MODELING, SIMULATION,
PROTOTYPING & VALIDATION

Characterizing and Modeling Lightweight Structural Composites at High Strain Rates for use from Arctic to Desert Environments

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Overview

- Background
- Objectives
- Methods
- Results & Discussion
- Conclusions



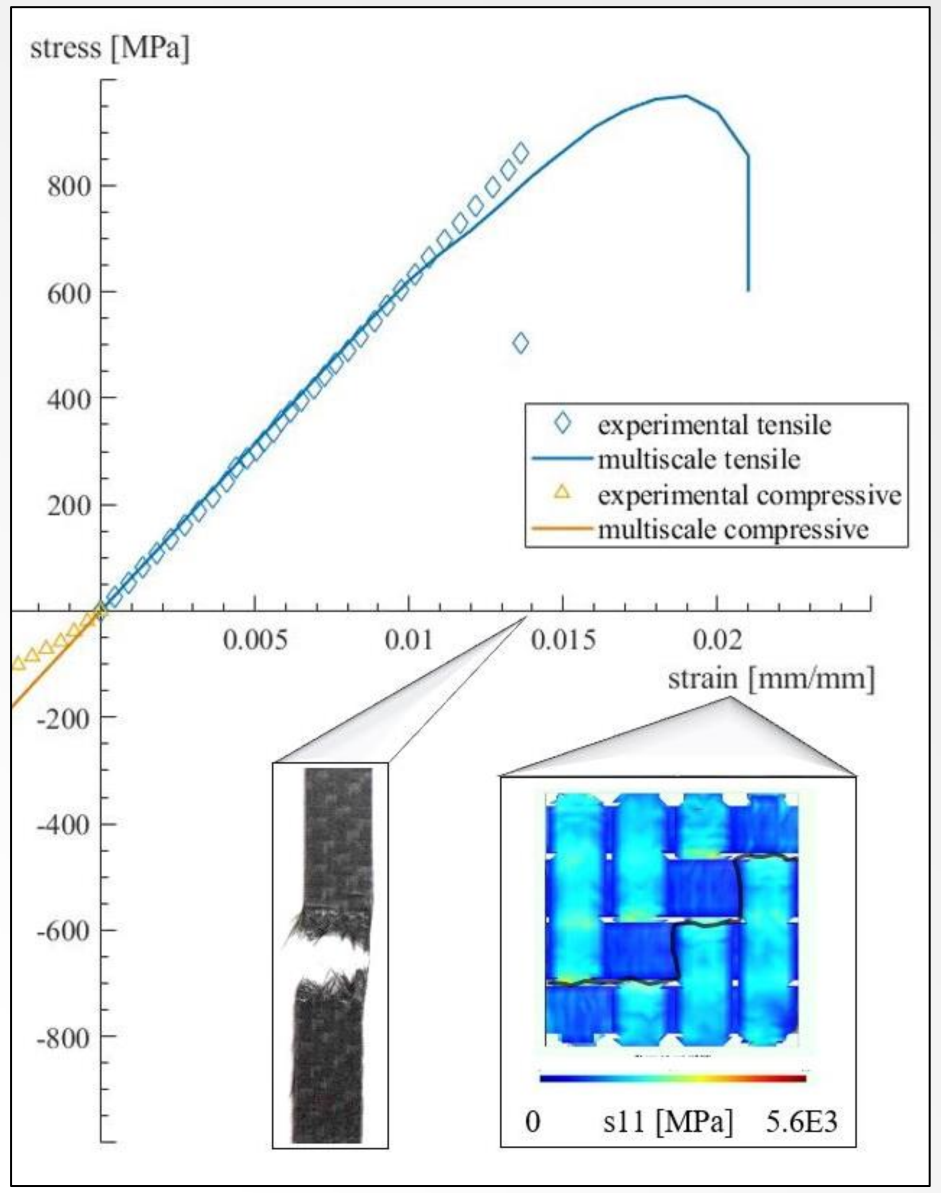

Background

Military Ground Vehicle Lightweighting:

- Lightweight materials & lighter weight structural components are necessary to offset the weight added by improved performance capabilities.
- Hard Points – Distinct weight thresholds where crossing that threshold affects a capability. i.e. If vehicles grow in weight beyond certain limits, they outgrow certain support vehicles (air transportability, bridges, etc).
- Lightweight structures (even non-ballistic ones) must withstand mobility, shock, vibration, thermal, and other loads.

Historical Barriers to Integrating Composite Materials in Ground Combat Vehicles

- Raw Material Cost
- **Design Methodologies / Modeling & Simulation (M&S)**
- Manufacturing / Tooling Cost
- Flame / Smoke / Toxicity Characteristics
- **Environmental Exposure/ Durability** (MIL-STD-810H, others)
- Integration techniques



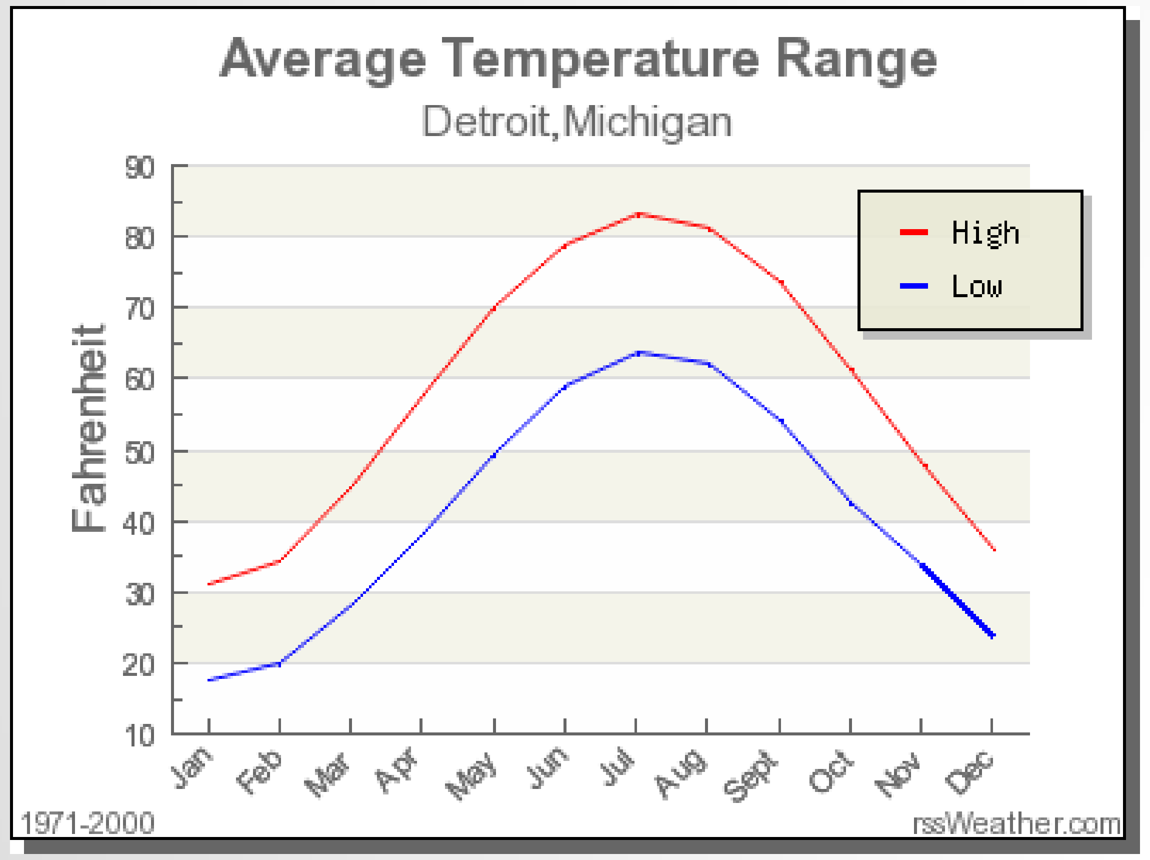
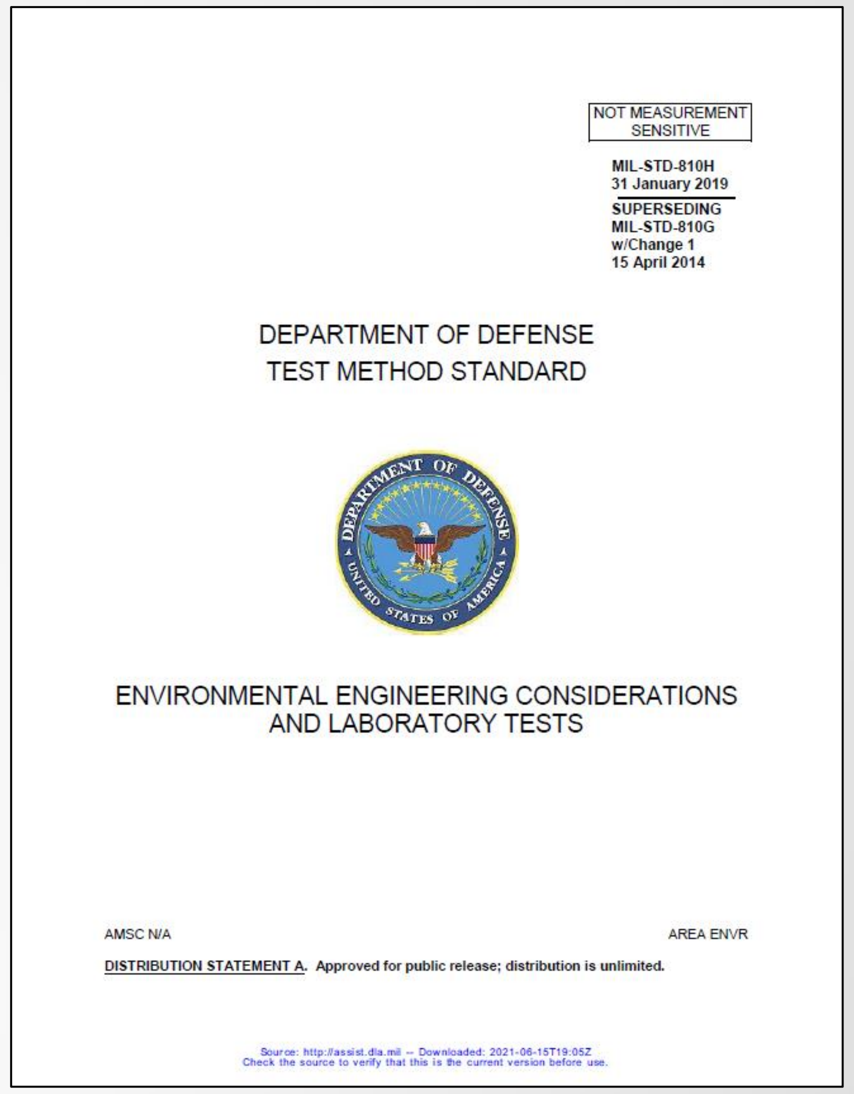


Table 501.7-I. Summary of high temperature diurnal cycle ranges.[1]

Design Type	Location	Ambient Air °C (°F)	Induced [2] °C (°F)
Basic Hot (A2)	Many parts of the world, extending outward from the hot dry category of the southwestern United States, northwestern Mexico, central and western Australia, Saharan Africa, South America, southern Spain, and southwest and south central Asia.	30 - 43 (86 - 110)	30 - 63 (86 - 145)
Hot Dry (A1)	Southwest and south central Asia, southwestern United States, Saharan Africa, central and western Australia, and northwestern Mexico.	32 - 49 (90 - 120)	33 - 71 (91 - 160)

Table 502.7-I. Summary of Low Temperature Cycle Ranges.

DESIGN TYPE	LOCATION	TEMPERATURE[1]	
		Ambient Air °C (°F)	Induced Environment (Storage & Transit) °C (°F)
Basic Cold (C1)	Most of Europe; Northern contiguous US; Coastal Canada; High-latitude coasts (e.g., southern coast of Alaska); High elevations in lower latitudes	-21 to -32 (-5 to -25)	-25 to -33 (-13 to -28)
Cold (C2)	Canada, Alaska (excluding the interior); Greenland (excluding the "cold pole"); Northern Scandinavia; Northern Asia (some areas), High Elevations (Northern and Southern Hemispheres); Alps; Himalayas; Andes	-37 to -46 (-35 to -50)	-37 to -46 (-35 to -50)
Severe Cold (C3)	Interior of Alaska; Yukon (Canada); Interior of Northern Canadian Islands; Greenland ice cap; Northern Asia	-51 (-60)	-51 (-60)


NOT MEASUREMENT SENSITIVE

MIL-STD-810H
31 January 2019
SUPERSEDING
MIL-STD-810G
w/Change 1
15 April 2014

DEPARTMENT OF DEFENSE
TEST METHOD STANDARD

ENVIRONMENTAL ENGINEERING CONSIDERATIONS AND LABORATORY TESTS

AMSC N/A AREA ENVR

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Objectives

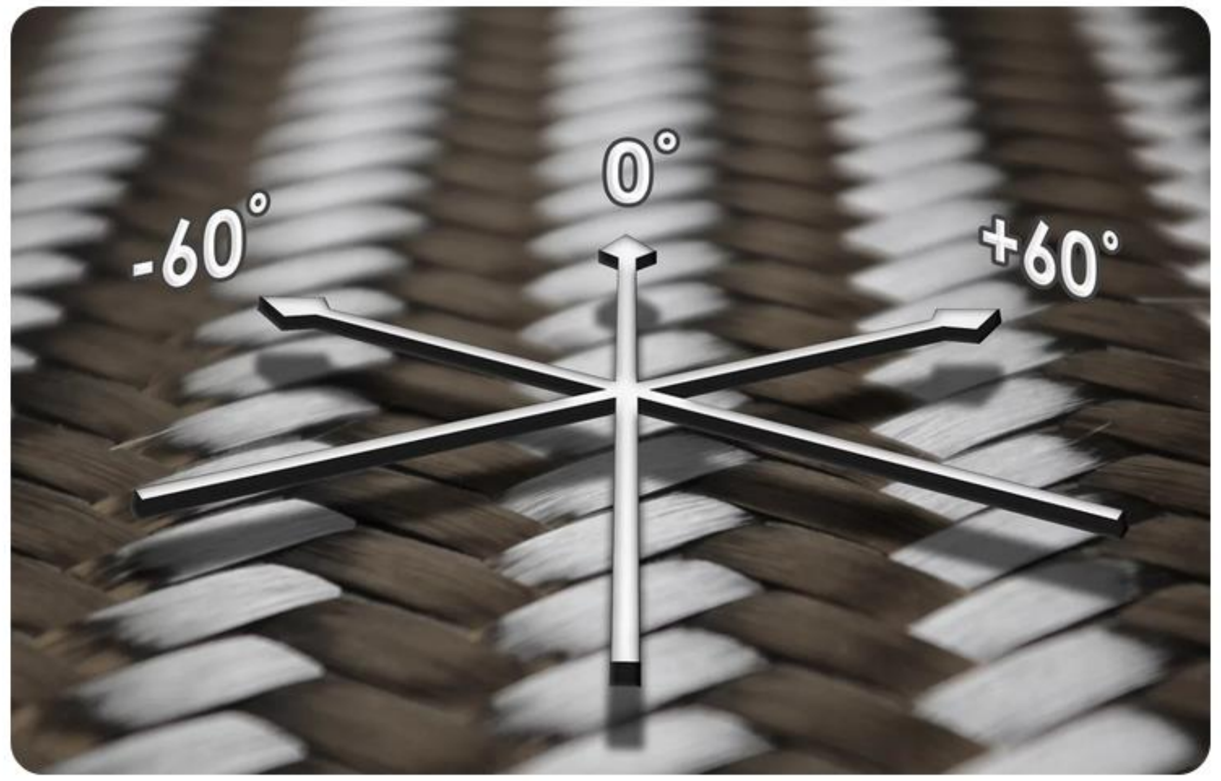
This study focused on gaining greater understanding into the temperature- dependent and strain-rate dependent mechanical properties of a triaxial carbon fiber – epoxy composite that has potential for reducing the weight of secondary structures in military ground vehicles.

- Mechanical characterization tests were performed from -60 °F (representing extreme arctic conditions) to 180 °F (representing arid desert conditions) and at strain rates from 0.01 s^{-1} (quasi-static) to 1,000 s^{-1} (dynamic).

Methods

Composite Manufacturing

- The composite laminate tested in this study utilized a triaxial braided fabric, QISO-HW-48, from A&P Technology.
  - The fabric consists of T-700 SC 12K 50C fibers braided into a single layer, balanced 0, +/-60 fiber architecture.
  - The fabric was laminated into panels using SC-15 toughened epoxy resin and processed using vacuum assisted resin transfer molding and post oven cure cycle.
  - Panels were manufactured to nominal thicknesses of 1/8”, ¼”, and ½” (see Figure 1) in order to satisfy the geometry requirements of the mechanical characterization testing.



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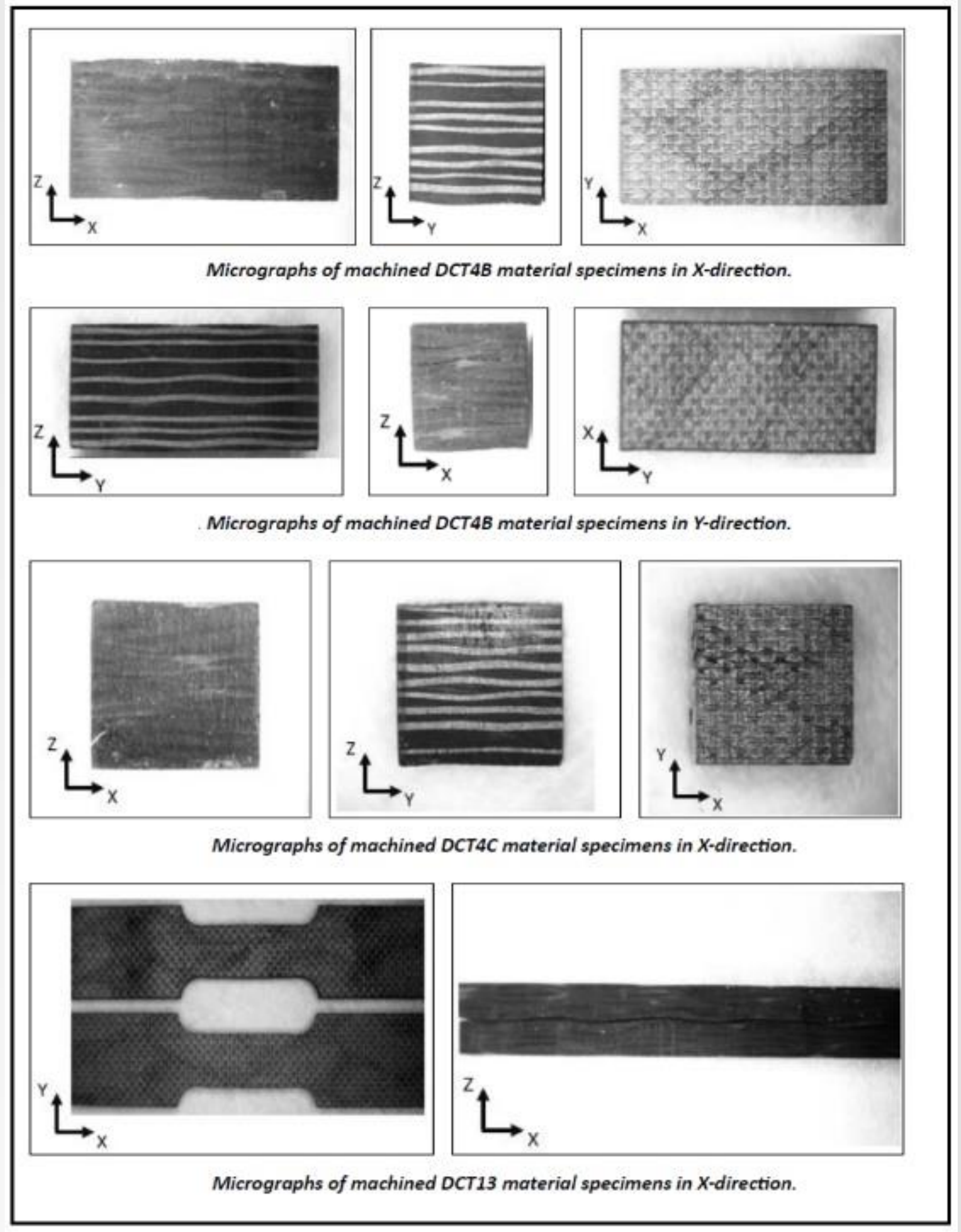
Methods

Material Characterization

- Tests were performed to determine the elastic properties and failure limits in tension, compression, and shear for the range of strain rates and environmental conditions expected in vehicle operation.
    - Tensile, compression, shear, and mode I & II fracture tests were performed at strain rates of 0.01 s^{-1} (Quasi-Static, QS), 1 s^{-1} (Quasi-Dynamic, QD), and 1,000 s^{-1} (Dynamic, D), with each test repeated under environmental temperatures of -60 °F (referred to as low temperature, or LT), Room Temperature (RT), and 180 °F (referred to as high temperature, HT).
    - A servo electric test module was utilized for lower strain rate testing, while a split-Hopkinson pressure/tension bar (SHPB/SHTB) was utilized to gather high strain rate data. In each test setup, environmental chambers were utilized to isolate and control the environmental temperature during each test.



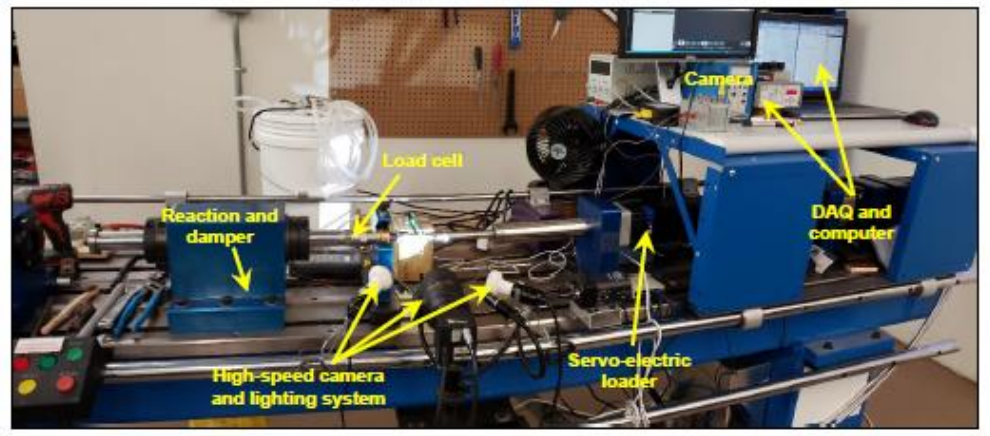


Figure 17. Quasi-static test setup using K&C's Servo-machine at room temperature.

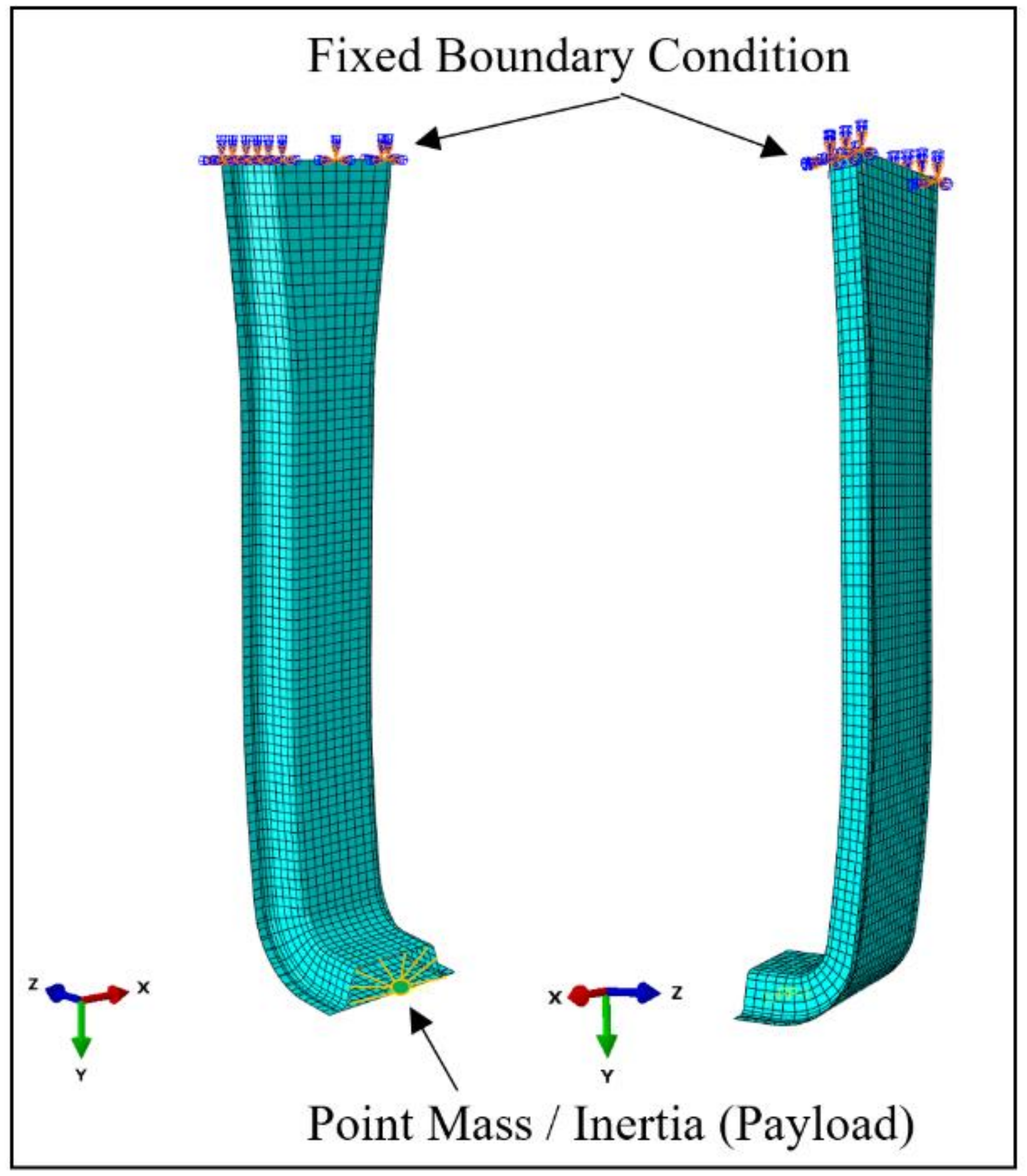
(a) SHPB

(b) SHTB

Methods

Finite Element Methods

- For this study, a hat section type of structure was selected, which includes relevant design features and geometry that could apply to a structural member within a military ground vehicle.
  - The generalized structure was modeled in Abaqus CAE with 3-D solid shell elements, and the elastic properties were assigned as determined from the tension and compression tests.
  - Both “static” and “shock” loads were applied to the structure in separate analyses in order to understand the structure’s response under general mobility loads and more severe shock loads.
  - The static analyses were conducted by applying a G-load multiplication factor to the payload in the vertical direction (y-direction in Figure 4), where as the shock analyses were conducted through a linear-perturbation procedure with the shock load being applied as a displacement-based perturbation on the fixed boundary condition in the vertical direction (y-direction in Figure 4).
  - The static analyses were performed using quasi-static (QS) test data at 0.01 s^{-1} and repeated using material properties at LT, RT, and HT. The modal dynamics analyses (shock analyses) were conducted using the quasi-dynamic (QD) test data at 1 s^{-1}.



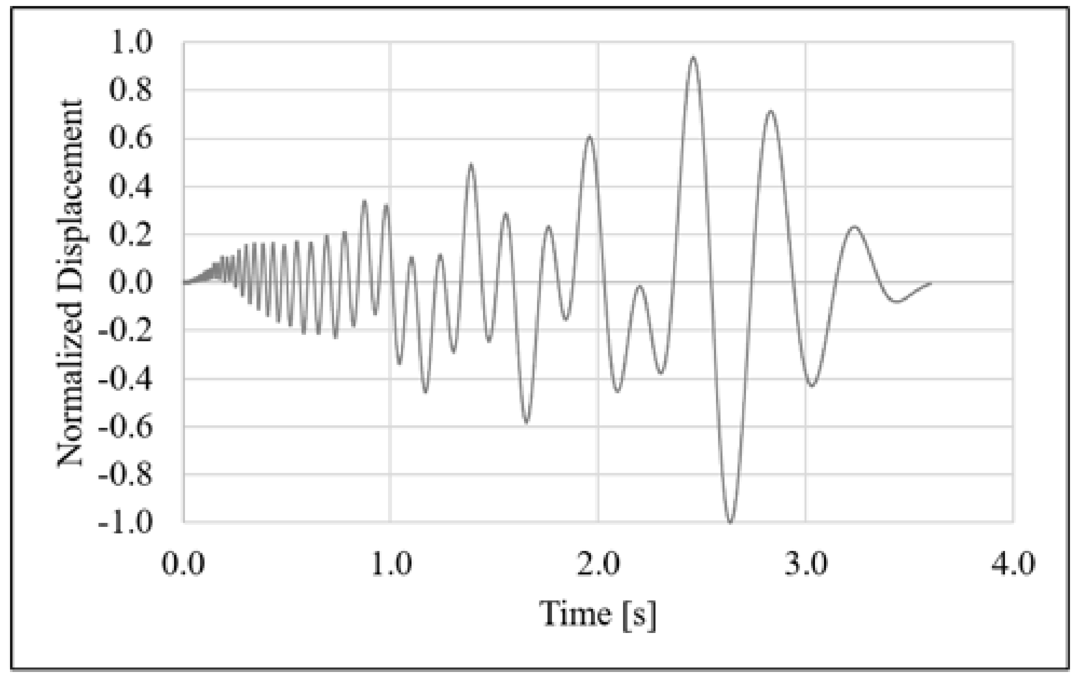


Figure 5: Generalized Shock Profile Applied to the Y-Direction Boundary Condition within Linear Perturbation Step of FE model.

Results & Discussion

Mechanical Characterization – Influence of Strain Rate

- At room temperature, the slope of the initial elastic region was highest in the 1,000 s^{-1} test (highest elastic modulus) and the tensile strength was also highest in the high strain rate test.
- Across all environmental temperatures tested in this study, as the strain rate increased, tensile strength was observed to increase as well.
- When increasing from 1 s^{-1} to 1,000 s^{-1}, the elastic modulus clearly increased with strain rate.
- For compression tests, the highest compression strength was observed under the 1000 1 s^{-1} test, and lowest compression strength was observed at the lowest strain rate of 0.01 1 s^{-1}.

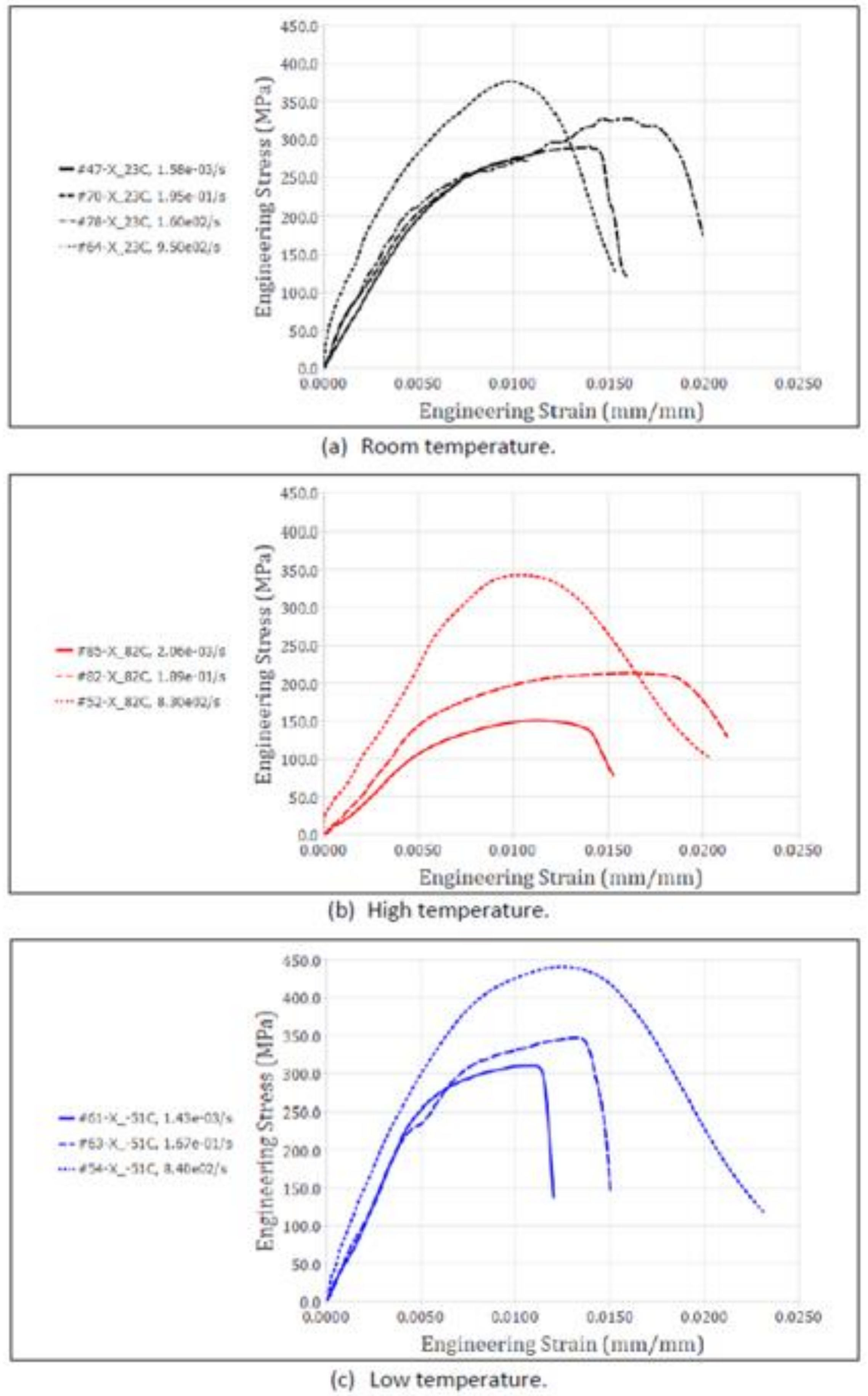


Figure 6: Comparison of stress-strain curves under varying strain rates for tensile tests conducted in the x-direction at (a) room temperature, (b) high temperature, and (c) low temperature.

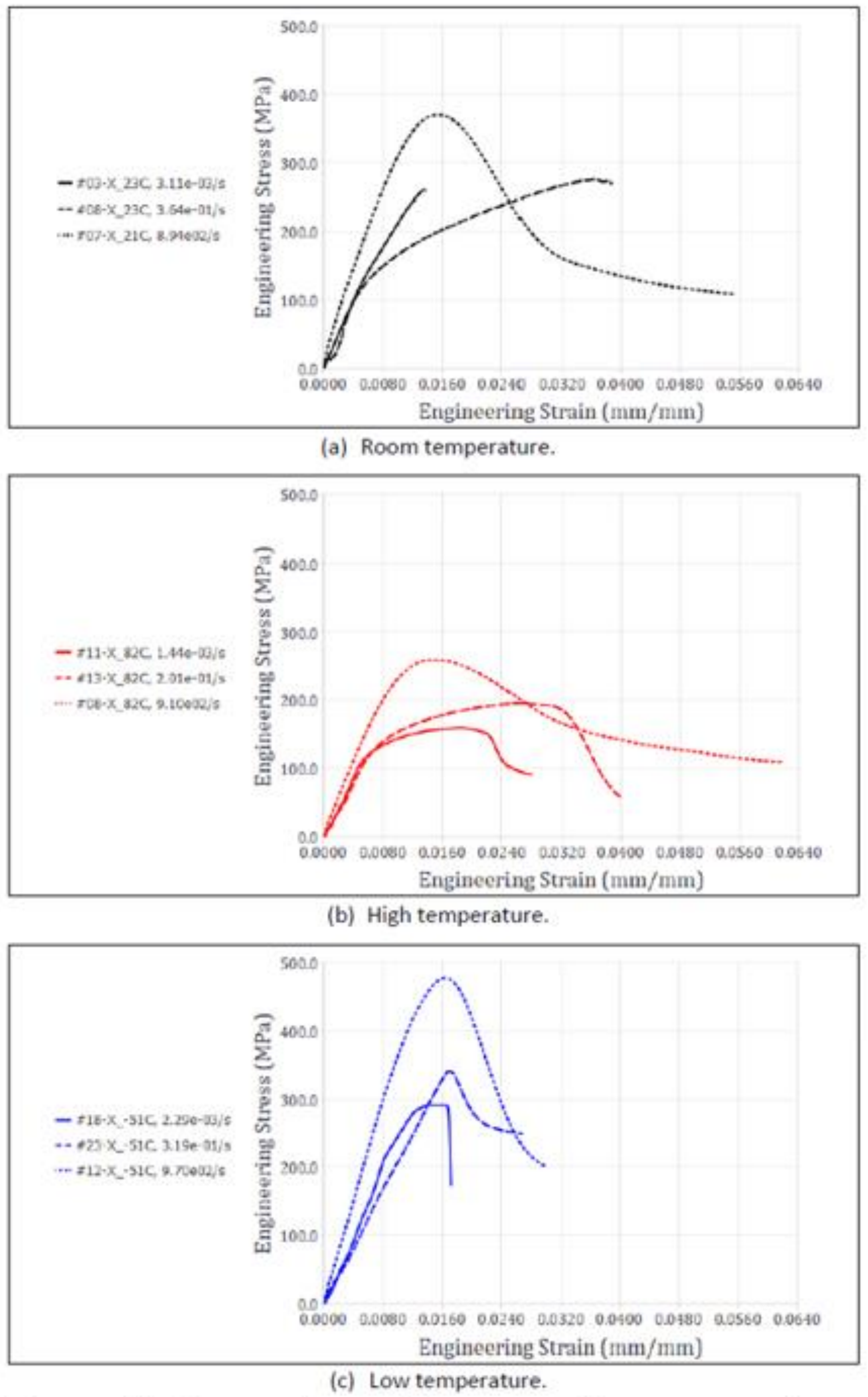
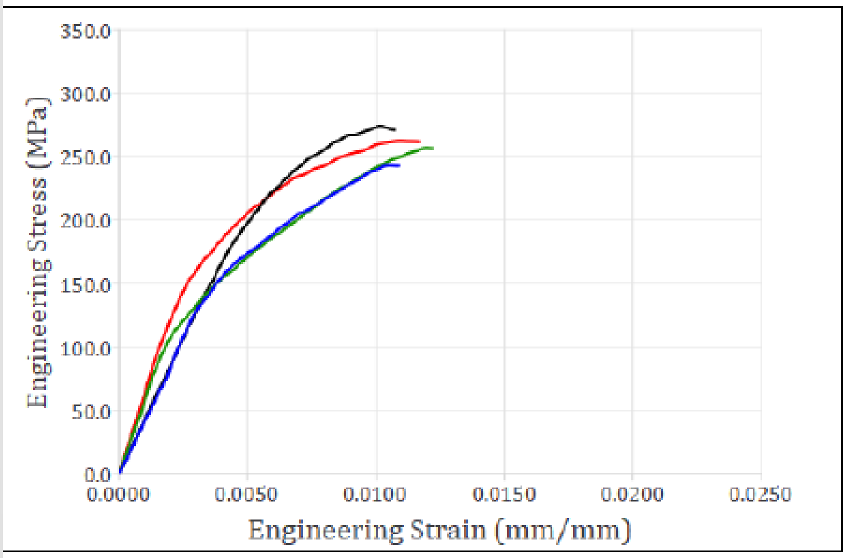


Figure 7: Comparison of stress-strain curves under varying strain rates for compression tests conducted in the x-direction at (a) room temperature, (b) high temperature, and (c) low temperature.

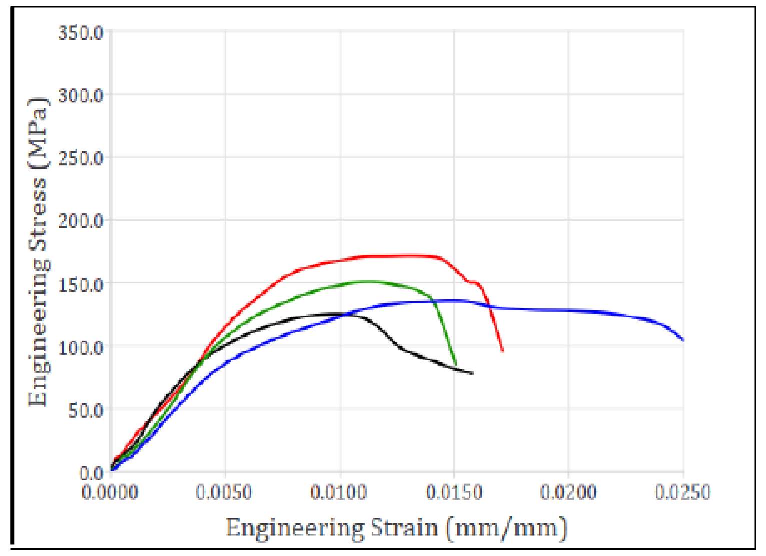
Results & Discussion

Mechanical Characterization – Influence of Temperature

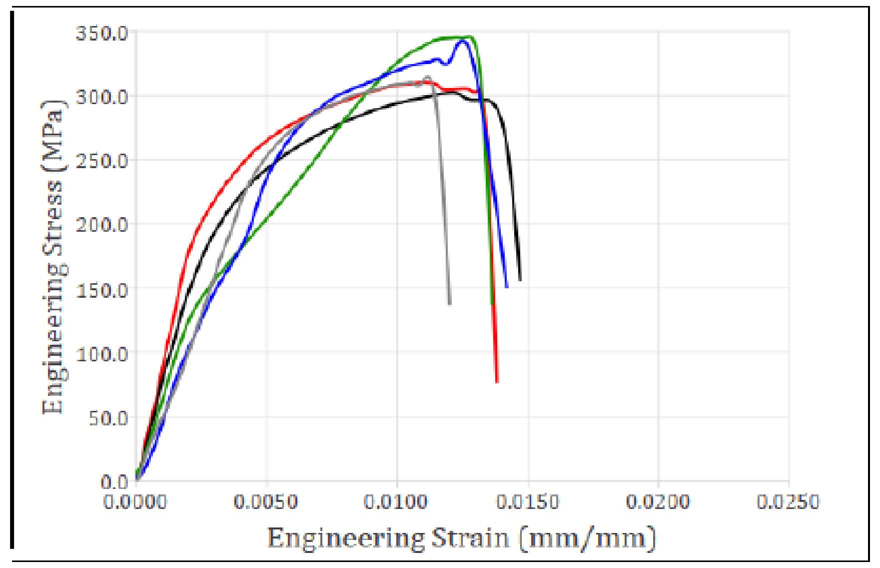
- At a given strain rate, the lowest elastic modulus and lowest strength was observed in the high temperature test, and the highest modulus and strength was observed in the low temperature test.



(a) Room temperature.

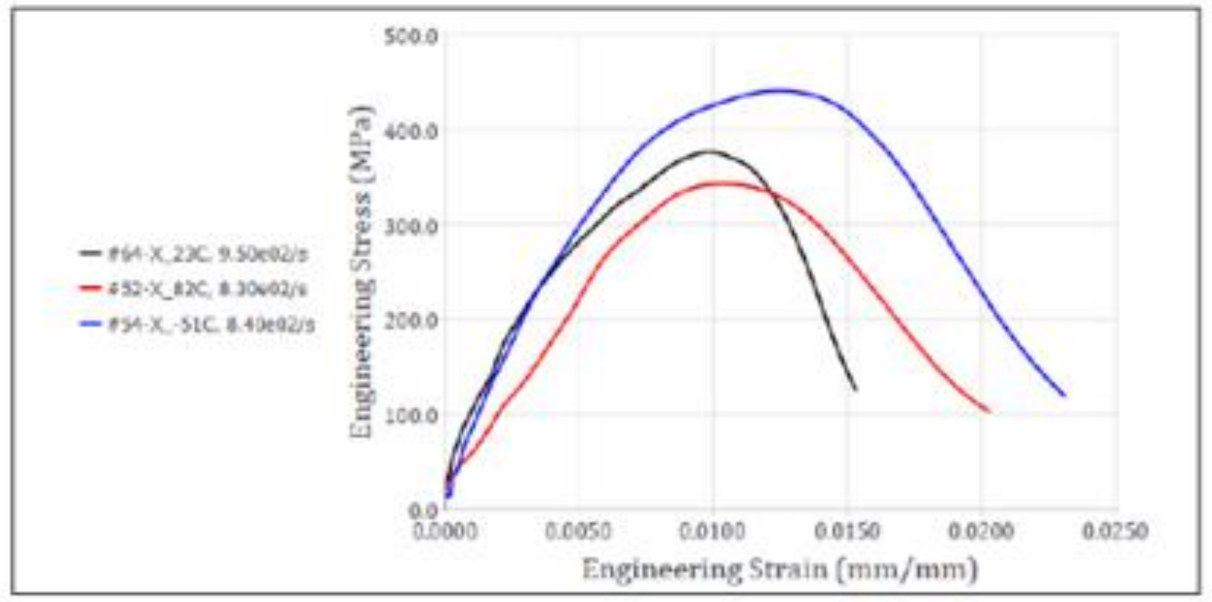


(b) High temperature.

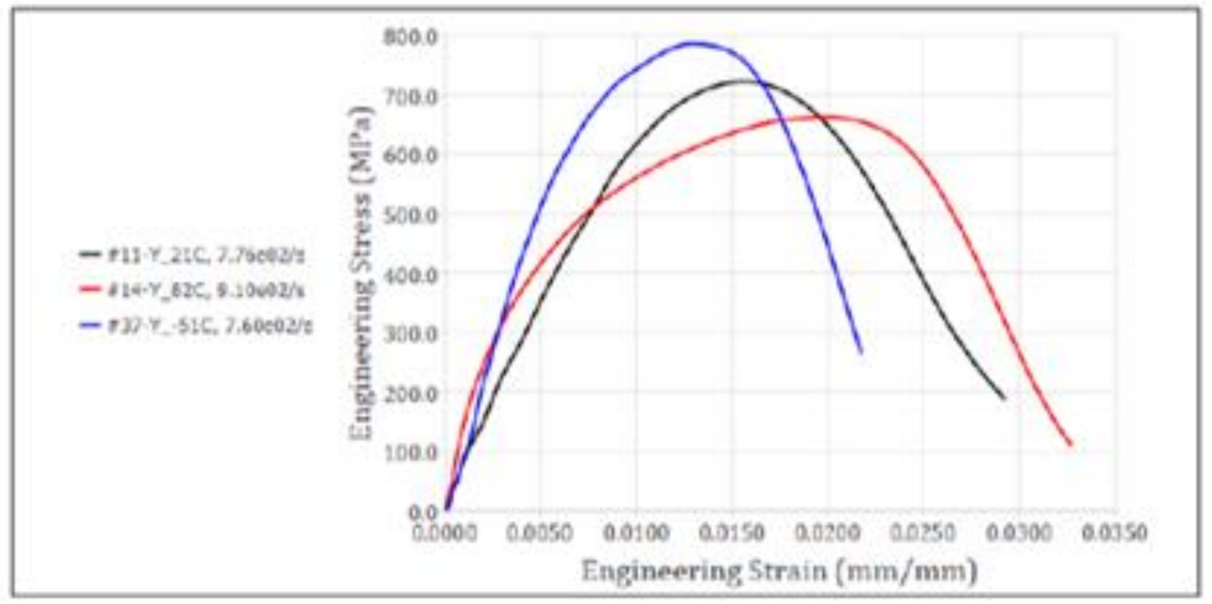


(c) Low temperature.

Figure: Individual Tensile Test specimens at 0.01/s strain rate, showing specimen to specimen variation in response at (a) room, (b) high, and (c) low temperature.

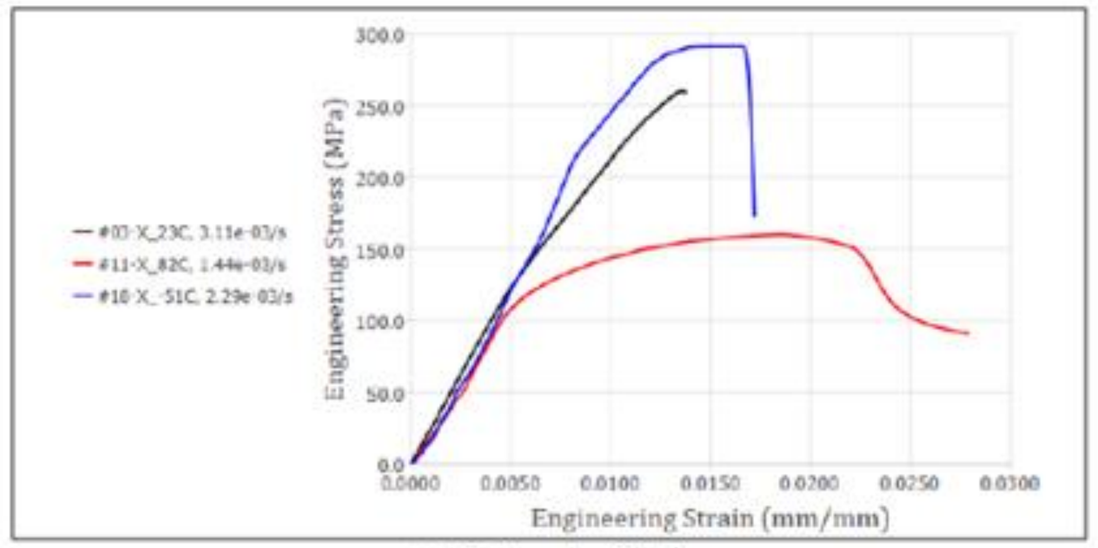


(a) x-direction tension tests at 1,000 /s

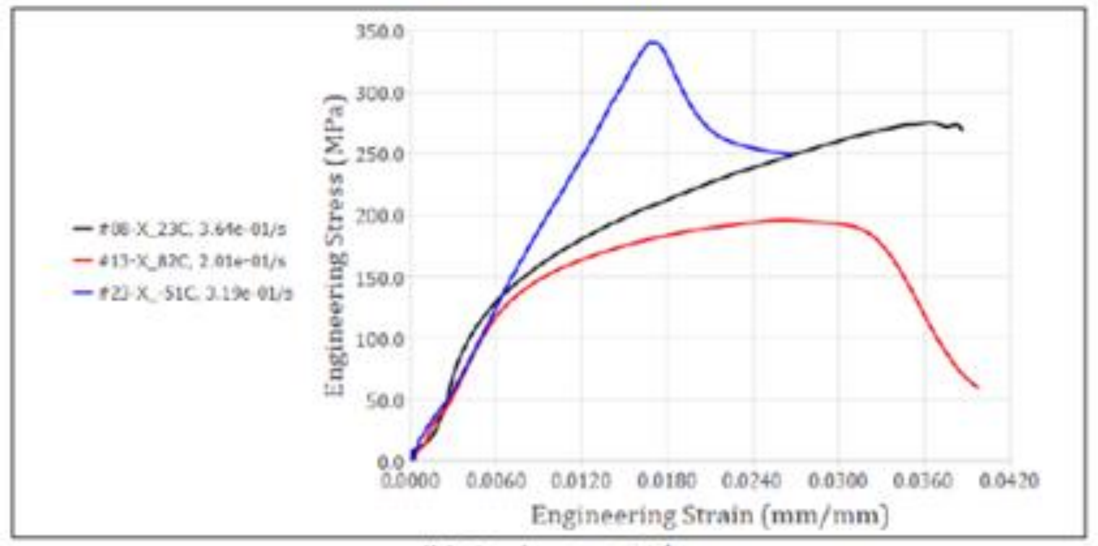


(b) y-direction tension tests at 1,000 /s

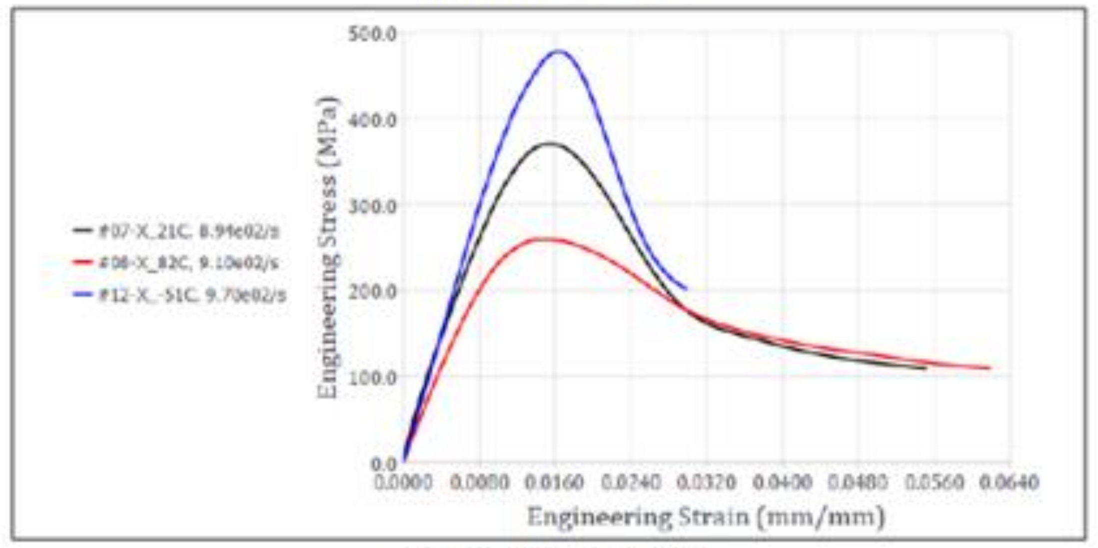
Figure 8: Comparison of stress-strain curves under varying environmental temperatures for tensile tests (a) conducted in the x-direction at 1000 / s strain rate and (b) conducted in the y-direction at 1000 / s strain rate.



(a) Strain-rate: 0.01/s.



(b) Strain-rate: 1.0/s.



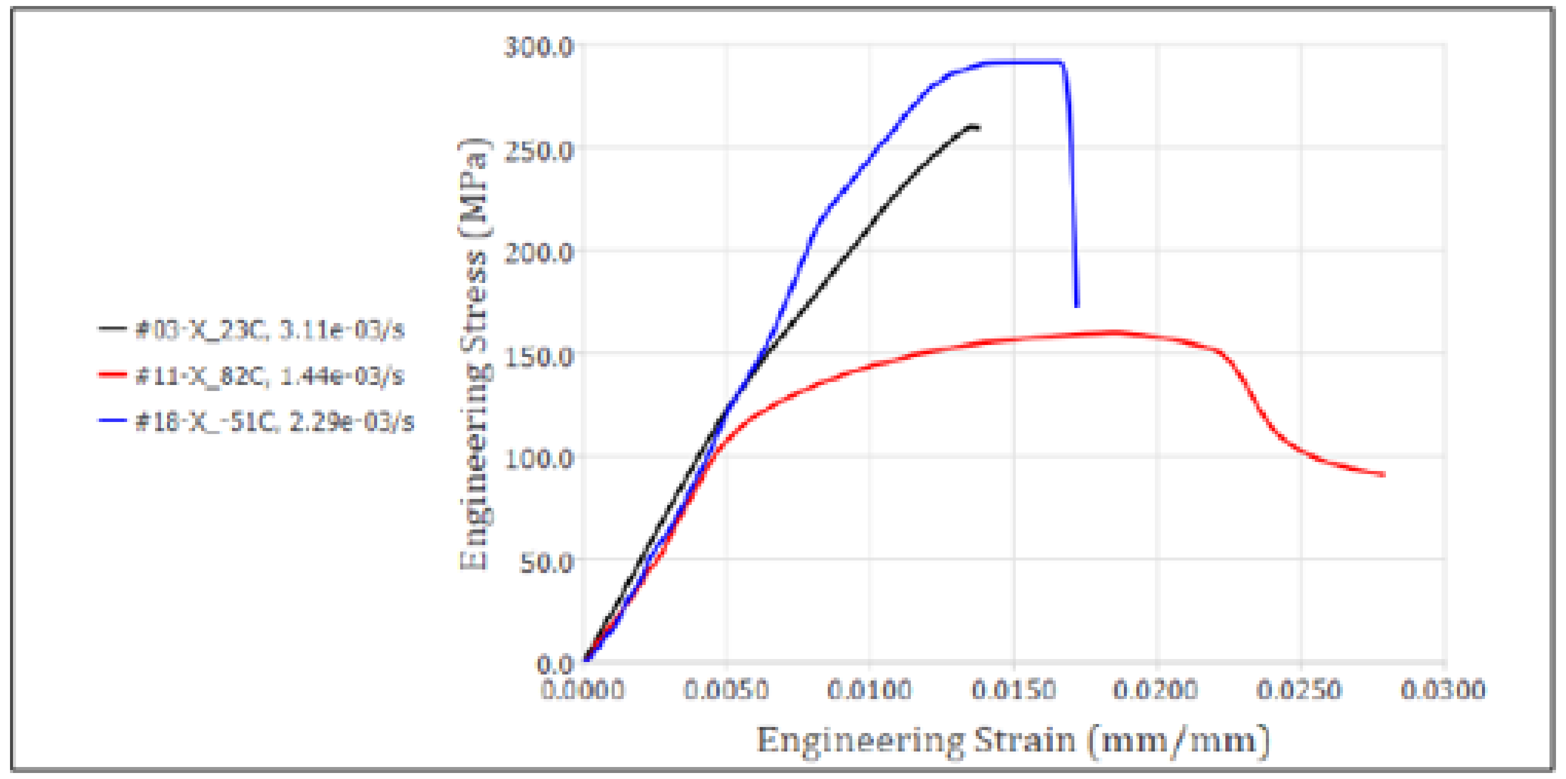
(c) Strain-rate: 1,000/s.

Figure 9: Comparison of stress-strain curves under varying environmental temperatures for compression tests conducted in the x-direction at (a) 0.01 / s strain rate, (b) 1.0 / s strain rate, and (c) 1000 / s strain rate.

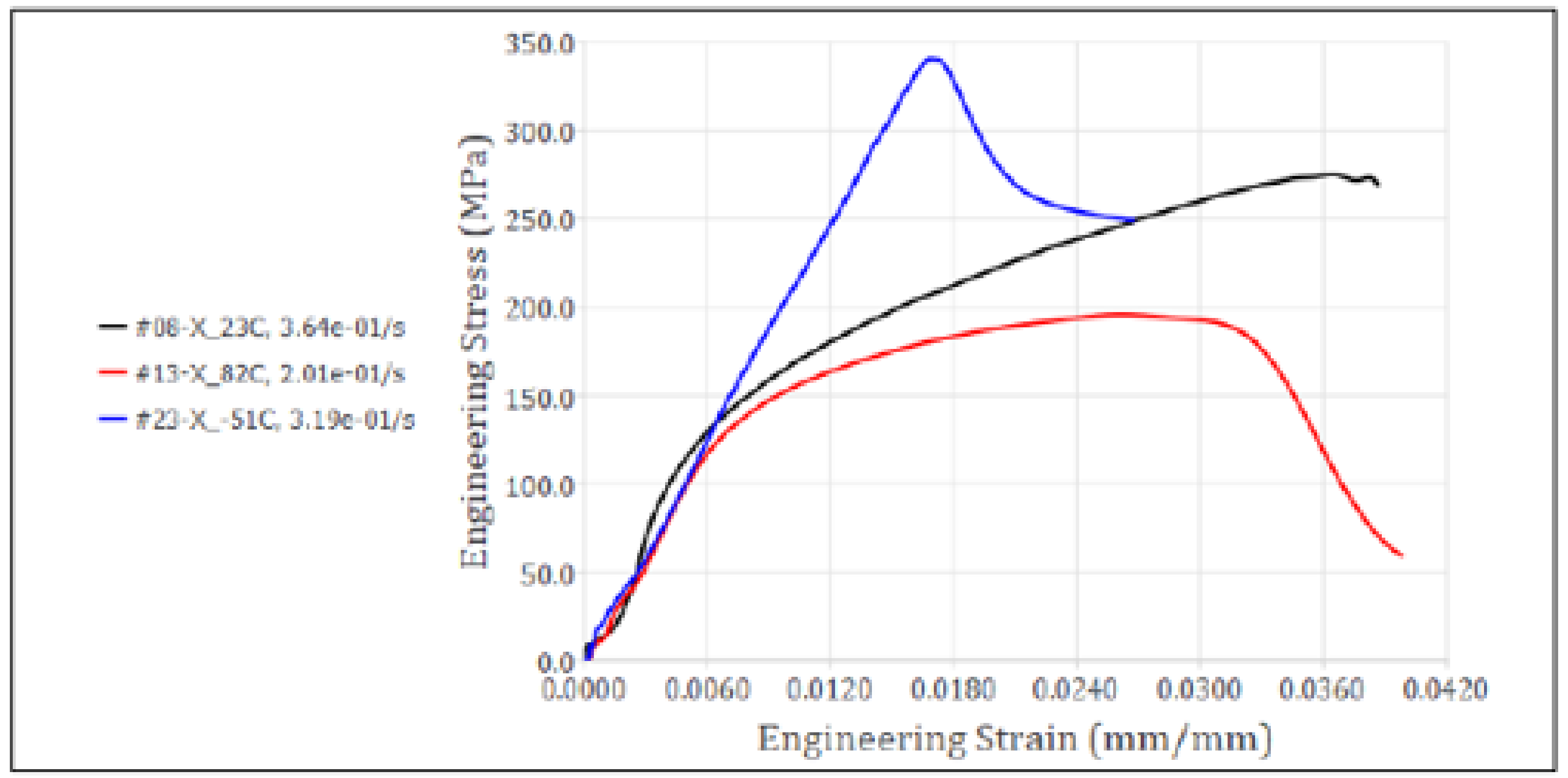
Results & Discussion

Mechanical Characterization – Material Properties

- The mechanical properties of the composite material were extracted from individual test specimens and summarized in Table 1.
  - It is important to note that these mechanical properties are determined from single coupon tests, and have not been characterized extensively enough to determine statistical significance. Under this context, these properties were used within this study to observed how the temperature and strain rate trends discussed above impact performance in a structural application in a military environment.



(a) Strain-rate: 0.01/s.



(b) Strain-rate: 1.0/s.

Table 1. Mechanical Property Data for various Strain-Rates and Environmental Temperatures, Based on Single Test Curves in Figures 6-9

Density [g/cc]	1.513		
	Quasi-Static (QS)		
	LT_QS	RT_QS	HT_QS
Elastic Modulus [GPa]	53.4	42.7	21.5
Tensile Strength [MPa]	313.2	277.0	152.6
Compressive Strength [MPa]	286.9	256.4	157.0
	Quasi-Dynamic (QD)		
	LT_QD	RT_QD	HT_QD
Elastic Modulus [GPa]	53.2	49.4	27.8
Tensile Strength [MPa]	351.1	294.5	216.7
Compressive Strength [MPa]	328.7	265.1	190.7
	Dynamic (D)		
	LT_D	RT_D	HT_D
Elastic Modulus [GPa]	62.9	61.2	41.6
Tensile Strength [MPa]	446.3	380.3	346.1
Compressive Strength [MPa]	470.0	271.0	255.4

Results & Discussion

Finite Element Results – Static Analyses

- As temperature increases from low temperature (LT) to room temperature (RT) to high temperature (HT), the maximum deflection of the composite structure increased.
- It was also observed in the FE analyses that as temperature increased, maximum principal stress decreased, however the rate at which the maximum principal stress decreased was less than the drop in tensile strength due to temperature.
  - This trend resulted in the lowest safety factor in tension of 2.0 for the static, high temperature analysis, based on the Maximum Principal Stress criteria, which is a common failure criteria for fiber reinforced composite materials.

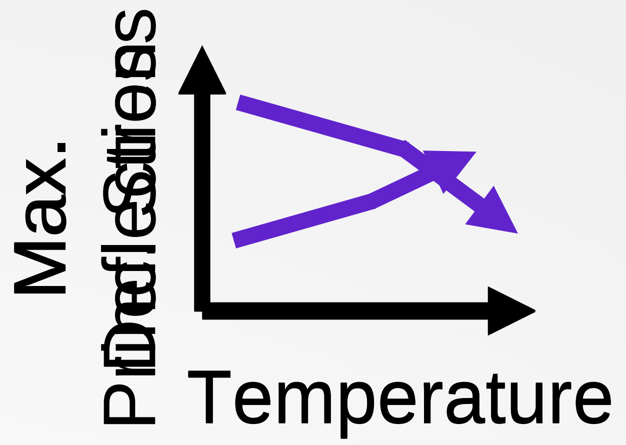


Table 2. FE Results for Static Load Case (Positive Mobility G Load)

	LT_QS	RT_QS	HT_QS
Maximum Deflection [mm]	7.42	8.98	15.6
Maximum Principal Stress [MPa]	81.6	81.3	77.0
Tensile Strength [MPa]	313.2	277.0	152.6
Safety Factor (Tension)	3.8	3.4	2.0
Minimum Principal Stress (Abs Value) [MPa]	33.2	33.0	32.5
Compressive Strength [MPa]	286.9	256.4	157.0
Safety Factor (Compression)	8.6	7.8	4.8

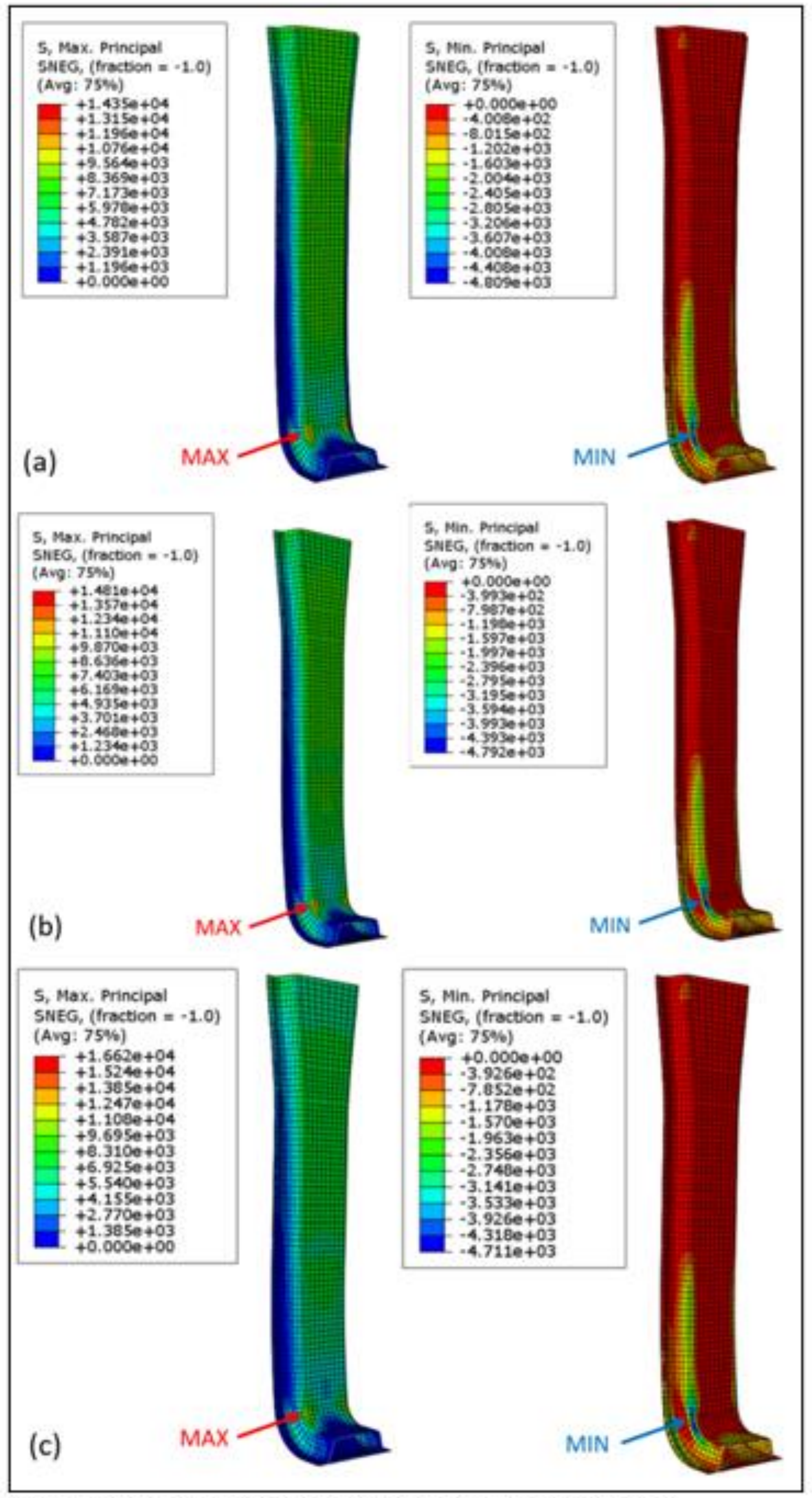


Figure 10: Maximum and minimum principal stresses in the composite hat section for static analysis (units of stress are in PSI)

Results & Discussion

Finite Element Results – Shock Analysis Using Modal Dynamics Load Step

- The modal dynamics analysis required approximately 30 minutes to run on a PC using 4 processors, and consisted of approximately 17,500 time steps.
- A frame-based field output was created so that at each node, the maximum (or minimum) value of the deflection and stress results were recorded from the maximum value observed over the 17,500 frames

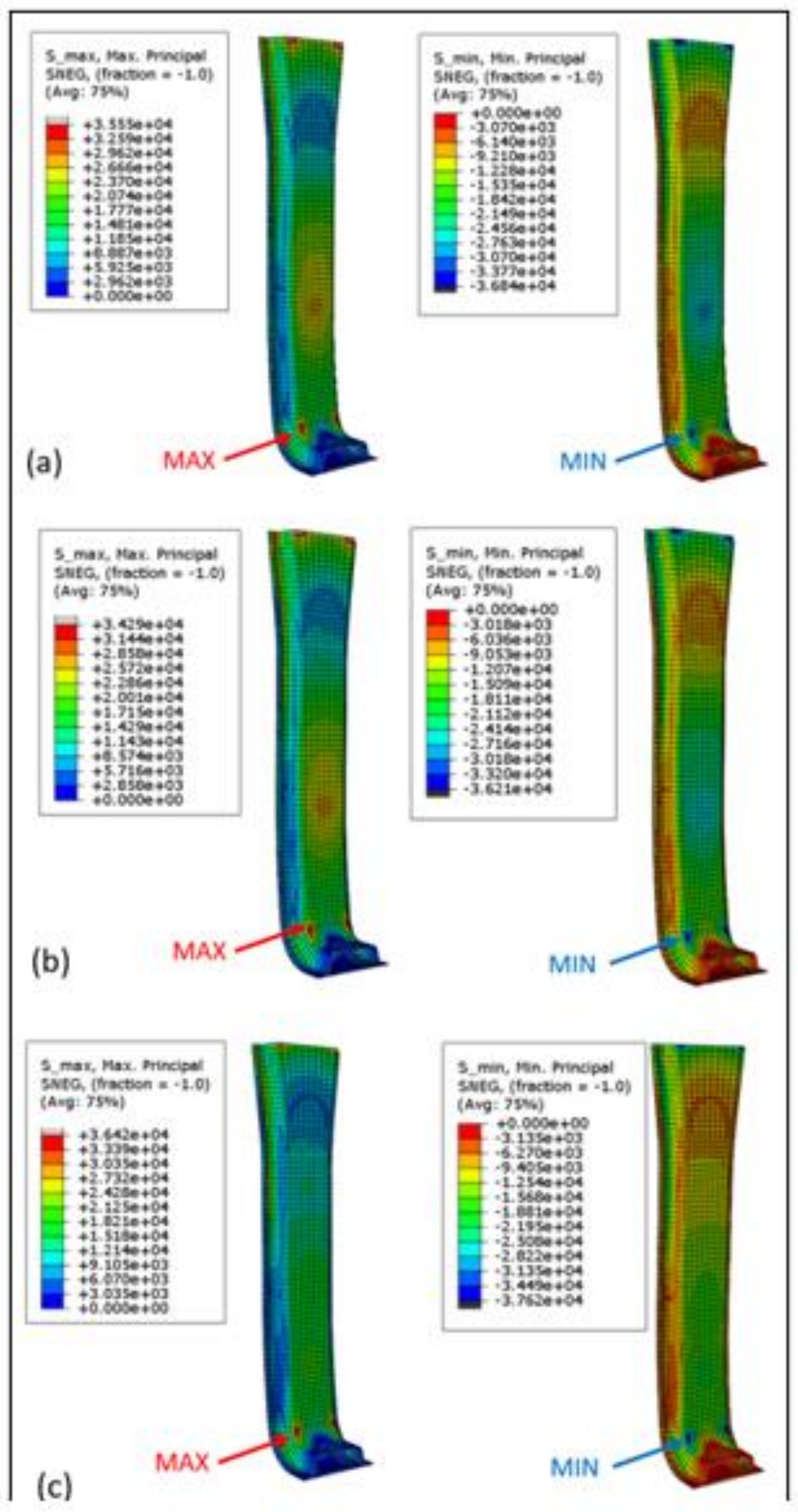


Figure 12: Maximum and minimum principal stresses at (a) Low, (b) Room, and (c) High Temperature (units of stress are in PSI)

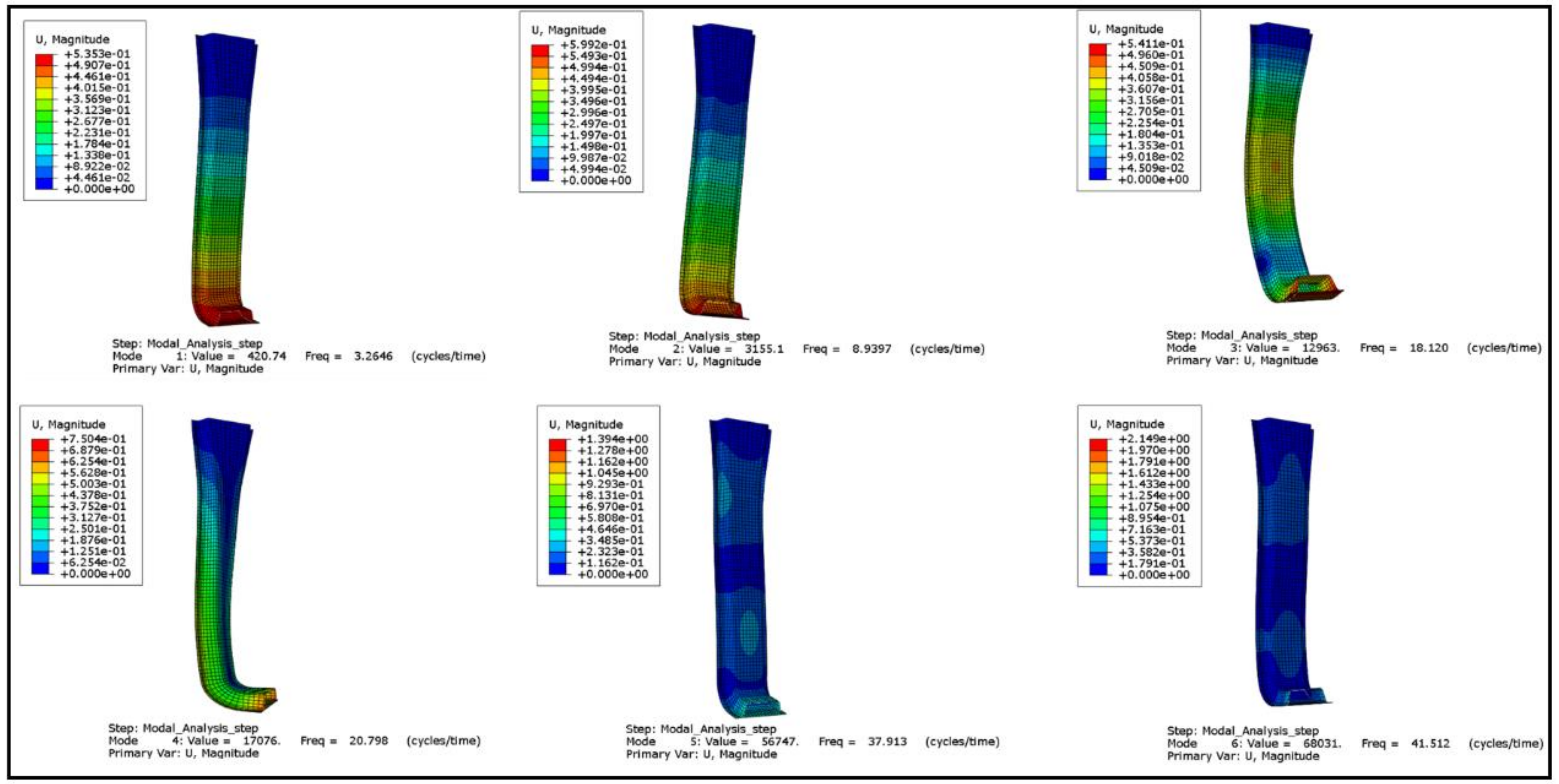
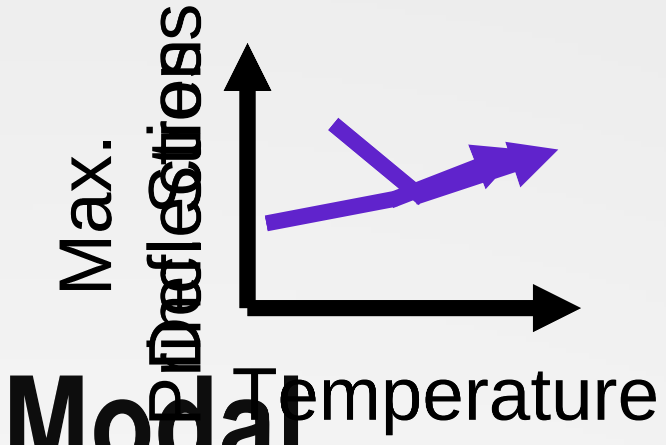


Figure 11: First six mode shapes and frequencies from modal analysis step (units of deflection are in inches)

Results & Discussion



Finite Element Results – Shock Analysis Using Modal Dynamics Load Step

- As temperature increased, maximum deflection increased, and the highest principal stresses were observed in the high temperature test.
- The high temperature condition resulted in the lowest quasi-dynamic material strength, meaning that with the higher stresses and lower material strength in the high temperature condition, the safety factor was adversely affected.
- When observing safety factor, across all shock analyses at low, room, and high temperature, the safety factors were all lower than the corresponding static analyses. The high temperature condition resulted in the lowest safety factors in both static and shock analyses, with the safety factor reaching values of 0.9 and 0.7 in tension and compression, respectively. This result indicates that the failure criteria have been reached locally within the composite hat section at the high temperature condition,

Table 3. FE Results for Shock Load Case using Shock Profile in Figure 5

	LT_QD	RT_QD	HT_QD
Maximum Deflection [mm]	7.42	7.63	11.4
Maximum Principal Stress [MPa]	245.1	236.4	251.1
Tensile Strength [MPa]	351.1	294.5	216.7
Safety Factor (Tension)	1.4	1.2	0.9
Minimum Principal Stress (Abs Value) [MPa]	254	249.7	259.4
Compressive Strength [MPa]	328.7	265.1	190.7
Safety Factor (Compression)	1.3	1.1	0.7

Results & Discussion

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Both the environmental temperature and loading rate (i.e. strain rate) have significant influence on predicted safety factor in a design optimization problem

Conclusions

- In this work, triaxial carbon fiber – epoxy composite laminates were manufactured and tested to determine the influence of environmental temperature and strain rate on the mechanical properties.
- As environmental temperature increased, the strength and elastic modulus were observed to decrease. Across all three environmental temperatures tested in this study, as the strain rate increased, tensile strength was observed to increase as well. The effect of strain rate on elastic modulus was not so clearly evident when comparing the 0.01 s^{-1} and 1 s^{-1} tests, however when increasing from 1 s^{-1} to 1,000 s^{-1}, the elastic modulus clearly increased with strain rate.
- In the shock analyses, the maximum principal stresses were higher compared to the static analyses at the same temperature, however the highest stresses were observed in the high temperature shock analysis, resulting in the lowest safety factors in tension and compression.
- These trends may indicate that for FE models where low strain rates are expected and the response is kept well within the elastic regime, elastic modulus from a quasi-static test may be sufficient, however for higher strain rate events and highly dynamic analyses, high strain rate dependent properties may be required in order to model an accurate response.
- Regardless of the strain-rate effect, the results highlighted the importance of characterizing material properties under the range of environmental temperatures expected, and in this study, the highest operational temperature resulted in the lowest observed safety factor.
- When applying this to a structural application in a ground vehicle, it suggests that in order to accurately design around the most conservative safety factor, for this material (and other similar composites experiencing the same temperature-dependent effects), the material properties at the highest operational temperature should be used in the FE model.

Thank you

Q&A

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