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Abstract:

Due to technological advancement in the manufacturing methods of composites, these materials find a plethora of applications which include but are not limited to wind energy projects in the form of turbine blades. These blades at times are exposed to temperatures as low as -40°C. Therefore, there is a need to study low-temperature effects on such materials under different loading scenarios. This study investigates the possibility of utilizing MAC/GMC as a simulation tool to match trends of mechanical properties such as fatigue performance and stiffness variation of a given Glass fiber/Epoxy composite at 23°C (room temperature) and -40 °C, under fully reversed (R=-1) and tensile (R=0.1) loading cases. The results show remarkable consistency with the published data.

Key Words: Low temperature; Micromechanics modelling; Glass Fiber Reinforced Polymer (GFRP); Fatigue; Biaxial Laminates

1. Introduction:

Literature on the effects of low temperature on static mechanical behavior of glass fiber/epoxy composites is limited and unfortunately not very dependable due to noticeable variation is experimental results and reported data. These variations can be attributed to dissimilarities in experimental setups and restricted resources that do not allow for opportunities to limit errors or apply exact loads, which could ultimately provide skewed results. For example, Toth[1] worked on composites at cryogenic temperatures to show the increase in static strengths and fatigue life under reversed loading but could not quantify the increase in strength as their equipment was not capable of breaking the specimen at those temperatures. The experiments conducted also vary in important material parameters like fiber volume fraction, type of glass fiber used, the grade of epoxy that was utilized to develop the composite, all of which could cause a certain amount of deviation in results. However, most studies focus on variation of composite properties as a single entity. None of the research being conducted aims to study quantitatively, the behavior of the constituents in the composite.

Although there is lack of literature supporting a specific trend in composite behavior at low temperature, there is a noticeable prediction that is repeatedly observed regardless of experimental variations in the stiffness and strength trends of the composites at low temperatures when compared to their room temperature values. These composites find various applications that are aimed towards improving efficiency or enhancing cost savings in specific projects. A specific research group funded by the National Science and Engineering Research Council (NSERC) conducted tests specific to composites that were used in wind turbine blades to understand how low temperatures affected these specimens. The composites in the wind turbine are known to experience cyclic loading which is the focus of this paper. Effects of cyclic loading is one of the more important phenomena studied as wind turbines are expected to undergo such loading scenarios during their life. Some papers that report on results from fatigue testing observe no effects of temperature variation on fatigue life of the composite. The intent behind this current research is to develop a clear understanding of the abilities of MAC/GMC and utilize it to predict low temperature properties of the constituents of a composite at low temperatures. Henceforth, applying those properties to a $[\mp 45]_{2s}$ layup, ultimately studying the trend of the laminate's fatigue life over a range of stresses under reversed as well as tensile loading scenarios.

Table 1

Author	**Material Tested**	**Test**	**Condition**	**Conclusion**
Dutta	UD Glass-Epoxy	Tensile	-56°C and RT	Strength Reduction
Karjalainen and Segercrantz	UD glass-epoxy	Tensile 0°, 30°, 90°	-40°C	Strength Improvement
Dutta	S2 glass-epoxy, $[90_2/0]_s$	Tensile at RT	-60°C to 60°C upto 150 cycles	Large initial reduction and slow stabilization of strength
Dutta	UD Glass-Epoxy	Tensile at RT	-60°C to 60°C cycles	slight strengthening, then strength reduction
Bulmanis	Wound glass-epoxy [0/90]s	Tensile	2 years exposure to northern Russian climate	No effect
Shen and Springer	CFRP	Static Tensile	-73°C - 149°C	Little effect on tensile strength and modulus in fiber direction but could affect laminates with off-axis fibers
Nijssen and Cormier	UD Glass-Epoxy	Tensile	-40°C, $v_f = 0.48$	Tensile strength increases
Cormier and Joncas	UD E Glass-Epoxy	Tensile	-40°C, $v_f = 0.55$	Tensile and interlaminar strength increases
Dutta	[±45°] S2 glass-epoxy	Tensile	-60°C and 23°C	No effect
Dutta	Pultruded glass polyester	Tensile	-60°C and 23°C	Increase in compressive strength
Sys	±10° glass-unsaturated polyester	Fatigue; R=0.1, R= -1	-20°C, 20°C and 50°C, $v_f = 0.5$	Results based on strain basis suggest no effect on fatigue performance
Nijssen and Cormier	UD E glass-epoxy laminates	Tensile and reversed fatigue	-40°C	Little to no negative effect on fatigue performance
Bureau and Denault	2-2 glass twill-polyester construction	Flexural Fatigue, R= 0.1	-40°C to 50°C, $v_f = 0.6$	Stress Life curves were superimposed at both temperatures

	biaxial glass fabric-polypropylene stacking	Flexural Fatigue, R= 0.2	-40^{o}C to 50^{o}C, v_f = 0.6	Showed an increase in fatigue life
Kujawski and Ellyin	[±45^{o}] glass-epoxy laminate	Cyclic Loading		Creep induced strains observed and test frequency affects creep rate
Susumu Kumagai, Yasuhide Shindo, Akihiro Inamoto	GFRP woven laminate	Tensile-Tensile Loading	RT, 77K and 4 K	As stress increases life decreases
Torabizadeh M A	UD Glass Fiber-Epoxy composite	Tensile	RT, -20^{o}C, -60^{o}C	Tensile strength increases by 12% over temp range

2. Modelling Approach

2.1 Brief overview of MAC/GMC

Seeing from the table above, there are various conclusions that can be drawn about the behavior of composite in different environments under different loading scenarios. MAC/GMC is to be used to provide computational proof to the experimental results, and thereby making it a possibility to predict behavior of these composites at low temperatures. MAC/GMC stands for Micromechanics Analysis code for the Generalized Method of Cells which is an executable code that depends on an ASCII input file from the user. This was created by NASA to study the discrepancies and similarities if any between the behaviors of composites at a constitutive versus the macroscopic level. Full details about the software are provided by Bednarcyk and Arnold [2,3].

2.2 Methodology

Laurent Cormier and Simon Joncas reported a significant increase in tensile strength and modulus of a glass fiber/epoxy composite at -40^{o}C when compared to its room temperature properties by 33%. The laminate presented in their research was a complicated layup that involved stitching to create the laminate. Each pair of $\mp 45^{o}$plies were pre-stitched fabric that was ultimately stitched together using a polyethersulfone (PES) thread running in 0^{o} and 90^{o} directions. Each pair was made up of a +45^{o} and -45^{o} 600 TEX E glass fibers at 47% fiber volume fraction separated by a 68 TEX E glass strands at 90^{o}. It is worth noting that the layers had different mass densities. The epoxy used to bind all these plies together was a momentive epikote, RIMR 135 epoxy resin cured with RIMH 134 and 137 curing agents. These specimen were made to match those that tend to be used in wind turbine blades in order to get comparable results. Detailed information about the specimen used in this experiment and the manufacturing method that was used to make the epoxy can be found in Laurent Cormier [4]. Their research was inspired by the lack of information available on the fatigue behavior of composites that are used in wind turbine blades at low temperatures. They concluded in their paper that fatigue life improved by almost a decade in both cyclic loading scenarios. There were interesting observations recorded when the composites were under reversed loading. The mode of failure changed from failure of individual plies and extensive delamination at room temperature to tensile failure at low temperatures. Tensile cyclic loading showed the similarity of failure initiation in the specimen, because multiple nucleation sites could be seen due to the loads the composite was experiencing, but there was variation in the crack propagation at low temperature. It exhibited a more localized failure behavior at low temperature when compared to room temperature as can be seen in Figure [1].

The idea was to replicate the laminate using MAC/GMC to perform fatigue simulations. Certain assumptions were made to make the process smoother and easier. The simplified layup of the laminate can be seen in Figure [2]. This layup ignores stitching of the plies as well as the 90^o orientation of the 68 TEX-E glass fiber layer between the 600 TEX E-glass fiber layers in the ∓ 45 orientation sub plies. MAC/GMC presents certain hurdles when simulations are to be performed for composites. A myriad of input parameters are required in order to perform an analysis which is explained further below. Further research lead to papers that performed tests on unidirectional glass fiber/epoxy composites. Tensile tests were conducted using a unidirectional glass/epoxy specimen at various environmental conditions. Cormier, L [5] presented results that show an increase in the composite stiffness when temperature is brought down to -40^{o}C at dry conditions. However there is no commonly available literature that describes the change in the behavior of the fiber and the epoxy as separate entities over a given temperature range. A unidirectional laminate was created using MAC/GMC to replicate the laminate presented in the paper by Cormier L [5]. A parametric study was performed to learn about the dominant properties in the composite. Using the results presented under Figure [3], properties of the fiber are manipulated to match the composite properties at the low temperature (-40^{o}C). These material properties are then used in the layup presented in the wind turbine layup. A parametric study is conducted to study the dominant properties in a matrix that is an off-axial laminate. Based on these collected results, the material properties of the $[\mp 45]_{2s}$ laminate are adjusted to match the values presented in the quasi-static tensile tests conducted by Cormier L. [4]. This process allows for the successful calculation of the material properties of the constituents at both the required temperatures (room temperature and -40^{o}C). It is interesting to note the difference between the dominant properties in each layup as will be discussed further.

2.3 Damage Model

MAC/GMC is a very effective computational tool that is utilized in this research study. The code is initiated from a command prompt in the form of a .txt file as explained in detail by Bednarcyk [2]. A multitude of factors are to be kept in mind while creating a model that accurately depicts the composite that is to be replicated and studied. A certain number of assumptions are made in order to simplify the designing of the laminate as mentioned under the methodology section of this paper. The required input parameters are listed in the text file that can be founded in the Appendix. Properties such as axial and transverse stiffness, axial and transverse poisons ratio, shear modulus and the coefficients of thermal expansion of the fiber and the epoxy respectively are to be specified at required temperatures. The code follows a specific format with keywords that are built into the program. Each keyword begins with an asterisk and is programmed to perform a specific task as discussed below.

Initially a unidirectional laminate constituting glass fiber and epoxy with a fiber volume fraction of 55% was created as can be seen under Appendix, Code. The keyword “*CONSTITUENTS” recognizes properties of the fiber and epoxy as they are listed as “MAT” 1 and 2. As mentioned above, all the required properties are listed initially at room temperature. These properties were calculated using a trial and error method. As can be seen from the results presented in Cormier, L [5] the composite properties are clearly listed at the required temperatures. The constituent properties are varied until a perfect match is found. Prior to manipulating the material properties of the constituents of the composite that are namely the glass fiber and the epoxy, it is important to study the effects that each property has on the composite stiffness of the laminate. A parametric study was conducted to study the dominant property of the composite with a unidirectional laminate. The unidirectional layup can be identified from the “ANG” specification for each ply that forms the laminate. The thickness of each layer is treated not as an absolute value but rather as a ratio between consecutive layers. Therefore, it is of utmost importance that they add up to one. The code also allows for various architectural ID’s of the subcell that constitutes the repeating unit cell. This code uses an “ARCHID=7” a geometry of which is shown under Figure [4], as it showed the right balance between accuracy and efficiency. The laminate being considered is an 8 ply laminate, which is initially not subjected to any manner of loading (mechanical or thermal). The code was used to study only the composite stiffness of the laminate. The keyword “*THERM” shows the temperature at which the code assumes the laminate is being tested. Since MAC/GMC is a computational tool there are multiple numerical methods that can be called upon to perform the required simulation. The keyword “*SOLVER” performs this exact function. Forward Euler method is utilized to perform the stiffness calculation in this case. This method requires the user to specify the time step that is to be used throughout the simulation. The outputs from the code are user controlled. There is a large amount of information that can be gathered using the “*PRINT” command. This specific code calls for “NPL=6”, which calculates the effective stiffness matrix as well as the ABD matrix output at each time step. However the effective engineering moduli values in the axial direction are noted in order to study the trends as presented.

This allowed for a good chance to study the dominant properties that affected the composite stiffness of the laminate drastically, which will be discussed further. The material properties of the fiber and the epoxy were manipulated based on the results gathered to match the properties at low temperature as can be seen under Figure [5]. These material properties are listed under Table [2].

Since the properties can be found using the stiffness code as shown listed under Code [1], in the Appendix, these calculated properties are used as input parameters in the glass fiber/ epoxy laminate with $[\mp 45]_{2s}$ with a 47% fiber volume fraction as is shown under Code [2], which is considered the damage model. It is worth noting that the general formatting of the code remains the same. The various loading scenarios are simulated by adjusting different keywords. Mechanical loading is simulated using “*MECH”. MAC/GMC is capable of applying loads in two different directions. The load can be applied by manipulating the loading option which is signified with “LOP”. Loads applied in the axial and transverse directions are 1 and 2 respectively. There are four points of load application that are specified. It is programmed to be a 200s cycle. As mentioned in Bednarcyk [3], mode 2 is resultant force when performing a laminate analysis. The magnitude of the applied force is specified. Tensile as well as reversed loading scenarios are studied.

Tensile Loading: It is a type of loading condition where the magnitude of the minimum stress in a certain percent of maximum stress applied on a material, which varies sinusoidally being in tension the entire time. In this study R=0.1, where R is defined as the ratio of minimum stress to the maximum stress applied.

Reversed Loading: It is defined as the type of loading where the maximum stress and minimum stress applied on a material are equal in magnitude but vary sinusoidally between tension and compression. R= -1, where R is the ratio between the minimum stress and maximum stress applied.

This is achieved by manipulating the values under “MAG”. As the code does not register temperature as a separate individual entity, it is treated similar to data points, instead of an actual thermal load. Similar magnitudes of stresses are applied on the laminate at both room as well as low temperature, at both the loading scenarios mentioned above. A clear trend is observed and recorded.

The damage model requires additional input parameters that are specific to the materials being utilized to create the composite. There are two different mechanisms that are offered by the code that can be chosen to perform the desired fatigue analysis. Strength degradation, which is recommended when the failure mode is expected to occur from the fiber breakage and stiffness reduction, which is more valuable when the composite failure mechanisms are dependent on the epoxy properties and the composite is expected to fail due to the shear stresses in the laminate, which is expected to be the case for this specific laminate. Quick analysis of each of these models showed that eliminating strength degradation did not affect the results to any extent, therefore both these models were kept functional to get more accurate results. Bednarcyk [4] and Aboudi, J. [6] can be referred for additional information regarding the different degradation models.

The keyword “*DAMAGE” requires the damage parameters of the composite’s constituents to be specified. The maximum number of load blocks that can applied on the laminate with this code was 100. Another parameter that is introduced into the damage model is the damage increment, which tends to affect fatigue life of the laminate. It also affects the time taken by a specific force/stress to completely damage the laminate. It can be treated as a time step in the analysis. It is a continuum based damage model that uses a subvolume elimination method as mentioned by Aboudi, J [6]. As it is similar to a time step, the smaller the step the longer the model takes to reach failure. A good balance between computation time and accuracy is to be reached while choosing this value. The Figure [9] shows a trend at room temperature for varying damage increment values shown as “Dinc”. This is a unique trend, but it can be noted that values below 0.2 do not vary with more than a 100 cycles, and the computation time is reasonable at this point. Therefore, 0.2 is chosen for all further analyses. The code once initiated applies load blocks with the mentioned magnitudes on the laminate until a failure criteria is satisfied. There are two ways in which a laminate is deemed as “failed” from the simulation.

1) When the damage increment for each cell has reached the value that is mentioned in the damage model.
2) The number of load blocks applied on the laminate reaches its maximum value and the composite still shows “remaining life”.

When either one of these circumstances occur, the model deems the laminate as “failed” and ends execution. The applied resultant forces/stresses in these models were manipulated to get a plot that accurately depicts the strength/stiffness degradation of the engineered laminate over a range of stresses that are comparable to the magnitudes mentioned in the research papers presented by Cormier, L [4].

The failure of the subcells are characterized using the ultimate strength values listed. A linear strength degradation model is assumed with the initial and final ultimate strengths of the fiber with the corresponding number of cycles at the specific strengths. The damage properties of the epoxy were taken from Bednarcyk [3]. More information about these degradation models can be found in Aboudi, J [6]. Similarly failure criteria for the sub cells are specified. The failure cells operate under a 5% strain condition. Axial failure stresses and in-plane failure shear stress magnitudes are specified under the "*FAILURE_CELL" criteria. The outputs are restricted to effective laminate properties and architectural information at each time step with "NPL=3". In addition to the composite properties, mid-plane normal strain and force resultant in the axial direction are also outputted.

The applied loads are chosen based on the loads applied in the experimental published work. It is also to be kept in mind that the values do not match exactly due to the assumptions made in the simulation, they are however comparable.

3. Results and Discussion:

This research attempts to use MAC/GMC to simulate different cyclic loading scenarios to the composite with a $[\mp 45]_{2s}$ layup and compare its fatigue behavior with published results over a specified stress range. As can be seen from Figures [12] and [14], the results when the laminate is subjected to tensile and reversed loading are comparable to the results shown under Figures [11] and [13]. The applied stress ranges are comparable to the experimental values. The fatigue life for both the loading scenarios appears to have improved at low temperatures by a certain factor. The stiffness of the constituents also shows an increase of 3.7% in the fiber and 28.7% in the matrix at low temperatures in order to match the values presented in published work as can be seen under Table [3].

To reach the aforementioned conclusions a process that is described under methodology is followed closely. The target values for the laminate of interest as shown under Figure [6] are kept in mind. Initially, a unidirectional laminate is created to study the stiffness variation of glass fiber/ epoxy composite over a temperature range. The parametric study performed on the unidirectional glass fiber/epoxy composite as shown in Figure [3] proved the dominance of fiber axial stiffness properties on the stiffness of the composite. It can be inferred from this study that the effect of varying any other parameters in the composite is of negligible importance. It is important to note that glass fiber is isotropic in nature, which calls for the stiffness in both the axial and transverse directions to be of equal value. Using these observations it is therefore viable to use the properties of the fiber at room temperature to predict material properties at -40ºC. Varying this specific material property to match the stiffness of the composite at this low temperature is shown under Table [2]. The composite stiffness is linearly dependent to the stiffness of the fiber. These material properties are further used as input parameters in the layup of interest which is the biaxial laminate.

The direction of orientation of each layer of a laminate tends to affect the effective stiffness properties of the composite. Therefore, it is important to perform another parametric study with the layup of interest, the results from which are shown under Figure [7]. This shows interesting variation with the previously performed parametric study results. The composite stiffness of this laminate shows a strong dependence on the properties of the epoxy in the axial and transverse stiffness as well the shear modulus of the epoxy. The importance of this dependence is highlighted under Figure [8], which shows equal percentage increase in each of the properties of the constituents with respective change in composite stiffness values. It can be seen that the composite stiffness is more sensitive to the epoxy stiffness values relative to the fiber which is unlike the unidirectional laminate trends recorded. The final material properties of the constituents of the laminate are listed under Table [3].

Tensile Loading:
Published work regarding this loading scenario presents results that show the failure occurring in the form of extensive delamination and individual ply separation. However, the failure mode does not change when the composite is exposed to lower temperatures. An increase in fatigue life can be observed which is comparable to the simulated results under Figure [12].

Reversed Loading:
An interesting takeaway with this loading scenario is the change is the failure mechanism that occurs when the composite is exposed to low temperatures as shown in the Figure [13]. There is also a pivot point that can be observed in the SN curve for this type of loading that signifies th the change in the failure mechanism. Simulated results from this loading is comparable in the sense that the life of the composite tends to increase as temperatures decreases. However, the change in failure mechanism cannot be observed from the simulated results. It can also be noted that reversed loading tends to provide a lower fatigue life relative to the tensile loading condition.
An important aspect in the damage model is the specified damage increment. Variation of fatigue life with respect to change in damage increment is of interest as shown in Figure [9]. The tradeoff with decreasing damage increment value is the time taken by the simulation to reach complete failure. With decreasing values of damage increments the time increases but the life of the laminate never really reaches zero.

Although certain aspects of the results are comparable with the published work there are certain aspects of the study that do not agree with it entirely. This could be attributed to the assumptions that were made while engineering the laminate. Simplifying the model might affect the way the laminate reacts to the applied loading conditions. The assumptions made might also have affected the resultant properties of the epoxy at room and low temperatures, which could in turn cause the discrepancy in the results. The model also does not take into account residual stresses in the composite, which might alter the failure mechanisms based on material properties of the constituents at different temperatures. More work needs to be done to develop a model that accurately simulates all the above mentioned characteristics and that could provide closer matches to the published work.

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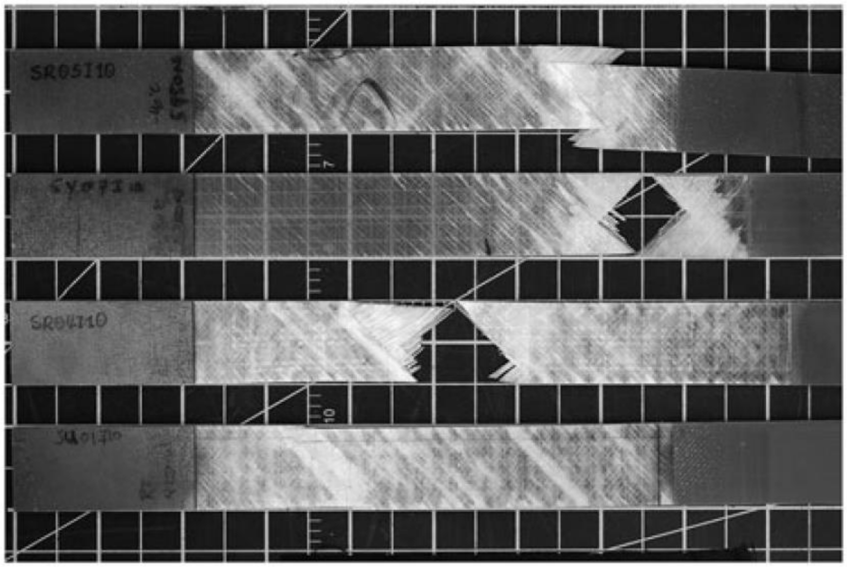
Appendix



Typical failed $R = 0.1$ fatigue specimens. From top: $-40°C$, 5950 N (86 MPa); $-40°C$, 4250 N (63 MPa); 23°C, 5950 N (87 MPa) and 23°C, 4250 N (66 MPa).

Figure 1: Post mortem specimen from published data under tensile cyclic loading

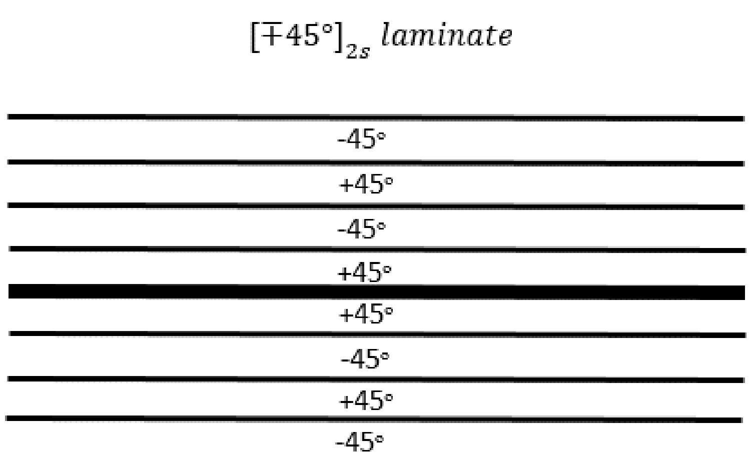


Figure 2: [-/+45]2s laminate

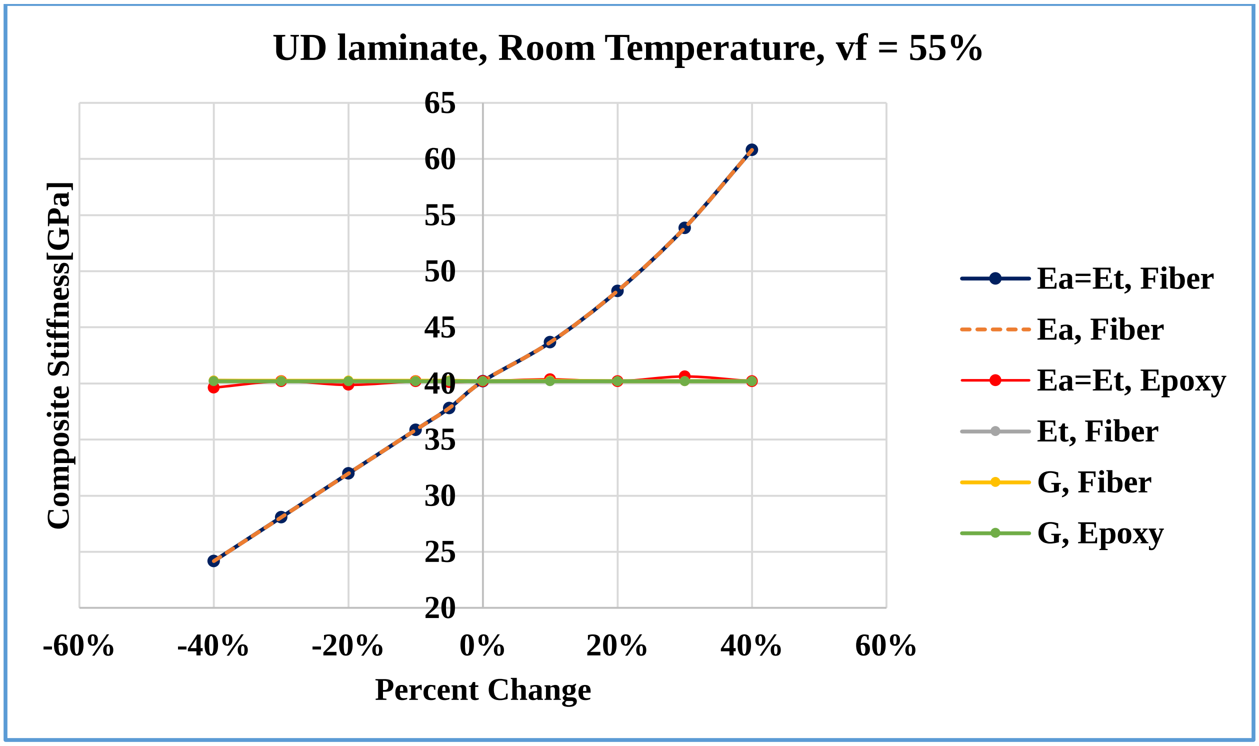


Figure 3: Parametric study of a unidirectional laminate at room temperature

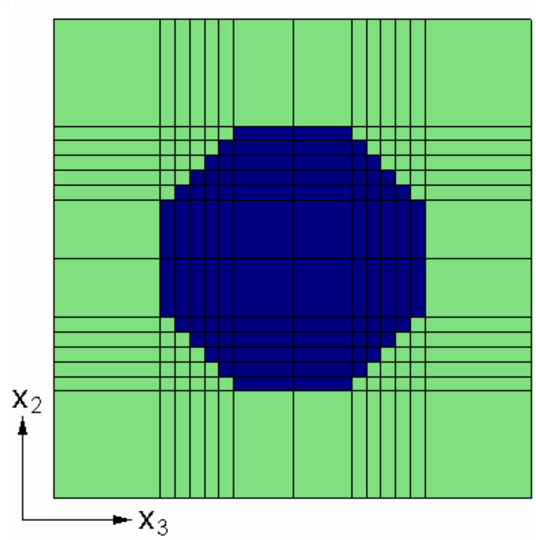


Figure 4: Schematic of the architecture of the subcell

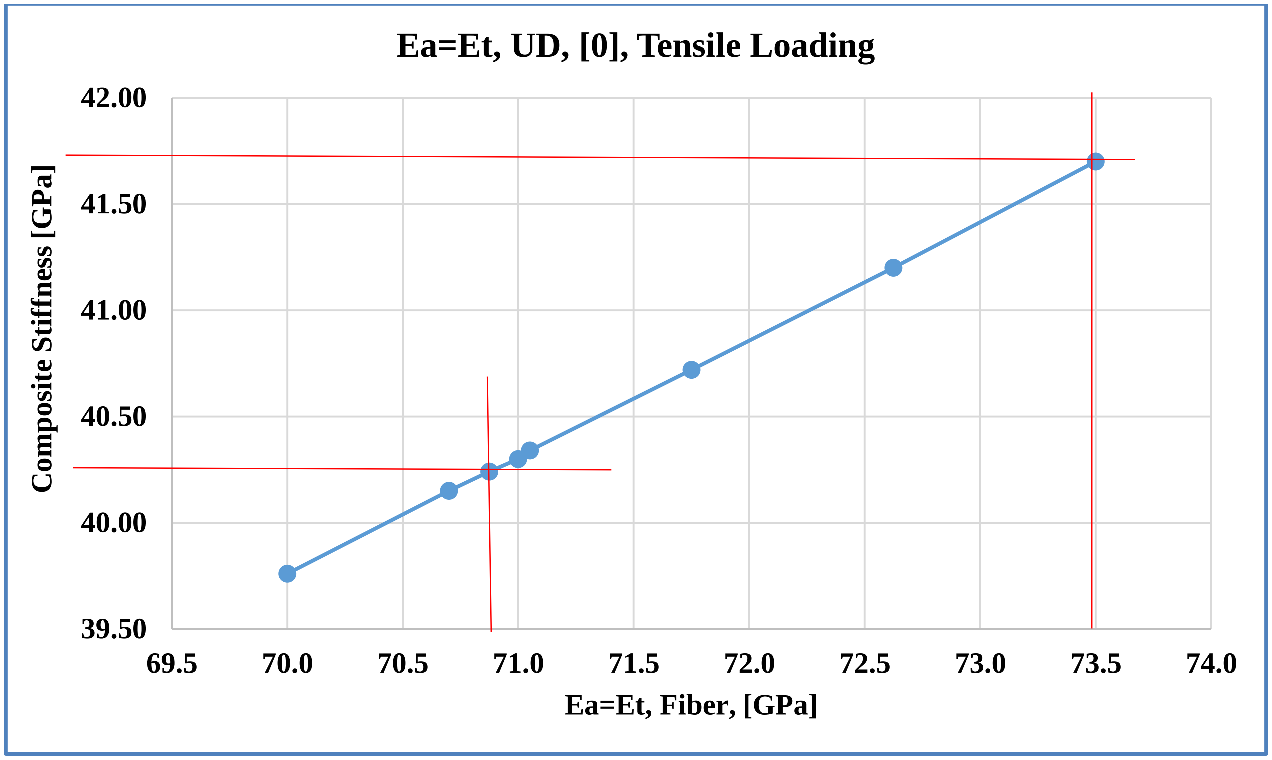


Figure 5: Fiber stiffness prediction at low temperature

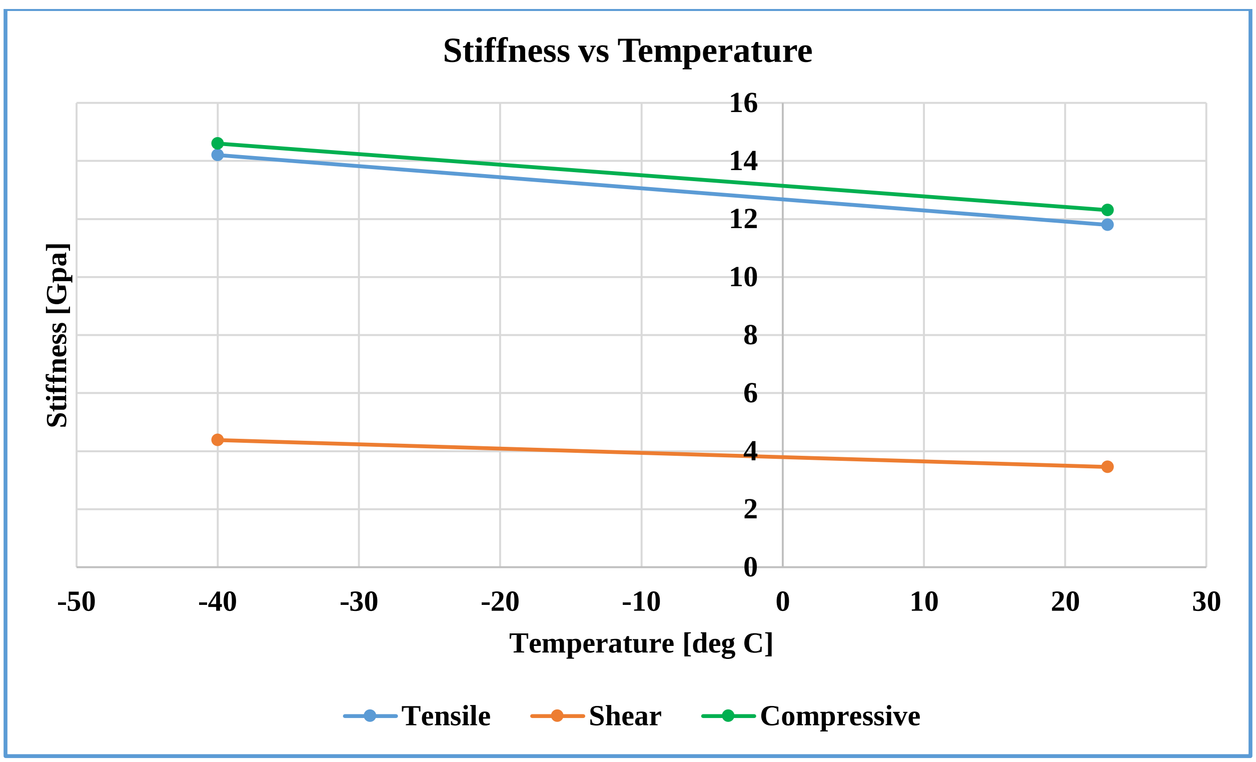


Figure 6: Target composite stiffness values at temperatures of interest

Table 2: Constituent properties of unidirectional laminate temperatures of interest

	Fiber				Matrix			Composite Stiffness[Gpa]
	Ea	Et	v	G	Ea	v	G	
	70.0	70.0	0.2	29.17	2.75	0.36	1.01	39.76
	70.7	70.7	0.2	29.46	2.75	0.36	1.01	40.15
RT	**70.9**	**70.9**	**0.2**	**29.53**	**2.75**	**0.36**	**1.01**	**40.24**
	71.0	71.0	0.2	29.58	2.75	0.36	1.01	40.30
	71.1	71.1	0.2	29.60	2.75	0.36	1.01	40.34
	71.8	71.8	0.2	29.90	2.75	0.36	1.01	40.72
	72.625	72.625	0.2	30.26	2.75	0.36	1.01	41.2
-40 C	**73.5**	**73.5**	**0.2**	**30.63**	**2.75**	**0.36**	**1.01**	**41.70**

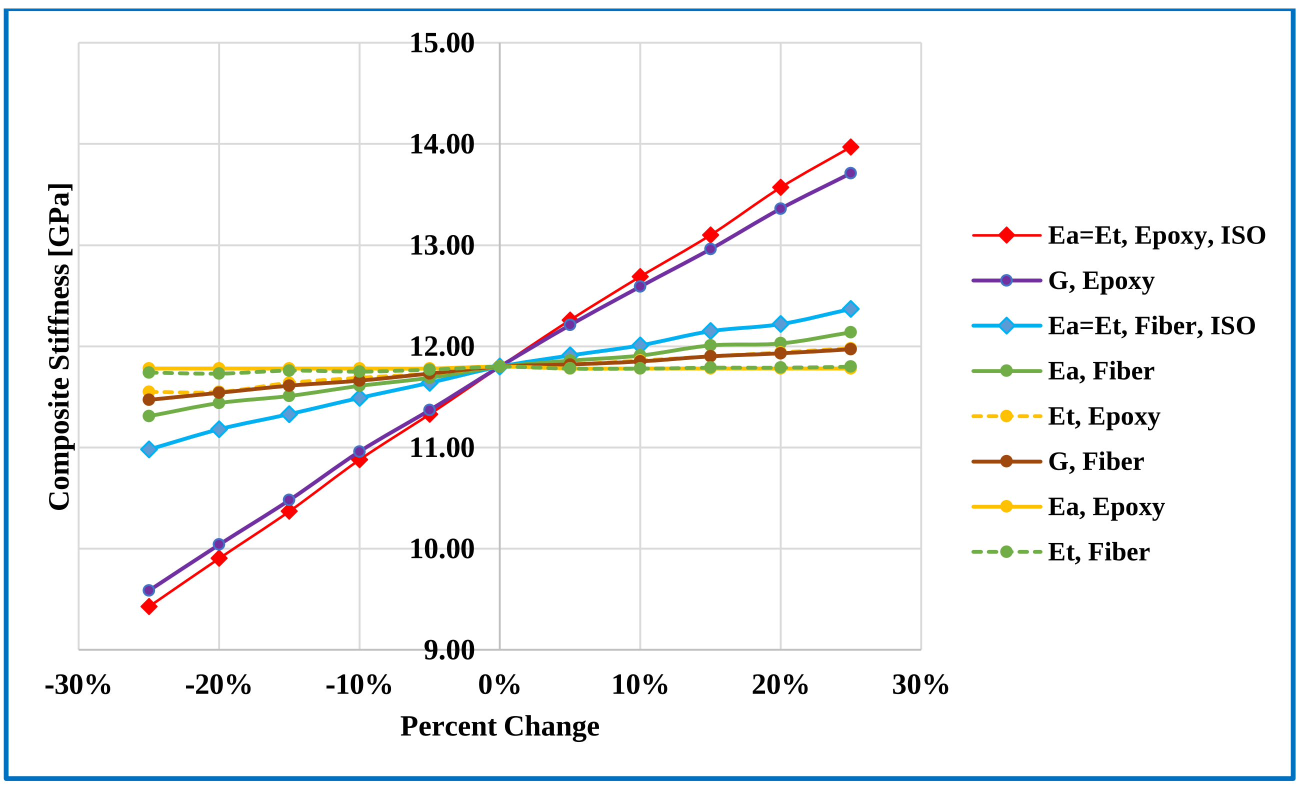


Figure 7: Parametric study of $[\mp 45]_{2s}$ laminate at room temperature

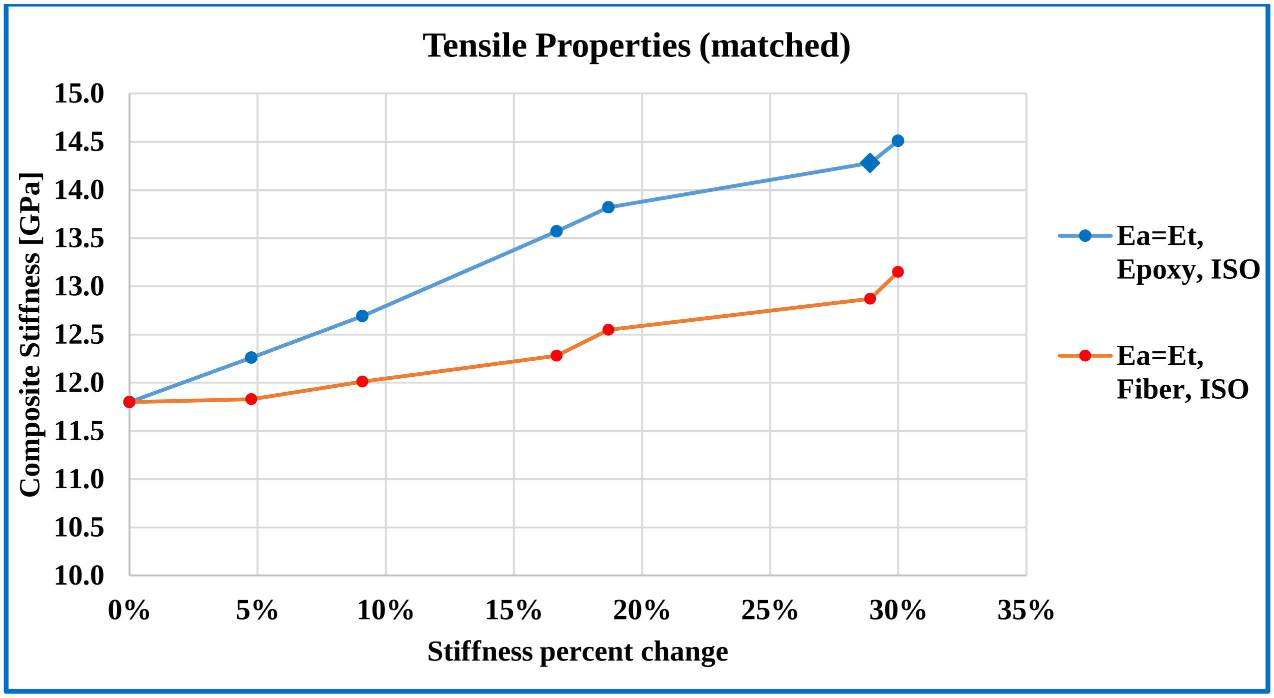


Figure 8: Composite stiffness dependence on dominant constituent property

Table 3: Constituent material properties at temperatures of interest

Target Properties (Gpa)		
	23°C	-40°C
Tensile	11.8	14.2
Shear	3.45	4.38
Compressive	12.3	14.6

Fiber [Gpa]			
	23°C	-40°C	% increase
Ea	70.88	73.5	3.70%
Et	70.88	73.5	
v	0.2	0.2	
G	29.53	30.63	

Matrix [Gpa]			
	23°C	-40°C	% increase
Ea	4.29	5.53	28.90%
Et	4.29	5.53	
v	0.29	0.29	
G	1.66	2.14	

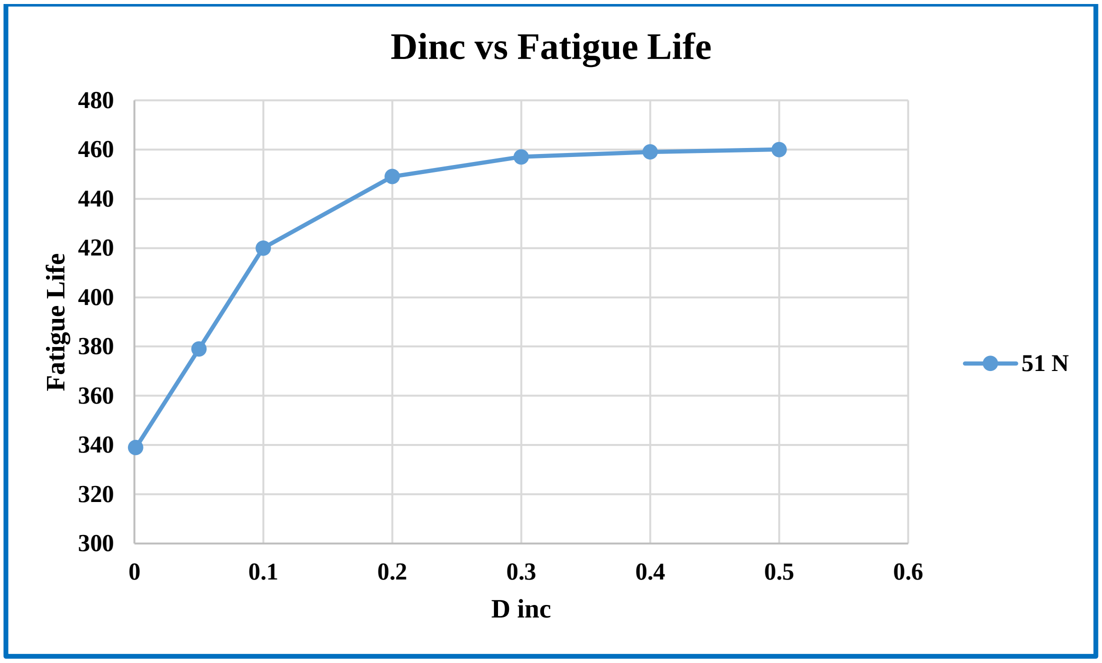


Figure 9: Damage increment dependence of fatigue life

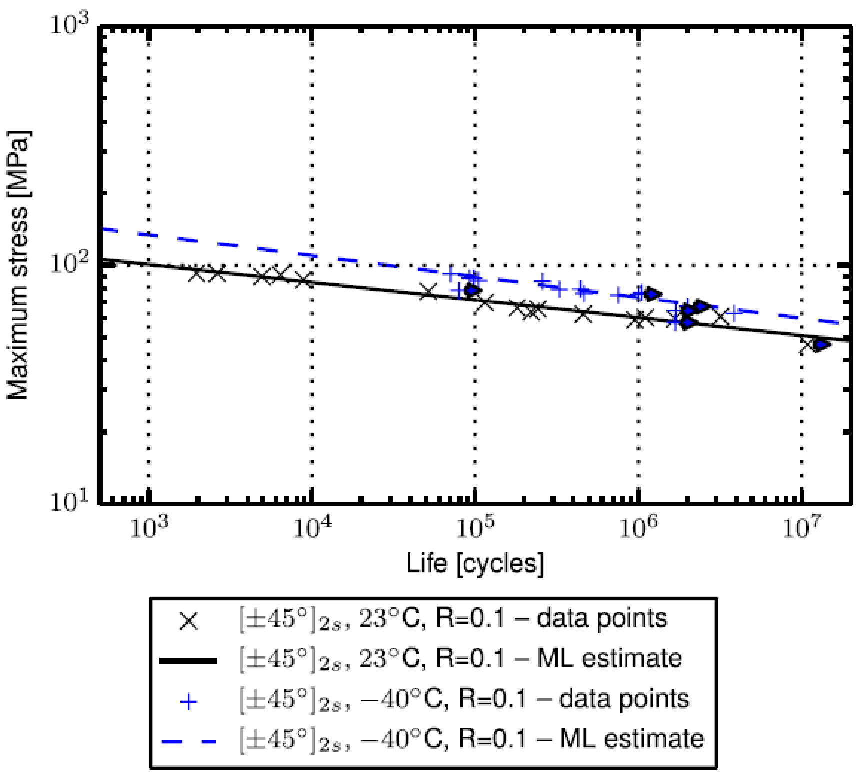


Figure 10: Published results of composite under tensile loading

Table 4: Simulated results of composite under tensile loading

D inc = 0.2, Tensile Loading , R= 0.1			
Stress_max [MPa]	Stress_min [MPa]	23°C	-40°C
39	3.9	inf	inf
39.5	3.95	inf	inf
40	4	570239302	999999999
41	4.1	157156893	284527340
42	4.2	72903493	88160172
43	4.3	39898444	46834854
44	4.4	23708737	27403633
45	4.5	14794318	16948257
48	4.8	4160142	4724447
49	4.9	2795775	3176787
50	5	1884965	2146327
52	5.2	1268557	974156
51.5	5.15	fail	fail

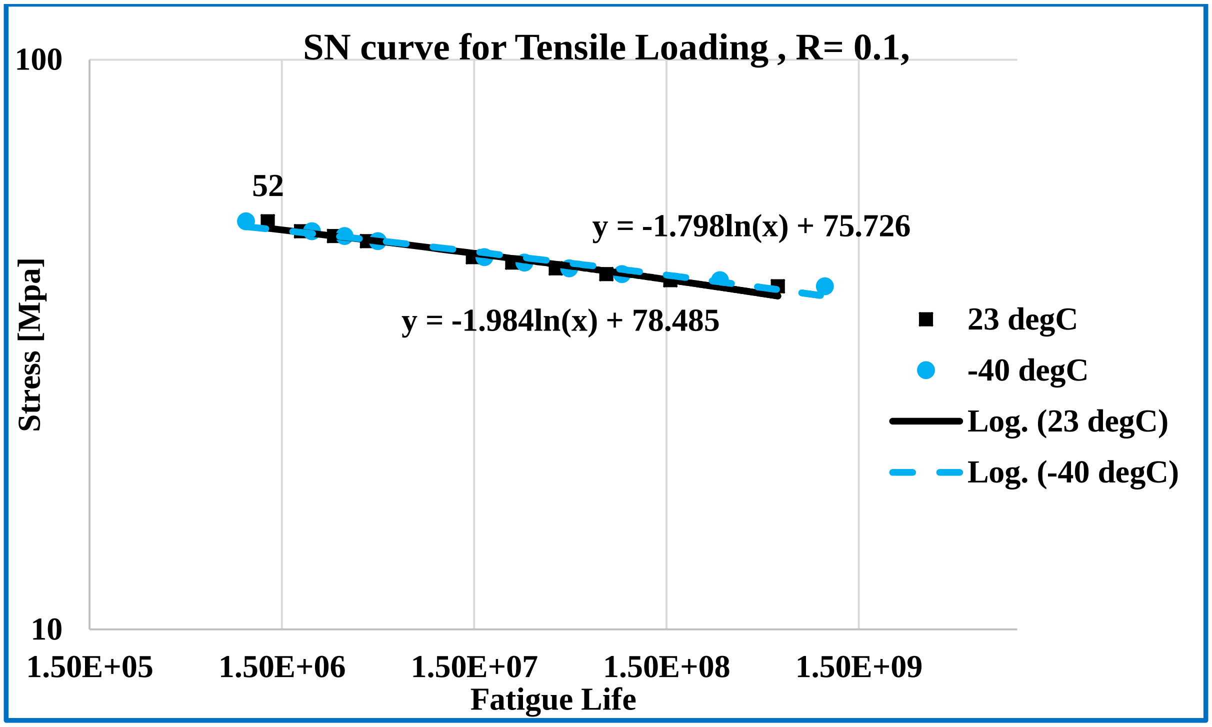


Figure 11: Simulated SN curve of composite under tensile loading

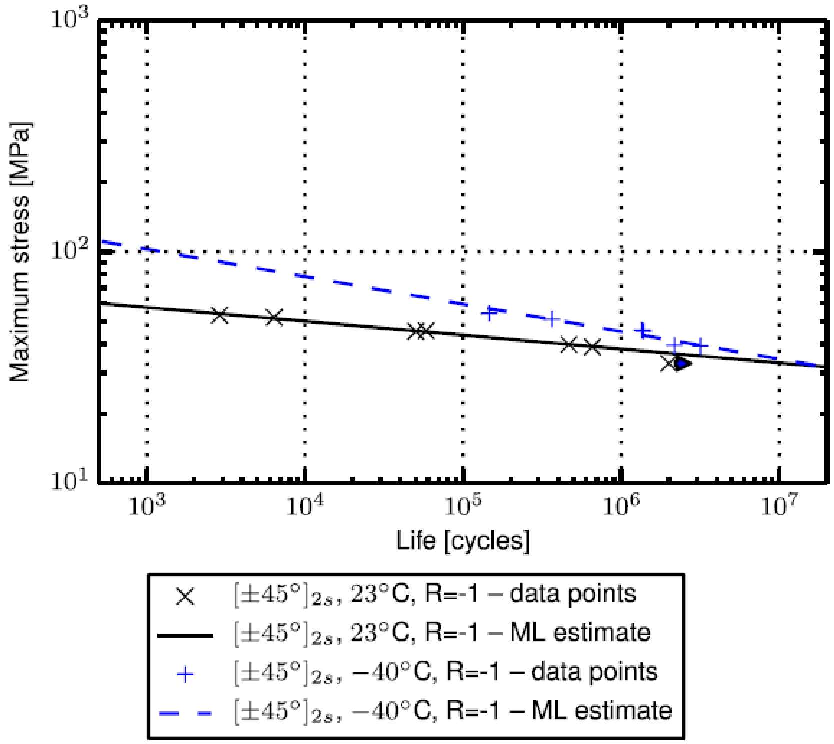


Figure 12: Published results of composite under reversed loading

Table 5: Simulated results of composite under tensile loading

D inc = 0.2, Reversed Loading , R= -1			
Stress_max [MPa]	Stress_min [MPa]	23°C	-40°C
53	-53	0	0
52	-52	0	343
51.1	-51.1	437	356
51	-51	449	504
50	-50	636	705
49	-49	879	976
48	-48	1215	1344
47	-47	1682	1844
46	-46	2294	2524
45	-45	3223	3535
40	-40	15830	9060
39	-39	22090	17258
35	-35	88712	96500
30	-30	643854	697763

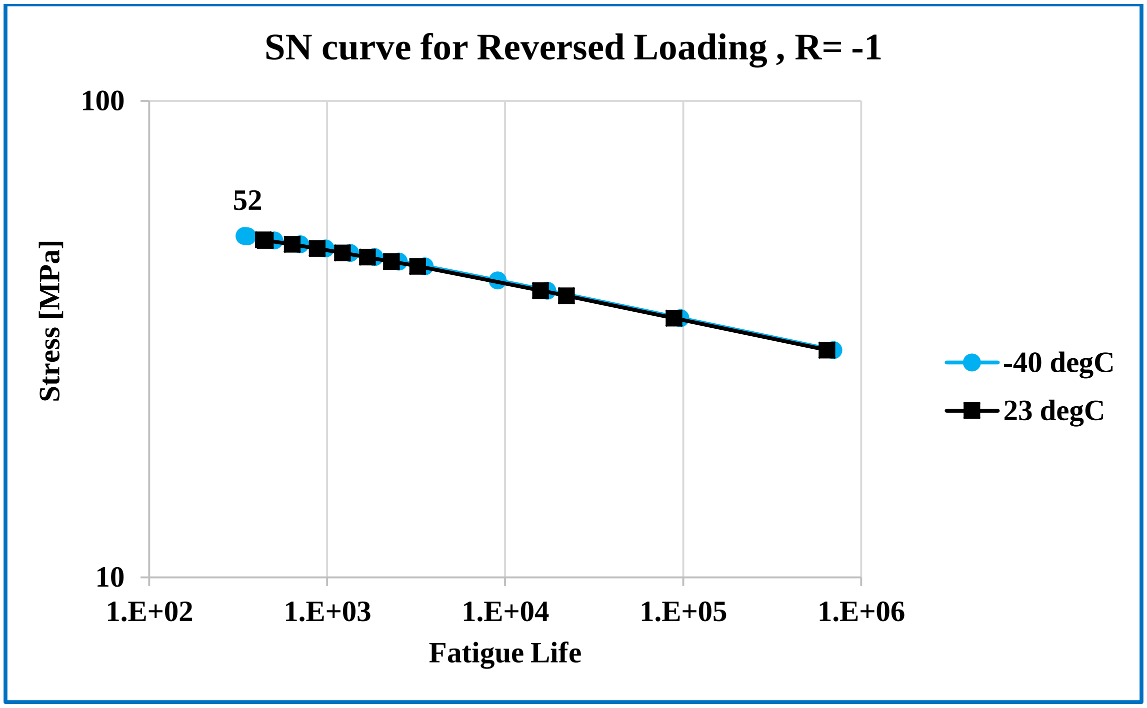


Figure 13: Simulated SN curve of composite under tensile loading

[1] Code: .txt files

Unidirectional laminate stiffness text file

```
#Eglass composite lamina analysis
*CONSTITUENTS
NMATS=2
M=1 CMOD=6 MATID=U MATDB=1
NTP=1
TEM=23
EA=70.88E3
ET=70.88E3
NUA=.2
NUT=.2
GA=29.53E3
ALPA=5.0E-6
ALPT=5.0E-6
M=2 CMOD=6 MATID=U MATDB=1
NTP=1
TEM=23
EA=2.75E3
ET=2.75E3
NUA=.2
NUT=.2
GA=1.3E3
ALPA=54.E-6
ALPT=54.E-6
*LAMINATE
  NLY=8
  LY=1 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=2 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=3 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=4 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=5 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=6 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=7 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
  LY=8 MOD=2 THK=0.125 ANG=0 ARCHID=7 R=1 VF=0.55 F=1 M=2
*THERM
  NPT=4 TI=0.,50.,100.,150. TEMP=23.,23.,-40.,-40.
*SOLVER
  METHOD=1 NPT=4 TI=0.,50.,100.,150. STP=1,1,1
*PRINT
  NPL=6
*END
```

[2] Code: .txt file

$[\mp 45]_{2s}$ *Laminate at Room temperature - Fatigue Damage Model*

```
#Eglass composite lamina analysis
*CONSTITUENTS
NMATS=2
M=1 CMOD=6 MATID=U MATDB=1
NTP=1
TEM=23
EA=70.88E3
ET=70.88E3
NUA=.2
NUT=.2
GA=29.53E3
ALPA=5.0E-6
ALPT=5.0E-6
M=2 CMOD=6 MATID=U MATDB=1
NTP=1
TEM=23
EA=4.29E3
ET=4.29E3
NUA=0.29
NUT=0.29
GA=1.66E3
ALPA=54.E-6
ALPT=54.E-6
*LAMINATE
NLY=8
LY=1 THK=0.125 ANG=-45 MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=2 THK=0.125 ANG=45  MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=3 THK=0.125 ANG=-45 MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=4 THK=0.125 ANG=45  MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=5 THK=0.125 ANG=45  MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=6 THK=0.125 ANG=-45 MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=7 THK=0.125 ANG=45  MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
LY=8 THK=0.125 ANG=-45 MOD=2 ARCHID=7 R=1. VF=0.47 F=1 M=2
*MECH
LOP=1
NPT=4 TI=0.,50.,150.,200. MAG=0.,51.,-51.,0. MODE=2,2,2
*THERM
NPT=4 TI=0.,50.,150.,200. TEMP=23.,23.,23.,23.
*SOLVER
METHOD=1 NPT=4 TI=0.,50.,150.,200. STP=10.,10.,10.
*DAMAGE
MAXNB=100 DINC=0.2 DMAX=1.0 BLOCK=0.,200.
NDMAT=2
MAT=1 MOD=2 SU1=3500,91.2,91.2,31.4,134.,134 &
SU2=2000.,91.2,91.2,31.4,134.,134. &
N1=1000,1000,1000,1000,1000,1000 &
```

```
N2=300000000,300000000,300000000,300000000,300000000,300000000
MAT=2 MOD=1 ANG=0. BN=0.0 BP=0.0 OMU=1. OMFL=1. OMM=1. ETU=1. &
ETFL=1. ETM=1. BE=9. A=0.05 SFL=27. XML=150. &
SU=80.
*FAILURE_SUBCELL
NMAT=2
MAT=1 NCRIT=1
CRIT=1 X11=3500. X22=91.2 X33=91.2 X23=31.4 X13=134. X12=134. &
 COMPR=SAM
MAT=2 NCRIT=1
CRIT=1 X11=80. X22=80. X33=80. X23=40. X13=40. X12=40. &
 COMPR=SAM
*FAILURE_CELL
NCRIT=1
CRIT=2 X11=0.05 X22=0.05 X33=0.05 X23=0.05 X13=0.05 X12=0.05 &
 COMPR=SAM
*PRINT
NPL=3
*XYPLOT
FREQ=1
LAMINATE=1
NAME=45_rt_fatigue X=1 Y=10
MACRO=0
MICRO=0
*END
```