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Structural behavior of sandwich panels with asymmetrical boundary conditions

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ABSTRACT

Asymmetrically supported and loaded sandwich panels with a polyurethane soft core and isotropic or orthotropic steel faces were analyzed in laboratory tests and numerical simulations. The influence of the steel face microprofilation on the mechanical and kinematical responses of the sandwich panel is considered in the paper. The real experiments were conducted for two supporting systems. For each supporting system isotropic and orthotropic sandwich faces were taken into account. The numerical simulations, in which 2D composite shell elements were used, correspond to the real experiments. The laboratory tests showed that introducing the orthotropic face layer significantly increases the load capacity of the sandwich panel. In the case of asymmetrically supported systems effective flexural rigidity increases too. The paper demonstrates that a relatively simple FE model can be successfully used to assess the global behavior of sandwich panels in complex boundary conditions. Satisfactory consistency of the numerical and real results in the linear range of structural behavior was obtained. Further improvement of the model is possible by introducing a definition of the failure criteria.

1. Introduction

Sandwich panels are composite structures that consist of two thin external faces and a thick core. In civil engineering applications the faces have high-strength and are usually made of steel or aluminum. The core material has low-density and is made of mineral wool, polystyrene, or polyurethane foam. The cross-section of the faces can be flat, lightly profiled (microprofiled) or deep-profiled. The bending out-of-plane stiffness of the flat and lightly profiled face is negligible while the bending stiffness of the deep-profiled face is significant. Therefore, the flat faces carry bending moments as tensile and compressive stresses and the core carries shear force. If the faces are deep-profiled, they convey additional bending moment and shear force related to their bending and shear stiffness.

The lightly profiled face is characterized by a rib depth of less than 2 mm. The main aspect of the use of lightly profiled face raised in literature concerns the increase of the allowable wrinkling stress level. The experimental investigation of the local buckling problem was presented in [1]. The interaction of the flexural wrinkling and local buckling effects in case of lightly profiled faces was discussed in [2], whereas the influence of the transverse joints on the wrinkling strength was taken up in [3]. In this approach, the material is isotropic and the behavior of a 3D structure depends on the geometry of the faces. The paper [4] deals with the buckling phenomenon of facings of sandwich panels subjected to shear monotonic and cyclic loads. These types of shear loads occur in the case of the sandwich panels considered as a diaphragm in steel buildings.

Contrary to the above-mentioned approach, many problems were formulated using an orthotropic material definition of layers of sandwich structure. The majority of the works deal with the local and global stability phenomena. In Ref. [5], the authors verified the accuracy of the existed simple column buckling formulas in the case of composite or sandwich structures. In Ref. [6,7], the exact formulas of local and global loss of stability for sandwich beams and plates that are axially loaded along their short edge were shown. Nevertheless, the derived formulas concern only sandwich structures with symmetrical orthotropic layers. The interactive buckling involves the interaction between the global and local buckling modes. This phenomenon in the case of sandwich struts with orthotropic core layer was described by an analytical model in Ref. [8], while in Ref. [9,10] it was described by a nonlinear variational model. The paper [11] adapts the interactive buckling phenomenon of compressed sandwich struts for bent and compressed sandwich struts. The problem of local and global loss of stability of the sandwich beam with an orthotropic layer in the context of the varied boundary conditions was presented in Ref. [12].

Many authors have shown that sandwich structures are sensitive to concentrated load. The approximate method of the analysis of the sandwich panel with orthotropic faces subjected to localized load was presented in Ref. [13]. Parametric studies demonstrated that the failure caused by local bending depends on the thickness of the loaded face.

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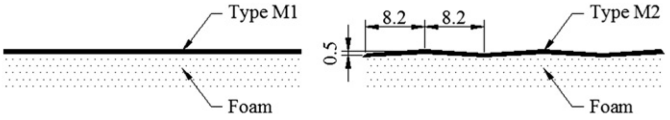

Fig. 1. Geometry of the upper faces of sandwich panels: M1 — flat, isotropic and M2 — microprofiled, orthotropic.

In Ref. [14], the response of the orthotropic sandwich panels subjected to the localized load was presented. It was demonstrated that the results obtained by the use of higher order theory are in satisfactory agreement with the exact elasticity solutions available in literature, while the results obtained by classical and shear deformation theory underestimate strains by more than an order of magnitude. The experimental investigation of the local bending effect of a symmetrically supported sandwich beam in a three-point bending test was presented in Ref. [15]. It should be noted that, as in Ref. [13–15], most of the papers concern the problems with symmetrical support and load conditions.

A slightly different problem of the homogenization of the cross-section of the sandwich with orthotropic layers is also undertaken often. Several homogenization methods were presented in Ref. [16]. The homogenized model of a sandwich shell with a hexagonal honeycomb core was discussed in Ref. [17,18]. Homogenization of the orthotropic, corrugated-core sandwich panel was considered in the case of torsion [19], static thermal loads [20] and a free vibration problem [21].

In this paper sandwich panels with a lightly profiled face are considered. The material of facings is isotropic, but because of the micro-profiling, the behavior of the face is different with respect to the direction of loading. The approach presented in the paper consists of experimental examination of the face, and then the application of the results to define the micro-profiled face as an orthotropic layer. Orthotropic layers of the sandwich structure were often discussed in literature, but usually with regard to symmetrical problems. In this paper sandwich panels are subjected to asymmetrically applied concentrated force. Two types of support conditions are considered. The problem of non-uniform load and support conditions occurs in civil engineering applications due to concentrated loads due to the weight of equipment, or to supporting at the edges of the building etc. The results of conducted numerical simulations were compared with real experiments.

2. Description of the problem

The present paper concerns sandwich panels with thin steel faces and soft polyurethane foam core. Two types of faces are considered: isotropic (flat) and orthotropic (microprofiled). The types of faces were named M1 and M2, respectively. Face microprofiling is performed in the longitudinal direction of the panel during the manufacturing process. It applies to increase the sandwich capacity due to a local loss of stability (wrinkling) of compressed face in bending. Cross sections of the considered steel faces are presented in Fig. 1.

The aim of the paper was assessment of the impact of such defined orthotropy on the structural behavior of asymmetrically supported and loaded sandwich panels. The load capacity and the stiffness of the structures were investigated by full-scale laboratory tests and FE analyses. The load capacity was measured by the level of failure load (usually associated with local buckling of the compressed face) while the stiffness was measured by the deflection of the panel. Real and numerical results were compared to determine the permissible range of application of a simple FE model. A reliable FE model helped in the analysis of complex states of stress and strain occurring in sandwich panels with asymmetric boundary conditions.

To achieve the goals, two sets of tests were planned and carried out: type A — sandwich panel supported on two edges with asymmetrically applied downward concentrated force; type B — sandwich panel supported on three edges with asymmetrically applied downward concentrated force, see Fig. 2.

In Fig. 2 the supported edges are marked with dashed lines while the point of the applied load F is marked by a black square. The longitudinal microprofiling is along the direction x_1. Each type of test (A and B) was carried out for both the sandwich panel with flat faces and the sandwich panel with microprofiled upper face and flat bottom face. It should be stressed that in the case of the laboratory tests, all panels (isotropic and orthotropic) were from the same batch. Hence, the compatibility of mechanical parameters of the sandwich core and faces was assured. Moreover the strains and the displacements in carefully selected points were measured during the experiments. In the case of FE analyses the composite shell finite elements were used. The geometrical dimensions and material constants of sandwich panel layers in FE analyses were taken respectively from the appropriate measurements and tests.

3. The geometrical dimensions and material parameters of sandwich panel layers

The sandwich panels considered in this paper consist of two thin steel faces and a thick and soft polyurethane core. The following parameters of polyurethane foam core were measured: the thickness $d_C = 0.08$ m, the shear modulus $G_C = 3.20$ MPa, and the Poisson ratio $\nu_C = 0.05$. The zinc-coated steel faces have a total thickness of $t_F = 0.460 \cdot 10^{-3}$ m. The thickness of the pure steel core $t_F^c = 0.420 \cdot 10^{-3}$ m were obtained. The following, effective material parameters were determined on the basis of the tensile test: the Young modulus E_F, the upper yield point R_{eH}, the tensile strength R_m, the ultimate elongation A, and the maximal tensile force F_u. All determined effective material constants were related to the thickness t_F (zinc-coated steel). The test specimens were rectangular 20 × 230 mm with the original gauge length of 80 mm. The tests were performed using a force gauge applicable in the range from 0.5 kN to 10.0 kN. Additionally, during the tests an extensometer was used. The velocity of the traverse beam was 12 mm/min. The statistical data from six tensile tests are listed in Table 1, where $\bar{x}$ and δ denote the mean value and standard deviation, respectively.

The statistical data included in Table 1 should be elaborated on. The stress–strain relations in tension tests are presented in Fig. 3. The dotted line represents results for the flat face (M1), while the dashed and the continuous lines illustrate tension test of a microprofiled face (M2) along direction x_1 and direction x_2, respectively.

The following observations arise from the analysis of the stress–strain curves presented above. Firstly, the material constants and mechanical response are the same for the tensioned flat face and the microprofiled face tensioned along x_1. Secondly, the stress–strain relationship obtained for microprofiled face from the tensile test along x_2 is non-linear even below the yield point. Thus, the Young modulus

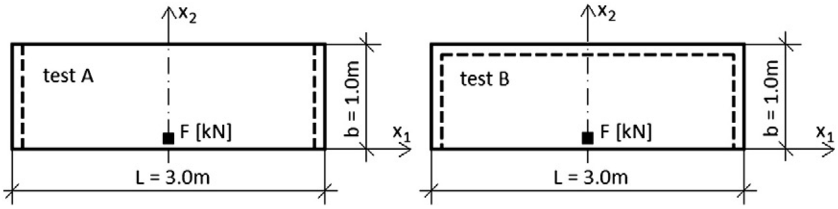

Fig. 2. Schemes of boundary conditions of conducted tests; x_1 and x_2 — axes of the coordinate system.