Wide sandwich beams under uniform pressure loading.
Comparison of predictive methods and correlation with test results

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Abstract

This paper presents results from a round robin exercise aimed at comparing predictive methods for sandwich panel behaviour. The case studied is a wide sandwich beam loaded under uniform pressure. First, results from different analytical methods and finite element codes are compared. Then test results are presented for a glass/epoxy facing-PVC foam core sandwich panel. Finally predicted strains and out-of-plane displacements are correlated with experimental results.

Introduction

Sandwich materials are finding extensive applications in the transport industry where their high stiffness to weight ratio is very attractive. In many applications it is the maximum deflection of panels which is the primary design consideration, and finite element (FE) packages are widely used to predict this deflection. However, these codes are rarely validated by comparing with experimental results from any but simple beam structures. Some examples of comparisons between predictions and sandwich structure behaviour have been reported recently, both for static [e.g. 1,2] and higher rate loading [e.g. 3,4] but the correlations are often not very good. The aim of the present study, performed within the DOGMA (Design Optimisation and Guidelines for Multimaterial Applications) project, a European thematic network, is to examine how different analytical and FE calculations compare both amongst themselves and with respect to experimental data for a sandwich structure.

A series of tests on wide sandwich beams was performed by IFREMER within the BRITE-COMAST (Composite Material in Marine Structures and Components) project, BREU0178-C. The results from these tests, both material properties and structural test results, were made available to the DOGMA project participants in order to evaluate different modelling methods. This report presents a first summary of results.

First, the test configuration will be described. Then the input data given to each participant will be presented. In the third section the two analytical approaches and sixteen FE models (using 7 different FE packages) will be described. It should be noted that not all of the models were intended to predict the tests, some simpler calculations were run in order to compare with more complex analyses. In the fourth section the experimental data will be presented, and finally the comparison will be made between predictions and experiment. It should be emphasised that this project is still running and the results presented are those generated in the first round of 'blind' predictions. A second round, in which further studies are being made of differences between predictions and test data, is still underway.

1. Test description

The sandwich panel, glass/epoxy facings on a PVC foam core, is mounted in a 100 ton capacity test frame and loaded from below by uniform pressure applied via air cushions, Figure 1. The stiffeners push against the test frame crosshead beams to react the applied load.

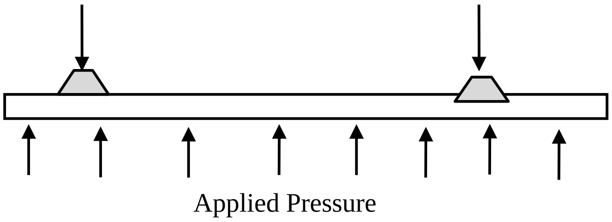


Figure 1. Principle of loading of wide sandwich beam.

A photo showing the panel on the test frame before loading is shown in Figure 2.

The panel dimensions are 2 metres long by 1 metre wide, Figure 3. The stiffeners (shaded) are made of 2 layers of quadriaxial fibres on a lightweight (35 kg/m^3) core. The letters on Figure 3 indicate measurement points.

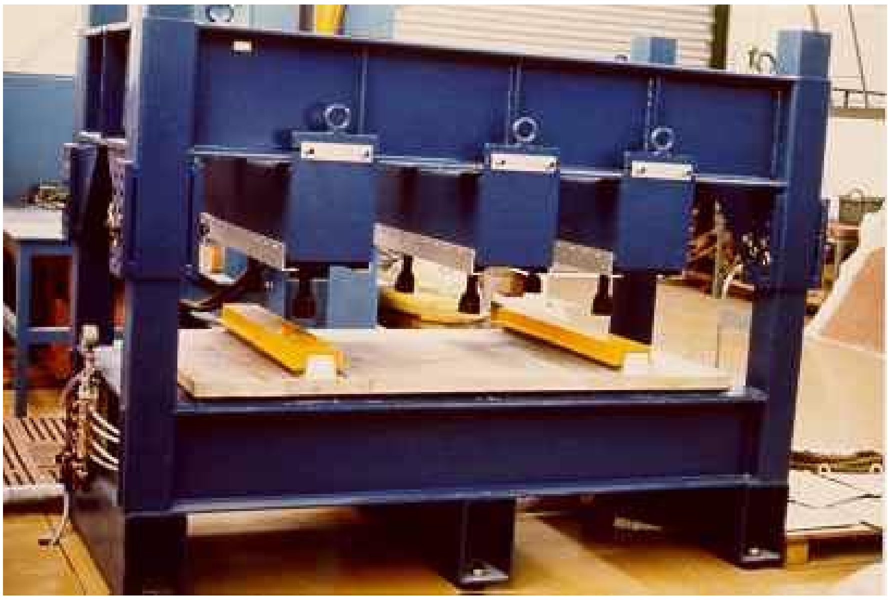


Figure 2. Photo of sandwich panel on test bed.

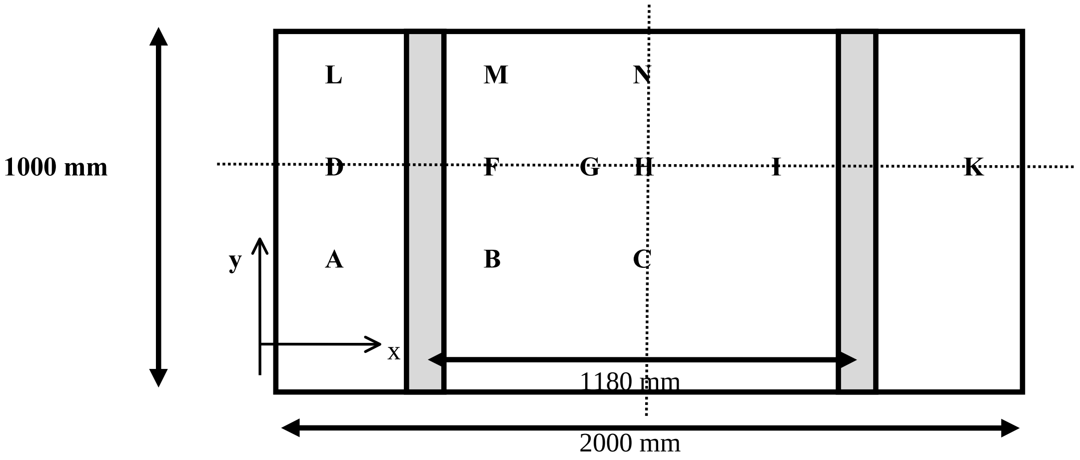


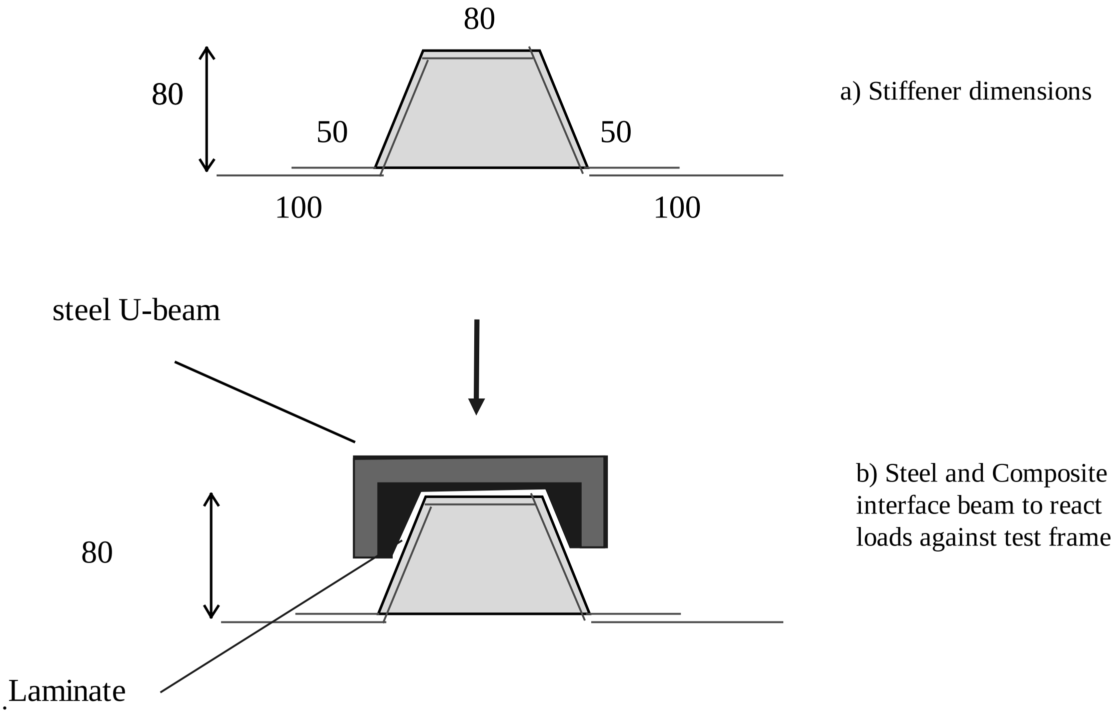
Figure 3. Panel and measurement points (displacements and strains)

Out-of plane displacements and facing strains were measured at the points shown in Table 1 below: The bottom facing is the pressurised side.

Point	x (mm)	y (mm)	Displacement	Strains (facing)
A	220	150	✓	
B	600	150	✓	
C	1000	150	✓	✓ Top
D	220	500	✓	✓ Top
F	600	500	✓	
G	800	500	✓	✓ Top
H	1000	500	✓	✓ Top & Bottom
I	1400	500	✓	
K	1780	500	✓	
L	220	850	✓	
M	600	850	✓	
N	1000	850	✓	

Table 1. Co-ordinates and references of measurement points.

The stiffeners are reacted against the test frame via metal and laminate caps, as shown in Figure 4 below. Stiffener dimensions are given, showing overlap layers laminated onto the sandwich panel (two layers, at 50 and 100mm from the stiffener base). The stiffeners are loaded by a steel U-beams which are placed on top of the stiffener (see also Figure 2). The transfer of load from U-beam to stiffener is assured by moulding a composite laminate to the contours of the stiffener inside the U-beam



a) Stiffener dimensions

b) Steel and Composite interface beam to react loads against test frame

Figure 4. Details of stiffeners

2. Material property input data

The sandwich panels were produced by hand lay-up at the Ifremer Centre in Brest. Tensile tests were performed on facing laminates and shear tests on foam cores to produce a set of input data for calculations, Table 2 and Figure 5.

	Material, dimensions	Properties
Core	PVC foam, 80 kg/m^3 Core thickness = 40 mm	Non-linear stress-strain curve (Figure 5) G = 33 MPa E = 86 MPa
Facings	3 layers of quadriaxial E glass (Cotech 1034 g/m²) in epoxy resin (Sicomin SR1500) Fibre vol. fraction 37% Facing thickness = 3.5 mm	Linear elastic E_1= *15.5 GPa E_2 = 15.5 GPa G_{12} =5.5 GPa ν_{12} = 0.31

Table 2. Material input data with 1 the long axis direction of the panel, 2 the width direction

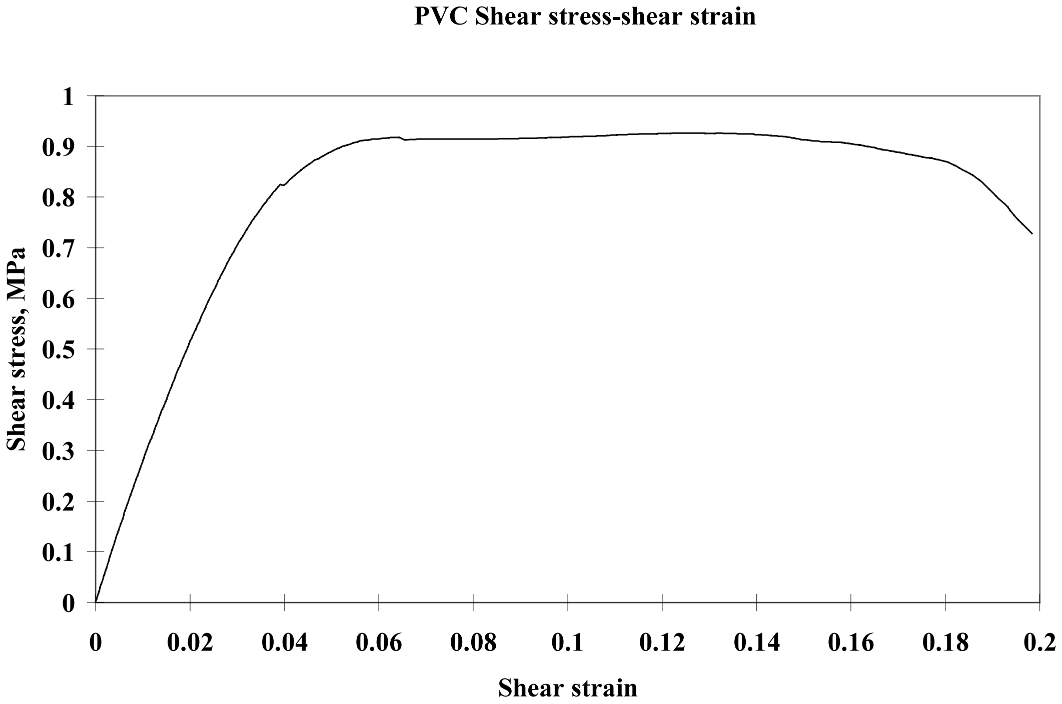


Figure 5. PVC core shear stress-strain behaviour

These data, together with the geometrical data for the test configuration described in section 1, were given to each participant running the models. Displacements and strains at 0.02 and 0.1 MPa pressures were requested.

3. Models used

Table 3 presents a summary of the models employed by the different participants. Details of the calculations are given in the Appendix.

Participant	Model type	Model	Boundary	Brief description
IDMEC	FE In-house	Linear elastic & non-linear geometric and material	Without stiffener, no rotation	Skin: orthotropic shell elements (80) Core: one 20-node volume element (60)
FYC	FE NISA 7.0	Linear 3-D	Stiffener modelled	Core solid elements (160), facings shell (240)
IFREMER	FE ADINA 6.0	Linear & Non-linear geometric 3-D	Stiffener modelled	20 node solid elements core (324), MITC shell elements skins (300)
OBU	FE ABAQUS 5.4	Linear 2-D	Transverse nodes restricted over 100mm	2D plane strain 4 noded rectangular elements. 4 mesh sizes tried
PAVIA	FE SAMCEF	Linear	Half stiffener fixed	3D core 2D face
SINTEF	FE ANSYS 5.3	Linear elastic 3-D	Without stiffener, no rotation & With stiffener	Skin: Orthotropic Shell elements (80) Core: one 20-node volume element (60)
VTT	FE COSMOS/M2.0	Linear & Non-linear geometric	Various conditions	Nine cases studied

		3D		
VTT	Analytical	Simple Beam theory	Simply supported & Clamped	
TNO	Analytical	Linear, Higher order (Frostig) plate		Adapted Frostig sandwich beam theory

Table 3. Models applied to simulate wide beam behaviour.

Essentially the models can be classified as:
i) analytical, simple or higher order
ii) linear elastic FE,
iii) non-linear geometric linear elastic material FE,
iv) non-linear geometric non-linear material FE.

The results for each will now be discussed.

3.1. Analytical models

Two analytical approaches were used. The first is based on simple beam theory [5], with either simply supported or clamped boundary conditions. The second is based on higher order sandwich theory, adapting the beam solutions of Frostig [6] to plates. These analytical solutions assume linear geometrical and material behaviour. The boundary conditions for the higher order theory are a uniform distributed load over a 100 mm region to represent the stiffener reaction. Table 4 shows central displacement and strain results for the point H (x=1000, y=500mm) in Figure 2, obtained from these analytical expressions.

Analytical model	Central displacement, mm	Central strain upper facing microstrain
Beam simply supported	59.8	7900
Beam clamped	20.9	-
Panel higher order	29.1	3800

Table 4. Analytical expression for displacement and strain at 0.1 MPa pressure

Even the simple comparison using beam theory shows the considerable influence of boundary conditions in this calculation, resulting in a factor of three change in displacement for the two extreme cases.

3.2 Linear elastic FE

Most of the FE models used were run in a linear elastic form first, more complex variations were then tried in some cases. Table 5 shows a comparison of the central displacements and strains at 0.02 MPa, Table 6 shows the same comparison for 0.1 MPa.

FE Code & Model	Central displacement, mm	Central strain upper facing (microstrain)
IDMEC In-house No stiffener		-
NISA	**4.43**	**550**
ABAQUS	**3.92**	**550**
ADINA		
SAMCEF		
ANSYS No stiffener model	3.5	430

ANSYS Stiffener modelled	**4.4**	**570**
COSMOS No stiffener model	6.06	770
COSMOS No stiffener, no rotation	4.04	490
COSMOS Stiffener, inner support	3.28	420
COSMOS Stiffener, both edge support	**4.14**	**560**
COSMOS Stiffener, Steel frame z-support	**4.08**	**550**
COSMOS Stiffener, frame xyz-support	**3.96**	**560**

Table 5. FE predictions for central displacement and strain, 0.02 MPa
(similar boundary conditions in bold)

FE Code & Model	Central displacement, mm	Central strain upper facing (microstrain)
IDMEC In-house No stiffener	19.8	-
NISA	**22.2**	**2740**
ABAQUS	**19.6**	**2749**
ADINA	**20.8**	**3068**
SAMCEF	24	3000
ANSYS No stiffener model	17.2	2040
ANSYS Stiffener modelled	**22.1**	**2850**
COSMOS No stiffener model	30.3	3850
COSMOS No stiffener, no rotation	20.2	2440
COSMOS Stiffener, inner support	16.4	2100
COSMOS Stiffener, both edge support	**20.7**	**2780**
COSMOS Stiffener, Steel frame z-support	**20.4**	**2750**
COSMOS Stiffener, frame xyz-support	**19.8**	**2790**

Table 6. FE predictions for central displacement and strain, 0.1 MPa
(similar boundary conditions in bold)

Mean(standard deviation) of bold values at 0.1 MPa are 20.8 (1.0) mm, 2818 (116) microstrain. In spite of the differences in codes, numbers of elements and types of element when similar (but not identical) boundary conditions are assumed, the predicted values of displacement and strain are very similar, the coefficient of variation for both (ratio of standard deviation to mean value) being less than 5%. Given the considerable differences in mesh refinement (from 300 to over 17000 elements) this is reassuring. The deformed shape of the panel can also be defined from these calculations and Figure 6 shows the predictions.

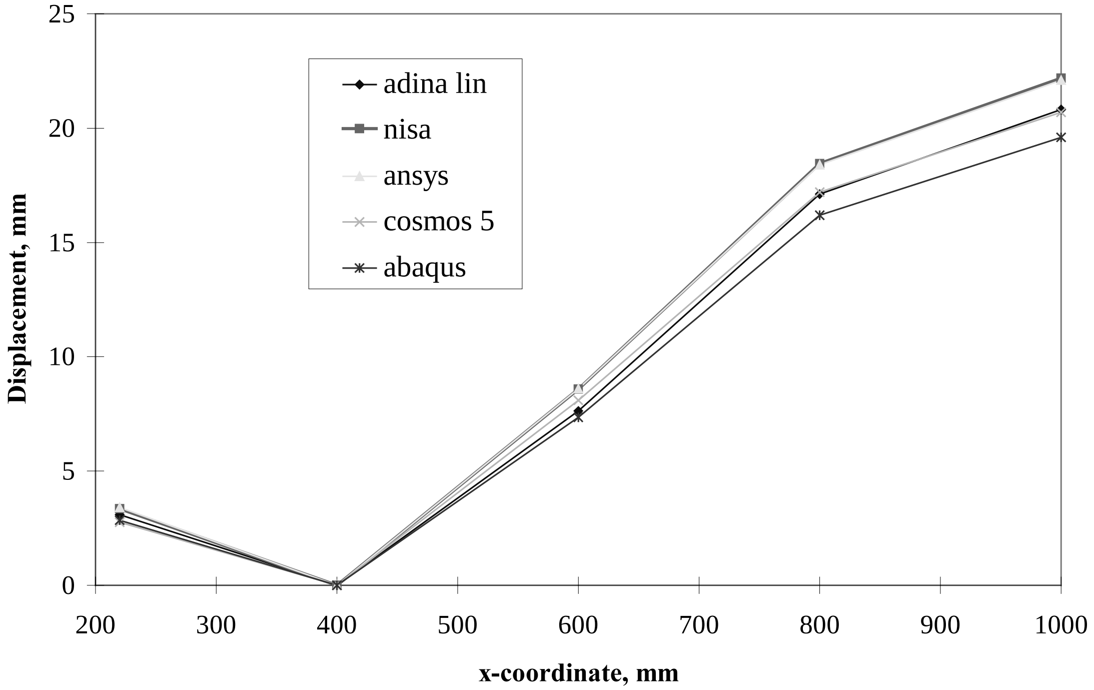


Figure 6. Predicted deformed shapes from linear elastic FE models,
along mid plane (y=500 mm), half of panel (symmetry in all models).

3.3 Non-linear geometric, linear elastic material FE

The displacement predicted by the linear elastic calculations indicates that at a pressure of 0.1 MPa the central deflection is a significant proportion of the panel thickness (50% or more). Some calculations were therefore performed to examine whether it was necessary to take non-linearity due to large displacement into account. Figure 7 shows one example, in which the panel deformed shapes are presented for the same (COSMOS) models and boundary conditions with and without the geometric non-linearity option. It is clear that the difference is quite small,

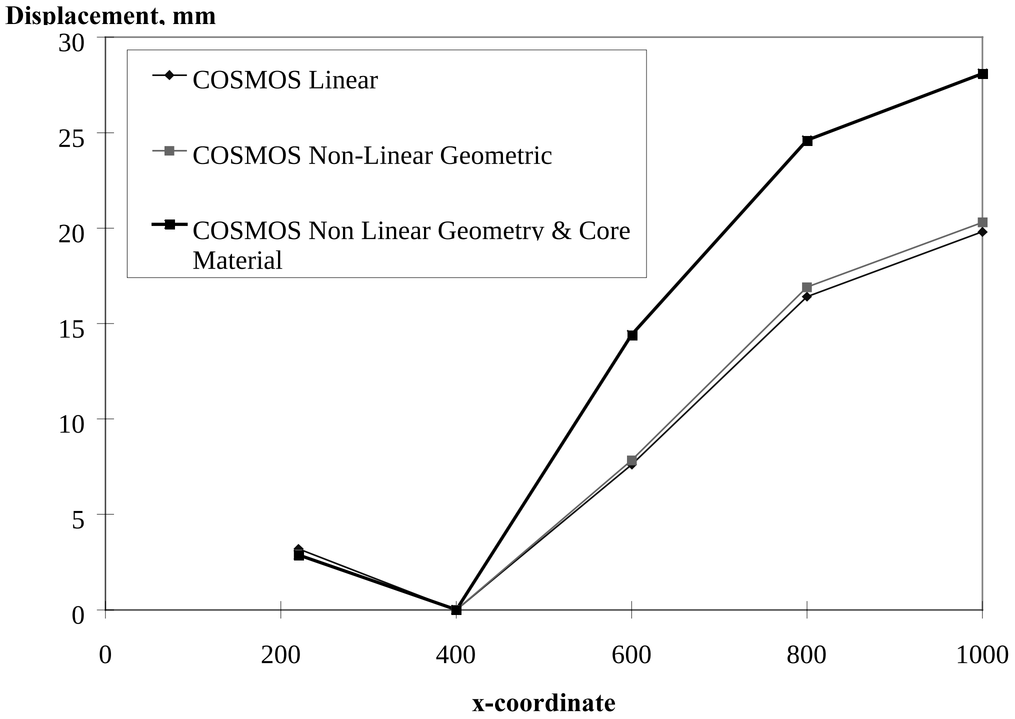


Figure 7. Influence of geometric and material non-linearity.

3.4 Non-linear geometric, non-linear material FE.

It was noted during the analysis of results that core shear stresses were quite high in the region round the stiffeners. If the core yields in this region this may have a significant effect on the deformed shape of the panel so a calculation was run, again using COSMOS, to examine this possibility. The core was modelled using the data in Figure 5 as a multi-linear stress-strain curve with a Huber-von Mises plasticity model. The displacements are also shown in Figure 7 and it is clear that there is a strong effect on the panel response. A closer look at the displacements at point F using this model also shows a strong non-linearity in this region above about 0.07 MPa, Figure 8.

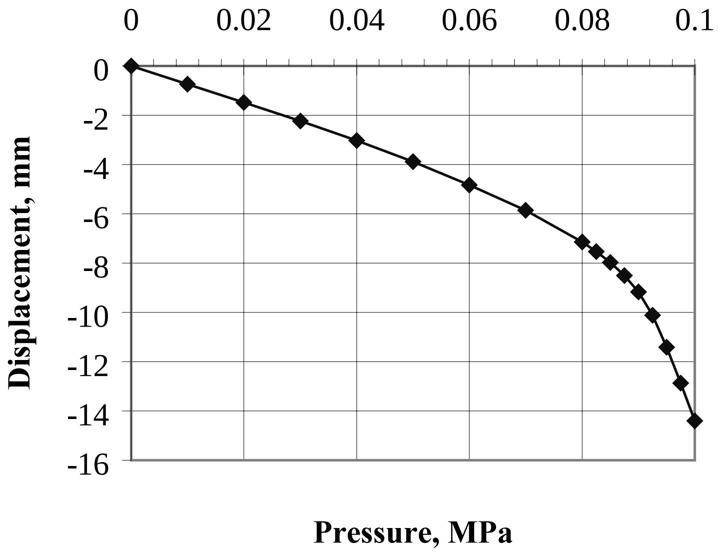


Figure 8. Predicted displacement at point F, COSMOS non-linear model.

4. Experimental results

Two tests were performed on a sandwich panel, loading up to 0.12 MPa in steps. Out-of plane displacements were measured using 12 inductive transducers checked with calibration blocks just before the test and mounted on a rigid frame (Figure 9), in-plane strains were measured using triaxial strain gauge rosettes bonded to the facings (21 strain gauges). Data acquisition of the 34 channels (displacements, strains and pressure) was performed using a Schlumberger data logger and then transferred to a PC for analysis.

Figure 9. Photo showing displacement transducer arrangement

Figure 10 shows the pressure-displacement recordings for different points, Figure 11 shows pressure-strain plots.

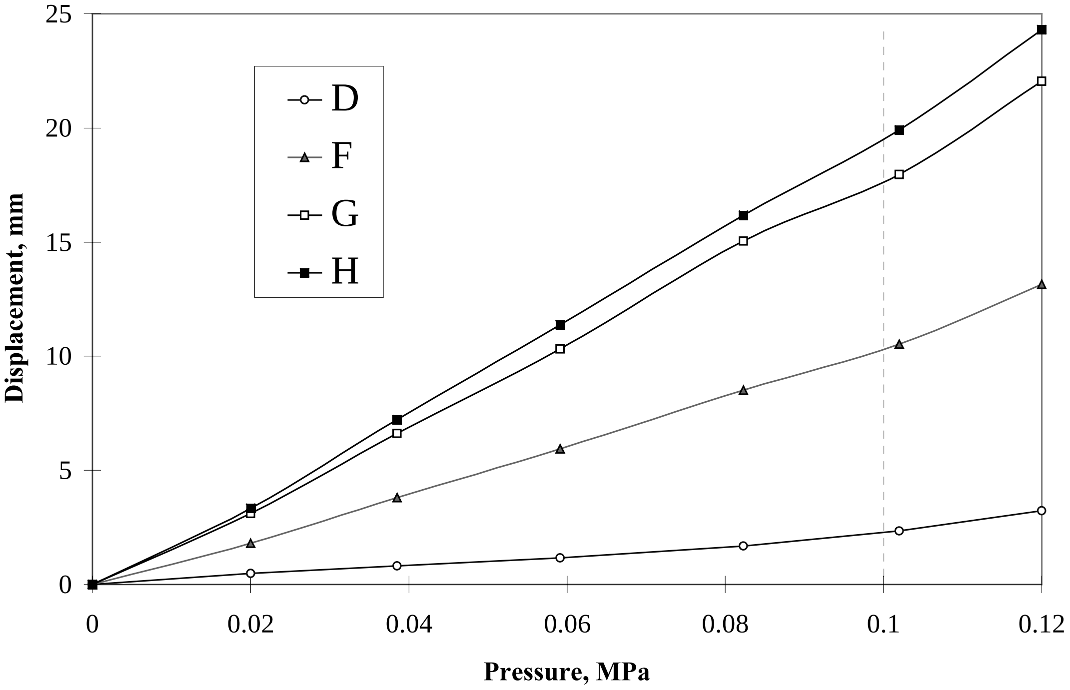


Figure 10. Measured displacements versus applied pressure, test 1.

The displacement at the centre is quite linear, the displacements nearer the stiffener show some small non-linearity

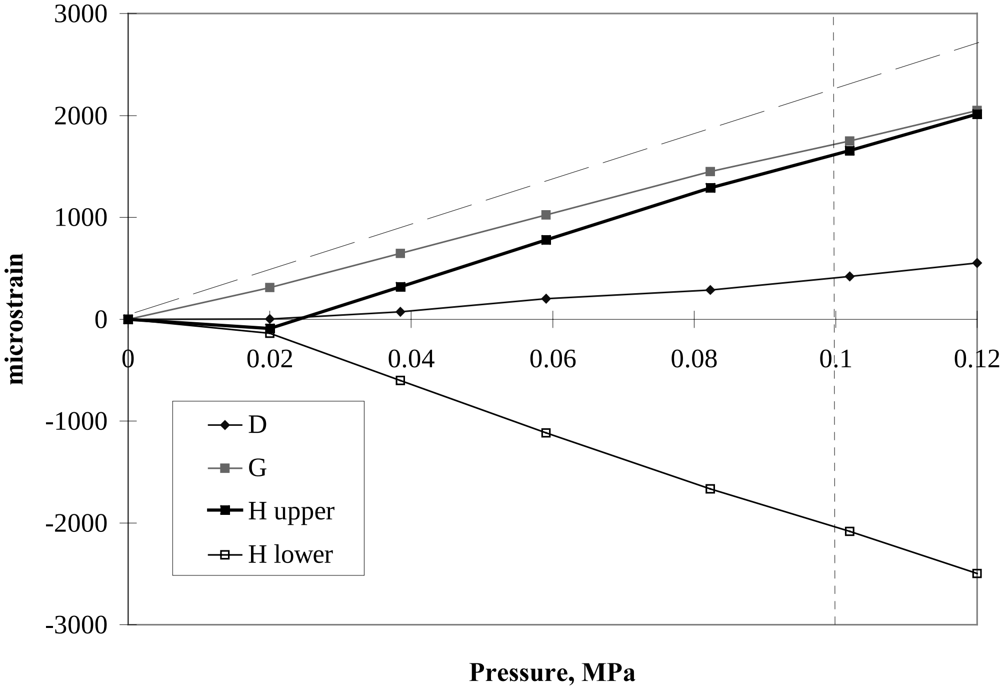


Figure 11. Measured strains (in x-direction) versus applied pressure

The behaviour at the start of the test is interesting, as both the mid-section (H) strain gauges show a delay before increasing, as if the centre of the panel is first lifted slightly without bending, before the strain starts to increase linearly with pressure. This is presumably caused by the test conditions, and may be related to the time for the air cushions to pressurise the panel uniformly in the centre. The other strain gauges all increase as soon as pressure is applied however. This offset makes correlation with prediction more difficult, but by extrapolating using the same slope and removing the offset (dashed line on Figure 11) the value at 0.1 MPa can be estimated.

Some anticlastic bending was measured during the test and this is shown by the three transducers along the line x=1000 mm (points N, H, C), in Figure 12.

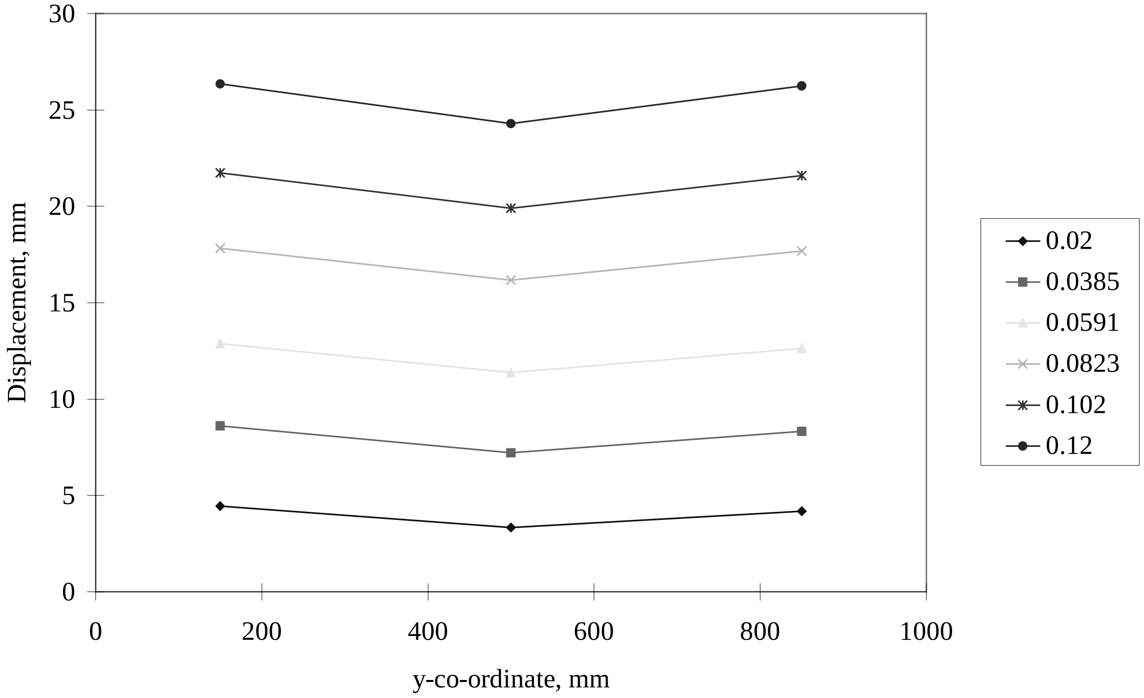


Figure 12. Anticlastic bending at mid-plane (x = 1000 mm) for different applied pressures.

Finally, an aspect of particular importance is the behaviour of the stiffeners during the loading. This was recorded photographically during tests and examples of the panel displacements at different pressures are shown in Figure 13.

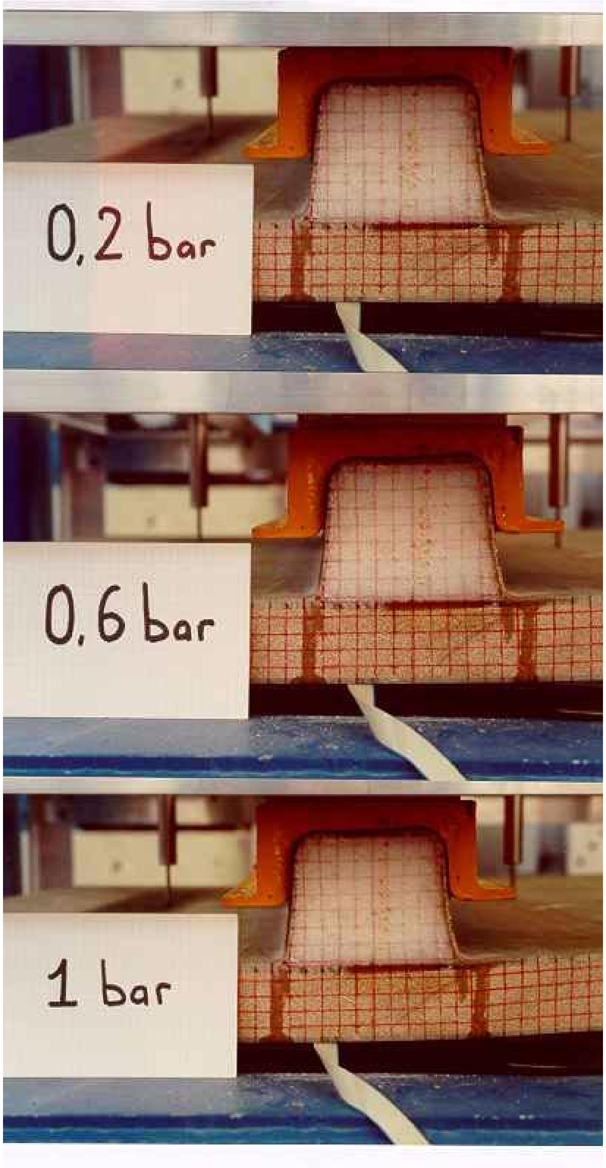


Figure 13. Stiffener end movement during loading.

These give an idea of how the stiffener rotates under pressure and could be used to correlate with predicted stiffener displacements.

5. Correlation between Predictions and Experimental data

The correlations between measured and predicted data are presented in three parts: first, the central displacements are considered, then the central strains, and finally the deformed shapes are compared.

5.1 Central displacement (point H)

Table 7 shows all the predicted and measured central displacements at 0.02 and 0.1 MPa pressures.

Model	**Central displacement, mm**		**% difference compared to test**	
	0.02 MPa	**0.1 MPa**	**0.02 MPa**	**0.1 MPa**
Measured value (mean)	3.34	19.91, 18.72 (**19.3**)		-
IDMEC no stiffener		19.8		+3%
NISA	4.43	22.19	+33%	+15%
SAMCEF		24		+24%
ABAQUS	3.92	19.6	+17%	+2%
ADINA				
Linear		20.82		+8%
NL		23.80		+23%
ANSYS				
no stiffener	3.5	17.2	+5%	-11%
with stiffener	4.4	22.1	+32%	+15%
COSMOS				
1 Linear panel only	6.06	30.3	+81%	+57%
2 Linear panel only, y-rot^n limit	4.04	20.2	+21%	+5%
3 Non linear, panel only	6.06	30.3	+81%	+57%
4 NL panel + stiffeners	3.28	16.4	-2%	-15%
5 Linear panel + stiffeners	4.14	20.7	+24%	+7%
6 As 5 but stiffener z-support	4.08	20.4	+22%	+6%
7 As 5 but stiffener xyz-support	3.96	19.8	+19%	+3%
8 As 5 but NL	4.00	20.3	+20%	+5%
9. Core yield, NL	3.95	28.1	+18%	+46%
Simple beam theory (VTT)				
Simply supported		59.8		+210%
Clamped		20.9		+8%
Higher order theory (TNO)	5.81	29.1	+74%	+51%

Table 7. Central panel displacements at 0.02 and 0.1 MPa pressures

In general the finite element model predicted central displacements overestimate the measured values but are quite close , particularly for 0.1 MPa.. The mean value from all the linear elastic FE analyses for which stiffeners were modelled, 20.8 mm, is within 10% of the measured value.

5.2 Central strains, point H upper skin

Table 8 shows the predicted and measured strains at the centre of the panel on the upper skin for a pressure of 0.1 MPa.

Model	**Central microstrain**	**% difference compared to**	**% difference compared to**

		measured values	**extrapolated value of 2110 (see Figure 11)**
Measured value (mean)	1655, 1465 (**1560**)	-	-
ANSYS			
no stiffener	2040	+31%	-3%
with stiffener	2850	+83%	+35%
NISA	2740	+76%	+30%
SAMCEF	3000	+92%	+42%
ABAQUS	2750	+76%	+30%
ADINA	3068	+97%	+45%
COSMOS			
1	3850	+147%	+82%
2	2440	+56%	+16%
3	3910	+151%	+85%
4	2100	+35%	0
5	2780	+78%	+32%
6	2750	+76%	+30%
7	2790	+79%	+32%
8	2800	+79%	+33%
9	2900	+86%	+39%
Simple beam theory Simply supported	7870	+405%	+273%
Higher order theory	3825	+145%	+81%

Table 8. Central strains at 0.1 MPa pressure

While at first glance the measured values appeared to be much lower than the FE predictions after closer examination of the strain readings and extrapolation of the central strains the correlation is much closer, within 30% in many cases and sometimes even closer. The close correlation with COSMOS model 4 suggests that the boundary conditions used in that case, vertical displacement zero at the inner edge of the stiffeners, may be closer to the experimental conditions than other models based on stiffener centre line constraint.

Given the uncertainties associated with all measured material property input data, together with the difficulty in establishing correct boundary and loading conditions during testing, this seems quite encouraging for a set of blind predictions.

5.3 Deformed shape

Figure 14 shows examples of the predicted and measured deformed shape of the panel. In general the calculations tend to predict a more pointed deformed shape than the measured values, and all underestimate deflections near the stiffeners. This suggests that there may be local effects near the stiffener, which result in a flatter form and hence lower strains in the centre. The calculations performed to include the core shear yielding behaviour tended to increase the central displacement, Figure 7, and did not significantly change the central strain value predictions but there may be other effects which the FE analysis does not pick up.

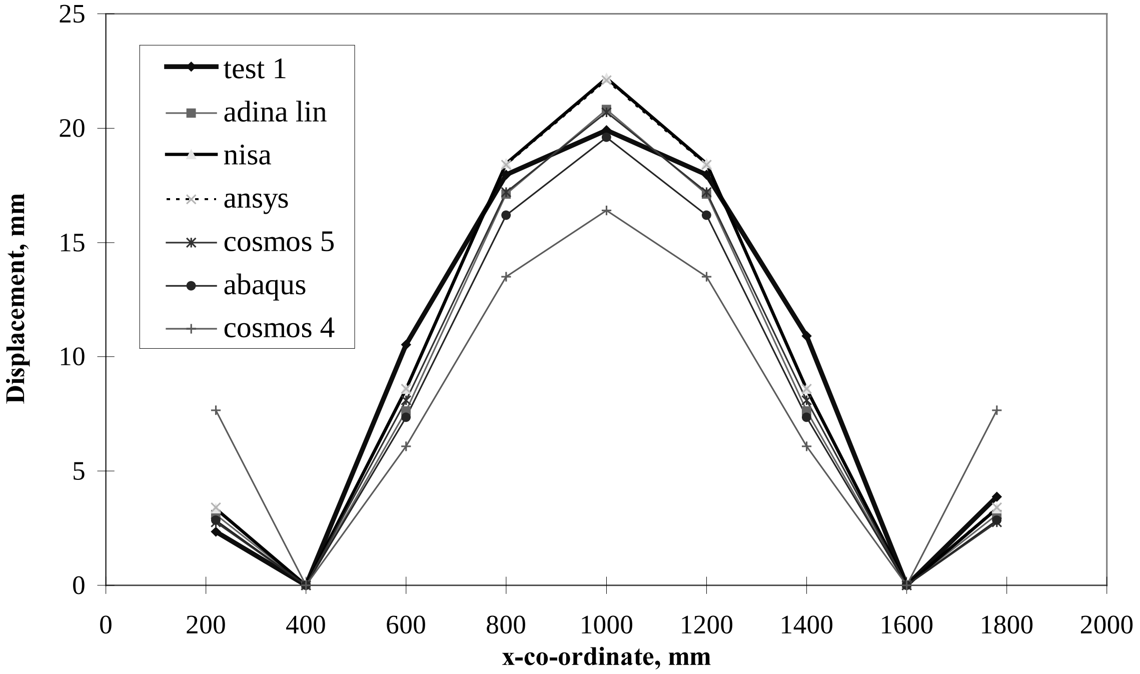


Figure 14. Deformed panel shape along central axis at 0.1 MPa pressure.

Concluding remarks

This paper has presented first results from a round-robin study performed within the DOGMA thematic network to compare different predictions of out-of-plane displacements and in-plane strains for a pressure-loaded sandwich panel both between themselves and with experimental results. First analysis of the results indicate a reasonable prediction of both global displacements and strains. The work on sandwich panels is continuing, to examine whether local effects are responsible for differences between predicted deformed shapes and those measured during tests. A second round robin exercise is also underway, in which methods for the prediction of failure of bonded joints are being evaluated.

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