective of the paper is to provide an overview of the mechanical effects, which determine the occurrence and severity of localized bending effects in sandwich structures, and, in addition, to provide a survey of the available structural sandwich models, with special emphasis on their ability to describe local bending effects. Moreover, the paper will focus on and address the experimental characterisation and assessment of local effects in sandwich structures based on realistic engineering practice examples including sandwich panels with core materials of different stiffness (core junctions) and junctions between sandwich panels of different curvature. The issues of general load response (global and local) as well as failure and fatigue of such sandwich structures subjected to out-of-plane and in-plane loads are discussed in some detail, with the inclusion of recent theoretical and experimental results

Introduction

Sandwich structures are notoriously sensitive to failure by the application of concentrated loads, at points or lines of support, and due to localized bending effects induced in the vicinity of points of geometric and material discontinuities [1, 2]. The reason for this is that, although sandwich structures are well suited for the transfer of overall bending and shearing loads, localized shearing and bending effects, as mentioned above, induce severe through-thickness shear and normal stresses. These through-thickness stress components can be of significant magnitude, and may in many cases approach or exceed the allowable stresses in the core material as well as in the interfaces between the core and the face sheets [2]. In addition, localized bending effects may induce in-plane stress concentrations in the face sheets, which, depending on the loading situation and the boundary conditions, may exceed the “globally” induced stresses, and thereby seriously endanger the structural integrity. The majority of failures in sandwich structures, due to either static overloading or fatigue loading conditions, are caused by localized effects as described above [2].

Accordingly, it is of utmost importance to develop physically consistent models that enable accurate assessment of the local stress and strain fields in the vicinity of geometric and material discontinuities in sandwich panels. Moreover, it is necessary to develop methods and methodologies that enable assessment of the effects of the locally induced stresses/strains upon the structural integrity under quasi-static and fatigue load conditions.

In the following an overview of the available structural sandwich models will be given, with special emphasis on their ability to describe local bending effects. Moreover, the experimental characterisation and assessment of local effects in sandwich structures will be discussed based on realistic engineering practice examples including sandwich panels with core materials of different stiffness (core junctions) and junctions between sandwich panels of different.

Analysis of sandwich structures – survey and discussion

There are several suggestions for the development of theories for the analysis of sandwich panels. The simplest approach is to use the classical laminated plate theory (CLT) based on the classical Love-Kirchhoff assumptions, as described by e.g. Whitney [3] and Jones [4]. A more refined approach includes transverse shear effects, and was suggested by Reissner [5] and Mindlin [6] who assumed a linear through-thickness distribution of the in-plane displacements, and a uniform through-thickness distribution for the transverse displacements (first-order shear theory). The Reissner-Mindlin approach is suggested in the monographs of Vinson and Sierakowski [7], for the analysis of general laminated composites, and Vinson [1] for the analysis of sandwich structures.

A special class of so-called "antiplane" plate theories has been developed for the analysis of sandwich structures. The features of the "antiplane" sandwich theories are summed up in the monographs by Zenkert [2] and Librescu [8]. The term "antiplane" is equivalent to the terms "weak" or "compliant", and is used to describe an idealized sandwich core in which the stretching and shearing stiffnesses in planes parallel with the sandwich panel face sheets are zero, but where the shear modulus perpendicular to the face sheets is finite.

Neither of the Love-Kirchhoff, Mindlin-Reissner or "antiplane" plate theory formulations include the trough-thickness (or transverse) flexibility. Consequently, they cannot account for localized bending effects where the face sheets tend to bend about their own middle plane, and where the thickness of the sandwich plate assembly may change during deformation.

High-order theories have been proposed by among others Lo et al. [9], Stein [10], Reddy [11,12] and Savoia et al. [13]. In these references, high-order through-thickness displacement fields in the form of polynomials of varying order or trigonometric series are assumed a priori. One particular feature of high-order theories based on polynomial displacement distributions that are assumed a priori is that, in some formulations, terms appear in the governing equations, as well as in the boundary conditions, which are difficult to attribute any physical meaning. A special high-order formulation for the analysis of symmetric sandwich plates was suggested by Librescu [8] which includes the presence of transverse normal stresses in the core material. The transverse flexibility is not included in the formulation, however, thus ignoring the effects associated with changes of the plate/panel thickness.

Frostig et al. [14-15] have developed a high-order theory especially adapted for sandwich panels with soft/compliant cores. In this particular formulation, no restrictions on the through-thickness displacement distributions are imposed a priori. The formulation includes the transverse flexibility of the core material, thus enabling the description of localized bending effects associated with local changes of the sandwich panel thickness. The high-order sandwich theory was validated experimentally by Thomsen and Frostig [16].

In the following, a brief presentation of survey of recent developments regarding the formulation and application of high-order sandwich models will be presented based on realistic engineering practice examples. See also the review paper by Thomsen et al. [17].

Sandwich panels with core junctions

The use of core materials of different densities in sandwich panels, as shown schematically in Fig. 1, is common practice in many branches of industry utilising composite materials and sandwich structures. Such changes of core density/stiffness do not significantly affect the overall stiffness of the sandwich structure and the overall load response, but they do improve the structural performance with respect to parameters/quantities such as the shear strength and/or the resistance against local indentation. However, junctions between cores of different density/stiffness cause the formation of locally induced additional stresses in the vicinity of the material or geometric discontinuities. The local stresses may be comparable or even exceed the global stresses in the sandwich constituents, and this may lead to premature failure of the whole sandwich assembly.

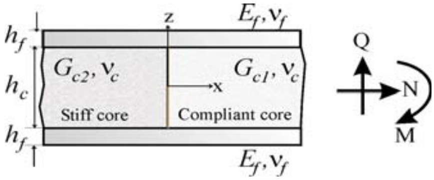


Figure 1. Schematic illustration and geometric definition of core junction in sandwich panel

The local effects induced near junctions between different cores in sandwich panels may be analysed using Finite Element Analysis (FEA) [18], high-order sandwich theory [14-16] or the special high-order analytical model developed on the basis of the 2-D theory of elasticity by Skvortsov and Thomsen [19]. The latter provides closed-form solutions for all the locally induced stresses in the vicinity of material discontinuities. A brief presentation of the theoretical model [19] is given in [20], which also includes an experimental validation of the model. In essence, the proposed high-order model appears as a 3rd order shear plate theory, which is asymptotically exact.

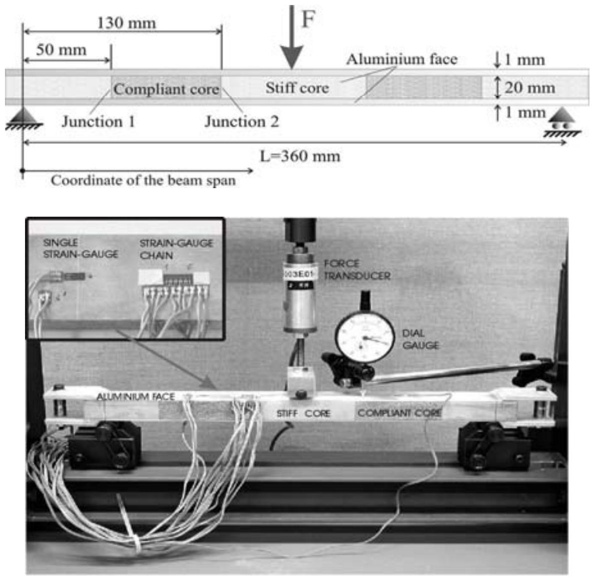


Figure 2. Sandwich beam with two different cores loaded in the three-point bending
(Top: Layout & Bottom: Experimental set-up) [20].

The presence of material/geometric discontinuities causes the inducement of local stresses in all the sandwich constituents. These local stresses consist of normal stresses in the faces and transverse normal and shear stresses in the core. It is important to mention in this context, with reference to [19,20] for details, that the local effects (expressed in terms of stresses or strains) can be shown to be proportional to the global shear stress resultant at the junction between the different cores. In addition, the local effects are proportional to the ratio of the elastic shear moduli of the adjacent core materials (i.e $G_{compliant\ core}/G_{stiff\ core}$). According to the model, the closed-form estimates of the local face and core stresses can be expressed in the form:

$$\begin{aligned}\sigma_f &= \tau_0 f_1\left(\sqrt{G_{compliant\ core}/G_{stiff\ core}},\ param\right)\\ \sigma_c &= \tau_0 f_2\left(\sqrt{G_{compliant\ cor}/G_{stiff\ core}},\ param\right)\\ \tau_c &= \tau_0\left(1+f_3\left(\sqrt{G_{compliant\ cor}/G_{stiff\ core}},\ param\right)\right)\end{aligned} \quad (1)$$

where f_1, f_2 and f_3 are known functions depending on the mechanical and geometrical parameters of the sandwich constituents and the in-plane coordinate x measured along the panel length. f_1, f_2 and f_3 attain their extreme values exactly at the core junction, and vanish at some characteristic distance away from it. The ratio $(G_{compliant\ core}/G_{stiff\ core})^{1/2}$ defines the amplitude of the local stresses (the larger shear moduli ratio the larger the local stresses).

To experimentally characterise the local effects induced near core junctions, a simply supported sandwich beam assembled with two different PVC foam core materials (Divinycell H60 and H200), and subjected to central load as shown in Fig. 2, has been considered. The beam width was 40 mm, and the remaining geometric parameters are indicated in Fig. 2. An experimental investigation of the face strain distributions was performed using the experimental set-up shown in Fig. 2. The face strains across the core junction were measured using strain-gauge chains (see zoomed area in Fig. 2) placed at the outer surface of the face as well as at the face-core interface. Each chain consisted of five 1 mm long strain gauges placed with a mutual distance of 2 mm.

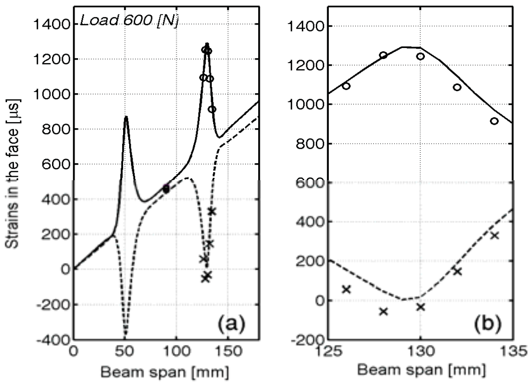


Figure 3. (a) Normal strains in the bottom face (half of span) of sandwich beam loaded in the 3-point bending with F=600 N; (b) Zoom at junction 2 (see Fig. 1). The model results are shown by solid and dashed lines for the outer and inner surfaces of the face, respectively (**O**: Experimental data outer surface; **X** : Experimental data inner surface) [20]

The experimentally obtained strains in the beam face are illustrated in Fig. 3, together with the corresponding theoretical estimates [19, 20], and it is seen that the accuracy of the proposed high-order model is very good. In addition to the severe local bending effects induced in the faces, stress peaks in the form of transverse stresses and shear stresses are induced in the vicinity of the core junction. For this particular sandwich configuration tensile transverse normal stresses (peel stresses) and shear stresses are induced along the top face-core interface, and the combination of these stresses will in some case cause the initiation of debonding, which in turn may lead to progressive delamination and failure of the entire sandwich assembly.

The closed-form high-order model can be used successfully for the prediction of the magnitude and extension of local effects in sandwich panels with material/geometrical discontinuities in the form of core junctions. For more details concerning the modelling, experimental characterisation and failure due to static and fatigue loads (transverse shear, bending and in-plane loads) see [19,20], Bozhevolnaya et al. [21-23], Thomsen et al. [24], Jakobsen et al. [25] and Johannes et al. [26].

Local effects in sandwich structures induced by changes of curvature

Local effects in sandwich structures may be caused by localised loads, changes of stiffness or changes of geometry. The geometrical change of a straight sandwich panel into a cylindrically curved sandwich panel loaded in shear of bending represents a simple case of the latter. A model case of this is shown in Fig. 4, but the localised bending problem associated with change of curvature is highly realistic and often experienced in practical sandwich structures, e.g. in ship hull structures, wind turbine blades and sandwich tank structures to mention a few [17].

The physical mechanism causing the occurrence of localised effects in this case is associated with the fact that the straight sandwich panel part will tend to deform without change of sandwich panel thickness, whereas a change of panel thickness is an inherent part of the load response of the curved sandwich panel part subjected to external bending or shear loading (see Fig. 4). The localised bending problem associated with a change of curvature in sandwich panels was treated by Lyckegaard and Thomsen [27, 28]. A numerical investigation was conducted in [27] where a geometrical non-linear high-order sandwich model was adopted to capture the thickness change effects, which govern this problem. In continuation of this, the results of an experimental investigation based on Electronic Speckle Pattern Interferometry (ESPI) are presented in [28].

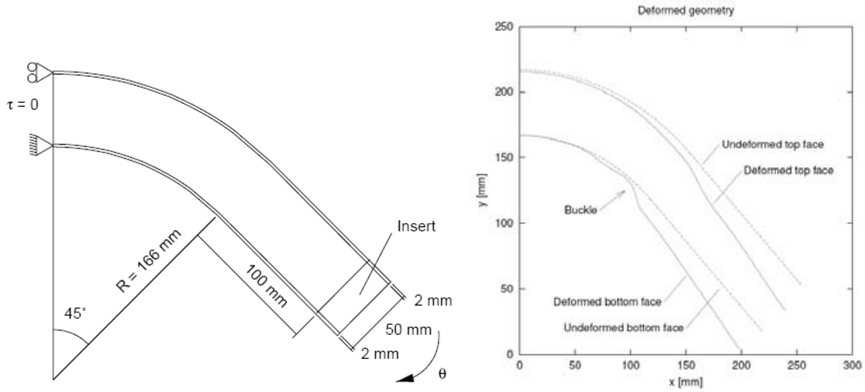


Figure 4. Left: Modelled curvature junction. Right: Geometry of the face mid surfaces in undeformed and deformed ($\theta \approx 0.16$ rad) configurations [27]

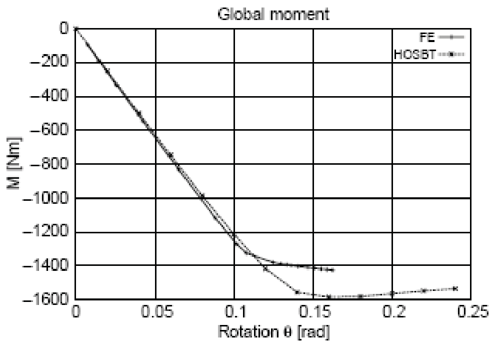
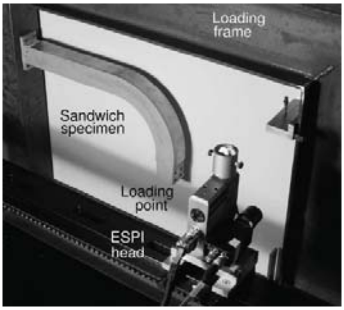


Figure 5. Global moment vs. prescribed deformation (rotation θ). Dashed line: Geometrical non-linear high-order sandwich beam theory. Solid line: Non-linear Finite Element Analysis results [27].

Localised effects associated with curvature change induce severe local stress concentrations in the faces and the core, including transverse normal stresses in the core near the point of curvature change. Geometrical non-linearity plays a major role in this problem, as the lower face "buckles" locally under the external bending moment loading depicted in Fig. 4. The predicted load response curve, i.e. applied bending moment vs. deformation (rotation θ), is shown in Fig. 5. It is seen that the sandwich assembly looses all stiffness at a certain value of the applied bending moment, and the structural response is characterised by "limit point" behaviour at that load level. The local "buckle" displayed in Fig. 4 (right) for the lower face in the deformed state corresponding to $\theta \approx 0.16$ rad signifies this "limit point". Under controlled/prescribed loading, the sandwich assembly will loose structural integrity (collapse) at this level of loading, as a "snap through" is the most likely event to follow when the "limit point" load is exceeded (see Fig. 5). The formation of the local "buckle" as well as the "limit point" behaviour predicted by the non-linear models (proposed high-order and FEA models) is inherently associated with non-linear interactions due to the thickness change of the sandwich panel near the junction and the geometric non-linearities (rotations).



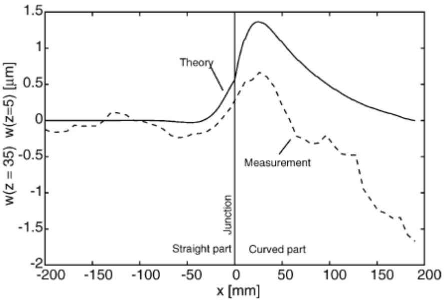


Figure 6. ESPI set-up and measured changes of thickness of the sandwich panel specimen. The junction is located at x=0 [28].

To validate the model predictions based on the non-linear high-order sandwich theory (and the FEA results), an experimental investigation was conducted. As the thickness changes are very small it was chosen to apply Electronic Speckle Pattern Interferometry (ESPI), which is a very sensitive non-contact full field measuring technique [28]. Fig. 6 shows the ESPI setup as well as the measured and predicted changes of sandwich panel thickness. The junction is located at x=0. The thickness change of the straight part is predicted to be zero, which is in reasonable agreement with the measurements although some waviness is seen in the measurements. It is important to note here that the maximum change of thickness is about 1.5 µm, which corresponds to the sensitivity of the ESPI technique. Near the junction there is a significant change of thickness, and this leads to local bending of the face sheets. In the curved part the two datasets seem to diverge towards the end of the sandwich panel, which suggests that the boundary conditions used in the numerical model do not correspond exactly to the boundary conditions imposed in the experimental set-up. However, the overall trends of the measured and predicted thickness changes are very similar.

The results show that there is good correlation between the experimental data and the result obtained through the modelling. Thus, the results generally show good agreement within the accuracy of the measurements, thereby indicating that the gross response of the model is predicted accurately by the high-order sandwich theory. Moreover, the results verify that local bending effects may be significant in the vicinity of curvature changes in sandwich structures.

Summary

The paper presents a brief discussion and overview of localized effects in sandwich structures. It is argued that localized effects are inherently associated with the presence of geometrical and material discontinuities, and, that the presence of localized effects may prove detrimental for the structural integrity and durability of sandwich structures. The mechanical effects causing the formation of localized effects are discussed, and it is argued that the occurrence and severity of localized effects can only be predicted accurately if the through-thickness flexibility is included in the modelling. Several such high-order sandwich models are discussed. Moreover, the paper addresses the experimental characterisation and assessment of local effects in sandwich structures based on realistic engineering practice examples including sandwich panels with core materials of different stiffness (core junctions) and junctions between sandwich panels of different curvature. It is demonstrated that severe local effects are present in both cases, and that the predictions of proposed high-order models compare well with the experimental measurements.

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