DTU Library

Tensile and compression properties of hybrid composites – A comparative study

Raghavalu Thirumalai, Durai Prabhakaran; Løgstrup Andersen, Tom; Markussen, Christen Malte; Madsen, Bo; Lilholt, Hans

Published in:
Proceedings of the 19th International Conference on Composite Materials (ICCM19)

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

TENSILE AND COMPRESSION PROPERTIES OF HYBRID COMPOSITES – A COMPARATIVE STUDY

R.T. Durai Prabhakaran, Tom L. Andersen, C.M. Markussen, Bo Madsen, Hans Lilholt
[1] Section of Composites and Materials Mechanics, DTU Wind Energy, Roskilde, Denmark
* Corresponding author (rtdp@dtu.dk)

Keywords: *epoxy, glass fibres, carbon fibres, hybrid fabric, compression properties*

1 Introduction

One of the major scientific challenges for the composite engineers is the development of new stronger and tougher lightweight structural materials supporting latest technologies and design concepts for the complex shaped structures like aircraft, automotive structures, and large wind turbine blade structures [1]. The development of composite materials improving their performance limits based on the reinforcement of two or more fibres (synthetic fibre with another synthetic fibre or synthetic fibre with natural fibre or synthetic fibre with metallic fibres) in a single polymeric matrix, which leads to the advanced material system called hybrid composites with a great diversity of material properties, is still in its infancy [2]. This is a major challenge that can only be met through an understanding of the relationships between materials architecture and mechanical response, as well observing microstructure formation.

The literature covering research work in the field of mechanical properties of hybrid fibre reinforced composites include: Marom et al. [3] studied the hybridization i.e. positive or negative hybrid effect of a selected mechanical property from the rule of mixture behavior of carbon/carbon/epoxy and glass/carbon composites. None of the mechanical properties, excluding the fracture energies show signs of a positive hybrid effect. Manders and Bader [4] studied hybrid effect and failure strain enhancement of up to 50% for the glass fibre/carbon fibre/ epoxy composite. The authors considered different glass:carbon ratios and states of dispersion of the two phases. The failure strain of the carbon phase increased as the relative proportion of carbon fibre was decreased, and as the carbon fibres were more finely dispersed. Yerramalli and Waas [5] have considered carbon/glass hybrid composite with an overall fibre volume fraction of 30%. With varying carbon/glass fibre ratios, maintaining same fibre volume fraction, ranging from pure glass to pure carbon including hybrid laminates were tested for compression loading to study the failure mechanisms. To study the failure mechanisms, modeling like iso-stress and iso-strain models were considered. Splitting and kinking failures were noted while loading the hybrid laminates under static and dynamic loading rates. Zhang et al. [6] studied mechanical performance for a hybrid composites made of carbon/glass reinforcements, and the processing method used is "wet lay-up" which is not a best practice for obtaining high quality laminates. Five different lay-up schemes were considered: $[C]_8$, $[C_2G_2]$s, $[CG_3]$s, [CGCG]s and $[G]_8$, where C and G denote carbon fibre and glass fibre respectively. The five laminate series were tested under static loading - tensile, compression, and 3-point bending. With the glass/carbon (50:50) hybrid composition, the stacking sequence did not show noticeable influence on the tensile properties but affected the flexural and compressive properties significantly. The current composite system exhibited more matrix failure under flexural loading and more reinforcement failure under compressive loading.

To get more insight about the hybrid composite performance, standard epoxy matrix material and uni-directional (UD) hybrid fabric consists of glass and carbon fibres are considered. The ratio of glass fibres to carbon fibres was varied to get a range of hybrid ratios, starting from pure glass to a mixture of glass and carbon and to pure carbon. The carbon/glass fibres/epoxy UD hybrid composites were made by fabrics and by filament winding techniques. Reference laminates of glass fibre/epoxy and carbon fibre/epoxy were made by filament winding technique. The comparisons are made to evaluate fibre architecture and its parameters influence on tensile and compression properties.

2 Materials and Manufacturing

2.1 Materials

Materials used in the current study include commercially available epoxy resin, from DOW Airstone (760E/766H). The reinforcement materials used are commercially available carbon/glass hybrid fabric, carbon fibre and glass fibre rovings. Raw material suppliers include hybrid fabrics from Devold AMT AS - Norway, carbon fibre rovings from Zoltek Panex 35 (50K tow) with a Young's modulus in tension 242 GPa, and glass fibre rovings from PPG Hybon 2026 (2400 tex) with a Young's modulus 82.7 GPa. The overall fibre volume fraction of the composites was approximately 50%.

2.2 Manufacturing

Both hybrid and non-hybrid composite laminates were manufactured by using the standard processing technique "vacuum infusion" as shown in Fig. 1.

2.2.1 Fabric - Hybrid composites

Most research and technological developments in textile industry show new fabric designs, which have been implemented in hybrid fabric developments. Hillermeier [7] demonstrated new hybrid fabric performances for the development of large turbine blades. In the current study of carbon/glass hybrid composites, hybrid reinforcement layers (fabric) as shown in Fig. 1b were stacked on to a mould followed by infusing the epoxy resin under vacuum.

2.2.2 Filament wound - Hybrid composites

Several researchers implement filament winding procedure as a start, to develop any composite systems with new fibre reinforcements in order to check the laminate performances. The fibres are wound on to a metal frame, developing a fibre pattern of uni-directional fibres as shown in Fig. 1a for the manufacturing of hybrid carbon/glass reinforced epoxy laminates. The pre-processing step provides a better fibre alignment through the absence of backing material and stitching yarns yielding reference laminates for comparison to fabric based hybrid laminate. The infused laminates were cured at elevated temperature, demoulded and post cured to reduce any residual stresses.

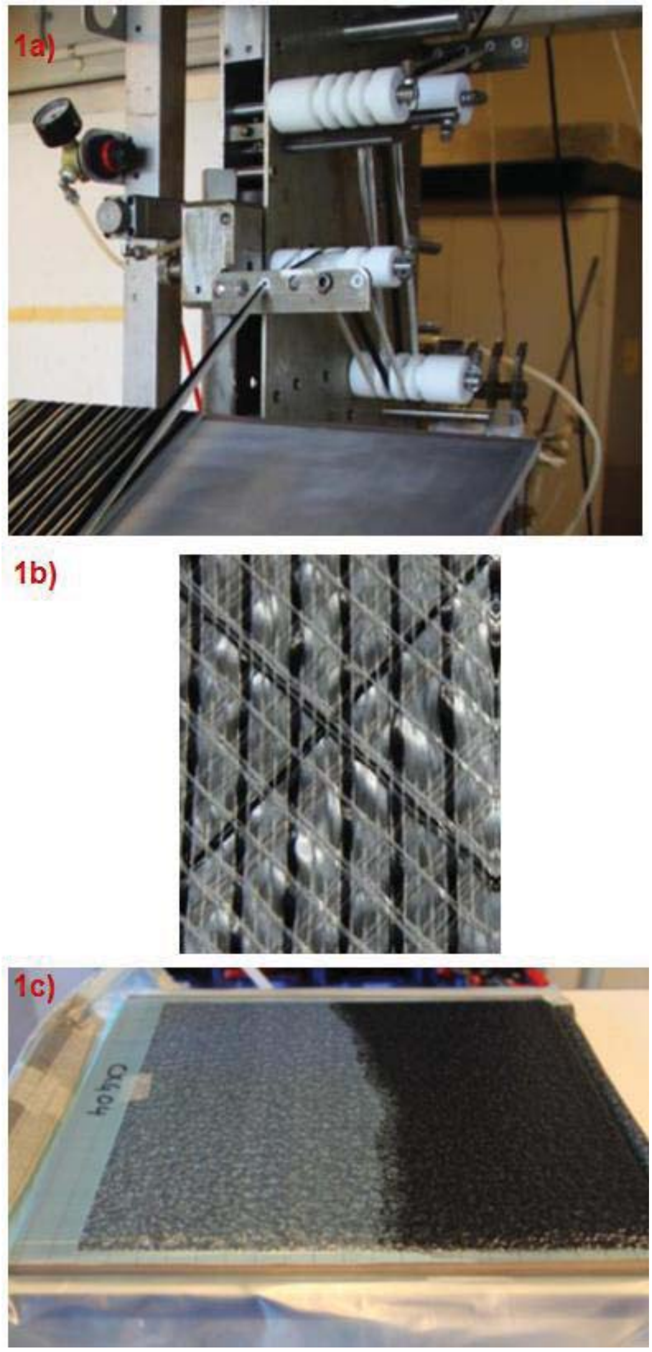


Figure 1. a. Filament winding setup
b. Carbon/glass hybrid fabric
c. Vacuum infusion process trails

2.2.3 Filament wound – Reference composites

The non-hybrid composites were made by filament winding, as described in section 2.2.2. The glass fibre rovings were wound on to a metal frame and infused with the epoxy resin. Similarly to develop carbon/epoxy laminates, carbon fibre rovings were wound on to a metal frame and infused with the epoxy. The infused laminates were cured at elevated temperature, demoulded and post cured. These laminates form reference laminates in order to compare the mechanical performances of the carbon/glass/epoxy hybrid composites.

2.3 Quality control

Hybrid laminates produced by vacuum infusion technique are evaluated for quality. Both the composites density and constituents of hybrid composites were evaluated. Table 1 demonstrates the quality of the laminates produced. Hybrid laminates made by fabrics gave slightly higher porosities compared to filament wound laminates, but the values are still in the acceptable range. In general less than 2% porosities are considered as high quality laminates. Therefore the laminates considered in the current study are of high quality, as shown in Fig. 2, and can perform better while loading them.

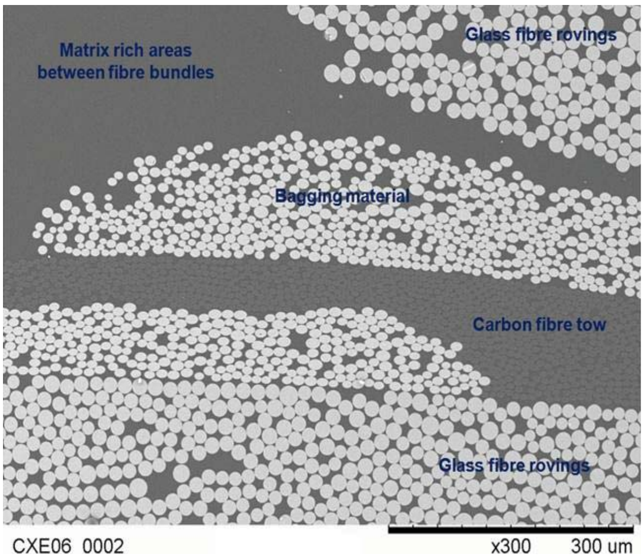


Figure 2. Microscopic image for a hybrid fabric carbon/glass/epoxy composite

Table 1. Experimentally determined density and volume fractions of the composite constituents

Sl. No.	Laminate	Tow ratios Carbon: Glass	Density (g/cm^3)	Carbon fibre (Vol. %)	Glass fibre (Vol. %)	Porosity (Vol. %)
1	Carbon/glass/ epoxy **(Fabrics)**	1:4	1.73	17.8 ± 0.2	32.0 ± 0.2	1.1 ± 0.4
2	Carbon/glass/ epoxy **(Filament wound)**	1:4	1.84	20.6 ± 0.7	37.8 ± 1.0	0.0 ± 0.1
3	Glass/epoxy	0:1	1.99	-	58.7 ± 0.9	0.0 ± 0.1
4	Carbon/epoxy	1:0	1.51	53.0 ±0.2	-	0.1 ± 0.2

3 Mechanical Characterizations

The uni-directional composites (both hybrid and non-hybrid laminates) were considered for measuring its mechanical performance under tensile and compression loading.

3.1 Tensile Tests

Tensile tests are performed according to standard ISO 527 [8]. A servo-hydraulic Instron universal testing machine with a load cell 100 kN was used with a constant displacement rate of 1.5 mm/min throughout the test. The strain measurements were made with mechanical extensometers of 50 mm gauge length clamped directly on both sides of the test specimen. The outputs of the extensometers were handled via a strain gauge amplifier unit. The test setup and test specimen before the test and after the test can be seen in Fig. 3a. Around 10 specimens were tested in each series of laminates for measuring the tensile properties. The average tensile data for hybrid and non-hybrid composites are shown in Table 2.

Table 2. Tensile properties - hybrid and non-hybrid composites

Sl. No.	Laminate	Volume fraction (%)	Thick (mm)	Tensile modulus (GPa)	Tensile strength (MPa)	Strain to failure (%)
Hybrid Laminates						
1	Carbon/glass/ epoxy **(Fabrics)**	17.8 (C) 32.0 (G)	3.4	58	920	1.5
2	Carbon/glass/ epoxy **(Filament wound)**	20.6 (C) 37.8 (G)	3.0	72	966	1.3
Non-Hybrid Laminates						
3	Glass/epoxy	58.7	2.9	48	1023	2.4
4	Carbon/epoxy	53.1	3.4	110	1337	1.2

Stress-strain graphs shown in Fig. 3b demonstrate the comparison between hybrid and non-hybrid laminate performances in tensile loading. As described in section 2.1, the modulus quoted by the material supplier for carbon and glass fibres are 242GPa and 82.7GPa; back-calculating the carbon fibre and glass fibre modulus from the tensile data of non-hybrid composites give 205GPa and 79GPa. This shows glass fibre modulus is nearly equal to supplier's value whereas for the carbon fibre the modulus obtained is less than supplier value. The carbon fibre modulus can vary depending upon the degree of the graphite structure alignments at microstructure level.

3a)

3b)

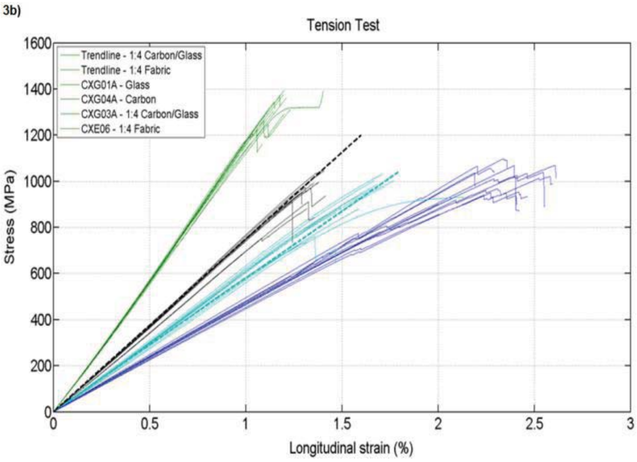
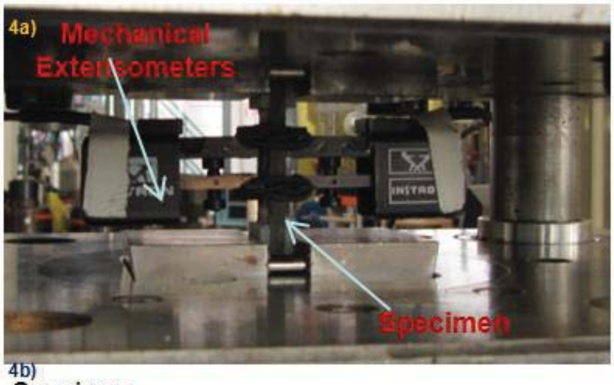


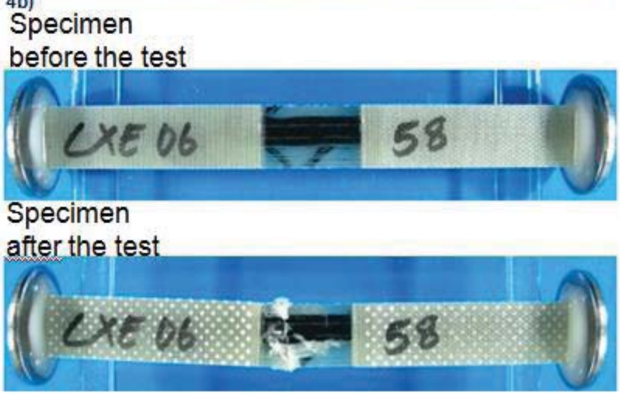
Figure 3. a. Tensile test setup with mechanical extensometers and specimen, before and after test

b. Comparison of stress-strain graphs – hybrid and non-hybrid carbon/glass composites

4a)



4b)



4c)

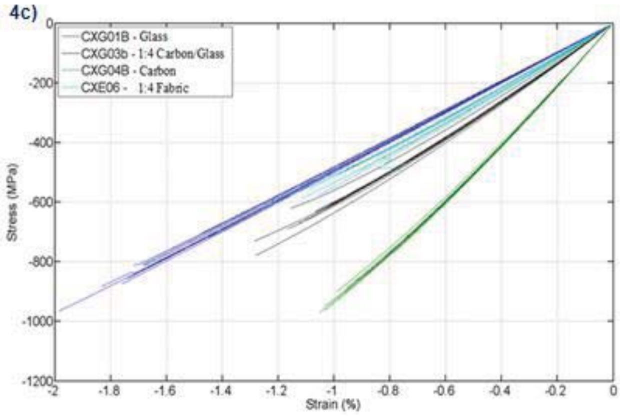


Figure 4.a. Test specimen fixed in the MCL fixture.

b. Specimens before and after the compression test

c. Comparison of stress-strain graphs – hybrid and non-hybrid carbon/glass composites

3.2 Compression Tests

Compression tests are performed according to standard ISO 14126 [9]. An Instron test machine with a test fixture developed at Risø DTU [10] i.e. Mechanically Combined Loading (MCL) compression fixture was used for testing hybrid and non-hybrid composites. All test specimens were mounted with strain gauges on both sides of the specimens to observe test specimen bending ratio. The test setup and test specimen before the test and after the test can be seen in Fig. 4b. Around 10 specimens were tested in each series of laminates for measuring the compression properties. The average data for hybrid and non-hybrid composites are shown in Table 3.

Table 3. Compression properties - hybrid and non-hybrid composites

Sl. No.	Laminates	Volume Fraction (%)	Compre Modulus (GPa)	Compre Strength (MPa)	Strain to Failure (%)
Hybrid Laminates					
1	Carbon/glass/epoxy **(Fabrics)**	17.8 (C) 32.0 (G)	56	540	1.0
2	Carbon/glass/epoxy **(Filament wound)**	20.6 (C) 37.8 (G)	67	657	1.1
Non-Hybrid Laminates					
3	Glass/epoxy	58.7	49	820	1.7
4	Carbon/epoxy	53.1	104	900	1.0

The stress-strain graphs shown in Fig. 4c give a better comparison for the compression loading performance of hybrid and non-hybrid composites. The width of the specimens is considered based on unit cell calculations. Since the carbon fibre rovings are placed in between the glass fibre rovings in the design of the fabric structure, the unit cell width considered in the current study is 14.8mm which is the distance from one carbon fibre rovings to another carbon fibre rovings (three glass fibre rovings are next to one carbon fibre rovings). This helps to include one carbon fibre roving in each test specimen as shown in the Fig. 4b to ensure that the test is performed on hybrid coupons. For filament wound specimens the width of the coupons is 20mm, and this includes both carbon and fibre rovings. The non-hybrid (glass/epoxy and carbon/epoxy) specimens are prepared as per standard with a specimen width of 15mm. As per standard the modulus measured from the experimental data are in the range of 0.05 – 0.25% strain. The data obtained from the test shows if any bending occurs while loading the specimen, by evaluating the bending ratio. The bending ratio is defined based on the strain measurements obtained back to back on the specimen. If the bending ratio is very high (greater than 0.1) the results were discarded.

4 Results and Discussions

The ratio of glass fibres to carbon fibres were varied to get a range of hybrid ratios starting from pure glass to a mixture of glass and carbon and to pure carbon. The mix fibre ratio considered in the current study is 4:1 (4 glass roving, 1 carbon roving) which is 0.35 by volume. Laminates made with this mix ratio were considered to study the tensile and compression characteristics.

Fig. 3b and Table 2 demonstrates the comparison between hybrid and non-hybrid composite performances in tensile loading. Stress-strain graphs show the carbon/epoxy composites fail at lesser strain to failure compared to glass/epoxy laminates. Strain to failure for the carbon/epoxy specimens are recorded half of the values compared to the glass/epoxy specimens. For hybrid cases the tensile properties fall in between non-hybrid (reference) composite properties. Among the hybrids the filament wound composites show little better tensile strength and stiffness compared to hybrid fabrics.

Compared to tensile, compression properties are significant in any composite product design. The compression properties recorded experimentally are given in Table 3 and the stress-strain plots for the hybrid and non-hybrid composites are shown in Fig. 4c. Both glass/epoxy and carbon/epoxy show nearly equal compression strength whereas strain-to-failure is less for carbon/epoxy compared to glass/epoxy. This is mainly due to carbon fibres. For both hybrid composites the compression properties are recorded in between glass/epoxy and carbon/epoxy composites. The hybrid fabric composite performance in compression loading is not similar to hybrid filament wound samples. This show the fibre architecture plays a significant role in compression loading. In the present case, the fabrics contain backing threads to hold carbon and glass fibres in place to form a weave structure. In the filament wound samples, both glass and carbon fibre rovings are wound on to a metal frame and then infused without any additional backing threads (see Fig. 1b). Therefore the alignment of fibres is more accurate with 0 deg orientation compared to fabrics. Even if small degree of mis-oreintation exits in fabrics prior to infusion or during the processing trials, laminates will finally demonstrate poor performance in compression loading [11]. Comparing the stress levels for the hybrids, the fabric based specimens recorded lesser strength and strain to failure compared to filament wound specimens, see Fig. 4c.

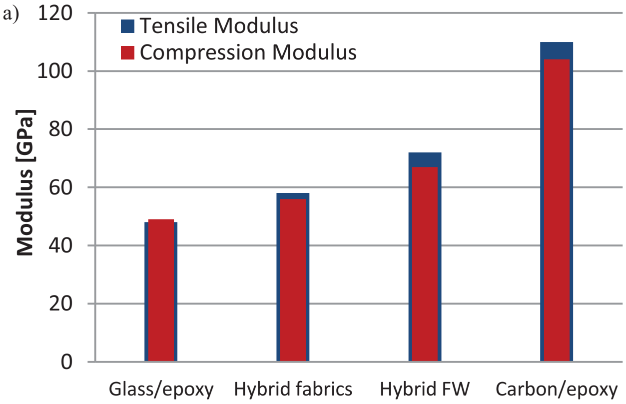
From the bar chart shown in Fig. 5a, the trend in the increase in modulus (both tensile and compression) can be seen from glass/epoxy to carbon epoxy. From the literature it is known for composites, that the compression modulus is either equal to or less than the tensile modulus. Current experimental study demonstrates the same trend. Comparison of tensile and compression strength for the hybrid and non-hybrid composites can be clearly seen in Fig. 5b. As expected the tensile strength is higher than the compression strength for the specimens considered. Fig. 5c indicates variation of stiffness versus fibre mix ratio for hybrid and non-hybrid composites. This helps to consider correct proportion of carbon:glass for achieving higher stiffness values.

The above discussions indicate fibre architecture and its parameters have significant influence on compression properties. Moreover filament wound specimens give a better understanding compared to fabric based composites, while tested for their tensile and compression properties.

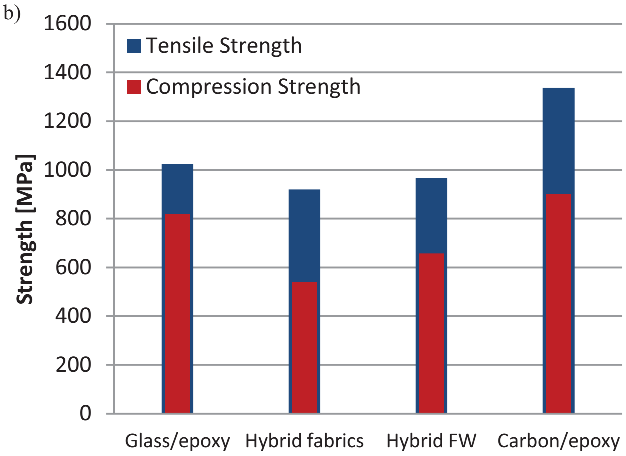
5 Conclusions

The paper presents a preliminary study on hybrid and non-hybrid composite performances and its comparison. The results demonstrate that both hybrid composites made by fabrics and filament wound fibre configurations perform similarly in tensile loading whereas in compression loading filament wound laminates show better performance compared to hybrid fabrics. The performances of non-hybrid composites are relatively better and demonstrate clear boundaries for glass fibre reinforced epoxy and carbon fibre reinforced epoxy, while comparing tensile and compression properties. Optimizing fibre architecture and its parameters is also significant for developing new hybrid fabrics for composite product developments. This demonstrates there is a need for development of compatible fabrics and the sizing for both carbon and glass fibre reinforcements suitable for epoxy and polyester resin systems.

a)



b)



c)

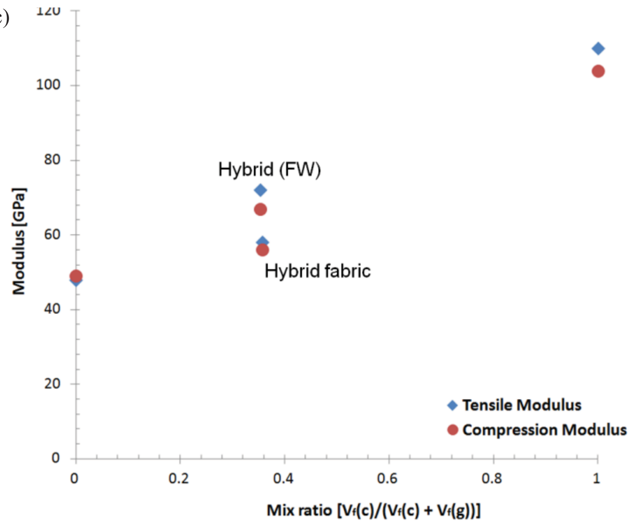


Figure 5.a. Bar graph demonstrating the comparisons of hybrid and non-hybrid stiffness

b. Bar graph demonstrating the comparisons of hybrid and non-hybrid composite strengths

c. Modulus versus fibre mix ratio by volume

Acknowledgments

The authors thank *Danish National Advanced Technology Foundation (HTF)* for their financial support. Thanks are also extended to project partners and material suppliers for fruitful discussions and encouragement.

6 References

[1] M. N. Gururaja and A.N. Hari Rao "A review on recent applications and future prospectus of hybrid composites", *International Journal of Soft Computing and Engineering (IJSCE)*, Vol. 1 (6), pp 352 – 355, 2012.

[2] R.T.D. Prabhakaran, B. Madsen, H. Toftegaard and C.M. Markussen "Flexural Properties of Hybrid Natural Composite-Micromechanics and Experimental Assessment". *Proceedings of 3rd Asian Conference on Mechanics of Functional Materials and Structures (ACMFMS 2012)*, Indian Institute of Technology, New Delhi, Vol. 1, pp 469-472, 2012.

[3] G. Marom, S. Fischer, F.R. Tuler, and H.D. Wagner "Hybrid effects in composites: conditions for positive or negative effects versus rule-of-mixtures behavior". *Journal of Materials Science*, Vol. 13, pp. 1419-1426, 1978.

[4] P.W. Manders, M.G. Bader "The strength of hybrid glass/carbon fibre composites. Part 1 Failure strain enhancement and failure mode". *Journal of Materials Science*, Vol. 16, pp. 2233-2245, 1981.

[5] C. S. Yerramalli and A. M. Waas "Compressive behavior of hybrid composites", *Proceedings of 44th AIAA/ASME/ASCE/AHS structures, Structural Dynamics and Materials Conference,* 07-10 April 2003, Norfolk, Virginia (AIAA-2003-1509).

[6] J. Zhang, K. Chaisombat, S. He, C. H. Wang "Hybrid composite laminates reinforced with glass/carbon woven fabrics for light weight load bearing structures", *Materials and Design*, Vol. 36, pp 75-80, 2012.

[7] R. W. Hillermeier "New composite hybrid reinforcements for the wind turbine industry". *JEC Composites Magazine*, Vol. 49, pp 36-38, June 2009.

[8] Plastics -- Determination of tensile properties -- Part 5: Test conditions for unidirectional fibre-reinforced plastic composites, International Standard ISO 527-5:2009, International Organization Standard, Geneve 20, Switzerland.

[9] Fiber-reinforced plastic composites – Determination of compressive properties in the in-plane direction, International Standard ISO 14126: 1999, International Organization Standard, Geneve 20, Switzerland.

[10] J. I. Bech, S. Goutianos, T. L. Andersen, R. K. Torekov, P. Brøndsted "A New Static and Fatigue Compression Test Method for Composites". *Strain*, Vol. 47 (1), pp 21–28, February 2011.

[11] R.T. Durai Prabhakaran, Lars Pilgaard Mikkelsen and Hans Lilholt "Failure analysis of steel/polyester composites - compression Properties", *Proceedings of 3rd Asian Conference on Mechanics of Functional Materials and Structures (ACMFMS 2012)*, Indian Institute of Technology, New Delhi, Vol. 1, pp 522 – 525, 2012.