LOCALIZED EFFECTS IN STRUCTURAL SANDWICH PANELS: PRACTICAL OCCURRENCE, ANALYSIS AND DESIGN

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ABSTRACT

The objective of the present paper is to provide an overview of the mechanical effects, which determine the occurrence and severity of localized effects in sandwich panels, and, in addition, to provide a survey of the available structural sandwich models, with special emphasis on their ability to describe local bending effects. The paper includes a brief presentation of the various structural models, including classical, "first-order shear", "high-order", and continuum mechanics based models. Recent developments regarding the formulation and application of especially the later two classes of models are presented based on realistic engineering practice examples including sandwich panels with core materials of different stiffness (core junctions), and sandwich panels with rigid inserts. The issue of failure is discussed in some detail, with the inclusion of recent theoretical and experimental results.

1. INTRODUCTION

Structural sandwich panels can be considered as a special type of composite laminate where two thin, stiff, strong and relatively dense face sheets, which may themselves be composite laminates, are separated by a thick, lightweight and compliant core material. Such sandwich structures have gained widespread acceptance as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength and high buckling resistance [1-5].

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 [5]. 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 [5].

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 vast majority of failures in sandwich structures, due to either static overloading or fatigue loading conditions, are caused by localized effects as described above [5].

Accordingly, it is of utmost importance, from a scientific as well as an engineering practice point of view, 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 effect of the locally induced stresses/strains upon the structural integrity under quasi-static and fatigue load conditions.

2. ANALYSIS OF SANDWICH PANELS – 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 [6] and Jones [7].

A more refined approach includes the transverse shear effects, and was suggested by Reissner [8] and Mindlin [9] 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 [10], 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 Plantema [2], Allen [3], Stamm and Witte [4] and Zenkert [5]. 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 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 plate assembly may change during deformation.

Higher-order theories have been proposed by among others Lo et al. [11], Stein [12], Reddy [13,14] and Savoia et al. [15]. In these references, high-order through-thickness displacement fields in the form of polynomials of varying order or trigonometric series are assumed a priori. All of the quoted high-order theories use integration through the thickness, along with a variational principle to derive the governing equations and the appropriate boundary conditions. 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 [16], including 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 thickness.

Frostig et al. [17-18] 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, and the high-order effects predicted by the theory are results of the formulation. 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, as applied for the analysis of 3-layer sandwich beams with soft/compliant cores, was validated experimentally by Thomsen and Frostig [19].

In the following, a brief survey of some recent developments regarding the formulation and application of "high-order" sandwich models will be presented based on realistic engineering practice examples including sandwich panels with core materials of different stiffness (core junctions), and sandwich panels with rigid inserts.

3. SANDWICH PANELS WITH CORE MATERIALS OF DIFFERENT STIFFNESS

The use of core materials of different densities in sandwich panels, as shown schematically in Fig. 1, is common practice in many branches of composites industry [20]. Such changes of core density/stiffness do not significantly affect the overall stiffness of the sandwich structure and the overall load response, but it does 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 elastic discontinuities. The local stresses may be comparable or even exceed the global stresses in the sandwich constituents, and this may endanger the structural integrity of the whole sandwich assembly.

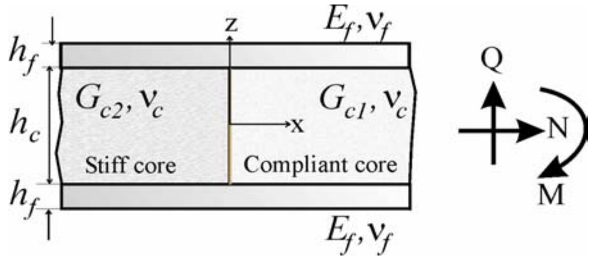


Fig. 1. Schematic illustration and geometric definition of core junction in sandwich panel.

The local effects induced near junctions between different cores in sandwich panels may be analysed using the finite element method (FEM) [21], high-order sandwich theory [17-19] or the special high-order analytical model developed on the basis of the 2-D theory of elasticity by Skvortsov and Thomsen [22]. 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 [22] is given in [23], 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.

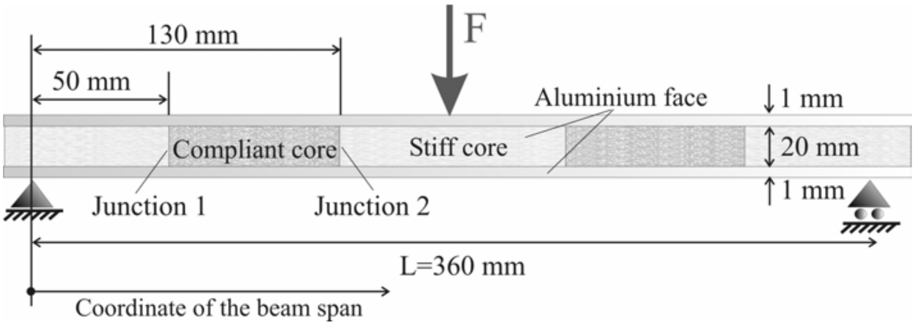
The presence of material/elastic discontinuities cause the inducement of local stresses in all the sandwich constituents. These local stresses consist of normal stresses in the faces and transverse normal and shear stresses in the core. It is important to mention in this context, with reference to [22,23] for details, that the local effects (expressed in terms of stresses or strains) can be shown to be proportional with the global shear stress resultant at the junction between the different cores. In addition, the local effects are proportional with the degree of elastic dissimilarity of the adjoined materials, expressed in terms of the ratio G_{core}/G_{insert}. According to the model, the closed-form estimates of the local face and core stresses can be expressed in the form:

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

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. The functions f_1, f_2 and f_3 display their extreme values exactly at the core junction, and vanish at some characteristic distance from it. As mentioned, the ratio of the core shear moduli $(G_{core}/G_{insert})^{1/2}$ defines the quantitative level of all the local effects, i.e. the larger the disagreement between the elastic properties of the adjoining materials the larger the locally induced stresses. It is emphasized that the closed-form analytic estimates are only valid for the case of a butt junction.

In order to demonstrate the nature of the stresses induced locally near core junctions, a simply supported sandwich beam assembled with two different core materials, and subjected to central load as shown in Fig. 2, has been considered. The beam width is 40 mm, and the remaining geometric parameters are indicated in Fig. 2. The elastic properties of the sandwich beam constituents are given in Table 1.

Fig. 3 shows the distributions of the stresses in the face and the core near core junction 2 (see Fig. 2) obtained using the analytical model proposed in ref. [22,23]. Note that the stresses are tensile in the bottom face (Fig. 3(a)). In the top face, the stress distribution is similar but with opposite sign, since the top face is in compression (see Fig.2). The pure bending stress in the face at the location of the junction equals 49 MPa according to classical sandwich theory [1-5]. The proposed solution, which accounts for the localised effects, shows that the face stresses varies significantly through the face thickness; from 12 MPa at the face-core interface to 86 MPa at the free surface of the beam. This phenomenon is rather important to account for in the design phase. For instance, when designing sandwich structures with carbon fibre composite faces (CFRP), it is well known that the compressive strength of CFRP materials may be as much as three times lower (numerically) than the tensile strength [6,7].

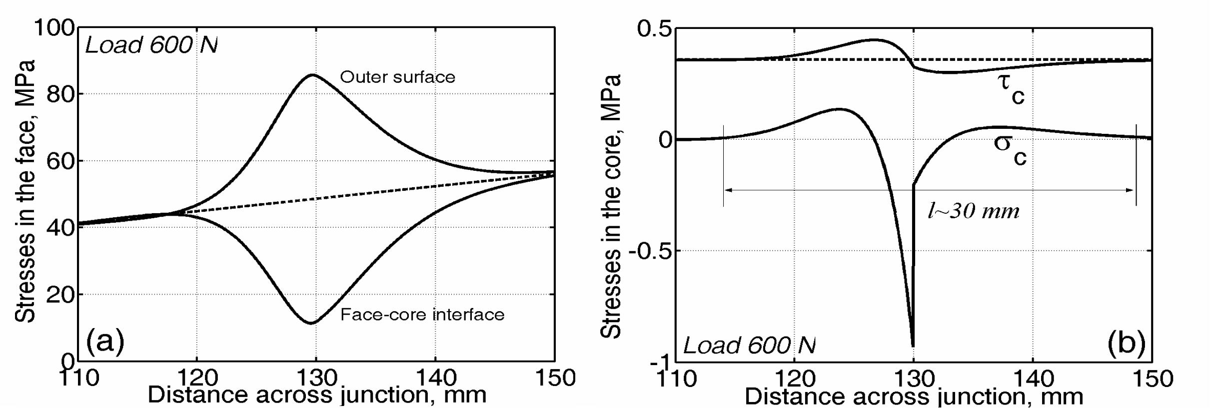


“**Fig. 2.** Sandwich beam with two different cores loaded in the three-point bending.”

“**Table 1.** Data of the sandwich beam with core junctions shown in Fig. 2.”

Sandwich constituents	Young´s Modulus [MPa]	Shear modulus [MPa]	Strength [MPa]
Faces: Aluminium, 2024-T6	$70{\cdot}10^3$	-	σ_y=340
Compliant core: Divinycell® PVC H-60	60[a]	22	$\sigma_{\text{tens/comp}}$ =1.6 / 0.8 τ_y =0.7
Stiff core: Divinycell® PVC H-200	310[a]	103	$\sigma_{\text{tens/comp}}$ =4.8 / 4.5 τ_y =3.3

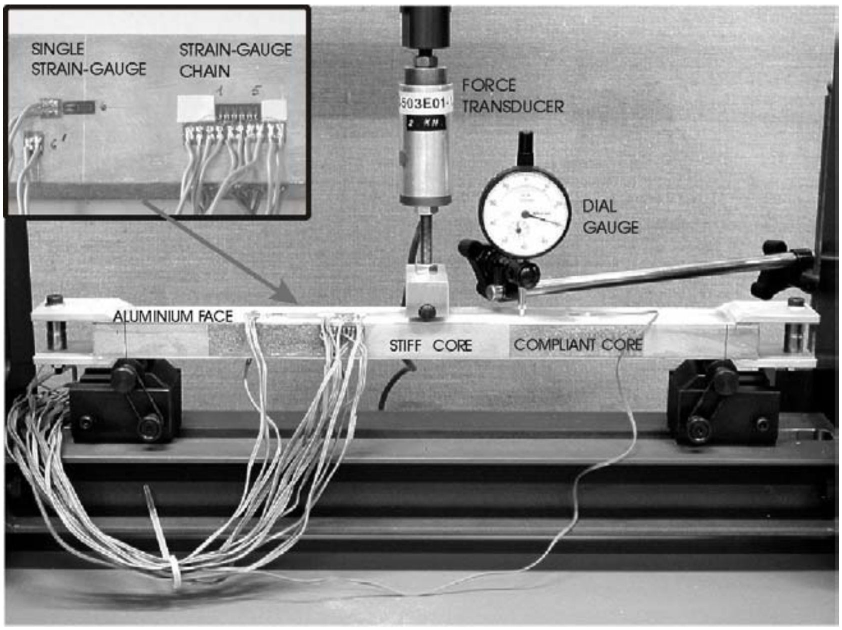
[a] - compressive modulus



“**Fig. 3.** (a) Tensile normal stresses in the bottom face of the beam near junction 2 (see Fig. 2). The dashed line represents the global stress at the centroid of the face due to pure bending. (b) Distributions of transverse normal and shear stresses along the lower face-core interface near junction 2 (see Fig. 2). The dashed line corresponds to the constant shear stress.”

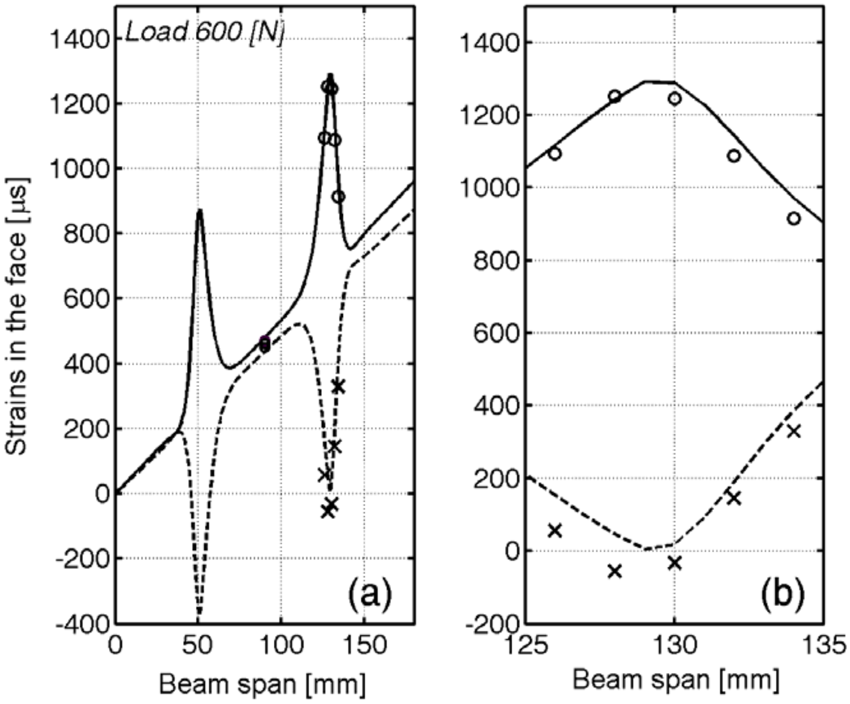
It is emphasized that classical sandwich theories [1-5] cannot account for the presence of transverse normal stresses in the core, and that these theories predict the core shear stresses to be constant through the core thickness. Fig. 3(b) demonstrates that for the given central load of 600 N, the transverse normal stress at the junction reaches a value of about 1 MPa, which is comparable with the compressive strength of the cores (Table 1). At the lower face-core interface the transverse normal stress is compressive, while it is tensile at the upper interface. The presence of non-zero transverse normal stresses as well as the variation of the core shear stresses will in many cases significantly degrade the structural performance under dynamic and fatigue load conditions. Another important information, which follows explicitly from the modelling [22,23], is that the local effects occurs within some characteristic length which is also illustrated in Fig. 2(b) ($l \approx 30$ mm).

An experimental investigation of the strain distributions in the faces of the tested sandwich beam was performed using the experimental set-up shown in Fig. 4.



“**Fig. 4.** Experimental set-up for the investigation of the local effects in the faces of sandwich beam loaded in three-point bending.”

The loading of the beam was achieved using a step motor (not shown in the figure), and the applied load was monitored by means of a calibrated force transducer. The strains in the face across the core junction were measured using strain-gauge chains (see zooms in Fig. 4). These were placed not only at the outer surface of the face, but also at the face-core interface. Each chain consisted of five 1 mm long strain gauges placed with a mutual distance of 2 mm.



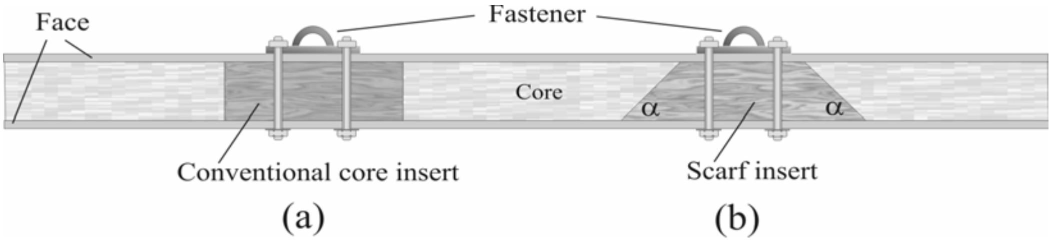
“**Fig. 5.** (a) Normal strains in the bottom face of sandwich beam loaded in the three-point bending with F=600 N. (b) Zoom at junction 2 (see Fig. 1). The theoretical estimates are shown by solid and dashed lines for the outer and inner surfaces of the face, respectively. The experimental data are indicated by **O** and **X** for the outer and inner surfaces, respectively.”

The experimentally obtained strains in the beam face are illustrated in Fig. 4, together with the corresponding theoretical estimates [22, 23], and it is seen that the accuracy of the theoretical modelling is very good. Thus, the proposed 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.

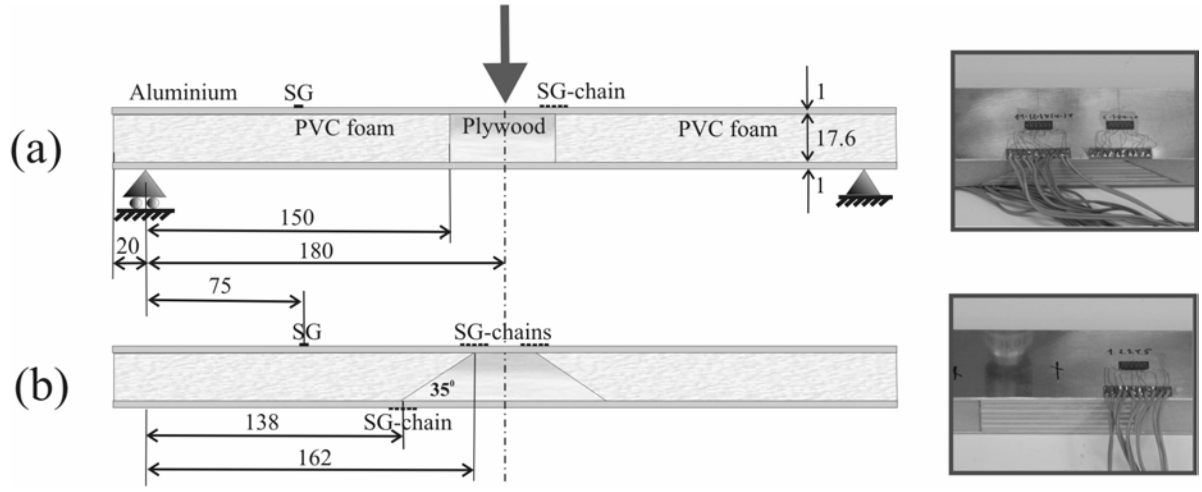
4. CORE INSERTS IN SANDWICH PANELS

The practical functionality of sandwich structures is inherently associated with the possibility of joining them with other structural parts, and, in addition, with the introduction of fasteners for the attachment or rigging of different appliances [20,24-26]. This implies the inducement of localized/concentrated loads to which sandwich structures are notoriously sensitive, as described in chapter 1. A practical method of redistribution of concentrated loads to a larger area is to use so called stiffeners or reinforcing/backing plates [20,27,28]. A variety of different terms is used in this connection. In this paper the term *core insert* is adopted to denote a piece of a stiffer core, plywood, wood, polymeric material, metal or the like, which substitutes a part of the original core in the sandwich panel with the purpose of achieving a local reinforcement.

The purpose of using core inserts is to facilitate the transmission of external loading (via normal and shear stresses) through the thickness of the sandwich panel without siginificant impairment of its structural integrity. However, any inclusions in a sandwich panel bring about material discontinuities, which inevitably results in local effects near the discontinuities similar to those discussed in chapter 3. Due to the significant difference in the elastic properties of the reinforcing insert and surrounding core, the locally induced stresses will be quite high if a conventional insert design (Fig. 6(a)) is adopted. Instead, a structurally graded core insert is suggested as shown in Fig. 6(b). The idea behind this new design of core inserts is to reduce the local effects in the sandwich assembly.



“**Fig. 6.** (a) Butt insert – conventional design of a core insert. (b) Scarf insert – structurally graded core insert.”



“**Fig. 7.** Geometry of sandwich beams used for the three-point bending tests: (a) beam with butt insert; (b) beam with the scarf insert. The zooms on the inserts show the positioning of the strain gauge chains on the faces across the core junctions.”

In the following, the conventional type of insert is called a *butt insert*, while the new type of insert is called a *scarf insert*, in accordance with the terminology adopted in the technical literature in relation to composite structures [20,25]. It is emphasized, that the in-plane shape of the insert may be rectangular, circular or any other practical contour.

To demonstrate the applicability and efficiency of the suggested design of core inserts, with respect to reducing/diminishing the presence of local effects in the sandwich faces, two sandwich beams, of width 40 mm, were manufactured for experimental investigation and subsequent Finite Element Analysis (FEA). The two sandwich beams, which are shown in Fig. 7, were made with aluminium faces and Divinycell H130 PVC foam core. The first beam was manufactured with a conventional birch plywood insert, while the second beam contained a scarf insert made of the same material. All beam constituents were joined using epoxy resin. The mechanical properties of the beam constituents are given in Table 2, whereas the geometrical parameters of the sandwich beams is defined in Fig. 7.

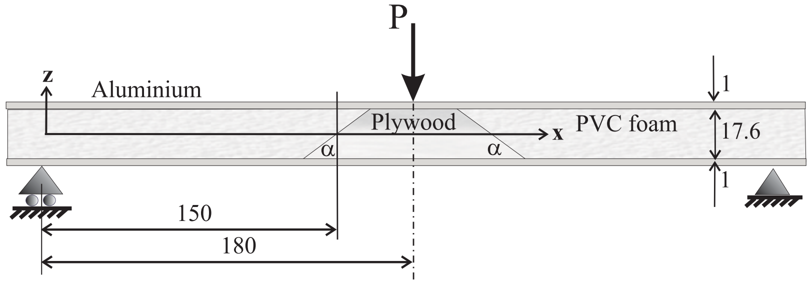
“**Table 2.** Mechanic parameters of the constituents of the sandwich beams with inserts.”

Sandwich constituents	Young´s Modulus [MPa]	Shear modulus [MPa]	Strength [MPa]	Poisson’s ratio
Faces: Aluminium, 7075-T6	70.000	-	$\sigma_y = 340$	0.32
Core: PVC, Divinycell H130	175	57	$\sigma_{tens/comp} = 3.4/2.6$ $\tau_y = 1.8$	0.32
Insert: Birch plywood	7070^1 1130^2	530^a 130^b	$\sigma_y = 31$	

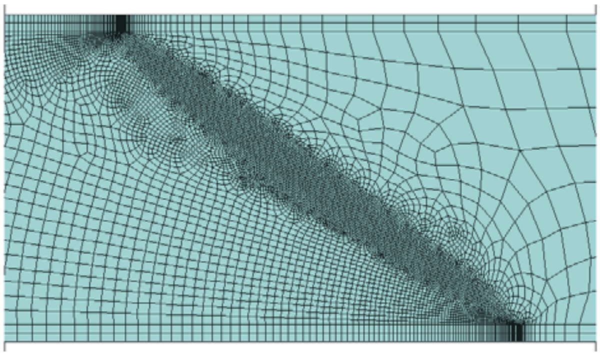
^{a} – in-plane characteristics ^{b} – transverse characteristics

As mentioned in chapter 3, the shear stress resultant determines the level/magnitude of the local effects across core junctions [22,23]. This substantiates the choice of the three-point bending scheme for the experimental study. This particular loading configuration (indicated in Fig. 7(a)) provides a constant shear stress resultant across the left and right halves of the centrally loaded beam. Both beams were furnished with strain gauge chains positioned across the junctions between the core and the plywood at the outer surfaces of the beam faces (see details in Fig. 7). Each chain consisted of five 1 mm long strain gauges placed with a mutual distance of 2 mm.

(a)



(b)



“**Fig. 8.** Detail of FE-mesh used for the analysis of sandwich beam with scarf insert”

The numerical analyses of the stress and strain states of the tested sandwich beams were carried out using the commercial FEA software package ANSYS. The faces and the primary core were modelled as linear elastic isotropic materials, while the plywood was modelled as a linear elastic and transversely isotropic material (see Table 2 for material properties). In the FEA model, 2D plane strain assumptions were adopted. The aluminium faces were represented by two layers of 8-node isoparametric elements. The core and insert were modelled using approximately 11,000 elements, where the characteristic size of the mesh near the junction was about *0.05 mm*. Due to symmetry of the beam geometry and external loading, only the right half of the beams were modelled. The adopted FE-mesh is illustrated in Fig. 8.

Fig. 9 shows the strain distributions along the outer surface of the lower face for the beam with a butt insert (α=90^0 in Fig. 7(a)) and the beam with a scarf insert (α=35^0 in Figs. 7(b)). The strains were measured and calculated for a central load of 400 N. It is seen that the local strains, that appear in addition to the global strains across the butt junction (Fig.9(a)), are higher than the local strains induced across the scarf junction (Fig. 9(b)). In fact, the intensity of the local effects in the faces is almost halved, when a smoother change of the elastic properties of the adjoining materials is provided via introduction of the structurally graded scarf insert. Thus, it is demonstrated that the change of the junction geometry leads to a significant reduction of the locally induced strains.

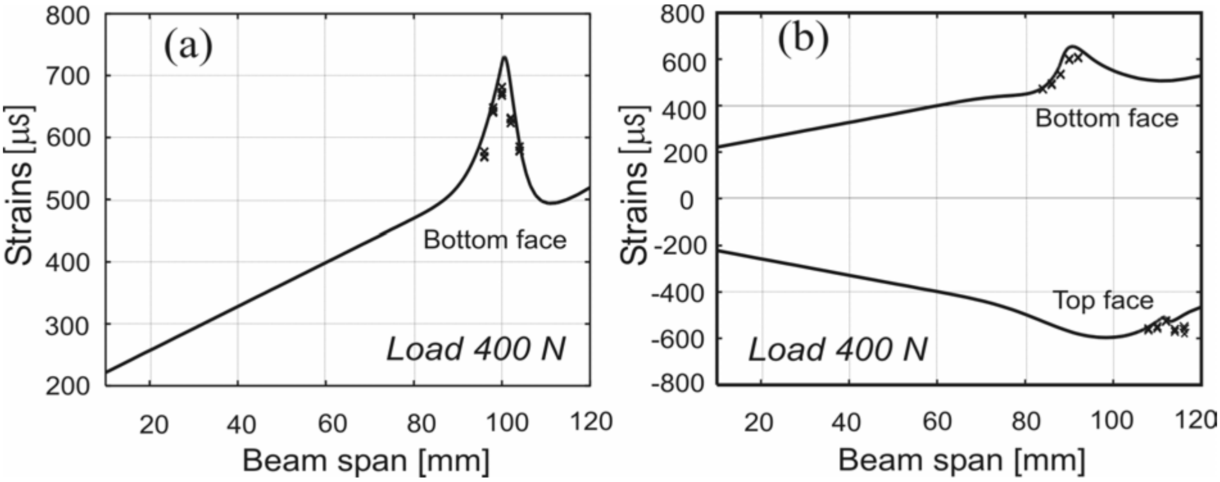


Fig. 9. Strain distributions along outer surfaces of the sandwich faces in the beams with a butt insert (a) and scarf insert (α=35^0) (b). Solid lines represent the FEM calculations, and **x** corresponds to the strain gauge measurements. The positioning of the strain gauges is shown in Fig. 7.

The experimentally measured strains deviate slightly from the numerical predictions. This might be caused by a number of factors. Firstly, the finite length of the strain gauges inevitably flattens the measured peaks of the local effects across the junctions. Deviations of the mechanical properties of the sandwich constituents, from those given by the producers, and shown in Table 2, might be also a source of the slight disagreement between the experimental and numerical data. Overall, however, the maximum discrepancy between the experimental and the FEA data in Fig. 9 was less than 10% for both sandwich beam configurations in the entire range of applied loads.

It should be noticed, that optimisation of the transition zone between different materials with the objective of reducing/diminishing local effects caused by material discontinuities is not an entirely new idea. For example, Daniel and Abot [29] suggested filling the cells of the honeycomb core with epoxy in a special manner. Miers et al. [30] designed and investigated an edge insert with a special optimised shape, which has been proven to minimize the local stress concentrations at the beam supports. Both designs ([29] and [30]) provide smoother transition zones between the core and the insert.

The proposed structurally graded core inserts have been shown to display high performance with respect to strengthening the faces of the sandwich structure, which in turn improves the overall strength of the whole sandwich. Although failure may also occur in different parts of the sandwich components [31-33], it is natural to expect that local stresses in the surrounding core will also be relieved by using of the new design of core inserts.

4. CONCLUSIONS

The paper has presented 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, in addition, 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 (also frequently referred to as "bending boundary layers" or "localised bending effects") are discussed in some detail, and it is shown that the occurrence and severity of localized effects can only be predicted accurately if structural models that include the transverse stress components are used. Several such structural high-order sandwich models are discussed.

Moreover, the paper presents a brief survey of some recent developments regarding the formulation and application of "high-order" sandwich models based on realistic engineering practice examples. These include sandwich panels with core materials of different stiffness (core junctions), and sandwich panels with rigid inserts.

The presented results show that the developed closed-form model (an asymptotically exact 3rd order shear theory for sandwich plates) accurately predicts the locally induced face stresses and transverse normal and shear stresses in the core in the vicinity of core junctions.

In addition, the paper discusses the issue of rigid inserts (core inserts) in sandwich panels, which is inherently associated with severe local effects as described above (severe local stress concentrations).

Finally, a novel structurally graded core insert design is proposed, and it is shown experimentally as well as through numerical analysis, that this novel design displays significantly lower local stress and strain concentrations than the conventional insert design. Thus, the new so-called *scarf insert* displays superior mechanical performance compared with the conventional *butt insert*.

ACKNOWLEDGEMENTS

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References

1. **Vinson, J.R.**, "The Behavior Sandwich Structures of Isotropic and Composite Materials", *Technomic Publishing Company*, Lancaster, (1999).
2. **Plantema, F.J.**, "Sandwich Construction", *John Wiley & Sons*, New York (1966).
3. **Allen, H. G.**, "Analysis and Design of Structural Sandwich Panels", *Pergamon Press*, Oxford, (1969).
4. **Stamm, K. and Witte, H.**,"Sandwichkonstruktionen", *Springer-Verlag*, Wien (in German), (1973).
5. **Zenkert, D.**, "An Introduction to Sandwich Construction", *Chameleon Press Ltd.*, London, (1995).
6. **Whitney, J. M.**, "Structural Analysis of Laminated Anisotropic Plates", *Technomic Publishing Company*, Lancaster, (1987).
7. **Jones, R. M.**, "Mechanics of Composite Materials", Second Edition. Taylor & Francis, (1999).

8. **Reissner, E.**, “Finite Deflections of Sandwich Plates”. *Journal of Aerospace Sciences*, **15**/7 (1948), 435-440.
9. **Mindlin, R.D.**, “Influence of Rotatory Inertia and Shear on Flexural Motions of Isotropic Elastic Plates”, *Transactions of the ASME, Journal of Applied Mechanics*, **18** (1951), 31-38.
10. **Vinson, J.R. and Sierakowski, R.L.**, “The Behavior of Structures Composed of Composite Materials”, *Kluwer Academic Publishers*, Dordrecht (1986).
11. **Lo, K.H., Christensen, R.M. and Wu, E.M.**, “A High-Order Theory of Plate Deformation”, *Transactions of the ASME, Journal of Applied Mechanics*, **44** (1977), 669-676.
12. **Stein, M.**, “Nonlinear Theory for Plates and Shells Including the Effects of transverse Shearing”, AIAA Journal, **24**/9 (1986), 1537-1544.
13. **Reddy, J.N.**, “A Simple Higher-Order Theory for Laminated Composite Shells”, *Transactions of the ASME. Journal of Applied Mechanics*, **51** (1984), 745-752.
14. **Reddy, J.N.**, “Exact Solution of Moderately Thick Laminated Shells”, *Transactions of the ASCE, Journal of Engineering Mechanics*, **10**/5 (1984), 794-809.
15. **Savoia, M, Laudiero, F. and Tralli, A.**, “A Two-dimensional Theory for the Analysis of Laminated Plates”, *Computational Mechanics*, **14** (1994), p. 38-51.
16. **Librescu, L.**, “Elastostatics and Kinetics of Anisotropic and Heterogeneous Shell-Type Structures”, *Noordhoff International Publishing*, Leyden, (1975).
17. **Frostig, Y. and Shenhar, Y.**, “High-order Bending of Sandwich Beams with a Transversely Flexible Core and Unsymmetrical Laminated Composite Skins”, *Composites Engineering*, **5** (1995), 405-414.
18. **Frostig, Y. and Baruch, M.**, “Localized Load Effects in High-Order Bending of Sandwich Panels with Transversely Flexible Core”, *Journal of ASCE, EM Division*, **122**/11 (1996).
19. **Thomsen, O.T. and Frostig, Y.**, “Localized Bending Effects in Sandwich Panels: Photoelastic Investigation versus High-Order Sandwich Theory Results”, *Composite Structures*, **37**/1 (1997), 97-108.
20. **Zenkert, D.** (Ed.), “The Handbook of Sandwich Construction”, *Chameleon Press Ltd.*, London, (1997).
21. **Noor A.K., Burton W.S., Bert C.W.**, “Computational Models for Sandwich Panels and Shells”. *Applied Mechanics Review*, **49** (1996), 155-199.
22. **Skvortsov, V., Thomsen, O.T.**, “Analytical Estimates for the Stresses in Face Sheets of Sandwich Panels at the Junctions between Different Core Materials,” In: *Proceedings of the 6-th International Conference on Sandwich Structures (ICSS-6)*, Ft. Lauderdale, Florida, March 31-April 2, 2003, 501-509.
23. **Bozhevolnaya, E., Thomsen, O.T., Kildegaard, A., Skvortsov, V.**, “Local Effects across Core Junctions in Sandwich Panels, *Composites Part B: Engineering*, **34** (2003), 509-517.
24. **Bratukhin A.G. and Bogolyubov, V.S.** (Eds.), “Composite Manufacturing Technology”. *Chapman & Hall*, London, 1995.
25. **Clarke, J.L.** (Ed.), “Structural design of polymer composites”. *EUROCOMP Design Code and Handbook. E & FN Spon*, London, 1996.
26. **Gay. D., Hoa, S.V., Tsai, S.N.**, “Composite Materials: Design and Application”, *CRC Press*, New York, 2003.
27. **Smith, C.S.**, “Design of Marine Structures in Composite Materials”, Elsevier, London,1990.
28. **Shenoi, R.A. and Wellicome, J.F.** (Eds.), “Composite Materials in Maritime Structures, *University Press*, Cambridge,1993.
29. **Daniel, I.M., Abot, J.L.**, “Fabrication, Testing and Analysis of Composite Sandwich Beams”, *Composite Science and Technology*, **60** (2000), 2455-2463.
30. **Miers, S.A., Ligon, J.B., Miskioglu, I.**, Design of Edge Inserts for Composite Sandwich Beams. *Experimental Techniques*, **25**/4 (2001), 39-42.
31. **Triantafillou, T.C., Gibson, L.J.**, “Failure Mode Maps for Foam Core Sandwich Beams”, *Materials Science and Engineering*, **95** (1987), 37-5
32. **Kim, J., Swanson, S.R.**, “Design of Sandwich Structures for Concentrated Loading”, *Composite Structures*, **52** (2001), 365-373.
33. **Daniel, I.M., Gdoutos, E.E., Wang, K.-A., Abot, J.L.**, “Failure Modes of Composite Sandwich Beams” *International Journal of Damage Mechanics*, **11** (2002), 309-334.