

Experimental Study of Lightness Factors and Loading Abilities of Sandwich Structures

Mirosław Rodzewicz
 Warsaw University of Technology
 Nowowiejska 24, 00-665 Warsaw, POLAND
 miro@meil.pw.edu.pl

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Abstract

The objects of interest are glass-fiber-reinforced-plastics (GFRP) and carbon-fiber-reinforced-plastics (CFRP) composite sandwich shells with a foam core. Such a structure has been common since the beginning of composite applications in aircraft construction. The strength-lightness factors of typical sandwich structures are large in comparison to laminate structures without a foam core. However, the loading abilities of laminate structures are not fully consumed in both structures. For example, a typical GFRP sandwich shell in a glider wing spar shear-web is able to consume about 60% of loading abilities of pure GFRP laminate subjected to tension load along the warp direction. This is caused by buckling phenomenon of the shell under shear loads. The significant influences on the buckling phenomenon have physical properties of the foam core material and the relation between elastic modules of the foam core and laminate shell. When the same kind of foam core is applied for CFRP sandwich structures, the level of CFRP laminate loading ability to consume is worse than in GFRP sandwich structures. This feature of sandwich structures could be improved by application of additional reinforcement inside the foam core. Described are the successful results of experimental investigations aimed to improve loading abilities of CFRP sandwich shells without worsening the strength-lightness factors.

Introduction

It is widely known, aerodynamic performance of gliders strongly depends on the wing aspect ratio because the ratio influences the induced drag. The requirement of a high aspect ratio creates several problems regarding materials and strength since the wing of high performance gliders works as a thin, slim beam. Therefore, the wing must be designed with a proper safety margin and a mass as small as possible. Since German engineers were the pioneers of polymer composite application in gliders technology, the first standards of composite structure design were elaborated in Germany. In 1981 German aviation authorities issued an advisory document regarding composite wing spar design¹. This document contains several charts, which are constructed as shown in Fig. 1. The vertical axis of the chart concerns the values of stress in the wing spar flanges, while the horizontal axis concerns the values of the structure stress rate (SSR) in a shear-web.

The definition of the SSR in case of compression is given by the following expression²

$$K_{\sigma D} = \frac{q_{\sigma D}}{\overline{m}_{ef} \cdot g} \quad (1)$$

where $q_{\sigma D}$ is the distribution of force in the direction of the compressed fibers (calculated by the formula given in Fig. 3), \overline{m}_{ef} means "effective areal density" and is defined by

$$\overline{m}_{ef} = k_{\approx} \cdot \overline{m} \quad (2)$$

where \overline{m} is the value of the areal density of all fabrics in the laminate and k_{\approx} is a mass ratio of fibers oriented in the load direction (for standard fabrics with equal number of warp and weft fibers $k_{\approx} = 0.5$) and $g = 9.81 \text{ m/s}^2$ is the gravity acceleration.

Note, $q_{\sigma D}$ also can be expressed by the formula,

$$q_{\sigma D} = \sigma \cdot \delta \quad (3)$$

where σ is the stress (measured in the direction of the compressed fibers) and δ is the thickness of the laminate without the optional foam (formed under pressure).

The index D comes from German "Druck" (press). In case of tensioned fibers, the Z index is used (from "Zug"). The values of $K_{\sigma D}$ or $K_{\sigma Z}$ for $\sigma = R_c$ or $\sigma = R_m$ are labeled as K_{Rc} or K_{Rm} . They both have the sense of lightness factors and are peculiar material constants².

This paper concerns loading abilities of composite shells. Results of some experiments are presented regarding different shell structures subjected to the shear loads.

Comparison of laminar and sandwich shells strength properties

First, the differences in the strength properties of laminar and classic CFRP sandwich shells were investigated. Experiments were performed using composite specimens of flat, 0.2 x 0.2 m plates. The shear load was introduced using a special four-joint steel frame (Fig. 2). It was assumed that all

layers of the fabrics used in the shells had their fibers oriented in the same, proper direction; oriented for optimal applied loads (Fig. 3). Both types of shell structures were considered: laminar (without a foam core) and sandwich. Materials used for the specimens are listed in Fig. 2: L4, L6 – specimens with laminar structure, consisting from 4- and 6-layers of carbon fabric and S4/6, S4/8, S4/12 – specimens with sandwich structure with the foam thickness of 6, 8 or 12 mm.

Two kinds of test were conducted: shear stiffness measurements and critical load determinations. During both tests, the specimens were cyclically loaded on the strength machine achieving load-deflection hysteresis loops. Later analysis of those loops allowed investigated parameters to be estimated. The external loads of the specimens were transformed to loads on direction of fibers (see Fig. 3) and were related to the areal density of the reinforcement fabrics using Eq. (1).

FEM analysis of shell buckling

Simultaneously with the experimental investigations, FEM analysis of the shells subjected to shear loads was conducted using MSC Nastran 2001 software. A linear model of buckling (algorithm Lanczos) identified the bifurcation points. The physical model and explanations of bifurcation points estimated in the FEM analysis are displayed in Fig. 4. The examples of derived results are displayed on the right side of the Figure. As can be seen in the graph, the simulated buckling of the shell was similar to the real behavior.

Investigation results

The comparison between measured and calculated critical loads of the CFRP shells is shown in Fig. 5. As seen in the chart, both results are consistent. Figure 6 presents hysteresis loops, when the load was applied in the form of cycles with increasing amplitude, with visible symptom of buckling and failure. The results of shear stiffness measurement, expressed by the product $G_x \delta$ are shown in Fig. 7. The principle of

$G_x \delta$ value estimation is explained below the chart. Parameter x was measured by a linear displacement transducer fixed to the specimen supports. All possible skids were eliminated.

The specimens representing laminar structure (L4 & L6) increased $G_x \delta$ with thickness according expectation. In Fig. 7, can be seen a significant tendency of $G_x \delta$ reduction with higher load which is explainable by buckling deformations. This behavior did not occur with the sandwich specimen. Looking at the values presented in Fig. 7 and at the comparison of masses and thickness (Fig. 8), one can conclude that laminar shell L6 has a larger shear stiffness, while the mass is not very different than the mass of sandwich shell S4/6 (just 13% higher). Having in mind easier manufacturing process and smaller thickness (which is important when the shell is applied as a wing surface of a thin airfoil), it seems that laminar shell L6 could be competitive (in certain conditions) for sandwich shell S4/6.

Another significant result, from Fig. 7, is that since the thickness of the foam core increases in sandwich shells, one can observe a small decrease in shear stiffness. The decrease may be explained by deterioration of transversal stiffness of the foam core when thickness increases. The deterioration is due to lower impregnation and lower saturation of the foam cells by the resin inside the core. Unfortunately, a quite different result occurred from more detailed analysis with the consideration of stiffness versus weight rate, critical loads and safety factors illustrated in Fig. 1. In this approach to shear stiffness analysis, it is better to use the factor K_{G_x} . This is a specific kind of lightness factor which gives the information on how many shear stiffness can be obtained from the unit of areal density of all fabrics in the laminate². The factor is given by

$$K_{G_x} = \frac{G_x \cdot \delta}{\overline{m}_{ef} \cdot g} \quad (4)$$

where symbol G_x is a shear stiffness modulus for laminate reinforced by fibers oriented as shown in Figs. 2 and 3 (earlier, the other symbols were explained). It was assumed for the shear stiffness case that $\overline{m}_{ef} = \overline{m}$. The results of this analysis are shown in Fig. 9. On horizontal axis are marked critical loads expressed by $K_{\sigma D}$. Horizontal arrows ended by short line segments show the usable limits (i.e. critical loads divided by the typical safety factors $1,5 * 1,15 = 1,725$).

It is visible in Fig. 9, that the six-layer laminar plate can be competitive to sandwich plates only for small values of $K_{\sigma D}$ (less than 10 km). Taking into consideration that the practical maximum allowable value of $K_{\sigma D}$ is $K_{R_c} = 93$ km (see next section), this means that the effectiveness of using strength properties of the carbon fabrics would be small.

Improving loading abilities of CFRP sandwich shells

As can be seen in Fig. 1, the recommended value of SSR in the classic GFRP wing spar shear web is 15 km. The wing spar is I-shape in cross section¹. The K_{R_c} value for glass fabrics is 41 km and means that only 37% of loading abilities of pure laminate would be used in the wing spar web². Considering the value of 25.8 km is interpreted as the minimum required compression strength at 54°C means that only 63% of loading ability of the composite is consumed. This is not efficient use of material. The inefficiency is caused by the buckling tendency of the shell subjected to the shear loads which manifests itself much before the stress in compressed fibers reaches the level of the compression strength. The problem which occurs here is how to increase this rate without worsening the strength-lightness factors?

In order to answer this question, additional experimental investigations were conducted with CFRP shells. The same four-joint steel frame was used for shear load application as was used in experiments described in the second section. All specimens were loaded in the way shown in Fig. 2 up to destruction. Then, the $K_{\sigma D}$ values were calculated for each specimen and the ratio $K_{\sigma D}/K_{RC}$.

Description of the specimens

Six specimens were prepared (Figs. 10 and 11): five had a sandwich structure (standard or modified type) and one had a laminar structure which was made for comparison of strength properties. It must be emphasized that *all sandwich structures had almost the same weight* because it was assumed that any modification of the structure could not increase the mass.

Results and conclusions

The results are shown in Fig. 13. The assumed K_{RC} value for CFRP laminate, applied in calculations of loading abilities of the shells, was equal to 93 km (this value was obtained by the author in other investigations). Standard sandwich structure is represented by CFRP1 and CFRP2 specimens. As can be seen in Fig. 13, the rate of loading abilities consumption in this type of structure is worse than in case of GFRP shear-web. The best result obtained by the CFRP shells with a non modified foam core was about 55% (CFRP1), while an expected value for GFRP shell should be at least 63%. The modified sandwich structures were represented by the CFRP3, CFRP4 and CFRP5 specimens. While the flat shear webs that formed parallel to the edge of the specimen did not cause any effect, the flat shear webs that formed along the line of P force (Fig. 2) gave a significant result of 72%. This result is more than in case of GFRP shells! On this pattern, the value of loading abilities consumption for laminar specimen CFRP_L looks modest. Also the concept of cylindrical shear webs was not proven in practice.

Comprehensive testing of reinforced foam core sandwich concept

Promising results of testing flat CFRP sandwich plates with reinforced foam cores became a basis for comprehensive tests. The idea of those tests was to build the composite beam boxes, which can simulate (to a certain degree) the construction structure of a glider wing, and to test those specimens under complex loads. Two beam boxes of similar mass were made from typical GFRP composites; one with classic sandwich structure and the other with a reinforced foam core. In the previous experiments, the CFRP5 foam core reinforcement mode was more efficient. But, taking into consideration planed loading schema (Fig. 16), especially the domination of bending moment and shear force over torsional moment like in a real wing, the CFRP4 foam core reinforcement mode was chosen. Some details of those specimens are given in Fig. 14.

Before the ultimate strength test, the beams were subjected into stiffness tests. The results are shown in Fig. 15. While the bending stiffness in both specimens was the same, the torsional stiffness of improved sandwich structure was a little bit lower. This was due to a small drop in the moment of inertia value of the beam box cross-section caused by transfer of some fibers from the external surface of the beam-box to the interior of the core. The ultimate strength test was done using the test bed shown in the schematic in Fig. 16. The chart in Fig. 17 presents load versus deflection of the beam tip. As can be seen, the result obtained for the improved sandwich structure is much higher than for the classic sandwich structure (almost 137%).

Final conclusions

Comparing results from Fig. 9 and Fig. 13, it is concluded that laminar structures of CFRP shells subjected to shear loads could be competitive to sandwich structures only in case when the assumed-admissible value of the $K_{\sigma D}$ in the wing spar shear web was below 10 km. This result is far from full consumption of the loading abilities of CFRP laminate. When the lightness factors of the structure are most important for the designer, it is necessary to apply reinforcement inside the foam core (assuming that typical synthetic foams are used like Divinacell, Rohacell and other foams of similar strength properties). The results of the tests herein prove that this way of improving the loading ability of sandwich shells is efficient. Unfortunately, while the improvement of sandwich shells used in the wing spar web is not too difficult for both cases of shear webs orientation in the core (i.e. perpendicular or diagonal), the application of shells with reinforced core in the wing skin is possible only in the direction presented in Fig. 18.

Acknowledgement

Some results from experiments made in preparation of their B. Sc. or Master Thesis by the author's former students K. Czajkowska, P. Grzywna and Ł. Łukaszewski were used in this paper. Thanks for nice and fruitful collaborations.

References

- ¹"Vorläufige Dimensionierungswerte für Holme von Segelflugzeugen und Motorseglern", Luftfahrt-Bundesamt, Stand: 20, August 1981.
- ²"Dimensionieren von Bauteilen aus GFK (Glasfaserverstärkte Kunststoffe)", VDI 1313, VEREIN DEUTSCHER INGENIEURE, Januar 1970.
- ³Rodzewicz M., Cieśla P., Sudejko A., "Investigation into shear load carrying capacity of laminar or sandwich composite structures", Proc. of. Conf.: "Lightweight Structures in Civil Engineering", Local Seminar of IASS Polish Chapter, Warsaw 2005.

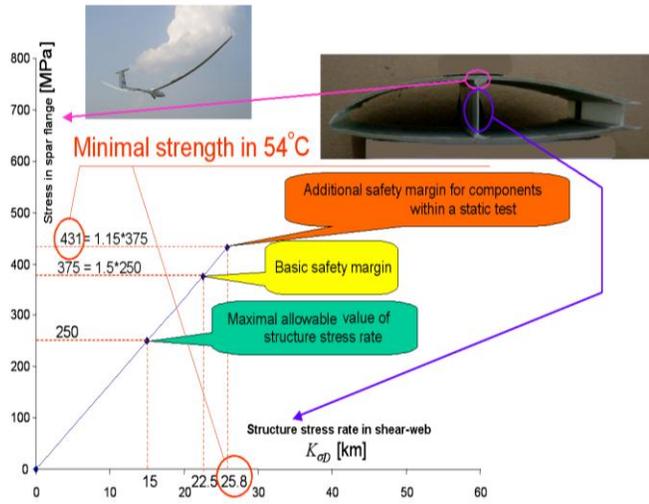


Figure 1 Example of the advisory chart regarding composite wing spar with GFRP spar flanges and GFRP shear-web.¹

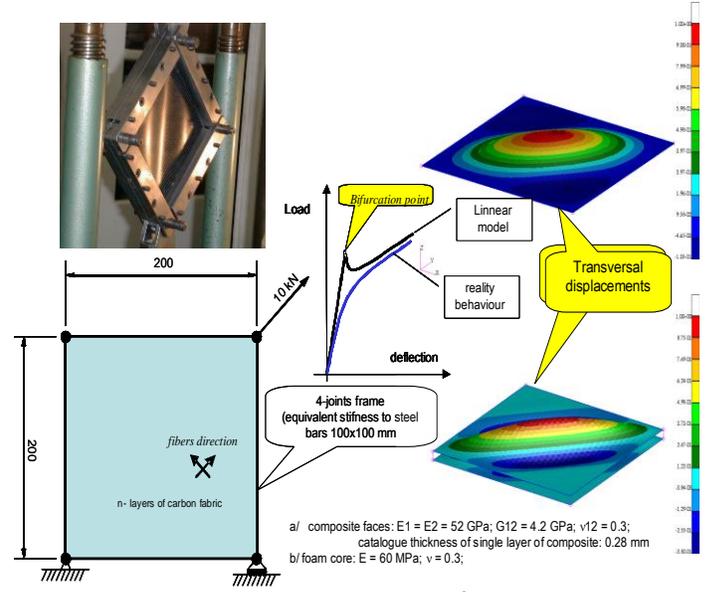


Figure 4 Physical model of the specimen.³

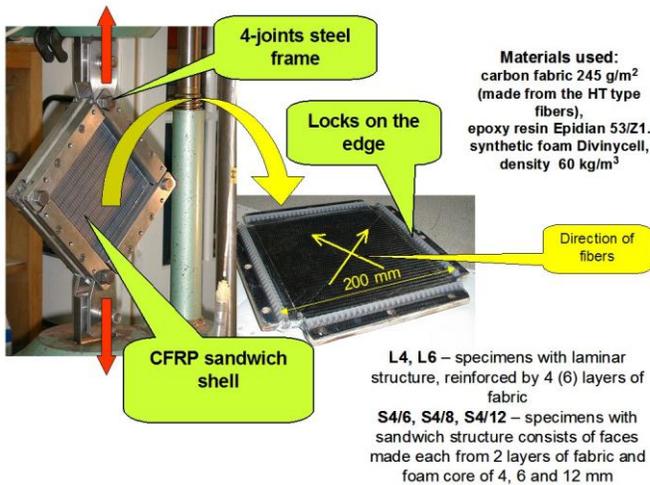


Figure 2 The specimen structure.

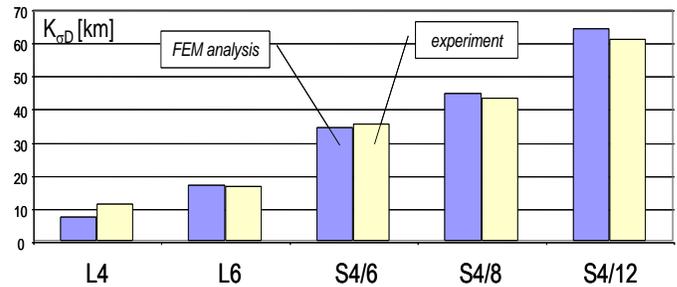


Figure 5 The values of critical loads of composite plates.

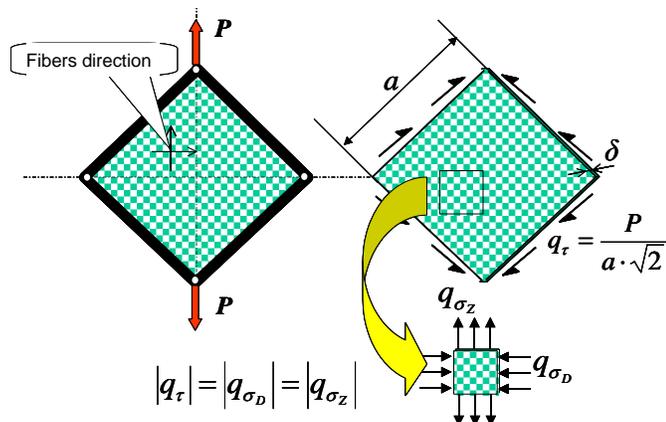


Figure 3 The loads of the specimen structure.

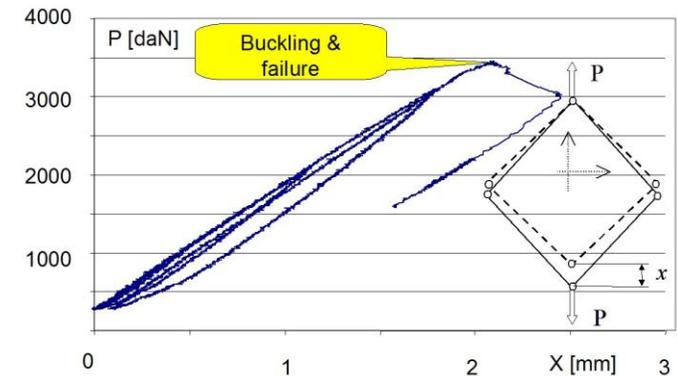


Figure 6 Behavior of the shell subjected to shear loads with increasing amplitude.

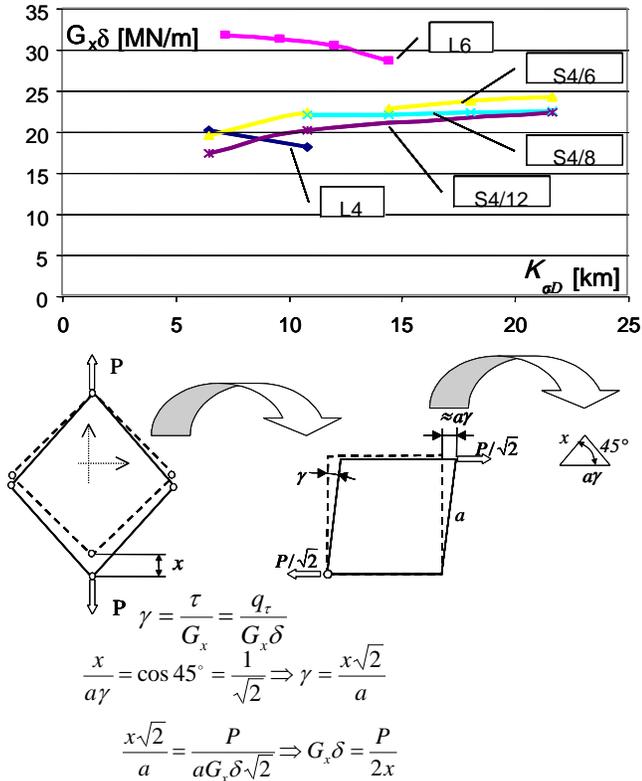


Figure 7 Comparison of shear stiffness and principle of $G\delta$ value estimation.

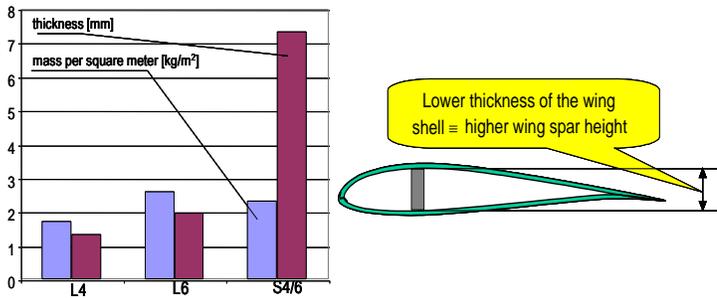


Figure 8 Mass and thickness of some chosen plates.

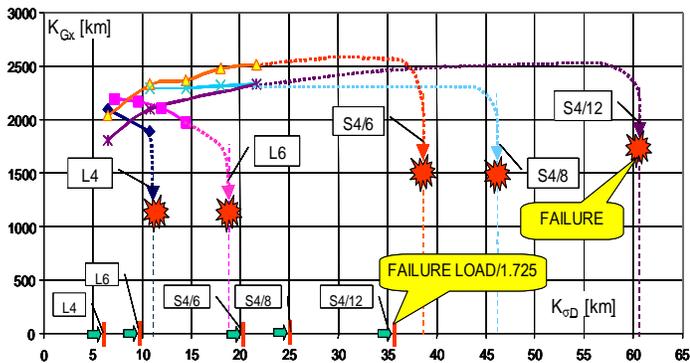


Figure 9 The stiffness to weight ratio and useable ranges for different shells (dashed lines mean extrapolation up to failure load).

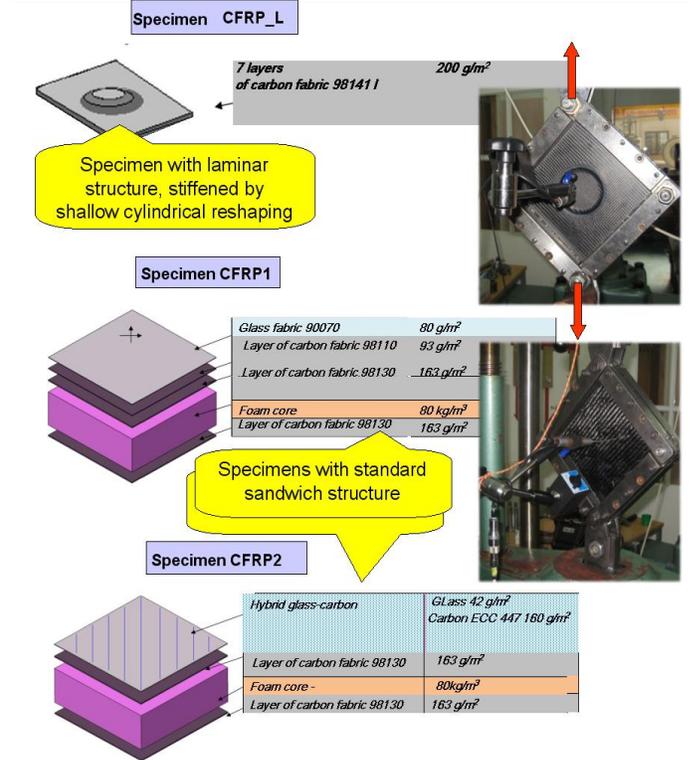


Figure 10 Specimen of shell with laminar structure, stiffened by shallow cylindrical reshaping and specimens with standard sandwich structure.

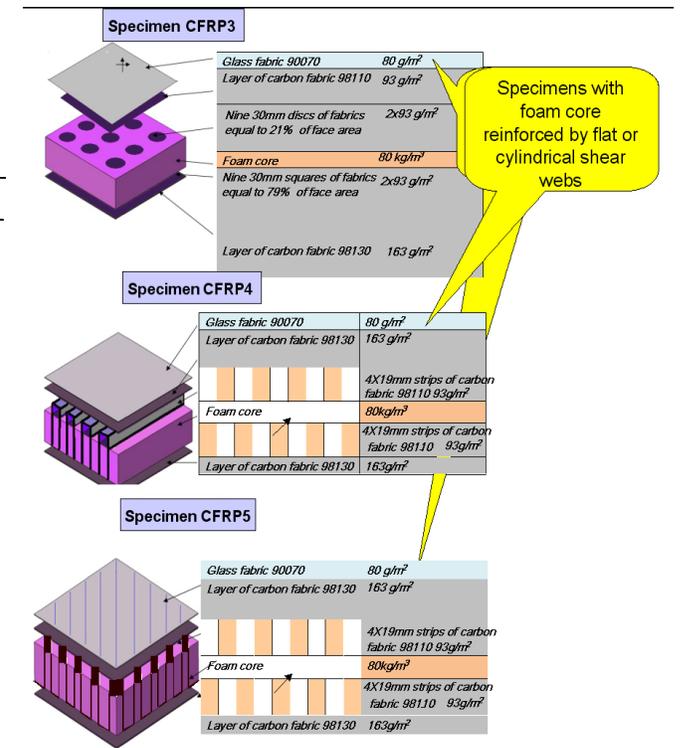


Figure 11 Specimens with foam core reinforced by flat or cylindrical shear webs.

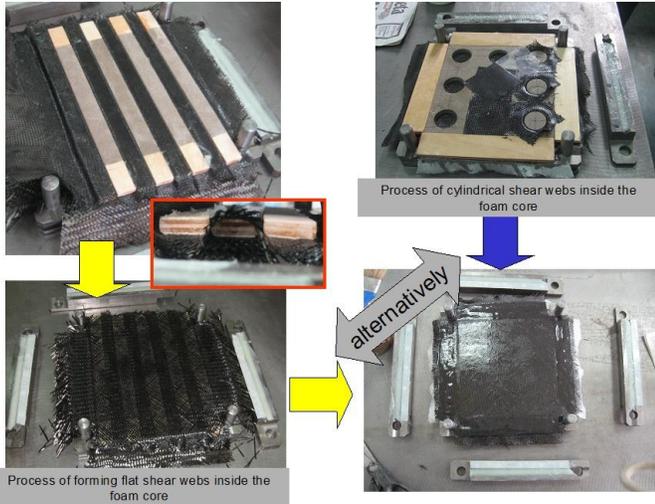


Figure 12 Methods of foam core reinforcement.

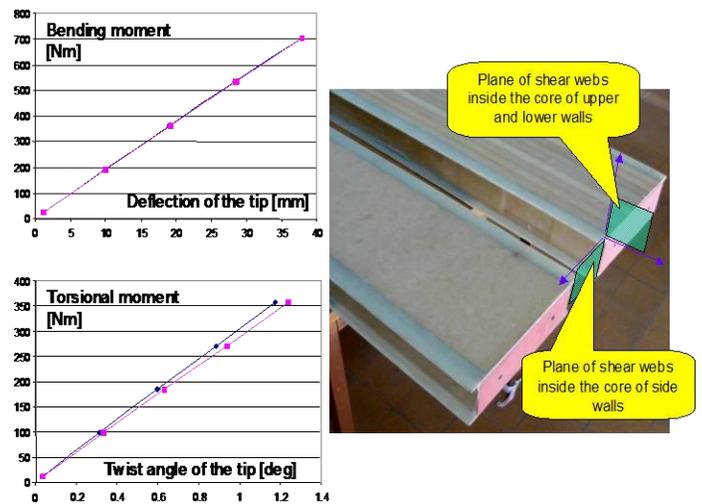


Figure 15 Comparison of specimen stiffness.

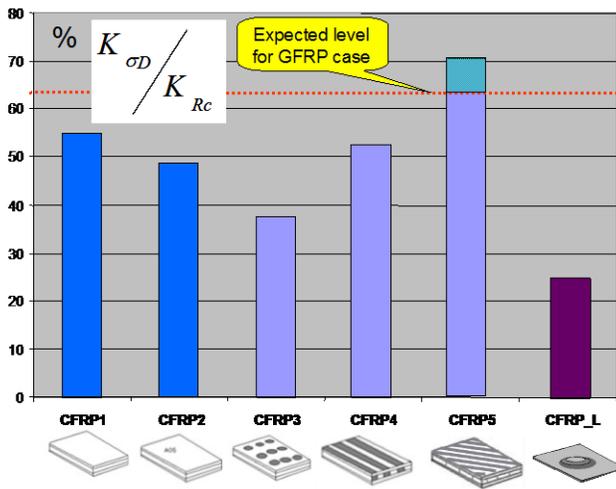


Figure 13 Loading abilities of different CFRP shells subjected to shear loading.

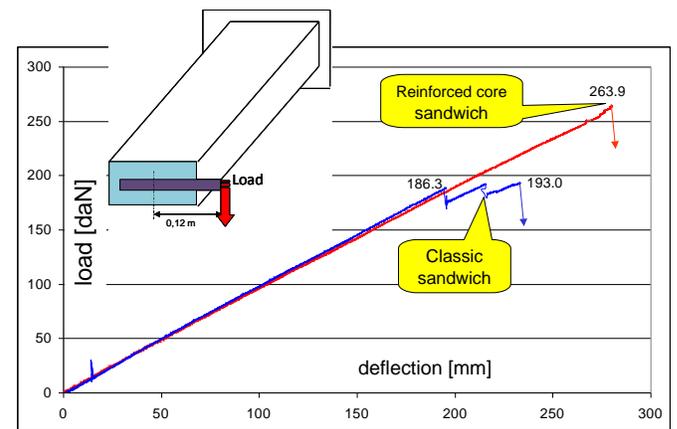


Figure 16 Load versus deflection of both specimens.

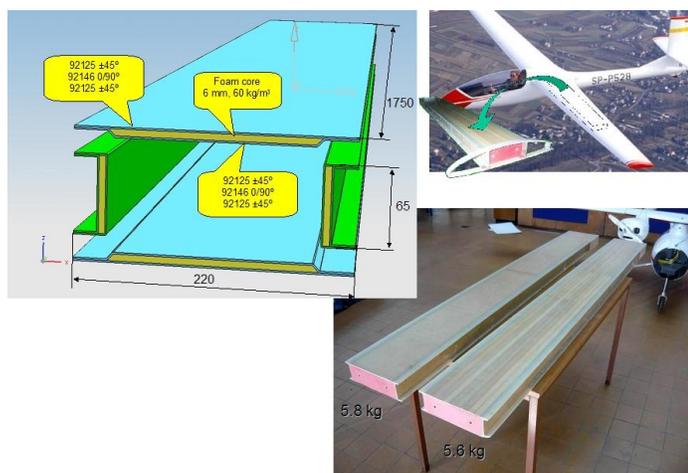


Figure 14 Shape and weight of the specimens for comprehensive testing.

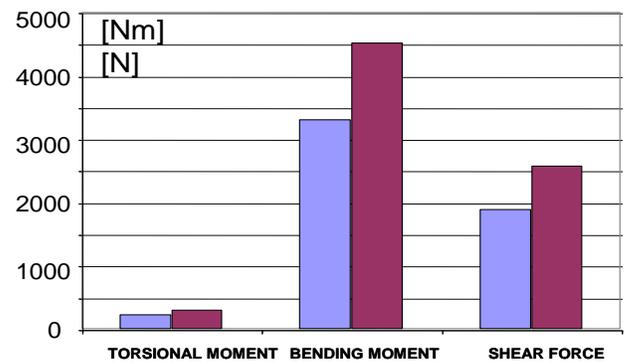


Figure 17 Comparison between particular loads in the roots of beam boxes.

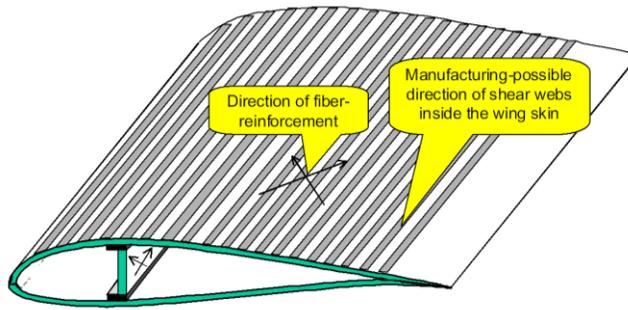


Figure 18 Idea of sandwich structures with reinforced foam core.