Collapse of FRP/syntactic foam sandwich panels

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Abstract

In the framework of a wider research project, large scale testing of composite sandwich panels has been carried out at the DINAV shipbuilding laboratory. The skins of the sandwich are made of fibre glass epoxy prepreg and the core consists of a syntactic epoxy foam. Strain gages have been bonded on the outer skins and also located in between the core and the skins. The captioned material is currently used for small components of naval ships (e.g. shields, stanchions, etc.) either in single skin laminates or sandwiches: the final goal of the project is to study its applicability in building pleasure craft hulls, taking advantage of its high strength. The large scale tests have been completed by usual testing on small scale specimens, according to well-known international standards and analytical and finite elements (FE) numerical models have been calibrated with the experimental data. Different options of FE codes have been investigated in order to catch their capabilities and approximations in modelling the composite material and their damage up to collapse. Some advice on the behaviour of quite large sandwich panels is reported, highlighting the effects of the size of the structure on the material mechanical properties.
Keywords: FRP, prepreg, syntactic epoxy foam, composite sandwich, laminates, mechanical tests, large scale tests, numerical simulation (FEM).

1 Introduction

Composite sandwiches are commonly adopted in marine and aeronautical engineering for structures or structural elements requiring high stiffness and strength, mainly to flexural loads, together with low specific weight.

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This paper presents the main results of an experimental and numerical study on the mechanical behaviour of a type of sandwich currently used for small components of naval ships (e.g. shields, stanchions, etc.).

The external facings of the sandwich (*skins*) are *prepreg* glass-fibre/epoxy-matrix composites whereas the central part of the sandwich (*core*) is a syntactic foam consisting of hollow glass microspheres embedded in an epoxy resin matrix.

The final goal of the project is to study the applicability of such material in building entire hulls of pleasure craft, taking advantage of its high strength.

It is remarked that prepregs have very high mechanical properties, also against fatigue and shock and syntactic foam is a core fabric with superior physical properties, (Greene [1]). Another significant advantage concerns prepreg low environmental impact, with no styrene emission. In fact, more and more reducing VOC (Volatile Organic Content) requirements force builders to look for alternative construction methods; it is therefore expected that demand will drive more prepreg manufacturers towards the development of products specifically suited for the marine industry. Other distinct advantages are ease of handling and excellent resistance against water, seawater, oil and hydrocarbons, (Greene [1]).

Main advantages of the syntactic foam adopted are lightweight, high resistance against stability loss due to compression, quite high strength against impact loads.

An attractive option for structural optimization seemed to limit the stiffening of the shell plates using sandwich panels and gradually varying the lamination sequences of the skins and of the core thickness in the different hull areas, according to loads demands. Design of such structures needs a reliable and quite precise numerical model of the whole hull shell. Therefore, analytical and numerical finite elements (FE) models have been studied as well.

The mechanical characterization of this highly heterogeneous material (or rather, structural element) has been carried out at the Department of Naval Architecture and Marine Technologies (DINAV), Genoa University, with the collaboration of Centro Tecnologico Sperimentale S.r.l., La Spezia for small scale testing and Nuova Connavi S.r.l. for experimental data about the syntactic foam, through the following sequence of steps: (a) experimental testing on small specimens of the material adopted for the skins; (b) collecting data about the syntactic foam material adopted for the core; (c) experimental testing of the sandwich panels, both on large and small scale; (d) development of analytical and numerical FE models calibrated with the experimental data, firstly simulating the small scale tests, then the large scale ones.

The paper is organised as follows. In Section 2, the sandwich under study is fully described. Section 3 is devoted to the construction of the numerical model with reference to the theoretical formulations used and the judgement of their applicability. The numerical simulations of tests carried out on small scale specimens and the description of large scale tests together with relevant results are presented respectively in Section 4 and Section 5. Lessons learned are briefly resumed in Section 6.

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2 The sandwich under study

The FRP/syntactic-foam sandwich under study was manufactured by Nuova Connavi s.r.l. (Italy). The sandwich structure is represented in Figure 1.

The materials adopted for the skins are called EPREG UD 52™ and EPREG DIAG 43™ and are prepregs obtained by impregnation with an epoxy resin system of an E-glass tissue. EPREG UD 52™ is a unidirectional composite with 97% of fibres oriented longitudinally and 3% transversally whereas EPREG DIAG 43™ is bidirectional and has ±45° fibres.

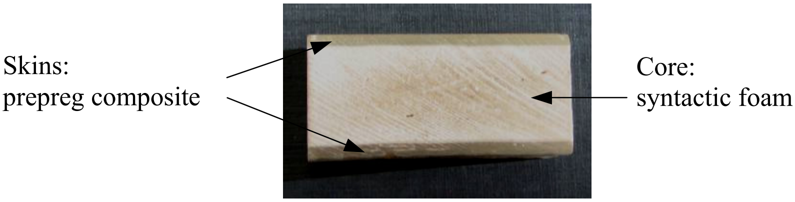

Figure 1: The sandwich under study.

The syntactic foam core, whose trademark is EFOAM™, is assembled with the same epoxy matrix as EPREG™ which embeds hollow air-filled glass microspheres, mixing resin and hardener under vacuum and by adding microspheres repeatedly until full homogenization. Bubbles have an average diameter of 70 mm and an average wall thickness of 0.58 mm. The density of the resulting syntactic foam averages 0.53 g/cm^3 (see [2] for all details).

3 Material modelling

To analyze a sandwich structure, many challenging issues need to be addressed such as the complexity of the mechanical interactions between material constituents, particularly when applied loads produce local damage and sequential failure. The mechanisms of failure in FRP sandwich structures are entirely different from that of conventional steel structures. Static/dynamic failure involves matrix cracking, fibre buckling and rupture, and layer delamination in an interrelated manner. The complexity of the mechanical response of FRP sandwich structures presents great difficulties in predicting reliably composite's performance, nevertheless, finite element method (FEM) is becoming a very popular and powerful tool for simulating an engineering system.

After a preliminary study of a few commercial finite element codes, the software ANSYS® has been adopted for all the numerical simulations performed. This code allows to model composite materials with specialized elements called *layered elements*. Several formulations are available: linear and nonlinear, shell and solid, with different capabilities. SHELL91 and SHELL99 in particular have been used because fitting better the material under study. SHELL 91 is an

8-node, nonlinear, layered element with 6 degrees of freedom at each node that supports plasticity and large-strain whereas SHELL 99 is an 8-node, linear, layered element, without the nonlinear capabilities of SHELL91. Each of these shell elements is shear deformable and allows failure criterion calculations, [3]. The first input required within the software is the definition of the layered configuration, obtained by specifying, layer-by-layer, ply thickness, ply orientation and material properties.

To this aim, being the sandwich skins assumed made of an orthotropic material, the widely known micromechanics formulations have been applied, by superimposition of elementary layers. These equivalent layers have unidirectional fibres and are characterized by the same content of reinforcement as a given layer, whatever the type of reinforcement used. In order to determine the elastic characteristics of that equivalent layer, classical rule-of-mixtures equations for longitudinal moduli and modified equations for transverse and shear moduli have been then used, (Tsai and Hahn [4]). It is remarked that similar formulations are adopted within the HSC Code, [5], whereas semi-empiric formulations are adopted by Class Society, estimating average properties but not accounting for fiber orientation, lay-up method (e.g. manual, prepreg or infusion), stacking sequence, etc.

The material used for the sandwich core has been considered as homogeneous and isotropic.

Failure analysis has been carried out as well, using the capabilities of the software adopted. Within ANSYS®, possible failure of the material can be evaluated by up to six different criteria, of which three are predefined (max strain, max stress and Tsai-Wu). In this study, two failure criteria were examined, max stress and Tsai-Wu, but, since a complete analysis of the sequential collapse is quite difficult to be implemented in the ANSYS® environment, this tool has been used to determine only the first ply failure, leaving to further developments of the research the automatization of the procedure for the progressive failure.

Concerning the sandwich core, Drucker Prager criterion has been considered, supported by the code as well.

The elastic properties for the materials under study are presented in Table 1: as regards the sandwich skins they are calculated as previously mentioned whereas the core characteristics have been provided by the manufacturer.

Table 1: Elastic properties for the materials under study.

	E_x (MPa)	E_y (MPa)	E_z (MPa)	$G_{xy}=G_{yz}=G_{xz}$ (MPa)	ν_{xy}	ν_{yz}	ν_{xz}
EPREG UD 52™	29966	12584	10833	4282	0.207	0.208	0.127
EPREG DIAG 43™	27125	10613	8783	3413	0.212	0.204	0.121
EFOAM™	1512			582	0.300		

4 Small scale testing

The mechanical behaviour of the sandwich and its components (skins and core) has been investigated through the following series of tests on specimens directly prepared by the manufacturer: tension, compression, three point bending tests and short beam tests as regards the skins, [6], three point and four point bending tests, uniaxial compression, uniaxial tension, constrained compressive tests on the core, (Cecchinelli [2]), and, concerning the specimens taken from the sandwich panels, three and four point bending tests, [6]. For each group of tests, specimen shapes and sizes have been chosen according to the relevant standards.

FE models of all tests have been developed as mentioned before and nominal dimensions have been considered. A few significant results are presented as an example in Table 2, Figure 2 and Figure 3, comparing the averaged experimental data for the three point bending tests and short beam tests on EPREG UD 52™.

Satisfactory agreement between tests and calculations was found for skins laminates while larger difference exists for the sandwich specimens. Such discrepancies may be explained taking into account that small single skin specimens were specifically made for tests while large sandwich panels, from which small specimens were taken, were built according to the usual shipyard practice.

Table 2: Comparison between averaged experimental data and FEM results for the three point bending tests (TPB) and short beam tests (SBT).

	TPB - EPREG UD 52™					
	f_{max} exp (mm)	σ_{max} exp (MPa)	f_{max} FEM (mm)	σ_{max} FEM (MPa)	Error f_{max} exp/FEM	Error σ_{max} exp/FEM
Weft	8.54	638	8.85	656	4%	3%
Warp	2.12	54	2.82	54	25%	0%
	SBT - EPREG UD 52™					
	τ_{max} exp (MPa)		τ_{max} FEM (MPa)		Error τ_{max} exp/FEM	
Weft	47.77		59.00		19%	
Warp	8.15		11.00		26%	

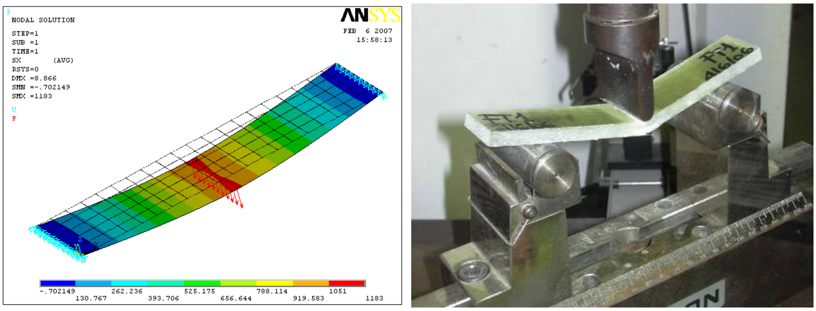

Figure 2: Example of a FE model with the corresponding experimental test.

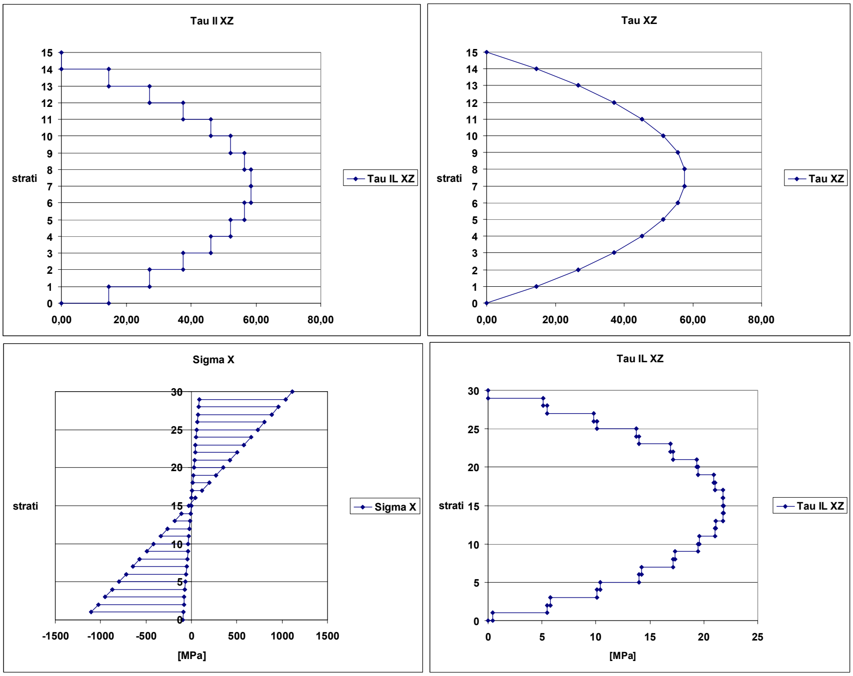

Figure 3: Examples of distributions of stresses in the layers from FE analyses (interlaminar shear and shear of short beam test, tension and interlaminar shear of three points bending).

5 Large scale tests

Large scale tests have been carried out at DINAV ship structures laboratory on two 2000x1000 mm sandwich panels supplied by Nuova Connavi S.r.l. The three point bending test has been deemed the most significant for the mechanical characterization and for comparisons with small scale tests.

5.1 Panel 1

Panel 1 has a lower skin (in tension) with a 5-ply [0/90/±45_2/0] staking sequence and a 4-ply [0/90/±45_2] staking sequence upper skin (in compression); each layer has a nominal thickness of 0.4 mm, whereas the core is 50 mm thick.

Strain gages have been bonded on outer skins following the map of Figure 4: the three mid-span channels are rosettes, placed to evaluate the on-plane shear stress as well as the longitudinal stress induced by bending moment. This layout has been repeated also in between the lower skin and the core to evaluate interlaminar shear stresses. Signals of gages have been recorded using a routine developed on purpose in Labview® and analysed by means of some Matlab® routines: some examples are shown in the following Figure 6 to Figure 8.

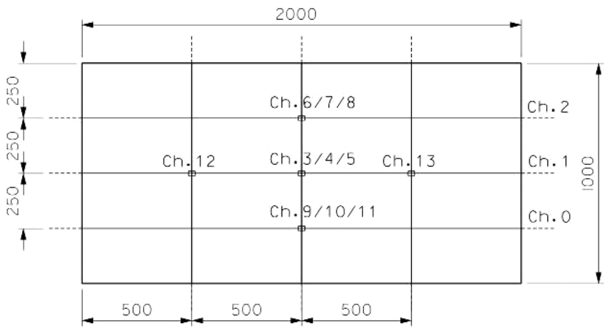

Figure 4: Strain gages layout bonded on Panel 1.

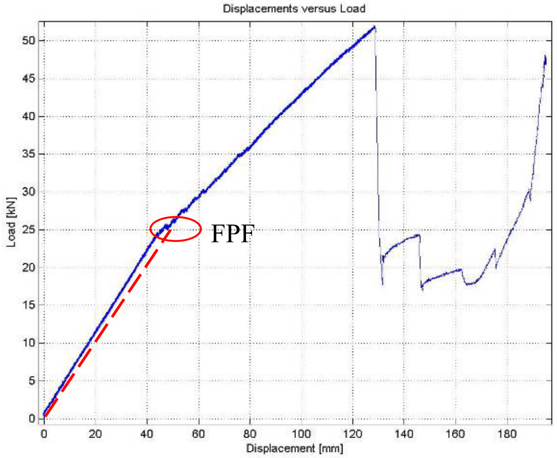

Figure 5: Comparison of Load-Displacement experimental data of panel 1 with FEM calculation — — — of First Ply Failure (FPF).

Panel collapsed at 52 kN with 130 mm displacement and FPF (First Ply Failure) has been reached at 25 kN with 45 mm displacement. Figure 6 shows the behaviour of some significant gages and FPF may be noted. Such curves highlight that some areas of panel collapsed at 25 kN and others maintained residual strength up to the final collapse.

Shear stresses have been evaluated using the rosettes signals (Figure 7).

Moreover, three constantan wires (Ch.0, Ch.1, Ch.2) have been inserted between the lower skin and the core to obtain the bending average deformation. It is worth to point out that all wires, other than Ch.2 whose signals went lost due to wiring connection problems, behave in the same way: they all failed to provide electrical signals only when the panel collapsed, reaching a strain of nearly 5000 $\mu\varepsilon$. FPF may be noted when the slope of plots in Figure 8 suddenly changes.

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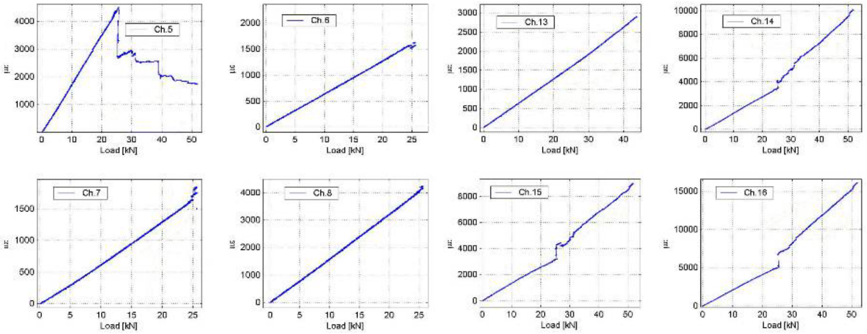

Figure 6: Examples of plots representing gages signals vs. load.

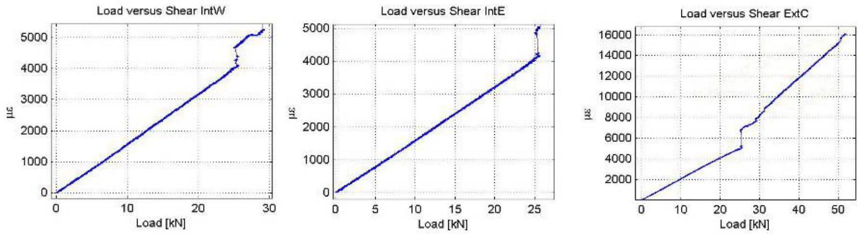

Figure 7: Load vs. shear stress calculated by internal east and west strain gages (IntW & IntE) and by external center strain gage (ExtC).

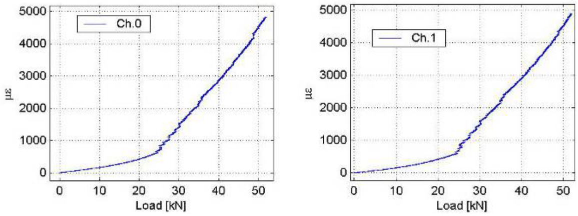

Figure 8: Constantan wires signals of panel 1.

Figure 9: Large scale test and panel collapse.

5.2 Panel 2

Panel 2 has both skins with 8-ply $[0/90/\pm45_2]_2$ staking sequence; each layer has a nominal thickness of 0.4 mm, whereas the core is 30 mm thick.

Strain gages have been bonded according to the map of Figure 4. Constantan wires have been also placed and recorded data are shown in Figure 11.

The final collapse occurred just after the FPF, probably because of the symmetry of the skins and of the lower thickness of core with respect to panel 1. Strain gages provided signals similar to the ones of panel 1, not reported here for sake of shortness.

FEM calculation estimates exactly the collapse load of panel 2 (60 kN) but overvalued the displacement (191 mm instead of 180 mm).

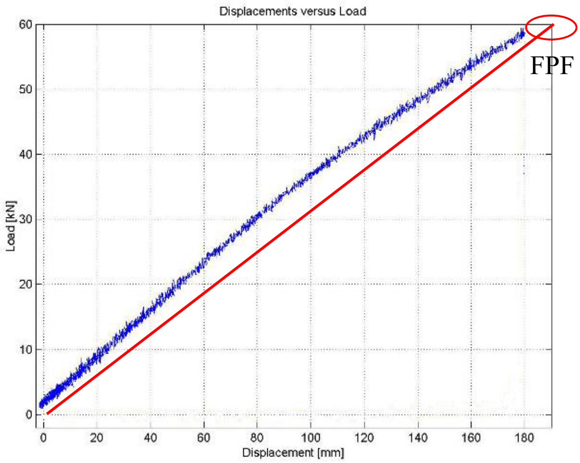

Figure 10: Comparison of Load-Displacement experimental data of panel 2 with FEM calculation —— of First Ply Failure (FPF).

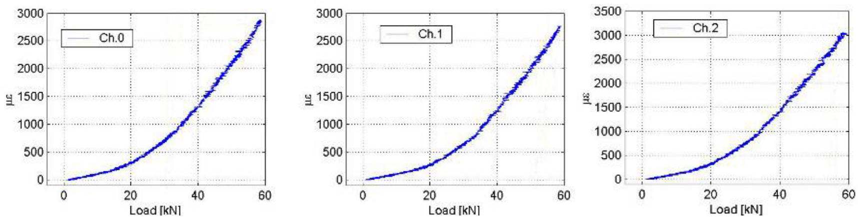

Figure 11: Constantan wires signals of panel 2.

6 Lessons learned

The study presented in this paper highlights that material characterization needs to be carried out looking towards the overall size and behaviour of the structure.

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While failure modes of small scale tests are clearly identifiable, the failure of the large scale specimens follows a progressive collapse where different areas of the sandwich are affected by different failure modes. The interaction of different failure modes might not be simply superimposed.

FE models are in substantial agreement with the small scale tests while larger differences have been found with the large scale ones. Further to the manufacturing defects, whose density may be higher in larger structures, interaction of failure modes may lead to lower material strength.

A larger number and size of defects have been noted in the 50 mm thick core with respect to the 30 mm one because of the different manufacturing procedures. This impacted onto the strength of the panels.

The gages and the constantan wires inserted between the lower skin and the core allows estimating the interlaminar shear stresses and shows that bonding of skins and core is better than in traditional sandwich used for pleasure craft, probably because of the same origin of the constituent materials.

Finally, it is believed that constantan wires can be used to realize a cheap and very light system for structural monitoring of very large areas of FRP hulls. Constantan wires would be weaved in glass reinforcement fabric as weft or warp. Of course, prototypes cited in this paper need to be further developed and tested.

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