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Analysing mechanical behaviors of carbon fiber reinforced silicone matrix composite materials after static folding

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Karbon Fiber Takviyeli Silikon Matrisli Kompozit Malzemelerin Statik Katlama Sonrası Mekanik Davranışlarının Analiz Edilmesi

Araştırma Makalesi / Research Article

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ÖZ

Bu makalenin konusu geleneksel malzemeler dışında bir malzeme olan karbon fiber takviyeli silikon matrisli kompozitlerin (KFTS-K) mekanik davranışları hakkında literatüre bilgi sağlamaktır. Mekanik bir yük altında, silikon matris yüksek elastik deformasyonlara izin verirken, karbon fiber takviyeside yüksek çekme gerilmelerine dayanım sağlar. KFTS-K malzemelerinin sıradışı olan bu davranışı, bize ek ağırlığa sebep olan mekanik menteşelere bağımlı olmaksızın katlanabilir malzeme dizaynı sağlar. Katlanabilir malzemeler, daha küçük hacim avantajı sağladığı için uzay yapılarında kullanılmaktadır. Bu çalışmada, KFTS-K malzemeleri piyasada bulunabilen iki farklı silikon ve düz dokumalı çift yönlü karbon fiber kumaş ile üretilmiştir. Farklı tabaka sayılarına sahip numuneler hazırlanmış ve 90º katlanarak belli süreler boyunca statik olarak katlı bırakılmıştır. Sonrasında çekme testi uygulanarak tabaka sayısının, silikon türünün ve katlı kalma sürelerinin mekanik davranışlara etkisi incelenmiştir.

Anahtar Kelimeler: Katlanabilir malzemeler, kompozit, silikon, elastik, karbon fiber.

Analysing Mechanical Behaviors of Carbon Fiber Reinforced Silicone Matrix Composite Materials after Static Folding

ABSTRACT

Subject of this paper is to provide information about mechanical behavior of a novel material to the literature: carbon fiber reinforced silicone matrix composite (CFRS-C). Under a mechanical load, silicone matrix allows large elastic deformations while carbon fiber reinforcement can bear high tensile stresses. This rare behavior of CFRS-C allows us to design foldable materials without being in a bind for mechanical hinges which bring additional weights. Foldable materials are used in space structures to gain advantage of smaller volumes. In this study, CFRS-C were manufactured with two different silicone type can be found in market and one type of plain woven carbon fiber fabric. Specimens were prepared and kept folded 90º statically in various periods of time. They were subjected to tensile testing afterwards, to investigate effect of number of layers, silicone type and duration of folding to mechanical behavior.

Keywords: Foldable materials, composite, silicone, elastic, carbon fiber.

1. INTRODUCTION

Most of the space structures which become functional on space after landing are selected from foldable materials. These materials can be folded to minimize volume and reduce transportation costs at the same time [1-5]. The structure can be achieved by selecting appropriate materials which allows high elastic deformations with small stresses [6-10]. When a soft matrix composite material bends, the stress especially in the compression side releases due to the elastic deformation capability [11]. There are various studies on these novel structures. An example can be given from Technical University of Munich. Datashvili et. al. [12] designed triaxial carbon fiber fabric reinforced silicone matrix space antenna model and deployed it to a smaller volume as can be seen in Figure 1. They suggest that large deployable reflectors with high surface stiffness can be utilized up to about 5-8 m diameters and they introduced a new design of the technical University of Munich which is a carbon fiber reinforced silicone. This new umbrella shape reflector has a stiffness which is smaller than large deployable reflectors and bigger than the ones with metal mesh [12].

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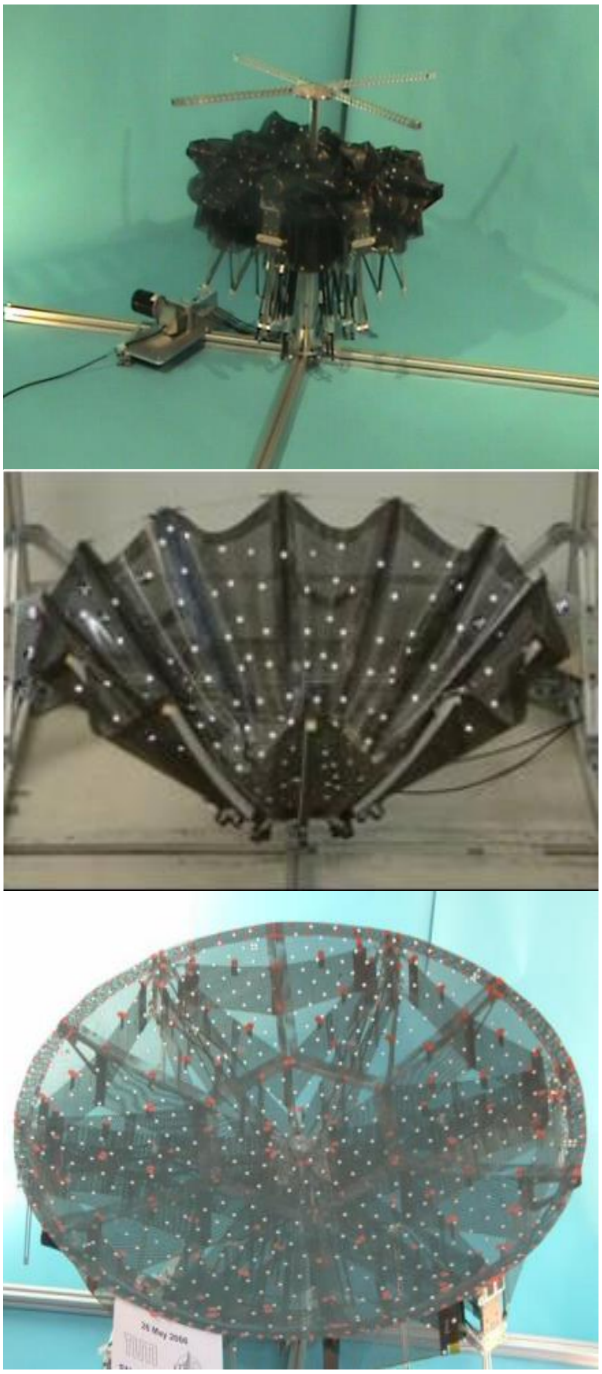

Figure 1. Deployable antenna model developed in Technical University of Munich.[12].

Similar work was done by Composite Technology Development Incorporated (CTD, Inc.) in which reflective surface could be folded to umbrella shape as shown in Figure 2 [13]. CTD Inc. discovers and presents mainly silicone matrix carbon fiber reinforced materials because of folding ability of this materials. These materials can be utilized in design of spacecraft structures such as solar systems, cubesat and nanosat constituents and reflector antennas [13]. Another soft-matrix related study was done on morphing aircraft structure which allows changing wing length in one direction [14]. Figure 3 shows the structure of the wing. Wing skin can extend in one direction intentionally and flight control can be made without in need of mechanical hinges by this way. [14].

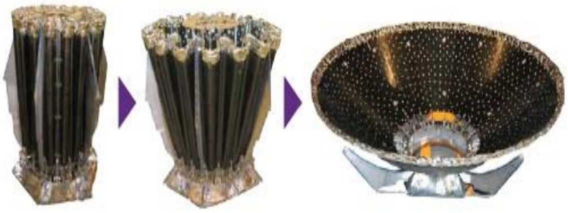

Figure 2. TEMBO deployable reflective surface designed by CTD, Inc. [13]

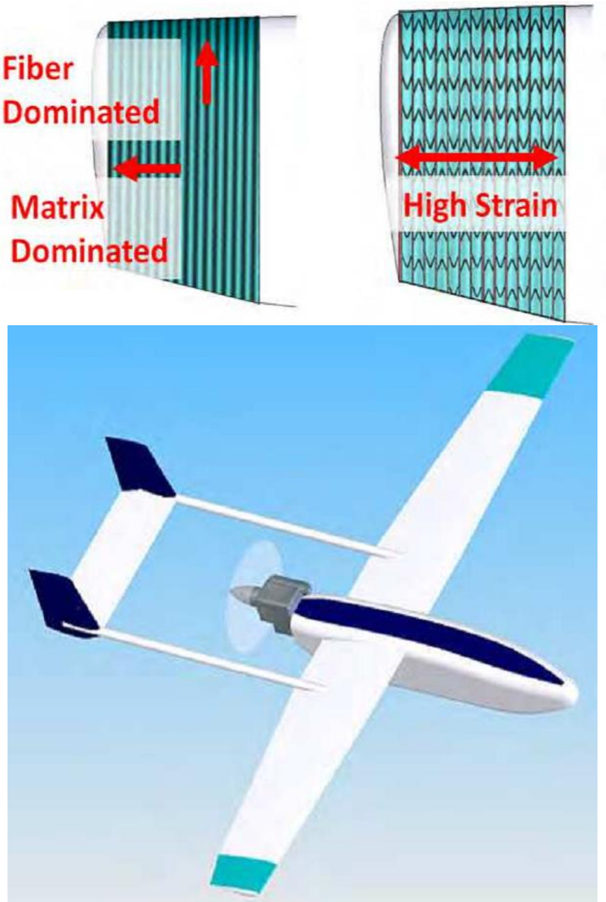

Figure 3. Morphing wing structure developed by using soft matrix. Matrix extends in one direction and fibers in that direction are in crimped structure which allows extension. [14].

One of the important problems of traditional composite materials with thermoplastic matrix is higher probability of damage within the compression side than the tension side during bending [15]. This problem occurs because breaking of fibers during microbuckling within a stiff matrix [15-19]. Altering this situation for deployable material design, many experimental and theoretical studies have been done recently as mentioned above.

Silicone matrix is presented as a solution in these studies as hyperelastic behavior of silicone elastomer allows fibers to microbuckle without or small amount of fiber damage [8-10,12,14-15,17-18]. In our experimental study, the mechanical behavior of plain woven carbon fiber reinforced silicone composite is investigated after and before static folding process. Two different types of silicone matrix were used. The effect of folded time period, type of silicone and number of composite layers were examined. In the literature, there are small numbers of studies that investigates the effect of number of layers to the mechanical behaviors after folding process. Also no studies on the effect of folding period to the plain woven carbon fiber reinforced soft polymer have been discovered.

2. EXPERIMENTAL PROCEDURE

This experimental procedure was designed to investigate effect of various numbers of layers and silicone types to the mechanical behavior of statically folded CFRS-C. Other variation in the experiments was time period of folding. Experimental procedure will be explained in 3 parts: manufacturing of specimens, static folding process and tensile testing process.

2.1 Manufacturing of Specimens

Carbon fiber fabric utilized in this experiment was 200 gr/m^2 plain woven Tenax-E HTA 40 3k. Before manufacturing main specimens, an initial work was done to investigate possible issues in advance. For this purpose a plate of specimen was fabricated by hand layup method. After this initial work it was seen that silicone and carbon fiber did not adhere properly. The silicone was peeled totally from the surface of carbon fabric as shown in Figure 4.a. The reason for this was connected to high viscosity of silicone resin firstly, because after peeling of cured silicone from the surface, no residual silicone was detected on or between fiber tows. Viscosity of silicone resin was reduced by adding 30% of xylene to get adequate flowability. Another specimen was produced after this modification and the result was better but not satisfactory. Figure 4-b presents the specimen produced after reducing viscosity of silicone and it can be understood from white spots highlighted with red circles that adherence was still poor. But the silicone could not be peeled and it means adherence performance was enhanced.

It was considered that another problem could be poor bonding because of epoxy sizing on fiber tows. Sizing is applied on fiber tows before putting on market as it protects fiber surface via coating and provides high bonding performance with traditional resin materials like epoxy [20]. Removing the sizing was the next step to improve adherence performance. Heat treatment of carbon fiber fabrics at 110° C for 20-90 minute in nitric acid solution is one of the ways to remove epoxy sizing [21]. So, 10% and 20% nitric acid solutions were prepared with ethanol, heated up to 110° C while carbon fiber fabrics were in them. After 60 minutes of heat treatment, fabrics were taken out of solution and soaked into pure ethanol for removal of acidic solution. Fabrics were dried in the oven at 100°C for 24 hours. Figure 5 may give a clue that the surface of fibers processed in 20% nitric acid solution was rougher than the ones processed in 10% solution and non-modified ones. Rougher surface may result in more surface area which can be better for silicone-carbon fiber interface bonding. Although rough surface of fiber may decreased the mechanical strength of fiber itself, this situation could be altered by better bonding of fiber and silicone and improve the strength of composite material. Finally, samples manufactured with modified silicone and carbon fibers and this product was performed best in terms of bonding as illustrated on Figure 4.c.

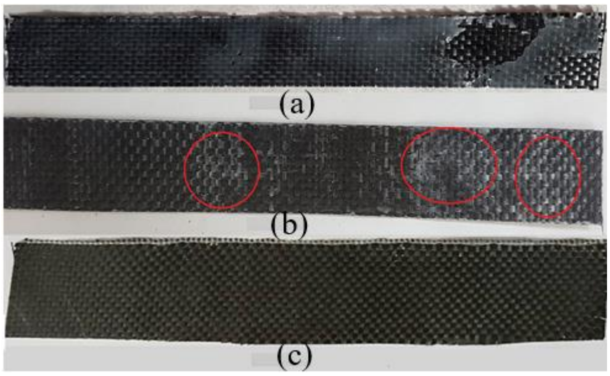

Figure 4. a) CFRS-C materials manufactured without any carbon fiber fabric surface modification and silicone viscosity modification. b) CFRS-C materials manufactured after reducing viscosity of silicone. c) CFRS-C materials manufactured after both carbon fiber fabric surface modification and silicone viscosity modification.

After discovering the adequate way to prepare samples with the help of initial works, next step was to manufacture testing specimens. Specimens were produced with two different types of transparent silicones: TSE 3488 T and RTV 830 which could be found on market. Tensile strength of RTV830 and TSE 3488T is 4.4 and 6.1 MPa and elongation percentage is 540 and 380 respectively. Number of layers of composite was decided to be one, two and four to see the effect of this variation. Four specimens were manufactured for each parameter.

CFRS-C were manufactured by hand lay up method but silicone could not be spread with brush and spatula was used instead. After hand lay up finished, plates were placed between two PVA sheets and than put between Carver Hot Press machine (Figure 6.c) blocks, which aplies pressure and heat at the same time. Curing temperature of silicones are indicated by supplier so CFRS-C were cured at 150º C for 30 minutes. On the other hand, there were no information about manufacturing of CFRS-C materials with hot press machine and hence amount of pressure was not certain. The materials fabricated below 2.3 bar pressure were extremely thick and others pressured above 2.3 bar had silicone free regions on surface.

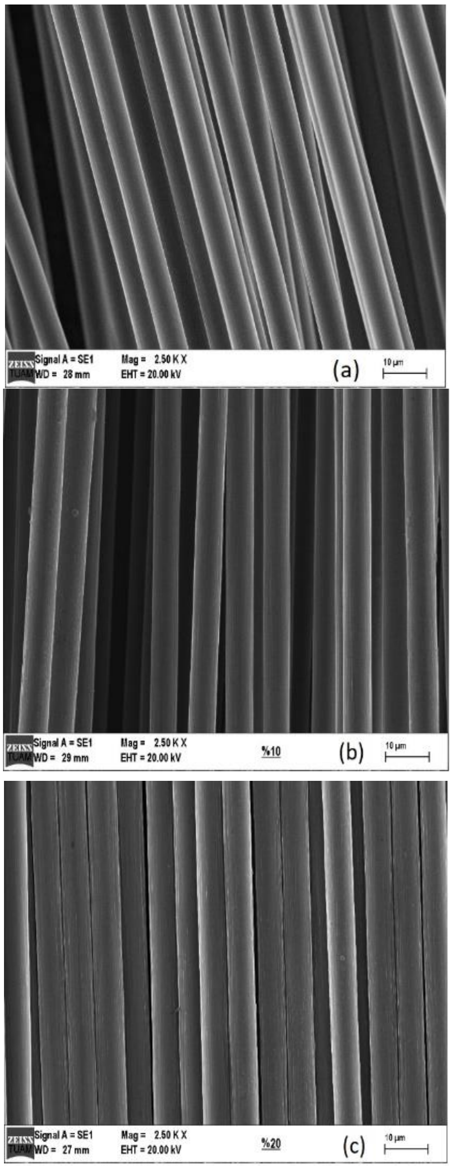

Figure 5. Carbon fiber fabric SEM images: a) Non-modified carbon fiber fabric b) carbon fiber fabric modified iin 10% nitric acid solution and c) carbon fiber fabric modified in 20% solution.

CFRS-C were manufactured by hand lay up method but silicone could not be spread with brush and spatula was used instead. After hand lay up finished, plates were placed between two PVA sheets and than put between Carver Hot Press machine (Figure 6.c) blocks, which aplies pressure and heat at the same time. Curing temperature of silicones are indicated by supplier so CFRS-C were cured at 150º C for 30 minutes. On the other hand, there were no information about manufacturing of CFRS-C materials with hot press machine and hence amount of pressure was not certain. The materials fabricated below 2.3 bar pressure were extremely thick and others pressured above 2.3 bar had silicone free regions on surface. According to these outputs, the amount of pressure decided to be 2.3 bar for all manufacturing processes of this experiment.180 x 250 mm CFRS-C plates were produced and specimens were cut by razor blade from it according to ASTM D 3039. The dimensions of specimens were 25x250 mm and thickness varied between 0.34 mm and 1.56 mm depending on the number of layers and carbon fiber-silicone volume fractions. Four samples were manufactured for same parameters. After manufacturing step was finalised, static folding step was started.

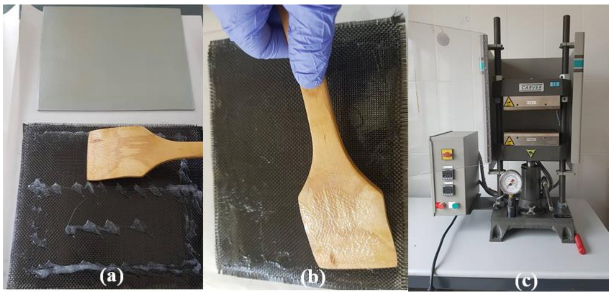

Figure 6. Manufacturing process of CFRS-C and the hot press machine utilised after hand lay up.

2.2 Static Folding Process

Target in this study is to present mechanical behavior of a foldable design. As these structures are folded on earth and sent to space, it has to be considered that they remain folded over a period of time. This part of study was arranged to explore mechanical response of CFRS-C materials shown on Figure 7.a, after remained folded on a 90° cable box, as can be seen in Figure 7.b, over 2, 8 and 12 weeks. The corner radius of cable box is 13.8 mm. Structure of layered CFRS-C is represented in Figure 8.

Figure 7. CFRS-C materials after being cut from plate: a) normal position b) Folded 90° on cable box.

Figure 8. Represantation of CFRS-C layered structure

2.3 Tensile Testing Process

One, two and four layered CFRS-C prepared as reference materials to explore mechanical behaviors before folding. Samples with same specifications were prepared and remained folded for 2, 4 and 12 weeks as shown in Figure 7.b. As 50 mm of samples would be gripped inside testing jaws from each end, tent fabric was bonded to the ends with epoxy to avoid high stress on these sides and early breakage inside the jaws. Testing configuration is given in Figure 9.

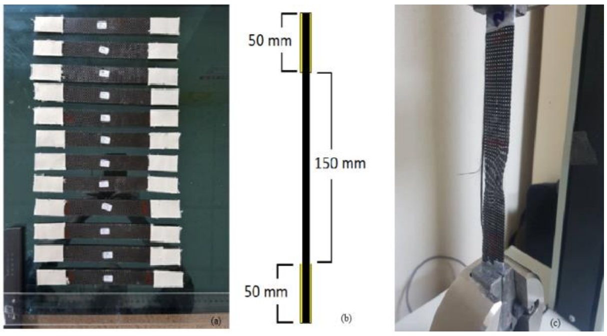

Figure 9. Demonstration of tensile test setting. a) Tent fabric application to specimen ends to prevent preliminary breakage b) Illustration of specimen dimensions and structure c) Tensile testing setup.

All samples were tested with Shimadzu AG-IJ 10 kN universal testing machine with 2 mm/min. deflection speed. Four specimens were tested for each parameter.

3. RESULTS AND DISCUSSION

3.1 Tensile Testing of Reference Materials

According to the data provided from supplier, tensile strength of TSE3488T silicone is 37% higher than of RTV830 silicone's but % elongation of RTV830 silicone is higher. Tensile test results of reference CFRS-C materials are parallel to the data given that can be understood from Table 1. Table 1 also clarifies that as the number of layers increased, elongation also increased and maximum strength decreased for both carbon fiber reinforced RTV830 composite (CF-RTV830) and carbon fiber reinforced TSE3888T composite (CF-TSE3488T). Increasing number of layers may lead to increasing volume fraction of silicone which explains test results of reference specimens. It can be understood from Table 1 that, as the number of layers increase, maximum tensile strength of CFRS-C decreases but maximum elongation percentage increases. The constituent with lower tensile strength and higher elongation capability is silicone. According to rule of mixtures shown in Equation 1 and the outcome mentioned above, tensile strength of composite may decreased by increasing volume fraction of silicone and elongation rate may do so by the same way. By that way, decreasing maximum tensile strength and increasing maximum elongation percentage by increasing number of layers can be explained by increasing volume fraction of silicone by the same way.

$$\sigma_c = \sigma_f v_f + \sigma_m v_m \qquad \text{Equation 1}$$

In Equation 1, σ_c, σ_f and σ_m are tensile strength of composite material, fiber and matrix respectively where ν_f is volume fraction of fiber and ν_m is volume fraction of matrix.

Table 1. Test results of CFRS-C materials.

Name of Specimen	Number of Layers	Max. σ (MPa)	E (MPa)	Maks. ε (%)
CF-RTV830				
Ref-R1-avg.	1	335.93	18806.16	2.35
Ref-R2-avg.	2	351.21	14355.43	3.15
Ref-R4-avg.	4	265.94	7863.98	3.97
CF-TSE3488T				
Ref-T1-avg.	1	434.22	22175.01	2.25
Ref-T2-avg.	2	380.05	14344.18	3.02
Ref-T4-avg.	4	311.52	9421.95	3.4

3.2 Tensile Test Results of Statically Folded Materials

Figure 10 and Figure 11 displays tensile test graphs of statically folded materials for 2, 8 and 12 weeks for CF-RTV830 and CF-TSE3488T materials respectively. As mentioned before, volume fraction of silicone matrix increased by increasing number of layers and deformation capability of the composite increased. Micro-buckled fibers are highlighted by red circles in Figure 12. Near the folded area the stress transferred from matrix to micro-buckled fibers is less and fiber breakage is lesser and this is an advantage of being embedded in a soft matrix.. As a result of the elastic deformation capability of silicone matrix, increasing number of layers would lead to less decrease in mechanical strength, associated with folding time period. This assumption can be made for both CF-RTV830 and CF-TSE3488T which can be supported with Figure 10 and Figure 11.

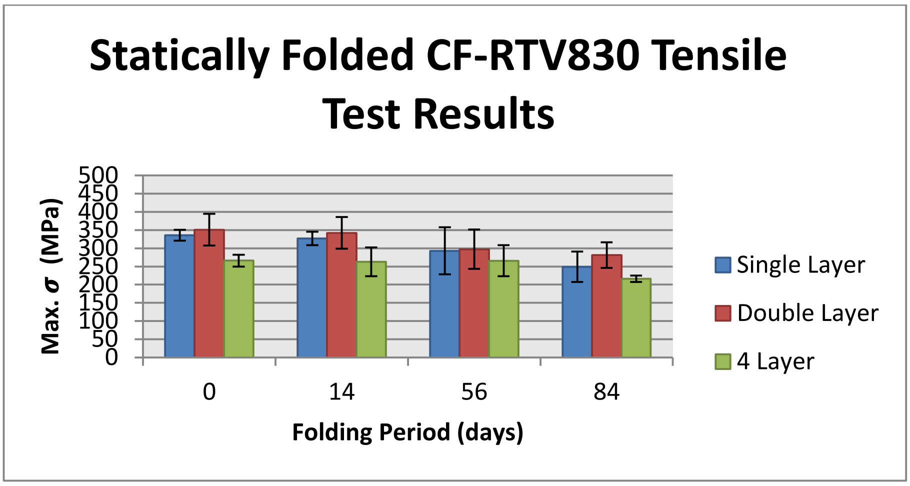

Figure 10. Mechanic response of single, double and four layers CF-RTV830 to folding time period of 14, 56 and 84 days.

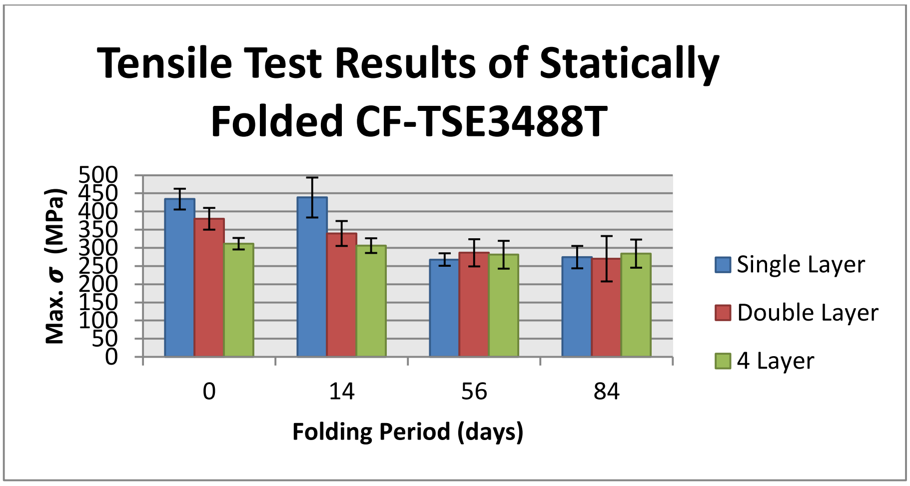

Figure 11. Mechanic response of single, double and four layers CF-TSE3488T to folding time period of 14, 56 and 84 days.

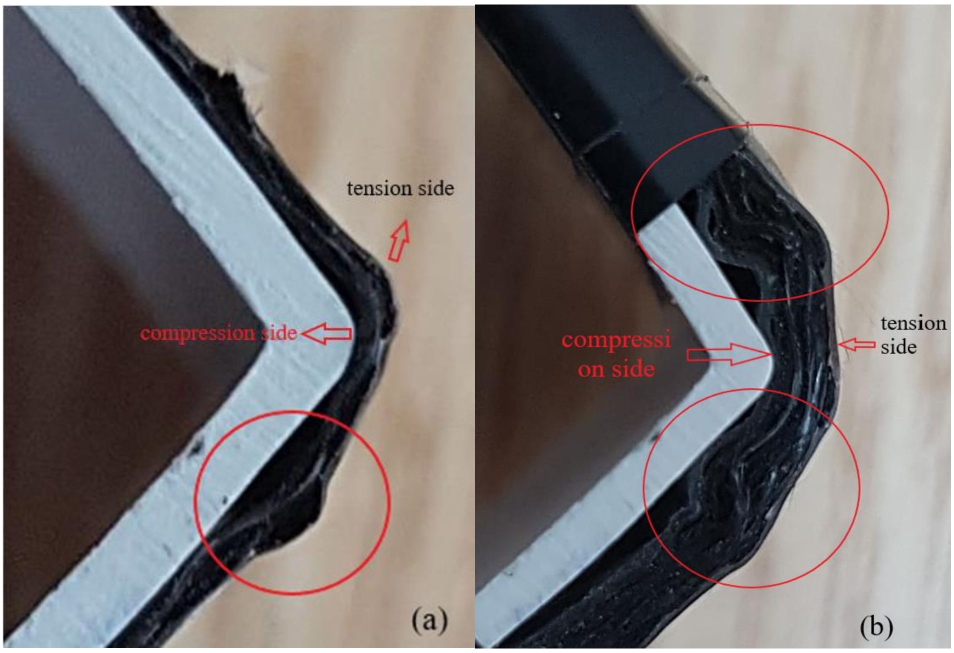

Figure 12. Micro-buckled fibers near folding region are indicated by red circles. a) Microbuckling within 2 layer composite material in folded position., b) Microbuckling within 4 layer composite material in folded position.

Table 2. Percentage of decrease in mechanical strength in relation with number of layers and folding time period.

CF-RTV830				**CF-TSE3488T**			
CF-RTV830				**CF-TSE3488T**			
	Percentage of decrease in mechanical strength				**Percentage of decrease in mechanical strength**		
Number of layers	**Folded for 14 days**	**Folded for 56 days**	**Folded for 84 days**	**Number of layers**	**Folded for 14 days**	**Folded for 56 days**	**Folded for 84 days**
Single	2.7	12.8	25.8	**Single**	-1.03	38	36
2	2.56	15.38	20	**2**	10.6	24.6	29
4	1.12	0.02	9.3	**4**	1.76	9.74	8.78

Table 2 exhibits percentage of decrease in mechanical strength after folding CFRS materials. When kept folded for 14 days, single layer CF-RTV830 and CF-TSE3488T, double layer CF-RTV830, 4-layer CF-RTV830 and CF-TSE3488T materials performed similar mechanical performance to equivalent reference materials. Within the materials kept folded for 56 days, 4-layer CF-RTV830 performed best and also the decrease in mechanical performance of CF-TSE3488T is less than 10%. In terms of the materials kept folded for 84 days, mechanical performance of 4-layer CF-TSE3488T and CF-RTV830 decreased less than 10%.

CFRS-C materials showed linear-elastic behavior and stress-elongation graph of CF-RTV830 is presented in Figure 13 as an example. All other specimens showed similar stress-elongation behavior.

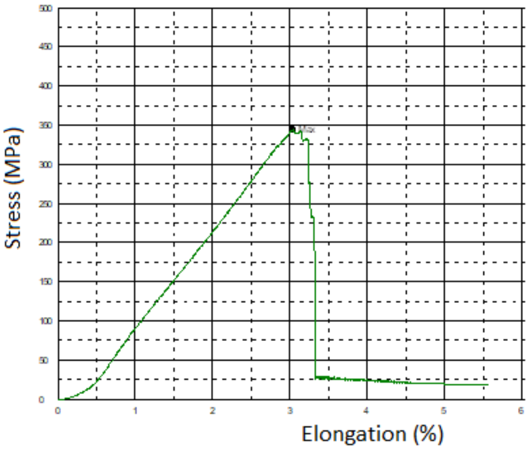

Figure 13. Stress-elongation graph of single layer reference material: CF-RTV830.

During the tensile test of single layer composites, it was seen that they were generally broken from middle section and fiber breakage was detected (Figure 14.a). Double layer composites have generally shown similar failure behavior to single layer composites (Figure14.b). After inspected by eyes, separated laminates and fiber breakage were detected in four layer composites and two examples were given in Figure 14.c. Detailed illustration is given in Figure 15. Second and third layers slipped between the first and fourth layers. The tabs stick to the ends with epoxy may hold first and fourth layers strongly when the jaws tighten and prevent them from slippage. But second layer and third layer were sticked to the neighboring layers via silicone. As shear force of epoxy is higher than silicone, first and fourth layers, which sticked to the fabric tent by epoxy, were held between jaws and second and third layers slipped.

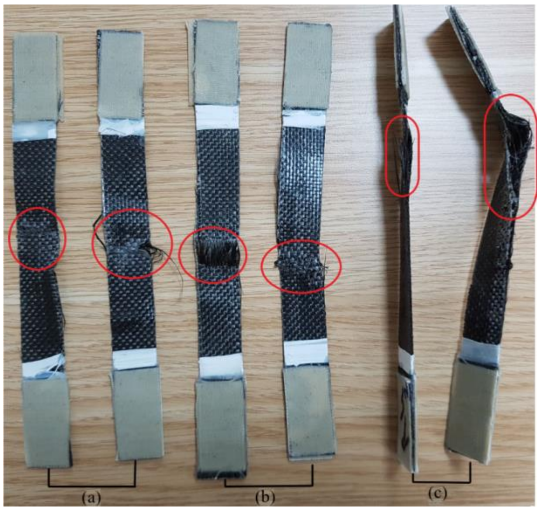

Figure 14. Tensile failure behavior of fabricated CFRS-C materials: a) Failure of single layer composites and fiber breakage indicated via red circle, b) Failure of double layer composites and fiber breakage indicated via red circle, c) Failure of four layer composites and seperation of layers are shown via red cicrcles.

Figure 14 and Figure 15 displays that no crushing inside testing jaws was faced during tensile test. Bonding tent fabric near specimen ends by epoxy can be a good solution to crushing or slipping of material between jaws. All fabricated specimens experienced final rupture, nu crushing by jaws and slipping between jaws. Mejiha-Ariza and his friends [22] faced crushing of specimens problem, between hydraulic jaws. They solved crushing problem by changing hydraulic grips with mechanical ones but fiber glass tabs were split from specimen that time and only one specimen were broken [22].

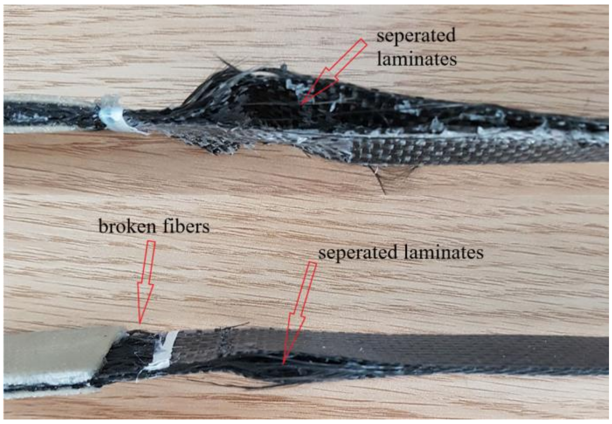

Figure 15. Detailed illustration of failure behavior of four layer composites after tensile test with two examples.

4. CONCLUSION

During fabrication processes, different challenges were faced like peeling of silicone from carbon fiber surface, silicone-free regions and poor bonding of silicone to fibers on some regions. Optimal fabricating parameters for this study can be listed as:

- Application of heat treatment to fiber fabrics at 110° C for 20-90 minute in 20 % nitric acid is a solution for poor bonding and peeling of silicone,
- Mixing silicone matrix with 30% xylene reduces the viscosity of silicone which also provides adequate bonding performance,
- When examined by eyes, silicone-free regions on specimens cured in hot-press machine under 2.3 bar pressure at 150 ° C were seem to be less compared to other trials.

Tensile testing of silicone resin composite materials was also a challenge because testing jaws generates high stress regions at specimen ends. Bonding various tab materials like fiber-glass epoxy to each end was utilized as one way of solution but shear failure of tabs occurs due to uniaxial loading [22]. In this study canvas fabrics were attached to each end with epoxy and shear failure of canvas-epoxy did not occur. Damage of test coupons generally started from middle section.

When specimens kept folded 90º, materials with higher silicone volume fraction performed less damage because micro buckle of fibers was allowed within silicone matrix which has the capability of high elastic deformation. Due to the dominant mechanical characteristics of plain woven carbon fibers, CFRS-C materials showed linear elastic performance opposite to findings of Pellegrino and his friends [23] and similar to Maqueda and his friends [24]. The reason for this may be the different silicone matrix type and manufacturing steps.

Because of higher silicone volume fraction, tensile strength and stiffness of 4-layer CFRS-C materials decreased less after folding periods. Tensile strength of CF-RTV830 materials generally decreased less because RTV830 silicone has higher elongation rate.

In terms of the failure behaviors, fiber breakage was detected in one and two layer composite materials but separation of layers was detected in 4-layer composites by visual inspection as shown in Figure 14 and Figure 15.

FUTURE WORK

In this study, a work has been done about mechanic response of silicone-carbon fiber composite material to the static folding process. Two different types of silicones and plain woven carbon fiber fabric were utilized. In future works, specimens prepared with space qualified silicones and multiaxial fiber fabrics may be investigated and testing environment temperature may be adjusted to space environment temperature to recommend materials for direct use in space.

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