FAST JOINING AND REPAIRING OF SANDWICH MATERIALS WITH DETACHABLE MECHANICAL CONNECTION TECHNOLOGY

Jörg Feldhusen and Sivakumara K. Krishnamoorthy

RWTH Aachen University, Chair and Insitute for Engineering Design (IKT)
Steinbachstr. 54B, D-52074 Aachen
e-mail: krishnamoorthy@ikt.rwth-aachen.de, webpage: www.ikt.rwth-aachen.de

ABSTRACT

This paper presents design principles, tools, methods and experiments for joining sandwich materials. The connection technique presented here requires neither adhesive nor inserts for joining different components and enables fast joining and repairing since standard screw elements are used for connection. The novelty of the solution approach presented in this paper lies in its universal applicability for connecting different materials in a T-, L- and V-joint joint connections without major changes in the calculation procedure. A new simplified conservative-failure criterion for sandwich material is proposed which can be used as a basis for FEM calculations at connection interfaces. For that, only 2 experimental set ups are required to obtained necessary material data. Tools and methods of avoiding strength and stiffness discontinuities are also discussed.

1. INTRODUCTION

There are several advantages of using sandwich material as a primary structural component in general mechanical engineering applications. Some advantages include light-weight design, efficient energy absorption, increased mechanical damping and good thermal and acoustic isolation. However, sandwich structures are sensitive to heat loads that often lead to delamination of the face sheet. Unexpected local and impact loads may result in permanent deformation of the structure. These problems constrain the applicability of sandwich structures in general mechanical engineering. In such cases, techniques that allow fast joining and repairing of sandwich components can help to overcome this constraint.

Kempf in his work [1] has focused exclusively on finding a variety of principle solutions to mechanically connect sandwich panels with in a plane. A principle solution usually demonstrates the physical effect (for ex. friction), effect carrier (material) and qualitative embodiment parameters (geometry) [2]. About 850 such principle solutions have been discussed in his work for connecting two sandwich elements with in a plane. One such a principle solution is shown in Figure 1a). However, because of the lack of sandwich material data, only functional models were developed earlier to demonstrate some principal solutions. Figure 1b) shows its functional model.

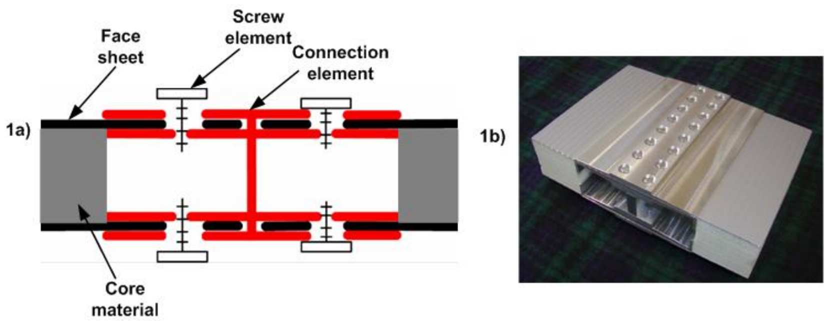

Figure 1: Principle solution and a functional model

This paper describes experiments, methods and tools that can be adopted for proper dimensioning of sandwich materials, screw elements and sandwich connection elements as defined in Figure 1. Some reasons for the consideration of this connection technique in particular are:

- It allows joining and repairing with standard mechanical elements.
- It requires less time to prepare sandwich materials and allows easy positioning.
- It needs comparatively lesser elements to transmit forces and moments.
- Furthermore, strength calculations of such screw elements are well known.

Efficient application of such connection techniques for commercial purposes requires strength proofs of dimensioning sandwich materials, screw element and connection element under complex loading conditions. This paper restrains itself providing such proofs for sandwich materials with PUR-foam core materials separated by steel face sheets under static loading.

2. DIMENSIONING SANDWICH MATERIALS

Literatures and standards describe a series of tests to determine material parameters of sandwich materials. Performing most of these tests to determine necessary material parameters would be time and cost intensive because it requires a number test benches, test specimens of different shapes and sizes, preparation time etc. The number of material parameters that have to be determined depends on chosen failure criteria and modelling methods. Hence the failure criteria, modelling methods should be chosen in such a way that it allows good usage of the sandwich material at less experimental cost. Also the test benches that shall be considered should provide much information about sandwich materials. Hence this part describes basic material information that shall be obtained through a test series, for proper designing of sandwich and sandwich connection elements. The change of strength characteristics of the material as a result of fatigue or impact loads is not considered in this paper. The procedure suggested here can also be applied for conservative dimensioning of sandwich materials in general engineering applications. Since the face sheet of sandwich materials are usually made of metallic materials, whose mechanical properties and failure criteria are well known, it is not considered any further.

2.1 Failure criteria and modeling assumptions for sandwich materials

The failure theories for composite materials can be in general classified in three groups according to Daniel [3]. They are, the so called "non-interactive theories" that suggests failure based on one stress value (ex. Maximum stress theory), the "interactive theories" that suggests failure based on interaction between two or more stress components (ex. Tsai-Hill, Tsai-Wu) and the theories that are purely based on mode of failure of the material. The choice of theory for any particular application depends on available data, experimental facilities and conformity with experimental results. When experimental results of various failure criteria are compared in a plane-stress condition, Tsai-Wu criterion prove to have a relatively good compliance in results. This compliance is also applicable to polymer foam core materials, which is used in the manufacture of sandwich materials [4]. Another important advantage of this failure criterion is that, it has been already implemented in commercial FE-Programs such as ANSYS™ and ABAQUS™. Therefore, only this theory and the material parameters those are required for this theory is discussed further.

Five failure parameters are essential to describe Tsai-Wu criterion in a plane-stress condition and the details are described for instance in literature [5]. They are tensile and compressive strengths of sandwich material in each direction of the considered plane and the shear strength in this plane. One can make a further simplification by making an assumption that the foam core is macroscopically homogeneous. This assumption reduces the required parameters to three since compressive and tensile strengths in each direction are assumed to be the same. In this paper, these parameters are identified by F_{1d} (Tensile strength), F_{1z} (Compressive strength) and S (Shear strength). Such a derived-Tsai-Wu criterion can be written as:

$$\frac{1}{\boldsymbol{F}_{1d}\boldsymbol{F}_{1z}}(\boldsymbol{\sigma}_1^2+\boldsymbol{\sigma}_2^2)+(\frac{1}{\boldsymbol{F}_{1z}}-\frac{1}{\boldsymbol{F}_{1d}})(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)-\frac{\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2}{\boldsymbol{F}_{1z}\boldsymbol{F}_{1d}}+\frac{\boldsymbol{\tau}^2}{\boldsymbol{S}^2}=1 \quad (1)$$

where, $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$ and $\boldsymbol{\tau}$ are the stress variable in plane stress condition.

If these three parameters are known, the load carrying capacity of sandwich core under general forces (F_x, F_y und F_z) and moments (M_x, M_y and M_z) and at a random combination can be determined easily using finite element simulation programs. Figure 2 represents general forces and moments in the Cartesian coordinate system. Additionally, simulation of a sandwich core in a FEM program requires at least two linear-elastic constants; for instance, Young's modulus (E), Poisson's ratio (υ) or shear modulus (G). Hence it can be said that dimensioning sandwich materials requires at least 5 material constants and of course the corresponding test benches to determine these constants.

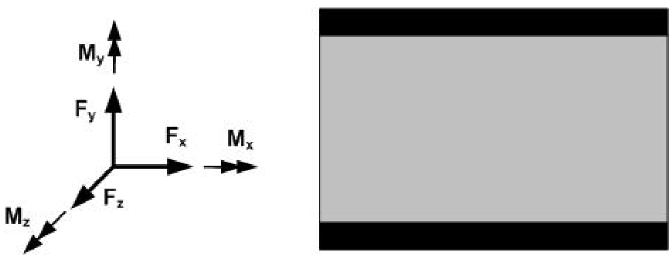

Figure 2: Genaral forces and moments in a sandwich element

2.2 Choice of test benches

In the discussion above (See 2.1.), the strength properties of the glue material that connects the sandwich foam core with face sheets are not considered. Strength proof of the complete sandwich element requires that the strength of the glue material is also considered in the calculations. Hence it would be ideal to choose test benches in such a way that it accounts for determining the strength both glue and core materials and also enables determining more than one necessary material constant.

The tensile test benches as illustrated in DIN 53292 or ASTM C297-61 and compressive test benches as illustrated in DIN 53291 or ASTM C365, can be employed to obtain respective strength values (F_{1t} & F_{1c}) and can be additionally used to understand the strength properties of glue materials. One more advantage is that, it can be also used to determine the linear-elastic constant Young's modulus (E). Shear testing fixture as illustrated in DIN 53294 or in ASME C273 can be preferred for obtaining other two constants (S & G). Hence it can be said that at-least 3 test benches are required to obtain the necessary 5 constants.

Developing test benches for compression testing is much easier than developing test benches for tensile testing. If it is well-known that compressive strength of particular core materials is weaker than its tensile strength, further simplifications in the failure criteria can be made by avoiding tensile testing. This is usually the case for most of the polymer foam core materials; PUR and PS as given by Zenkert [6]. Hence by making simplification $\boldsymbol{F_{1d}}=\boldsymbol{F_{1z}}$, the formula 1 can be written as:

$$\frac{1}{\boldsymbol{F}_{1d}^{2}}(\boldsymbol{\sigma}_1^2+\boldsymbol{\sigma}_2^2-\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2)+\frac{\boldsymbol{\tau}^2}{\boldsymbol{S}^2}=1 \qquad (2)$$

But this further reduction in the number of parameters has a negative impact in calculations as illustrated further. To enable 2D illustration of failure criterion described by formula 1 and formula 2, a constant K can be defined to relate shear stresses with shear strength as, $\boldsymbol{\tau} = \mathrm{K}\,\boldsymbol{S}$. Figure 3 demonstrates the ellipses described in formula 1 (green dotted) and formula 2 (red straight) for a PUR foam with compressive strength of 0.4 MPa, tensile strength of 0.5 MPa and K=0.75. It can be clearly seen that this simplification results in under-estimation of strength properties of the material in bi-axial compressive regions. This may lead to a catastrophic premature failure in commercial applications.

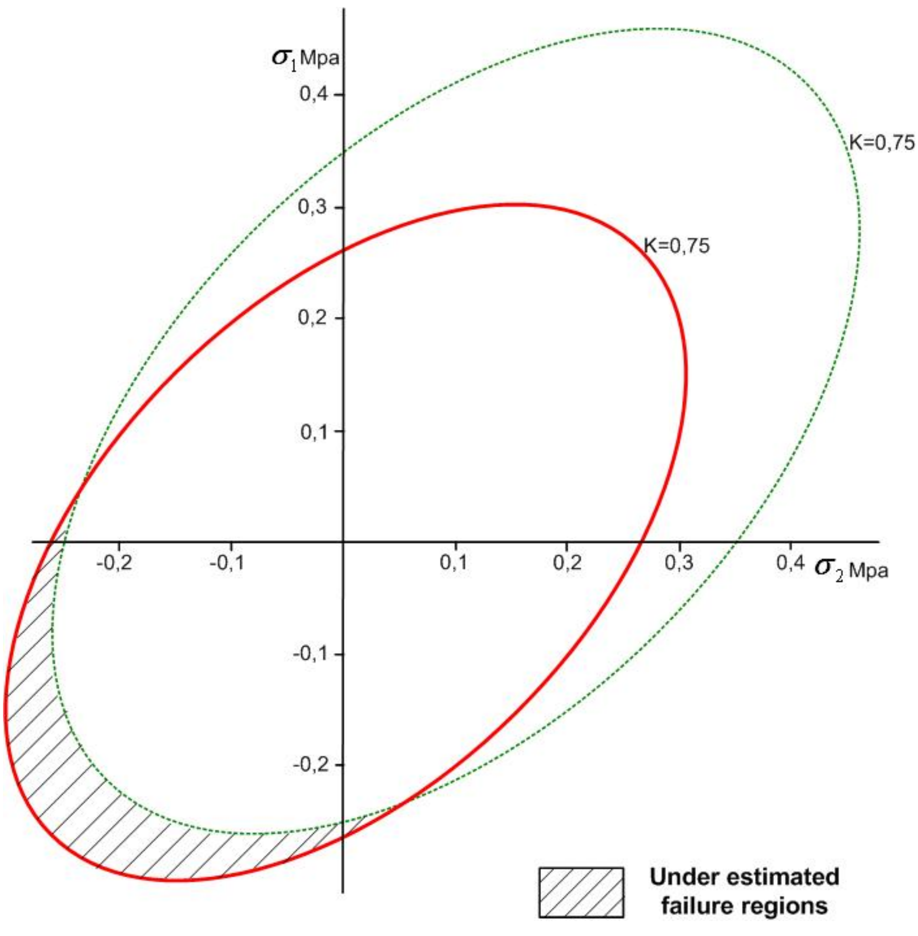

Figure 3: 2D illustration of failure criteria- a comparison

To enable a conservative-failure-criterion that lies within the derived-Tsai-Wu criterion, a conservation shear strength value ($\boldsymbol{S}^*$) shall be substituted in formula 2 and can be written as:

$$\frac{1}{F_{1d}^2}(\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2) + \frac{\tau^2}{S^{*2}} = 1 \quad (3)$$

To determine this value, an experiment must be so chosen, that the failure occurs under biaxial compression and shear stresses. Four point bending test bench allows such a combined stress condition. Other advantages of four-point bending tests are its universally applicability in static and dynamic (fatigue) characterization of materials. Shear modulus can also be determined by using formulas mentioned in ASTM C393. Therefore, this test fixture is preferable to shear test benches described earlier. Bending tests shall be performed until core shear failure as illustrated in Figure 6c. With the help of four-point bending FE-Simulation, the tensor components σ_1, σ_2 und τ at the corresponding failure region shall be determined. By substituting these tensor components in Formula 3, the conservative shear strength value (S^*) can be obtained. Figure 4 shows failure ellipse 1 according to derived-Tsai-Wu failure criterion having compressive strength of 0.4 MPa, tensile strength of 0.5 MPa and K=0.75. For the failure ellipse 2, the simplification with $F_{1d} = F_{1z}$= 0.4 MPa is considered. Instead of a FE-Simulation, the point (-9.24 MPa, -0.174 MPa) in biaxial compressive region is chosen from failure ellipse 1 to determine the conservative shear strength S^*. Substituting these values along with formula 4, results in value of K^* to 0.85. The failure ellipse 2 represents the simplified conservative-failure criterion which lies inside the failure ellipse 1.

$$\tau = K^* \cdot S^* \quad (4)$$

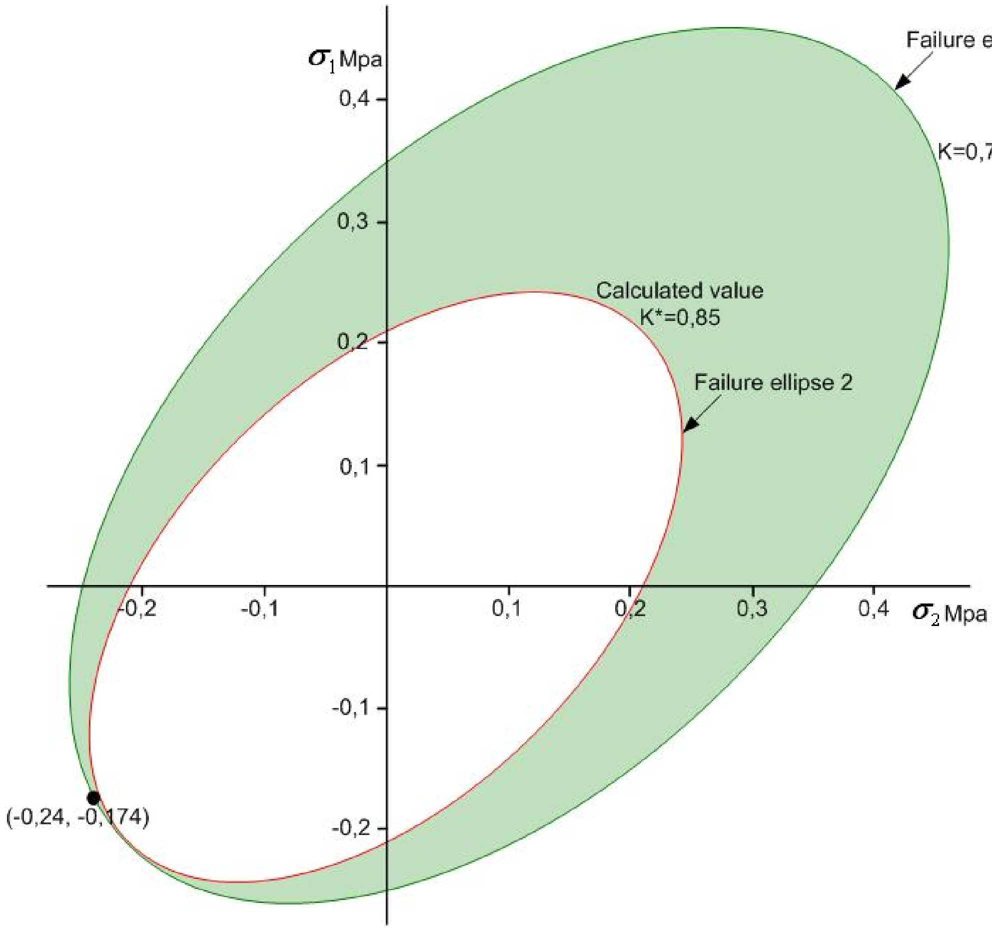

Figure 4: Simplified conservative-failure criterion

2.3 Result

Hence it can be said that by using four-point bending test benches and compressive test benches, two linear-elastic parameters (E & G) required for numerical simulation and also two strength values ($\boldsymbol{S}^*$ & $\boldsymbol{F_{1d}}$) required for simplified conservative-failure criterion can be obtained. These values are good enough to describe the load carrying capacity of sandwich beam under combination of general force and moment components described in Figure 2. If additional experimental facilities and time required to perform experiments and preparation of specimen are available, then other tests can also be done.

3. DIMENSIONING SCREW ELEMENTS

A general methodology for dimensioning screw elements, based on understanding its strength properties is given. To achieve this, the force transmission behavior from sandwich beam to the screw elements and its surroundings under general forces and moments (F_x, F_y, F_z, M_x, M_y and M_z) must be understood. This can be done by making an assumption that sandwich and connection elements are rigid bodies and the forces and moments they in-take are transmitted without any changes to the screw elements. Since this assumption is made on "safe side" basis, no negative influences in strength calculations of screw elements are expected. This assumption enables to determine the resultant force components transmitted to the most critically loaded screw element as suggested schematically in a functional black box (Figure 5).

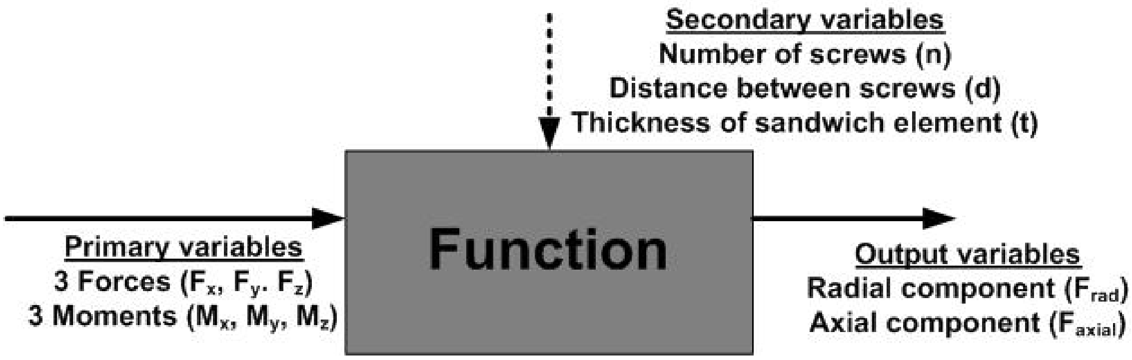

Figure 5: Black box

Kempf in his work [1] has provided such a calculation for dimensioning screw elements for joining two sandwich materials with in a plane. The two formulas given below describe axial and radial force components on a screw element for a worst-case scenario. The number of screws (n), the distance between them (d) and other necessary details for designing with screws can be taken directly taken from VDI-Guideline 2230 [7].

$$F_{rad} = \sqrt{\left(\frac{|F_x|}{2n} + \frac{|M_z|}{nt} + \frac{3|M_y|(n-1)}{d(n^3-n)}\right)^2 + \left(\frac{\frac{1}{2}|M_x|t}{t^2+(n-1)^2d^2} + \frac{|F_z|}{2n}\right)^2} \tag{4}$$

$$F_{axial} = \frac{\frac{1}{2}|M_x|(n-1)d}{t^2+(n-1)^2d^2} + \frac{|F_y|}{2n} \tag{5}$$

Such an abstract description of forces, defined through a function has several advantages. In particular, it enables calculation of transmitted forces and detailed designing of screw elements for:

- sandwich elements in a T-, L- and V-joint
- sandwich elements with other structural components
- sandwich elements with different material properties

without any change in the formulas 4 and 5. This can be demonstrated in Figure 6 in which a principle solution is given for connecting 3 different sandwich materials in a T-Joint. The radial and axial components of forces on the screw element loaded critically can be calculated using the same formula described above.

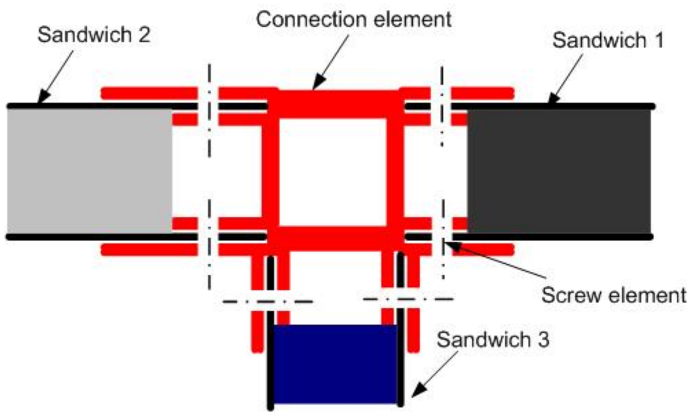

Figure 5: Principle sketch of a T-joint connecting 3 different sandwich materials

4. EXPERIMENTS, METHODS AND TOOLS FOR DIMENSIONING CONNECTION ELEMENTS

Before dimensioning connection elements for sandwich materials, it is important to know if it is absolutely essential to find the optimum geometry of connection element for a given load case. Finding a solution optimum usually consumes a lot of time, effort and resources. Other factors against such a consideration include; restrictions in manufacturability of specific shapes (radius, thickness of the tongue etc.), change of solution optimum due to change in loading conditions and spatial restrictions. So the aim of this part of this paper is not to find the optimum dimension of the connection element but to determine a geometry that allows smooth transmission of forces and moments with minimized stiffness discontinuities at sandwich interfaces. Therefore only the tools and methods that can be adapted to achieve this are discussed here. This paper is restricted in determining proper geometry of connection element joining two sandwich beams within a plane under bending loading condition.

4.1. Experiments

The suggested two experiments in chapter 2 are performed to determine 4 necessary material parameters. Figure 6a) shows the four-point bending test fixture and figure 6b) shows compression testing. The determined values are E= 14 MPa; G= 5.93 MPa; F_{1d}~0.3 MPa and S*= 0.28 MPa. It shall be noted that, difficulty may arise in determining S* value, since the beam usually undergoes local failure and shear failure may not be realised easily for PUR foam core materials. During such circumstances, it is necessary to force the sandwich beam to fail predominantly under shear as given in literature [8]. Figure 6c) shows such a forced shear failure by adding additional plates of 2mm thickness.

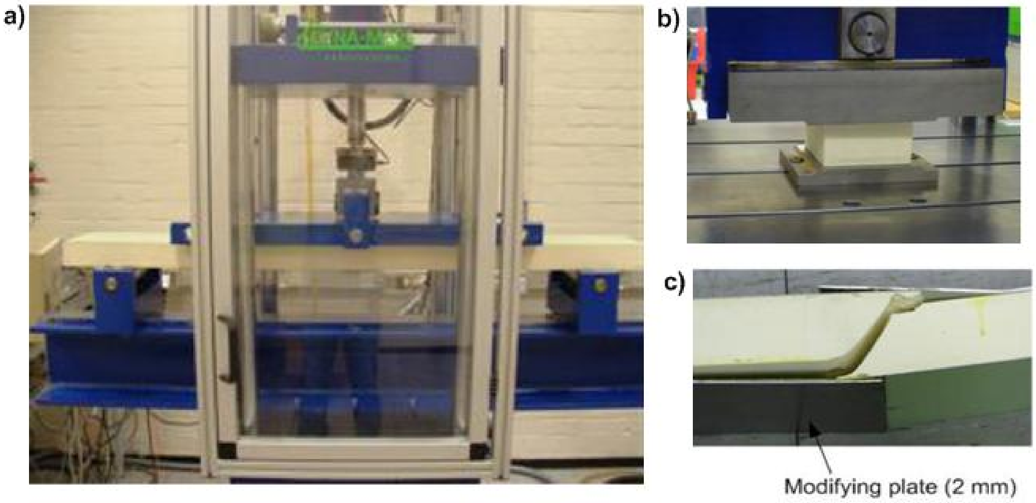

Figure 6a): four-point bending; Figure 6b): Compressive test; Figure 6c): Shear failure

4.2 Tools and Methods

Basic profile dimensions of connection element in form of I-, ☐- or T-Profiles are to be obtained based on bending stiffness of the sandwich beam. The embodiment parameters of I-profile for smooth transmission of forces in considered further. The solution field is generally quite large to match the dimensions of the I-profile in bending load. The most efficient way of finding a solution is by following guidelines for dimensioning as suggested in literature [1]. Once the basic dimensions are chosen, FE-Simulation can be used to verify whether the stresses in sandwich beam and the I-profile satisfies their respective failure criterion. For sandwich beam, the simplified conservative-failure criterion can be chosen and for I-profile which is in this case made of steel, Von-Mises criterion shall be chosen. Differences in displacement results at interfaces can be used to check stiffness discontinuities. If geometrical solution is not satisfying for particular application and difficulty persists in finding an appropriate solution, then proper geometry can be find using shape optimization tools. In shape optimization, the outer boundary of the structure is modified to solve the optimization problem. Using finite element models, the shape is defined by the grid point locations. Hence, shape modifications change those locations [9]. 2D-Modelling and simulation will be the most appropriate method for shape optimization since it requires simplified modelling effort and reduced simulation time. Such modelling approach has conforming results with theory and 3D-modelling approaches [10]. Shape optimization for using commercial softwares such as Altair® Optistruct® allows change of shape of tongue of connection elements until specific stress criteria and deflection values are satisfied. Figure 7 shows such a connection element with minimized stress and stiffness discontinuities at connection interfaces in a 2D finite element bending simulation.

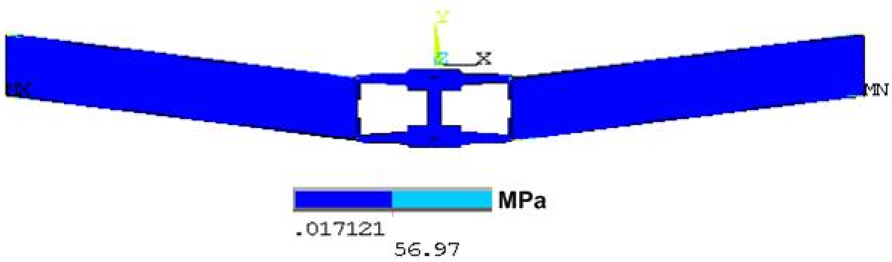

Figure 7: 2D simulation results of sandwich beam with I-profile

6. SUMMARY

Design engineering methods, tools and experiments suggested in this paper can be used for joining any polymer foam sandwich materials to its surrounding components and the procedure can be summarized as guidelines given below:

- Designing connection technique for sandwich elements requires information about the load carrying capacity of the sandwich material under multi-axial loading conditions. Using the test procedures suggested here, the necessary material parameters can be determined for the appropriate failure criterion.
- Application specific force and moment components data shall be collected based on homologation requirements of respective industry (railway/aircraft construction) or using experiments and simulation.
- The number of screw elements and the distance between them is calculated based on the cross-sectional geometry of the sandwich material and conforming to suggestions of VDI-Guideline 2230. Once the secondary and the primary variables as suggested in chapter 3 are known, strength calculations for screw elements can be performed.
- The basic dimensions of the connecting element can be chosen based on available profiles. 2D-FE simulation is one of the efficient tools to quantify the geometrical profile based on strength and stiffness continuity requirements. To achieve this appropriate failure criterion and displacement requirement has to be satisfied. If necessary, shape optimization tools shall also be used. By employing extrusion profiles, the appropriate geometry requirement of the connection element can be satisfied.

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