BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVI (LX), Fasc. 3, 2010
Secţia
CONSTRUCŢII. ĂRHITECTURĂ

A COMPARATIVE STUDY OF THE ANALYSIS, NUMERICAL MODELLING AND EXPERIMENTAL TEST ON A SANDWICH PANEL WITH PLANE AND PROFILED FACINGS

BY

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Abstract. Sandwich panels are remarkable products because they can be as strong as a solid material but with less weight. The analysis that is required to predict the stresses and deflections in panels with flat or lightly profiled facings is that of conventional beam theory but with the addition of shear deformation. Knowing that the profiled sheets bring an increase of the flexural stiffness, formulas showing the calculus of a panel with flat and profiled facings are established. A comparison between the results of a mathematical calculus, an experimental test and a numerical modelling is provided.

Key words: sandwich panel; layers; deflection; failure mode calculus.

1. Defining the Sandwich Structure Concept

The sandwich panel concept is very spread today and it has all the reasons to be used in many applications. The one that discovered it long ago, Fairbairn around year 1849, produced a great impact on the way many things developed after [1].

To express it in a simpler form, the sandwich structure generally means a three layer structure, in which the two external layers that are strong, stiff and thin are bonded and work together through a lightweight intermediate layer that has a reduced rigidity and strength, with the important feature that they will exhibit the best qualities of their constituents and often some qualities that neither constituents posses [2].

Consequently one of the immediate effect is to lower the elements own weight by using new performant materials. It also reduces the structural elements cross-section and provides the functional delimitation of the layers that compose the sandwich structure, ensuring the industrial fabrication for the construction elements and for construction as well.

2. Bonding and the Sandwich Effect

In a sandwich structure the outer layers (facings) resist the most part of the axial forces, provide the stiffness and general stability, give the stable geometric configuration of the element and contribute to resistance requirements against aggressive agents. The facings also provide the aesthetic and architectural features of the sandwich construction.

The sandwich core must be stiff enough to keep constant the distance between the facings and be rigid enough in shear so that the faces do not slide over each other. The core must not allow the faces wrinkling by providing enough transverse stiffness and a strong bond between the outer and the intermediate layer. Other requirements involve resistance to moisture absorption, performance in fire, sound insulation, and high thermal insulation properties.

In a sandwich panel not only the exterior faces and the core are significant but also a very important role has the interface. The joining at the interface can be represented by a thin layer of adhesive or a direct connection between the two layers (*e.g.* the polyurethane foam that during the foaming phase is very bonding active and adheres strongly to surfaces with which it comes into contact).

The interface role is to achieve a good bonding between the layers, to prevent sliding, transfer the shear stresses and resist the tension stresses normal to the sandwich plane.

The adhesion must be durable, stable, less sensitive to creep, with stable properties during service temperatures, resists the degradation factors aggression and enables the association with different materials [3].

To obtain the sandwich effect the layers and interface must simultaneously fulfil all the requirements specified above.

3. Sandwich Element Analysis

The sandwich beam is considered similar with a double T beam, where the flanges are similar in function with the sandwich facings and the web takes the place of the core. The only difference is that the sandwich beam has the material in the web different from the material in the facings and it usually fills completely the space between the external layers.

The analysis that is required to predict the stresses and deflections in panels with flat or lightly profiled faces is essentially that of conventional beam theory but with the addition of shear deformation [4].

The relationships between the stress resultants and deformations are

$$M_s = B_s\gamma_2' = B_s\left(\gamma' - w''\right),\quad V_s = A_c G_{\text{eff}}\gamma, \tag{1}$$

where: a prime denotes differentiation with respect to x which is measured along the length of the panel; M_s – the bending moment on the span of sandwich; V_s – the shear force;

$$B_s = \frac{E_{f1}A_{f1}E_{f2}A_{f2}e^2}{E_{f1}A_{f1} + E_{f2}A_{f2}}$$

is the bending stiffness of the sandwich; A_{f1}, A_{f2} – the cross-sectional areas of the facings 1 and 2, respectively; E_{f1}, E_{f2} – the Young's moduli of the faces 1 and 2, respectively; e – the distance between the centres of the facings; γ – the shear strain of the core; w – the total deflection; $A_c = be$ – the effective area of the foam core; $G_{\text{eff}} = G_c e/d_c$ – the effective shear modulus of the core; G_c – the shear modulus of the core; d_c – the depth of the core; w – the total deflection.

An alternative form that is more convenient for the statically determinate cases is represented by

$$w'' = -\frac{M_s}{B_s} + \frac{V_s'}{A_c G_{\text{eff}}}, \tag{2}$$

$$\gamma = \frac{V_s}{A_c G_{\text{eff}}}. \tag{3}$$

These relations enable the understanding the fundamental behaviour of the sandwich structure. Considering relation (2) it can be noticed that deflection depends on the bending and shear terms, and, in addition, it can be stated that the bending moments are carried entirely by the facings and the shear forces by the core.

For the statically determinate panels the flexibility of the core increases the deflections and so the stresses can be considered the ones given by the theory of bending. For the statically indeterminate panels (*e.g.* panels continuous over two or more spans), the stresses resultants are also influenced by the flexibility of the core [4].

In this paper the simply supported panel with a point load in the middle of the span will be considered (Fig. 1).

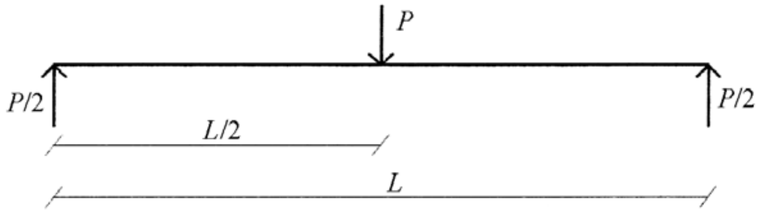

Fig. 1 – Simply supported panel with a point load.

This is a case of a statically determinate beam and we can adopt following relations:

$$M_s = PL(1-\varepsilon)\xi - PL\{\xi-\varepsilon\},\quad V_s = P(1-\varepsilon) - P\{\xi-\varepsilon\}, \tag{4}$$

where: the quantities in the curly brackets are only considered when their content is positive; ε – the distance to the load application point; ζ – the distance to where the maximum bending stresses and deflections are.

For the special case of the load in the centre of the panel, $\varepsilon = 0.5$, the maximum bending stresses and deflections occur at mid-span where $\xi = 0.5$.

The above equations become

$$M_{\max} = \frac{PL}{4},\quad \sigma_{F\max} = \pm\frac{PL}{4eA_f}\ \text{and}\ w_{\max} = \frac{PL^3}{48B_s}(1+4k), \tag{5}$$

where

$$k = \frac{3B_s}{A_c G_{\text{eff}} L^2}.$$

4. Stiffness Evaluation

For the purpose of global structural analysis panels in which both faces are flat are treated in a similar manner with those lightly profiled (profiling depth less than 4 mm) [4]. When at least one or both facings are profiled corrections should be made for the own stiffness of the deeply profiled layers.

The difference consists in the addition of face bending moments, M_{F1} and M_{F2}, with the corresponding shear forces, V_{F1} and V_{F2} (Figs. 2 and 3).

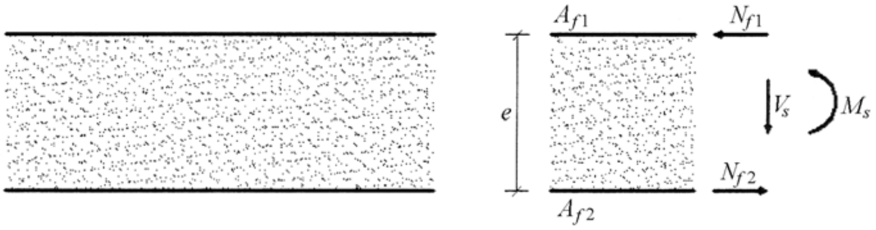

Fig. 2 – Stress resultants in a thin faced sandwich panel [5].

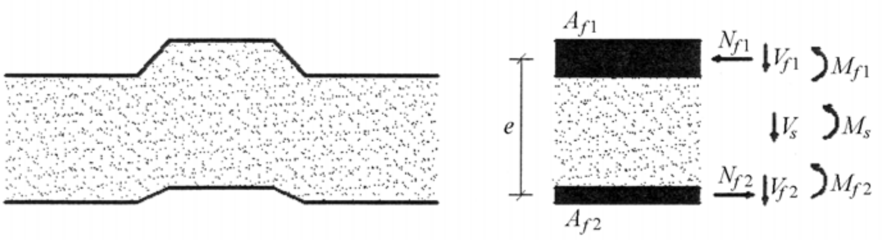

Fig. 3 – Stress resultants in a thick faced sandwich panel [5].

For the simply supported panel with a point load anywhere in the span having faces whose stiffness cannot be neglected the bending moment and shear force are given by

$$M = PL\left(1-\varepsilon\right)\xi - PL\left\{1-\varepsilon\right\}, \quad V = P\left(1-\varepsilon\right) - P\left\{1-\varepsilon\right\}^0 , \tag{6}$$

and the particular solutions are [4]

$$\begin{cases} w_1 = \dfrac{PL^3}{B}\left[\dfrac{1}{6}\left(1-\varepsilon\right)\xi\left(2\varepsilon-\varepsilon^2-\xi^2\right)+\dfrac{1}{\alpha\lambda^2}\left(1-\varepsilon\right)\xi-\dfrac{1}{\alpha\lambda^3}\cdot\dfrac{\sinh\left(1-\varepsilon\right)}{\sinh\lambda}\sinh\lambda\xi\right], \\ w_2 = \dfrac{PL^3}{B}\left[\dfrac{1}{6}\varepsilon\left(1-\xi\right)\left(-\varepsilon^2+2\xi-\xi^2\right)+\dfrac{1}{\alpha\lambda^2}\varepsilon\left(1-\xi\right)-\dfrac{1}{\alpha\lambda^3}\cdot\dfrac{\sinh\lambda\varepsilon}{\sinh\lambda}\sinh\lambda\left(1-\xi\right)\right], \end{cases} \tag{7}$$

$$\begin{cases} \gamma_1 = \dfrac{PL^2}{B}\left[1-\varepsilon+\dfrac{\sinh\left(1-\varepsilon\right)}{\sinh\lambda}\sinh\lambda\xi\right], \\ \gamma_2 = \dfrac{PL^2}{B}\left[-\varepsilon+\dfrac{\sinh\lambda\varepsilon}{\sinh\lambda}\sinh\lambda\left(1-\xi\right)\right]. \end{cases} \tag{8}$$

Considering the point load applied at a position given by $x = l$, that is $\xi = l/L = \varepsilon$, the equations with index 1 are valid for $0 \le \varepsilon$ and the ones with index 2 for $\varepsilon \le \xi \le 1$.

5. Structural Response of Sandwich Panels with Profiled Facing Subjected to Bending

During a training period abroad at National Technical University of Athens, Greece, a complete analysis on a structural response of sandwich panel with profiled faces has been carried out.

The sandwich panel was made of steel sheets with one profiled face and polyurethane foam (Fig. 4).

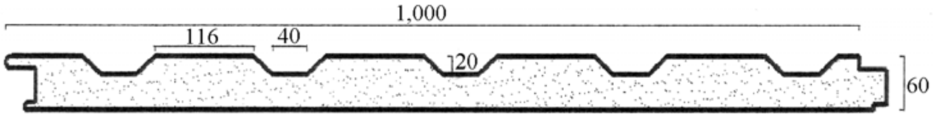

Fig. 4 – Cross-section of the sandwich panel.

The panel was considered simply supported with a midspan concentrated load. This load was a downward force applied on the panel to simulate the ”Interaction between bending moment and support force” test [6]. This required test was carried out at a full scale in the laboratory of the Faculty of Civil Engineering, Jassy. Simultaneous values of applied load and of the transverse deflection on a LVDT transducer have been recorded.

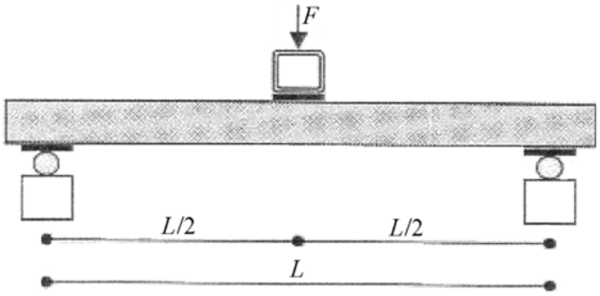

Fig. 5 – Representation of the ”Interaction between bending moment and support force” test [6].

Using the Abacus software package the sandwich panel has been numerically analysed and the main results are shown in Figs. 6 and 7.

Using the numerical values (the dimensions of the analysed part in Fig. 8): $P = 553.4$ N, $L = 43.00$ mm, $e = 60 - 0.42 = 59.58$ mm, where: P is the applied force, L – length of the panel, e – distance between the centroids of the faces, $\varepsilon = 0.5$, meaning that the load is applied in the centre of the panel, $\zeta = 0.5$, meaning that maximum bending stresses and deflections are at the middle of the panel.

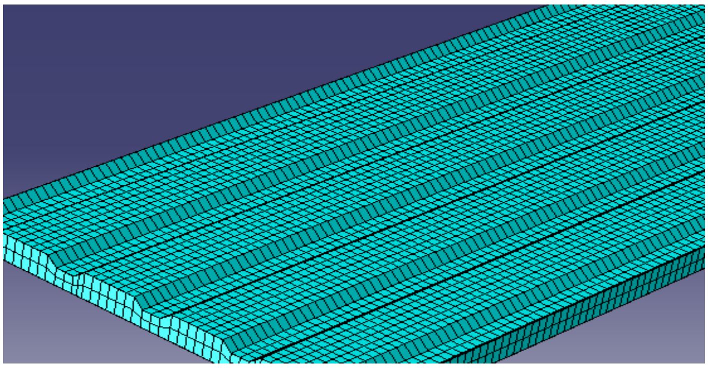

Fig. 6 – Sandwich panel meshing.

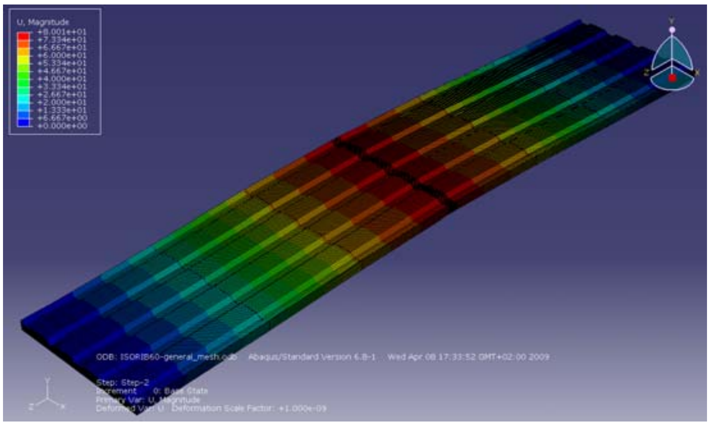

Fig. 7 – Sandwich panel stresses.

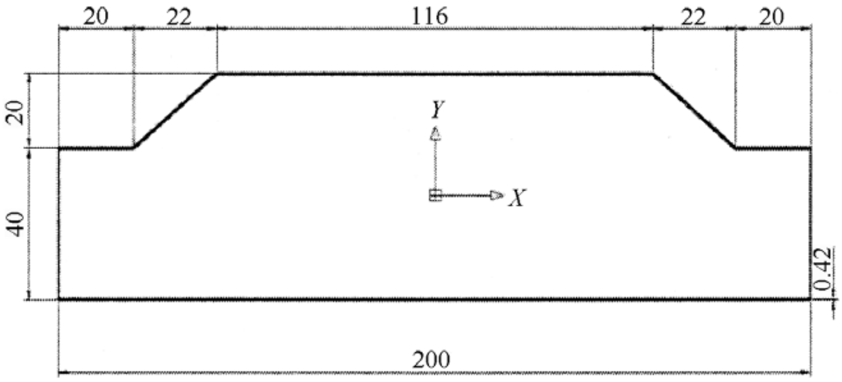

Fig. 8 – Cross-section dimensions of the analysed part.

It is noticed that $\varepsilon \leq \zeta \leq 1$ and relations (7_2) for deflection, is used.

Considering the calculus values $B_d = 0.1317 \times 10^{10}$ N.mm^2, $B_s = 3.2474 \times 10^{10}$ Nmm^2, $B = B_d + B_s = 3.3791 \times 10^{10}$ N.mm^2, A_c = 10,585 mm^2, d_c = 40 mm, E_{foam} = 4.1 N/mm^2, $\nu = 0.3$, it results

$$G_{\text{eff}} = \frac{G_c e}{d_c} = 2.8013\ \text{N/mm}^2,\ \alpha = \frac{B_d}{B_s} = 0.0405,\ \beta = \frac{B_s}{A_c G_{\text{eff}} L^2} = 0.0592,\ \lambda = \sqrt{\frac{1+\alpha}{\alpha\beta}} = 20.83,$$

where: α is the stiffness ratio, β – reduction factor, λ – working coefficient.

The reached value for the displacement using equation (7_2) is w = 43.87 mm. The displacement obtained for this panel from the numerical modelling is an average of w = 33.46 mm and the one resulted from the experimental test is w = 39.35 mm.

As a conclusion, there can be observed that these values are in a close range, meaning that the numerical calculus verifies the experimental test and the finite element modelling.

6. Conclusions on Failure Modes

In structural sandwich panels there are several potential failure modes which may limit and determine the load-bearing capacity of the panel.

In the case of a panel with flat or lightly-profiled faces subjected to a distributed load (wind or snow) these failure types are [4]

a) tensile failure of the facings (when these are too thin or of inadequate strength);

b) wrinkling failure of the facings (local buckling due to faces small thickness or inadequate restraining – Fig. 9);

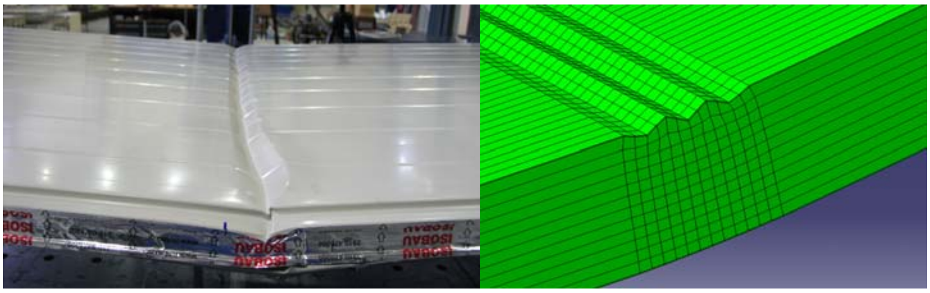

Fig. 9 – Failure of sandwich panels obtained from experiments and Abacus simulation.

c) shear failure of the core (due to its low shear strength and stiffness) or adhesion between the core and face (slippage of faces relative to each other);

d) crushing failure of the face and core at a support.

The debonding of the connection between the core and the outer layer, which leads to the separation of the components, is a specific failure type of layered elements [7].

The influence of the core failure can be neglected in the case of panels with profiled facings.

Compressive strength of a facing can be limited by the yielding of the material or by buckling, represented by the appearance of a wave or wrinkle. Focusing on the case presented before, the panel failure belongs to the category of local buckling due to compressive stress. This meant that the upper lightly-profiled metal face wrinkled.

Profiling the metal faces increases the flexural stiffness and also the buckling stress.

The sandwich elements, as a whole, are asked to fulfill, according to their destination, a wide area of conditions: strength, stiffness, durability, keeping the carrying capacity characteristics in difficult service conditions, light weight, fatigue strength, the capacity to be easily repaired and maintained [3].

Elucidating the mechanisms through which the sandwich element modifies its structure during fabrication and service is very important because of the possibility to obtain elements with pre-established mechanical properties and select the conditions in which they are going to be used [7].

Received, April 5, 2010

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STUDIUL COMPARATIV AL MODULUI DE CALCUL LA PANOURILE SANDVIŞ CU FEȚE PLANE ŞI CELE CU STRATURI EXTERIOARE CUTATE

(Rezumat)

Panourile sandviş sunt structuri efficiente deoarece se pot comporta la fel ca un material solid dar având o greutate proprie mai mică. Analiza necesară pentru a obține tensiunile şi deformațiile în panourile cu fețe plane sau uşor profilate este cea a teoriei grinzii convenționale la care se adaugă deformația din forța tăietoare. Sunt stabilite formulele de calcul ale unui panou cu fețe plane şi profilate, fiind cunoscut faptul că fețele cutate aduc o îmbunătățire a rigidității la încovoiere. Totodată, în lucrare se realizează şi o comparație a valorilor obținute în urma unui calcul matematic, ale unui test experimental şi a unei modelări numerice pentru un anumit tip de panou sandviş.