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Experimental Analysis of Behavior and Damage of Sandwich Composite Materials in Three-Point Bending. Part 1. Static Tests and Stiffness Degradation at Failure Studies

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Экспериментальное исследование прочности и повреждения многослойных композитных материалов при испытаниях на трехточечный изгиб. Сообщение 1. Исследование разрушения и понижения жесткости при статических испытаниях

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Экспериментально исследовано изменение жесткости и проанализированы механизмы разрушения при статических испытаниях многослойных композитных пластин и их компонентов. Многослойные композитные пластины с перекрестными слоями из стекловолокна и эпоксидной смолы, изготовленные методом вакуумной отливки, подвергали нагружению трехточечным изгибом. Исследовали два варианта пластин с однотипными наполнителями из пеновинилопласта различной плотности. Рассмотрено влияние плотности и толщины внутреннего слоя наполнителя на поведение и повреждение композита. Показано, что композит с наполнителем большей плотности обладает более высокими характеристиками статической прочности и устойчивости по сравнению с композитом, имеющим наполнитель меньшей плотности.

Ключевые слова: пеновинилопласт, механизм разрушения, многослойные композитные пластины с перекрестными слоями, статический трехточечный изгиб, наполнитель.

Introduction. A sandwich composite material results from the bonded assembly (or welding) of two thin skins typically made of materials having good characteristics in tension (high strength and high Young's modulus) and a much thicker core with low density possessing good compression properties [1]. The obtained sandwich structures combine lightness and stiffness. In the case of bending, the stiffness and resistance increase quickly with the structure thickness. Since only the external layers are taking most of the imposed loads on the structure, considerable benefit can be obtained by replacing the inner part (i.e., between the outside layers) with a very light core to obtain a sandwich material.

Sandwich structures are known to possess good resistance to weight ratios compared to conventional materials. However, these structures can present complicated failure mechanisms [2–4]. Although qualitatively it is well known from the classical work of Allen [5] that compressed sandwich panels sometimes fail by a combination of overall (Euler) buckling and local buckling (wrinkling) of face plates, it is only recently that this has been formulated in a geometrically non-linear framework. The interaction can lead to extremely unstable localized buckling which is highly sensitive to initial imperfections in the geometry [6]. Triantafillou and Gibson [7, 8] studied the various modes of degradations of a sandwich subjected to bending and classified them as follow:

– plastic deformation of the skin;
– buckling of the skin in compression (or wrinkling);
– rupture in shear, tension or compression of the foam;
– indentation of the foam by the upper roller;
– rupture of the interface core/skin.

It is found in the literature that the greater proportion of sandwich panels tested to failure tend to fail when the face plate comes apart from the core surface [9–11]. This type of delamination was also noticed by Wadee and Blackmore [12].

In the last decade, sandwich structures have appeared as ideal candidates in mechanical applications where weight saving is of paramount importance to ensure a maximum effectiveness. It is undoubtedly in the fields of launchers, shuttles and satellites that the problem of weight saving is most crucial. For example, each kilogram saved on the launcher represents for ARIANE E.S.A. (EUR) rocket a profit of 30,000 US dollars in payload [13]. The first industrial interest in sandwich composites occurred at the Second World War (during the late 1940's), when the use of sandwich materials (laminated with a balsa core) as structural elements for the 'Mosquito' aircraft [14, 15] was first investigated in Great Britain. Since then, the development of core materials continued in an effort to reduce the weight of the sandwich laminates. The late 1940's saw the arrival of honeycomb core materials, developed mainly for aerospace industry. Honeycomb cores currently offer the greatest shear strength and stiffness to weight ratios; but require care in ensuring a strong bond to the skin. The core materials have been produced in various forms and developed for a range of applications, generally using the hexagonal cell shape for an optimal effectiveness. The high cost of the cores in honeycomb limited their application mainly to aerospace industry. The late 1950's and early 1960's saw the arrival of the polyvinyl chloride (PVC) and polyurethane (PURE) core materials generally employed today in low and medium cost applications [15]. PVC found widespread applications: in medium and high velocity ocean liners [16, 17], in freezer trucks [18] and in numerous sandwich structures for civil and military applications. However, effective exploitation of these cores require proper understanding of their mechanical behavior and properties. For marine applications, the sandwich structures are often used in hulls where high local stiffness exists to maintain the structural integrity and hydrodynamic effectiveness. The late 1960's were the first time sandwich techniques were applied in minesweepers of the Swedish Royal Navy such as the 'Vikste'. Sandwich structures have been used mainly because of their nonmagnetic properties and their resistance to underwater explosions [19]. Several researchers have indicated the insufficient reliability of the standard available procedures used to characterize foam core materials, even for the basic properties such as shear strength and elasticity modulus [20, 21]. Moreover, very little is known about the behavior of foam core under impact loading, particularly significant for applications in mine counter-measure vessels and surface effect ships. Only fracture mechanics was applied to the core [22] in order to model delamination phenomena, frequent in the sandwich structures with thin coatings. The fundamental principles of sandwich manufacturing and the investigation of experimental and analytical methods have been originally described by Allen [5], while Zenkert [14, 15] and Clark et al. [23] undertook further work in this subject. Gibson and Ashby summarize in [24] the basic mechanical properties of polymeric foam core and in the description of their specific cellular structure.

Because of the critical applications of composite sandwich materials, understanding of damage mechanisms and the prediction of the fatigue life in service are of particular interest. Due to their constitution, the mechanical properties of these materials can be adapted by using various materials for the skins (identical or not) and the core, and acting on the thickness of each phase. Accordingly, our contribution consists of an experimental investigation of composite sandwich materials behavior and the damage modes under three-point bending tests, both in static and fatigue. The material investigated consists of two cores of expanded PVC foam, of the same composition and of different densities; the skins being a cross-ply laminate glass/epoxy. This type of sandwich material, which associates good mechanical properties at a relatively low cost, is particularly adapted to a wide range of industrial applications. Our analysis is within an industrial context for which the means of characterization and analysis of materials may be easily implemented.

1. **Materials and Experimental Technique**.

1.1. ***Materials***. Two types of sandwich materials with different kinds of cores were investigated. The skins were cross-ply laminates $(0_2/90_2)_s$ consisting of unidirectional glass fibre fabric with a surface density of 300 g/m^2 and epoxy resin SR 1500/SD whose principal characteristics are given in [25]. This lay-up's stacking sequence is chosen for this work since it was found to have strong fatigue resistance compared to other stacking sequences investigated by the author [26, 27]. Two similar types of PVC foam of different density were used. Herex C70 55 and a C70 75 foams were expanded polyvinyl chloride (PVC) provided by the Airex company and marketed by SICOMIN company in panels of 15 and

25 mm thickness. The two foams used were different in density: 60 kg/m^3 for the Herex C70 55 and 80 kg/m^3 for the Herex C70 75. The diameter of the pores varied between 620 and 880 μm for the C70 55 and between 280 and 500 μm for the C70 75. These same types of core were tested in shear, indentation and in tension by Lolive [28]. The principal characteristics of these foams provided by SICOMIN are given in Table 1.

Table 1

Characteristics of the Foams Used

Foam type	Nominal density (kg/m^3)	Compression stress (MPa)	Bulk modulus (MPa)	Tension stress (MPa)	Tension modulus (MPa)	
C70 55	60	0.85	58	1.30	45	
C70 75	80	1.30	83	1.95	63	
Foam type	Shear stress (MPa)	Shear modulus (MPa)	Shear failure (%)	Impact resistance (kJ/m^2)	Thermal conductivity (W/m·K)	Maximal temperature (°C)
C70 55	0.8	22	20	0.5	0.023	70
C70 75	1.2	30	30	0.9	0.025	75

The sandwich manufacturing was carried out at the laboratory using a vacuum bag moulding technique. The manufacture of the sandwich, the skins and the joining of the core, was carried out at the same time with the laying up of the skin plies and then by interposing the core and the second skin. The sandwich was impregnated at room temperature, and then was vacuumed at a pressure of 30 kPa for 10 hours inside the mould. Before any tests, the plates were left at room temperature for 2 to 3 weeks in order to allow a complete polymerization of the epoxy resin.

As previously carried out by the authors [29], the specimens (foams, skins and sandwich) were cut out using a diamond saw from plates of 300×300 mm according to ASTM C393-00 standard. Dimensions of these specimens are given in Table 2.

Sandwich SD 1 and SD 2 have the same core thickness of 15 mm; they are differentiated by the foam core density. The same foam (C70 75) core is used for SD 2 and SD 3; the only difference lays in the thicknesses of the core which were respectively 15 and 25 mm.

1.2. ***Experimental Setup and Test Procedure***. Testing of the specimens was carried out in three-point bending (Fig. 1) using a universal hydraulic monotonic testing machine (INSTRON model 8516 of capacity ±100 kN) whose control and data acquisition were performed by a computer. The applied load was monitored with a 5 kN load cell, the displacement by a LVDT sensor, and the deformation using an extensometer. The supports were of cylindrical shape of 10 mm diameter for the two lower supports and 15 mm for the central support. A minimum of five tests were carried out for each type of specimen, the loading rates in the static tests being 5 mm/min for the foam core and the sandwiches, and 2 mm/min for the skins.

Table 2

Specimen Dimensions of the Sandwiches Used

Specimen	Dimension (mm)			
	Total length L	Span length l	Width b	Specimen thickness h
SD 1 (C70 55)	300	280	40	18.9
SD 2 (C70 75)	300	280	40	18.9
SD 3 (C70 75)	460	435	50	29.0
Laminated skin $[(0_2/90_2)_s]_s$	300	280	40	4.0
Foams C70 55 and C70 75	300	280	40	15.0

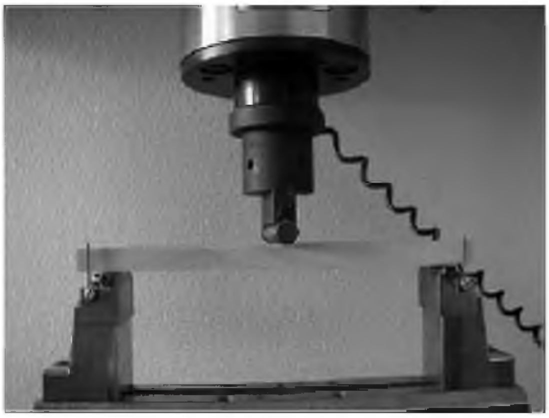


Fig. 1. Three-point bending experimental setup.

2. **Static Tests.**

a) ***Cores***. Foam core Herex C70 55 and C70 75 specimens were cut out with a diamond disk or with a cutter, with dimensions (length and width) similar to the sandwich specimens and were subjected to static flexural load tests. The resulting load–displacement curves are given in Fig. 2. It was observed that the behavior of the load versus displacement comprises three distinct stages:

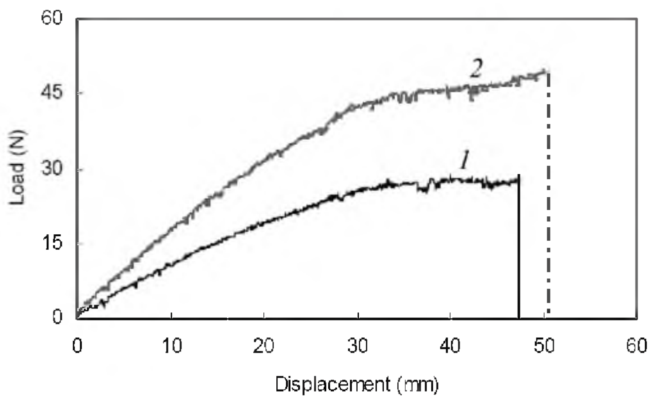


Fig. 2. Influence of the 15 mm thickness cores [C70 55 (*1*) and C70 75 (*2*)] density on the load–displacement evolution.

– stage 1: for low values of flexural displacements, the foam core has an elastic linear behavior;

– stage 2: flexural stiffness decreases gradually in a nonlinear way;

– stage 3: the curve reaches a pseudo steady state beyond which the force does not vary significantly, until catastrophic failure of the specimen.

The comparison between the two foams shows that C70 75, the densest, is most rigid with a larger displacement and load at failure. The presence of the oscillations can be interpreted by the viscoelastic characteristic behavior of the foam core.

b) ***Skins***. The two sandwich's skins laminates were bonded to each other using their curing resin, creating a new $[(0_2/90_2)_s]_s$ lay-up. A number of specimens of 4 mm thick and 40 mm long were made up of this lay-up and then subjected to a three-point bending static test with a distance between test rig supports of 285 mm. The load–displacement behavior of the two skins laminate of sandwich elements SD 1 and SD 2 is presented in Fig. 3. It can be noticed that the specimens' load–displacement behavior is linear until a displacement of nearly 42 mm. Beyond this displacement, the behavior becomes nonlinear; this was more likely due to a slip of the specimens under the lower supports. No catastrophic failure of these specimens occurres during these tests.

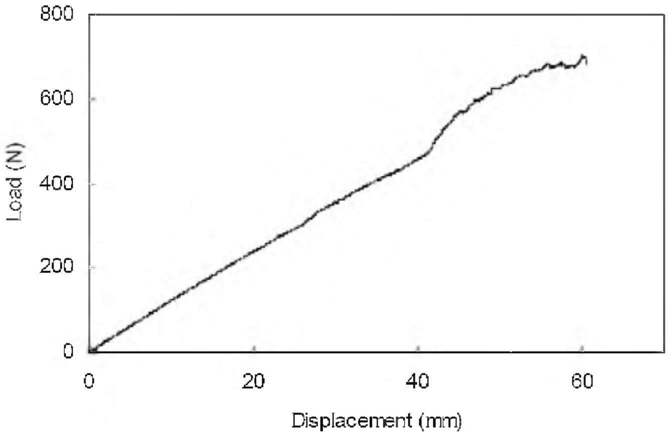


Fig. 3. Load–displacement behavior of the laminated skins $[(0_2/90_2)_s]_s$.

c) ***Sandwiches***. *Core Type Influence*. Figure 4 represents the load–displacement behavior for both sandwich specimens SD 1 and SD 2, obtained from the three-point bending static tests. This evolution proceeded in various stages: at the beginning of the test, the load F increased linearly with displacement, and then the behavior became nonlinear up to maximum loading where it decreases non-linearly for a short period before linearly and gradually decreasing until the rupture of the specimen. The latter occurred after an abrupt fall of the load. The initial linear behavior corresponds to that of the skin laminate in tension, whereas the nonlinear behavior depends on the properties of the foam core under the effect of the indentation and shearing forces. Sandwich SD 2 having the densest core C70 75 was most rigid and had the largest rupture load (Fig. 4).

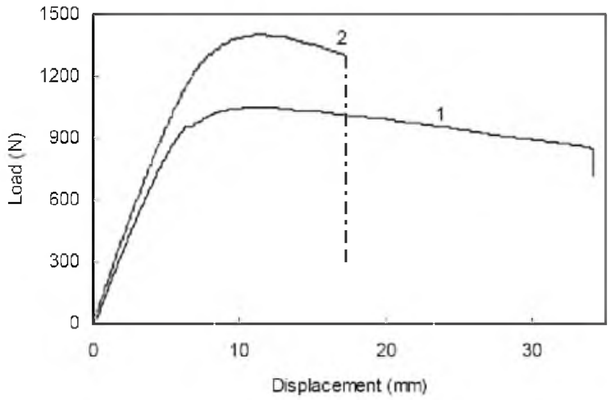


Fig. 4. Influence of the sandwich [SD 1 (*1*) and SD 2 (*2*)] core type on the load–displacement evolutions.

Core Thickness Influence. In order to highlight the influence of the core thickness on the static behavior of the sandwich, two thicknesses of foam core (15 and 25 mm) of the same type C70 75 were investigated. Figure 5 represents the evolution of the load versus the displacement for the sandwich specimens SD 2 and SD 3. From the obtained load–displacement curves, it can be possible to derive the following observations:

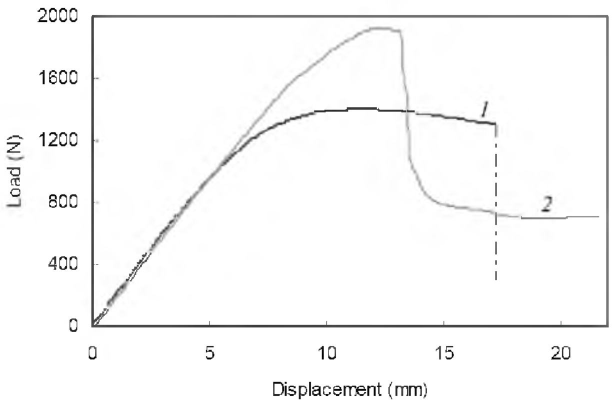


Fig. 5. Influence of the sandwich [SD 2 (*1*) and SD 3 (*2*)] core thickness in the load–displacement evolutions.

As noted earlier, the load–displacement evolution of sandwich specimen SD 2 which has a 15 mm foam core thickness, proceeded as follows: linear then nonlinear passing by the maximum loading followed by a small reduction in the force and finally it suddenly and catastrophically fails. Whereas in the case of sandwich specimen SD 3, which has a 25 mm foam core thickness, the load–displacement curve behaves linearly until around 7 mm, then it becomes slightly non-linear until it reaches the maximum load. Then the load–displacement curve decreases non-linearly for a shorter period compared to SD 2 behavior before a sudden drop in load and specimen rupture occurs. However, it can be noted that the specimen still withstands load at around 800 N until a displacement of 25 mm where the test is then terminated.

In addition, it was observed that the rigidities of sandwiches SD 2 and SD 3 were practically identical for lower displacements (below approximately 7 mm). The effect of the thickness allowed an increase of 37% of the load at the rupture of sandwich specimen SD 3 compared to that of sandwich specimen SD 2 (Table 3).

T a b l e 3

Summary of the Sandwiches Mechanical Characteristics and Their Components Determined from the Experimental Static Tests

Composite	Mechanical characteristics		
	Stiffness (N/mm)	Load at failure (N)	Displacement at failure (mm)
Foam			
C70 55	1.01	28.86	47.38
C70 75	1.67	49.31	50.40
Laminate $[(0_2/90_2)_s]_s$	11.60	–	> 60
Sandwich			
SD1 C70 55	168.31	1051.11	11.60
SD2 C70 75	185.01	1400.60	11.51
SD3 C70 75	193.05	1929.79	12.22

d) ***Comparison between the Sandwich Specimens and Their Components***. Table 3 combined with the superposition of the load–displacement evolution curves of the sandwich specimens and those of their components (Fig. 6) make it possible to compare their characteristics as detailed below:

Stiffness: the load at rupture and the mass of the foam core were negligible comparative to those of the skins and those of the sandwich specimen because of:

– the stiffness of sandwich SD 1 was 166 times higher than that of foam core C70 55;

– the stiffness of sandwich SD 2 was 110 times higher than that of foam core C70 75.

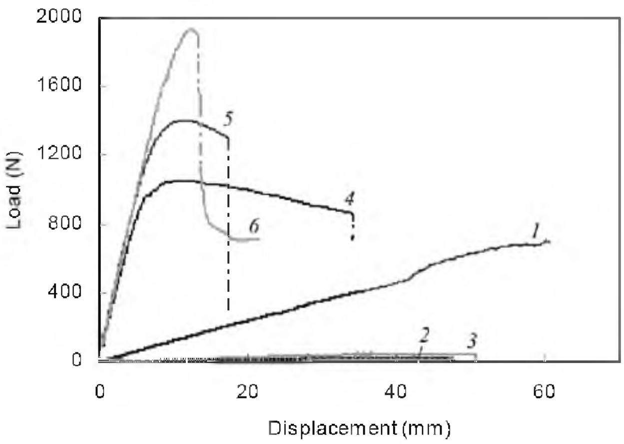


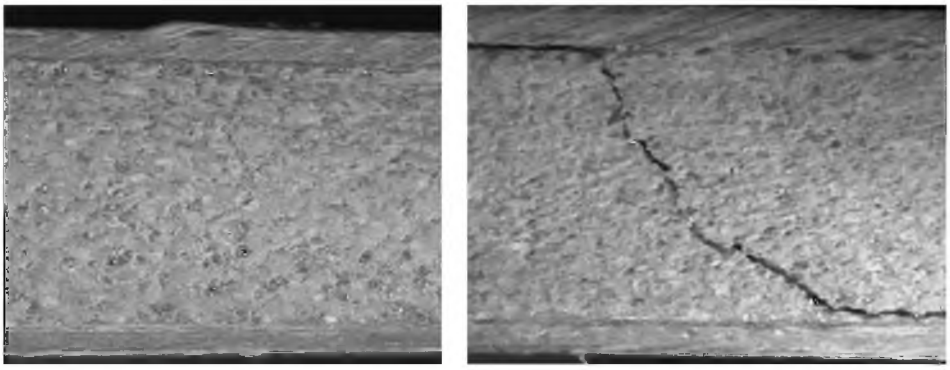
Fig. 6. Comparison of the sandwich load–displacement behaviors and their various components: (*1*) skin; (*2*) C70 55; (*3*) C70 75; (*4*) SD 1; (*5*) SD 2; (*6*) SD 3.

Stiffness values of the sandwich specimens were much higher than those of the skins although the difference of the masses was not significant. Consequently:

– stiffness and the load at rupture of sandwich specimen SD 1 increased respectively by factors of 15 and 1.5 times compared to those of the skins;

– stiffness and the load at rupture of sandwich specimen SD 2 increased respectively by factors of 16 and 2 times compared to those of the skins.

2.1. ***Observations of the Fracture Topographies***. The analysis of optical microscopic observations of the failed specimens under static tests shows that the rupture of the sandwich strongly depends on the type of foam core. Indeed, the failure of sandwich specimens SD 1 was obtained essentially by the rupture of the upper skin and compression with an indentation of the foam core in the vicinity of the central support (upper roller) as shown in Fig. 7a. On the other hand, the failure of sandwich specimens SD 2 was primarily by shearing of the foam followed by a delamination between the two skins and the core (Fig. 7b).



a *b*

Fig. 7. Fracture topographies of Sd 1 (*a*) and SD 2 (*b*) sandwich specimens after static tests.

Conclusions. The behavior and damage propagation under static loading in three-point bending of three sandwich composite materials in one hand and their components (skins and cores) on the other hand have been presented. The static tests were able to determine the characteristics necessary for determining the types of fatigue tests and to identify the resulting mechanisms of damages. The load–displacement behavior of the sandwich panels during static loading revealed three distinct phases, and the final failure was not obtained until a sudden fall of the load. Compared to its components, the sandwich structure possessed much more desirable mechanical characteristics in terms of stiffness and load at failure. In addition to static studies, fatigue tests of sandwich specimens were performed, their results will be presented in Part 2.

Резюме

Експериментально досліджено зміну жорсткості та проаналізовано механізми руйнування при статичних випробуваннях багатошарових композитних пластин і їх компонентів. Багатошарові композитні пластини з перехресними шарами зі скловолокна та епоксидної смоли, що виготовлені методом вакуумної відливки, піддавали навантаженню триточковим згином.

Досліджували два варіанти пластин з однотипними наповнювачами з полівінілопласта різної щільності. Розглянуто вплив щільності і товщини внутрішнього шару наповнювача на поведінку та пошкодження композита. Показано, що композит із наповнювачем великої щільності має більш високі характеристики статичної міцності і стійкості порівняно з композитом із наповнювачем меншої щільності.

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