Numerical modelling of sandwich panels with a non-continuous soft core

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Abstract. The paper presents the problem of static analysis of sandwich structures with a non-continuous soft core. In the numerical 3D FE models, the core is divided into separated parts. The contact between these parts has the form of unilateral constraints. The model also allows for local debonding of the facing and local imperfections of sandwich panel geometry. Particular attention is paid to the problem of local instability of the facing that is compressed during bending. The phenomenon of progressive damage and the influence of non-continuity of the core on the structural behavior of the sandwich panel is also discussed.

Keywords: sandwich panels, soft core, multi-layered structures, finite element method, unilateral contact, local instability

1 Introduction

Sandwich structures are commonly used in various branches of industry. The subject of the paper are sandwich panels used in civil engineering. They are built from three layers: two metal facings and a flexible core. A typical core is made of polyurethane foam, polystyrene or mineral wool. The core made of polyurethane foam is a continuous structure, while the core made of polystyrene or mineral wool is discontinuous. In the latter case, (mineral wool) the core structure is very interesting because it consists of small blocks which have the shape of elongated cuboids. These blocks are called lamellae. The lamellae have the same thickness as the thickness of the core in the panel. Lamellae are displaced parallel to each other but are not connected together. The core parts are only glued to the facings. This paper is aimed at analyzing the behavior of sandwich panels with a discontinuous core.

The rapid development of technology has forced the development of appropriate numerical models allowing for an appropriate analysis of laminated composites, including sandwich structures. An overview of numerical models has been presented, among others in [1-3]. The behavior of layered structures is closely related to certain phenomena. Many of these phenomena concern the appropriate failure mechanisms determining the scope of application of the structure and the safety of its use. Various failure mechanisms are analyzed and explained in numerous research papers. Among the important issues it is necessary to mention local instability (wrinkling of facing) [4, 5], shear of the core [6, 7],

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global loss of stability [8], debonding, which is often associated with the occurrence of concentrated dynamic loads [9] and indentation caused by the crushing of the soft core under the acting force [10, 11]. Of course, the analysis of these phenomena requires the use of appropriate models.

Against the background of the rich literature concerning various issues related to sandwich panels, surprisingly few papers concern the discontinuous core and the core made of mineral wool. On the one hand, there are considerable difficulties in finding complete information about the properties of mineral wool used in sandwich panels. This is because most of these cores are covered by patents. On the other hand, this topic is unpopular, perhaps due to strong ties to the technology of the production of sandwich panels. One of the few papers devoted to the structural behavior of sandwich panels with mineral wool concentrates on wrinkling phenomenon [12]. In the paper [13], the results of laboratory tests and numerical simulations of panels with a hybrid core were presented. The influence of different proportions of mineral wool and polyurethane foam on the results of the four-point bending tests were investigated. It should be clearly noted that a number of research projects devoted to panels with mineral wool core dealt with issues of fire resistance [14].

This paper presents the extension of the existing numerical model developed for laminated panels with a homogeneous core [15]. Structures with a discontinuous core are very interesting because of their complex structural behavior, impossible for providing an accurate analytical description. The numerical model was developed taking into account bending, shear, support capacity, local stability and debonding effects. The model is suitable for prediction of structure behavior with various boundary conditions.

2 Problem formulation

The layered structure shown in Fig. 1 is considered. Both facings are made of zinc-coated steel. In the discussed analyses, only cases of flat or micro-profiled facings are considered, although the presented model also allows for the analysis of sandwich panels with deep-profiled facings. The core is made of mineral wool. Please, note that the core material is orthotropic. The mineral wool is manufactured as a board with mainly horizontally arranged fibers. The board is cut into narrow and long pieces (lamellae). The lamellae are rotated 90 degrees in the sandwich structure, which provides higher stiffness of the core. The contact surfaces between lamellae are not glued. Therefore, the core is non-continuous with longitudinal and transversal, whole depth discontinuities (Fig. 1).

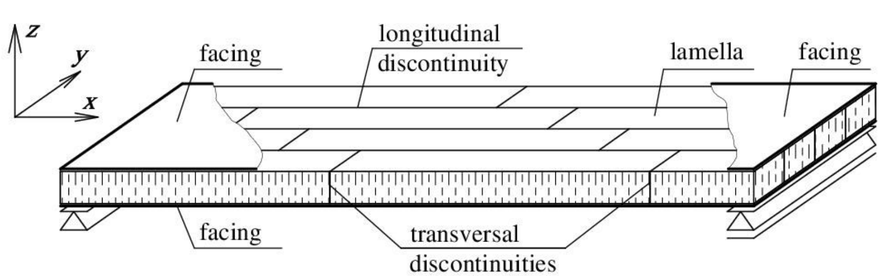


Fig. 1. Structure of a sandwich panel with mineral wool core

The aim of the paper is to analyze the influence of the core discontinuities on the sandwich panel behavior. It is important to explain the mechanism of damage and to explain the influence of material and geometric parameters on its initiation. The simplest static scheme of a single-span plate simply supported on two opposite (shorter) edges is considered. The plate is loaded uniformly on one surface. In all examples, suction was applied to the bottom facing of the sandwich panel. Such a simple static scheme was assumed because of the ease of interpretation of the results, although there are no obstacles to apply more complex boundary conditions.

3 Numerical model

The numerical model of sandwich structure was created based on previously carried out experimental and theoretical results. The model was prepared in the ABAQUS system environment. Material of steel facings was assumed as elastic - ideal plastic with: modulus of elasticity $E_F = 210$ GPa, Poisson ratio $v_F = 0.3$ and yield stress $f_y = 280$ MPa. Facings were modelled using S4R elements (four node, doubly curved, thin or thick shell, reduced integration, hourglass control and finite membrane strain). The core of the panel was modelled using eight node linear brick elements C3D8R. The behavior of the core material was defined using transversely isotropic elasticity. The following parameters of the core material were introduced: $E_1 = E_2 = 3$ MPa, $E_3 = 14$ MPa, $G_{12} = 1.43$ MPa, $v_{12} = v_{21} = 0.05$, $G_{13} = G_{23} = 6.36$ MPa, $v_{13} = v_{23} = 0.03$, $v_{31} = v_{32} = 0.14$. There are only five independent constants because of the relations $v_{31} / E_3 = v_{13} / E_1$, $v_{32} / E_3 = v_{23} / E_2$ and $G_{12} = E_1 / 2(1+v_{12})$. The total depth of the plate is 0.12, which consists of two facings, each 0.0005 m thick and the core (core with interfaces) of 0.119 m thick.

To enable initiation and propagation of the damage of the sandwich panel, between the facings and the core, a layer of interface was introduced. The 0.0005 m thick interface was modeled using COH3D8 8-node, 3D cohesive elements. Interactions between all parts were assumed as a TIE type, which makes equal displacements of nodes. The following elasticity uncoupled law for cohesive material of the interface was used:

$$\begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = \begin{bmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{bmatrix} \begin{bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{bmatrix} \tag{1}$$

where t_n is normal traction (stress) and t_s, t_t are shear tractions. Corresponding nominal strains are defined as $\varepsilon_n = \delta_n/T_0$, $\varepsilon_s = \delta_s/T_0$, $\varepsilon_t = \delta_t/T_0$ using separation δ and constitutive thickness of cohesive element T_0. The damage initiation criterion has the form of a quadratic nominal stress function. The damage is initiated when the function reaches a value of one:

$$\left\{\frac{\langle t_n \rangle}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 + \left\{\frac{t_t}{t_t^0}\right\}^2 = 1 \tag{2}$$

where the notation of Macaulay brackets is used:

$$\langle t_n \rangle = \begin{cases} 0, & t_n < 0 \ (compression) \\ t_n, & t_n \geq 0 \quad (tension) \end{cases} \tag{3}$$

The following parameters of the interface were used initially: $K_{nn} = 12000$ kPa, $K_{ss} = K_{tt} = 6000$ kPa, $t_n^0 = 140$ kPa, $t_s^0 = t_t^0 = 100$ kPa.

The mineral wool lamellae are glued to the facings, but there are no connections between the lamellae. The contact between the lamellae was modelled as the surface contact of 3D deformable bodies. Two types of contact in normal direction were used (Fig. 2): “hard” and an exponential pressure-overclosure relationship. The model of “hard” contact is described by the contact pressure p between two surfaces at a point, as a function of "overclosure" h:

$$\begin{cases} p = 0 & for\ \ h < 0 \quad (open), \\ h = 0 & for\ \ p > 0 \quad (closed). \end{cases} \tag{4}$$

In the case of exponential definition of the contact, clearance c_0 and pressure p_0 must be defined. To model tangential behavior of contacting bodies, the classical isotropic Coulomb friction model with the friction coefficient μ was applied:

$$\tau_{crit} = \mu p \tag{5}$$

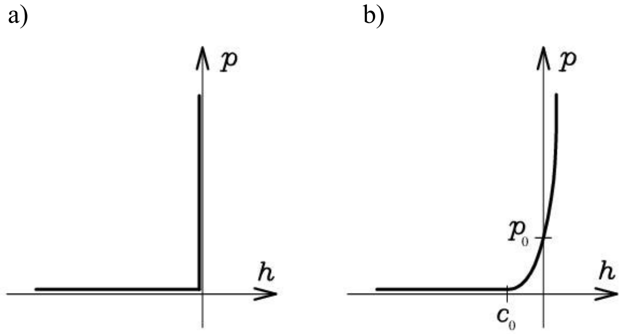


Fig. 2. Types of a contact definition in a normal direction: a) "hard" contact, b) exponential pressure-overclosure relationship

The numerical analyses were carried out for the following geometry: panel length $L = 4.80$ m, panel width $B = 0.50$ m and depth $D = 0.12$ m. The panel is based on two rigid supports with a width of 0.10 m, therefore, the span of the structure is 4.70 m. Both supports can rotate around the y-axis and, in addition, one of the supports can move in the x-direction.

The core consists of four rows of lamellae, each 0.125 m width and 0.119 m depth. The lamellae in the rows are mutually shifted 0.30 m along the x-axis. The original length of the lamellae is equal to 1.2 m, however a couple of them are cut due to the geometry of the panel. The arrangement of lamellae is shown in Fig. 3.

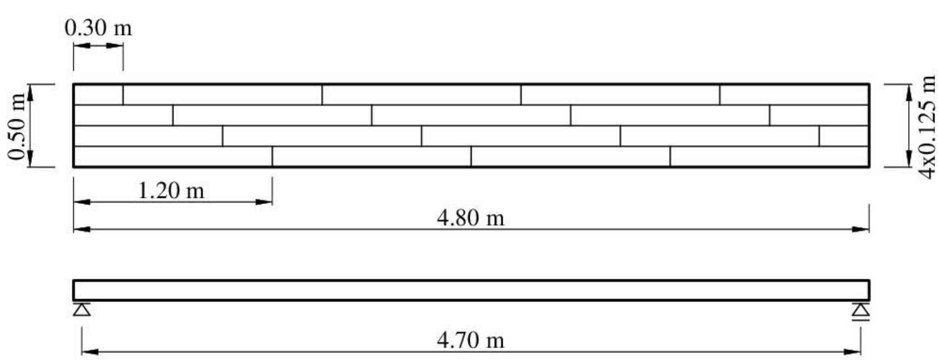


Fig. 3. The arrangement of lamellae in the sandwich panel

4 Results and discussion

In order to analyze the impact of the model parameters on the response of the structure, 6 models with different parameters of the interface and the contact between lamellae were considered. In each model, it was assumed that the facings are flat. A summary of these parameters is given in Tab. 1. The last column of this table contains one of the final results: the value of extreme tensile stress in the lower facing (in x direction). This value corresponds to the moment when the numerical solution loses convergence. Loss of convergence of the solution is due to interface damage and/or large deformations of the thin facing. The large deformation is hard to identify with the typical wrinkling of the facings, characteristic for panels with a continuous core, because in the case of a non-continuous core the local deformations of the facing are forced by vertical movement of the lamellae to each other. Two typical sandwich panel damages are shown in Figs. 4 and 5.

In the case of the Tep17_5 model (Fig. 4), the interface has been damaged near the support. When the interface has a lower strength (Fig. 5), the damage appears closer to the center of the plate. In every case, damage is initiated at the point of a contact between the two lamellae.

Table 1. Parameters and results of the numerical models

Model	Parameters of the contact between lamellae			Parameters of the interface		Extreme stress in the lower facing
	Normal behavior		Tangential behavior			
	p_0 [kPa]	c_0 [m]	Friction coefficient μ	t_n^0 [kPa]	$t_s^0 = t_t^0$ [kPa]	σ [MPa]
Tep17_1	0	0	0.10	140	100	177.3
Tep17_2	10	0.01	0.10	140	100	178.5
Tep17_3	10	0.01	0.50	140	100	184.5
Tep17_5	1	0.001	0.50	140	100	177.5
Tep17_6	1	0.001	0.50	70	50	105.2

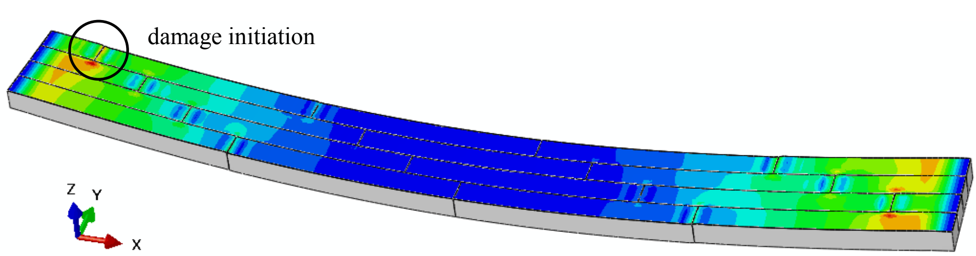


Fig. 4. Deformations that cause damage of the sandwich panel – model Tep17_5

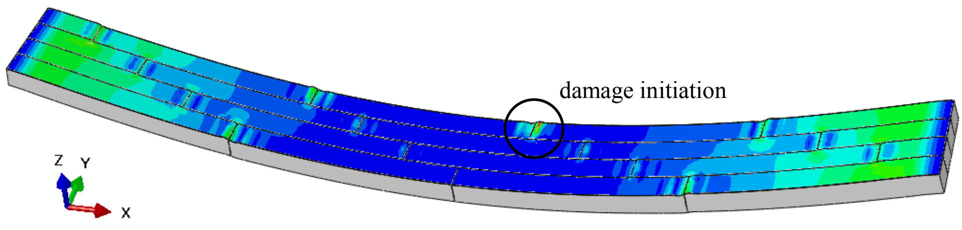
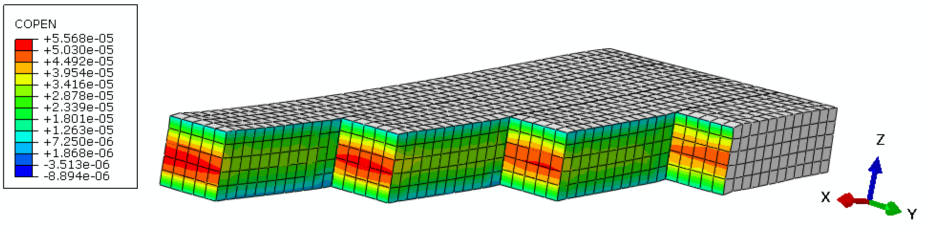


Fig. 5. Deformations that cause damage of the sandwich panel – model Tep17_6

The results shown in Tab. 1 show that the normal contact parameters have little effect on the final solution. Much more important is the coefficient of friction between the lamellae, although even a fivefold change in this factor has increased the load that causes damage by less than 4%. The strength of the interface layer is decisive. This may seem obvious, although it should be noted that in the case of a continuous and homogeneous core, the interface parameters are not as significant (assuming its reasonable strength). This was shown, among others in [16]. In the case of the core made of lamellae, however, the situation is somewhat different. The mutual movement of the lamellae causes strong deformation of the facings (and the interface), which leads to the failure of the interface and progressive damage. At low interface strength, there is damage near the support (this can be attributed to the shear effect). With higher interface strength, the damage occurs in the zone closer to the center due to the interaction of shear stresses and stresses caused by local instability of the facing. Damage always occurs at the surface of contact of lamellae.

To illustrate the typical phenomena occurring at the lamellae contact, Fig. 6 shows COPEN (contact opening at surface node) and CPRESS (contact pressure at surface node). The drawings clearly show that the opening between the lamellae occurs in the mid-height of the core.

a)



b)

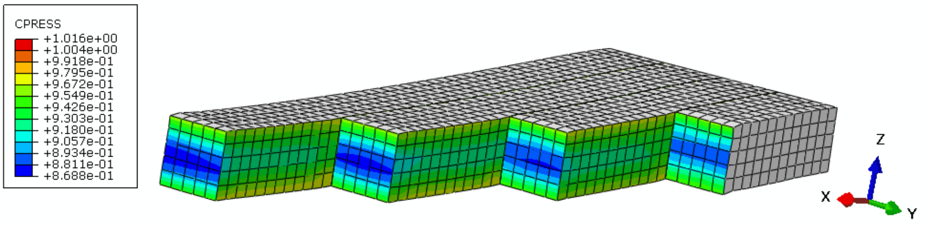


Fig. 6. Contact between lamellae: a) contact opening at surface node [m], b) contact pressure at surface node [kPa]

It is worth explaining one additional aspect. Models with defined contact are characterized by the dependence of results on mesh size. In the presented models, a mesh size of 0.025 m (5 spatial elements per core thickness) was used. Analyses based on a mesh size 0.06 m led to a very rapid loss of solution convergence. Several attempts on a denser mesh showed no significant difference in relation to the 0.025 m mesh size.
After identification of the failure mechanism, additional analyses were conducted to determine the impact of initial imperfections. For the Tep17_5 model, the first 10 buckling modes were determined. As the initial imperfection, the sum of the first and the second buckling mode multiplied by 0.00001 (Tep17_5_imp), 0.01 (Tep17_5a_imp) and 0.1 (Tep17_5c_imp) was assumed, respectively. As a result, in the Tep17_5c model extreme geometric imperfections reached locally 1.6 mm. Parameters of these models and the solution results are shown in Tab. 2. The presented results indicate that small imperfections are not significant. This is because the system of lamellae is a sufficient disturbance of the model needed to locate the failure.

Table 2. Parameters of the numerical models with initially defined imperfections

Model	**Parameters of the contact between lamellae**			**Parameters of the interface**		**Extreme stress in the lower facing**
	Normal behavior		**Tangential behavior**			
	p_0 [kPa]	c_0 [m]	Friction coefficient μ	t_n^0 [kPa]	$t_s^0 = t_t^0$ [kPa]	σ [MPa]
Tep17_5	1	0.001	0.50	140	100	177.5
Tep17_5_imp	1	0.001	0.50	140	140	177.5
Tep17_5a_imp	1	0.001	0.50	140	140	177.5
Tep17_5c_imp	1	0.001	0.50	140	140	146.3

Finally, the effect of micro-profiling of the facings and discontinuity of the core was also analyzed. Model Tep17_6 was used as a basis. In Tep17_4 model, the flat facings were replaced by micro-profiled elements (depth of profiling 0.5 mm). In Tep17_7 model, the discontinuous core (lamellae) was replaced by a continuous core having the same parameters as the lamella. The results are presented in Tab. 3.

Table 3. Parameters and results of the numerical models

Model	**Parameters of the contact between lamellae**			**Parameters of the interface**		**Extreme stress in the lower facing**
	Normal behavior		**Tangential behavior**			
	p_0 [kPa]	c_0 [m]	Friction coefficient μ	t_n^0 [kPa]	$t_s^0 = t_t^0$ [kPa]	σ [MPa]
Tep17_6	1	0.001	0.50	70	50	105.2
Tep17_4	1	0.001	0.50	70	50	106.3
Tep17_7	1	0.001	0.50	70	50	121.1

From Tab. 3, it follows that micro-profiling (Tep17_4) did not have much impact, although in my opinion this conclusion should be combined with the attention that this refers to the case of low strength of the interface. In the case of higher interface strength, the greater importance of micro-profiling of the facings (particularly the compressed facing) should be expected. Replacing the discontinuous core by the continuous element (Tep17_7) resulted in an increase in the sandwich panel capacity by about 15%. The research conducted by manufacturing companies shows that this difference may be greater. The influence on this may have several parameters related to the technology of the production of sandwich panels.

Conclusions

The analyses presented in the paper indicate a specific mechanism of failure of sandwich panels with a discontinuous core. Due to the lack of core continuity, as a result of load increment, there is a mutual displacement of the lamellae. The induced deformations result in damage of the connection between the core and the facing. In the numerical model, this corresponds to the failure of the interface layer. Depending on the interface parameters, damage occurs either in the support zone or in the center zone of the panel, whereby damage is always initiated near the contact surface of the lamellae.

Unlike in the case of panels with a continuous core, the interface parameters significantly affect the capacity of the structure. Of course, the stiffness of the core also has an influence on the load capacity of the panel, but the analysis of this problem has been omitted in this paper. In addition, unlike the structure with a continuous core, it turned out that micro-profiling of the facings and minor imperfections are much less important. These are interesting observations, although their generalization requires further numerical and experimental studies.

Discontinuity of the core reduces the capacity of the sandwich panel. Unfortunately, due to technological reasons, there is no way to avoid these discontinuities in the case of mineral wool core. For this reason, there are further interesting research areas, such as the optimization of an arrangement. Based on the review of the literature, it should be stated unequivocally that the problem of analysis of sandwich panels with discontinuous core has unfortunately not been thoroughly investigated.

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