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A DESIGN METHODOLOGY TO OVERCOME LOCAL EFFECTS IN JOINING SANDWICH MATERIALS

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ABSTRACT
This paper proposes a design methodology, which emphasizes usage of CAE tools to overcome local effects in joining sandwich materials at an early stage of product development. Several case studies have been carried out using finite element analysis to understand the local behavior of sandwich beams mainly under transverse loads. The results of simulations are used to minimize stiffness mismatching at the connection interfaces by deriving necessary functions, choice of materials and preliminary embodiment parameters of a sandwich connector. A demonstration example is used to illustrate the underlying principles.

Keywords: Sandwich materials, design theory, numerical simulation, joining techniques

1 INTRODUCTION
Sandwich structures are usually made up of two thin and stiff face sheets separated by a thick, lightweight and a compliant core material. In recent years, these structures have gained widespread acceptance within the marine, aerospace, wind energy, automotive and general transportation industries as an excellent possibility to obtain high performance lightweight components. However, the commercial usage of these panels implies the need for simple, low cost mechanical joining techniques with the adjoining components [1], [2]. One major difficulty in developing such techniques lies in the lack of proper understanding of local mechanical behavior at sandwich connection interfaces and in the missing reliable testing methods to measure these unwanted effects. Often large local stiffness mismatch occur in the vicinity of connection interface that lead to a large stress concentrations followed by a catastrophic failure of the structure. Bozhevolnaya et al. [3], [4] illustrates the importance of understanding the local effects in sandwich structures. It is also suggested by this group of researchers [5] that improving the local behavior increases the fatigue life of sandwich panels by a factor of 3. It is therefore necessary to have a thorough understanding of the local phenomenon before developing *principle solutions* [6] for joining sandwich materials. One effective way to realize this goal is by employing finite element tools. Based on these results, new principle solutions or even new functions can be derived at an earlier stage. This reduces the number of design iterations and hence the overall development time.
Kempf in his work [7] has focused exclusively on finding a variety of principle solutions to mechanically connect sandwich materials within a plane. The connection techniques presented in his work require neither adhesive nor insert for joining different sandwich components and enables fast joining and repairing. One of the best solution concepts according to Kempf is shown in Figure 1a. However, it can be clearly seen that this concept creates a thin air gap between the core and connection element, which happens due to unavoidable differences in tolerances. In Figure 1a, this air gap is presented in an exaggerated fashion just for illustration purpose. Furthermore, this air gap enlarges if the structure is subjected to transverse loading. Hence, the forces and moments are transmitted only through the face sheets to the connection element. This usually creates a large stiffness mismatching in the sandwich core close to the connection interface, which easily initiates local failure of the face sheet or delamination or combination of both. Cao et al. [8] has investigated similar joining concepts (Figure 1b) under transverse loading conditions using a 4-point bending test bench. The results of their investigation show that the failure has never occurred in the joint itself, but often located at the sandwich section close to the joint in the form of local failure of the face sheet under static loading. Fatigue loading conditions even worsens these unwanted local effects [5]. The terms stiffener or

connector is often used in this paper to describe the stiff adjoining component to the sandwich material.

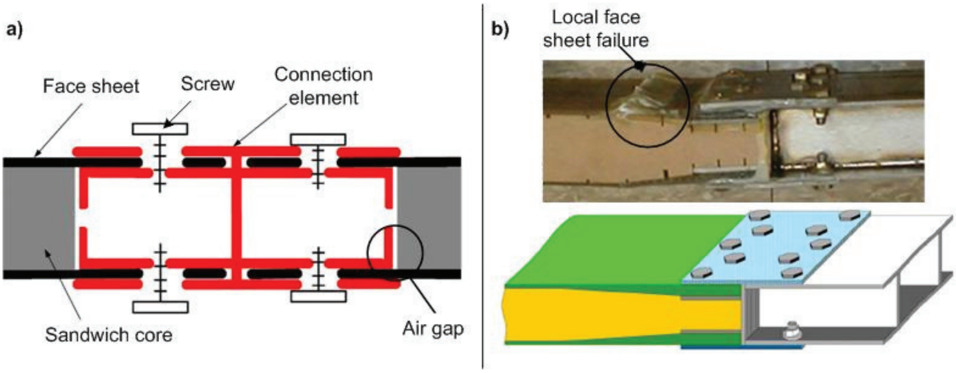

Figure 1. Solutions for joining sandwich materials [7], [8]

2 SCOPE

The studies presented in this paper using FE-Analysis were exclusively devoted to the cases of loading under transverse shear. Additionally, a case with tensile loading is considered. The discretization of the FE-mesh of sandwich components is done in such a way that it provides representative results. The global convergence of the solution is confirmed by comparing the displacement results with closed form solutions provided in Zenkert [9] and by previous experiments [10]. The results at the interfaces are strongly mesh-size dependent due to singularities and therefore the local convergence is not always guaranteed in the computations presented in this paper. Some strategies referred in literatures [3], [4] to overcome these singular problems are often time consuming to realize especially during the initial stage of design and may not be necessary if the measurements can be avoided at the singular regions. But these problems must be answered at the later stage of the product development, during quantitative embodiment design.

Within the framework of this paper, several case studies have been presented. These case studies serve to:

- Understand the local behavior of the sandwich materials under the above defined loading cases
- Determine proper functions, choice of materials and preliminary embodiment parameters based on which principle solutions can be derived
- Develop simple reliable test methods to verify the above mentioned theoretical predictions

Additionally, this paper provides a novel approach for measuring stiffness discontinuities at the connection interface.

3 SPECIMEN SPECIFICATIONS AND FE- MODELLING ASPECTS

There is in total five case studies presented in this paper. Though each case study includes a minor change in the dimensions of the specimen, the basic dimensions and the loading boundary conditions remains same in all the cases presented in this paper. These are shown in Figure 2. The thickness of the face sheet is 2mm.

The simulations are performed using commercial software package ANSYS® Version 11.0. 4-noded 2D-elements (plane 42) are used to model face sheets and the core of the sandwich material under plane strain assumptions. Only 4 layers of elements were used in the faces to capture bending (Figure 3). The choice of plane strain elements can be justified since the faces are much wider than the thickness of the sandwich core and hence they behave approximately in a plane strain manner. Steeves et al. [11] has already shown that such a modeling could capture the structural response of sandwich beams up to the point of fracture of the core or of the faces. Only one-half of beams have been modeled due to symmetry of the testing set up. A load of 6700 N has been applied in all the simulations, since the theoretical core shear failure load lies just above this load value. Due to symmetry, only a half of this load value has been applied in all simulations. The Table 1 presents the material properties of the specimen.

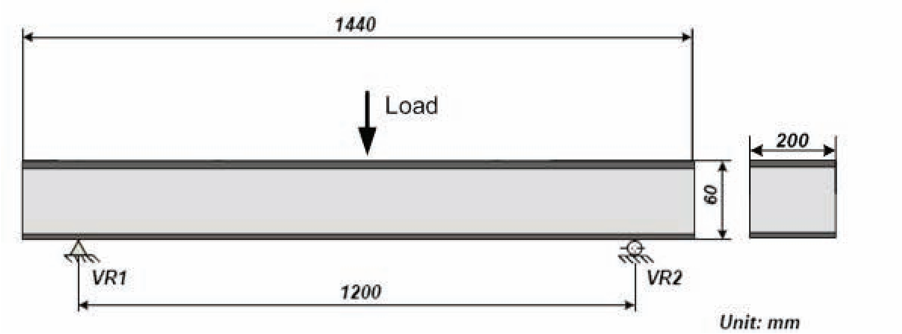

Figure 2. Basic dimensions and loading boundary conditions

Table 1. Material properties

Face sheet	**Sandwich core**
Material: Structural steel Young's modulus = 210,000 MPa Poisson's ratio = 0.3 Tensile strength = 235 Mpa	Material: PMI foam (Rohacell® 31 IG/IG-F) Young's modulus = 36 MPa Shear modulus = 13 MPa Shear strength = 0.4 Mpa Compressive strength = 0.4 Mpa

4 CASE STUDIES

4.1 Case 1: Reference Simulation

This simulation represents the ideal behavior of the sandwich beam without connectors. The purpose of this simulation is to provide ideal reference measurements, whose values are to be targeted by the connection techniques to be developed. Figure 3 demonstrates the refrence simulation set up. It is necessary to decide which component or components of strain shall be used as a reference measurement. Since the sandwich core material undergoes transverse shear deformation under 3-point bending; the appropriate choice of measurement would be the shear strain component ε_{xy}. One place to measure this shear strain component would be the core at the face-core interface (line 1), where delamination or local failure is expected. Bozhevolnaya et al. [3], proposes maximum principal core stresses in the core at the face-core interface (line 1) to be considered as the failure criterion. However, the drawback of such measurements lies in the difficulty to experimentally verify the stated hypothesis. Therefore, shear strain measurement ε_{xy} along the midline of the core is proposed (line 2) in this paper. The justification of such a measurement is as follows. The magnitude of shear strains along line 2 (Figure 3) is far greater than the measurements along line 1 and hence experimental verification for instance using clip gauges will be more reliable. The measured jump in strain values along line 2 and line 1 are almost proportional to each other. Therefore, the measurement of shear strains ε_{xy} along line 2 can be used as an indicator to measure stiffness mismatches along the line 1. The reference strain values ε_{xy} along line 2 is presented in figure 4. Not only the strains in the core plays an important role in causing stiffness mismatches, but also the strains in the face sheet, especially the component ε_y. By increasing the thickness of the face sheet locally as suggested by Feldhusen et al. [10], this problem could be easily overcome and hence not considered further in the case studies presented in this paper.

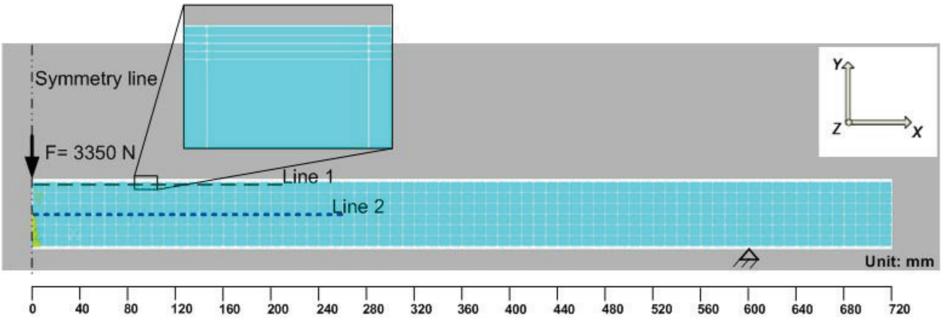

Figure 3. Reference simulation set up

4.2 Case 2: Influence of air gap

The influence of air gap in worsening the local effects is studied here. Two simulations have been carried out one with a gap of 10 mm and another with a gap of 1 mm between the sandwich cores. In both of the simulations, the position of gaps is placed at a distance 100 mm away from the line of symmetry. This is done in order to enable the transmission of large shear as well as bending moments only through the face sheets available above and below the gap. The results are presented in figure 4. Here the thick continuous line (reference) is the plot of shear strain along line 2 that represents the reference values. The dotted line (10mm gap) and the thin line (1mm gap) are the plots of the shear strains of the sandwich beams with 10 mm and 1 mm gaps respectively.

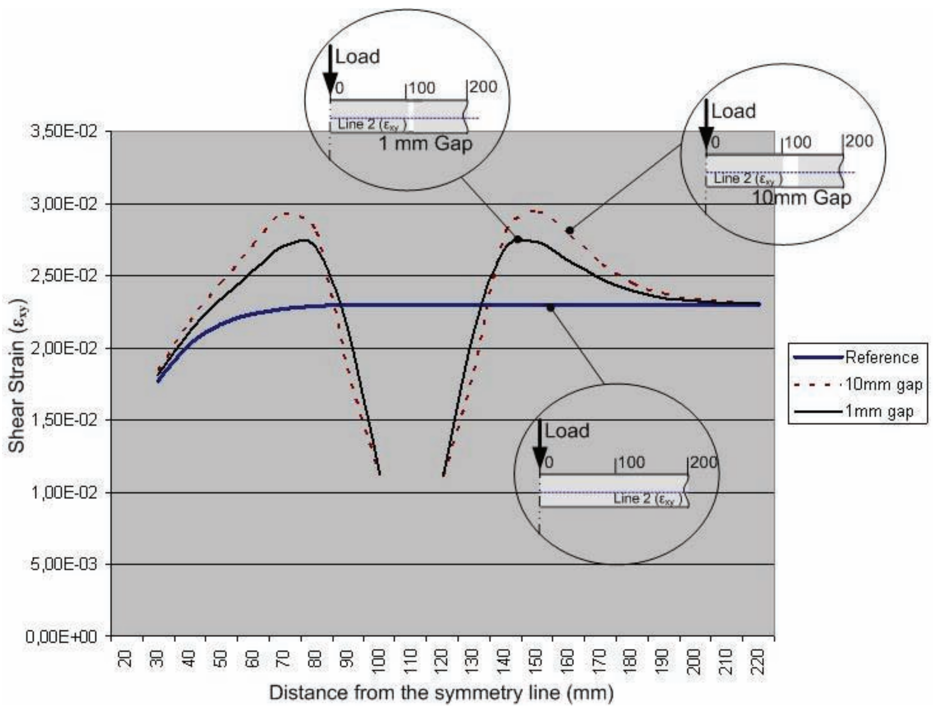

Figure 4. Influence of air gap

Discussion of results

It can be clearly seen that the air gap induces very strong stiffness mismatches in the core slightly away from the gap. There is a very large change in strain values within a distance of about 20 mm along the sandwich beam. When the length of the gap is reduced to say 1 mm, there is a small reduction in the change of strain. Nevertheless, the stifness mismatches even after reducing the gap are still quite significant and the strain shoot-up (peak) is still present. Furthermore, it shall be noted that this effect worsens if the adjoining component is a stiffer material, which is unfortunately the case when connectors or stiffeners are used.

This problem can be overcome by developing new principle solutions, which guarantees that no air gap emerges between sandwich and the connection element. One effective way to realize this in the principle solution presented in Figure 1a is by introducing pre-stressed spring elements between the sandwich core and the connection element. At this stage the preliminary shape of this spring element is quite difficult to define as the choice of the material and geometry in reducing the stiffness mismatches are not yet clearly understood. The following case studies (case 3 and case 4) are provided to understand these effects.

4.3 Case 3: Ideal no air gap solution – Choice of Materials

The aim of this case study is to understand the influence of the choice of material at connection interfaces in reducing the stiffness mismatches.

Modeling aspects

In the simulation, the sandwich core material is removed from 0 mm up to 110 mm in the reference configuration (See 4.1.). This area is filled by an edge stiffener, which shall transmit bending moments and shear forces directly from the sandwich core. In order to generate an ideal no air gap situation, a common set of nodes have been created that transmits forces and displaements from the core to the stiffener or vice-versa. This is achieved in ANSYS® 11.0 using the merging command NUMMRG, NODE where two coincident set of nodes are replaced by a common set of nodes. Hence, this simulation represents an ideal situation where no air gap exists between the adjoining components. The boundary conditions and the applied load are kept as defined in the reference configuration. The shear strain components of the core are measured along the line 2 from 130 mm to 250 mm. It is explicitly avoided that these measurements are taken from 110 mm since the results are expected to be strongly mesh-size dependent at this interface and therefore are not reliable.

Discussion of results

The simulation is carried out using a high performance polypropylene material as an edge stiffener (connector) having an elastic modulus of about 1500 MPa [12] and assuming a Poisson's ratio of 0.3. In Figure 5, this material is represented as "Material C". It can be clearly seen that through this ideal connection of adjoining components, the peak portion of the stiffness mismatching disappears. But still the change in strain values is significant within a small distance along the sandwich beam.This is due to the fact that the elastic modulus of the chosen core is about 41 times lesser than that of the chosen edge stiffener. "Material A" and "Material B" represent different high density foam core materials that could be used as well to overcome this problem. However, as edge stiffeners these materials are not suitable for well-known reasons. "Material D" represents a high performance polymer edge stiffener whose mechanical properties (density and elastic modulus) are far better than that of material C.

There exists a limit in choosing a particular material as a connector, which is influenced by several criteria such as joinability using screws, resistance to temperature, creep etc. The materials that satisfy this limit can be chosen as a connector material. This idea is schematically represented in figure 5. The materials that come under the shaded region in figure 5 can be considered as feasible materials, which shall be used as connectors.Hence, it can be concluded that just by "adjusting" the material alone, the stiffness mismatches cannot be reduced beyond a certain limit. There is a need for the change of geometry of the connector to reduce the mismatches further.

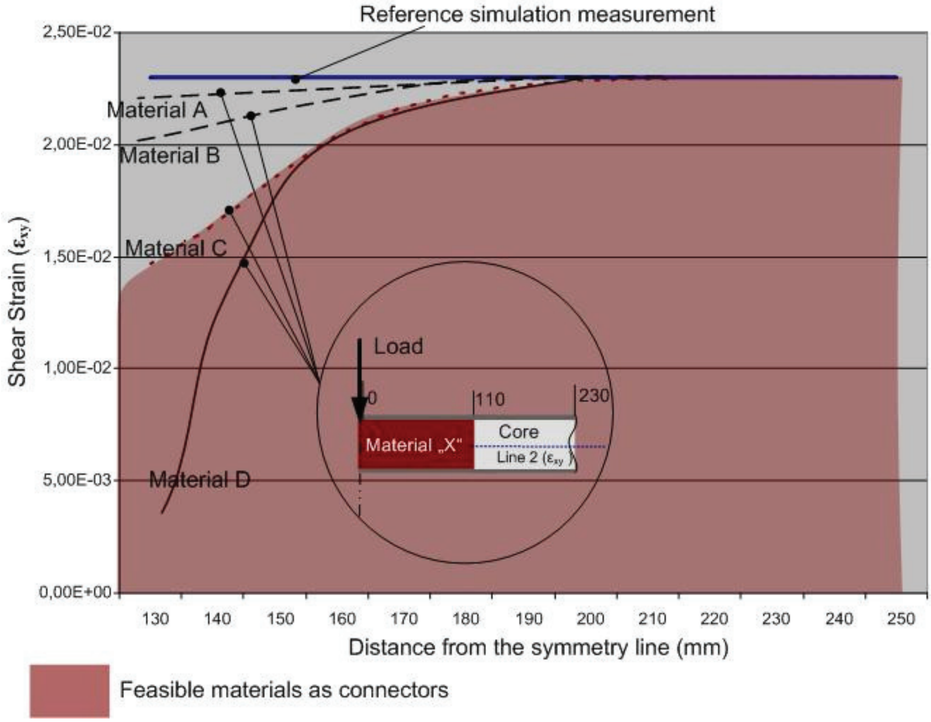

Figure 5. Influence of choice of materials in an ideal solution

4.4 Case 4: Ideal no air gap solution – Choice of Geometry

The goal of this case study is to understand the influence of the geometry in reducing stiffness mismatches. The numerical modeling aspects and the measurements are identical to case 3.

One effective way to realize the stated goal is by “softening” the adjoining geometry. For simulation purposes, “Material C” is chosen as the edge stiffener. The results of the simulations with qualitative changes in geometry of the edge stiffener are presented in Figure 6. It can be clearly seen that the change of strain can be considerably reduced by softening the connector at the interfaces. Hence, it can be concluded that once a proper material is chosen, further reduction of the stiffness mismatches is only possible by changing the geometry of the stiffener.

4.5 Case 5: Influence of axial loading

The aim of this case study is to present the influence of axial loads at the connection interface. Plane strain elements as presented in the previous case studies are able to capture the local effects under this loading condition. However, a very fine meshing of the interface area of the core, stiffener and the faces are required to capture these effects precisely. Bozhevolnaya et al. [3] has already studied this effect in which a high and a low density foam core materials are joined together. The local effect under axial loading presented by this group of researchers is universally valid; especially for stiffeners and foam core interfaces. Therefore, simulations are not carried out for this case. The results of the deformation behavior of the materials at the interfaces are shown schematically in figure 7. It can be seen that large local discontinuities occurs at the contact interfaces. Therefore, as suggested by the above group of researchers, in order to preserve the structural integrity, the curvature of the face should be concave down over the soft core and hence concave up over the stiffeners.

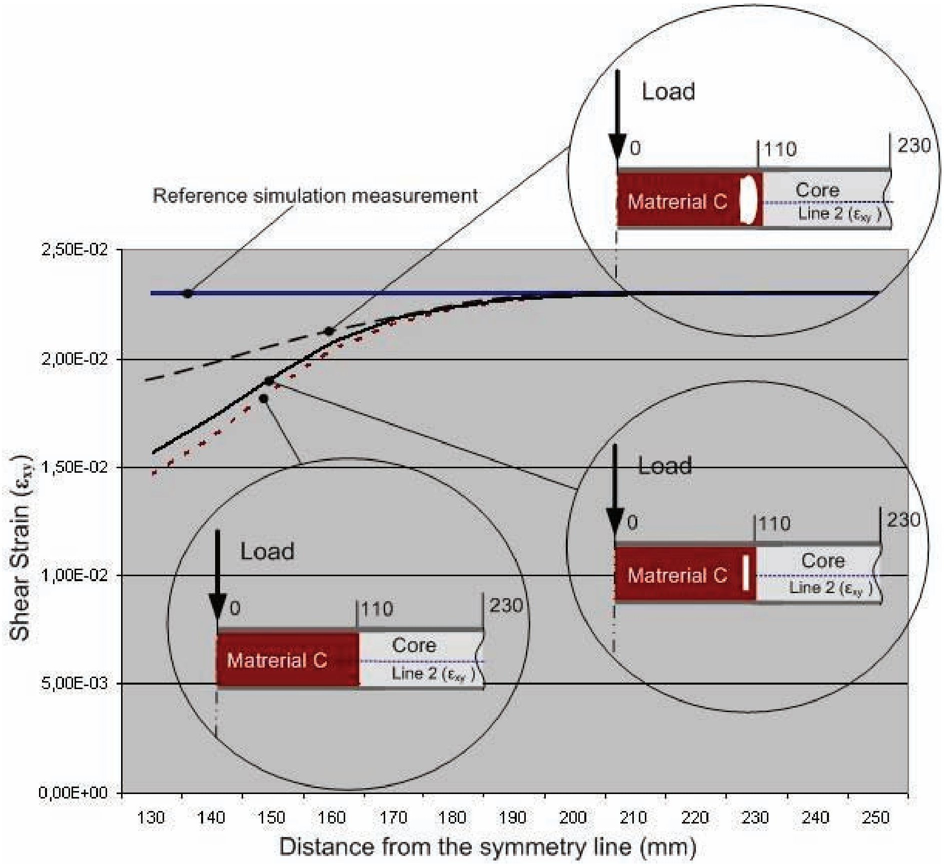

Figure 6. Influence of geometry in an ideal solution

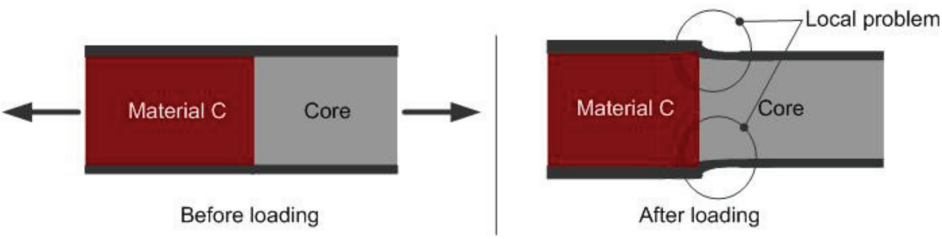

Figure 7. Axial loading

5 A DEMONSTRATION EXAMPLE

The results of the case studies presented above has a direct influence on determining functions, choice of materials and preliminary embodiment parameters for joining sandwich materials. Based on these results, a several number of principle solutions can be derived. This part of this paper presents how the presented case studies can be utilized in determining a single principle solution for a particular combination of materials. Since the solution field is quite large, the demonstration example restrains itself by using standard mechanical components such as screws as a part of the connection technology. The proposed principle solution shall enable the possibility to withstand local bending, transverse and axial loads. The evolution of a principle solution is shown in Figure 8.

Discussion

The choice of a material as a stiffener or a connector strongly depends on the chosen sandwich core material. The case study 3 presented in this paper (Section 4.3) shows that, there exists a limit in choosing a material as a connector. This limiting material is schematically presented in the Figure 8a) as “Material X”.

From the case study 5, it is obvious that the curvature of the face should be concave down over the soft core in order to overcome the local effects of tensile loads. Figure 8b) includes this proposal.

In the case study 2, it is illustrated that in order to minimize the magnitude of the strain shoot-up (peaks), it is absolutely essential to keep the air gap between the adjoining components as small as possible. By applying lateral forces along the stiffener, it is possible to minimize the air gap as shown in figure 8c).

In the case studies 3 and 4, it is demonstrated that it is not possible to minimize the change of strains beyond a certain range without changing the geometry of the stiffener. In the Figure 8d), the qualitative change of the geometry of this stiffener is presented which shall minimize the change of strains.

In the Figure 8e) the lateral forces are replaced by pre stressed spring elements as proposed in the case study 2. This initiates the need for stiff wall elements (for example metallic profiles) connected by screws in order to keep the springs under pre stressed condition.

Figure 8f) and figure 8g) contributes to the evolution of the principle solution presented in figure h). Figure 8f) illustrates the connection of two different foam core sandwich materials within a plane. Here a thin metallic “O-profile” is used at the centre in order to connect the face sheets of different core materials with screws. This particular design with the “O-profile” has no practical relevance and was chosen solely due to experimental reasons, since this design is expected to facilitate stronger discontinuities at the connector interfaces and therefore suitable for experimental comparison of strains for different configurations using clip gauges (see 4.1). In order to transmit bending loads, a X-shaped profile shall be preferred because both the upper and the lower “V-shapes” of the X-profile enables smooth transmission of the compressive and tensile load of the face sheets.

Until now, the form of the spring element is not decided. Bringing the spring element to a pre-stressed state and mounting it properly are two important functions that require additional working surfaces and may require additional components. This problem of course affects the compactness of the proposed solution. To overcome this problem, a concept is proposed in figure 8g). Here the functions of the spring and the stiffener are combined in to a single spring component. However, this concept has its inherent drawbacks. Firstly, to bring the tongues of this spring component in an exact position requires a preliminary analysis. Employing shape optimization FE- tools is one efficient way not only to solve this problem, but also to make sure that the developing stresses of the tongue (critical radius) are within the allowable limits. Secondly, as the transverse load increases, the tensile side of this spring component tends to lose contact with the core. This problem can be eliminated by proper calculation of the maximum allowable transverse load and the stiffness of the spring component.

In figure 8h), a CAD-Model and a cross-sectional drawing of the proposed principle solution for experimental verification is presented. Here, the mounting of the spring component in position requires additional working surfaces and components. The cross-sectional drawing shows a wedge shaped element adjacent to the spring component, which is employed to ensure proper mounting.

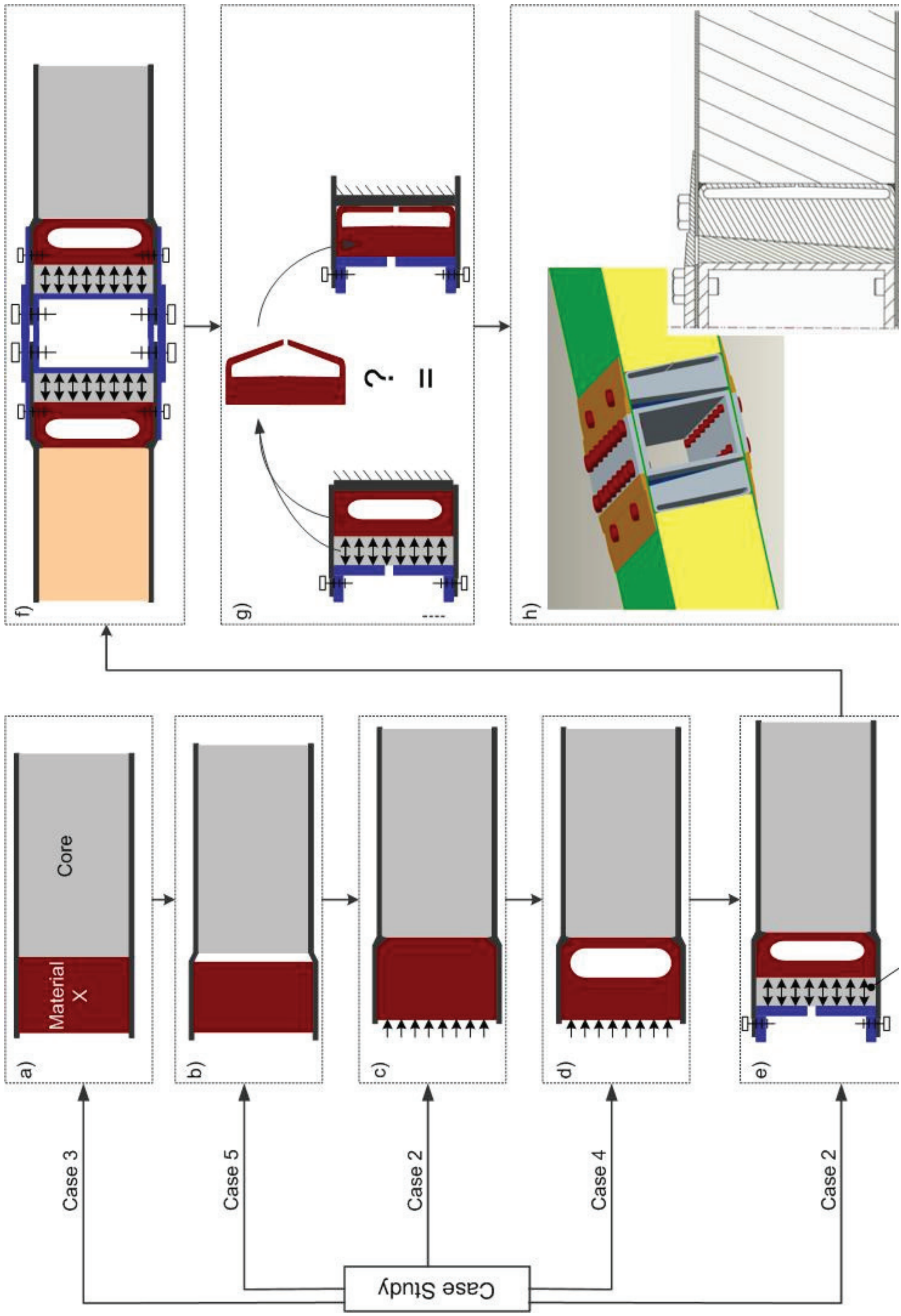

Figure 8. A principle solution for demonstration purpose

6 CONCLUSIONS

The results presented in the case studies using a 2D-plane strain element are quite reliable since the considered modeling approaches are well known and have been employed by a number of researchers in their computations; the deformation and failure behavior have also been experimentally validated. However, there are hardly studies that verify the local change of strains experimentally. Though FEM tools can be used to qualitatively measure the change of strains, there is a need to quantify these measurements. This can be only achieved through experiments. This paper proposes the measurement of shear strains along the midline of the core, since these values are reliable for experimental verification.

Several conclusions can be met based on the case studies presented in this paper. The air gap between the sandwich core and the connector worsens the stiffness mismatches between the adjoining components. Delamination or local failure of the face sheet or the combination of both is expected to occur slightly away from the gap; thereby initiating the failure. One way to eliminate this problem is by bringing components that transmit lateral forces.

Furthermore, it can be concluded that just by “adjusting” the material alone, the stiffness mismatches cannot be reduced beyond a certain limit. There is a need for the change of geometry of the connector to reduce these mismatches further.

The design methodological approach presented in this paper emphasizes employing simulation tools in an early stage of the product development. It is illustrated through an example that the understanding of the local effects at an early stage has a direct influence on determining functions, choice of materials and preliminary embodiment parameters for joining sandwich materials.

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