# ANALYSIS OF MECHANICAL AND THERMAL BEHAVIOR OF HYBRID CARBON/GLASS THIN-PLY LAMINATES

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## ABSTRACT

The paper presents analysis of mechanical and thermal behavior of hybrid carbon/glass thin-ply laminates. Thin-ply hybrid laminates with different lay-ups with different thicknesses were manufactured using vacuum infusion method. Different lay-up configurations having single, double and quadruple layers of carbon and glass fiber layers were designed to parametrically investigate the ultimate strength and strain to failure under uniaxial tensile loading and for analysis of thermal behavior under internal and external heating conditions. This was done in perspective of demonstrating potential of hybrid thin-ply laminates in multifunctional applications. Mechanical behavior was analyzed by performing ultimate tensile strength tests. Mechanical testing results indicate an increased ultimate tensile strength and strain to failure when carbon and glass/epoxy layers are distributed into thinner layers compared to laminates with equal amount of carbon and glass/epoxy layers assembled into thicker layers. Thermal behavior of hybrid carbon/glass thin-ply laminates with different layer thickness ratios were investigated by performing experimental tests under internal and external heating. In internal heating tests cyclic mechanical loading with relatively high loading frequency was applied in order to generate internal heating within material. In external heating tests a small-scale external heater was attached on the surface of laminate specimen. In both experiments transient temperature distribution along the thickness of specimens was measured and recorded using high performance/high resolution thermal imaging camera equipped with microscope lens. Obtained results demonstrate relatively large differences between carbon/epoxy and glass/epoxy layers as to be expected from their different thermal properties. Analysis of different hybrid thin-ply laminate configurations demonstrated high sensitivity to lay-up, external layer material and layer thickness in both internal and external heating tests.

## 1 INTRODUCTION

Carbon fiber reinforced polymers, over the recent decades, have been widely used in high-performance structures such as airplanes, wind turbine blades, cars and sports equipment due to their unique combination of high stiffness and low density. Despite the significant increase of use of composites in high-performance applications, the development of micro-damage such as fiber/matrix interface debonds, matrix cracks, delaminations and fiber breaks in composite layers during the service life is a significant limiting factor. Matrix cracks in transverse layers are typically the first damage mode to occur in the laminate layers due to weak properties in the transverse direction to the fibers and is a main cause for the appearance of subsequent damage modes such as delaminations and fiber breaks. Hence, to delay the final failure, it is highly desirable to suppress the initiation and development of transverse matrix cracks. In this context, laminates with thin plies, developed in the recent decade [1,2], is a new development direction for composite materials, expected to give superior damage resistance compared to conventional composite laminates due to increased in-situ transverse strength. There have been several studies demonstrating a significant increase of transverse strength and delayed or nearly suppressed micro-cracking in thin-ply carbon/epoxy laminates [3,4]. On the other hand, the increased strength and delayed micro-cracking leads to a highly brittle ultimate failure of the laminate which is not desirable in many applications [3]. One approach to decrease the brittleness of the composite laminate failure is fiber hybridization – the use of at least two different types of fibers in the composite. Typical example widely investigated in the literature is carbon/glass hybrid laminates, where the carbon fiber layers provide the stiffness of the laminate, while the glass fibers, which have a much higher failure strain, lead to a significantly more ductile failure behavior of the composite [5,6].

The thin-ply laminates and hybridization lead to a significant improvement in composite failure properties, however, rather few attempts have been made in the literature to combine both thin-ply architecture and the hybrid glass/carbon lay-up into a single laminate, e.g., [7,8]. According to [7] hybridization of thin carbon and glass fiber layers may lead to an improvement of 20% in the failure strain. Furthermore, the thin plies suppress unstable delamination and it becomes possible to avoid a significant load drop, when the brittle component, such as carbon fiber layer, breaks [8].

Along excellent mechanical damage resistance properties such hybrid laminates could also simultaneously utilize beneficial physical properties of materials, such as electrical insulation properties of glass fibers and thermal conductivity properties of carbon fibers ultimately designing a multifunctional material. Such materials could have a great potential for application in structural electronics [9], structural batteries [10], aerospace and automotive applications among others.

Such hybrid laminates with thin carbon and glass layers could be of particular interest in developing structural electronic components, where a significant weight reduction could be additionally achieved on the system level by integrating thermal conductivity function in the hybrid structural laminate for conducting away the excess heat from electronic components and thus eliminating the need for heavy liquid cooling and ventilation components. In the context of glass/carbon laminates, the carbon fiber layers would be very suitable for performing the heat conduction. Initial attempts in applications of such multifunctional glass/carbon hybrid laminates in printable circuit boards have been reported in [9].

The present paper aims to demonstrate and analyse the combined mechanical and thermal behavior of such hybrid thin-ply laminates. Different configurations (lay-ups) of hybrid thin-ply laminates were manufactured and experimental mechanical and thermal tests were performed. Mechanical tests were performed in a tensile loading until reaching ultimate failure. For thermal tests two different approaches were used for applying thermal loads: for external heating a small-scale external heater was attached on the surface of laminate specimen and temperature distribution in laminate layers was measured. In the second approach, which was internal heating, cyclic mechanical loading was applied to generate internal heating within laminate layers. 2D transient temperature distribution along the thickness and length of the specimens was measured. The main objective of the thermal behavior tests was to evaluate the heat transfer from the externally heated surface layer to the internal layers (in case of external heating) and to analyze heat flow and temperature distribution in hybrid laminate layers during internal heating (self-heating).

## 2 MATERIALS AND LAY-UP CONFIGURATIONS

Materials for the present study were manufactured from Textreme carbon fiber thin-ply plain weave fabrics supplied by Oxeon (Sweden) with areal weight of 100g/m$^2$ and glass fiber plain weave fabrics supplied by Interglas (Germany) with an areal weight of 80g/m$^2$. Epoxy resin LY1564 with XB 3404-1 hardener was used as the matrix system. Composite plates were hand stacked into selected lay-ups and vacuum infusion method was used for infusion of the epoxy, see Fig.1.

Figure 1: Manufacturing of hybrid thin-ply laminates using vacuum infusion method.

To enhance the flow of resin through the densely packed fabrics, small size metal pins were used to provide better flow conditions prior to the vacuum infusion process. The hybrid composite plates were cured in an oven at 80°C temperature for 8 hours. Hybrid carbon/glass laminates with various combinations of single, double and quadruple carbon and glass fiber layers were manufactured in order to parametrically study the effect of material system and layer thickness. Notably all selected laminates consist of 16 layers. For the hybrid laminate lay-ups there is always an equal total amount of 8 carbon and 8 glass layers with the difference being in the arrangement of these layers. The selected lay-ups and their notations are schematically shown in Fig.2.

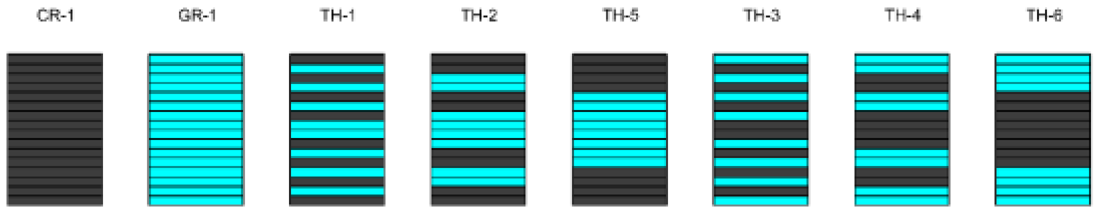


Figure 2: Schematic illustration of hybrid thin-ply laminate lay-ups

In Fig.2. CR-1 and GR-1 denote carbon/epoxy and glass/epoxy reference materials respectively. TH-1 to TH-6 are the used notations for hybrid carbon and glass/epoxy laminate plates with different layer configurations and thickness ratios.

## 3 EXPERIMENTAL TESTS

Mechanical and thermal tests were performed on the laminates listed in Fig.2. To perform the tests, the manufactured plates were cut into strips suitable for tensile testing with specimen width approximately 20 mm and the total length being 300 mm. Cutting was performed by diamond cutting blade. The selected dimensions correspond to ASTM D3039 recommendations.

### 3.1 Mechanical tests

Standard size tensile test specimens (according to ASTM D3039) were prepared to perform experimental tests for determination of elastic tensile modulus, maximum tensile strength and ultimate strain to failure of reference and hybrid composite laminates. To ensure sufficient gripping of specimens and to avoid premature failure, the specimen ends were reinforced with glass fiber composite tabs. Mechanical tests were performed on Zwick/Roell Z150 universal testing machine equipped with 150 kN capacity load cell. Tensile strain was measured using non-contact video-extensometer from Messphysik with gage length of 50 mm. Tests were performed at a rate of tensile strain equal to 1% per minute consisting of initial loading-unloading step up to 0.30% for measurement of elastic tensile modulus followed by loading step until the ultimate failure. 3 test specimens from each laminate lay-up were tested.

### 3.2 Thermal tests

Experimental part of the present study consisted of two different thermal tests. In the first experiment a small-scale (21 x 60 x 5 mm) self-regulating electrical heater with 15W capacity was attached on external surface layer of laminate specimen and the heat transfer to the internal layers was measured (Fig.3). In typical room temperature conditions, the external heater reaches 60°C temperature on the contact surface within approximately 60 seconds. The heater was attached to the test specimen with a thin double-sided scotch tape ensuring a uniform contact between the heater and the test specimen surface. The heating tests were conducted starting from room temperature both on the heater and the specimen. Recording of temperature distribution along the thickness of the specimens was performed using high performance thermography and thermal imaging camera model A6752sc from FLIR. The camera was equipped with FLIR 1X microscope lens (field of view 9,6 mm x 7,7 mm) allowing to accurately capture temperature distribution within the layers of laminate specimens with total thickness in the range between 1.6 to 2.0 mm. During the heating the specimens were mounted vertically in a holder and the camera was placed perpendicularly to the specimen edge.

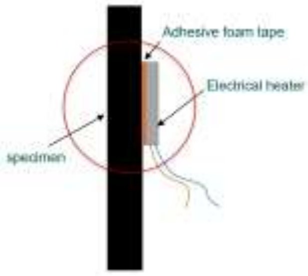


Figure 3: Test set-up for external heating

The second type of thermal experiment was self-heating test by subjecting the test specimens to cyclic mechanical loading. Cyclic mechanical loading was performed on Instron E10000 dynamic testing machine, equipped with a 10 kN load cell. The tests were carried out in tension-tension cyclic loading regime with fixed maximum and minimum strain levels. The load ratio was R=0.1 and the loading frequency of 20Hz was used unless stated otherwise. For sake of parametric analysis, loading cases with frequencies of 25Hz and 30Hz were also conducted on selected specimens. Maximum tensile strain levels in the range of 0.5% up to 0.9% were applied. Heat generation and temperature distribution within laminate layers were measured using the same set-up as for external heating tests, namely the FLIR A6752sc camera equipped with FLIR 1X microscope lens. Tests were started at room temperature and the cyclic loading of specimens was conducted until reaching steady state thermal conditions. After reaching the steady state (typically within 7-8 minutes) the cyclic loading was stopped but the specimen left in the tensile machine grips, and the cooling of specimen down to room temperature was also recorded with the thermal imaging camera. Test set-up for internal heating tests is shown in Fig.4.

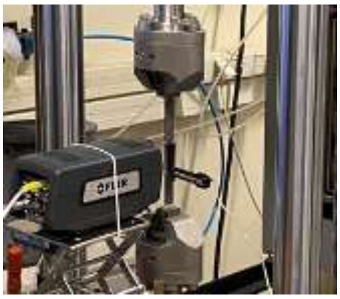


Figure 4: Set-up for internal heating tests using Instron E10000 testing machine and FLIR A6752sc thermal imaging camera.

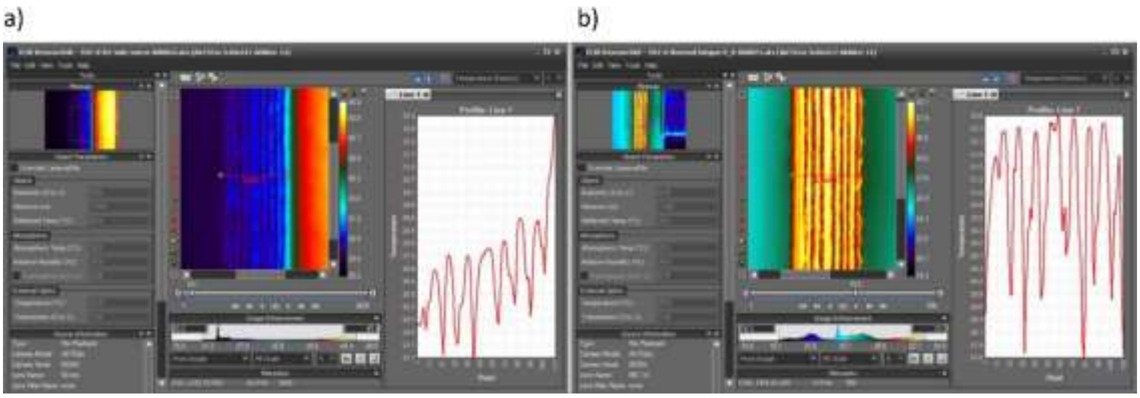


Figure 5: Examples of recorded temperature distributions in laminate layers during: a) external heating test; b) self-heating test.

Typical thermal camera images captured during external and internal heating tests are shown in Fig.5a and b respectively. Along full thermal image capture, temperature distribution along the thickness of the specimen were recorded.

## 4 RESULTS

Mechanical and thermal test results are shown in detail in sections 4.1 and 4.2 respectively.

### 4.1 Mechanical tests

The obtained stress-strain curves from tensile tests all demonstrated very good repeatability and low scatter both regarding the maximum stress and strain values.

Fig. 6 summarizes the elastic modulus values for all composite plates, including reference materials. Although hybrid laminates TH-1 to TH-6 have different lay-ups, the amount of carbon/epoxy and glass/epoxy layers in them is equal, hence the elastic modulus for these materials should theoretically be equal. Fig.7 shows a small discrepancy of elastic modulus possibly related to slight differences in volume fraction between different material plates.

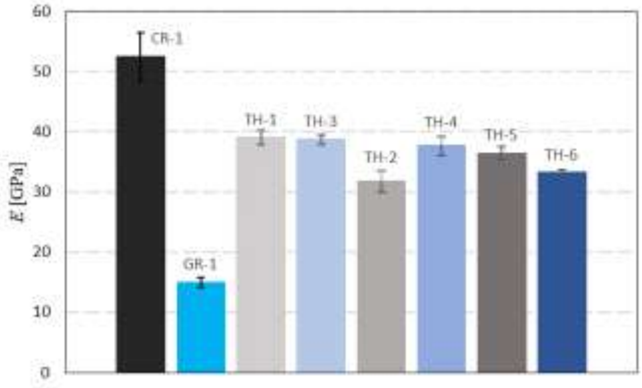


Figure 6: Elastic tensile modulus for reference materials and hybrid composites.

Fig.7 demonstrates the ultimate tensile strength results for the studied laminate lay-ups, including reference materials. The results in Fig.8 demonstrate a trend that the laminates with carbon and glass/epoxy layers distributed in thinner units (e.g. TH-1 and TH-3) exhibit higher strength compared to laminates with thicker carbon and glass/epoxy layers (e.g., TH-5, TH-6).

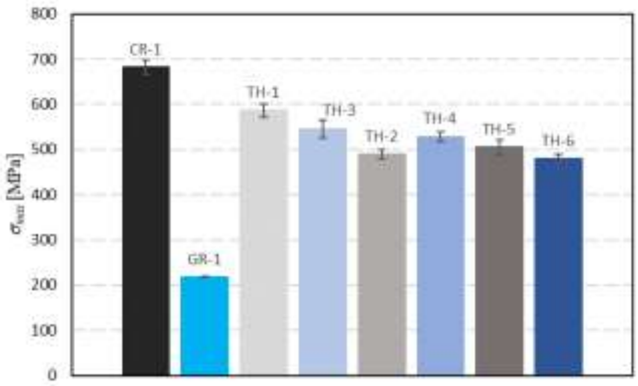


Figure 7: Ultimate tensile strength for reference materials and hybrid composites.

A similar trend was observed regarding the maximum strain to failure, presented in Fig.8. The hybrid laminates with thinner layers (e.g., TH-1, TH-3) exhibited larger strain to failure than the hybrid laminates with thicker layers (e.g., TH-5, TH-6).

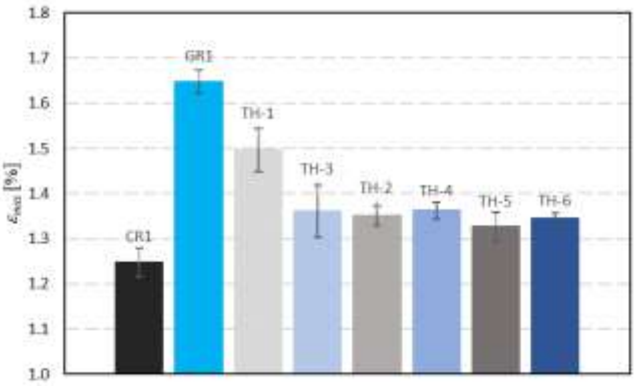


Figure 8: Maximum tensile strain at failure for reference materials and hybrid composites.

In order to account for the differences in elastic modulus and its possible effect on the ultimate strength, the tensile strength values were normalized with respect to elastic modulus measured for each lay-up. The results are presented in Fig.9. Ultimately, the trend of having higher strength for lay-ups with thinnest layer distribution (alternating carbon/glass layers) is still confirmed with the exception of TH6 laminate.

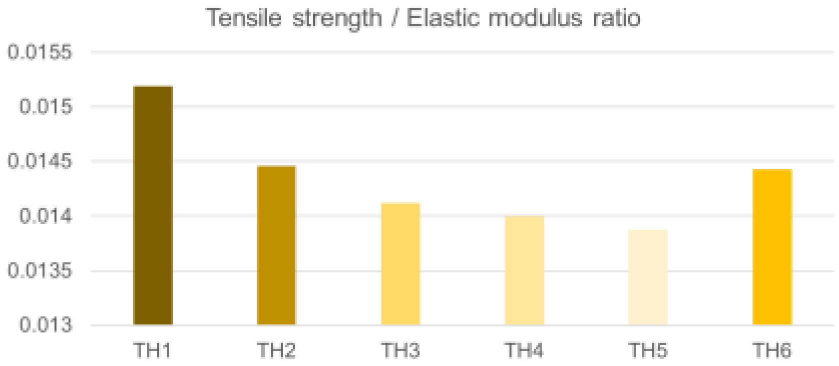


Figure 9: Normalized tensile strength.

Mechanical testing results are summarized in Table 1 where the average values of elastic modulus, tensile strength and maximum strain to failure are shown.

| Lay-up | Notation | $E$ [GPa] | $\sigma^{max}$ [MPa] | $\varepsilon^{max}$ [%] |
|---|---|---|---|---|
| $[CF]_{16}$ | CR-1 | 52.48 | 681.48 | 1.25 |
| $[GF]_{16}$ | GR-1 | 15.04 | 218.15 | 1.65 |
| $[CF/GF]_{4s}$ | TH-1 | 39.05 | 586.27 | 1.50 |
| $[GF/CF]_{4s}$ | TH-3 | 38.66 | 545.90 | 1.36 |
| $[CF_2/GF_2]_{2s}$ | TH-2 | 31.73 | 490.24 | 1.35 |
| $[GF_2/CF_2]_{2s}$ | TH-4 | 31.99 | 510.90 | 1.37 |
| $[CF_4/GF_4]_s$ | TH-5 | 36.41 | 505.16 | 1.33 |

Table 1: Summary of mechanical test results.

## 4.2 Thermal tests

Comparison of transient temperature distribution during external heating tests in reference materials, CR-1 and GR-1 is shown in Fig.10. The graphs show temperature distribution along the width of the specimen with the external heat source (60°C) being on the right hand side of the specimen. Results in Fig.10 clearly indicate differences between carbon (CR-1) and glass (GR-1) fiber composites in terms of thermal conductivity with relatively small gradient for carbon and evidently larger gradient for glass fiber composites as a result of lower thermal conductivity.

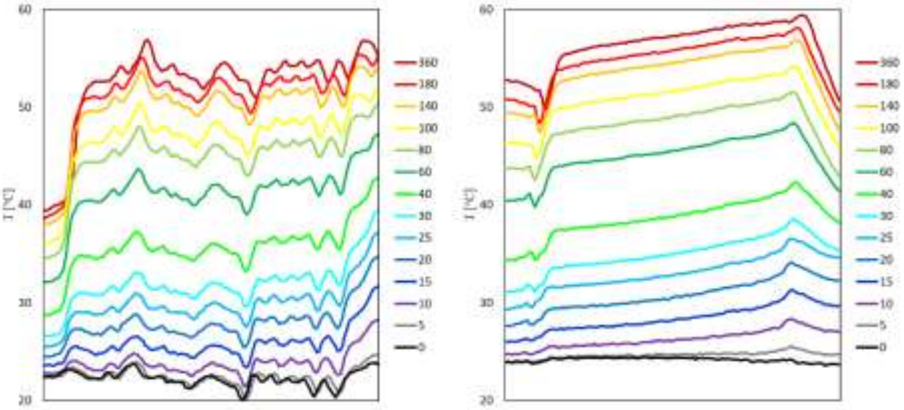

Figure 10: Transient temperature distribution in CR-1 (left) and GR-1(right) laminates

Fig.11 shows a comparison of transient temperature distributions in TH-1 and TH-2 laminates which both have carbon/epoxy external layers, however different layer thickness ratios.

Fig.12 shows a comparison of transient temperature distributions in TH-3 and TH-4 laminates which both have glass/epoxy external layers. From Figs.11 and 12 it appears that the hybrid laminates exhibit larger gradients as carbon/epoxy reference materials, however, much smaller gradients compared to reference glass/epoxy materials. The thickness ratio in different hybrid laminates seems to have a significant influence on local temperature distribution.

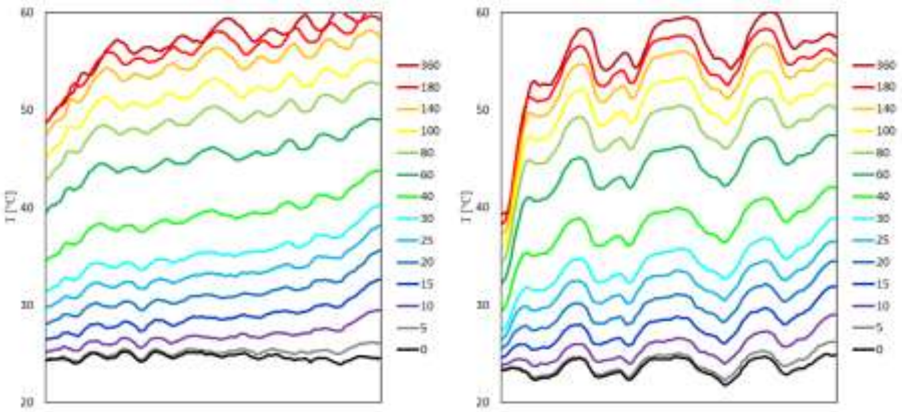

Figure 11: Transient temperature distribution in TH-1 (left) and TH-2 (right) laminates during external heating.

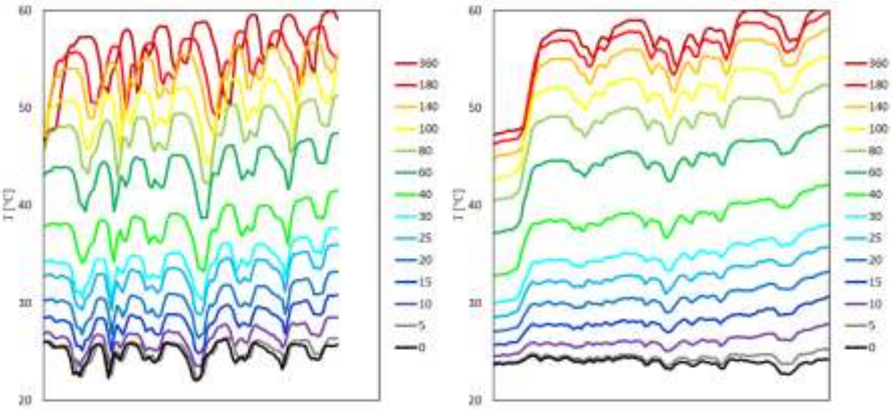


Figure 12: Transient temperature distribution in TH-3 (left) and TH-4 (right) laminates during external heating.

Regarding internal heating (self-heating) tests, Fig.13 demonstrates the results for reference carbon/epoxy laminates (CR-1). Fig. 13a shows the effect of applied maximum strain level on self-heating under 20 Hz loading frequency. A relative increase of temperature (ΔT) from room temperature in the laminate mid/plane is depicted on vertical axis in Fig.13 and in the further text. Expectedly, higher maximum strain level leads to larger self-heating/higher temperature. Fig.13b shows the effect of loading frequency showing relatively small effect of loading frequency on self-heating in the range between 20 Hz up to 30 Hz.

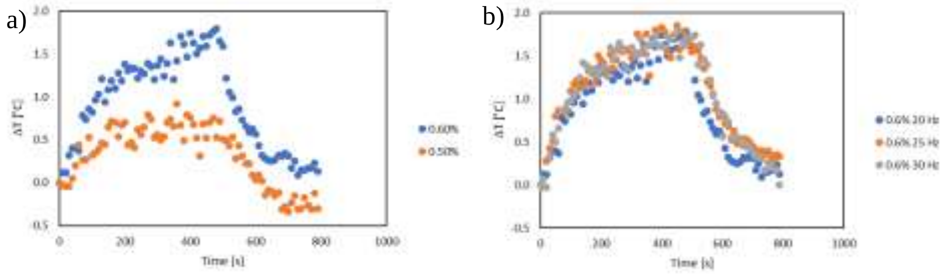


Figure 13: Average temperature in laminate mid-plane during self-heating of CR-1 laminates.

Fig.14 shows the self heating and how it is affected by maximum strain level for reference glass/epoxy material (GR-1). Results indicate slightly higher self-heating of GR-1 laminates compared to CR-1 laminates. Fig.14 also shows self-heating behavior under maximum strain levels up to 0.9% at which mechanical failure was observed.

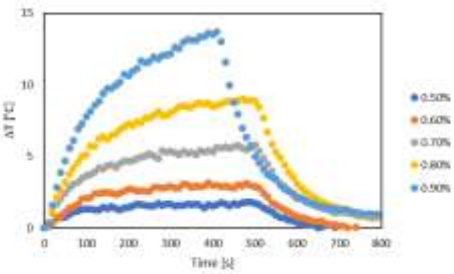


Figure 14: Average temperature in laminate mid-plane during self-heating of GR-1 laminates.

Finally, Figs.15 and 16 demonstrate self-heating behavior of TH-1 – TH-4 hybrid thin-ply laminates.

A clear dependency of self-heating on maximum strain level can be observed. Notably, the hybrid laminate lay-up TH-1 with thinnest possible layer configuration and with carbon/epoxy external layers demonstrates the highest self-heating compared to other hybrid laminate lay-ups.

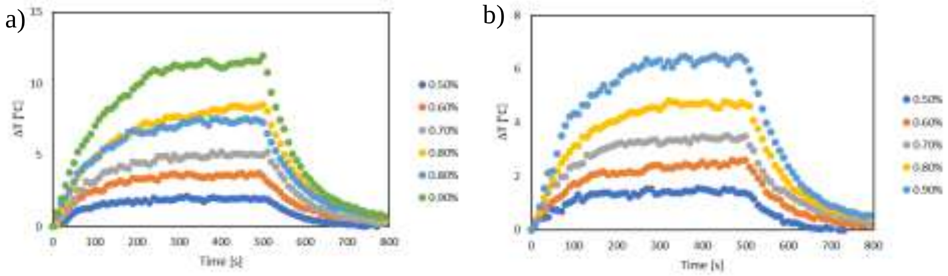

Figure 15: Average temperature in laminate mid-plane during self-heating of a) TH-1 laminates; b) TH-3 laminates.

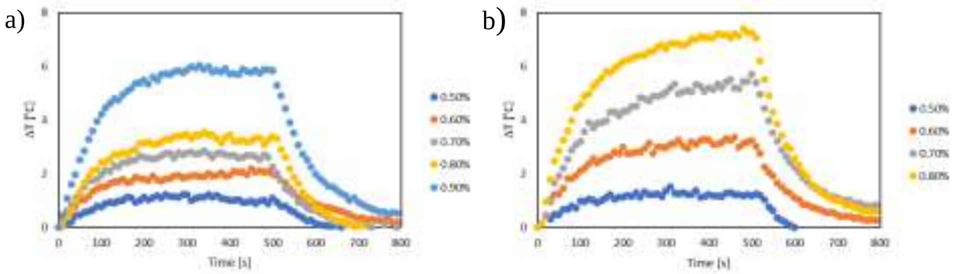

Figure 16: Average temperature in laminate mid-plane during self-heating of of a) TH-2 laminates; b) TH-4 laminates.

## 5 CONCLUSIONS

Present study was conducted to investigate the potential enhancement of laminate strength and strain to failure using thin-ply hybrid laminate lay-ups with different layer thicknesses. Hybrid carbon/epoxy and glass/epoxy laminates with different lay-ups were manufactured using vacuum infusion method. Present results show a notable increase of both the tensile strength and strain to failure for laminates with distributed carbon/epoxy and glass/epoxy layers compared to laminates with relatively thicker layers. Tensile test results also exhibited an overall brittle failure of hybrid composite materials, however, very good repeatability of the obtained strength and strain to failure values. Regarding thermal behavior, it can be concluded from the present study that external heating can lead to notable temperature gradients in glass/epoxy laminates, while carbon/epoxy laminates demonstrate rather uniform temperature distribution. Temperature gradients in hybrid thin-ply laminates consisting of carbon/epoxy and glass/epoxy laminate layers significantly depends on the actual layer thickness. It was also shown that laminate lay-up significantly influences the self-heating behavior of hybrid thin-ply laminates. A systematic trend was found that the hybrid laminates with thickest external carbon/epoxy layers have the lowest average temperature increase in the bulk of the laminate.


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## REFERENCES


[1] S. Sihn, R.Y. Kim, K. Kawabe, S.W. Tsai, Experimental studies of thin-ply laminated composites. *Composites Science and Technology* **67(6)**, 2007, pp. 996-1008.

[2] P.P. Camanho, A. Arteiro, A. Turon, J. Costa, G. Guillamet, E. Gonzalez, Structural integrity of thin-ply laminates, *JEC Composites Magazine* **49(71)**, 2012, pp. 91-92.

[3] G. Guillamet, A. Turon, J. Costa, J. Renart, P. Linde, J.A. Mayugo, Damage occurrence at edges of non-crimp-fabric thin-ply laminates under off-axis uniaxial loading, *Composites Science and Technology*, **98**, 2014, pp. 44-50.

[4] J. Cugnoni, R. Amacher, S. Kohler, J. Brunner, E. Kramer, C. Dransfeld, W. Smith, K. Scobbie, L. Sorensen, J. Botsis, Towards aerospace grade thin-ply composites: Effect of ply thickness, fibre, matrix and interlayer toughening on strength and damage tolerance, *Composites Science and Technology*, **168**, 2018, pp. 467-477.

[5] 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*, **16(8)**, 1981, pp. 2233-2245.

[6] Y. Swolfs, L. Gorbatikh, I. Verpoest, Fibre hybridisation in polymer composites: A review, *Composites Part A: Applied Science and Manufacturing*, **67**, 2014, pp. 181-200.

[7] M.R. Wisnom, G. Czél, Y. Swolfs, M. Jalalvand, L. Gorbatikh, I. Verpoest, Hybrid effects in thin ply carbon/glass unidirectional laminates: Accurate experimental determination and prediction, *Composites Part A: Applied Science and Manufacturing*, **88**, 2016, pp. 131-139.

[8] Y. Swolfs, Y. Meerten, P. Hine, I. Ward, I. Verpoest, L. Gorbatikh, Introducing ductility in hybrid carbon fibre/self-reinforced composites through control of the damage mechanisms, *Composite Structures*, **131**, 2015, pp. 259-265.

[9] D. Schatzel, Reliability of Carbon Core Laminate Construction in Printed Circuit Boards Utilizing StablcorTM, *National Aeronautics and Space Administration (NASA)*, NASA WBS: NAS7-03001 report 2009.

[10] D. Carlstedt, K. Runesson, F. Larsson, L.E. Asp, On the coupled thermo–electro–chemo–mechanical performance of structural batteries with emphasis on thermal effects, *European Journal of Mechanics*, *A/Solids*, **94**, 2022, art. no. 104586.