OLD DOMINION UNIVERSITY

IDEA FUSION

RESTORATION OF STRENGTH IN POLYAMIDE WOVEN GLASS FIBER ORGANOSHEET AFTER IMPACT BY HOT-PRESSING

ODU MECHANICAL AND AEROSPACE ENGINEERING

CMM COMPOSITES MODELING AND MANUFACTURING LAB

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IMPACT RESISTANT COMPOSITES FOR ELECTRIC VEHICLES

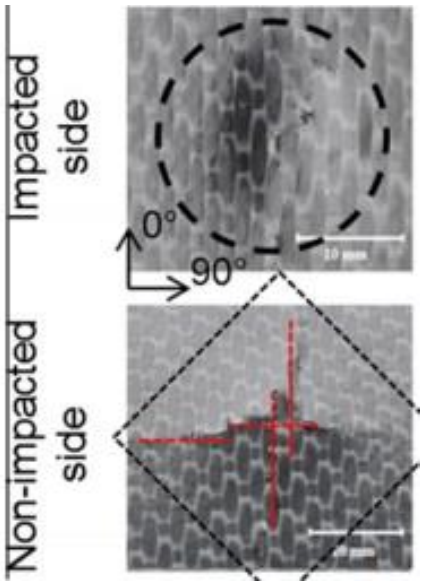
<u>Why impact resistant materials are necessary?</u>

- Enhanced Safety
- Durability
- Reduced maintenance cost
- Promoting sustainability

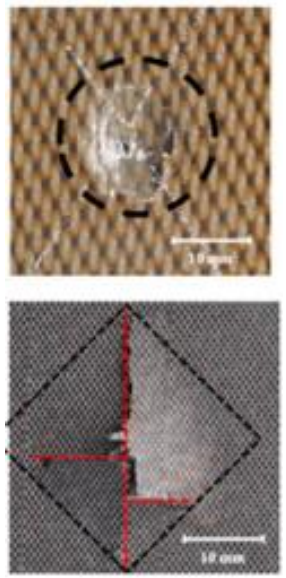
THERMOPLASTIC OVER THERMOSET

- Thermoplastic composites exhibit better impact resistance than thermoset composites.
- Increased matrix ductility in thermoplastic composites reduces transverse crack propagation, leading to higher damage tolerance and energy absorption capacity.
- Woven fabric reinforcement combined with thermoplastic binding maintains structural integrity, limiting through-thickness damage during impact.
- Thermoplastic composites have unlimited shelf life and allow for faster manufacturing cycles through thermoforming.
- The ability to be processed at flexible heating and cooling rates makes thermoplastic structures repairable and cost-efficient.

<u>Thermoplastic</u>

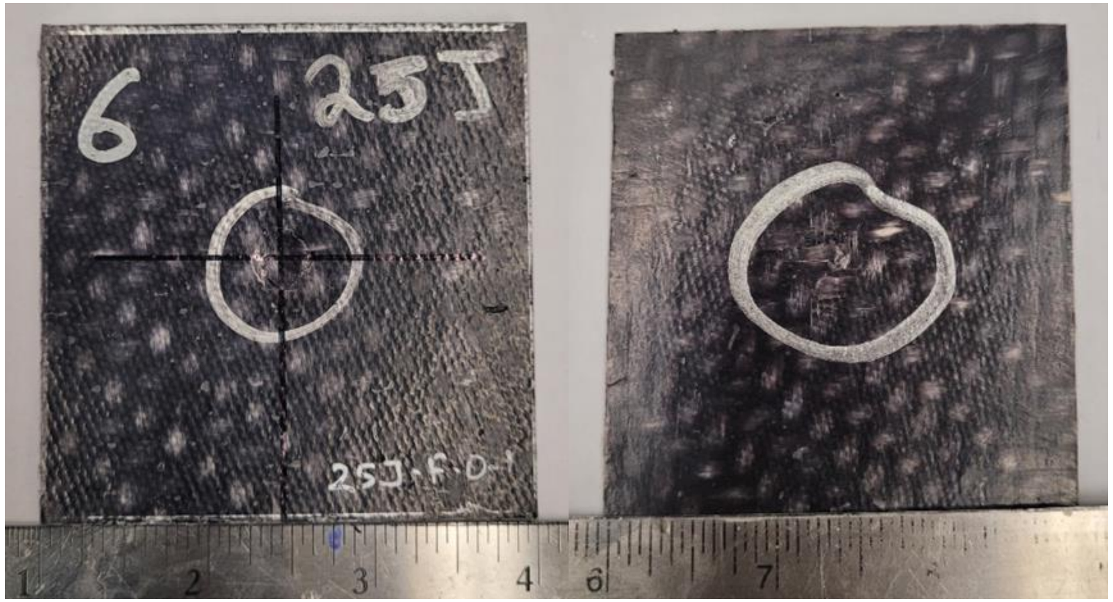


<u>Thermoset</u>



B. Vieille, V. M. Casado, and C. Bouvet, “About the impact behavior of woven-ply carbon fiber-reinforced thermoplastic- and thermosetting-composites: A comparative study,” Composite Structures, vol. 101, pp. 9–21, 2013. doi:10.1016/j.compstruct.2013.01.025

<u>Repairability of thermoplastic</u>



WHY REPAIR?

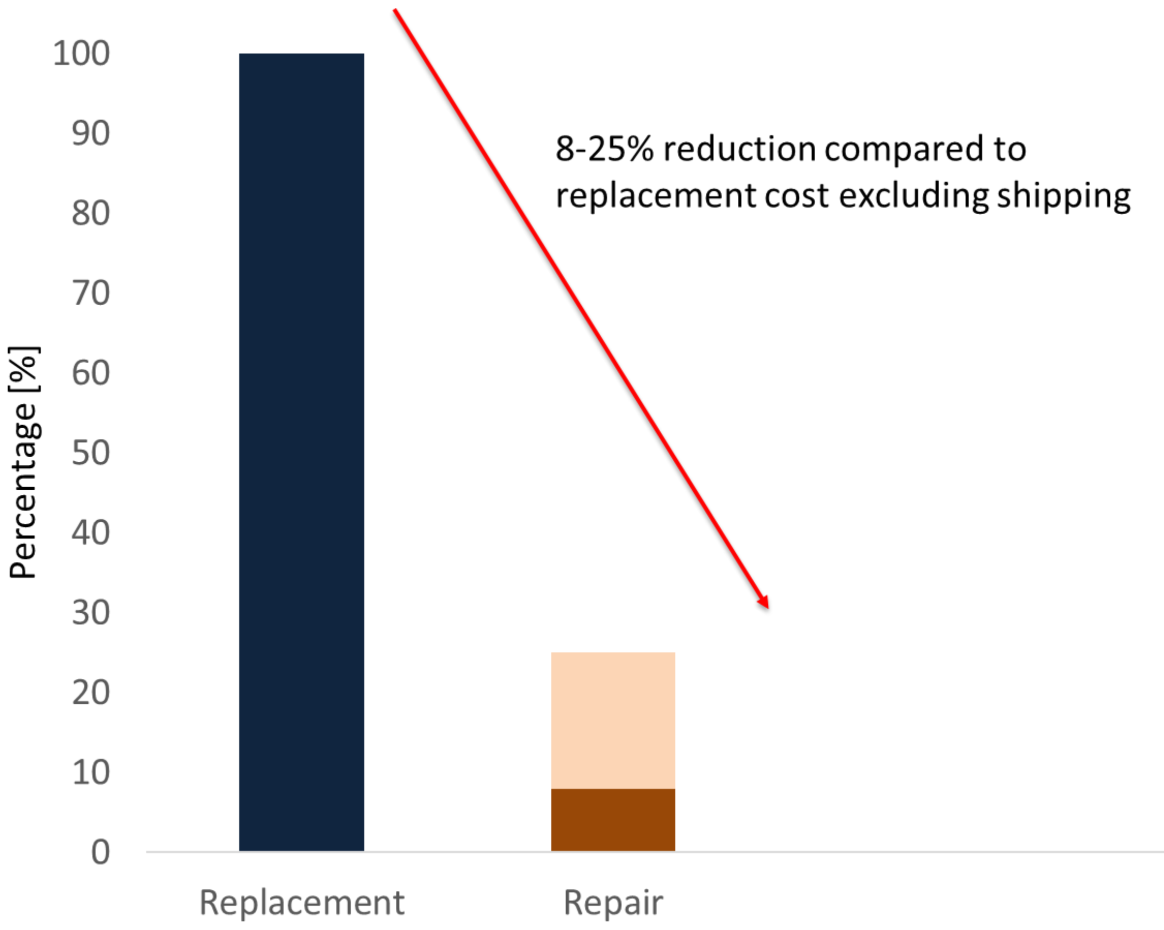
Benefits of repair

- Restoration of strength.
- Extending service life.
- Repair cost < Replacement cost.
- Less time required to bring back to service.
- Sustainability.

Types of repair

- Patch repair: Larger damaged area.
- Filler repair: small penetrated area.
- Fusion repair: damaged but not perforated.

Cost estimation



"Cost of repair vs replacement of aircraft structure", Julieta B. Robles, editor, Montreal, QC,2021

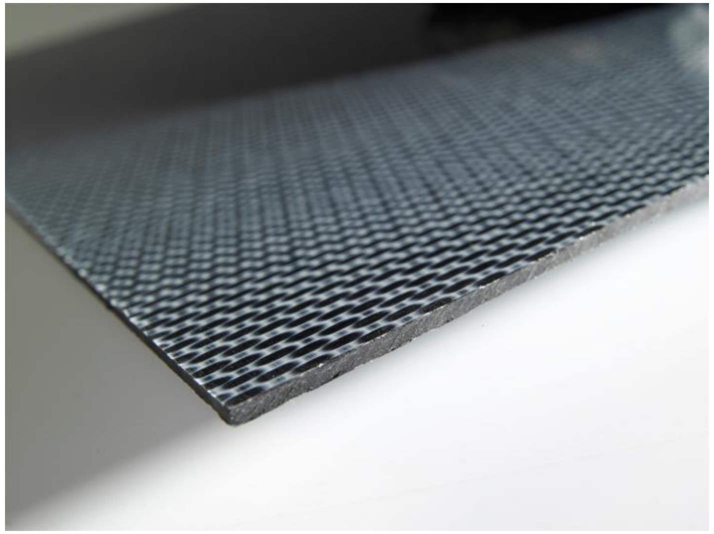
IMPACT RESISTANT REPAIRABLE COMPOSITE : WEAVE ORGANOSHEET

- Layers of intertwined fibers laced together, impregnated in an in-situ polymerized thermoplastic resin, also known as weave organosheet.

Uses: Aerospace components, Interior panels, automotive body parts, boat hulls, pole vault poles due to its lightweight, corrosion resistant and impact resistant characteristics.

- Recently under study for state-of-the-art use in electric vehicles (EVs) battery enclosures.
- Its potential as an impact resistant structure is wide due to its high energy absorption capacity, damage tolerance, repairability and design flexibility.

Woven composite sheet



Compression molding

Battery enclosure panel

"Designing a versatile, multi-material EV battery enclosure | CompositesWorld." https://www.compositesworld.com/articles/designing-a-versatile-multi-material-ev-battery-enclosure (accessed Jul. 30, 2023).

RESEARCH QUESTIONS

To ensure successful integration of woven (twill 2/2) thermoplastic (nylon) organosheets in structural applications, this study aims to answer the following research questions:

- How much energy can the glass fiber nylon organosheet absorb under increasing impact energy levels?
- How does the residual compressive strength after impact vary with different impact energy levels in 2/2 twill weave glass fiber reinforced polyamide composites?
- What is the effectiveness of hot-press repair techniques in restoring the strength and integrity of woven GF/PA6 organosheet after impact-induced damage?

MATERIAL SPECIFICATION

Woven thermoplastic composite

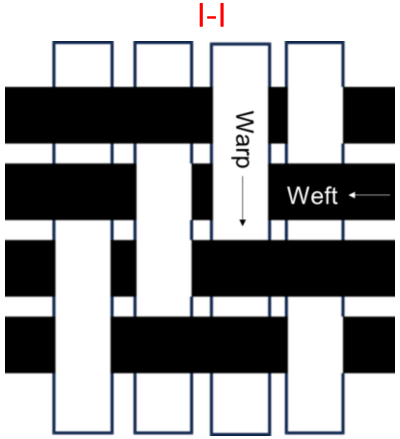
Matrix: Polyamide 6 (Nylon)
Fiber: Glass Fiber

Fiber Geometry

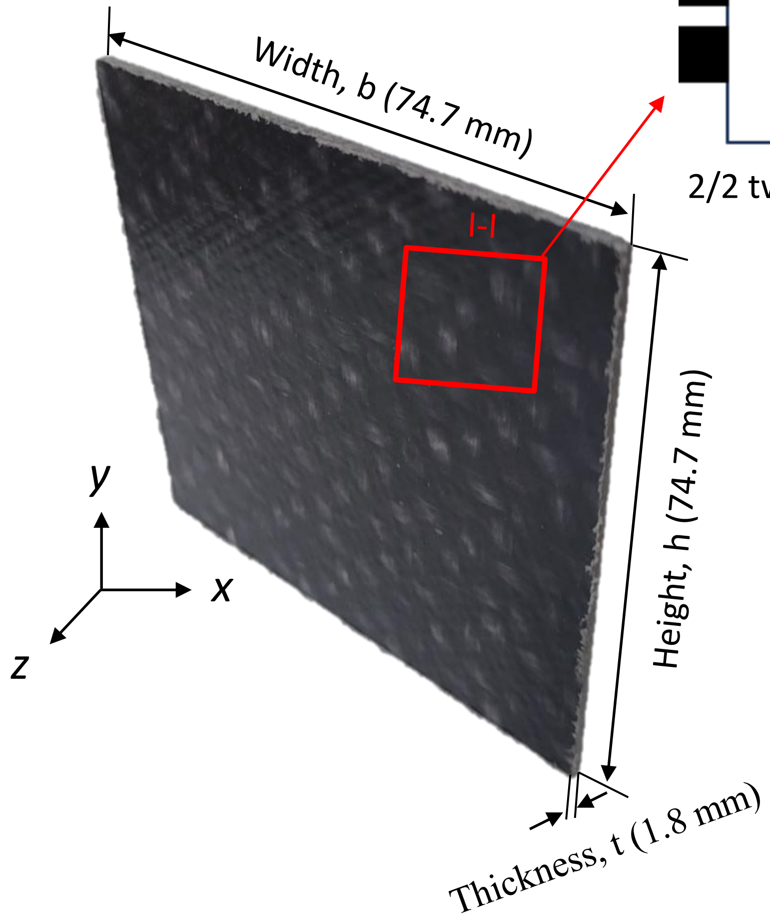
Fabric pattern: 2/2 twill weave, characterized by repeated sequence of 2 yarns over and 2 yarns under. The horizontal yarns in the weave, known as weft, were interlaced with the vertical yarns, called warp.
Fiber volume fraction, V_f: 40%

Specification

Dimension: 74.7 × 74.7 × 1.8 mm
Yarn areal density: 1200 g/m^2
Warp/Weft density: 2.25 yarns/cm
Fiber diameter: 16 µm



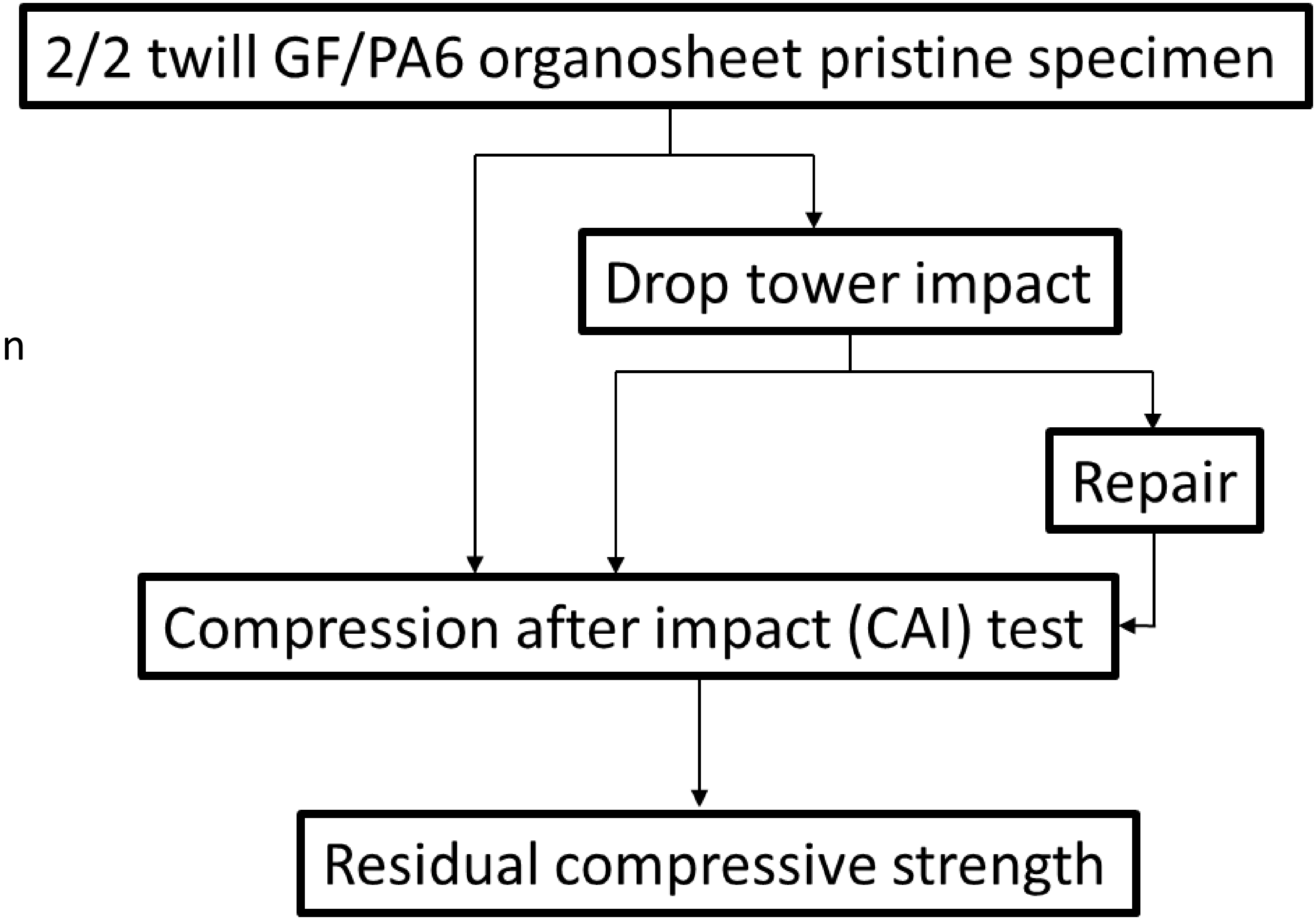
2/2 twill weave geometry



METHODOLOGY

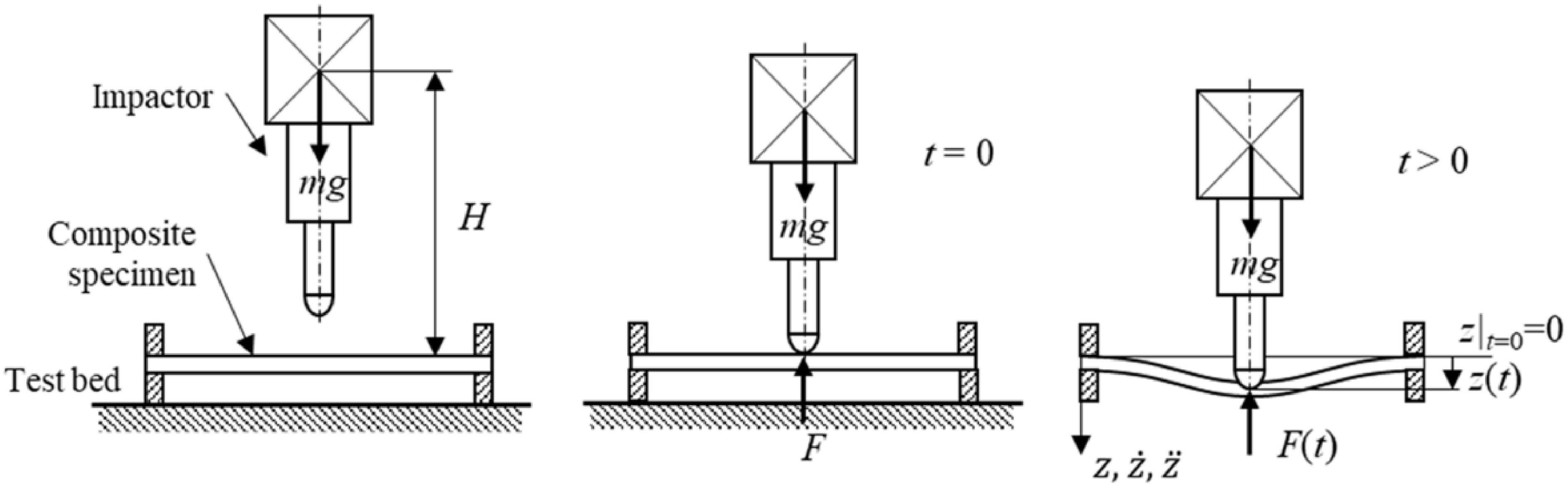
The impact and post-impact behavior of the woven organosheet was thoroughly examined using :

- Drop tower impact test
- Compression after impact (CAI) test
- Repair by localized hot-pressing



DROP TOWER IMPACT TEST

Three stages of the impact test



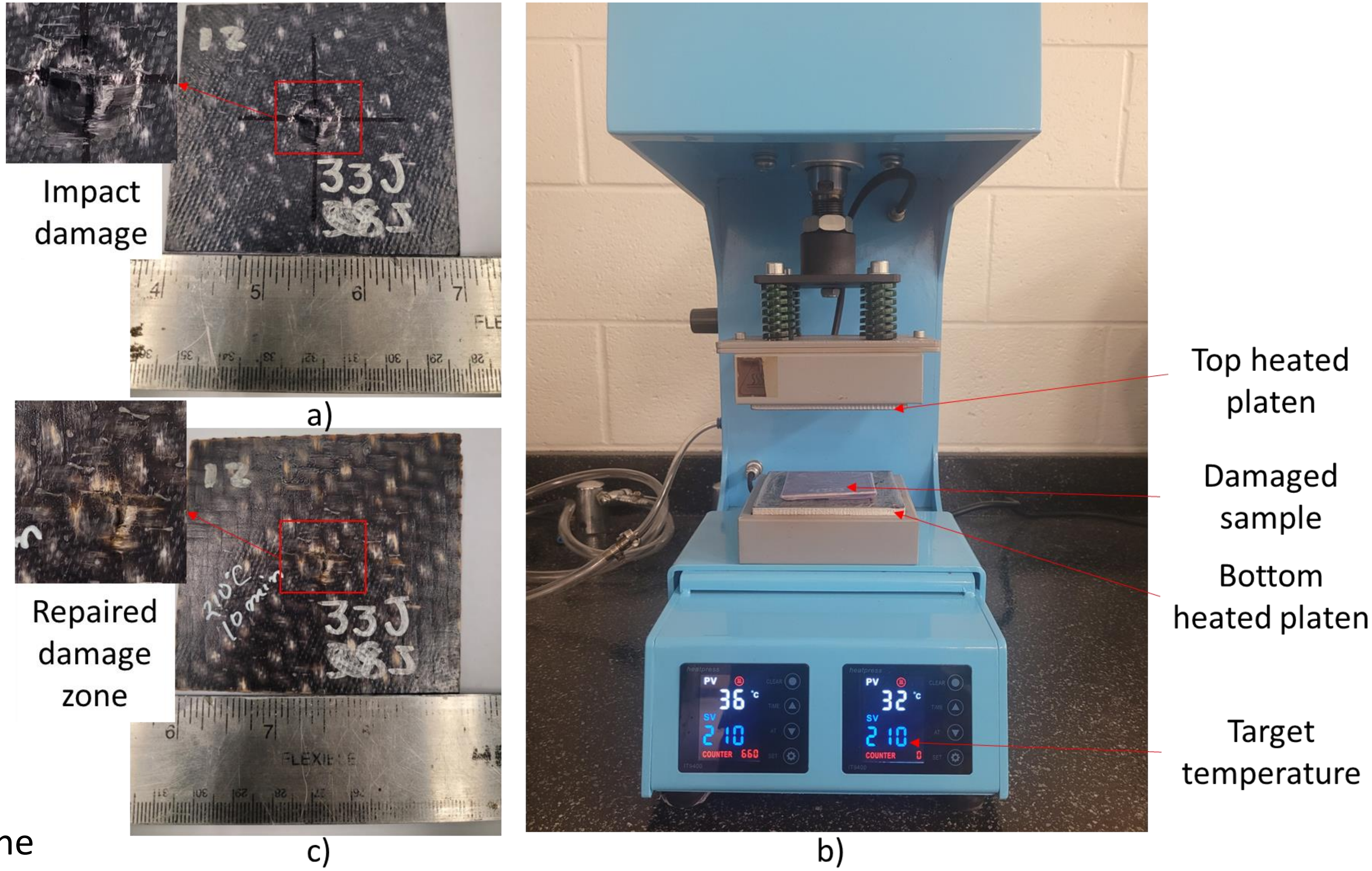
Impactor at rest Contact initiation Impactor downward travel

Parameters recorded for impact analysis:

- Impactor contact force, *F(t)*
- Impact energy, *E(t)*
- Velocity, *v(t)*
- Specimen out of plane displacement, *z(t)*

S. G. Kravchenko, C. Volle, and O. G. Kravchenko, “An experimental investigation on low-velocity impact response and compression after impact of a stochastic, discontinuous prepreg tape composite,” Compos Part A Appl Sci Manuf, vol. 149, Oct. 2021, doi: 10.1016/j.compositesa.2021.106524.

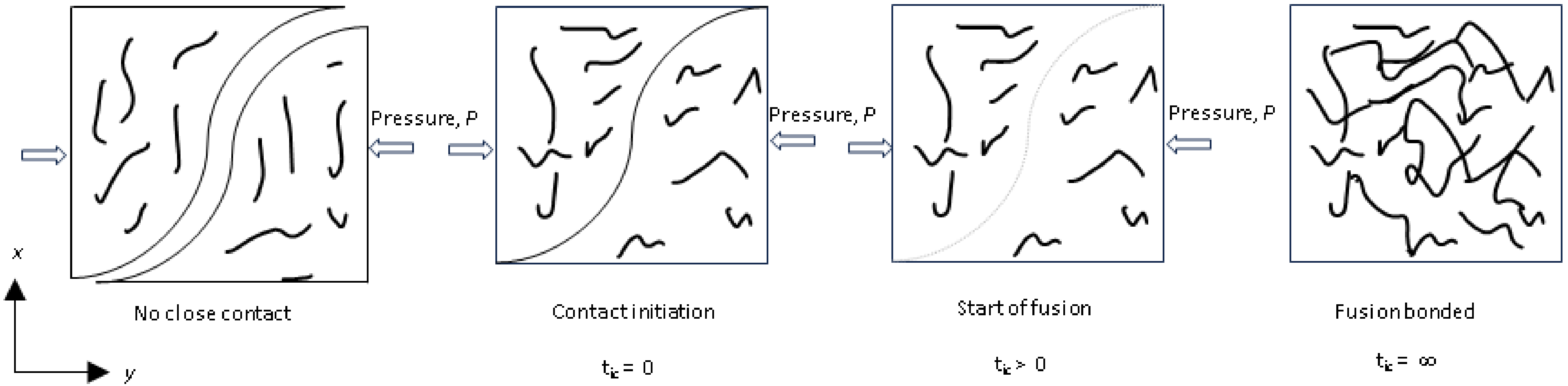
HOT-PRESS REPAIR



Repair procedure:

- Preheat the sample wrapped in Teflon film at 210°C for 10 minutes.
- Apply a pressure of 1.15 MPa closing the platens for 10 minutes.
- Allowed to air cool the sample.

HOW REPAIR (FUSION BONDING) WORKS ?



- Thermoplastic composite repair involves the coalescence of two surfaces in contact to form a single surface.
- The resulting composite strength depends on temperature, pressure, and time during the repair process.
- Two major factors influencing thermoplastic composite repair are close contact formation between surfaces and macromolecules fusion across the contact surface.
- The repair process by heating the sample above its glass transition temperature (T_g) and applying sufficient pressure for intimate contact.
- During the repair, polymer chains diffuse across surface boundaries, entangle, and strengthen the structure, resulting in a healed damage.

POLYMER-POLYMER BONDING

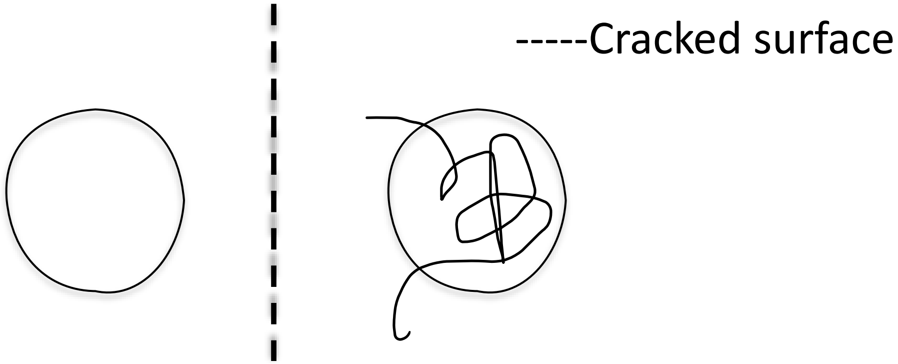
Stages of crack healing

Stage I : Surface rearrangement

Above T_g, molecule surfaces viscoelastically deform and polymer chain rearranges

Stage II : Cracked surface approach

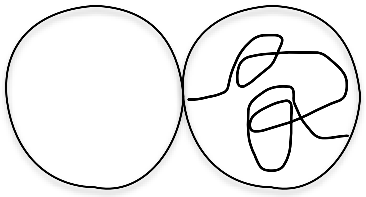
At this stage, due to intermolecular attraction the molecules initiate surface approach



Stage I & II

Stage III : Wetting

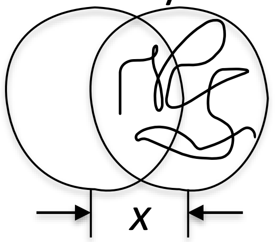
The molecules passes the cracked surface and comes in contact to improve contact area



Stage III

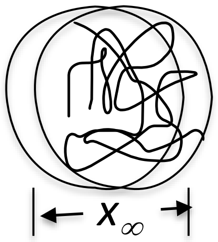
Stage IV: diffusion

Two molecule starts to coalesce, and polymer chains starts entangle crossing boundary



Stage IV

Stage V: Randomization



Stage V

R. P. Wool and K. M. O'Connor, "A theory crack healing in polymers," J Appl Phys, vol. 52, no. 10, pp. 5953–5963, Oct. 1981, doi: 10.1063/1.328526

COMPRESSION AFTER IMPACT (CAI) TEST

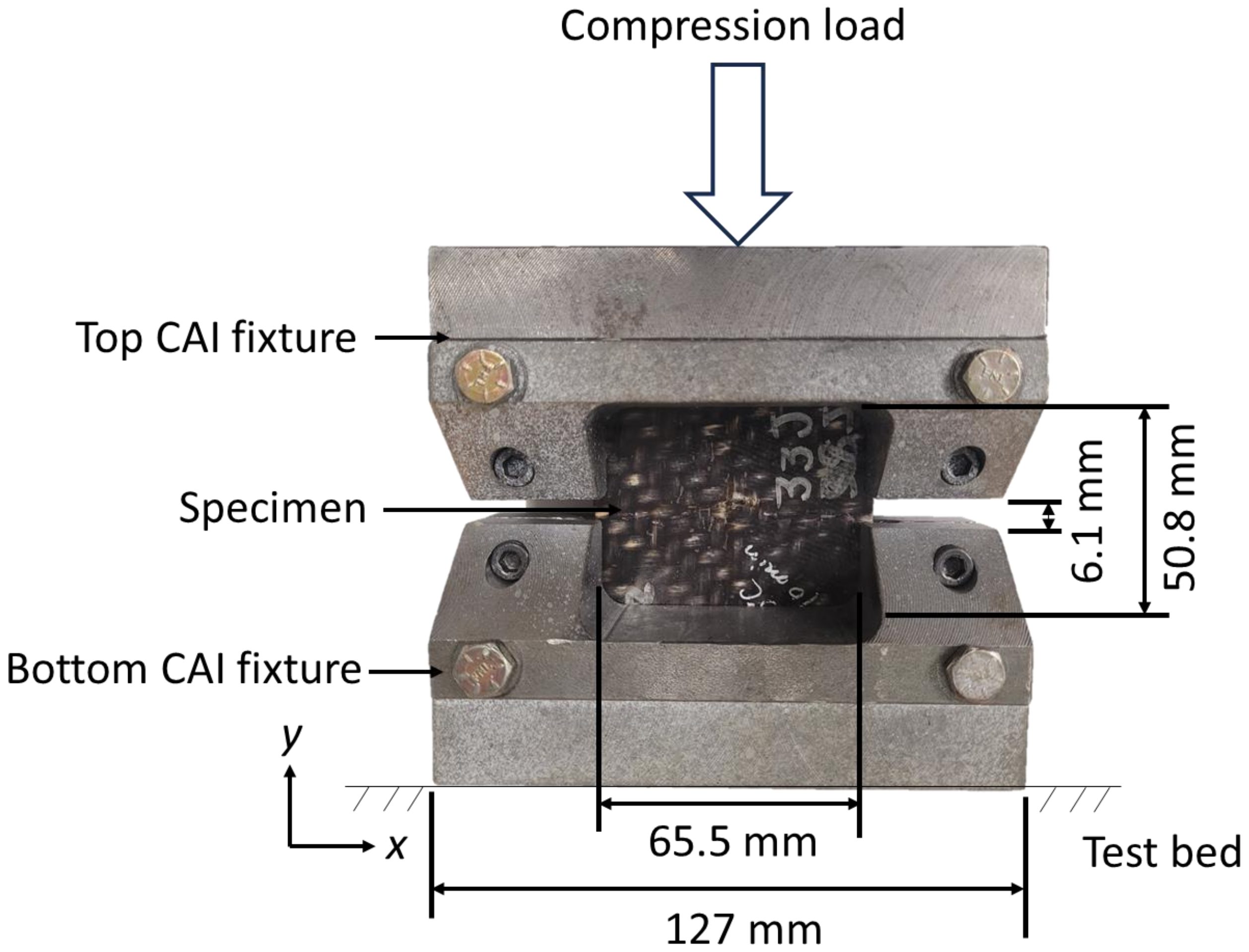
MTS machine with 100kN load cell was used to compress the specimens at a displacement rate of 2 mm/min. Force and crosshead displacement was recorded at 5 Hz frequency.

Compressive residual strength (σ_r) was calculated using the following eqn:

$$\sigma_r = \frac{P_{max}}{A}$$

Here, P_{max} is the critical load to failure and A is the cross-sectional area of the specimen

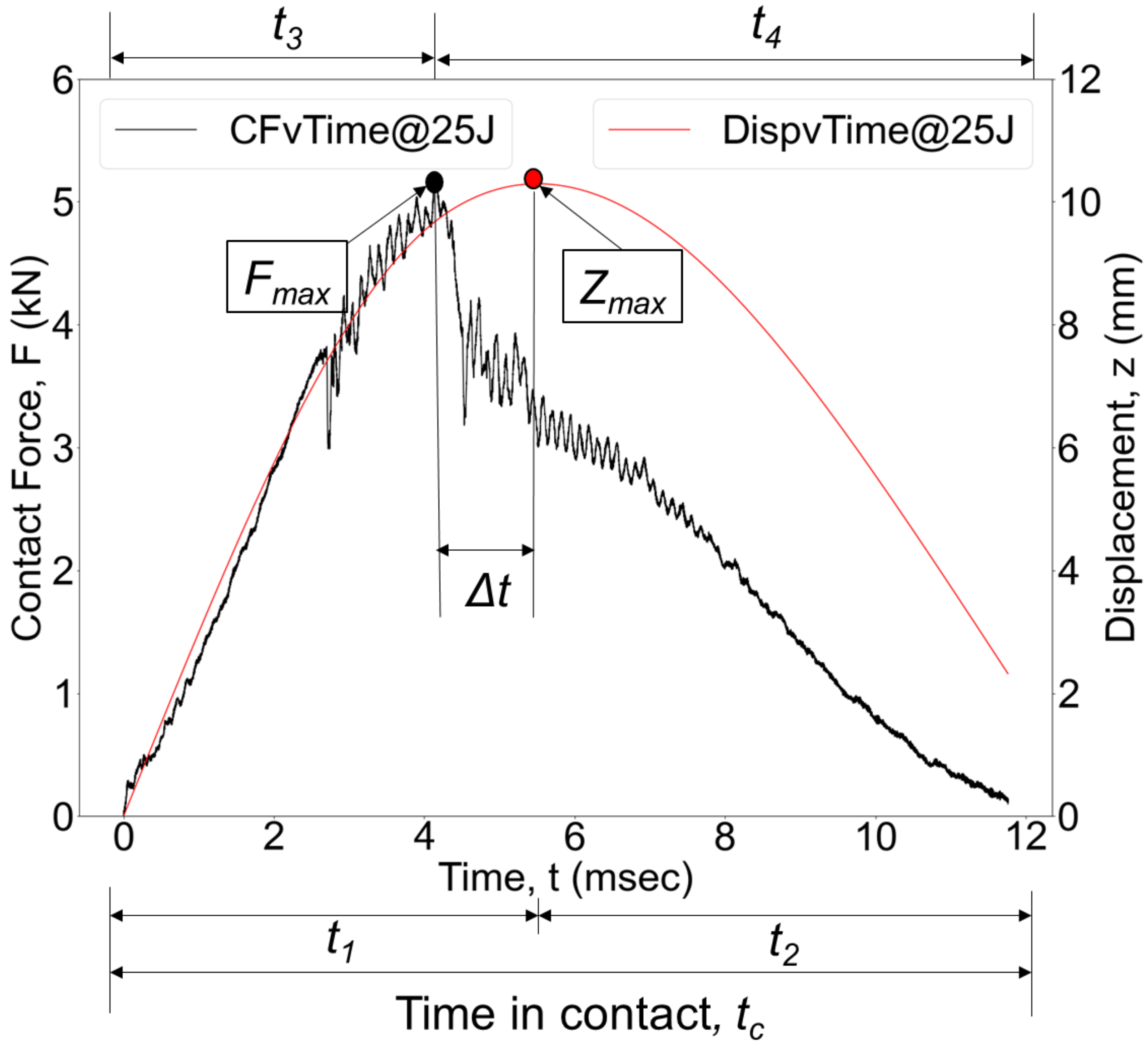
Impacted (30J) organosheet



Compression after impact (CAI) setup

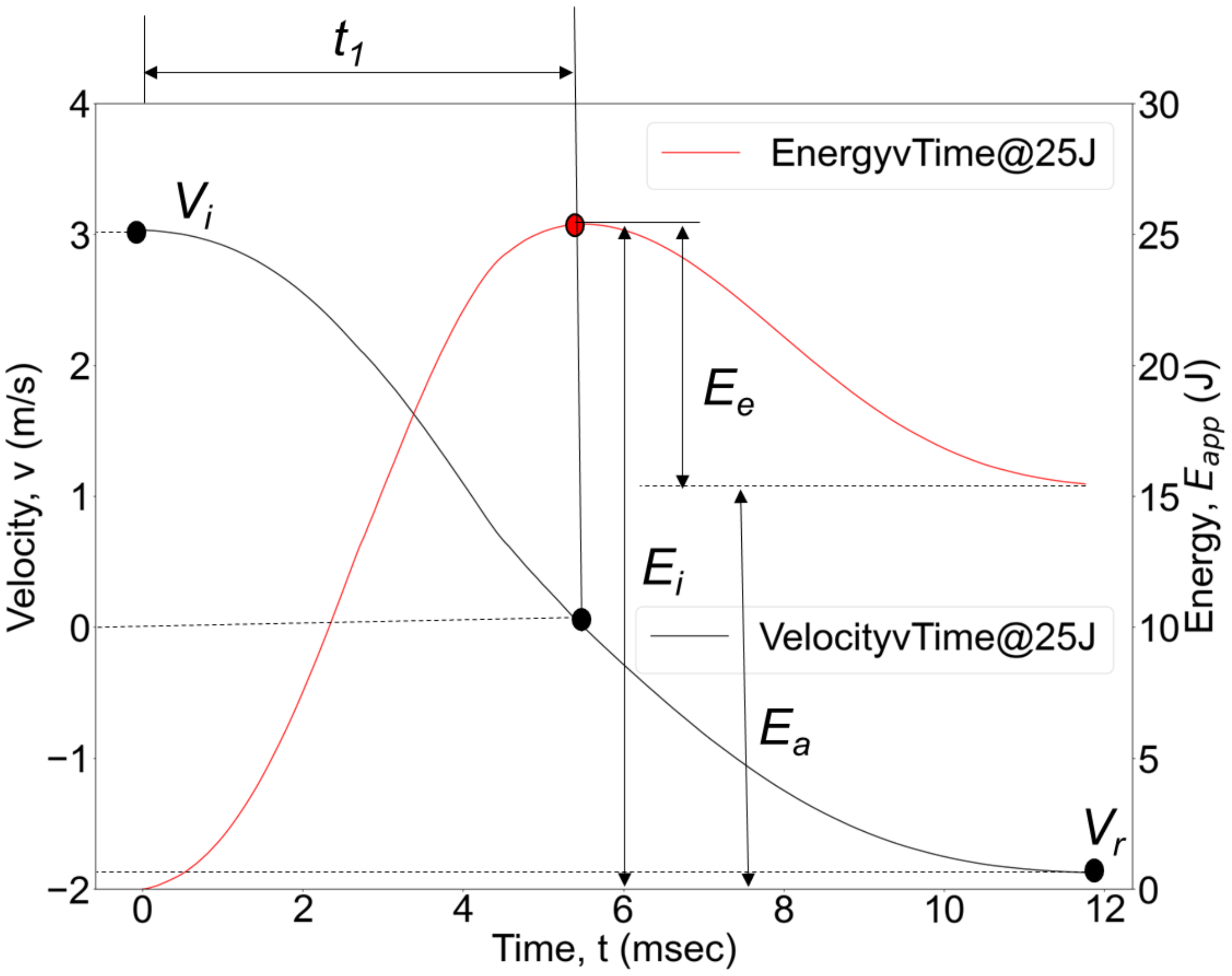
IMPACT BEHAVIOR OVER TIME

- The composite specimen exerts a reaction compressive force (*F*) on the impactor.
- The force-time (*F(t)*) curve shows a stage of steady force increase until reaching the peak load (F_{max}), with smooth or low-amplitude fluctuations.
- Temporary drops in the *F(t)* curve indicate the initiation and growth of local damage.
- It takes more time to reach z_{max} compared to F_{max}, resulting in a time delay (Δt) due to the development of damage mechanisms in the material.
- Inelasticity in the impact event leads to variations in the downward travel (t_1) and rebound (t_2) time for the impactor, as well as loading (t_3) and unloading (t_4) time.
- In case of a purely linear-elastic impact (Hertzian solution), $t_1 = t_2 = t_3 = t_4$ and $\Delta t = 0$ is expected, but inelasticity causes variations in these times.



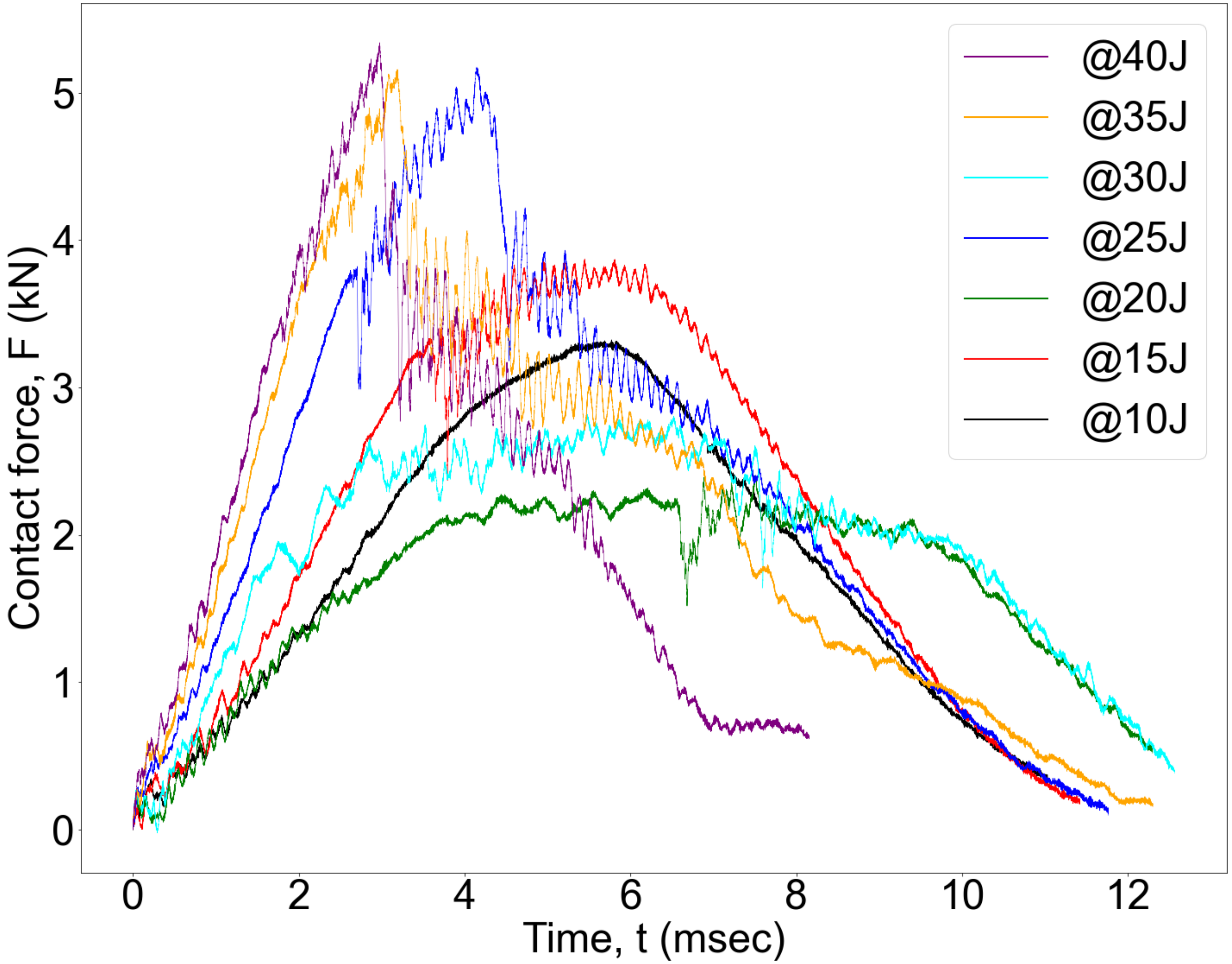
IMPACT BEHAVIOR OVER TIME

- During the impactor's downward travel, its kinetic energy is transferred to the composite specimen, temporarily stored as elastic strain energy, leading to an increasing $E_{app}(t)$ curve.
- Once the local material strength is reached, a portion of the applied energy dissipates through irreversible damage.
- When all the incident kinetic energy (E_i) of the impactor is transferred to the composite specimen, $E_{app}^{max} = E_i$.
- $E_{app}(t)$ gradually decreases as a fraction of the energy is transferred back to the impactor, causing it to bounce back.
- The energy curve eventually reaches a constant value, representing the total energy permanently absorbed (E_a) by the composite specimen.
- The part of E_i responsible for the impactor bouncing back is the elastic strain energy (E_e).



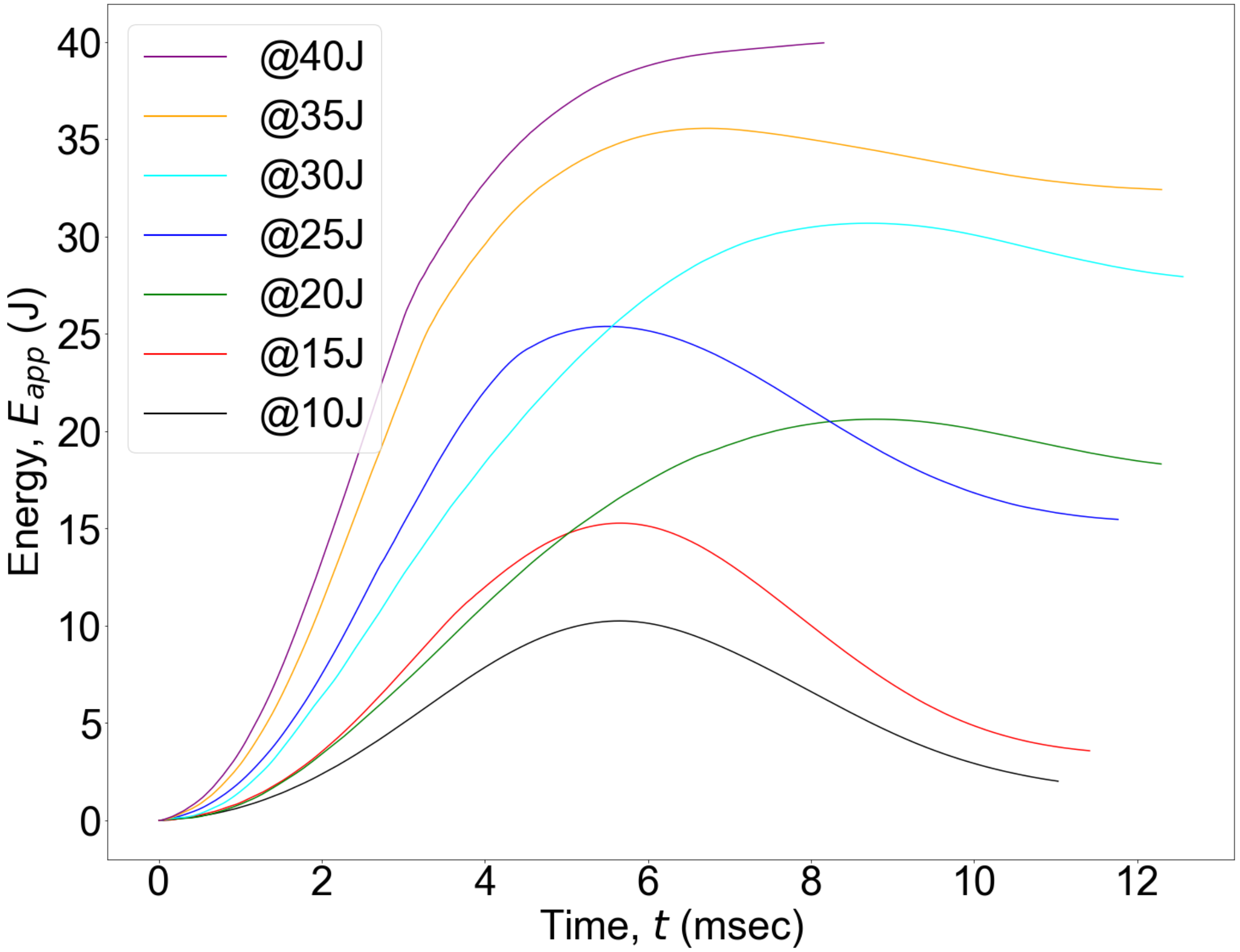
CONTACT FORCE VS TIME

- F_{max} increased with higher impact energy levels, and the time required to reach F_{max} decreased.
- The impactor's rebound time, t_4, also increased at higher energy levels, except for an anomaly observed at 20J impact.
- Prolonged rebound time at higher energy levels was attributed to quick damage initiation and extended time for damage growth.
- Steeper slopes were observed in the force-time curve at higher impact energies.



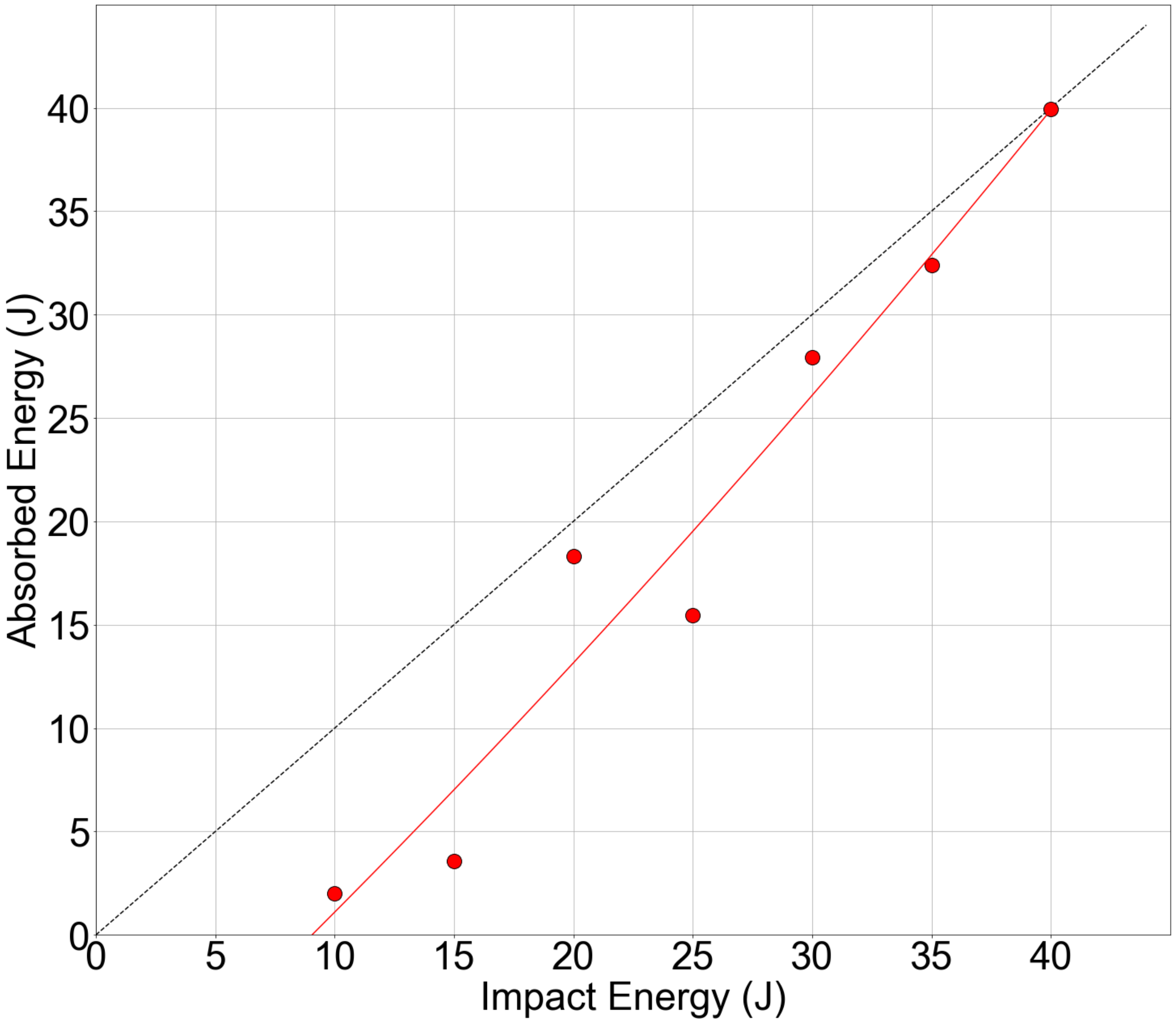
APPLIED ENERGY VS TIME

- The maximum energy value in the curve represents E_i, the total energy introduced into the specimen.
- After the contact and rebound phases, the final energy value equals E_a, which is the energy absorbed by the composite.
- For impacts below 15J, E_a is significantly smaller than E_i, indicating minimal energy dissipation during the impact event.
- Higher impact energies (exceeding 20J) show more pronounced energy dissipation through damaged surfaces, leading to an increase in E_a.
- At 40J impact, E_a equals E_i, signifying that the impactor has no energy left for rebounding, and all energy is absorbed by the composite specimen.



ENERGY APPLIED VS ENERGY ABSORBED

- The energy profile diagram includes a diagonal line representing equal energy between impact and absorption.
- Equal impact and absorbed energies signify that the specimen has fully absorbed the energy imparted during the impact event.
- Below 25J impact, the absorbed impact energies consistently remain less than the impact energies, except for the anomaly observed at 20J impact.
- Beyond 25J impact, the organosheet experiences an escalation in internal damage, absorbing approximately 90% of the incident energy.
- At 40J impact, the scatter plot aligns with the diagonal line, indicating that all the incident energy is absorbed by the organosheet.

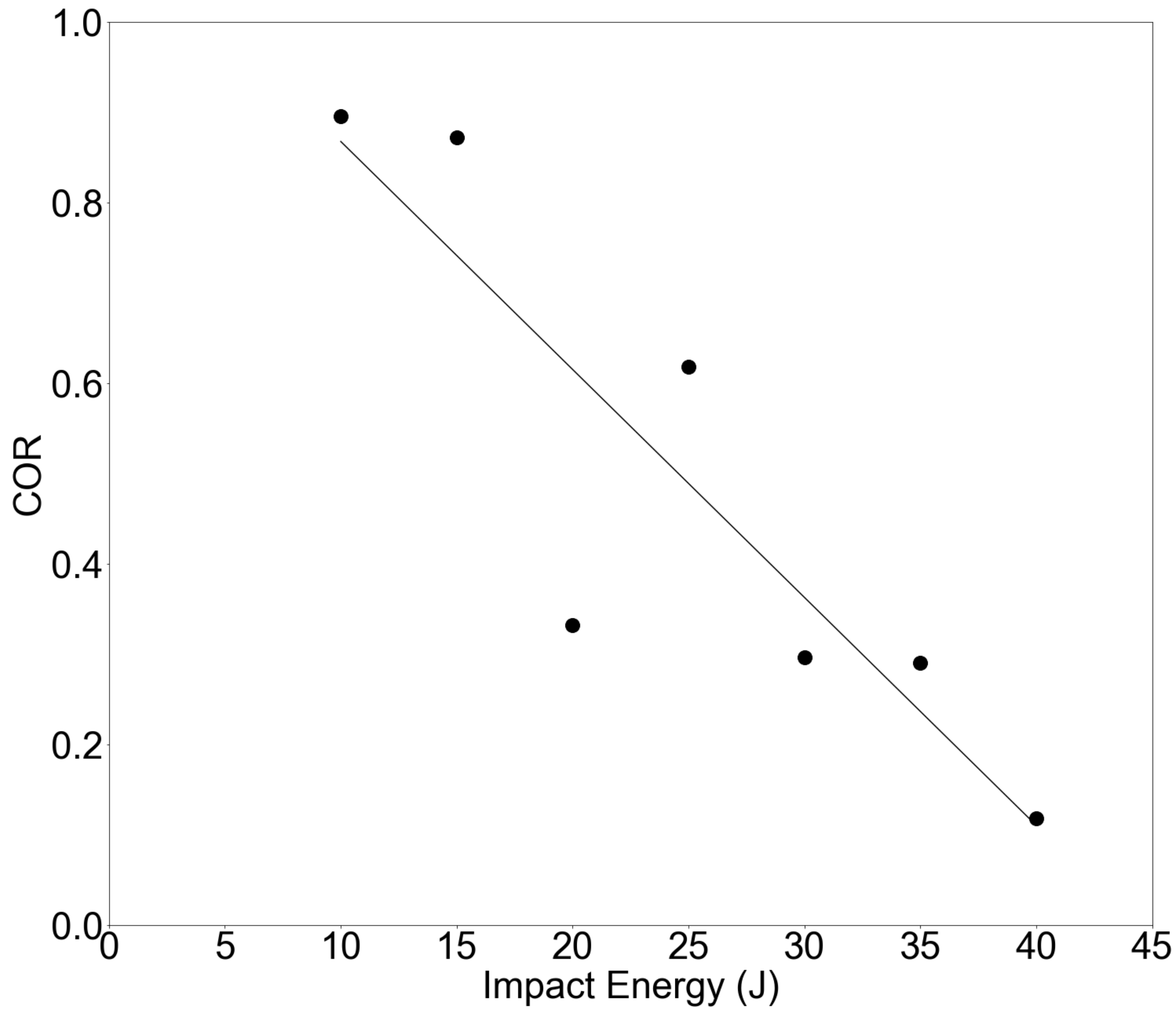


CO-EFFICIENT OF RESTITUTION (COR)

- Co-efficient of restitution, COR = $\frac{v_r}{v_i}$

  Here, v_r is the rebound velocity of the impactor and v_i is the incident velocity.

- 0<COR<1
- COR value close to 1 signifies no damage in the specimen and COR close to 0 means significant damage.
- With increasing E_i, COR decreased. At 40J impact, COR dropped down to 0.1 indicating significant damage and close proximity to penetration.



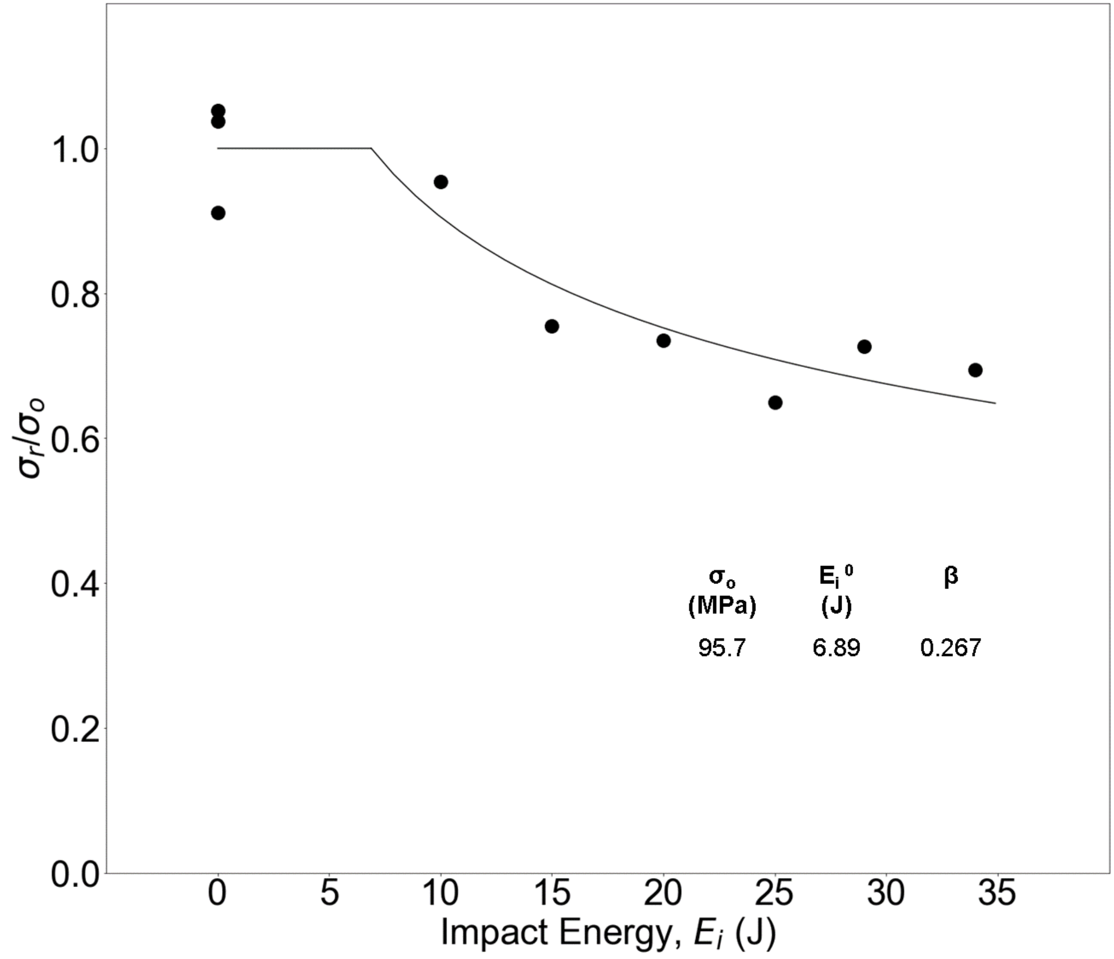
COMPRESSIVE RESIDUAL STRENGTH

The CAI test results exhibited some experimental scatter, which was fitted using the curve fitting equation:

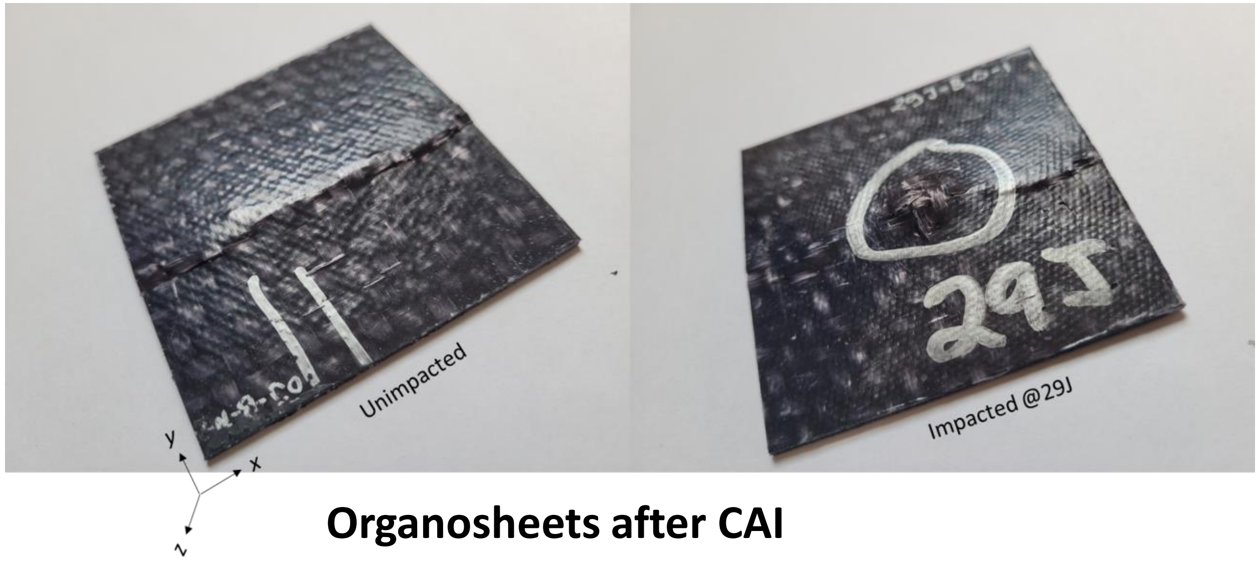
$$\frac{\sigma_r}{\sigma_0} = \left(\frac{E_i{}^0}{E_i}\right)^\beta$$

Here, E_i^o and β are the fit parameters. E_i^o represents the impact energy at which the compressive strength reduction begins for impacted specimens.

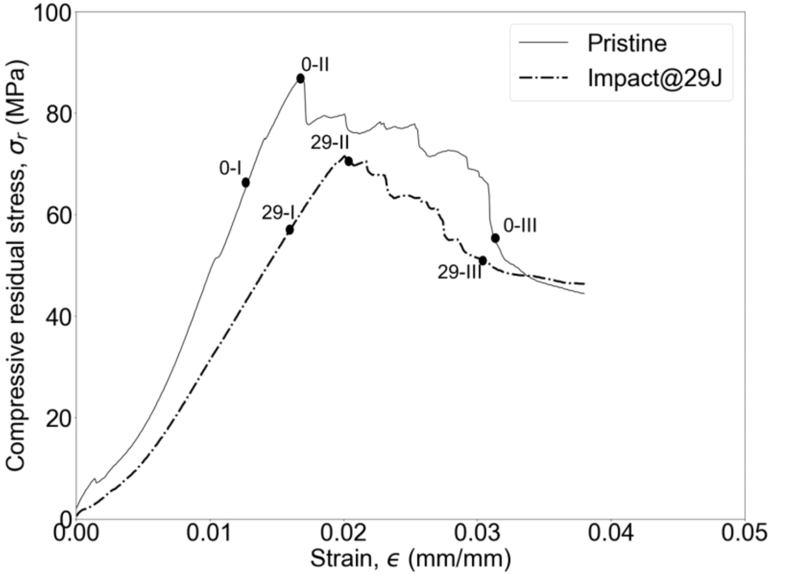
- The organosheet demonstrated high damage tolerance, with no strength reduction observed up to 6.89J impact.
- With an increase in impact energy, a downward trend in residual strength was observed.
- Above 25J impact, a significant drop in strength (31-38%) was observed, providing evidence of impact-induced damage in the specimen.



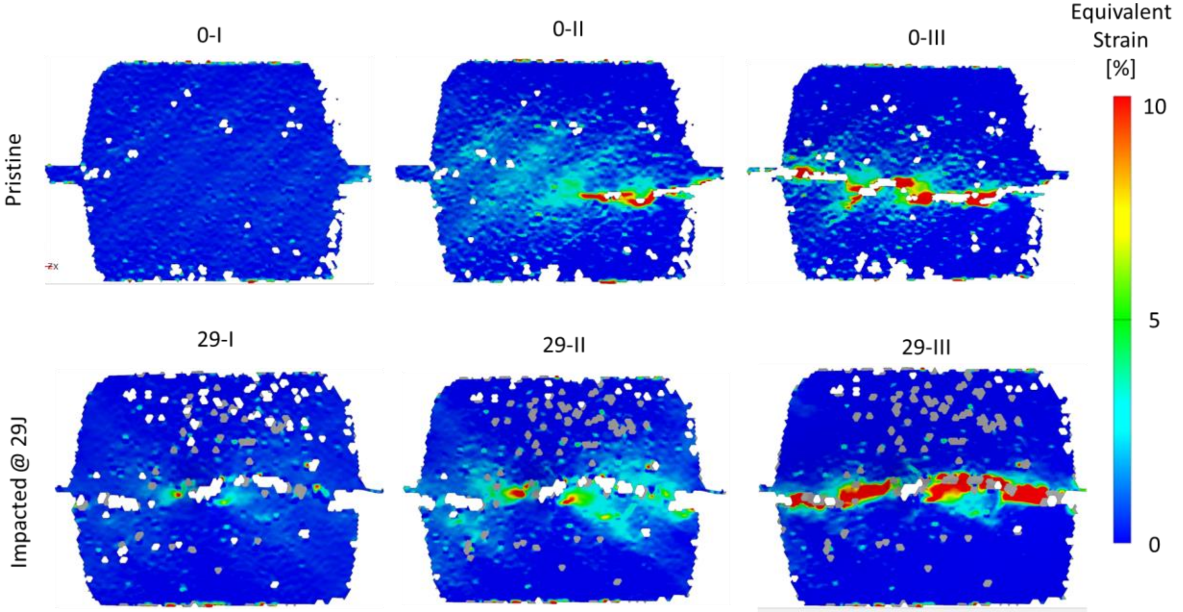
DIGITAL IMAGE CORRELATION (DIC) POST-MORTEM



Organosheets after CAI



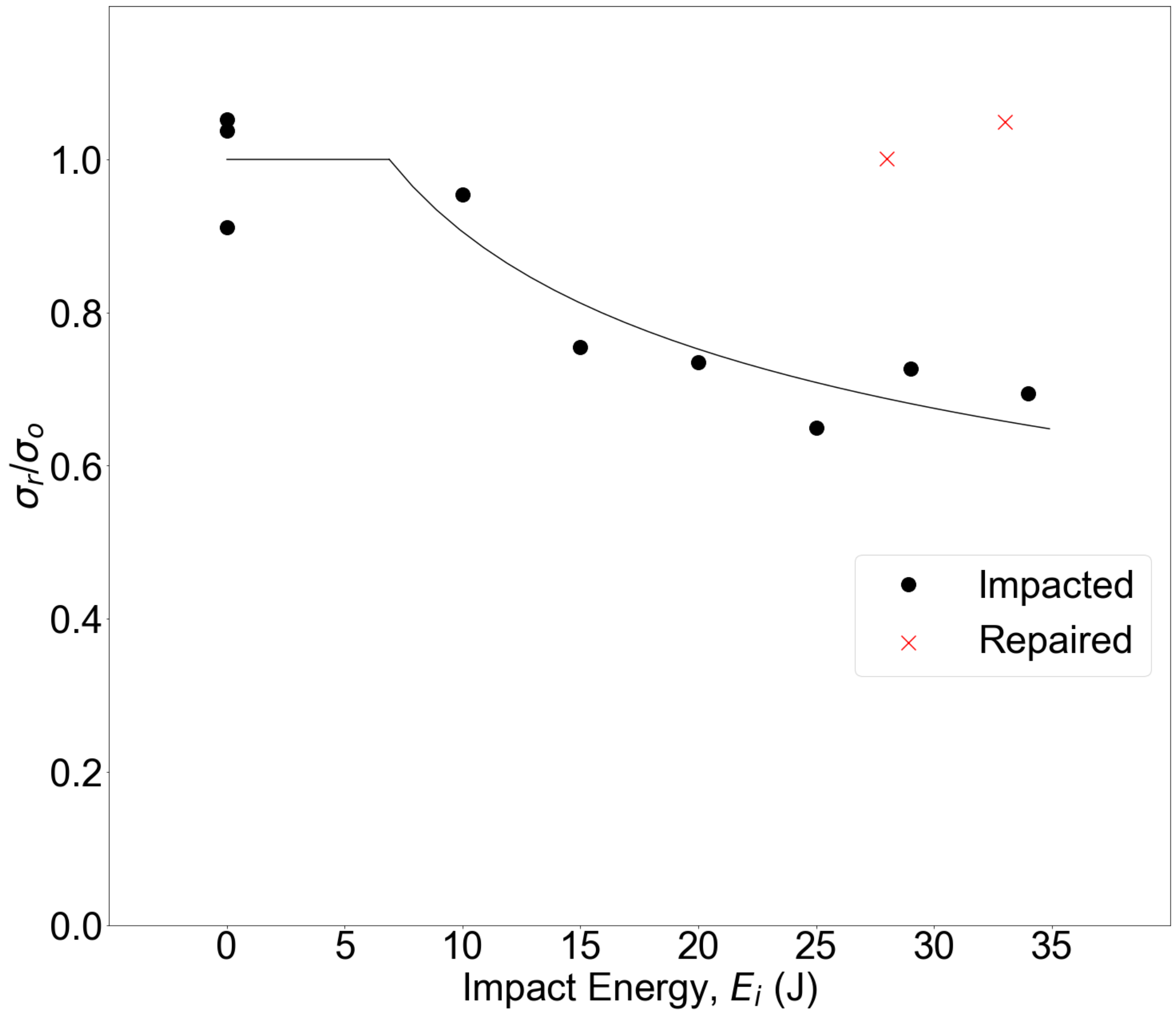
- Pristine sample exhibited buckling during failure with no significant crack propagation visible on the surface.
- DIC strain field in the pristine sample showed strain evolving from one side and progressing through the middle.
- Impacted specimen showed damage development during compressive loading originating from the initial impact damage site.
- The impacted specimen also failed due to buckling, which is different from the brittle behavior typically observed in thermoset matrix composites.



DIC strain evolution map

STRENGTH RESTORATION BY HOT-PRESSING

- Even after experiencing a high impact of 33J, the compressive strength was successfully restored to its original level.
- The restoration was achieved by utilizing the fusibility of thermoplastic nylon, allowing effective healing at high temperatures and pressures for certain period of time.
- Uniform pressure on the impacted zone realigned damaged fibers, while high temperature facilitated matrix flow, contributing to the strength restoration.



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CONCLUSION

- Investigated impact and post-impact behavior of woven glass fiber polyamide thermoplastic organosheet.
- Assessed impact damage response and proposed a cost-effective repair approach.
- Organosheet showed high damage tolerance, maintaining compressive strength up to 6.89J impact.
- Significant strength drop (31-38%) after 25J impact, indicating impact-induced damage.
- Localized heating technique employed for repair, effectively restored pristine compressive strength.
- Hot press reconsolidation post-heating restored original compressive strength, even after high-energy impacts (33J).
- Future work: Generate an optimized hot-press repair model.