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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

1st Industry Day
Fatigue Characterization

Fatigue Characterization of FRP composites: Classical vs Thermography approach

3 -5 May 2023, Gran Canaria

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Organization: University of Limerick (ULIM)

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Introduction

- Offshore renewable energy has a great potential to help us reduce CO_2 emissions & reach set climate goals.
- The demand for their construction and hence the materials required for the construction will rise exponentially.
- With the replacement of structural steel members, demand of composite material systems will rise too.
- With a long list of material systems and new resin and reinforcement materials releasing in the market, material selection becomes a daunting task.

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Material Selection

- Audit of commercially available FRP material systems.
- Audited material systems classified based on environmental credentials.
- Final selection of material systems based on:

Basalt – Arkema Elium 150 Thermoplastic Bidirectional (0/90) 450gsm fiber, Commercial thermoplastic Vacuum infusion and room temperature cure	45.9	-	440 ±27	17.55 ±1.2	3	-	-	-	Yaghoobi H *et al.* [57]
Recycled Carbon Fiber / Bio-Based Epoxy-Amine Thermosets Recycled CF - Resorcinol di-glycidyl ether / Diamine-allyl-eugenol	-	-	134±20	15.9±1.0	-	-	-	-	Mattar *et al.* [27]
Recycled Carbon Fiber / Bio-Based Epoxy-Amine Thermosets Recycled CF - Diglycidyl etherof bisphenol A / Hexamethylenediamine	-	-	126±14	12.8±2.7	-	-	-	-	Mattar *et al.* [27]
Flax – Epoxy FlaxPLY UD 180 (pre-treated with 16% epoxy) - Epoxy resin (R-180 +H180) Vacuum infusion, 24h room temperature cure and 8h post cure at 60°C (Flax fabric conditioned at 70% Relative humidity)	-	-	276 (288)	24 (21)	-	-	-	-	Moudood A *et al.* [14]
Sisal + Glass - Epoxy Bidirectional fiber, Room temperature cure, Hand layup (With 3% Silicon carbide additive)	-	-	158.16 (156.88)	2.74 (3.62)	5.8 (4.3)	-	-	-	Arpitha *et al.* [30]
Bamboo + Flax - Epoxy Crushed bamboo + flax- Alcali treated, hand layup, Room temperature cure 7h +85 °C Cure 5h. (Aged in room temperature water 60 days)	-	-	22.13 (23.5)	3.61 (3.89)	-	-	-	-	Salim S *et al.*[13]
Recycled Carbon fiber - Aeropoxy PR2032 Recycled carbon fiber - Epoxy-based sizing – Non-aligned fibres Resin transfer moulding - room temperature for 18 h (Recycled aligned fibres 0° with epoxy-based sizing)	20 (24)	-	93 ±9.5 (266 ±28)	11 ±0.7 (33.7 ±2)	-	-	-	-	Werken *et al.* [26]
Basalt - Epoxy Bidirectional 0/90 basalt fiber 450 gsm, Marine grade Epoxy 105 R 206. Vacuum infusion at room temperature.	46	-	355	18.57	2.1	-	-	-	Yaghoobi *et al.* [57]
Glass fiber – Epolam 2040 Epoxy NCF [0] 565gsm – Chromarat sizing for epoxies Vacuum infusion	46	7	860	40	2.45	64	14	1.7	Lorroet *et al.* [58]
Glass fiber – Vinyl EsterLEO M -8500 resin system NCF [0] 940gsm – E-glass PPG Hybon 2002 Sizing – proprietary Vacuum infusion	56	-	723	35	3.6	56.6	12	1.1	Fibreship[59]
Carbon fiber – Vinyl ester NCF [0/90] –Multicompatible sizing Atlac® E-Nova	59	2.2	1111.3 (999.6)	57.3 (57.5)	-	-	-	-	Bel Haj Frej[60]

- Suitable for production of large parts by out-of-autoclave process
- Retain material integrity in off-shore environments.
- Low environmental impact & carbon footprint, From production to end of life.
- Provide required mechanical properties!

Fatigue characterization…?

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Material Selection

Matrix	Fibre
Thermoplastic - Elium® (Tensile Strength: 56 MPa, Modulus: 2.6 GPa)	Glass – Hybon 2026 (NFC)
Thermoset - Infugreen® (Tensile Strength: 65 MPa, Modulus: 2.8 GPa)	

Composite	Lay-up	Reinforcement	Resin	Hardener / Initiator
GF/Thermoset	$[\pm45]_{2S}$	Saertex U-E 1182 g/m^2	SR Infugreen 810	SD8824
GF/Thermoplastic	$[\pm45]_{2S}$	Saertex U-E 1182 g/m^2	Elium 188X O	BP-50-FT

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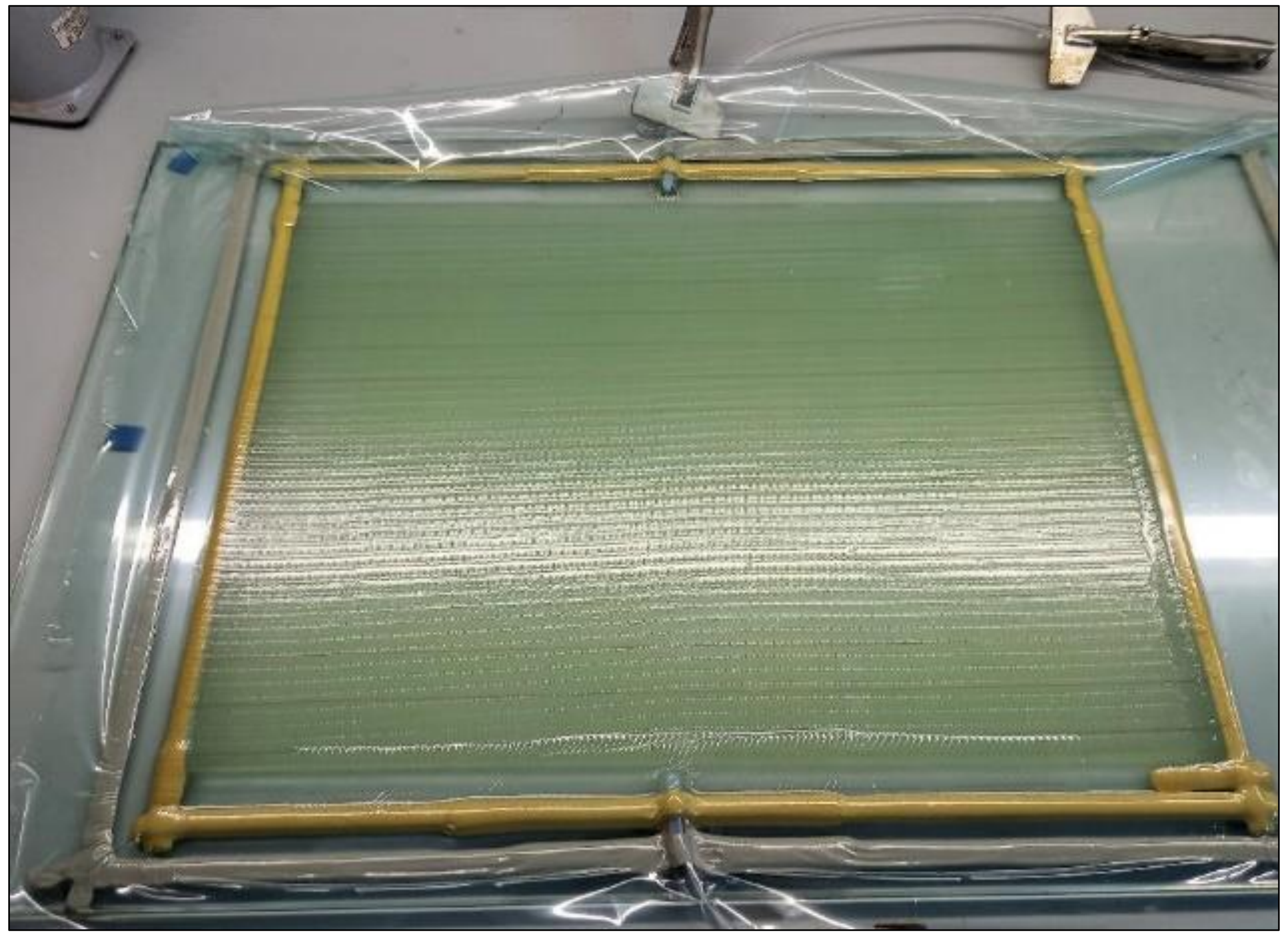
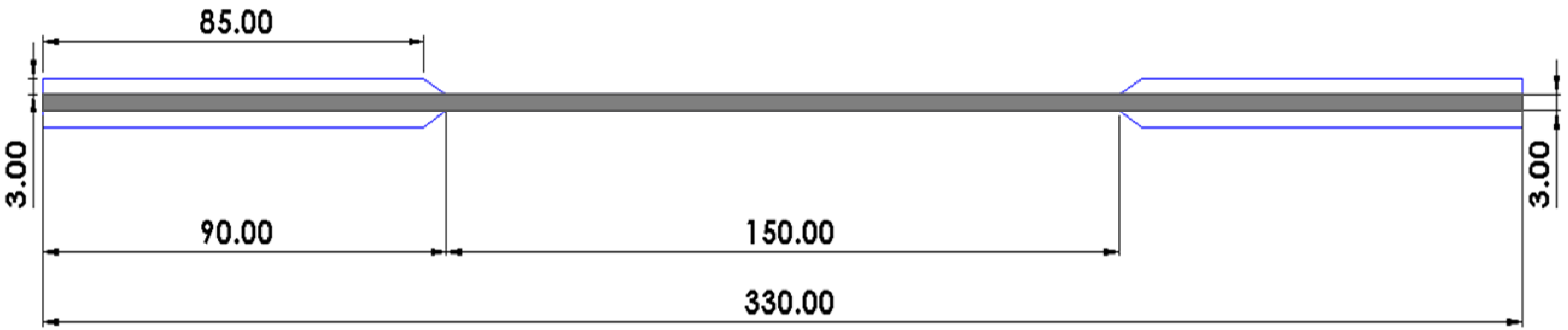
Materials & Methods

- Laminate manufactured by vacuum infusion method.
- Room temperature cure for 24 hours, GF/Thermoset Post cured at 60˚C for 16 hours & GF/Thermoplastic for 24 hours.
- Laminate quality validated using DMTA & burn-off test for volume fraction.
- 2 material systems tested in 5 layup configurations



Material System	Laminate Configuration				
Glass - Thermoset	[0˚]	[90˚]	[±45˚]	[±30˚]	Quasi Isotropic
Glass -Thermoplastic					

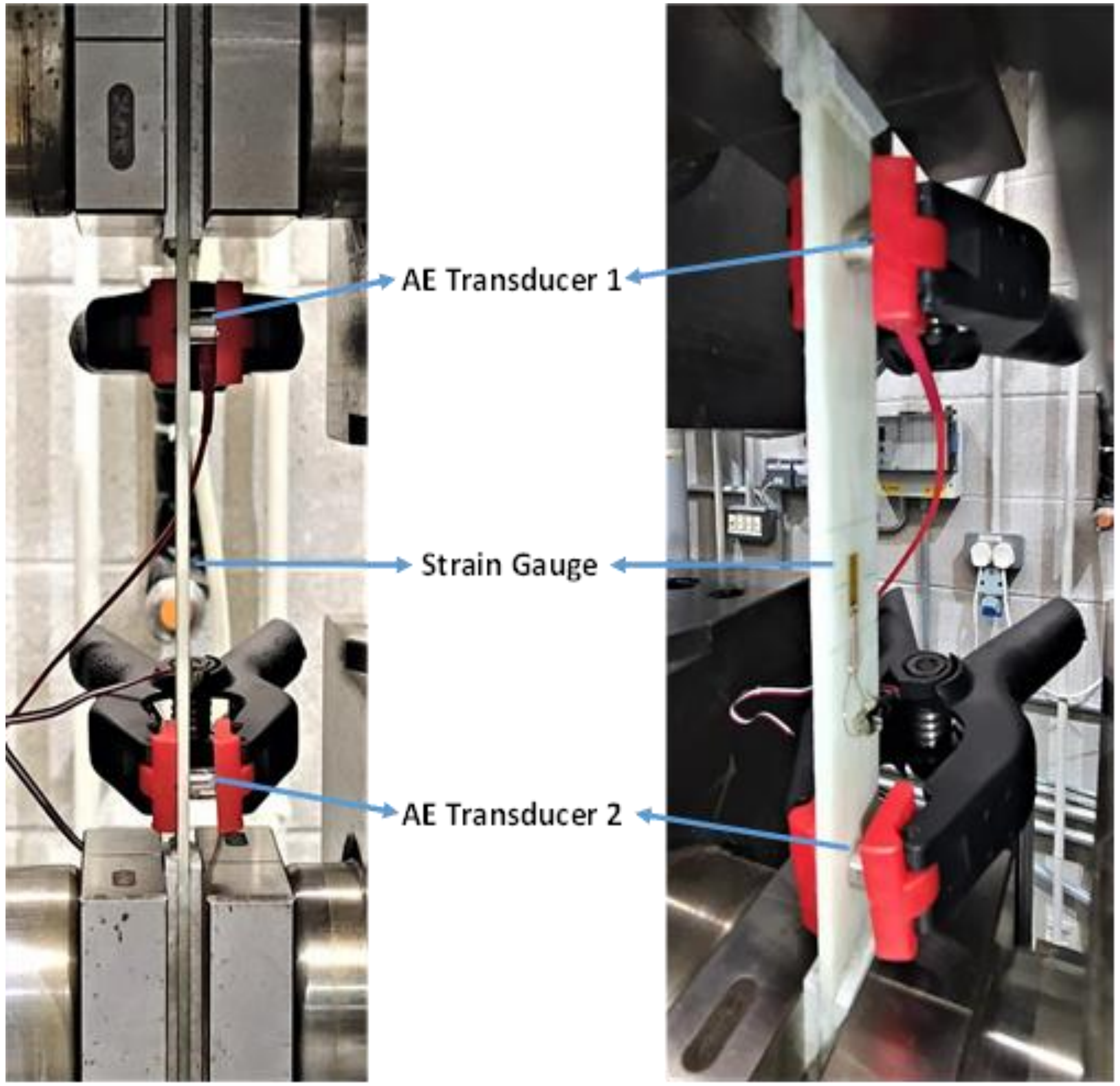
Materials & Methods



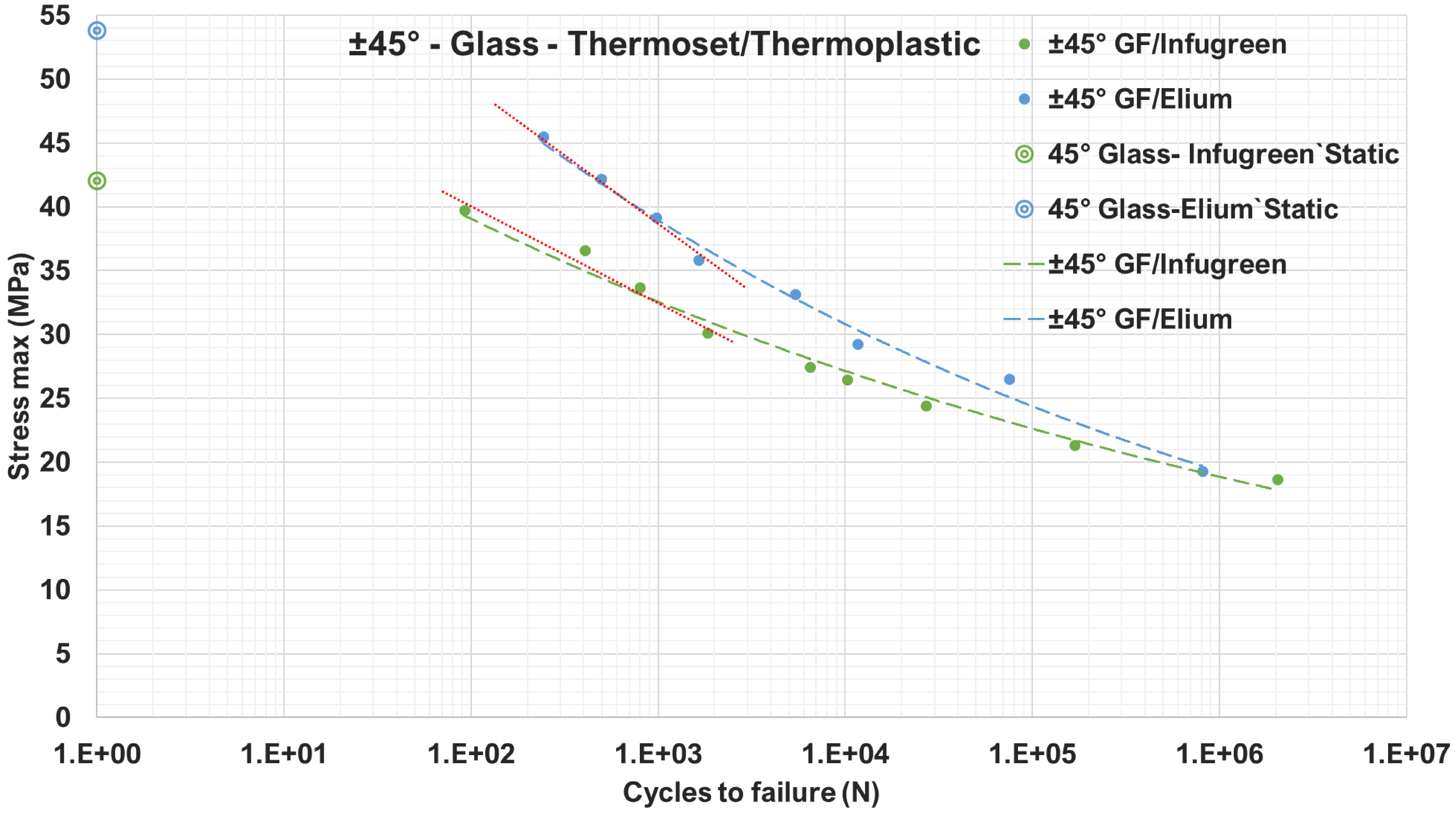
- Test specimen size standards: ISO 527 – 4
- Extraction of specimens from laminates by abrasive water jet cutting.
- Tabbing using bond line control adhesive (3M DP8005) or Cyanoacrylate glue.

Materials & Methods

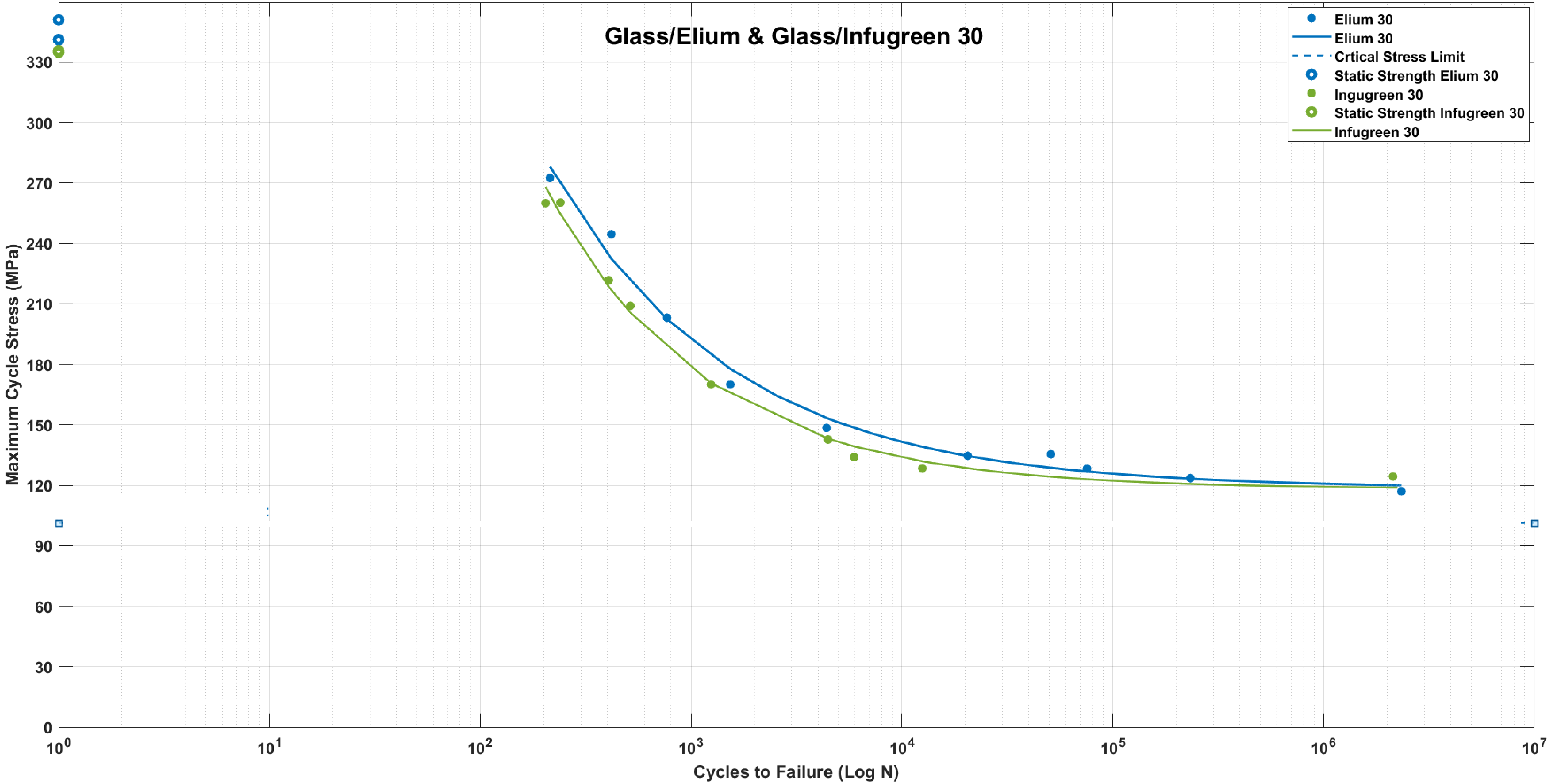
- Fatigue testing as per ISO 13003:2003 standard.
- Instrumentation:
  - Extensometer
  - Acoustic Emission transducer
  - IR Thermal Camera
  - Tested on Zwick-Roell Servo-Hydraulic test frame with 100 kN load cell.
- SN Curve obtained by classic approach of constant amplitude (Load) tests.



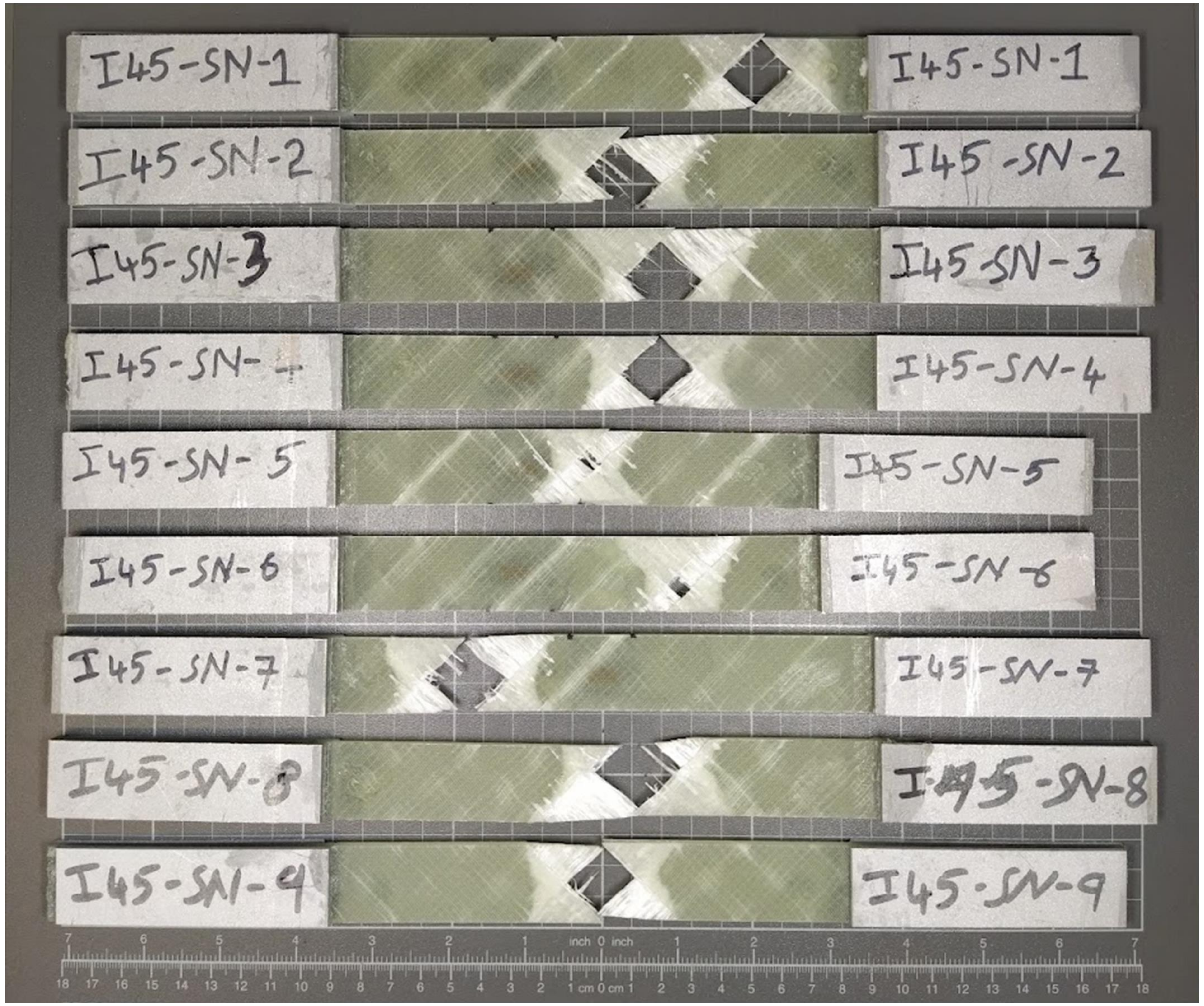
Results: Classic Fatigue Characterization – SN Curve

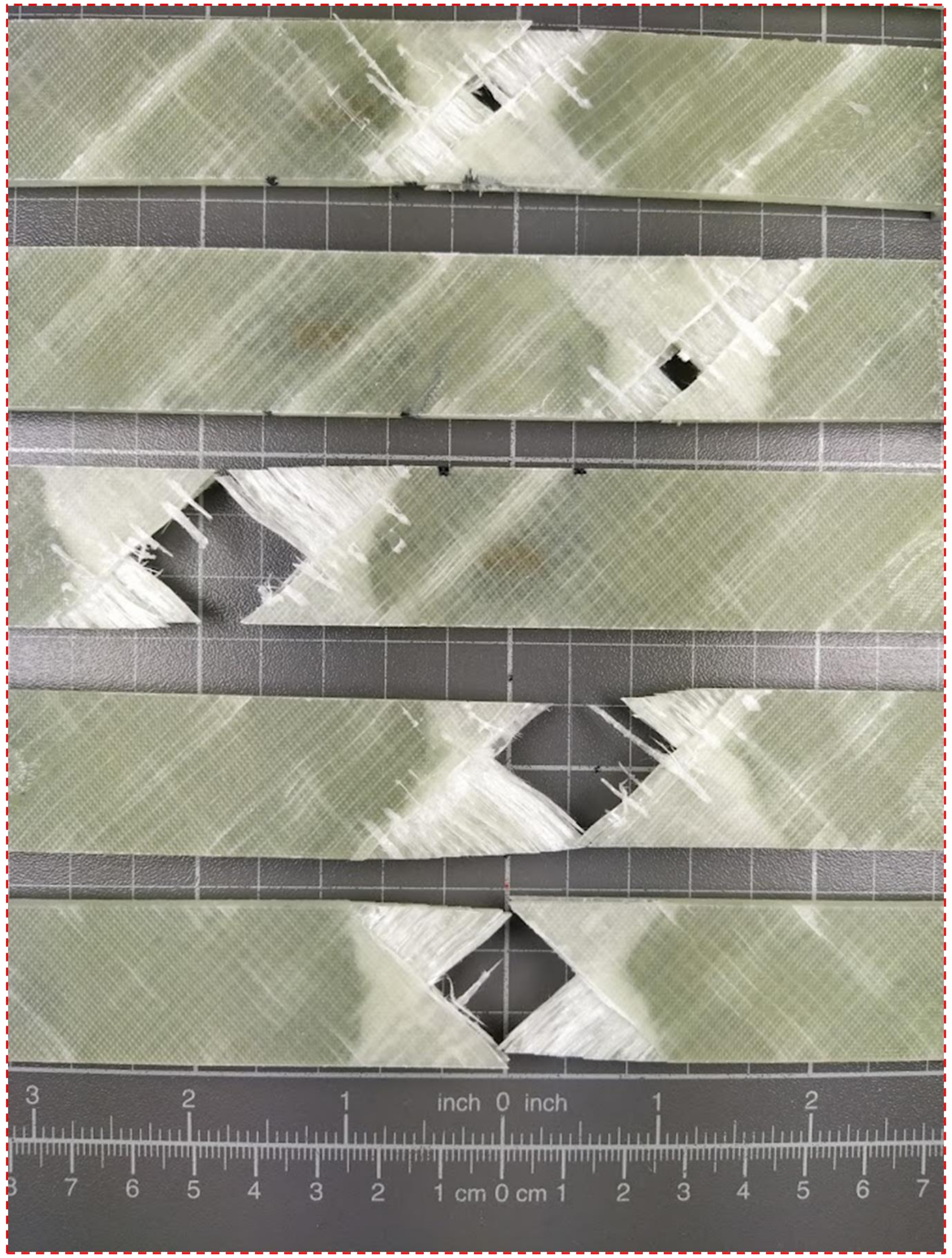


Results: Classic Fatigue Characterization – SN Curve



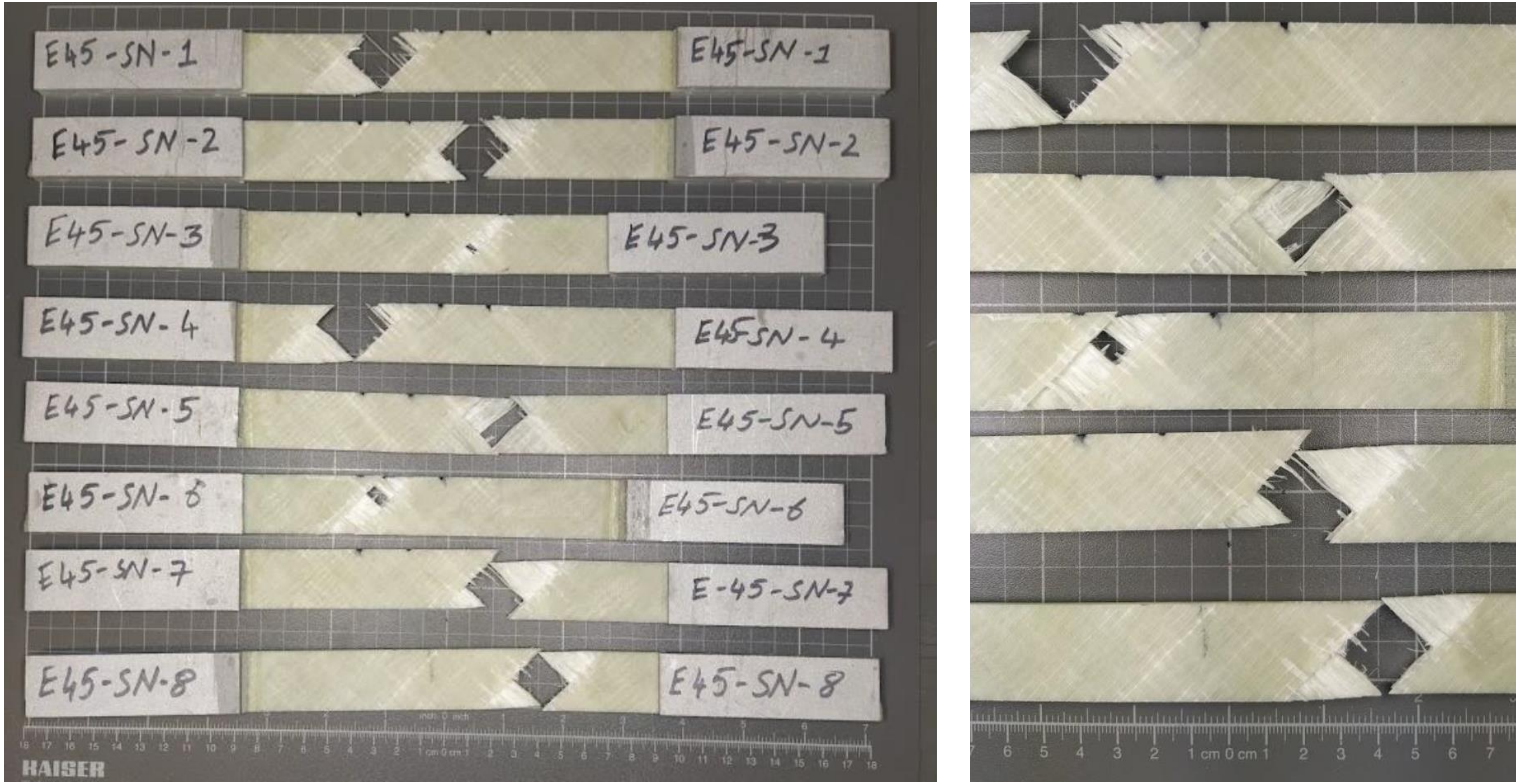
Results: Classic Fatigue Characterization – Fractography





Failed coupons: [±45°] Glass/Thermoset

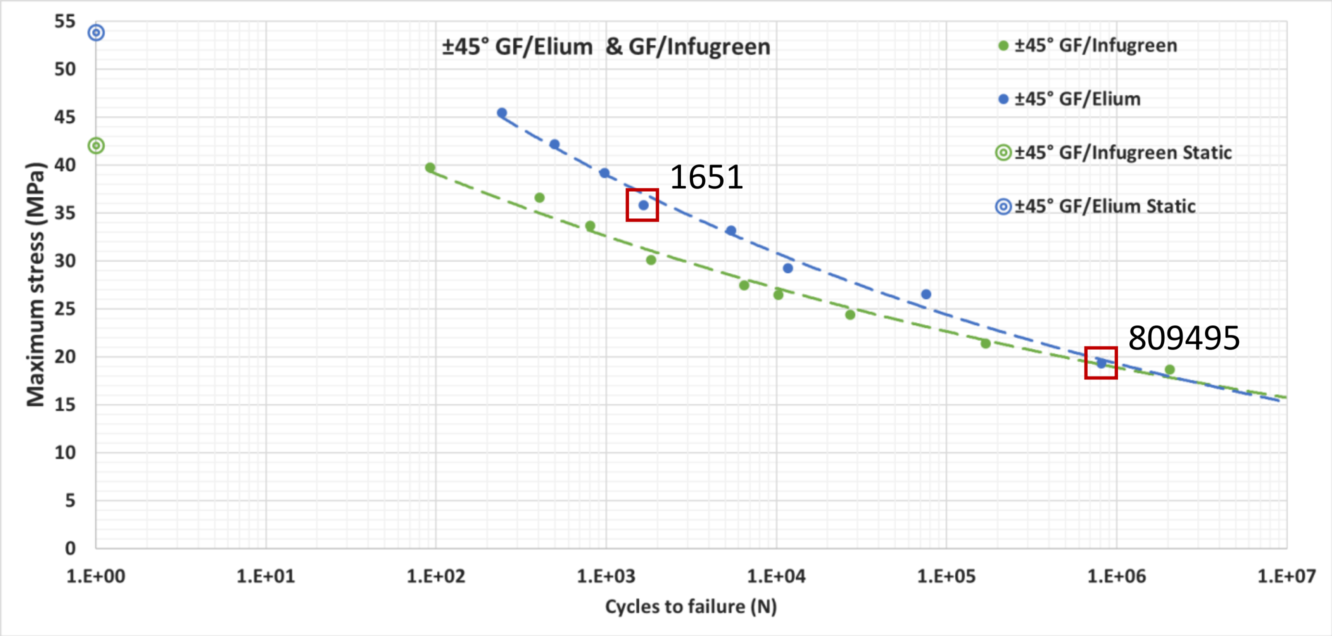
Results: Classic Fatigue Characterization – Fractography



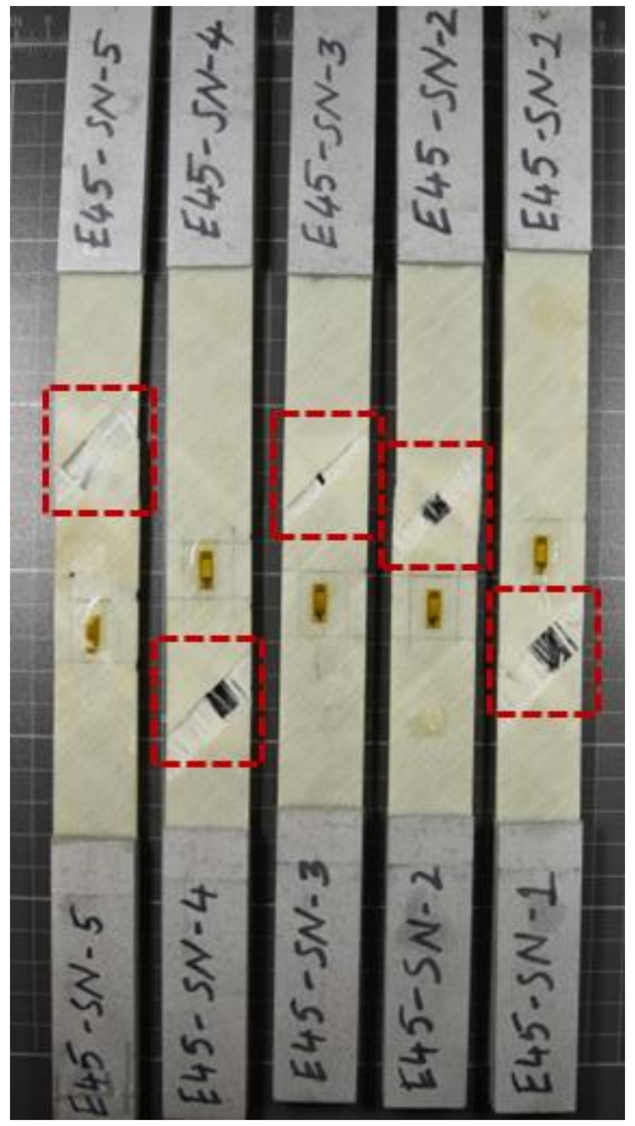
Failed coupons: [±45°] Glass/Thermoplastic

Results: Classic Fatigue Characterization – Fractography

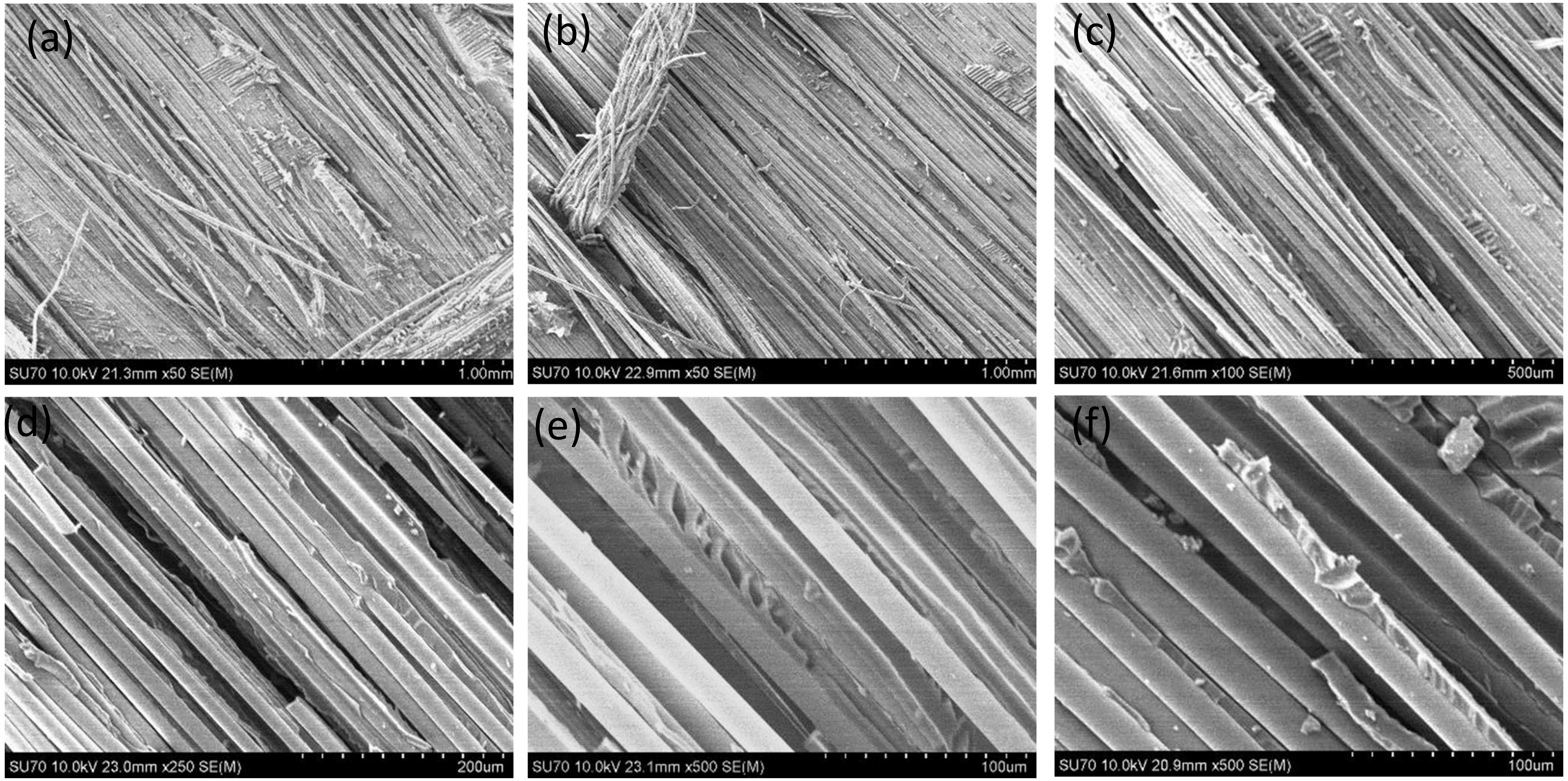
- **GF/Elium**



S-N curves of composites tested.



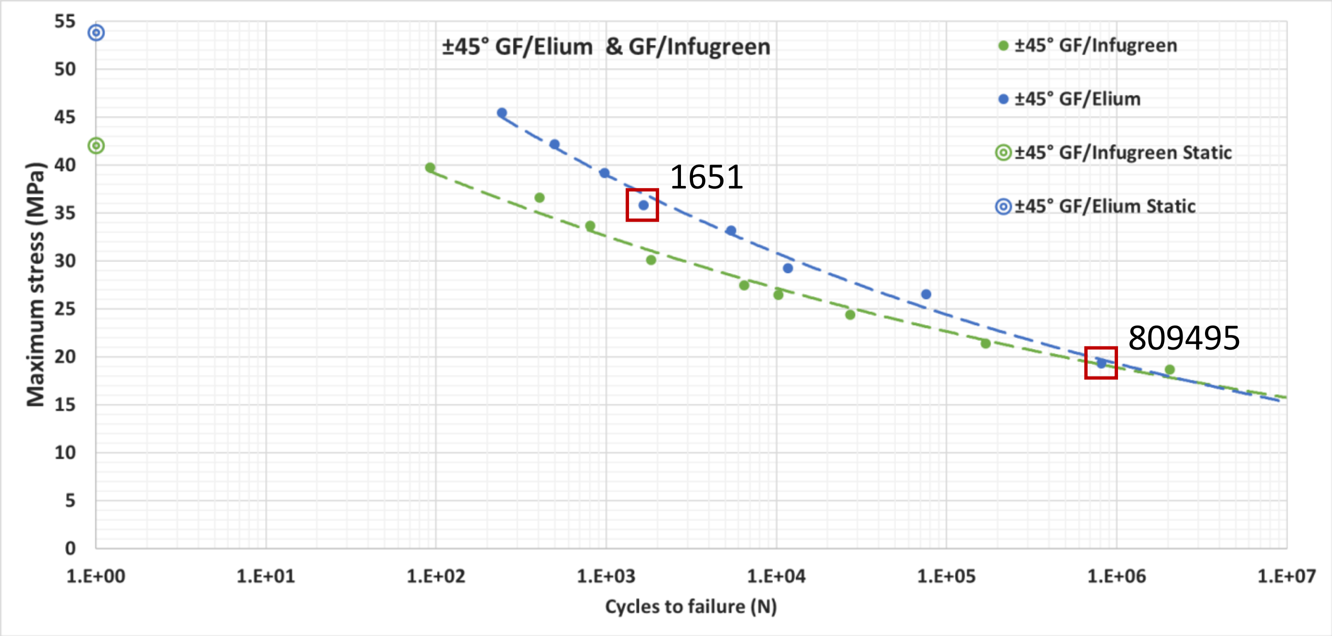
Location of final failure indicated on the specimens.



Low-cycle fatigue tested GF/Elium 45° specimen

Results: Classic Fatigue Characterization – Fractography

- **GF/Elium**



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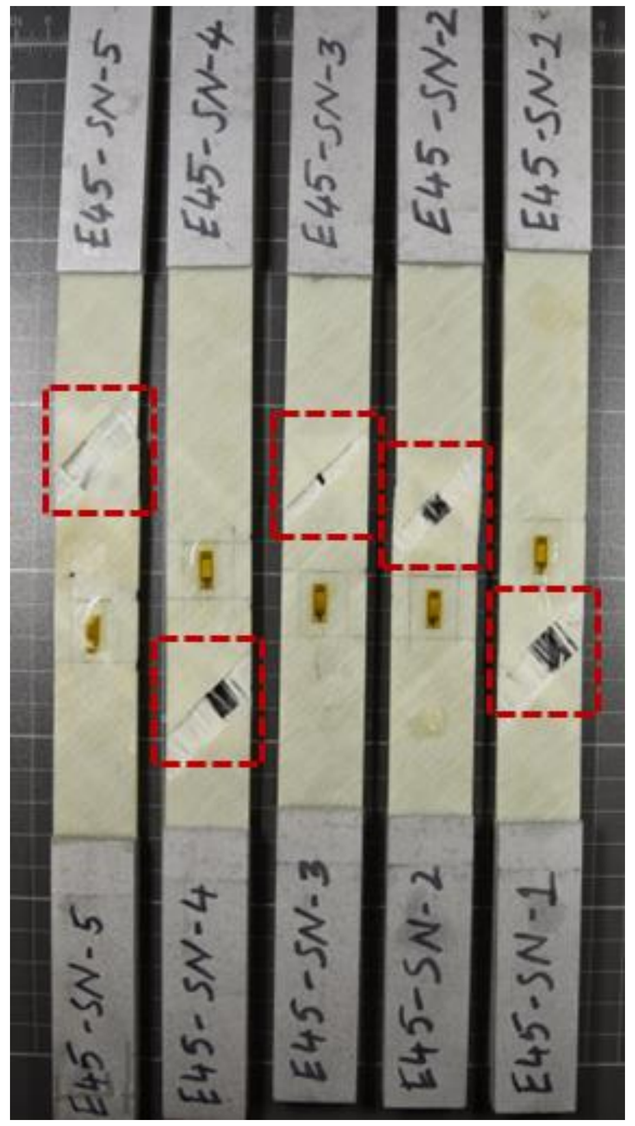
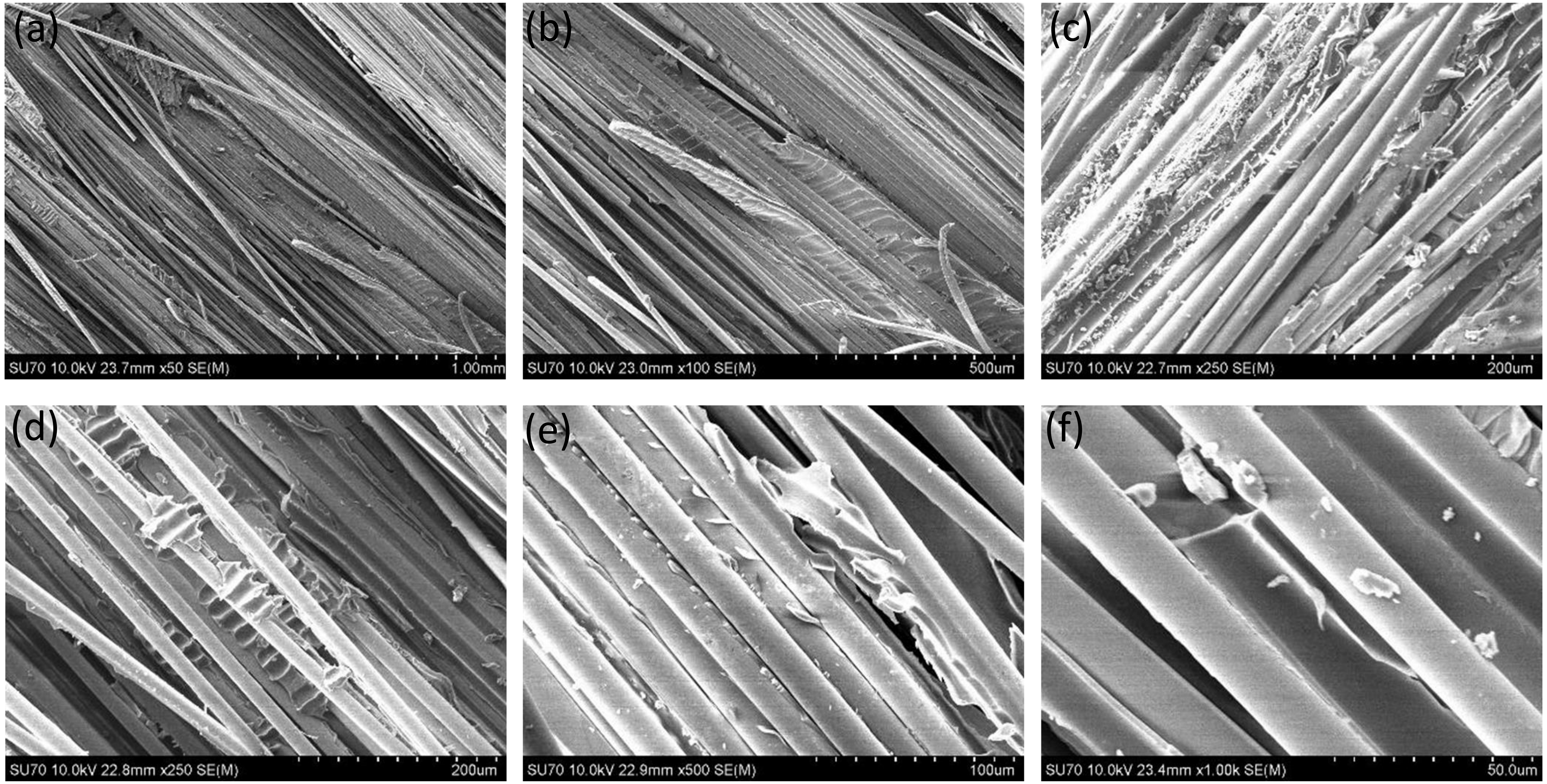


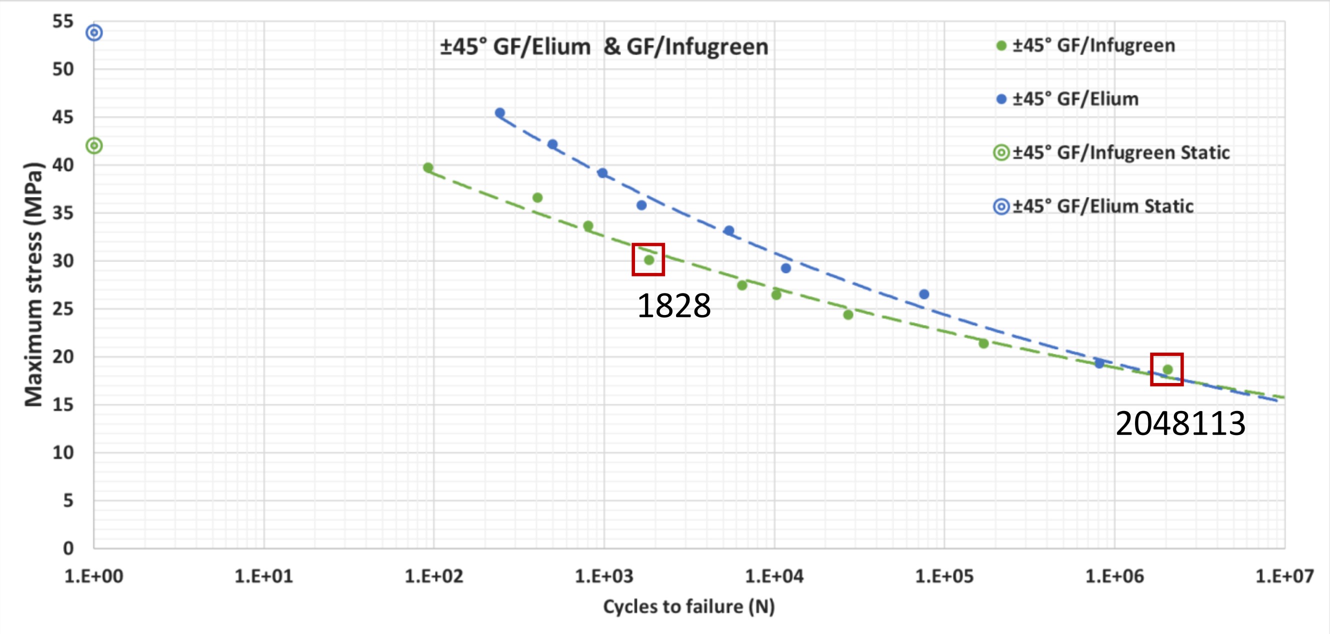
Location of final failure indicated on the specimens.



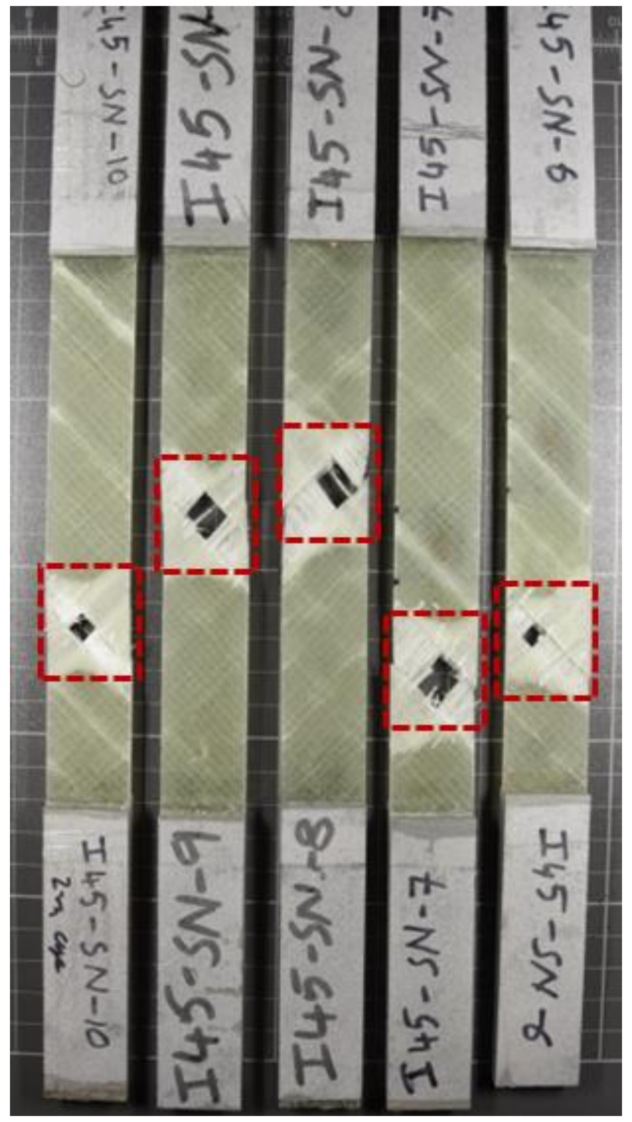
High-cycle fatigue tested GF/Elium 45° specimen

Results: Classic Fatigue Characterization – Fractography

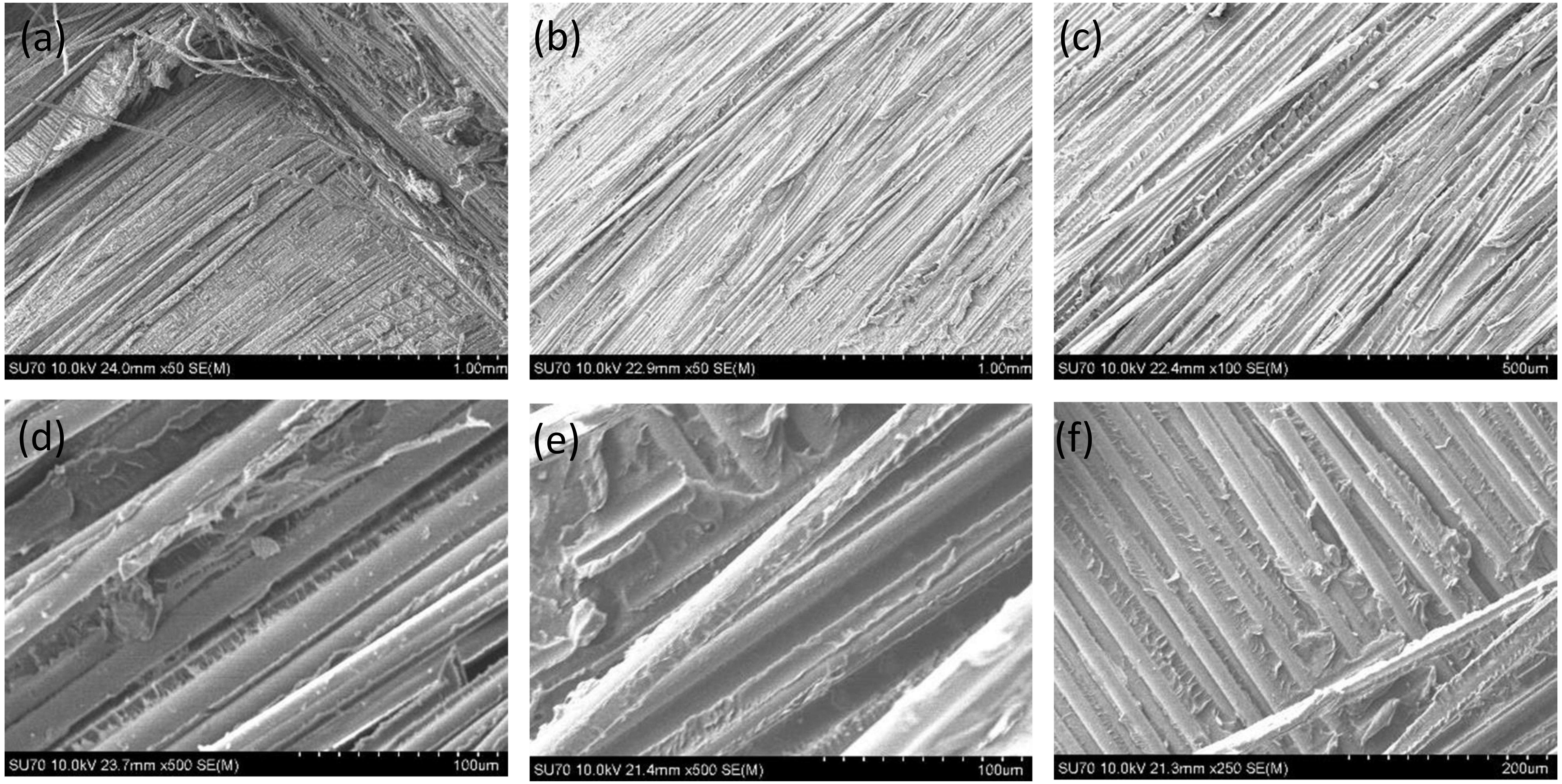
- **GF/Infugreen**



S-N curves of composites tested.



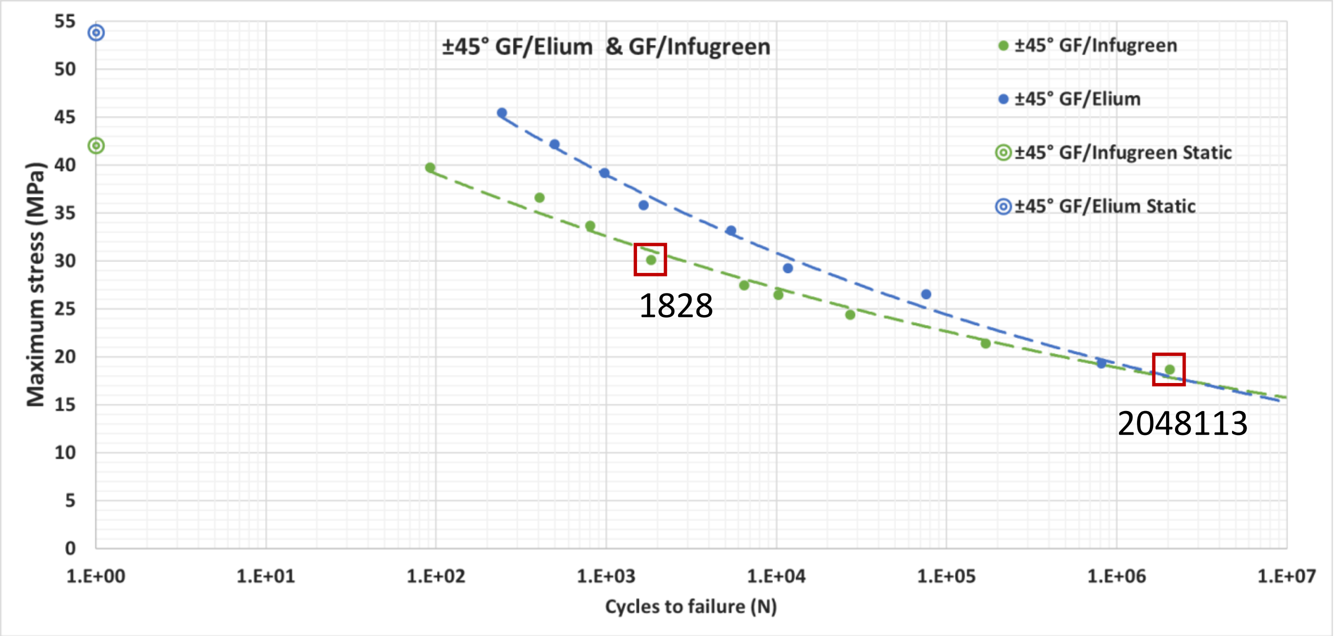
Location of final failure indicated on the specimens.



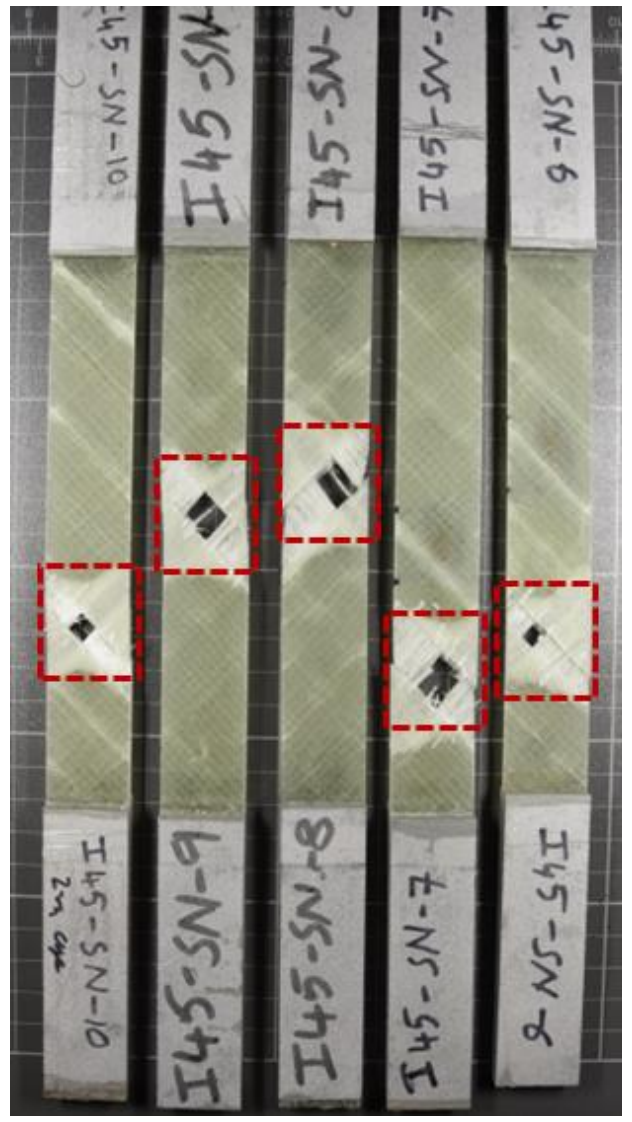
Low-cycle fatigue tested GF/Infugreen 45° specimen

Results: Classic Fatigue Characterization – Fractography

- **GF/Infugreen**



S-N curves of composites tested.



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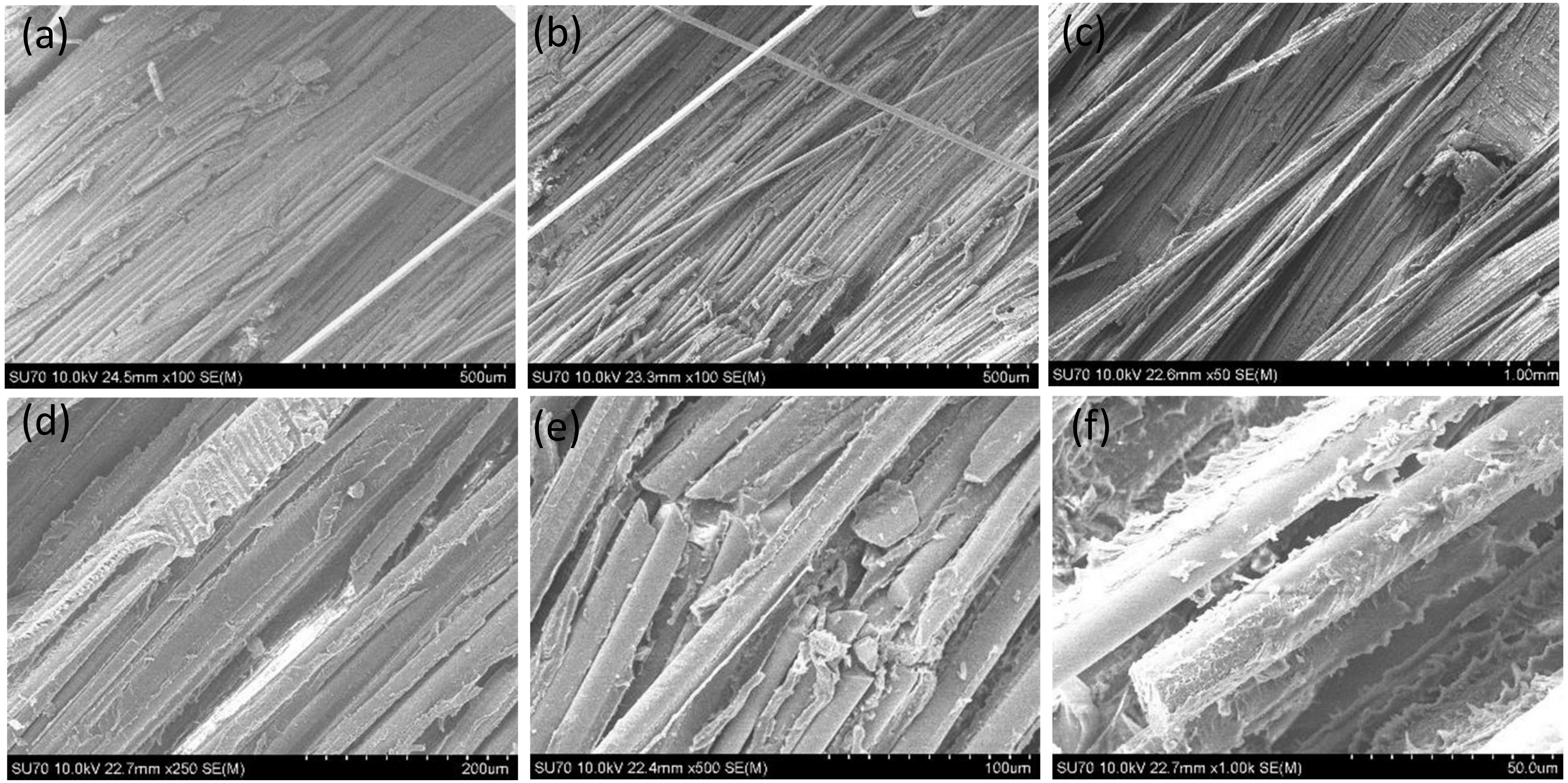
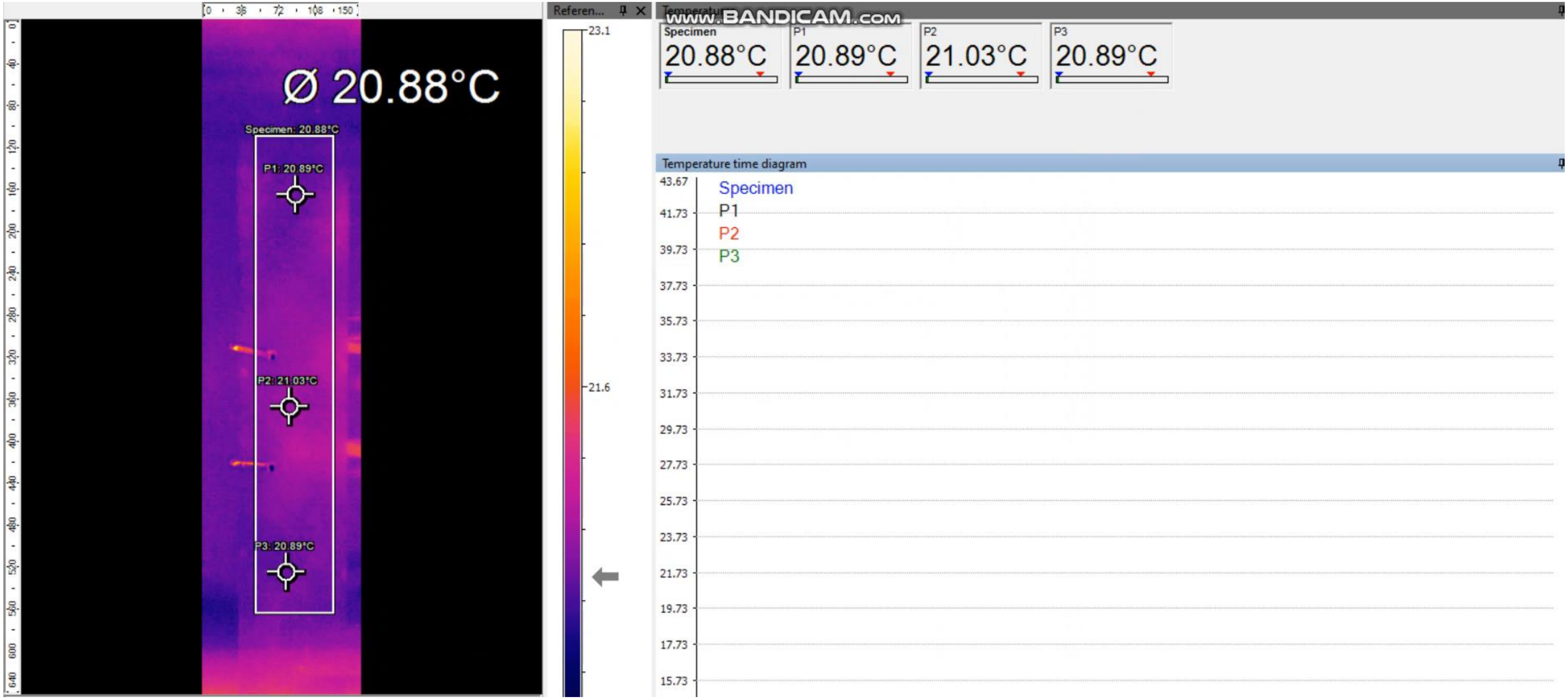


High-cycle fatigue tested GF/Infugreen 45° specimen

Results: Classic Fatigue Characterization – Sufficient..?

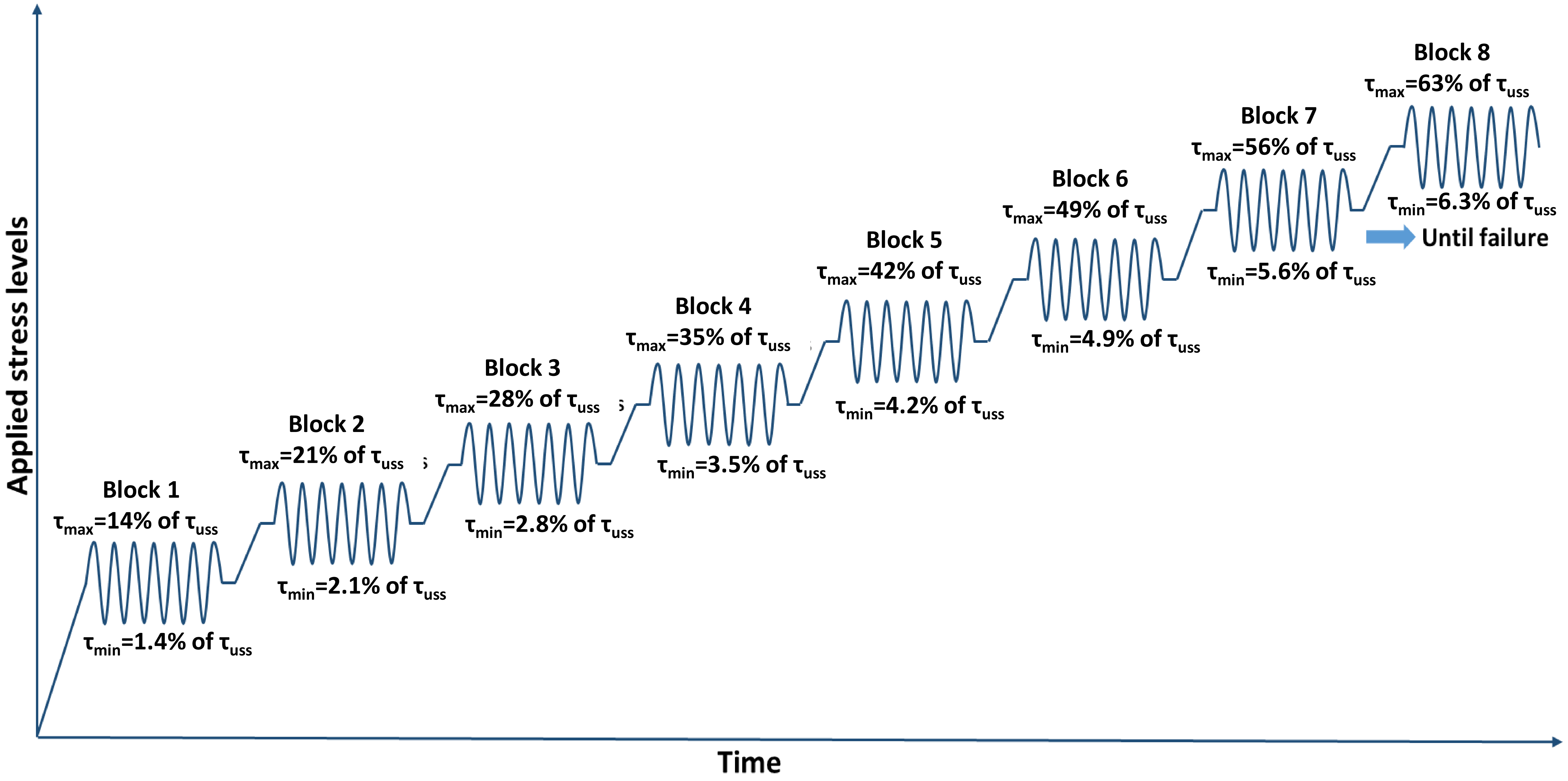
- Off-shore energy structures are supposed to last for 25 years and above.
- Normally, the structures undergo 50 – 100 million loading cycles in their lifetime.
- SN curve lasting up to 1 million cycles lacks crucial high cycle fatigue information.
- Cost and time of testing for long fatigue tests are high in the context of renewable energy sector.

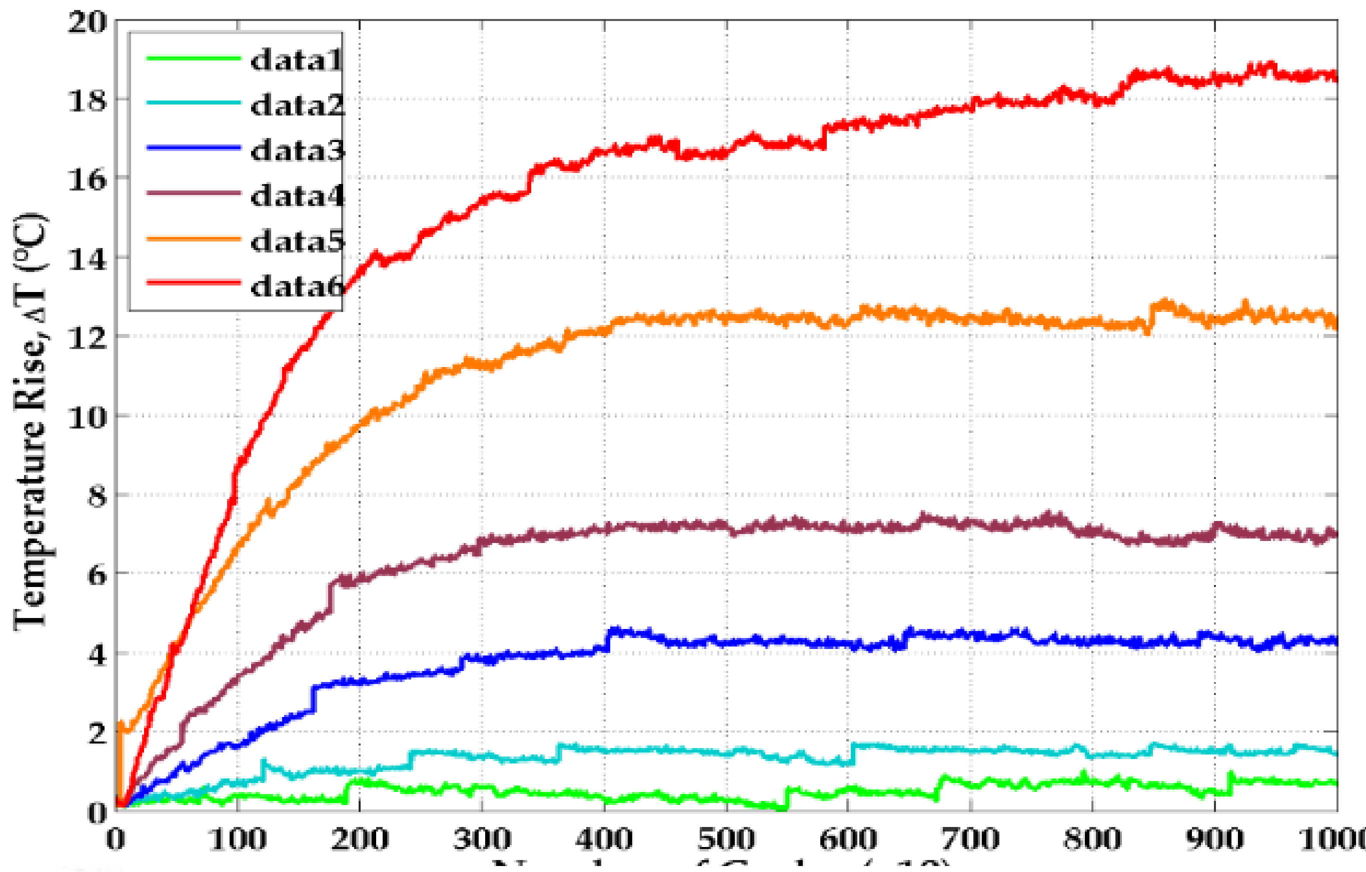
- Alternative: Step-wise tests with thermography.
- Part of energy required to start damage propagation is transformed into heat.
- Any deformation & damage in the specimen is followed by increase in temperature.

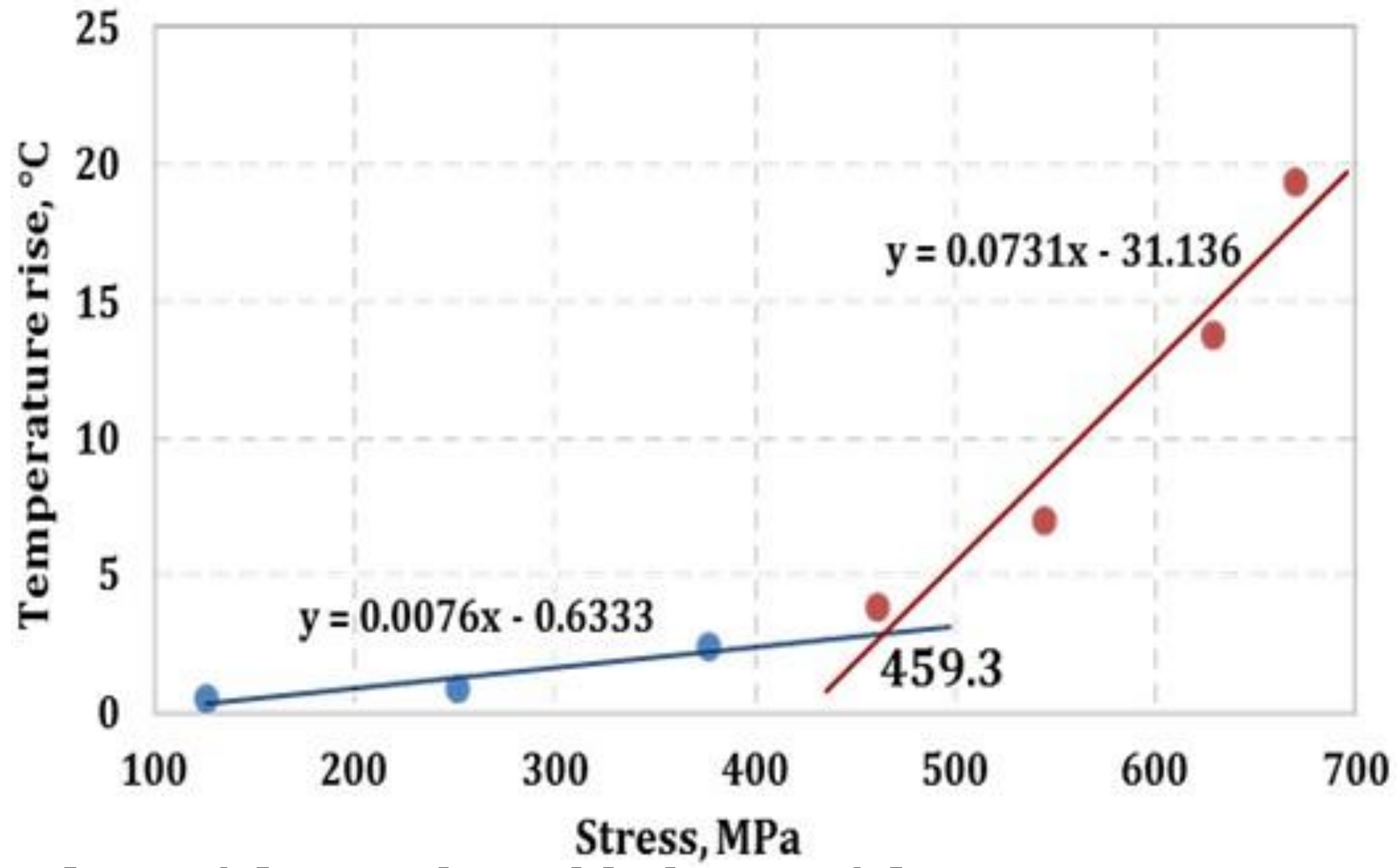


Ø 20.88°C
Specimen: 20.88°C
P1: 20.89°C
P2: 21.03°C
P3: 20.89°C
Referen...
23.1
21.6
www.BANDICAM.com
Specimen
20.88°C
P1
20.89°C
P2
21.03°C
P3
20.89°C
Temperature time diagram
43.67
41.73
39.73
37.73
35.73
33.73
31.73
29.73
27.73
25.73
23.73
21.73
19.73
17.73
15.73
Specimen
P1
P2
P3

Results: Thermography

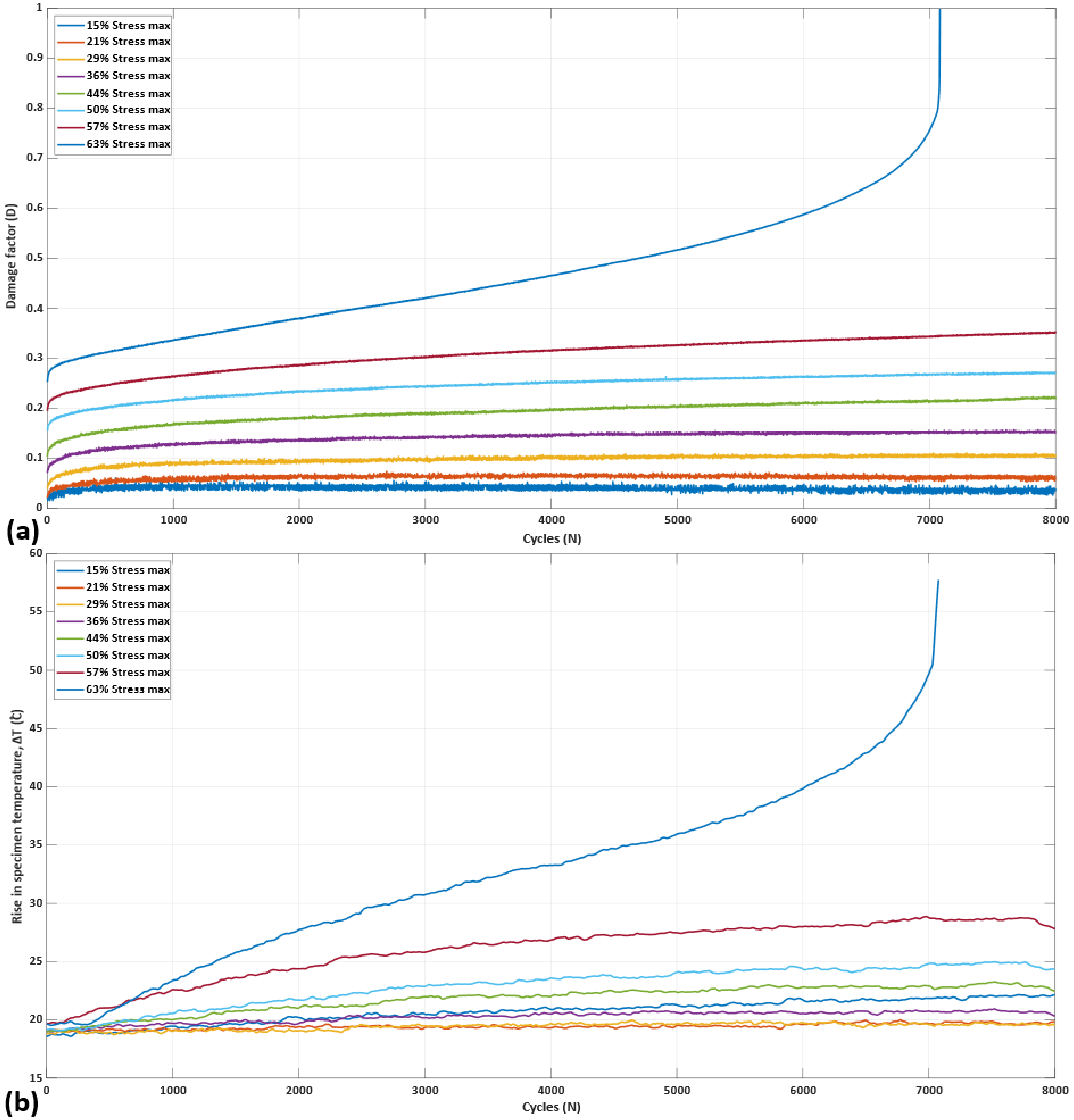




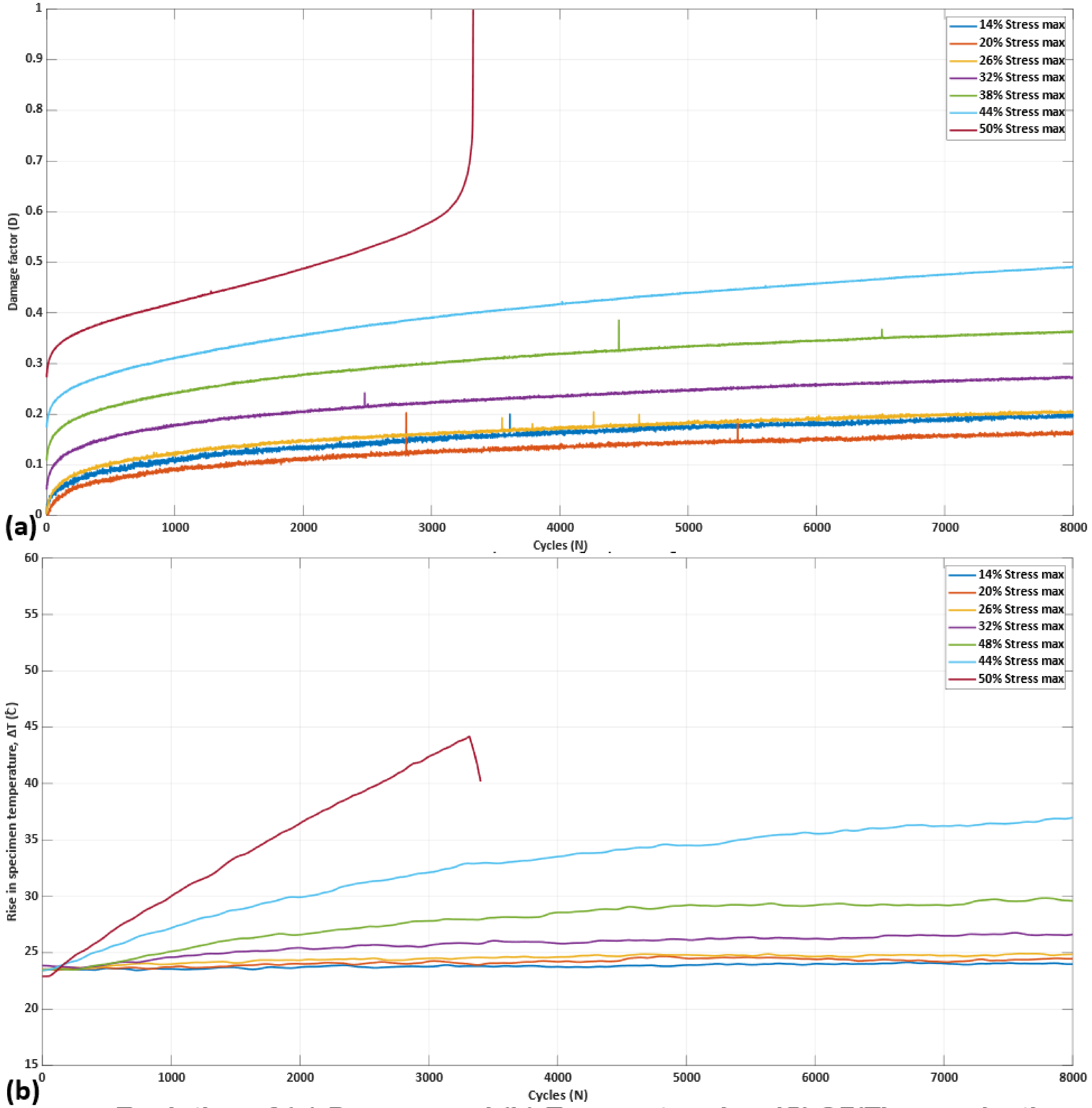


- <u>Critical Stress limit</u> - drastic increase in the rate of intrinsic dissipation/self heating.
- <u>Critical Stress limit</u>, in a <u>macroscopic</u> sense, is a <u>stress value</u> above which damage accumulation accelerates, indicated by a relatively high temperature rise.

Results: Thermography

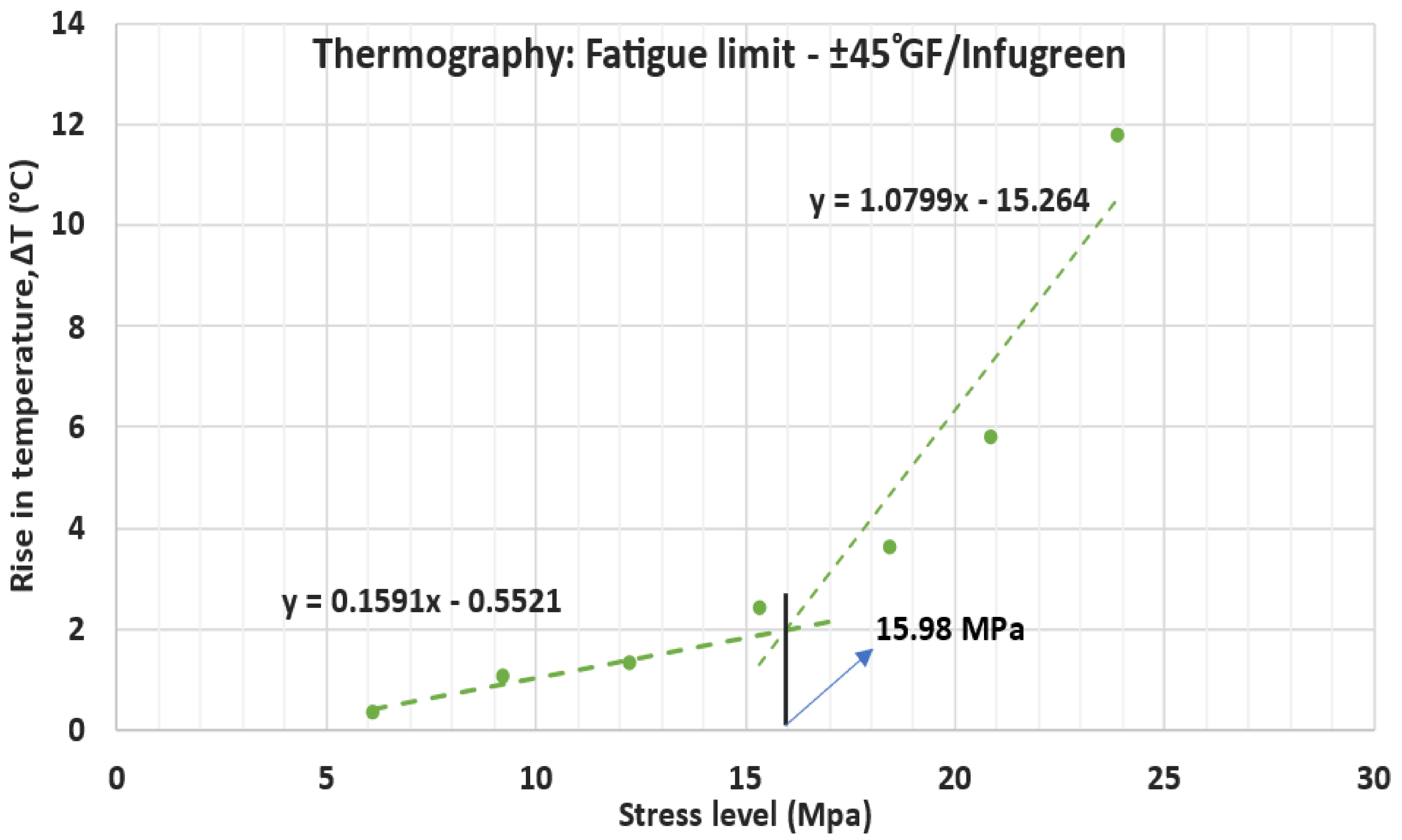


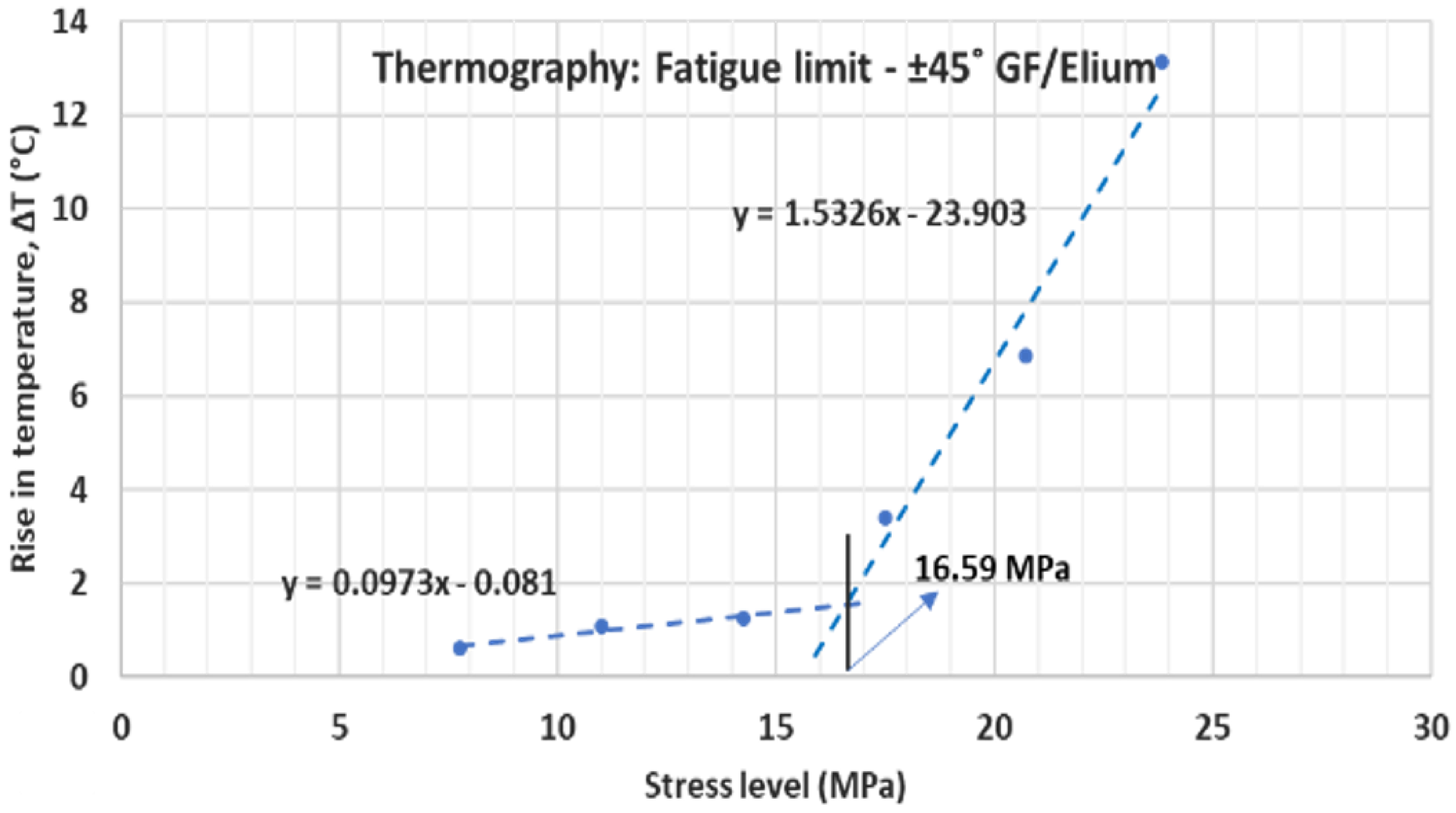
Evolution of (a) Damage and (b) Temperature in ±45˚ GF/Thermoset.



Evolution of (a) Damage and (b) Temperature in ±45˚ GF/Thermoplastic.

Results: Thermography





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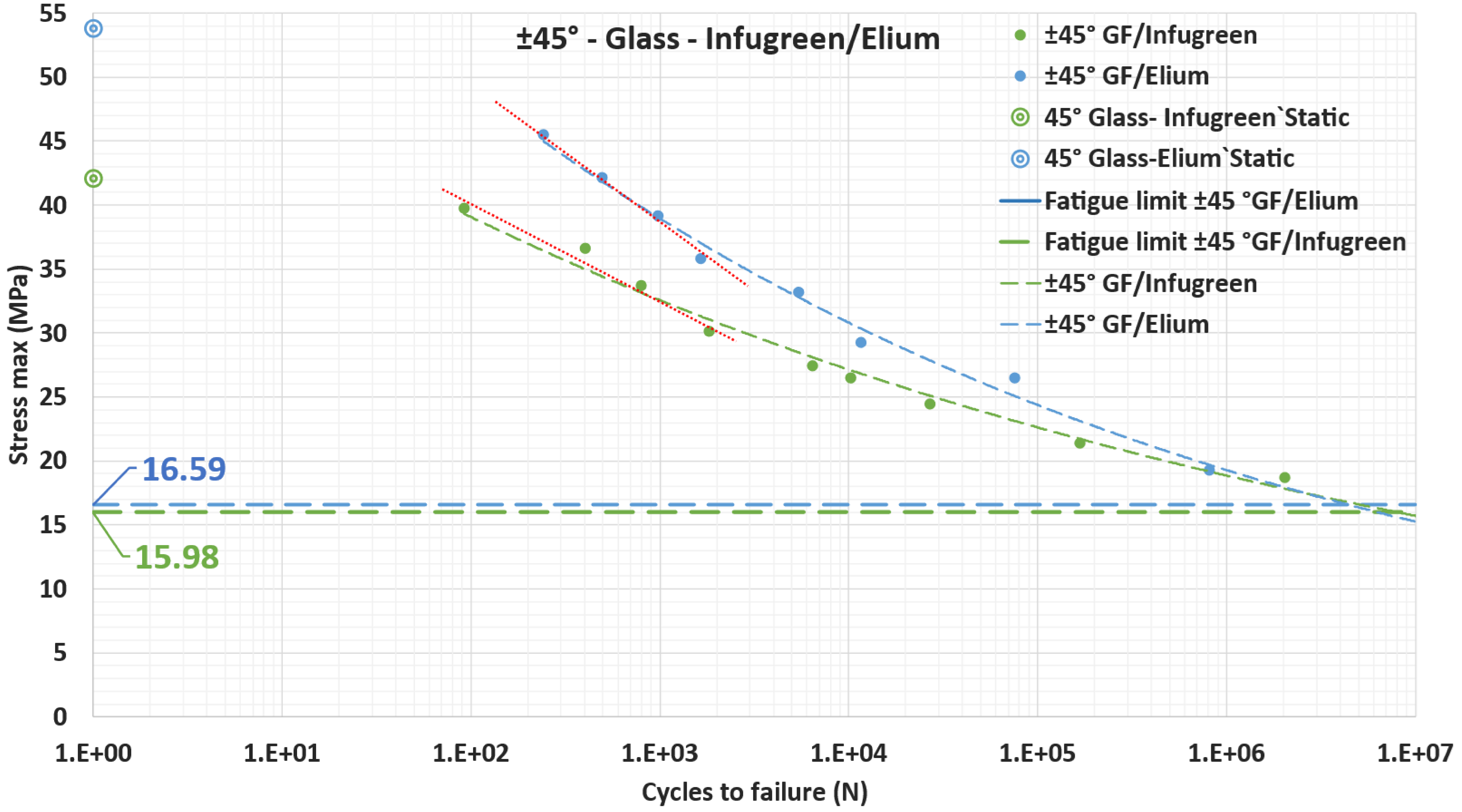
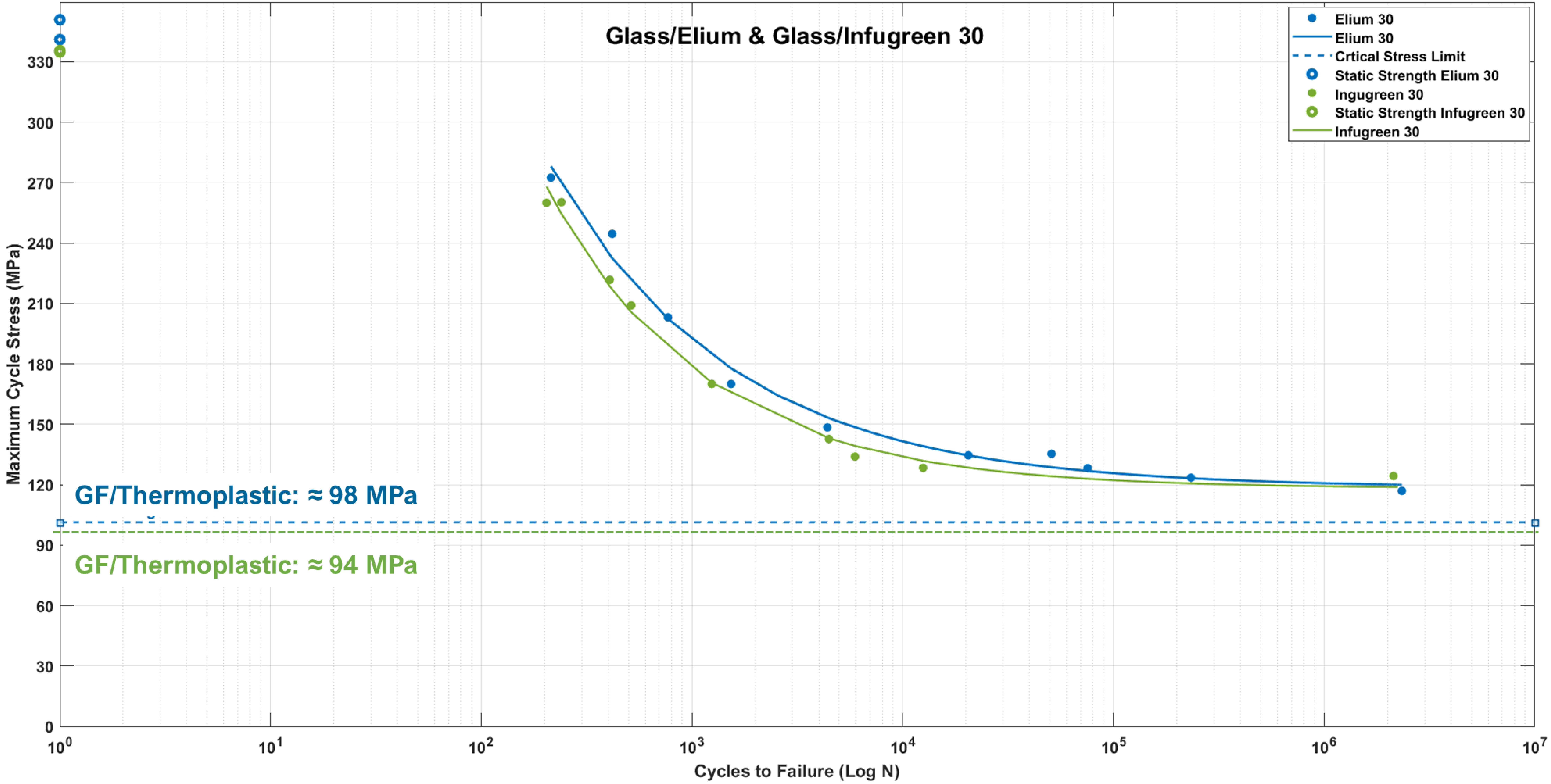
Results: Thermography



Results: Thermography



Conclusions

- The S-N curves for GF/Thermoplastic and GF/Thermoset in $\pm 45^{\circ}$ configuration was obtained, and suitable curve fitting was done with the available data whose trend agrees with findings from the literature.
- The estimation of critical fatigue stress obtained from stepwise tests (Temperature stabilization tests) agreed with stress limit obtained from interpolation of S-N curve.
- The thermography approach was validated for 2 material systems and 5 layup configurations.
- This method of critical stress level estimation can help quick and low-cost screening of composite material systems.
- This approach has few subjective selections which needs further investigation, to standardise the method.
- This approach saves time and cost for the offshore industry, keeping innovation costs low.

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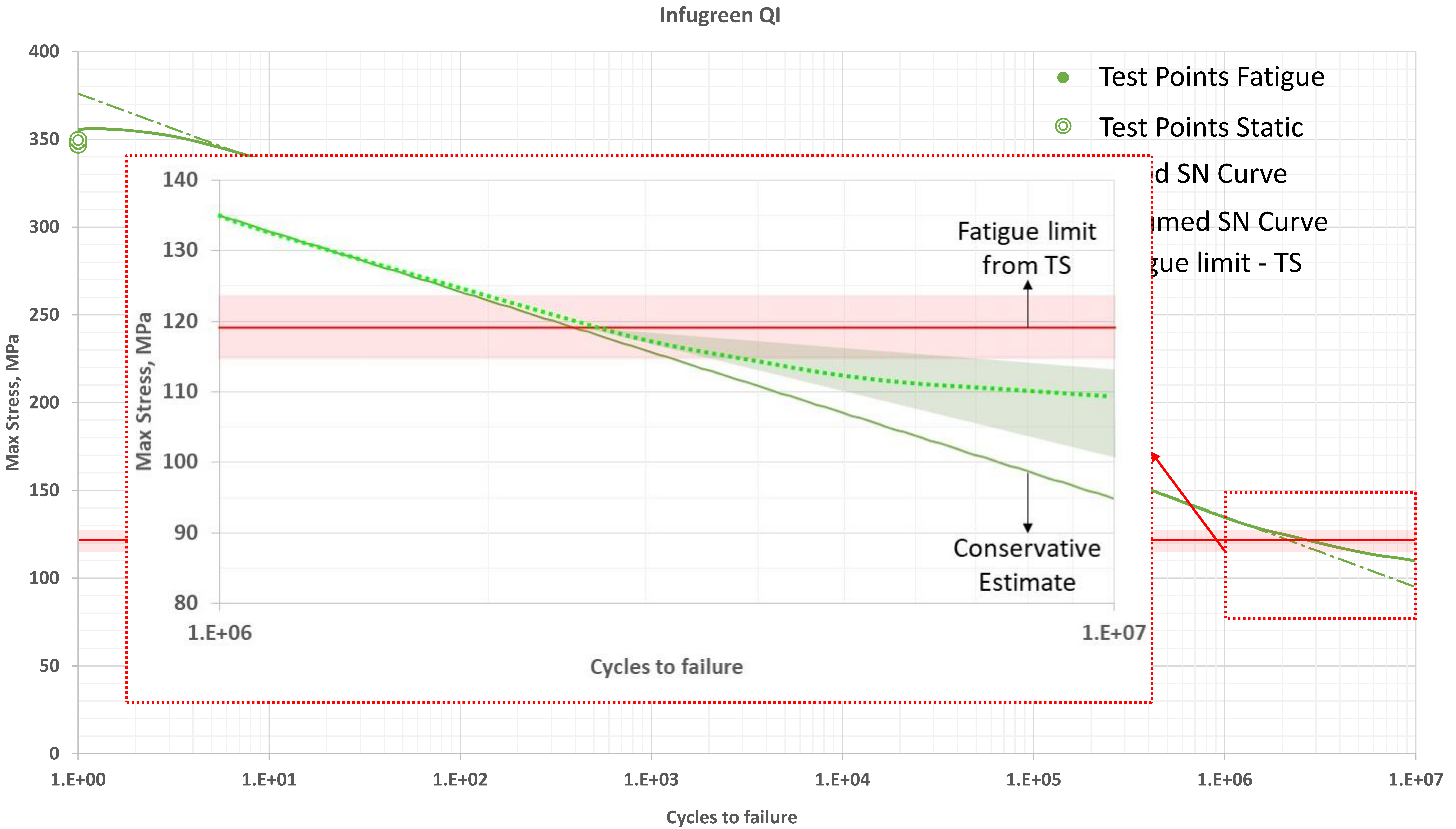
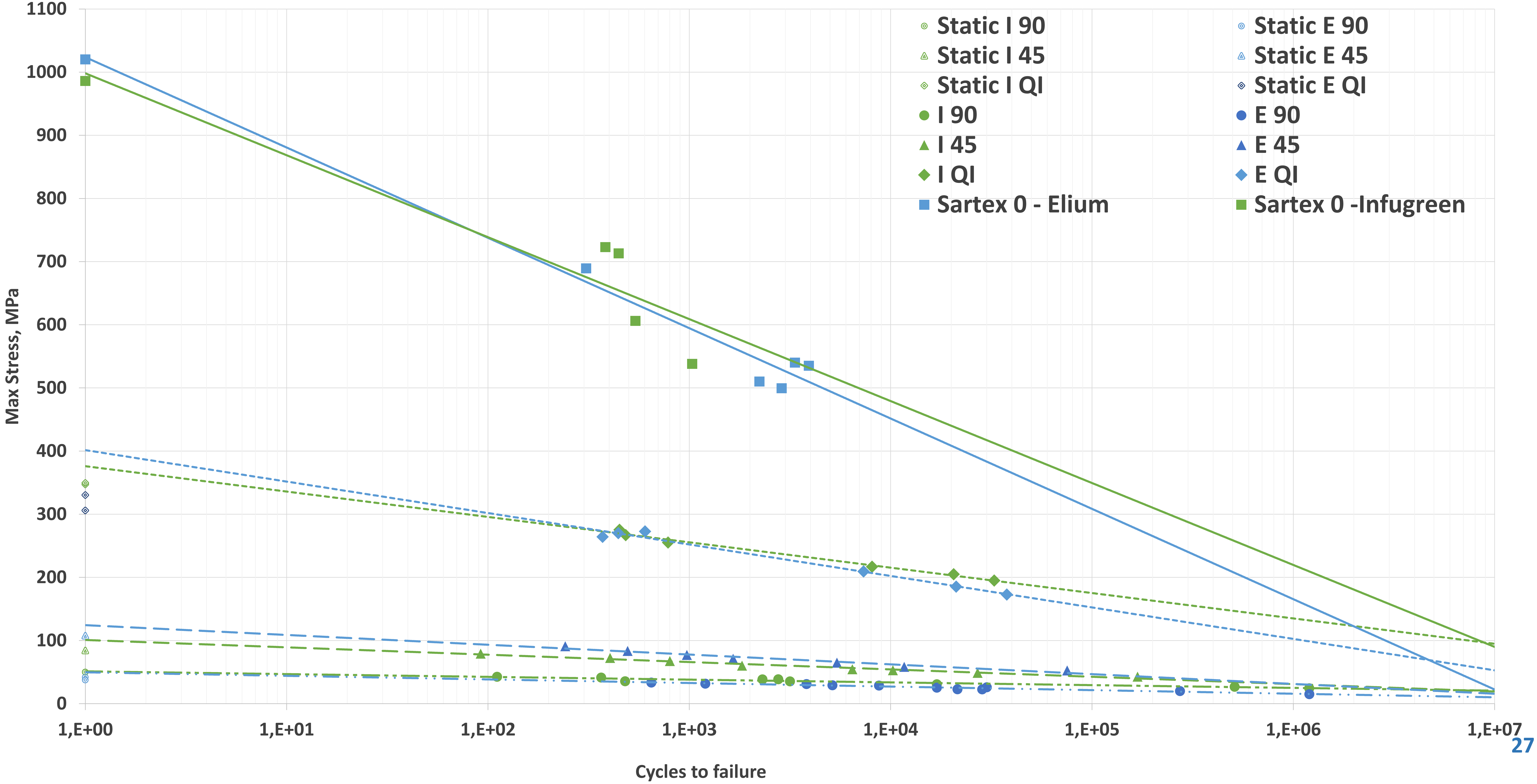
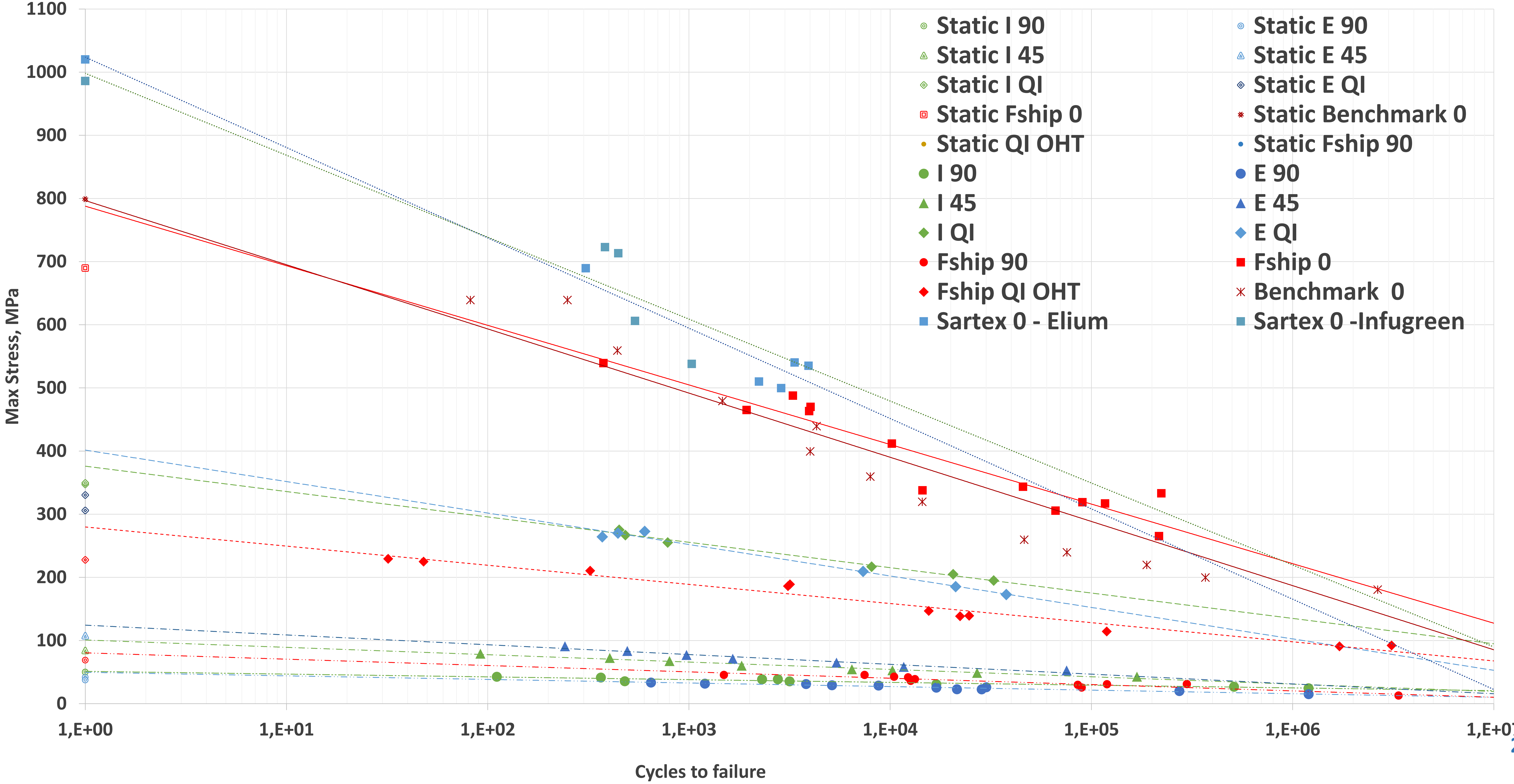
SN Curve Approximation



Fatigue results summary



Fibregy results with Fibreship



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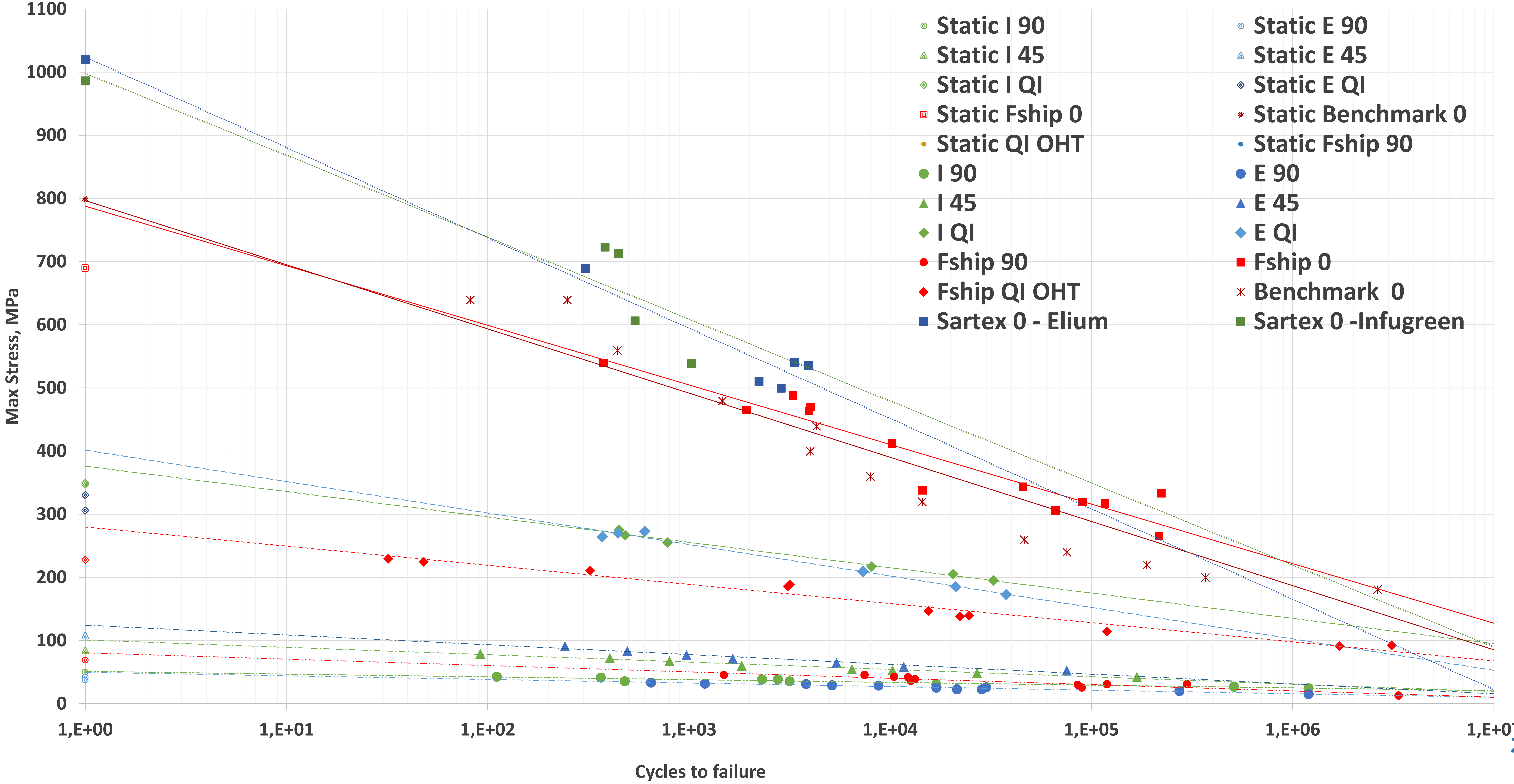
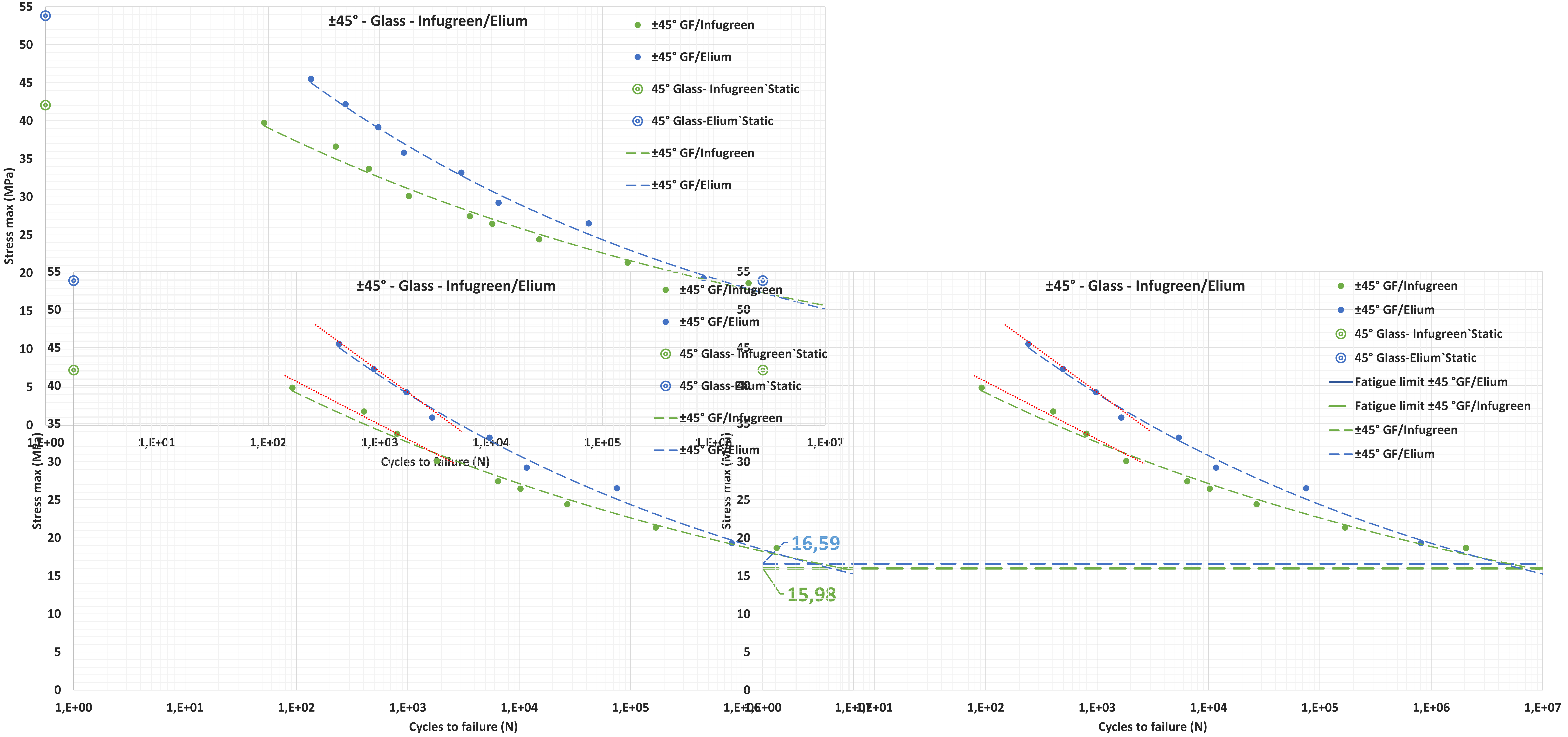


Static I 90
Static E 90
Static I 45
Static E 45
Static I QI
Static E QI
Static Fship 0
Static Benchmark 0
Static QI OHT
Static Fship 90
I 90
E 90
I 45
E 45
I QI
E QI
Fship 90
Fship 0
Fship QI OHT
Benchmark 0
Sartex 0 - Elium
Sartex 0 -Infugreen
Max Stress, MPa
1100
1000
900
800
700
600
500
400
300
200
100
0
1,E+00
1,E+01
1,E+02
1,E+03
1,E+04
1,E+05
1,E+06
1,E+07
Cycles to failure

Task 2.4: Results – ±45° - GF/Infugreen & GF/Elium



Task 2.4: Results – QI- GF/Infugreen & GF/Elium