Numerical and Experimental Investigation of Structural Performance of Polyurethane Sandwich Panels

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1. ABSTRACT

Polyurethane sandwich panels are commonly used in a variety of applications such as industrial buildings, agricultural facilities, and residential constructions. In the present paper, rigorous finite element models are performed for the prediction of the panel's shear and bending moment capacity, while a number of full-scale experimental tests are also conducted for the verification of the numerical models. The panels under consideration are fabricated by laminating two skin steel sheets to a prefabricated polyurethane foam core. A crushable-foam model with isotropic hardening is used in the commercial software ABAQUS/Standard for describing rigorously the polyurethane core response under severe loadings. The comparison between numerical results and experimental data indicates that the strength of a full panel can be predicted with good accuracy using the advanced finite element modeling tools presented.

2. INTRODUCTION

Sandwich panels with a polyurethane core and skin steel sheets are commonly used in cases where both low weight and high mechanical strength are required. From a general point of view, these polyurethane panels have some benefits compared to conventional materials, such as the high strength-to-weight ratio and high energy absorption capacity [1] to [5]. The combination of different length and overall thickness allows the engineer to choose a suitable panel, depending on whether shear or bending strength may be critical. More specifically, the core material supports the shear load and the two skin steel sheets sustain bending through tension and compression [6]. There exist several failure modes in those panels: shear or compression failure of the core material, and failure along the skin/core interface [7]. However, it is necessary to study the effect of panel thickness and length on the failure mode and its evolution, so that the dominant failure type is identified.

The scope of the present study is the numerical calculation of shear and bending design capacity of polyurethane panels. For this purpose, the methodology proposed in the EN 14509 standard is adopted. In order to calibrate and validate the numerical model data a series of experimental tests are also performed. The tests refer to tension, compression and shear coupon tests of pieces of the panels, conducted at the laboratory of Metallemporiki-Th.Makris S.A., in addition to a series of large-scale four-point bending tests of entire panels conducted in the Laboratory of Reinforced Concrete Technology and Structures of the Dept. of Civil Engineering at the University of Thessaly.

3. FINITE ELEMENT MODEL

3.1 Constitutive model

According to the EN 14509 standard, the capacity of a full polyurethane panel can be calculated with a series of full experimental testing. More specifically, the shear capacity can be determined by a 4-point bending test of a full panel with recommended length $L \leq 1000$ mm, while the bending capacity can be determined by a multi-point bending test with a length that varies depending on the panel thickness. The proposed experimental testing is simulated herein using rigorous finite element models. A critical step towards simulation of the above experiments is the selection of an appropriate material curve for the polyurethane core. The fact that the ultimate goal of this study is the prediction of the design capacity of the panels leads to a selection of a material curve provided by Metallemporiki-Th.Makris S.A., that is lower than most of the experimental material curves. Material modeling of the polyurethane is performed with the crushable-foam plasticity model with isotropic hardening, which is capable of describing the behavior of the polyurethane material during the panel's structural deformation. In order to determine the necessary parameters associated with the plastic flow and material hardening, compression tests conducted by Metalemporiki-Th. Makris S.A were used in such a way that the stress-strain curve of the material used in the model is lower than the corresponding experimental material curves. The material of the two outer skin steel sheets has been simulated using an isotropic-hardening von Mises plasticity model with a reduced yield stress equal to 243 MPa (corresponding to a safety factor equal to 1.15 on the nominal yield stress of 280 MPa) and a Young modulus of 200 GPa.

3.2 Model calibration

Based on the ‘small-scale’ test results, two uniaxial compression curves were chosen for calibrating the FEM model. The upper and the lower material curves were used for the calibration of two sets of parameters for the crushable foam material model. For the case of the upper material curve used a model with cross-sectional dimensions of 50×50 mm and a height equal to 50 mm, while for the case of the lower material curve used a model with cross-sectional dimensions of 100×100 mm and a height equal to 120 mm. The comparison between the experimental data and the numerical results, shown in Figure 1, demonstrates that the numerical model can predict the response of the polyurethane material quite satisfactorily.

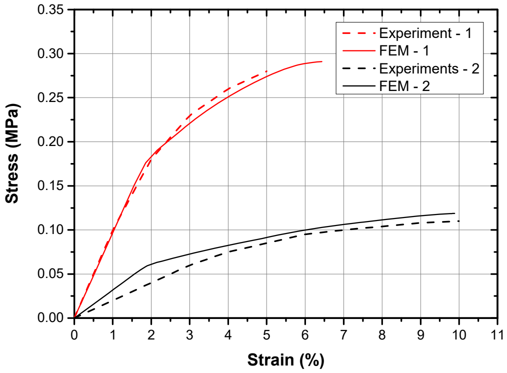

Figure 1. Numerical and experimental results of the compression tests corresponding to the upper (FEM - 1) and lower (FEM - 2) material curves for the foam core.

Shear tests were used for verifying the numerical model. All shear tests provided by Metallemporiki-Th.Makris S.A. have been simulated using the “upper-bound” and the “lower-bound” material curve. The comparison between experimental data and numerical results, for the case of a specimen with a height equal to 50 mm and the “upper-bound” material, is shown in Figure 2. The compression and the shear test were simulated using the numerical model shown in Figure 3.

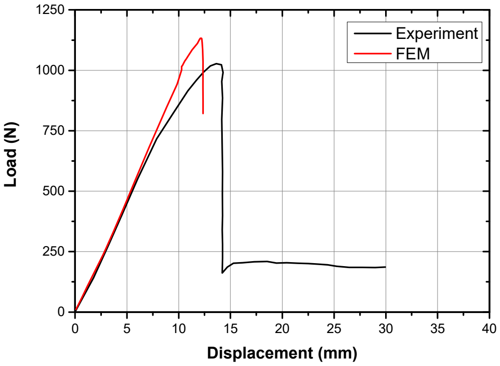

Figure 2. Shear test results versus numerical results corresponding to the upper- (FEM - 1) material curve for a 100×50×1000 mm specimen.

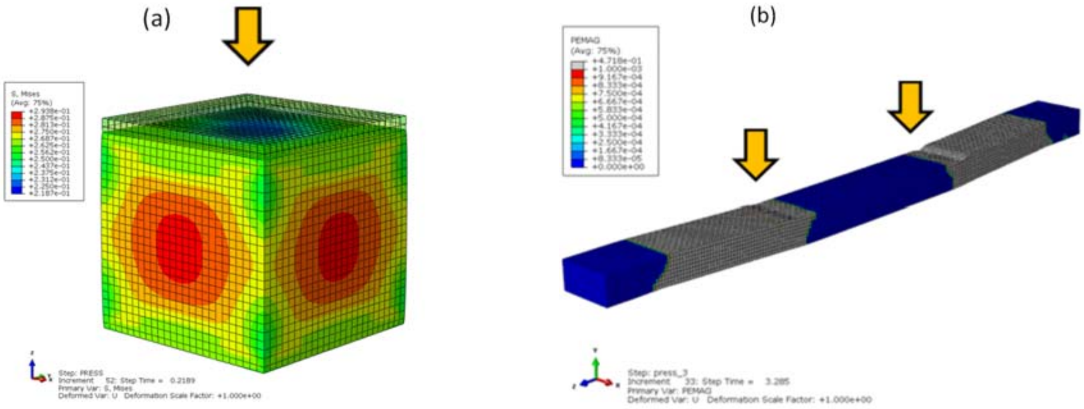

Figure 3. (a) Numerical simulation of the compression test; (b) Numerical simulation of the shear test.

It should be underlined that determining the material data used in the numerical simulation may not be a trivial issue. Herein, the FEM - 2 material is selected for the finite element model, based on the fact that more than 90% of the experimental results fall above this curve; therefore, it is a conservative assumption, suitable for developing design rules.

3.3 Three-dimensional numerical model

A finite element model was developed using a commercial software package ABAQUS in order to investigate the structural performance of the panels. More specifically, the geometry of the panels was simulated according to the manufacturing drawings provided by Metallemporiki-Th. Makris S.A. Due to symmetry, only half of the panel was simulated, as shown in **Error! Reference source not found.**4a, in order to reduce the computational time. The two skin steel sheets were simulated using reduced integration shell elements while the polyurethane core was modeled using three-dimensional solid elements. The specimens’ hinge and roller supports were simulated with appropriate coupling between a reference point and the corresponding area of the panel. Loading was applied through rigid shell plates of width equal to 100 mm as shown in Figure 4a. A sensitivity analysis with respect to the size of the elements was conducted and the final size of the elements for the polyurethane core was chosen equal to 6 mm. The mesh of the polyurethane is shown in Figure 4b and the mesh of the shell part of the two skin steel sheets is shown in Figure 4c. A special constraint was applied to the interface between the polyurethane and the steel sheets, which does not allow separation and relative sliding between the solid part (polyurethane) and the shell part (steel sheets) of the numerical model.

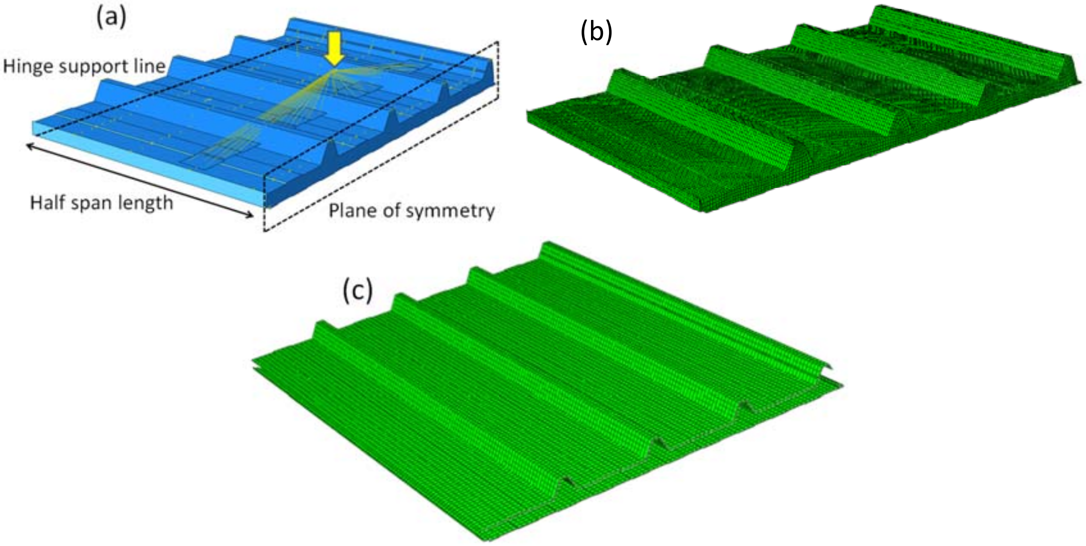

Figure 4. (a) Plane of symmetry and loading plates; (b) Mesh of polyurethane part; (c) Mesh of the two skin steel sheets.

4. SHEAR AND BENDING CAPACITY FOR ENTIRE PANELS

4.1 Experimental setup

Sixteen (16) 4-point bending tests were performed up to failure according to the EN 14509 provisions. The specimens were full-length panels with 1-meter width, while the thickness ranged from 30 to 100 mm and the length from 1.5 to 3 m. Deflection at midspan was measured with two DCDT's located symmetrically along the width of the panel. The agreement between the experimental and numerical results (Figure 5) was satisfactory.

4.2 Experimental-numerical comparison

In this section, a comparison between experimental and numerical results is presented. For the case of the 3-meter long panel with thickness 30 mm, the curves of applied load versus midspan displacement are shown in Figure 6. Initially the response of the panel is linear. Then, a first drop of the load was observed due to the local buckling of the upper steel sheet, followed by second drop of the load due to the polyurethane core's failure that led to the overall failure of the specimen (Figure 6). This "brittle" structural behavior of the panel is attributed mainly to the fracture of the polyurethane core.

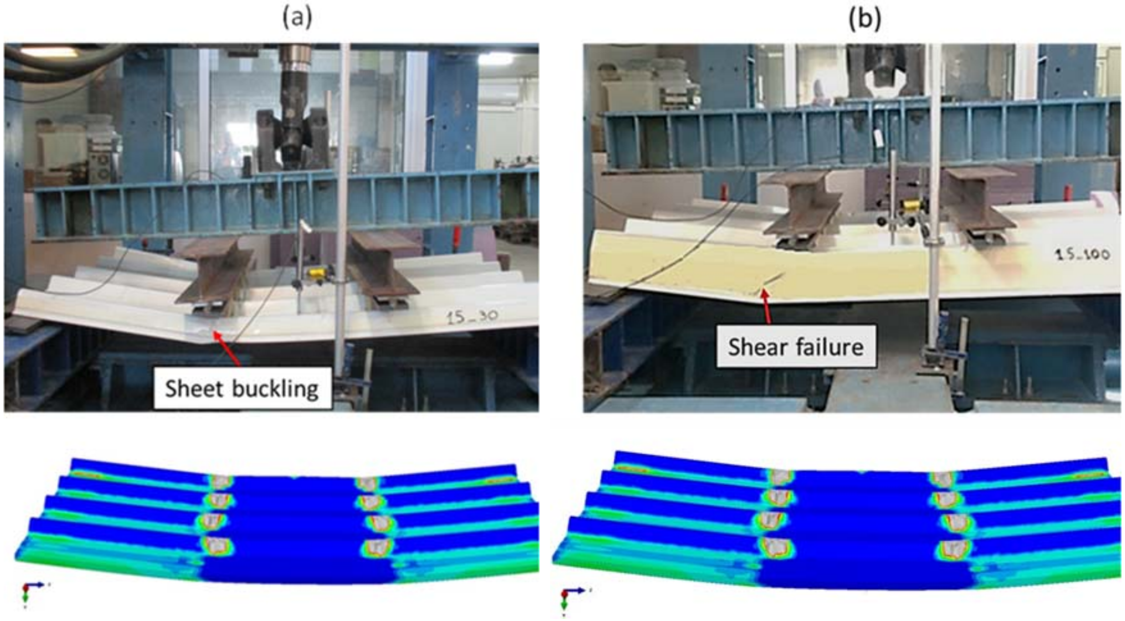

Figure 5. Experimental failure and numerical simulation for a 1.5meter-long panel with a thickness of: (a) 30 mm and (b) 100 mm.

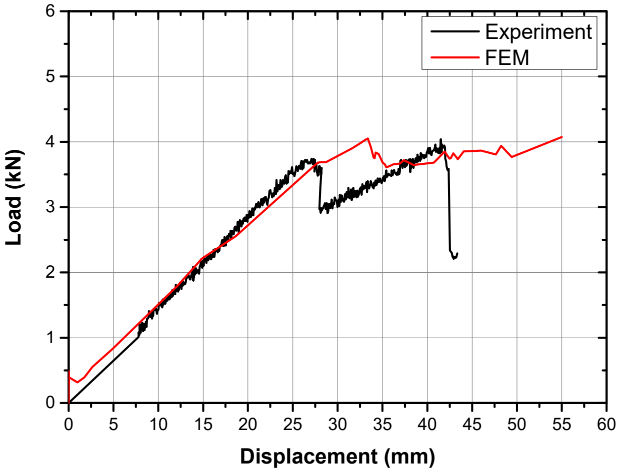

Figure 6. Numerical and experimental results for the 4-point bending test of the 3-meter long panel with a thickness of 30 mm.

5. CONCLUSIONS

The ultimate capacity of sandwich polyurethane panels has been investigated in the present paper, using numerical modelling, supported by experimental data. The failure mode of polyurethane panels may be either shear failure (mainly for high thickness over length ratio values) or bending failure in the region between the two supports due to positive bending or at the supports due to negative bending, or a combined mode. The numerical models developed for simulating the entire panel behavior provides satisfactory results in terms of the deformed shapes and failure mode, which are in good agreement with the experimental results. It should be noticed that the finite element models under consideration generally underestimate the real performance of the panel. This is mainly due to the conservative choice of the properties for the polyurethane core material used in the numerical model; the properties correspond to the weakest compression curve from the 'small-scale' tests. In any case, the satisfactory agreement of the test data and the numerical results demonstrates that the finite element models under consideration are capable of predicting the structural behavior of polyurethane panels and can be used for developing relevant design rules.

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Υπολογιστική και Πειραματική Διερεύνηση της Δομικής Συμπεριφοράς Πάνελ Πολυουρεθάνης

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ΠΕΡΙΛΗΨΗ

Τα πάνελ πολυουρεθάνης χρησιμοποιούνται σε ποικίλες εφαρμογές, όπως βιομηχανικά κτίρια, γεωργικές εγκαταστάσεις και κτηριακές κατασκευές. Συνήθως, ο υπολογισμός της μηχανικής αντοχής των πάνελ γίνεται μέσω πειραμάτων κάμψης τεσσάρων και πολλαπλών σημείων. Η διεξαγωγή πειραμάτων για τον υπολογισμό της διατμητικής και καμπτικής αντοχής γίνεται σύμφωνα με τα σχετικά πρότυπα που σχετίζονται με την πιστοποίηση του προϊόντος. Σε αυτή τη μελέτη χρησιμοποιούνται μοντέλα πεπερασμένων στοιχείων για τον υπολογισμό της διατμητικής και καμπτικής αντοχής. Επιπλέον, για την επαλήθευση των αριθμητικών μοντέλων διεξήχθησαν πειραματικές δοκιμές. Τα πάνελ κατασκευάζονται με την κόλληση δύο χαλύβδινων ελασμάτων σε έναν προκατασκευασμένο πυρήνα αφρού πολυουρεθάνης. Στην προσομοίωση πεπερασμένων στοιχείων (εμπορικό λογισμικό Abaqus) για την περιγραφή της μηχανικής συμπεριφοράς της πολυουρεθάνης κάτω από ισχυρές φορτίσεις χρησιμοποιείται το μοντέλο «crushable foam with isotropic hardening». Η σύγκριση μεταξύ των αριθμητικών και των πειραματικών αποτελεσμάτων δείχνει ότι η αντοχή των πάνελ μπορεί να εκτιμηθεί με ικανοποιητική ακρίβεια με βάση το παρόν βελτιωμένο μοντέλο πεπερασμένων στοιχείων.