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NUMERICAL ANALYSIS OF SANDWICH PANELS SUBJECTED TO POINT LOADS

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Abstract. *The paper concerns the problem of static structural behavior of sandwich panels. The panels are made of thin steel sheets and a thick, but soft core. The effects of the impact of concentrated loads on the structural behavior of the panels are discussed. Several different cases of concentrated loads were considered: load acting in the plane of the panel, load perpendicular to the panel and the additional action of concentrated bending moment. The loads are transferred to the panel by a small steel slab. The slab is attached to the facing of the panel. Described load cases correspond to situations encountered in engineering practice. In order to analyze the issue, a 3-D numerical model was used. Between the facing and the deformable core an interface layer was introduced, wherein the criterion of damage initiation and damage propagation were defined. Different failure modes were taken into account. Due to the character of the problem, the geometrically nonlinear analysis and Riks' method were applied. For each load case a failure load and extreme stresses leading to failure were determined. The differences in the obtained results were explained and the appropriate failure mechanisms were discussed. Analyzed sandwich panel has fixed geometries, however, made observations are universal. The obtained results tend to look more carefully at the problem of the impact of concentrated forces. This problem is particularly important in the case of sandwich panels, which due to its construction are very susceptible to local influence.*

1 INTRODUCTION

The paper concerns sandwich panels made of thin steel sheets and a thick, but soft core. The most commonly used are polyurethane foam cores. The sandwich elements are very attractive because of high load-bearing capacity at low self-weight and excellent thermal insulation. Therefore, these elements are used in the space industry, aerospace, shipbuilding, and automotive industries. Currently, it is also difficult to imagine civil engineering without the sandwich panels that are used as a building envelope (walls, roofs), partition walls and suspended ceilings.

The structural behavior of sandwich structural elements with uniform support and load conditions has been repeatedly studied and described [1, 2]. The analysis of systems subjected to a concentrated load is much more difficult. The existence of deformable core leads to sensitivity of sandwich panels with respect to localized effects [3]. One of these effects is wrinkling, which is a form of local instability of the sandwich facing. Wrinkling failures of sandwich columns under compression, beams in three- and four-point bending and cantilever beams under end loading were investigated in [4]. Analytical, numerical and experimental approaches to the problem of wrinkling in the case of nonlinear materials were presented in [5, 6]. Another form of damage is debonding. It occurs for example in the case of tensile forces between a core and a facing. The inter-layer failure modes are very often initiated by an impact [7, 8, 9]. An important failure mode is indentation. The failure is caused by the crushing of the core under a localized force. The problem of indentation loads was investigated in [10]. Recently, in order to better describe this phenomenon, sophisticated core models are applied [11]. Another, experimental approach was presented in [12].

In practice, the most common are three cases of concentrated actions: the impact of devices on the roof panel, interactions at the points of attachment of a sandwich panel to the supporting structure and the impact of equipment (e.g. advertising banners) on the wall panel. In the latter case, the load in the plane of the sandwich plate usually dominates, although it is almost always in combination with loads perpendicular to the plate. It should be noted that in the case of concentrated loads, we have to deal with the simultaneous occurrence of global and local phenomena (debonding, indentation, wrinkling). The difficulty in analyzing systems subjected to point loads stems not only from the nature of the load, but also its location. Structural analysis, in the case of asymmetric load conditions, requires the use of at least 2-D models [13]. This is very important because the sandwich systems are characterized by a material anisotropy deepened by different geometries of each layer. In this paper the described phenomena are analyzed using a 3-D model [14]. This article is focused on the case of point loads applied to the wall panel. Most attention was paid to the identification of failure mechanisms.

2 DESCRIPTION OF THE PROBLEM

Consider a wall sandwich panel that can be installed vertically or horizontally. For the brevity of presentation, a one-span panel is analyzed. The supporting structure is located inside the building. One can say that the panel is simply supported on two opposite edges, although a 3-D model will be considered, in which the depth of the panel has an impact on the description of the boundary conditions. Assume that the external loads are localized in the middle of the sandwich panel and are applied to the external facing of the panel (Fig. 1). The load conditions should simulate the impact of equipment (e.g. advertising banners) on the wall panel. Taking into account the expectations of the market, with full awareness it is assumed that the load will be applied only to the external facing, and there will be no additional elements to ensure cooperation between the two facings of the panel. This corresponds to the situation when a piece of equipment is attached to the external facing by glue or screws only.

In fact, there are not strictly 'point' forces, but rather distributed on a small surface. Therefore, it was assumed that the defined forces will be transferred to the sandwich panel by a square steel slab with a side length a and a thickness t (a=0.08 m, t=0.008 m).

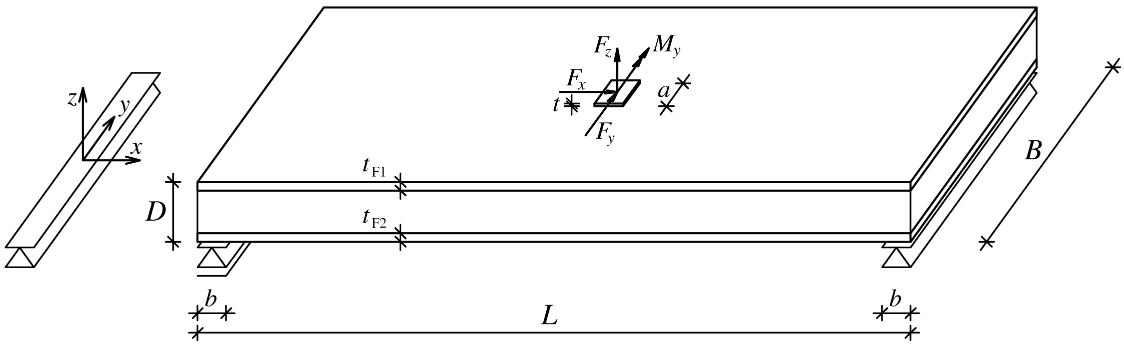

Figure 1: The 3-D model for the analysis of sandwich panels subjected to concentrated loads.

In general, on the upper surface of the steel slab, at its center, there may occur 3 forces and 3 concentrated moments. The paper examined the 6 load cases:
a) there is only F_x (the name of the model: *eco_21*),
b) there is only F_y (*eco_21h*),
c) the increasing of F_x accompanied by the constant compressive load F_z = –1 kN (*eco_21n*),
d) the increasing of F_x accompanied by the increasing of $M_y = 0.1F_x$ (*eco_22*),
e) there is only the tensile force F_z (*eco_24_ten*),
f) there is only the compressive force F_z (*eco_25_com*).
The above load cases correspond to the direct attachment of the loading element to the sandwich panel arranged vertically (*eco_21*) and horizontally (*eco_21h*). The additional localized effect of wind pressure was considered in model *eco_21n*. Model *eco_22* corresponds to the case of weight mounted on the arm 0.1 m. Cases of the load acting perpendicular to the sandwich panel (*eco_24_ten, eco_25_com*) were prepared for comparison with the other cases. Loads perpendicular to the sandwich panel simulate (to some extent) concentrated impacts on the ceiling. In all cases they were considered to be only static loads.

The aim of the paper is to identify the phenomena occurring during the action of concentrated loads on the sandwich panel. The key issue is to determine the failure mechanisms and estimate the values of load capacity. The problem of distribution of applied load is equally interesting.

3 THE NUMERICAL MODEL

The 3-D numerical model was prepared in the ABAQUS system. The parameters of the system correspond to the values determined in laboratory tests. A sandwich panel with a length 5.00 m is located on two supports with a width of 0.10 m. The width of the panel is B = 1.0 m. The total depth of the panel is 98.43 mm. The thickness of each of the faces is $t_{F1} = t_{F2}$ = 0.471 mm. The modulus of elasticity of the facing material is E_F = 195 GPa and Poisson's ratio equals ν_F = 0.3. The actual relationship between stress and strain was introduced. The yield strength was 360 MPa, and the ultimate strength reached 436 MPa. Facings were modeled using a four node doubly curved, thin or thick shell, finite membrane strain elements S4. At this stage of the study, the core was considered as isotropic material with a modulus of elasticity and E_C = 8.61 MPa and Poisson's ratio ν_C = 0.02. As a result, shear modulus is G_C = 4.22 MPa. The core was modeled using eight node brick elements C3D8.

To assess the cause of the failure of the sandwich panel, between the steel facing and the soft core, an interface layer of a thickness of 0.5 mm was introduced. The interface was modeled using COH3D8, 8-node 3-D cohesive elements. The following uncoupled elasticity law for cohesive material 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 failure initiation was conditioned by a stress state. The quadratic nominal stress criteria of damage initiation and linear softening damage evolution were used. 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 typical notation of Macaulay brackets is used. The following parameters of the interface were used: K_{nn} = 8.61 MPa, $K_{ss} = K_{ss}$ = 4.22 MPa, t_n^0 = 123 kPa, $t_s^0 = t_t^0$ = 112 kPa.

The point loads were applied in the middle of the external surface of the transferring steel slab. The mesh size was equal to 0.02 m over almost the entire FEM model. In the vicinity of the force application, the mesh was condensed to 0.0067 m. Interaction between all parts was assumed as the TIE type, which makes equal displacements of nodes. It is certainly not a perfect type of connection, however, it is sufficient to evaluate the most important phenomena. The supports were modeled using analytical rigid elements. Boundary conditions at reference points ensure the freedom of rotation around the *y*-axis. One of the supports is free to shift along the *x*-axis. Because the problem was expected to exhibit significant local effects, a geometrically nonlinear static analysis and the Riks' method were applied.

4 DISCUSSION OF THE RESULTS

For each static scheme was obtained the force causing local damage to the interface. In every case, the failure results from the tensile stress σ_{zz} in combination with shear stresses τ_{xz} i τ_{yz}. The respective values are given in Table 1.

Model	Failure load	Extreme normal stress σ_{zz} [kPa]	Extreme shear stress τ_{xz} [kPa]	Extreme shear stress τ_{yz} [kPa]
eco_21	F_x = 2.22 kN	+119.9 / –138.2	+20.66 / –24.93	+27.13 / –27.13
eco_21h	F_x = 2.21 kN	+119.0 / –136.5	+20.71 / –20.71	+20.32 / –24.81
eco_21n	F_x = 4.28 kN with F_z = –1 kN	+81.19 / –530.1	+42.32 / –106.2	+96.67 / –96.67
eco_22	F_x = 0.164 kN with M_y = 0.0164 kNm	+119.9 / –135.6	+21.43 / –22.96	+26.85 / –26.85
eco_24_ten	F_z = 0.670 kN	+115.3 / –0.934	+33.99 / –33.99	+34.46 / –34.46
eco_25_com	F_z = –1.95 kN	+17.86 / –431.6	+106.0 / –106.0	+96.03 / –96.03

Table 1: Failure load and extreme stresses in the interface layer.

Failure load is identical in the case of a load applied along the panel (*eco_21*) and crosswise the panel (*eco_21h*). This is despite the fact that in the latter case, the panel rotates about the axis *x*. The displacements are small because they do not exceed 1 mm. Applying an excitation force to the steel slab causes that the force acts on an arm in relation to the plane of the supports. As a result, the steel slab indents the sandwich core on the one edge and detaches the facing from the core on the other edge. This leads to the destruction of the interface. Interestingly, these phenomena occur only locally, i.e. in the immediate vicinity of the applied load (Fig. 2).

Also note that the small additional load compressing the panel (*eco_21n*) increases the load capacity, since it counteracts the detachment of the facing from the core. In the model *eco_22* even a slight bending moment results in a drastic decrease of the maximum force F_x. This leads to the conclusion that the attachment of any elements to sandwich panels should be avoided, if the attachment is realized only to one facing.

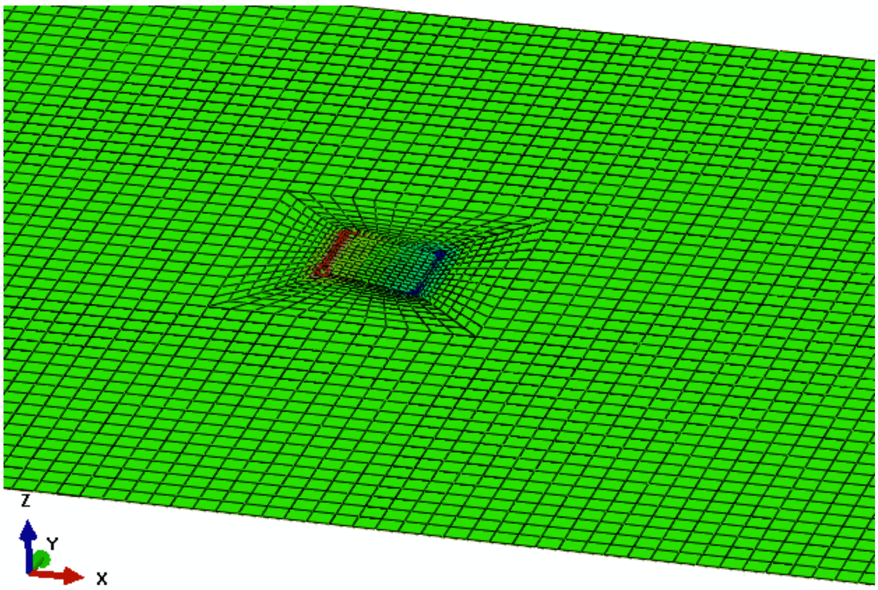

Figure 2: Distribution of the stress σ_{zz} in the interface layer of the model *eco_21*. Blue indicates compressive stress and red indicates tensile stress.

In the case of tension load directed perpendicularly to the facing (*eco_24_ten*), the maximum force reached the expected level, although somewhat surprising is the low redistribution of the applied load. In the case of compressive load (*eco_25_com*) there first appears the effect of plasticity of the steel facing, and later shear of the interface. Interestingly, there was no wrinkling of the steel facing, although the numerical model is suitable for the analysis of such phenomena.

5 CONCLUSIONS

Conducted numerical analysis shows that the problem of concentrated loads is very important. For each load case, local damage occurred between the facing and the core. Failure loads were low in value. A particularly unfavorable case is the load acting on an arm. Even a small bending moment causes locally high stresses with different signs. According to the authors of the paper, in the case of the bending moment, it is necessary to ensure close cooperation between the two facings of the sandwich panel. In the case of concentrated forces acting in the plane of one facing or perpendicular to the facing, the small load-bearing capacity of the panel should be considered. Local interface failure can lead to further damage propagation.

The discussed phenomenon, in particular the lack of significant redistribution of applied load, puts a new light on the classical approach to the problem of concentrated loads. Assessment of the effects of concentrated loads cannot be limited to the global effects, but must also take into account phenomena occurring locally.

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