THERMOPLASTIC SANDWICH FORMING - NUMERICAL AND EXPERIMENTAL RESEARCH

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Abstract. The forming of sandwich structures in complex three-dimensional shapes represents a big challenge. The purpose of the present work is to examine, using a validated numerical model, the deformation and some failure modes of a sandwich structure that occur within a forming process. The Econcore's Thermhex® honeycomb core with PP skins, developed at K.U. Leuven, has been used along this investigation. The validation of the numerical model has been done by correlating the results obtained from four-point bending experimental tests with those obtained by four-point bending simulations. The properties of the material from the FPB simulations that give the best correlation with the experimental tests are further used in the forming simulation. The results have proven that the predominant deformation mechanism is out-off-plane shearing due to the localized forming forces. The structure fails due to very high shear stresses. A solution to improve the forming process for this type of structure may be the use of non-rigid die or punch tools.

Keywords: sandwich structure, forming process, thermoplastics materials, FE simulation

1. Introduction

Periodic cellular structures, as components of sandwich panels, have proven to be very useful in many domains but a production limitation appears when there is a need of using complex shaped sandwich panels. The possibility of exploiting thermoplastic composites to facilitate processing of complex shaped sandwich structures has been investigated by Rozant [1]. Mohr and Straza, [2], formed successfully all-metal sandwich sheets with perforated cores. In another paper [3], Mohr pointed out the importance of the out-of-plane shear strength in a sandwich forming process with bending in one direction. Based on theoretical considerations, he derived a relation between the maximum allowed punch force (directly linked to the core shear strength) and the minimum allowed tool radius for a certain configuration of the tools, sandwich configuration and sandwich material. However, the production of sandwich panels with complex shapes still represents a big challenge. The drive comes from big industries, like automotive, where a tendency can be noticed to implement such complex structures in the mass production because of their multifunctional aspect (lightweight, high stiffness and strength, safety, comfort, cost, etc.).

An important and economic aspect in the research activity of sandwich structures forming capabilities is represented by FE analyses which allow detailed investigation, of the behaviour of the deformed structure, on a valid geometrical model. Such analyses have been conducted at K.U. Leuven, by Macaluso [4]; he performed a non-linear analysis on a geometrically detailed sandwich unit cell to determine the shear strength of the given core. Afterards, by using the formula derived by Mohr [3], he calculated the minimal allowed tool radius which corresponds to the determined shear strength. The determined minimal allowed radius was used to perform deep-drawing FE analyses with bending in one direction and two directions. The analyses showed that the out of plane shear behaviour is very important in forming sandwich components.

2. Investigation approach

The research purpose of this work is firstly to validate the FE model of a honeycomb sandwich beam made of PP, namely the Thermhex® honeycomb core with PP skins, developed at K.U Leuven [5, 6], that has to be used for a forming simulation, and secondly to perform the forming simulation itself which allows to further examine the deformation and some failure modes of the structure and to improve the forming process. The validation of the numerical model has to be performed by correlating the results obtained from experimental tests with those obtained by simulations. Adequate test methods can reflect the loading conditions most often met in the forming processes. During the forming process the material is bended in one or two directions, parallel with or orthogonal to the production direction. Moreover, the thickness will eventually determine the mechanical properties of the sandwich (sandwich effect). By considering these aspects, the Four-Point Bending (FPB) test was selected for the experiments.

3. Four-Point Bending tests

3.1. Test definition

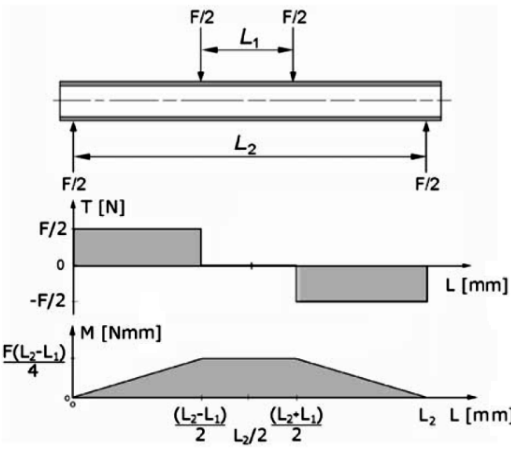

Figure 1. Schematic representation of a FPB test with the corresponding shear and moment diagram [7]

The FPB test, schematically shown in Figure 1, was accomplished on an INSTRON test machine. A load cell of 1KN was used.

The average dimensions of the samples with the corresponding deviations are presented in Table 1. The distances L1 and L2 between the outer and the inner contact cylinders were chosen to be as large as possible to reduce the bending moments. Thus, the achieved total deflection is higher, because failure, induced by buckling of the compressed face sheet, appears at larger deflections. The imposed displacement of the crosshead was 60 mm.

Table 1. FPB test parameters

Parameter	*Value*	*Deviation*	*Unit*
Samples length	308	±4	mm
Samples width	32,13	±2,5	mm
Samples thickness	8,7	±0,47	mm
L1	93	-	mm
L2	250	-	mm
Crosshead speed	5	-	mm/min

3.2. Results

Ten FPB experiments were conducted. The load-displacement curves were recorded. The most met premature failure mode during the experiment was the intracellular buckling, followed by the crushing of the core due to local compression.

From the ten FPB tests conducted, only 5 test results were used to calculate the average load-displacement curve, Figure 2. In these tests, the load goes over its maximum value without any failure appearing in the sandwich.

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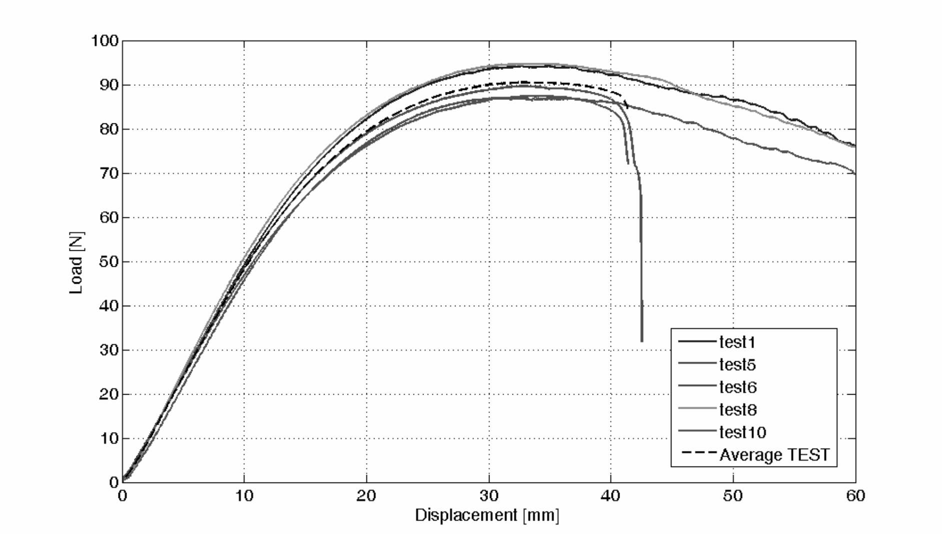

Figure 2. FPB test: average load-displacement curve

4. Four-Point Bending simulations and correlation of the results

The numerical simulations were performed using ABAQUS 6.7-4 software. A representative unit cell was built, figure 3, and used to create the sandwich beam by translating it in one direction. The single honeycomb wall thickness is 0.16 mm, the core height is 7.3 mm and the face sheet thickness is 0.8 mm.

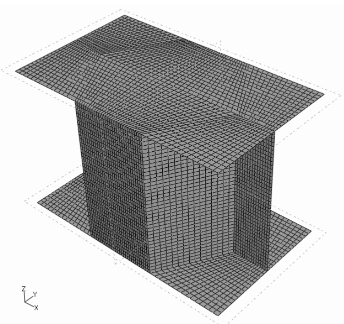

Figure 3. Model of the meshed unit cell

General-purpose shell elements (S4R) were used to create the mesh. The S4R element is a four-node element; each node has three displacement and three rotation degrees of freedom. Each of the six degrees of freedom uses an independent bilinear interpolation function.

4.1. Model definition

The FE model for the FPB Simulation, Figure 4, is reduced by exploiting the symmetry conditions. Thus, the FE model consists of an array of 17.5 unit cells, containing 1.196.976 degrees of freedom. The top right cylinder and the bottom right cylinder are analytical rigids, which means that they cannot deform and are defined by a single point named the reference point. On the top right cylinder a displacement of 60 mm was applied and, corresponding to the real experiment, the bottom right cylinder was fixed in space.

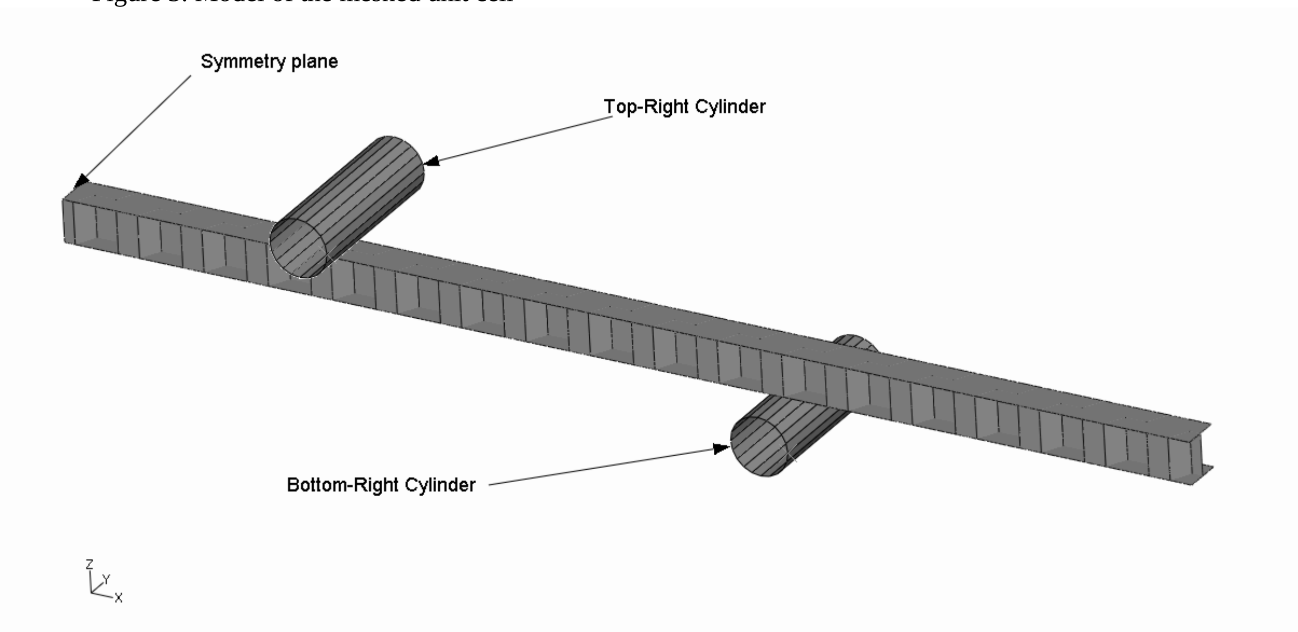

Figure 4. FPB FE Model

4.2. Results

The results of the FPB Simulation and correlation with the real experiment are presented in figure 5. The first correlation trial was done by including only the elastic properties of the material in the FE model, this case being represented by the Sim1curve in the results chart. Subsequent trials wich included plasticity in the FE model were done to get a better fit. It can be seen that the best fit with the experiments is represented by the dashed line (Sim11 curve). The properties of the material used on Sim11 are presented in Table 2 and Table 3.

The initial stiffness is predicted very well by the FE results. The maximum load reached is a little bit higher in the FE simulation. The uncertainties that can influence the results of the simulations can be classified in 3 categories, respectively:

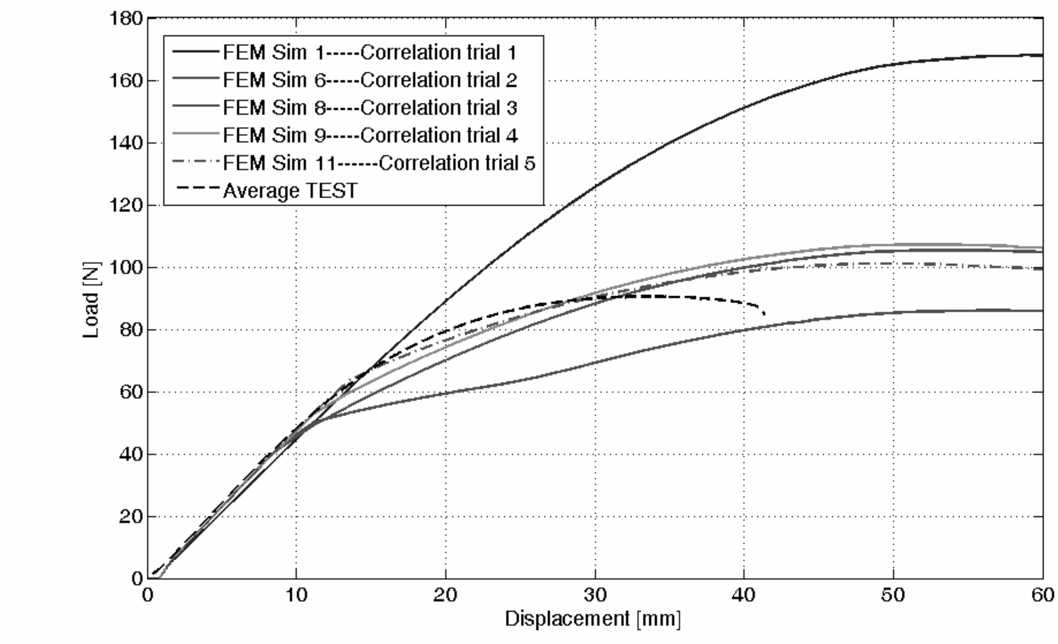

Figure 5. FPB FE simulation and correlation results

Table 2. Elastic properties

Young's modulus	*Poisson's ratio*
1810 MPa	0.3

Table 3. Plastic properties

Stress	*Strain*
13 MPa	0%
813 MPa	1%

- *material uncertainties*, which refer to the missing visco-elastic properties of the material and also to the elastic and plastic properties;
- *geometrical uncertainties*, which refer to the inclination of the cell walls; (the cell walls are perpendicular to the face sheets in the FE model but in reality there are inclined with an angle between 5 to 15 degrees);
- *uncertainties due to the technological process*, which refer to the straight shape of the walls and also to the adhesion of the face sheets to the core. In reality, the cell walls are curved due to the vacuum process.

In order to improve the correlation, the above mentioned categories of uncertainties have to be reduced.

5. Forming simulation

5.1. Model definition

The FE model for the Forming Simulation, figure 6, is reduced by exploiting the symmetry conditions. Thus, the FE model consists of an array of 28 unit cells, containing 2.070.831 degrees of freedom. The die, the holder and the punch are analytical rigid bodies, meaning that they can't be deformed and that they are defined by a single point named the reference point. A displacement of 60 mm was applied on the punch and the holder and the die was fixed in space.

The fine tuned properties of the material from the FPB simulation, presented in Table 2 and Table 3, were used in this simulation.

The minimum used tool radius was 2 mm while the maximum was 20 mm (figure 7).

5.2. Results

Figures 8 and 9 show details from an intermediate step of the forming simulation; it can be observed that the predominant deformation mechanism is out of plane shearing. The two analytical rigid bodies introduce the forming forces very locally leading to high shear stresses and buckling failure of the core.

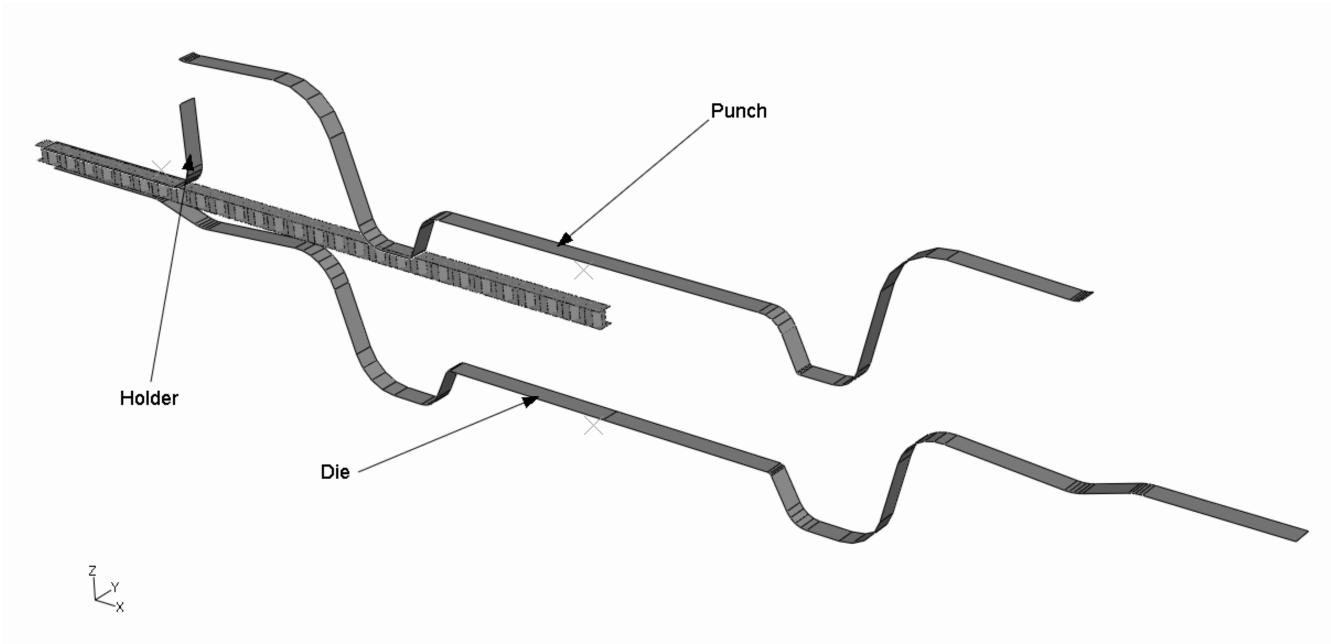

Figure 6. FE model of the forming process

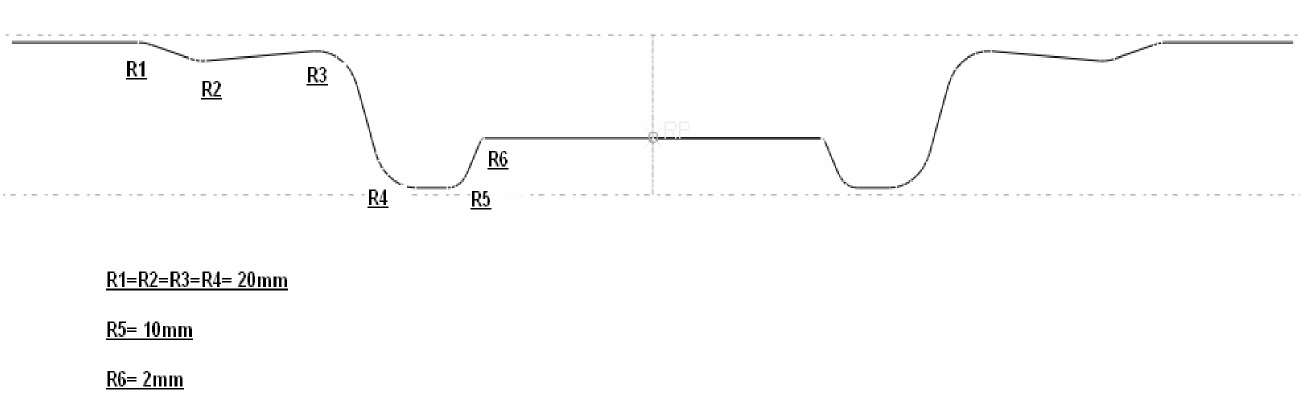

Figure 7. The geometry of the used die

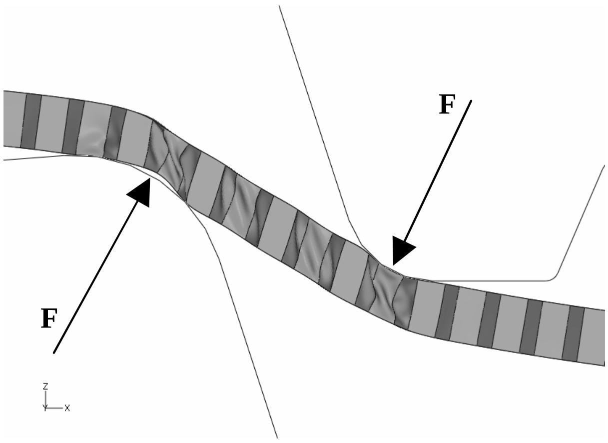

Figure 8. Out-of-plane shearing – detail 1

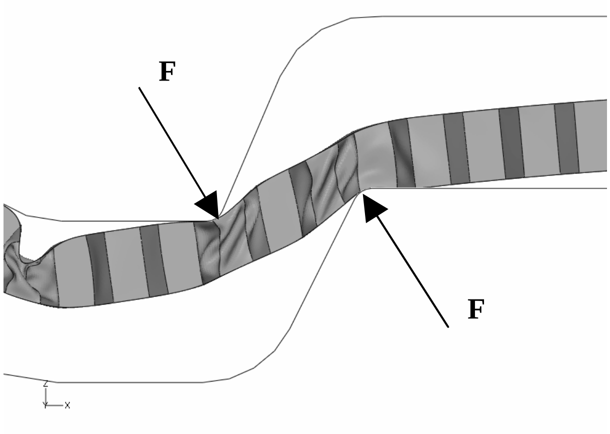

Figure 9. Out-of-plane shearing – detail 2

6. Discussion and conclusions

In big industries, such as the automotive one, a tendency to implement sandwich structures can be noticed due to their multifunctional aspect (lightweight, high stiffness and strength, safety, comfort, cost, etc). However, the production of sandwich panels with complex shapes still represents a big challenge. A honeycomb sandwich beam made of PP (Econcore's Thermhex® honeycomb core with PP skins) has been used in this work to investigate its forming capabilities. The results obtained show that the integrity of this sandwich structure, during the forming process, is affected by the following factors:

- *The minimum radius of the tools:*
  As Macaluso C. shows [4], the minimal allowed tool radius (for the considering Thermex® honeycomb core with PP skins) is 77 mm according to the equations derived by Mohr [3].
- *The core shear strength:*
  There is a direct relation between the core shear strength and the minimum allowed radius [3]. A compromise should be made when choosing the type of structure to be deformed, because higher shear strength will lead to a lower minimal tool radius allowed.
- *Heat influence:*
- The temperature influence was not taken into account in the analyses accomplished in the present work. According to the temperature distribution through the thickness of the structure, due to pre-heating, the stiffness properties of the structure will be decreased. This does not always represent a positive influence, mainly for the core material.

A solution proposal to improve the forming process for this type of sandwich structures is to reduce the shear force by using non rigid surfaces, e.g. a compliant material: a block of rubber, small silicone balls or the use of vacuum forming. In this way, the forming force will be distributed uniformly on the sandwich structure area. A number of international patents that refer to these forming principles are currently applied for simple sheet materials.

Acknwoledgement

This work was conducted at PMA division, Department of Mechanical Engineering from K.U. Leuven, Belgium. The authors gratefully acknowledge the support offered by engineer Calogero Macaluso and professor Dirk Vandepitte during the research period.

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