



HISTRATE

*Advanced Composites under High Strain Rate
Loading A Route to Certification-by-Analysis*

*2024 Conference
5th - 6th JUNE 2024*





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A Route to Certification-by-Analysis*

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PROGRAMME

DAY 1 05 June

WEDNESDAY

09:00 – 09:30 Registration

09:30 – 10:00 Welcome by Local Organizer and Opening Speech
Sabancı University

Hatice Sinem Şaş

10:00 – 10:30 Introduction by Action Chair
HISTRATE - A route to certification-by-analysis for impact-loaded
aeronautical composite structures

Patricia Verleysen

10:30 – 11:00 **COFFEE BREAK**

11:00 – 11:45 Keynote Speech
Length scale effects in high-strain rate testing with FBGs

Kara Peters

11:45 – 12:45 Session 1 - Novel simulation methods and best practices for
composites under high strain rates (WG4)

Chair:
Nenad Djordjevic

11:45 – 12:00 Modelling of high velocity impact on carbon fibre reinforced
plastics

Nenad Djordjevic

12:00 – 12:15 Constitutive model for fibre reinforced composites with
progressive damage based on the spectral decomposition of
material stiffness tensor

Rade Vignjevic - talk
presented by Nenad
Djordjevic

12:15 – 12:30 Characterization of matrix materials for composites considering strain rate
effect

Dayou Ma

12:30 – 12:45 An advanced rheological model to predict the behaviour of aromatic
hyperbranched polyester/RTM6 epoxy nanocomposites

Navid Ghavanini

12:45 – 14:00 **LUNCH BREAK**

14:00 – 15:00 Poster session with 3 minute pitches

15:00 – 16:00 **COFFEE BREAK WITH POSTER SESSION**



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WEDNESDAY

16:00 – 17:30	Session 2 - Novel composite materials for high strain rate applications (WG3)	Chair: Mauro Zarrelli
16:00 – 16:15	<i>The effect of hyperbranched polymers on fracture: from nanocomposites to composites</i>	Mauro Zarrelli
16:15 – 16:30	<i>Soft body impact loaded composite structures optimized for energy absorption</i>	Andreas Hornig
16:30 – 16:45	<i>A double bistable composite sandwich core for enhanced impact absorption</i>	Michele Meo
16:45 – 17:00	<i>Constitutive models for additive manufacturing in composite structures at high strain rate applications – A review of selected references</i>	Ivica Smojver,
17:00 – 17:15	<i>Effect of high strain rates on the out of plane properties of S2-Glass fiber reinforced polymers</i>	Çağatay Yılmaz
17:15 – 17:30	<i>Influence of high strain rates on the tensile properties of basalt fiber reinforced polymers</i>	Sara Saeed Abdulrahman Eltahir
18:45	BOAT TOUR AND DINNER <i>Boat departs from Üsküdar Pier</i>	



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DAY 2 06 June

THURSDAY

09:00 - 10:30 Invited Talks

**Chair: Tatjana
Glaskova-Kuzmina**

09:00 - 09:45 **Certification by Analysis OR how to eat an elephant**

André Haufe

09:45 – 10:30 **Simulation within the context of vehicle homologation; state of the art and options for the future**

Christian Bräunig

10:30 – 11:00

COFFEE BREAK

11:00 – 12:30 Session 3 - Multi-modal sensing for impact detection and damage characterisation (WG5)

Chair: Rohan Soman

11:00 – 11:15 *High and low velocity impact monitoring for the composite aerial structures*

*Krzysztof Dragan
(online)*

11:15 – 11:30 *Self-sensing composites for impact damage monitoring*

*Gabriele
Jovarauskaite*

11:30 – 11:45 *Post-impact and post-repair nondestructive evaluation of thermoplastic composites*

Pawel Malinowski

11:45 – 12:00 *Simulating an experimental setup for short-duration impacts on structures with Ti3C2-MXene sensors*

Julius Vincent Kruse

12:00 - 12:15 *Considering tensile resistance of Scot pine-MDF joint connected with 3D printed single dovetail fastener*

Samet Demirel

12:30 – 14:00

LUNCH BREAK

14:00 -14:30 Session 3 - Multi-modal sensing for impact detection and damage characterisation (WG5) – continued

Chair: Rohan Soman

14:00 – 14:15 *Mxene Fibers as Strain Sensors for Fiber Reinforced Composites*

Volkan Eskizeybek

14:15 – 14:30 *Comparative study of fiber Bragg sensors in remote and direct configuration for impact detection*

Rohan Soman



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DAY 2 06 June

THURSDAY

14:30 – 15:15	Session 4 - Advanced testing and instrumentation for composites under high strain rates (WG6)	Chair: Andrei Anisimov and Tatjana Glaskova-Kuzmina
14:30 – 14:45	<i>Optical instrumentation for high strain rate testing of composite materials: maximising the value of measurements</i>	<i>Andrei Anisimov</i>
14:45 – 15:00	<i>Mechanical properties of basalt fiber-reinforced epoxy composites modified with star-like polymers</i>	<i>Tatjana Glaskova-Kuzmina</i>
15:00 – 15:15	<i>Multiphysics characterization of composite materials at high strain rates</i>	<i>Mattia Utzeri</i>
15:15 – 16:00	COFFEE BREAK WITH POSTER SESSION	
16:00 – 17:15	Session 4 - Advanced testing and instrumentation for composites under high strain rates (WG6) - continued	Chair: Andrei Anisimov and Tatjana Glaskova-Kuzmina
16:00 – 16:15	<i>Enhancing impact resistance and tensile properties of 3D printed biobased photopolymers with ultra-low nanocellulose content</i>	<i>Oskars Platnieks</i>
16:15 – 16:30	<i>Impact toughness and tensile properties of Polylactic acid/ Polyhydroxyalkanoate/Poly(butylene succinate-co-adipate) blends</i>	<i>Alisa Sabalina</i>
16:30 – 16:45	<i>Graphene nanoplatelets and carbon nanotubes as effective high-strain property enhancers of an epoxy matrix</i>	<i>Miks Bleija</i>
16:45 - 17:00	<i>Static thermographic method for fatigue limit assessment of composite materials</i>	<i>Cosmin Popa</i>
17:00 – 17:15	<i>Speckle techniques with a high speed camera for deformation evaluation of composites during impact testing</i>	<i>Mikhail Levchenko</i>
17:15 - 17:30	SUMMARY AND FAREWELL	



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Poster Presentations

Özgen Çolak Çakır, Material Model Development from Quasi Static to High Strain Rate for Thermoset Polymers
Yıldız Technical University

Vineta Srebrekoska, Predicting the ballistic strength of composite laminates subjected to a perpendicular impact by a solid projectile
Goce Delcev University Stip

Nikoloz Chikhradze, Experimental Study of the Explosion Resistant Ability of Low Carbon Steel Plates with Intermediate Aluminum Sheet Layers
Mining Institute Georgia

Amine Haj Taieb, A review of textile Composite Structures under High Strain-Rate Loading Conditions
University of Sfax

Aleksandre Vanishvili, Development of basalt based Fiber-Metal Laminate with advanced mechanical properties
Mining Institute Georgia

Yang Zhang, Polish Simulation and Quantification Method of Crack Propagation Damage of Adhesively Bonded Composite Structures under High Strain Rates
Academy of Sciences

Müslüm Kaplan, Bartın Poly (Vinylidene Fluoride)/Carbon Nanotube/Semiconductor Inorganic Nanoparticles Composites for Piezoresistive Sensing
University

Elena Stoykova, Hidden defects detection under tensile loading by laser speckle photometry
Bulgarian Academy of Sciences

Maraym Viqar, Laser speckle photometry with binary patterns
Bulgarian Academy of Sciences

Tomasz Waldowski, FBG based lamb wave mode separation for damage localisation
Polish Academy of Sciences

Violeta Madjarova, Hilbert transform method for electronic speckle pattern interferometry to study plastic deformation of materials under tensile stress
Bulgarian Academy of Sciences

Petros Gkertzos, Machine learning based damage localisation utilising finite element modelling, intended for tinyML applications
University of Patras

Svetlana Risteska, Influence of strain rate and type of matrix on mechanical properties of carbon thermoplastic laminates under dynamic compression produce with LATP/LAFP
Goca Delcev University



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Speakers*

NAME	ORGANISATION	NAME	ORGANISATION
Hatice Sinem Sas	Sabanci University	Krzysztof Dragan	Air Force Institute of Technology (online)
Patricia Verleysen	Ghent University	Gabriele Jovarauskaite	Kaunas University of Technology
Kara Peters	North Caroline State University	Pawel Malinowski	Polish Academy of Sciences
Nenad Djordjevic	Brunel University	Julius Vincent Krause	ETH Zurich
Dayou Ma	Politecnico di Milano	Samet Demirel	Karadeniz Technical University
David Ghavanini	Ghent University	Volkan Eskizeybek	Canakkale Onsekiz Mart Üniversitesi
Mauro Zarrelli	CNR - National Research Council of Italy	Rohan Soman	Polish Academy of Sciences
Andreas Hornig	TUD Dresden University of Technology	Andrei Anisimov	TU Delft
Michele Meo	University of Southampton	Tatjana Glaskova-Kuzmina	University of Latvia
Ivica Smojver	University of Zagreb	Mattia Utzeri	Polytechnique University of Marche
Çağatay Yılmaz	Abdullah Gül University	Oskars Platnieks	Riga Technical University
Sara Saeed Abdulrahman Eltahir	Abdullah Gül University	Miks Bleija	Riga Technical University
André Haufe	DYNAmore GmbH, an Ansys Company	Cosmin Popa	Politehnica University Timisoara
Christian Bräunig	SGS-TÜV Saar	Mikhail Levchenko	Bulgarian Academy of Sciences

* listed per order of talks



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HISTRATE: A route to certification-by-analysis for impact-loaded aeronautical composite structures

Patricia Verleysen,^{1,*} and Michele Meo²

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Abstract: Launched in 2022 under the EU's Cost Action Programme, the HISTRATE project aims to remove certification barriers in the aerospace sector by paving the way for "certification-by-analysis for composite structures under high rate loading". HISTRATE is on a mission to bring about a significant change by substituting traditional validation methods with simulation-driven techniques, thereby reducing the necessity for complex testing. The project thrives on the collective expertise of a varied group of academic and industry professionals, fostering a culture of shared learning. By combining understandings from different scales, from the elements of materials to composite parts, HISTRATE is poised to transform the design and certification of ultra-high-performance, safe, and novel advanced composites for real-world applications facing high strain rate loading.

1. Introduction

The escalating demands of climate change and performance requirements in the aerospace industry have led to an increased reliance on fibre-reinforced composites. Particularly in applications subject to extreme dynamic events, there is a pressing need for a robust framework for the Certification-by-Analysis (CbA) of advanced composite load-bearing structures under high rate loading. Launched in 2022, the HISTRATE project, part of the EU Cost Action initiative, is dedicated to laying the scientific and technological groundwork necessary for this endeavour.

HISTRATE is pursuing a fundamental transformation in simulation techniques, high strain rate testing procedures, and intelligent sensing instruments to replace the conventional building block approach used for validation and product certification. This transition is intended to diminish the need for complex and laborious testing by the use of simulations, thereby enabling modifications in composition and performance without necessitating recertification.

The achievement of HISTRATE's goals is heavily dependent on the pooled knowledge within its wide-ranging network, which includes academic and industrial specialists in the expansive field of composites from both Europe and beyond. HISTRATE actively promotes collaborative interaction among partners, fostering knowledge exchange and cross-fertilisation across diverse fields of expertise. This includes material and component testing, measurement and monitoring techniques, modelling methodologies, and standardisation and certification processes. By combining knowledge across various length scales, from material constituents to structural elements, HISTRATE aims to radically transform the discovery, development, and design of ultra-high-performance, safe, and innovative advanced composites for real-world applications subjected to high strain rate loading.

2. Results and Conclusions

The foundation of virtual design and certification-by-analysis rests on two pillars: robust, multiscale and multiphysics modelling validated with novel testing, sensing and measuring techniques. Integration of knowledge and methodologies used in different fields is crucial. This is reflected in the targeted materials testing protocols: by the use of advanced sensors and state-of-the-art measurement techniques, and a far-reaching integration of numerical simulations from the test design to result analysis stage, significantly richer and more useful test datasets are aimed at. Maximizing the use of the currently available powerful measurement and modelling capabilities not only paves the way for more efficient testing schemes [1], but also enables the imposition of test conditions that closely mirror real-world scenarios. Integrating full field and discrete measurements, together with accurate and reliable in-situ and post-impact damage characterisation guarantees a more reliable calibration and validation of material model parameter.

The new simulation tools will feature a theoretical framework of configurational continuum mechanics, nonlocal continua and irreversible thermodynamics. The models for the new materials must be able to capture highly complex and localised phenomena, including damage initiation, progression and failure, under multiaxial loading. A consistent, physically-based multiscale simulation strategy informed by the dynamic properties of the

constituents, i.e., fibre, matrix and fibre/matrix interface, measured with novel testing and sensing methodologies is needed.

The process of defining activities and priorities within HISTRATE is driven by a comprehensive survey of the industry partners concerned. This survey revealed a significant gap between the standards set by certification authorities and the requirements imposed by the nature of the impact load scenarios. This mismatch often forces industry stakeholders to rely on testing, measurement and modelling techniques that are behind the state-of-the-art.

HISTRATE is committed to bridging this gap and fostering a shift in industry practices. By staying abreast of the latest advances and applying them to specific use cases proposed by industry, HISTRATE aims to demonstrate the many benefits of the CbA approach and thereby encourage its wider adoption for high rate loading composite structures.

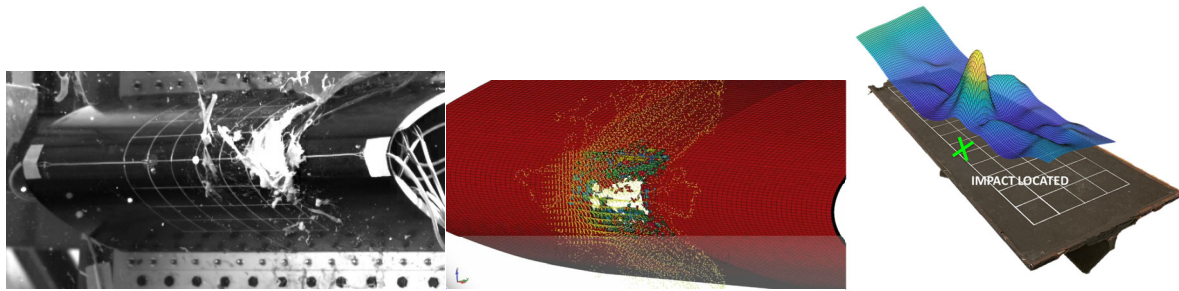


Fig. 1. Birdstrike on a wing leading edge engine blade: (left) test, (middle) FEM, and (right) Stiffened panel impact monitoring [2].

3. References

- [1] Pierron, F., 2023, "Material Testing 2.0: A brief review," *Strain*, 59, <https://doi.org/10.1111/str.12434>
- [2] Cuomo, S., Bätzel, T., Modler, N., Hornig, A., and Meo M., 2022, "High velocity impact on generic CFRP blade specimen: baseline free method for impact localisation and damage assessment on complex structures," *Smart Materials and Structures*, 31, <https://doi.org/10.1088/1361-665X/ac6d90>



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**Session 1 - Novel simulation methods
and best practices for
composites under high strain rates
(WG4)**

Modelling of High Velocity Impact on Carbon Fibre Reinforced Plastics

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Abstract: Thermodynamically consistent damage evolution model for carbon fibre reinforced composites (CFRP) was developed and coupled with a vector equation of state. This made the constitutive model capable of modelling shock wave propagation within orthotropic materials. Damage evolution was defined in terms of a modified Tuler Bucher criteria. The constitutive model was implemented into Lawrence Livermore National Laboratory (LLNL) DYNA3D nonlinear hydrocode [1]. The numerically obtained results were validated against post impact experimental data of spherical projectile impact on a composite panel at 1200m/s, where the discrepancy between the experiments and numerical results was within 8%.

Keywords: shock wave, impact, damage, composites, hydrocode;

1. Introduction

Across a large number of industrial sectors, the composites are the first choice of the design of lightweight, more energy efficient and net zero structures. However, the design of composite structures is still limited by the lack of understanding of composite materials, especially their response to high rate dynamic loading, such as the high velocity impacts. Complexity arises primarily from the extreme level of anisotropy and pronounced heterogeneity. Due to these uncertainties, modern simulation tools are limited in their capability to predict material degradation, its progression and failure. The challenging areas in the predictive modelling of dynamic behaviour of composite structures and materials remain to be modelling of damage and failure including damage induced by shock wave propagation outside of the impact zone as well as modelling of damage for the purpose of residual strength assessment and for structural health monitoring.

2. Constitutive Model for Damage

The key feature of a constitutive model, capable of modelling the shock wave propagation through material is decomposition of stress tensor, which consists of two parts: pressure that is updated in the Equation of State (EOS) and shear part updated in the strength part of the model. This stress decomposition for an orthotropic material formulation is complicated due to the fact that volumetric part of the deformation tensor is not colinear with the hydrostat. As the solution proposed by Anderson [2] was not capable of predicting material response accurately, an alternative decomposition of the stress tensor published in [3] was used in this model.

Damage part of the constitutive model was derived in the framework of irreversible thermodynamics, starting from Clausius-Duham inequality, with Helmholtz free energy $\psi(\varepsilon_{ij}^e, \varepsilon_{ij}^{in}, \omega)$ as thermodynamic potential, as:

$$\gamma = \left(\frac{1}{\rho} \sigma_{ij} - \frac{\partial \psi}{\partial \varepsilon_{ij}^{in}} \right) \dot{\varepsilon}_{ij}^{in} - \frac{\partial \psi}{\partial \omega} \dot{\omega} - \frac{1}{\rho} \frac{q \cdot \text{grad} \theta}{\theta} \geq 0 \quad (1)$$

Where σ_{ij} is stress tensor, ε_{ij}^e and ε_{ij}^{in} elastic and inelastic strain tensors, ω damage variables, ρ is density and θ and q are temperature and heat flux, respectively. Three terms in the inequality (1) above represent three different dissipative processes, but in the current model formulation, damage is the only dissipative mechanism. It is controlled by damage variable rate, $\dot{\omega}$, and the gradient of the free energy with respect to damage variable. Damage variable are obtained by using modified Tuler Bucher criterion [4], where a convenient function of stress, usually $(\sigma - \sigma_0)^\lambda$, is chosen and integrated for time to failure, t_{cr} . In the current version of the model, evolution of the damage variables for in plane failure and delamination are respectively defined as:

$$\dot{\omega} = \dot{\omega}(\omega, \sigma) = \Omega_\omega \left(\frac{\sigma}{C_m(1-\omega)} - \frac{\sigma_{CR}}{C_m} \right) H \left(\frac{\sigma}{C_m(1-\omega)} - \frac{\sigma_{CR}}{C_m} \right) \quad (2)$$

$$\dot{\omega}_{del} = \dot{\omega}_{del}(\omega, \sigma) = \Omega_{del} \left(\frac{\sigma_{33}}{C_{33}(1-\omega_3)} - \frac{\sigma_{CRdel}}{C_{33}} \right) H \left(\frac{\sigma_{33}}{C_{33}(1-\omega_3)} - \frac{\sigma_{CRdel}}{C_{33}} \right) \quad (3)$$

where: Ω_{ω} , Ω_{del} are material parameters – rate of damage evolution, σ and σ_{33} are in-plane effective stress and out of plane stress respectively, σ_{CR} and σ_{CRdel} are critical in plane stress and critical out of plane stress, C_m and C_{33} are maximum in-plane stiffness member and through the thickness coefficient respectively, H is Heaviside function. Stiffness tensor of damaged material is defined using energy equivalence principle [5], i.e.:

$$\tilde{\mathbf{C}} = \mathbf{M}(\omega)^{-1} : \mathbf{C} : \mathbf{M}(\omega)^{-T} \quad (4)$$

where $\mathbf{M}(\omega)$ is the damage effect tensor and $\mathbf{C}$ is the stiffness matrix of virgin material. Once the damaged stiffness matrix is calculated, the stress is updated to account for damage effects. The proposed damage model was implemented into the LLNL code DYNA3D [1] and coupled with an orthotropic elastic constitutive model and EoS.

3. Numerical Validation Results

High velocity impact of a spherical projectile on a woven CFRP plate tests in normal direction at 1200m/s were used for the model validation. CFRP was modelled as a quasi orthotropic material, with three elements through the thickness of a ply. The simulation results are shown in Fig. 1 and compared to the post impact measurements of diameters of the hole in two principle material directions and size of the delamination zone [6] in Table 1.

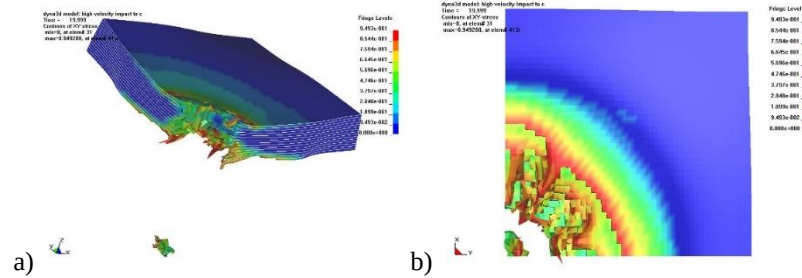


Fig. 1 Delamination distribution in the composite target: a) through thickness; b) back ply

Table 1 Diameter of hole (x1 – x2) and size of delamination zone in two perpendicular directions (y1 – y2)

	Impact face				Rear Face	
	x1 (mm)	x2 (mm)	y1 (mm)	y2 (mm)	y1 (mm)	y2 (mm)
Experiment	11.7	12.8	19.8	24.3	36.5	33.3
Simulation	11.1	11.7	19.02	20.26	35.40	32.24

4. Conclusions

Current version of the model was capable of predicting size of the hole and delamination zone for the considered impact case, with the accuracy within 8% for all measurements, but one – size of delamination zone on the impact face in material direction 2 (y2).

References

- [1] Hallquist J.O.; Lin J.I., 2005. "DYNA3D: A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics User Manual." Methods Development Group Mechanical Eng., LLNL.
- [2] Anderson CE, Cox PA, Johnson GR, Maudlin PJ, 1994, A constitutive formulation for anisotropic materials suitable for wave propagation computer programs-II, *Comput Mech*, 15(3), 994, doi:10.1007/BF00375030.
- [3] Vignjevic R, Campbell JC, Bourne NK, Djordjevic N., 2008, "Modelling shock waves in orthotropic elastic materials," *J Appl Phys*, 104(4), doi: 10.1063/1.2970160.
- [4] Tuler FR and Butcher BM, 1968 "A criterion for the time dependence of dynamic fracture," *International Journal of Fracture Mechanics* 4(4), pp. 431–437, doi: 10.1007/BF00186808.
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- [6] Hazell PJ, Cowie A, Kister G, Stennett C and G. A. Cooper, 2008 "Penetration of a woven CFRP laminate by a high velocity steel sphere impacting at velocities of up to 1875m/s," *Int J Impact Eng* 36(9), pp. 1136–1142, doi: 10.1016/j.ijimpeng.2008.12.001.

Constitutive model for fibre reinforced composites with progressive damage based on the spectral decomposition of material stiffness tensor

Rade Vignjevic^{1*}, Nenad Djordjevic¹, Agata Galka¹ and Kevin Hughes¹

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Abstract: The approach used in this work is based on decomposition of strain energy with spectral decomposition of the material stiffness tensor and an assumption that each strain energy component represents free energy for a characteristic deformation mode. The criteria for damage initiation are triggered when the strain energy for a deformation mode exceeds a specified critical limit. Damage evolution is modelled by reduction of the principal material stiffness based on the effective stress concept and the strain energy equivalence. The model is coupled with a vector shock Equation-of-State and implemented in LLNL-DYNA3d. Validation was conducted for a range of impact loadings, where the numerical results were within 10% of the impact experimental measurements.

Keywords: progressive damage in composites, dynamic loading, high velocity impact, finite element modelling

1. Introduction

Although the linear – elastic behaviour of the long fibres composites is well understood, there is still a significant uncertainty in prediction of damage initiation, damage evolution and material failure especially for dynamic loading cases characterised with triaxial state of stress or strain. Consequently, simplifying assumptions are often unavoidable in development of constitutive models capable of accurately predicting damage.

In the current version of the model, the deformation modes are not interacting at continuum scale due to orthogonality of the eigenvectors, i.e. the stiffness tensor symmetry. Damage and its evolution are modelled by reduction of the principal material stiffness based on the effective stress concept and the hypothesis of strain energy equivalence. The model is coupled with a vector shock Equation of State.

2. Model Formulation

The model is developed in the framework of irreversible thermodynamics at the continuum scale for transversally isotropic material symmetry, starting from the work published in [1], [2], where the material stiffness tensor is spectrally decomposed as:

$$\mathbf{C} = \sum_{i=I}^{VI} \lambda^i \mathbf{P}^i \quad \mathbf{P}^i = \mathbf{v}^i \otimes \mathbf{v}^i \quad (1)$$

Where: $i = I, II, \dots, VI$ represents the mode index, λ^i are eigenvalues, $\mathbf{v}^i$ are unit eigenvectors and $\mathbf{P}^i$ are projection operator tensors. There are six independent damage modes so the stiffness tensor of a damaged material is defined as:

$$\mathbf{C}(d^i) = \sum_{i=I}^{VI} (1-d^i)^2 \lambda_0^i \mathbf{P}^i \quad (2)$$

where d^i are scalar damage variables defined for each failure mode and λ_0^i and eigenvalues of the virgin/undamaged stiffness tensor. The stiffness tensor from Equation (2) constitutes the Helmholtz free energy as the thermodynamic potential, consisting of strain energy and damage mode associated potentials, which determine state of deformation and damage evolution, respectively:

$$\Psi(\boldsymbol{\varepsilon}, d^i, h^i) = \frac{1}{2} \sum_{i=I}^{VI} (1-d^i)^2 \lambda_0^i (\boldsymbol{\varepsilon}^i)^2 + \frac{1}{2} \sum_{i=I}^{VI} \kappa^i (h^i)^2 = \frac{1}{2} \sum_{i=I}^{VI} \left((1-d^i)^2 \lambda_0^i (\boldsymbol{\varepsilon}^i)^2 + \kappa^i (h^i)^2 \right) = \sum_{i=I}^{VI} \Psi_i$$

Where: κ^i and h^i are modal damage evolution parameter and modal damage evolution variable, respectively. Damage evolution begins when the strain energy reaches a critical value. The model is applicable for the levels of damage where the eigenvectors remain constant during the deformation process. More detailed model description can be found in [3].

3. Results

The constitutive model was implemented into Lawrence Livermore National Laboratory (LLNL) Dyna3d nonlinear transient finite element code [4]. The material model was verified in a series of single element tests and validated against experimental data of two plate impact tests carried out with an aerospace grade carbon fibre reinforced plastic.

Plate impact tests are the experiments for determination of the material parameters of Equation of State, where the materials undergo uniaxial state of strain. The tests used here were performed in two impact directions: through thickness direction and in a fibre direction, for which the experimental results were published in [5]. Fig. 1 shows comparison of the experimental and simulation results obtained for two impact directions at the back of the target plate.

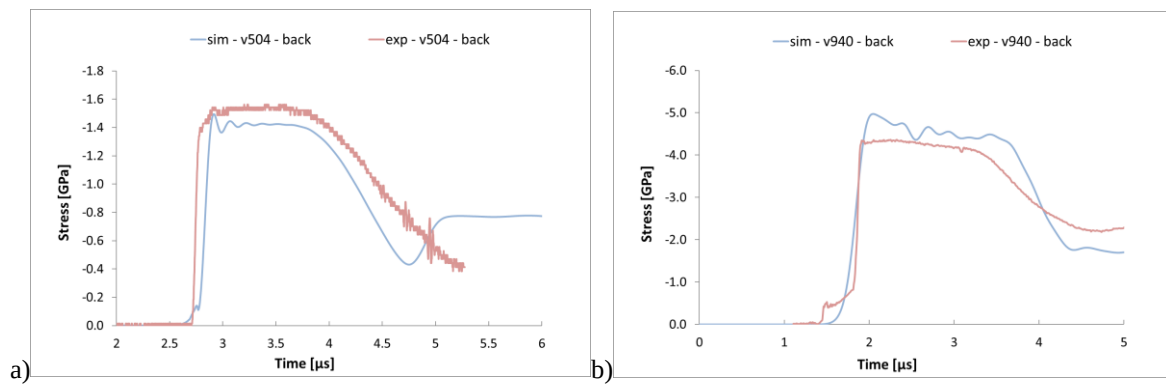


Fig. 1 Back surface stress trases for plate imact test: a) in through thickness direction; b) in a fibre direction

4. Conclusions

The constitutive model predicted the composite material response to the considered shock loading in through thickness direction with accuracy of 5%. In the fibre direction the accuracy was around 10%. The work in progress is focused on refinement of the formulation of vector Equation of State and interaction of the damage modes in order to improve performance of the model for complex stress states.

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Characterization of matrix materials for composites considering strain rate effect

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Abstract:

The assessment of composite materials under extreme loading conditions can be regarded as one of the most demanding cases, for both research and industrial applications. The correct understanding and calibration of dynamic mechanical properties of composites, among them the strain rate effect, is a key aspect for the design of composite structures towards specific needs under extreme conditions. Based on previous experimental activities [1-3], it has been concluded that the mechanical properties of the matrix involved in the manufacturing of composites are important for their global mechanical response under impact cases. Considering different types of polymers, which can be used as matrix for composites, their mechanical properties must be investigated in order to define the mechanical responses of the related composites under impact loading.

The main objective of present study is to investigate the mechanical properties of polymer materials for optimizing a matrix of fibre-reinforced polymer composites with high resistance to impact loading. Two different types of polymer materials were considered: epoxy (epoxy resin AR260 with AH260 hardener (AR/AH260) – 100/26 g/g ratio, supplied by Barracuda Advanced Composites) and polyurethane (castor oil with a hydroxyl value of 160 mg KOH/g and a functionality of 2.7, and polypropylene oxide with a hydroxyl value of 110 mg KOH/g and a functionality of 2.0.). While epoxy has been widely used as matrix material for composites due to its low density as well as stable chemical properties, polyurethane has only been recently introduced for its outstanding performance on large deformation and energy absorption. However, there is still room for investigation into the mechanical behaviour of these two types of polymers, especially when dynamic loading conditions are applied, i.e., different strain rates are considered.

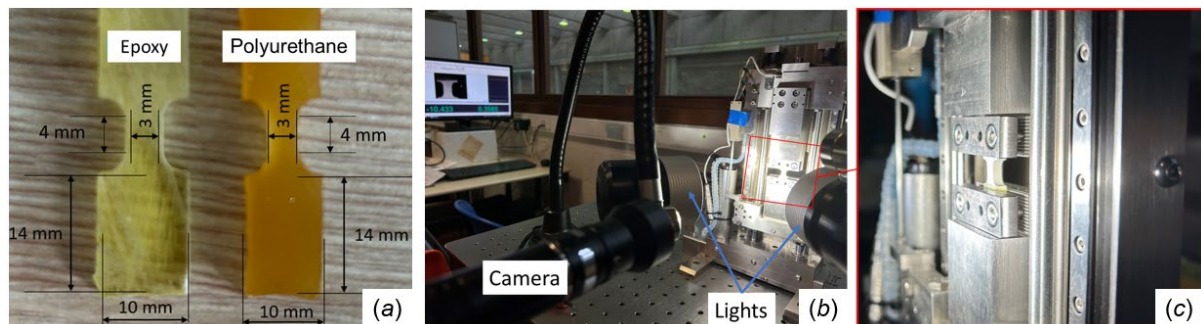


Figure 1 Sample dimension (a), experimental setups (b) and sample under testing (c)

As indicated in Figure 1, small samples with gauge length equal to 5 mm were considered in the current work in order to be dynamically tested by means of a split Hopkinson bar setup, for extremely high strain rates. For an accurate measurement of the deformation, which is especially critical for polyurethane because of the expected large deformation, the Digital Image Correlation (DIC) technology was applied. To this purpose, a very fine speckle pattern was painted on the front surface of the sample to obtain reliable strain measurements. Considering the primarily in-plane deformation of uniaxial tensile tests, a 2D-DIC setup consisting of a high resolution camera and two illumination lights was utilised in the present work, as shown in Figure 1.

Analysing the experimental results, significant differences can be found for epoxy and polyurethane under tension, Figure 2. Epoxy presents a higher strength compared with the polyurethane, but the elongation of the polyurethane at failure is much higher. Regarding the global response under tensile loading, the epoxy presents low capability on deformation and brittle failure, while the deformation of the polyurethane is more global, challenging the measurement of the strain, but indicating more resistance towards large displacement loading which might be

useful for impact cases. Besides, various strain rates were also considered in the work with a range between 0.1/s and 1/s, where the variation of the strength starts.

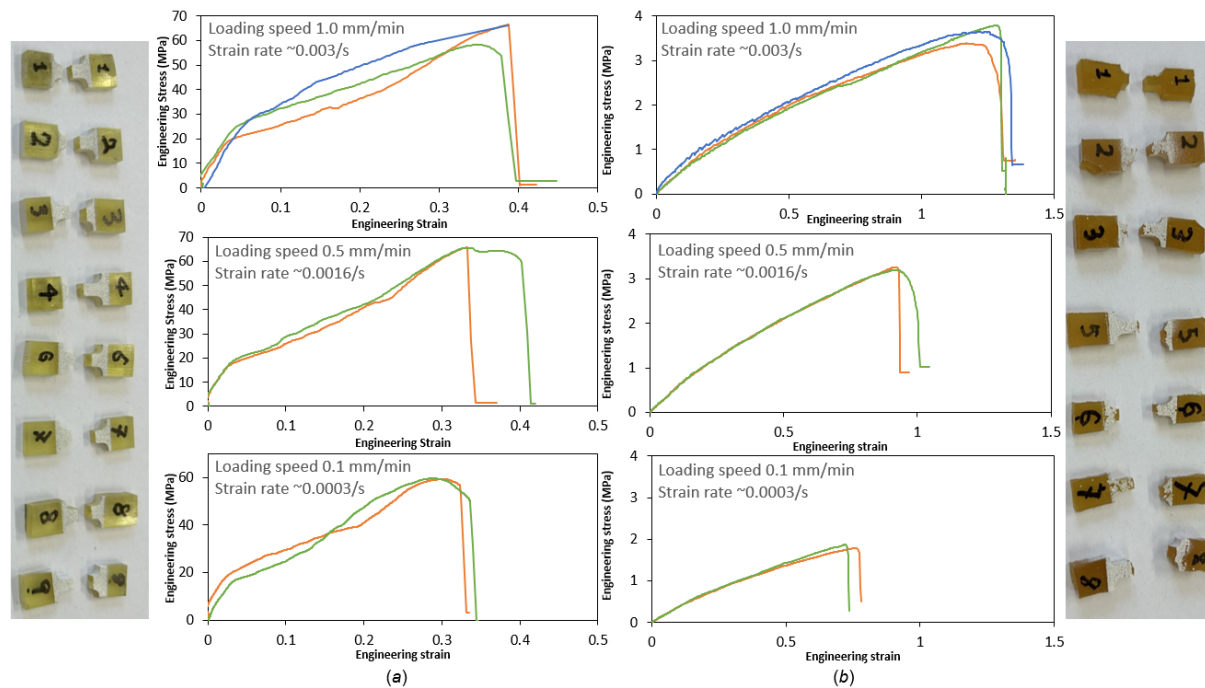


Figure 2 Engineering stress and strain curves with failure position for epoxy (a) and polyurethane (b)

The current experimental work provides an understanding on the behavior of the polymer materials, determining the mechanical features of epoxy with high strength and polyurethane with large deformation. Therefore, an optimal choice on the material of matrix for composite materials can be achieved according to the applications of composites for extreme loading considerations.

Acknowledgements

I would like to acknowledge the STSM (Short-Term Scientific Mission) award from HISTRATE COST Action (CA21155-Advanced Composites under High STRAIn raTEs loading: a route to certification-by-analysis) for financial support on the experimental activities in the current work.

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An advanced rheological model to predict the behaviour of aromatic hyperbranched polyester/RTM6 epoxy nanocomposites

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Abstract: Aromatic hyperbranched polyester (AHBP) epoxies exhibit highly nonlinear mechanical behaviour under different strain rates during monotonic loading. Due to their polymeric nature, conventional metal plasticity models often fail to represent their response accurately. In this study, we employed a three-network viscoplastic (TNV) rheological constitutive model, which effectively fitted experimental data. Material model parameters were calibrated using compression test data, and the results indicated that the model could effectively capture the strain-softening region of the plastic flow. Moreover, unlike the J2 plasticity model, the proposed model showed its ability to consider volume changes during deformation.

1. Introduction

Owing to their advantages of high modulus/strength, epoxy resins have been widely used in structural and aeronautical applications as adhesive or matrix materials [1,2]. However, due to their highly cross-linked microstructure, brittleness is an undesirable property of epoxy materials [3]. For this reason, the addition of toughening agents, including aromatic hyperbranched polyester (AHBP), has been considered to improve the impact resistance and vulnerability to crack propagation [4,5]. To characterize these materials, a wide range of experimental campaigns under different loading conditions at quasi-static and dynamic rates were conducted, as can be found in [1, 2, 4, 5]. Nevertheless, to date, there has been limited exploration into proposing an appropriate material model capable of accurately representing the behaviour of both neat and toughened epoxies [6,7]. In this work, three network viscoplastic (TNV) model, which follows a specialized parallel rheological framework (PRF) is used. More details about this constitutive model are given below:

2. Three-network viscoplastic (TNV) model

The three network viscoplastic (TNV) model is a general purpose viscoplastic constitutive model adept at mirroring the experimental behavior of numerous thermoplastics and thermosets. With its capacity to accommodate viscoelastic and viscoplastic deformation gradients alongside strain rate and pressure dependencies, it offers a comprehensive framework for capturing nonlinear polymeric responses. This constitutive model consists of three parallel networks, as shown in the rheological representation in **Fig. 1**, wherein the total deformation gradient F is the same on all three networks $F = F_A = F_B = F_C$, and the total Cauchy stress is given by $\sigma = \sigma_A + \sigma_B + \sigma_C$. The viscoplastic deformation gradient acting on a network can be decomposed into elastic and viscoplastic parts:

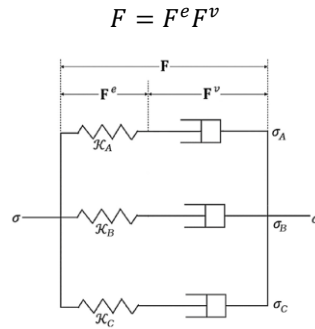


Fig. 1. Rheological representation of the constitutive three network viscoplastic (TNV) model.

The Cauchy stress acting on a specific network is given by the Yeoh model[8]:

$$\sigma = \frac{2f_e\eta}{J^e} \{C_{10} + 2C_{20}(I_1 - 3) + 2C_{30}(I_1 - 3)^2\} \text{dev}[\mathbf{b}] + [k_1(J^e - 1) + k_2(J^e - 1)^3 + k_3(J^e - 1)^5] \mathbf{I}$$

Where σ is the Cauchy stress, f_e is the plastic flow evolution factor, $[C_{10}, C_{20}, C_{30}]$ are the Yeoh parameters, J^e is the determinant of the elastic deformation gradient, η is the Mullins damage factor, $\mathbf{b}$ is the left Cauchy-Green deformation tensor, I_1 is the first principal invariant of Cauchy tensor, and $[k_1, k_2, k_3]$ are the bulk moduli.

The Mullins damage factor η is as the following:

$$\eta = 1 - \frac{1}{r} \operatorname{erf} \left[\frac{U_{dev}^{\max A} - U_{dev}^A}{\hat{U} + \beta U_{dev}^{\max A}} \right]$$

Where $[r, \hat{U}, \beta]$ are material parameters, and U_{dev}^A is the current deviatoric strain energy density in network A, and $U_{dev}^{\max A}$ is the maximum deviatoric strain energy density in the same network. The Mullins damage is not taken into account if $r = 0$. The plastic flow evolution f_ϵ can be derived using the following differential equation:

$$\frac{df_\epsilon}{dt} = \frac{1}{c_\epsilon} (f_s - f_\epsilon) \dot{\gamma}_A$$

Wherein $[f_s, c_\epsilon]$ represent material parameters, with the condition that $f_\epsilon = 1$ at $t = 0$ and $\dot{\gamma}_A$ serves as a constant introduced to ensure dimensional consistency. The velocity gradient of the viscoplastic flow of network A can also be written as:

$$\dot{\mathbf{F}}_A = \dot{\gamma}_0 \left[R \left(\frac{\tau_A}{f_p \cdot f_{ep} \cdot \hat{\tau}_A} - 0.001 \right) \right]^m F_A^{e-1} [N_A + b \operatorname{sign}(\operatorname{tr}[\sigma])] \mathbf{I} \mathbf{F}$$

Where $\hat{\tau}_A$ presents the flow resistance of the network, m is the stress exponent, f_p is the pressure-dependent viscoplastic flow, N_A is a tensor which specifies the direction of the driving deviatoric stress, and the term $b \operatorname{sign}(\operatorname{tr}[\sigma])$ provides the volumetric viscoplastic flow. $R(x) = (\frac{x+|x|}{2})$ is a ramp function, $\dot{\gamma}_0 = 1/s$ is a constant for dimensional consistency, and b is a material parameter.

3. Calibrated model

Using the briefly described constitutive equations, the material parameters of the model were identified using the compression data at different strain rates using the Levenberg-Marquardt optimization algorithm. This procedure was done using the Polyumod software MCalibration[9]. **Table 1** and **Fig.2** demonstrate the obtained material parameters and the prediction of the model compared to the experimental data.

Table 1. Calibration parameters of TNV model for neat epoxy

Description	Symbol [units]	Network A	Network B	Network C
Yeoh parameter 1	C_{10} [MPa]	13.84	291.72	226.01
Yeoh parameter 2 and 3	C_{20}, C_{30} [MPa]	0	0	0
Bulk modulus 1	k_1 [MPa]	3000	3000	3000
Bulk modulus 2 and 3	k_2, k_3 [MPa]	0	0	0
Flow resistance of the network	$\hat{\tau}_A$ [MPa]	-	20.43	53.27
Stress component	m	-	17.34	19.28
Volumetric flow coefficient	b	-	0*	0*
Pressure dependence of flow	p_0	-	0*	0*
Yield evolution of	f_f	-	2.69	0.2
Yield evolution of strain	ϵ_f	-	0.02	0.2

* if volume conservation and pressure independence assumptions are considered.

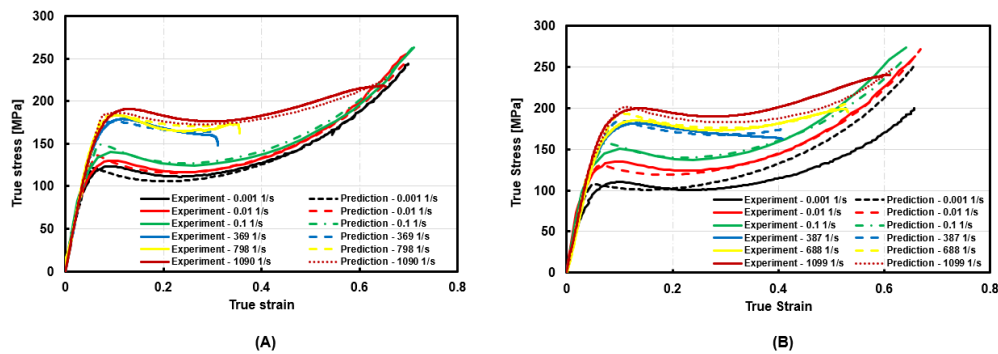


Fig. 2. Comparison between three network viscoplastic (TNV) model predictions and the experimental data of neat epoxy (A) and AHBP 5% (B)

As can be seen, the model was able to capture the stress-strain behaviour of the material well at different strain rates with a satisfactory fit.

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*Advanced Composites under High Strain Rate
Loading A Route to Certification-by-Analysis*

2024 Conference
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**Session 2 - Novel composite materials
for high strain rate applications (WG3)**

The Effect of Hyperbranched Polymers on Fracture: from nanocomposites to composites.

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Abstract. The effect on the mechanical properties of a patented epoxy resin of a glassy hyperbranched polymer (HBP), characterized by a Tg of 77°C, was investigated. The filler was dispersed into a hosting matrix by a solvent-free high shear rate mixing technique and the obtained nanocomposites were characterized in term of fracture toughness, revealing enhanced properties due to the HBPs presence ($\Delta K_{IC}=+9\%$, $\Delta G_C=+13\%$). Modified resin was used to impregnate UD carbon fibers to manufacture CFRP and later tested to analyze the Interlaminar Fracture Toughness in Mode I as well as Compression After Impact performance. It was found that while mode I toughness tests reveals a remarkable increase of both, onset and propagation ($\Delta G_{IC}^{onset}=+29\%$ and $\Delta G_{IC}^{prop}=+53\%$) the CAI tests record negligibly variations. Further investigations on fracture toughness under mode II configuration will be performed.

Materials and Methods

1.1. Materials

4,4-Bis(4-hydroxyphenyl) valeric acid (diphenolic acid), tin(II) 2-ethylhexanoate (Sn(Oct)2), tetrahydrofuran (THF), and water were purchased from Sigma-Aldrich and used as received. The epoxy system used for nanocomposites preparation is a patented epoxy resin, labeled HXE75 [1], characterized by a room temperature viscosity of about 10^4 Pas with a minimum plateau value at 100°C of about 1 Pas. The carbon fibers utilized in the composite fabrication process are Toray T700 UD, which possess a tensile strength of 4900 MPa and a tensile modulus of 230 GPa.

1.2. Hyperbranched (HBPs) synthesis and nanocomposites/composites manufacturing

The HBP was synthesized using a mass polycondensation of diphenolic acid in presence of tin octaoate as catalyzer, following the reported procedure in a previous work [2]. The synthesized material appears as a brown-amber glassy powder. The HBP powder was mixed with the epoxy resin by industrial high shear rate mixer with a high torque power and the filler concentration was set to 3wt% according to previous work results [2]. The uncured HBP loaded system was used to manufacture both crosslinked nanocomposite samples and modified carbon fiber reinforced composites. In both cases, the materials were cured according to the neat resin curing profile, e.g. 2h @120°C.

CFRP prepregs loaded with HBPs were manufactured by a modified hot melting plant, where uncured resin was firstly filmed on siliconized paper and then sandwiched on UD carbon fiber layer; later, the prepared prepregs were layered up according to the considered test standards.

1.3. Characterization

The Single Edge Notched Beam (SENB) geometry was employed to measure the nanocomposites Mode-I fracture toughness, and samples were manufactured with nominal dimensions $30 \times 7 \times 3.5$ mm³ and a notch depth of 3.5 mm. The crosshead speed was set to 10 mm/min, following the test standard ASTM D5045.

Modified CFRP were characterized in term of Mode I Interlaminar Fracture Toughness (G_{IC}) and Compression After Impact (CAI). According to ASTM D5528, the Mode I Interlaminar Fracture Toughness sample geometry was $125 \times 25 \times 4$ mm³ with a pre-crack length, realized introducing a 13µm kapton foil during lamination process, of 50 mm. CAI tests were performed, following the ASTM D7136 standard, by inducing a low-speed impact damage (32J impact event) into the composite specimen and later performing a guided compression test to assess the residual strength level. The CAI laminates are characterized by a multidirectional stacking sequence, i.e. $[45/0/-45/90]_{4S}$ with nominal dimensions of 150x100 mm. To acquire the laminate deformation, a Digital Image Correlation equipment (3C Vision Correlated Solution DIC Equip.) was set up during the tests, monitoring the full deformation field by applying a pattern on a specific area and recording the pattern changes by a high definition camera.

2. Results and Discussion

DSC analysis performed on the HBPs filler have shown a Tg of ~77°C, indicating that the material is in a glassy state: the high Tg value can be reasonably attributed to the stiffness of the aromatic segments in the macromolecular chains. Fracture toughness data have shown the effective potentiality of HBP filler on the fractural behavior of the hosting system: the addition of the G_HBP to the HXE75 resin will act as toughening agents into the hosting matrix with an increase of the critical stress intensity factor (K_{IC}) and critical strain energy release rate (G_C) of about 9 % and 13 %, respectively. Considering that the low filler content (in our case of 3 wt%) and the K_{IC} (1.59 MPa m^{1/2}) and G_C (0.76 KJ/m²) neat matrix values are higher among most of the commercial DGEBA-based epoxy resins, this is a significant improvement compared to other works.

In the case of composites, the G_{IC} curves as function of the crack length, also referred as R-curves, are shown in Fig. 1.a. As clearly reported, the presence of HBP will induce a remarkable improvement of mode I interlaminar fracture toughness in terms of both crack initiation (G_{IC}^{onset} - value of G_{IC} at 0 crack length) and propagation (G_{IC}^{prop} - plateau value of G_{IC}) values, highlighting a positive improvement of about 29% and 53%, respectively compared to the neat matrix UD composite.

The increase of interlaminar fracture toughness properties can be attributed to the improvement of the fibers-matrix adhesion (interphase). In fact, the SEM micrographs performed on the fractured samples show a remarkable variation of the failure mechanism, with a predominant cohesive fracture for un-modified samples (fig. 1.b) and a predominant adhesive fracture for the HBPs modified CFRP (fig. 1.c).

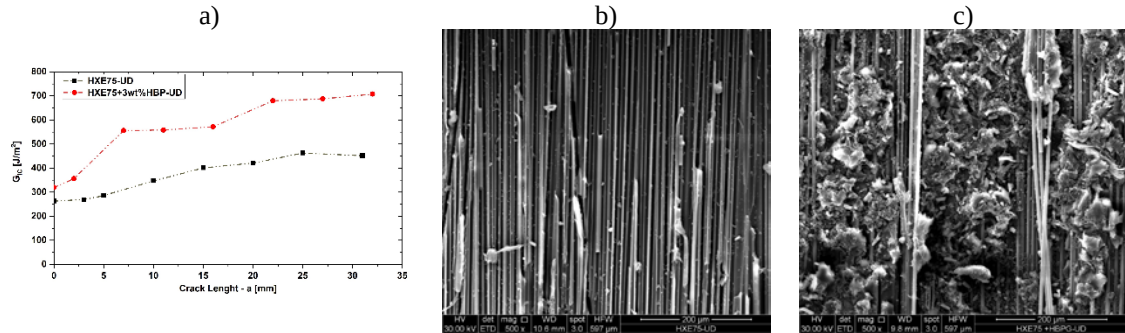


Fig. 1. a) R-curve of the tests CFRP; SEM micrographs of the mode I fractured samples: b) HXE75-UD and c) HXE75+3wt%HBP-UD.

For CAI tests a 32 J impact energy was chosen after preliminary survey energy impact tests. This energy level was identified as the most suitable to induce a BVID damage (i.e., a non-through indentation with a depth ranging from 0.2 to 0.5 mm) through the laminate. Upon the impacts, damaged specimens were tested in compression to evaluate their residual strength and stiffness (Fig. 2. a, b). It is worth to notice that the presence of HBP negligibly influences the residual strength, σ^{CAI} , of the composite laminate, since varying within the experimental error range. By using the Digital Image Correlation technique (DIC) it has been possible to evaluate the out-of-plane strain map of the unfilled (Fig. 2.c) and filled (Fig. 2.d) matrix composite laminates computing their residual stiffness. The most deformed areas are those closest to the central damage, with a typical local buckling deformation characterized by concave and convex points symmetric respect to the center. Table 1 resumes interlaminar fracture toughness and CAI tests.

Future work of the activity will investigate the effect of the hyperbranched filler on Mode II interlaminar fracture toughness of the UD composite and then CAI tests will be analyzed considering the filler induced changes in both Mode I and II testing configurations.

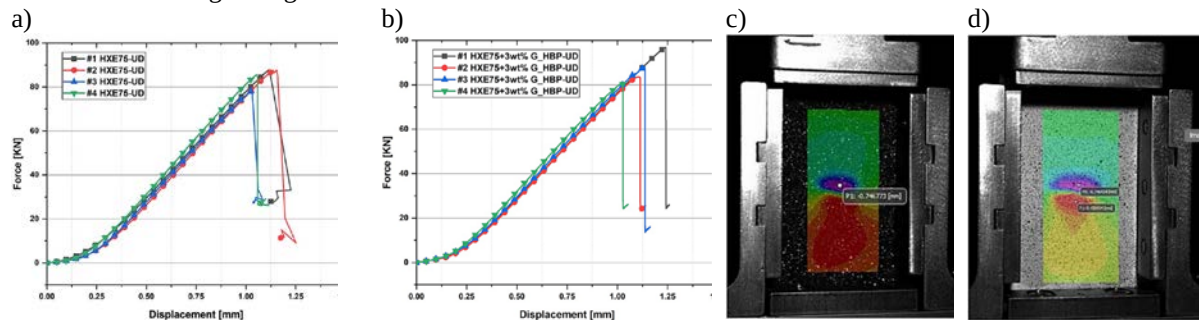


Fig. 2. Compression tests on the impacted a) un-modified and b) HBP modified laminates; deformation field of tested laminates evaluated with DIC technique: c) HXE75-UD and d) HXE75+3wt% HBP-UD.

Table 1. Results of Interlaminar fracture toughness and CAI tests.

Sample	G_{IC}^{onset} [J/m²]	G_{IC}^{prop} [J/m²]	σ^{CAI} [MPa]	E^{CAI} [GPa]
HXE75-UD	272±15	500±127	171±10	44±1
HXE75+3wt%HBP-UD	351±31	766±78	170±8	42± 1

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Soft Body Impact loaded composite structures optimized for energy absorption

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Abstract:

This study explores the enhancement of impact tolerance in fiber-reinforced plastic (FRP) composites, focusing on the controlled initiation of delamination to absorb impact energy and prevent critical failures. By modifying the interlaminar interfaces of FRP structures through perforated interface films, the research demonstrates that delamination can be tailored to improve energy absorption, especially under Soft Body Impact (SBI) loading conditions. Experimental and numerical analyses, including Charpy impact tests, SBI tests on generic blade-like plate structures and Finite Element Modelling (FEM) based optimization, validate the approach. The findings indicate that strategic interface modifications can significantly enhance the structural integrity and energy absorption of FRPs, preventing catastrophic failures while subjected to impact loading.

1. Motivation

Fibre-reinforced plastic composites (FRP) are predestined for use in large fan blades due to their high density-related mechanical properties. This material type also offers the possibility of targeted adjustment of the failure behavior, which is particularly important for load cases such as SBIs like bird strikes. A targeted allowance of delamination in impact-loaded FRP structures causes a reduction in intralaminar stresses [1], which can prevent critical fibre failure [2] and a resulting fan blade off. As a result, the primary effect of absorbing part of the impact energy is achieved by the initiation and propagation of delamination. As a secondary effect, the bending stiffness of the structure decreases, which reduces the stresses, particularly in the blade root. Blade loss due to fibre failure can thus be avoided and the structural integrity is maintained.

2. Methodology for optimizing energy absorption

2.1. Interface modification for tailored delamination behaviour

A rarely considered but promising approach to influencing delamination behavior is the reduction of the interlaminar properties, for example through interface modification using perforated interface films (Fig. 1), to increase the delamination tendency within defined limits [3,4]. The ratio between the area of the perforations and the total area is referred to as the interlaminar contact area.

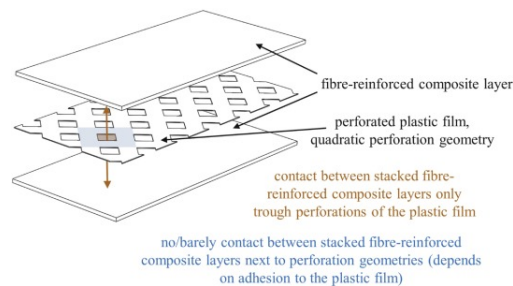


Fig. 1. Interface modification using perforated interface films [4].

In general, the interlaminar strengths and the strain energy release rates are influenced by the interface modification. In the case of adherent perforated films, the properties increase degressively with increasing contact area [3], whereas in the case of non-adherent films, the properties increase progressively [4].

2.2. Optimization strategy

The influence of the interface modification on structural failure is investigated experimentally and numerically by Charpy Impact tests. Experimental studies show that a uniform interlaminar interface modification can, on the one hand, increase the total energy absorption and, on the other hand, lead to a more pronounced "pseudo-ductile"

failure behaviour [4]. Using LS-DYNA, the failure behaviour of interface-modified composites under Charpy Impact loading is studied numerically using FEM [5]. The simulations confirm the results of the experiments: By deliberately inducing delamination, the structural energy absorption can be significantly increased. Furthermore, it was found that the variation of the interface design within one interface layer as well as the distribution of different modifications over the thickness have a small impact on the structural behavior.

3. Soft Body Impact experiments for validation of improved energy absorption

To investigate the influence of the interface design on the impact behaviour, a generic blade-like FRP plate is used (w x h: 300 mm x 140 mm, 24 prepreg layers, thickness: 6.9 mm). The gelatine SBI impactor has a total mass of 80 g. The centre of the impactor strikes the front edge of the plate at a height of 210 mm, so that the impactor is cut open at the front edge (Fig.2). The structural response of different interface modification configurations: without (#1), with one modified interface in the mid-plane (#2) and with three symmetrically distributed modified interfaces (#3). The interlaminar properties have an interlaminar contact area of 0.3.

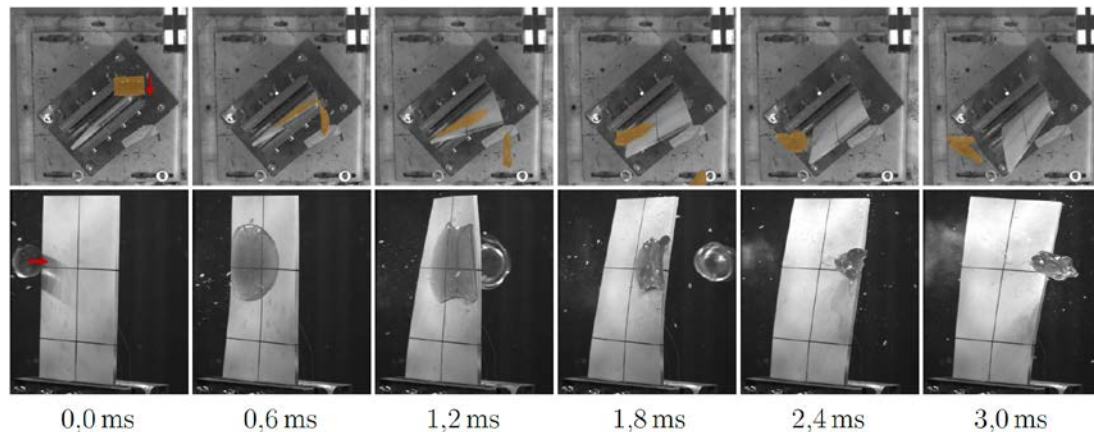


Fig. 2. Soft body impact on generic FRP fan blade.

In contrast to the reference structures (conf. #1), conf. #2 and #3 show significantly improved intralaminar damage behaviour due to the initiated delaminations. For example, intralaminar cracks are significantly smaller in conf. #2. Even a 10 % higher impact energy does not lead to a structural failure in conf. #2, but even more delaminations are observable. In conf. #3, no intralaminar cracks occur at all and the in-plane structural integrity is maintained, even with a 13% increase in impact energy. Furthermore, ultrasonic inspections indicate that no delaminations occur in reference conf. #1. This is in contrast to conf. #2 and #3, which show a pronounced delamination behaviour with fewer fibre breaks at increased impact energies at the same time. This effect can be exploited for example to prevent a Fan Blade Off at increased impact energies.

4. Conclusions

The results indicate that the impact tolerance and structural integrity of highly stressed FRP structural components can be significantly improved by the tailoring the interface layers. The reason for this is a reduction in intralaminar stress due to the formation of delaminations. This shift in failure mechanisms reduces the structural integrity and the impact energy can be absorbed by higher deformations. This allows the failure to be delayed while maintaining the same structural integrity and also increases the energy absorption capacity.

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A Double Bistable Composite Sandwich Core for enhanced impact absorption

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Abstract: This study introduces a novel Circular Prestressed Carbon Core (CPCC) designed to significantly improve the impact resistance of lightweight sandwich structures, making it ideal for aerospace applications. The CPCC leverages a unique combination of asymmetric fiber orientation and a bistable concept to enhance energy absorption and reduce damage from impacts. Through a combined experimental and numerical approach, the study demonstrates that the CPCC outperforms traditional aluminum honeycomb cores. The CPCC exhibits a substantial increase in maximum force and boasts considerably higher specific properties compared to traditional cores. These improvements translate to significantly better performance under impact, including a substantial reduction in displacement and damage area. These findings highlight the CPCC as a promising new design for lightweight sandwich structures demanding superior impact resistance.

1. The Concept

1.1. Circular Prestressed Carbon Core

The core, named Circular Prestressed Carbon Core (CPCC), is a pre-stressed bistable [1-2] carbon fibre composite core that leverages asymmetric fibre orientation and bistability to improve out of plane stiffness and strength and therefore reduce damage extension during impacts. The CPCC is designed as a 2D close-packing pattern of circular cells and manufactured by connecting pre-preg corrugated laminates in specific locations as shown in figure 1. The laminates are layered asymmetrically (single stability) and then connected (double stability) [3] to generate residual thermal stresses within the core, enhancing energy absorption and compressive properties.

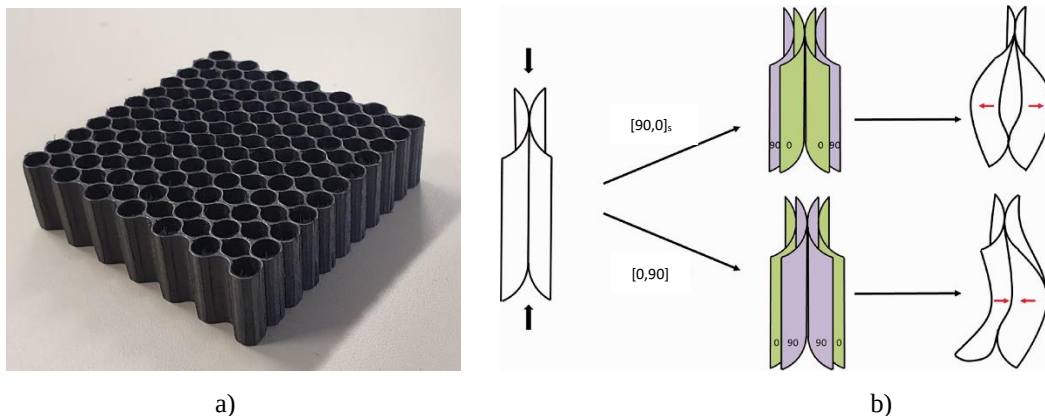


Fig. 1. a) Circular Prestressed Carbon Core. b) Bistable and failure mode

The CPCC demonstrated significant improvements compared to a traditional aluminium honeycomb core. The CPCC showed an increase in specific compressive strength by +84.6%, the in-plane compressive modulus of the CPCC was over +500% and the shear strength of the CPCC was improved by more than 20% compared to the aluminium honeycomb core.

Low Velocity experimental impact tests were performed on CPCC (CP samples), CPCC without prestress cycle (C samples) and aluminium honeycomb (H samples) sandwich structures at 20J and 45J.

The maximum force was improved up to 171%. The specific properties of the CPCC were considerably higher than the aluminium sandwich, with peak force values up to +75%. The displacement was reduced up to -71% with the CPCC compared to the aluminium honeycomb core. Non-destructive evaluation (NDE) tests showed a reduction of the projected damaged area by approximately 20% with the CPCC. The Specific Energy Absorption of the CPCC was +145% compared to the aluminium honeycomb core.

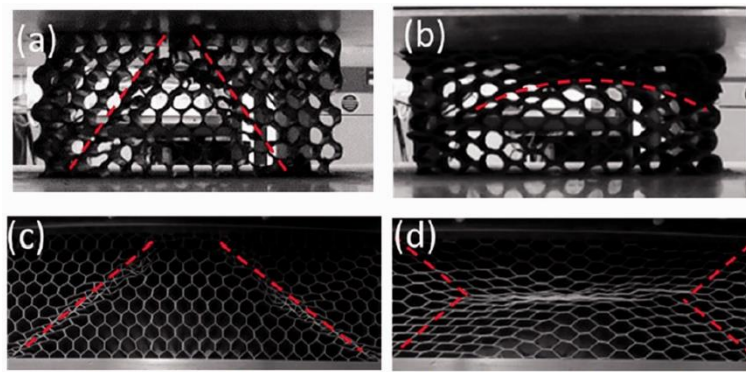
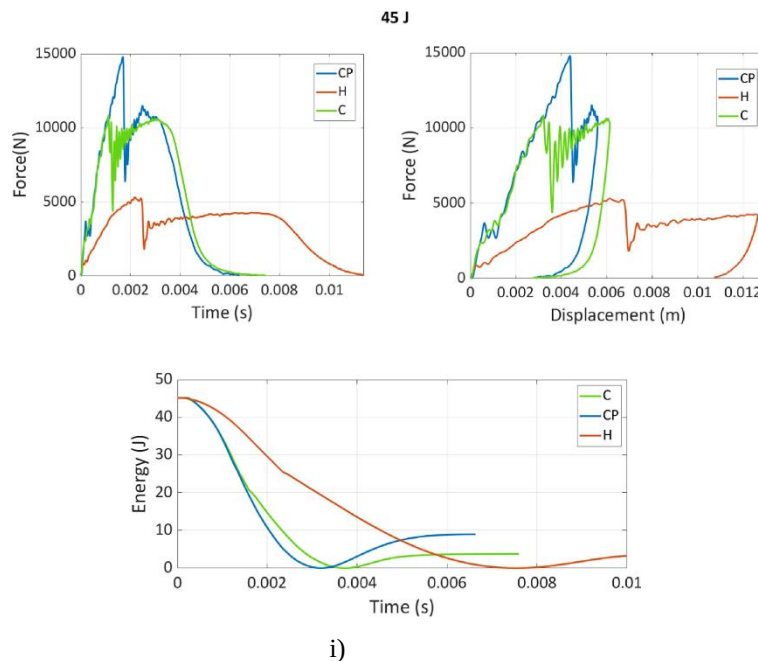
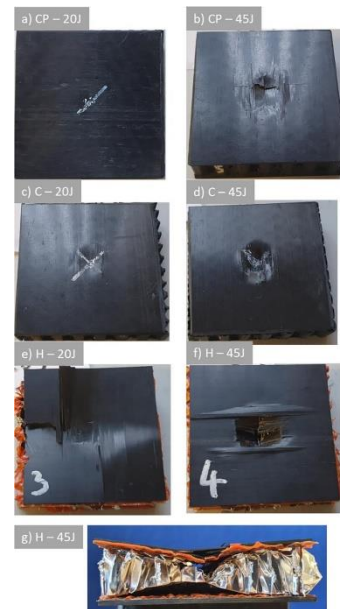


Fig. 2. a) In-plane compressive failure of CPCC (a) (l-direction) and (b) (w-direction) and aluminium honeycomb (c) (l-direction) and (d) (w-direction).



i)



ii)

Fig. 2. a) Force vs time, force vs and energy vs time representative curves obtained from 45J impact tests on CP, C and H sandwich samples. b) Impact Test at 20J (left) and 45J (right) CP (a and b), C (c and d), H (e and f) tested samples and a detail of the side view (g) of 45J H tested sample

These enhancements make the CPCC a suitable core for high-performance sandwich structures, particularly in aerospace and transport applications. It offers numerous advantages over traditional cores, including higher specific properties, the ability to manufacture complex sandwich structures, and better adhesion and compatibility with CFRP skins. The results suggests significant potential for the CPCC in energy absorption applications.

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Constitutive Models for Additive Manufacturing in Composite Structures at High Strain Rate Applications – A Review of Selected References

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Abstract: This contribution deals with constitutive models for additive manufacturing (AM) of composites applied in the high strain rate applications, such as crash, impact or hypervelocity debris. This relatively new field of application clearly demonstrates the potential of AM materials in general, as they enable very different geometries to be produced, with diverse material systems applied. First the examples of generalized constitutive models are listed, then particular models applicable in high-strain applications are analysed. Of particular importance are those applied in bio-inspired AM composites.

1. Introduction

Several technologies are available for additive manufacturing (AM) of FRP composites, such as: FDM (Fused Deposition Modelling), SLS (Selective Laser Sintering) and DIW (Direct Ink Writing). FDM is the most used one, where mostly thermoplastic polymers are used as material systems. Based on the available reference, the models to evaluate the applicable constitutive models for high-strain rate events are to be reviewed. Therefore, the extensive evaluation of the current applicable constitutive models has to be performed, as to continue research elaborated in the Conclusions section. This will include, among others, micromechanical approach based on the RVE as to determine composites mechanical properties; elasto-plastic models for evaluation of failure modes; phenomenological models etc. The presented review results are fundamental in selection of the most appropriate constitutive model as a basis for further development of a comprehensive constitutive model for additively manufactured composites, including self-healing ones, as well as other new composite material systems.

However, the number of references dealing with impact behaviour of additive manufactured composites is still limited, as compared to the large number of references dealing with the general topic of constitutive models in AM of composites. These include various material systems such as polymer matrix with carbon, ceramic, basalt and other fibre materials. Furthermore, this paper addresses several the most appropriate references related to the topic.

2. Constitutive Models Overview

General material characterisation is first step in defining behaviour of the AM materials/structures. These constitutive models must take into account the production technology as well the material system. In the reference [1] large format additive manufacturing has been investigated, with topology optimization performed as well. The classical approach, modelling at micro and macroscale level, has been applied. The ABS composite has been applied with 20% short carbon fibres. In order to develop a digital twin, experimental values have been compared to the results of the finite element simulation. Within the reference [2], constitutive model has been developed to optimize the stiffness and strength based on the fibre placement in AM composite. The infill patterns, describing how the space within the AM part is populated, have been modulated in order to assess the in-plane and out-of-plane strength, with appropriate failure modes applied by usual failure criteria. These references demonstrate solid base that could be applied in development of the models describing the behaviour of the AM structures in the high-strain rate environment.

In [3] authors have developed a comprehensive model that characterizes and predicts the failure of structure under impact. The crashworthiness of the structure has been accessed and numerical values have been correlated towards

the experimental results. In addition, authors managed to model the inter-layer damage manifested as a layer debonding.

Impact events involving strain rates of 100 s⁻¹ are investigated in the reference [4]. These include various cases of ballistic protection, protection in case of crash or blast, or different space impact scenarios such as space debris impact. The AM capabilities in producing various forms unattainable with other technologies are clearly proved. Although accent in this reference is not on composite structures, it covers the sandwich structures and cellular structures as well, what gives particular insight into the behaviour of various morphologies attainable using AM. This reference is of particular importance as it covers the topic in very systematic and comprehensive way.

Constitutive models and application of bio-inspired structures in energy absorption application are developed in [5] and [6]. The particular features of biological systems, animal or plant based, are used as an inspiration for structures that are highly efficient in the energy absorbing requirements. Application of AM enables structures with different structural shapes, including cellular of variable morphologies, lattice structures and different shapes of shell and plate AM composite structures. In some applications constitutive models for structures with fibres and matrix of biological origin have been investigated [6]. Thus, the AM enables rapid prototyping and variation of different forms with superior properties compared to classical composite structures, where defence applications are of particular importance.

3. Conclusions

The aforementioned theories represent the basis for the next phase of research within the recently established project DENNGA - Development of Numerical Methods in Modelling New Generation of Advanced Composite Structures (IP-HRZZ-2022-10-8845) financed by the Croatian Science Foundation, with the aim to further advance existing numerical methodology on simulating behavior of additively manufactured composites. Experience with e.g. self-healing composite structures was gained throughout the previous research of these co-authors within the project ACCESS (IP-HRZZ-2018-01-2248). The project resulted in development of constitutive models for the self-healing matrix material and for the self-healing FRP composite materials validated both with in-house conducted experiments and experimental results available in the literature. Recently, this research group has developed an advanced multiscale constitutive model for intrinsically self-healing polymer composites with matrix plasticity model, rate-dependant matrix micro-damage model and time-dependant healing model. These models will be applied in the AM composites in various applications, including the high-strain rate scenarios.

In addition, in the upcoming research, a relatively new class of polymers, vitrimers, are of special interest since they exhibit intrinsic self-healing ability. To obtain fully reprocessable composite, vitrimers could be combined with basalt fibres whose mechanical properties are comparable to carbon fibres.

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Effect of high strain rates on the out of Plane Properties of S2-Glass Fiber Reinforced Polymers

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Abstract: S2-glass fiber is high-strength and stiffness glass fiber used in several crucial applications ranging from ballistic purposes to running shoes. Although, there is a high demand for this new type of glass fiber in the construction of laminated composite, less is known about its out-of-plane mechanical properties. Therefore, herein, we study the effect of different strain rates on out-of-plane mechanical properties of S2-glass fiber-reinforced polymer produced with a vacuum infusion processing technique.

1. Introduction

S2-glass fiber has better mechanical properties than E-glass fiber which is a common reinforcing phase in most of the composite structure [1]. The better mechanical properties of S2-glass fiber make it a high-demand material in the composite material application. A comprehensive characterization of the material is needed to use S2-glass fiber in composite material applications. It is found that in the literature, most of the studies focus on E-glass fiber-reinforced and carbon fiber-reinforced polymeric materials[2–4], and these studies examine the fiber-reinforced polymers in a quasi-static manner. It is observed that the number research regarding testing of S2-glass fiber-reinforced polymeric composite in high strain rates is quite limited. For instance, in one study, only quasi-static out-of-plane mechanical properties of S2-glass fiber-reinforced polymeric composite and hybrid polymeric composite reinforced by S2-glass and carbon fiber are studied [5], and it is found that as the S2-glass fiber content increases, flexural modules decreases for hybrid composite. However, the literature lacks a detailed characterization of the mechanical properties of S2-glass fiber-reinforced polymeric. Therefore, we address here the out-of-plane mechanical properties of S2-glass fiber-reinforced polymer under high strain rates.

2. Material and Testing

S2-glass fiber-reinforced polymeric material is produced by stacking four layers of 800 gsm plain weave S2-glass fabric mats on top of each other. As a matrix material, Biresin CR 122 epoxy resin is mixed with CH122-5 hardener with a weight ratio of 100:30. Thereafter, the mixture is degassed for 10 minutes to remove the entrapped air bubbles introduced to the resin-hardener mixture during mechanical stirring. S2-glass fabric stack is impregnated by the resin mixture and then followed by a curing at 90 °C for 18 hours. Curing is completed on a heated plate and the consumables used in the curing is given in Figure 1. The produced plate is cut into test coupons as per the dimensions given in ASTM D790 by using a three axis CNC milling machine.

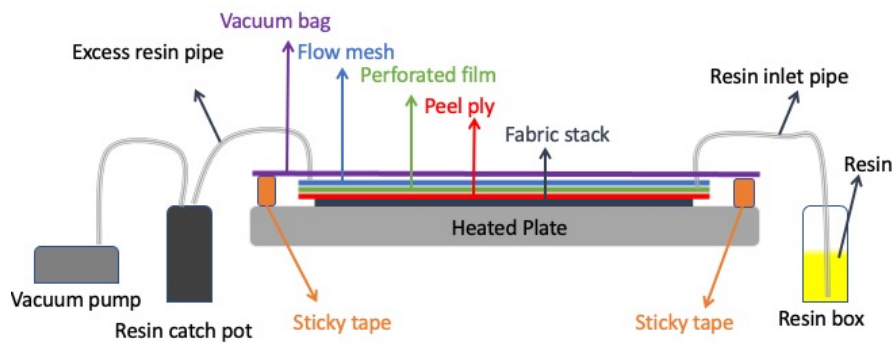


Figure 1: Schematic of the vacuum-infusion process and order of consumables used in the production of the composite test plate

The three-point testing is conducted with 20, 40, and 60 mm/min crosshead displacement rates with an Instron 8801 dynamic testing machine equipped with a load cell of 100 kN to measure the out-of-plane mechanical properties of the produced test coupons. For each crosshead displacement at least five specimens are tested to get an average result of flexural strength, flexural modulus, and flexural strain. Once the three-point bending test are completed, fractured samples are analyzed with an optical microscope to reveal the fracture mechanism of the tested samples.

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Influence of high strain rates on the tensile properties of basalt fiber reinforced polymers

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Abstract: This study contributes to the influence of high strain rates on the tensile mechanical properties of basalt fiber-reinforced polymers by filling a gap in the literature. The composite specimen is produced using the vacuum-infusion method and is tested by following the ASTM D3039 standard. Three high strain rate values of 75, 100, and 125 mm/min are tested on the Universal testing machine (UTM). The Ultimate tensile strength and Young's modulus are aimed to be obtained from the tensile test to observe the effects of high strain rates.

1. Introduction

Basalt is a volcanic rock that is suitable for fiber formation [1]. Recently, there has been an increasing interest in utilizing basalt fiber as a reinforcement material due to its remarkable mechanical properties that compete with Carbon fiber and surpass the properties of Glass fiber [2]. In addition, the applications of basalt fiber products are extremely vast including aeronautic and automotive industry, civil and naval constructions, wind turbine systems, and sporting equipment [3]. However, limited research has been conducted on the influence of high strain rates on the tensile properties of basalt/epoxy composite as compared to compression properties. Pan et al. (2015) investigated the effect of high strain rates on the compressive properties of 3-D braided basalt/epoxy composite materials. Moreover, Zhang et al. (2014) studied basalt fiber 2D woven-reinforced vinyl ester resin-laminated composite under a high strain rate compressive load. On the other hand, an ongoing study by Elmahdy et al. (2019) investigated high strain rates' effect on the tensile properties of woven basalt fiber-reinforced epoxy composite. Therefore, this study aims to add to the literature on the influence of high strain rates on the tensile properties of basalt fiber-reinforced composite materials.

2. Material and Testing

Basalt fiber type 220gsm plain weave is used along with Biresin CR122-5 epoxy resin to form basalt/epoxy composite plates using the vacuum-infusion method at a temperature of 92°C for 18 hours. The plates are cut following the dimensions in Fig. 1, using a Hannsa YL 1000-B three-axis CNC milling machine with a spindle speed of 1000 rpm and a feed rate of 0.1 mm/rev using a 6mm x 25 pyramid diamond cutting tool (Fig. 3). 18 specimens are produced, 6 specimens for each strain rate value. End tabbing of the specimens is performed to prevent stress concentration caused by grip serrations and improve estimates of tensile strength [7]. Fig. 2 shows the final assembly of the specimen.

The tensile test of the basalt fiber-reinforced polymer is conducted on a Universal testing machine, INSTRON 8801 following strain rates of 75, 100, and 125 mm/min. An extensometer is used to obtain more accurate strain values of the test while the rest of the test data is extracted from the machine. Furthermore, obtained data is processed using a MATLAB code, to gather the composite material's Ultimate tensile strength and Young's modulus.

BASALT SPECIMEN - ASTM D3039



Fig. 1. Specimen dimensions



Fig. 2. Basalt fiber-reinforced specimen (after tabbing)



Fig. 3. Cutting tool

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*Advanced Composites under High Strain Rate
Loading A Route to Certification-by-Analysis*

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**Session 3 - Multi-modal sensing for
impact detection and damage
characterisation (WG5)**

High and low velocity impact monitoring for the composite aerial structures

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Abstract: The article presents problems connected with the active impact monitoring for the unmanned aerial composite vehicles. Based on extensive both civilian and military missions the structure of the vehicle is subjected to impacts which may interfere with primary structural elements. Gathering the data about incident is crucial for the structural integrity. Article presents real case test scenario for the unmanned vehicle and results of low and high velocity impacts for structure integrity evaluation.

1. Introduction

One of the major issues which could increase safety of aircraft operation is automated early detection of different damage modes of composite structures [1,2]. There exist certain type of damage which can affect the performance and durability of composite structures and such as: disbonds, delamination, foreign object inclusion and porosity [3]. Furthermore, composites are vulnerable to Low Velocity Impacts (LVI) which can introduce in the structure the so called Barely Visible Impact Damage (BVID) [4]. BVID can be formed even for impacts of low energies and they decrease the stiffness and durability of a composite due to multiple delaminations and transverse cracks of composite layers (Figure 1).

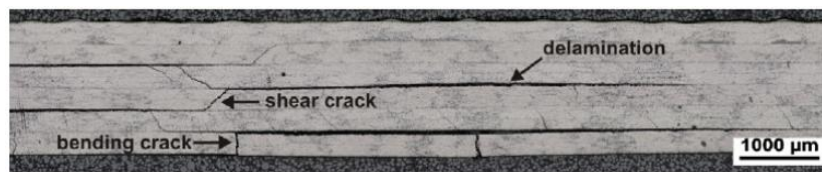


Figure 1 An example of BVID of a composite structure [5]

Moreover the composite aerial structures can be subjected to High Velocity Impacts (HVI) such as ballistic impacts – especially for observable UAV's military operation.

Depending on the impact Energy the general classification can be introduced:

- damage presence: HVIs induce damage, while for LVIs a damage is induced only if the impact force (energy level) overcome a certain threshold, that depends on the adopted material and the structure geometry;
- failure type: typically, the damages related to high energy LVI are BVID (e.g. delamination and debonding) while HVI commonly perforate the structure with several delaminations and cracking.

2. Experiment approach

For BVID visual structure evaluation is not possible, therefore other non-destructive techniques needs to be applied. The most commonly used non-destructive method for BVID detection and evaluation is ultrasonic testing. This method, with use of dedicated automated scanners, allows for precise damage localization and sizing, however the inspection is time consuming and can be only performed during aircraft maintenance on the ground. Maintenance procedures related to preserving integrity of platform structures may soon be highly inefficient, both

in terms of costs as well as the safety. Increasing usage of modern materials in the aerospace, composites in particular, will require development of new approach to structure maintenance.

In the article approach for SHM system for active monitoring of impact damage of composite structures which was developed and tested within projects on several levels [6] and subjected to LVI and HVI. The first level of tests was to use model composite substructures and test damage detection capability of the system on small scale structure. For model substructures, flat and stiffened CFRP panels were selected in accordance with the experiment setup. Impact damage detection capabilities of SHM system was verified, both for low velocity as well as ballistic impact damage, in the case of simple flat structure, as well as for structures of varying stiffness. The results obtained for model structures were further verified within the project on full scale composite component.

The results of active damage monitoring will be presented as follow:

- with use of non-destructive methods;
- based on Transfer Impedance approach;
- based on pitch-catch guided waves propagation;

both for model substructures as well as on full scale component. Article presents approach for experiment preparation, experiment run, data results as well as discussion for method capability and capabilities for advanced data processing.

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Self-sensing composites for impact damage monitoring

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Abstract: Self-sensing composites represent a significant advancement in aircraft structural health monitoring technology. This study focuses on the development of sandwich-structured composites comprising a honeycomb core dip-coated with MXenes, a glass-fibre interlayer spray-coated with carbon nanotubes, and a unidirectional carbon fibre interlayer. Damage detection relies on the piezo-resistive effect exhibited by the samples. Results from mechanical testing indicate an increase in resistance with the appearance of damage and agree with analytical model predictions. Such composites demonstrate promising capabilities for real-time remote monitoring of structural integrity.

1. Introduction

Composites are used in aircraft structures due to their outstanding weight-to-strength ratio, which contributes to reduced fuel consumption [1]. However, during the operation of the aircraft, composite structures are subject to cyclic and impact loads, which often cause various defects such as epoxy matrix cracking, interlaminar delamination, and fibre breakage [2]. Defects which are not detected in time can lead to decreased mechanical properties and reduced factor of safety. One of the most important aspects of the aviation industry is safety assurance therefore aircraft are continuously inspected during maintenance using non-destructive testing (NDT) methods and integrated structural health monitoring (SHM) sensors. NDT procedures require expensive equipment and properly trained personnel. On the other hand, structural health may be monitored with the help of strain gauges and optical fibres - but their capabilities are limited and adaptation is difficult [3].

An innovative and more advanced SHM method is smart-sensing composites. Conductive nanoparticles, such as carbon nanotubes (CNT), graphenes and MXenes, incorporated in the composite layers allow for an early stage damage detection based on the piezo-resistive effect [4]. This study aimed to develop a self-sensing sandwich-structured composite with a multilayered through-the-thickness conductivity. The introduction of such composites on aircraft would greatly enhance safety and reduce the time and resources spent on maintenance inspections, as the condition of the aircraft could be monitored in real-time.

2. Materials and methods

In this study, a sandwich-structured composite was investigated, as illustrated in Figure 1. The composite consists of a honeycomb dip-coated in water-based MXenes. The top and bottom layups were comprised of four glass fibre (GF) sheets. The inner top GF ply was spray-coated with CNT and was positioned facing the honeycomb for electrical current transfer. This GF layer was manually stitched with carbon fibre (CF) thread for electrical resistance measurements. A bottom interlayer consisting of unidirectional CF served as the current collector for the honeycomb surface. An analytical model was developed using Matlab based on Ohm's law to analyse current distribution in different layers. Mechanical testing was performed with in-situ electrical resistance monitoring.

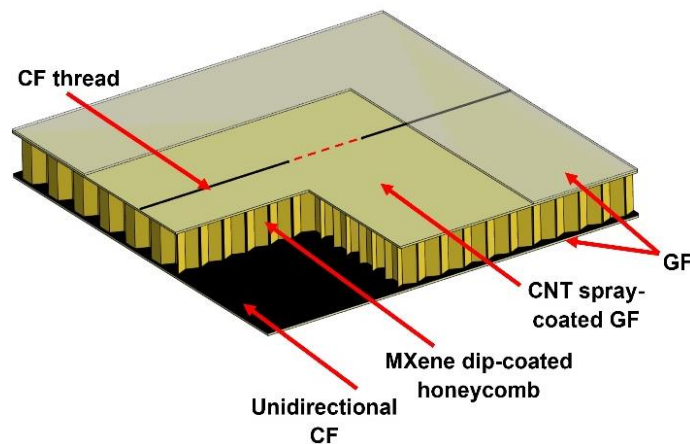


Fig. 1. Self-sensing composite sketch.

3. Results and conclusions

An analytical model showed that the composite's sensing range depends on the electrical conductivity ratio between different layers. By utilizing the analytical model, optimal concentrations of conductive nanoparticles for desired sensing field sizes were calculated. The composite's sensing capability relies solely on the electrical properties of CNT and MXenes because CF remains almost unchanged. Damage affects the electrical properties, with resistance increasing more significantly as the damage is closer to the channel and less as it moves further away. The model helped to predict the amount of resistance change depending on damage location and size. Similar results were obtained with local impact testing. Results indicate that the composite's resistance increases more significantly as damage is closer to the channel.

This study demonstrates that such self-sensing composites can detect complex damages such as honeycomb core buckling, fibre cracking, and interlaminar delamination. These findings imply practical applications for in-flight aircraft condition diagnostics.

Acknowledgements

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Post-impact and post-repair nondestructive evaluation of thermoplastic composites

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Abstract: The thermoplastic composites comprised of poly(lactic acid) and basalt fibers woven fabrics were studied. The non-perforating impacts were introduced with impact energy ranging between 1 J and 16 J. Selected impacted samples were first repaired by means of a hot plate press and then impacted again on the previously targeted positions. The laminate damaging after impact and after repair was assessed by nondestructive techniques: scanning laser Doppler vibrometry (SLDV) and electromechanical impedance. Results showed that thermoplastic laminates can be completely repaired.

1. Introduction

There is an increase usage of thermoset composites in demanding industrial applications. But their vulnerability is the damage tolerance and impact resistance [1]. This work focuses on thermoplastic composites, because they have numerous advantages in terms of recyclability, high specific strength and stiffness, corrosion resistance, enhanced impact toughness, cost effectiveness and flexibility of design [2]. In this work we used a reinforced composite based on poly(lactic acid) and basalt fibres woven fabrics to investigate the effect of low energy impacts. A repairing process was then applied and the capability of the composites to cope with additional low energy, consecutive impacts was assessed by using scanning laser Doppler vibrometry sensed guided elastic waves and electromechanical impedance.

2. Methods and samples



Fig. 1. Photo of impacted sample.

The samples excitation was realized by a surface bonded piezoelectric transducers of 10-mm diameter and 0.5-mm thickness that was used for the electromechanical impedance (EMI) spectrum measurements, as well as for elastic wave excitation. The transducer was placed on the impacted face at the middle of one of the shorter edges. In the EMI approach the difference in spectra were assessed by numerical indexes comparing the samples without and with impact damage. Meanwhile, in the wave-based approach the excited waves were sensed by scanning laser Doppler vibrometry (SLDV). The acquisition was made with single head of the PSV-400-3D vibrometer from Polytec. Thanks to the scanning capabilities of the device the measurements were gathered in 3723 points arranged into a 51x73 rectangular grid. The spacing between grid points was about 2.2 mm. The visualisation of the results was based on calculating of the root mean square (RMS) value of the time signal in each grid point [3]. This converts the 3D data (width, height and time) into 2D image (width, height) allowing to indicate the damage position.

An example of investigated sample with 5 impact locations is shown in Fig. 1. The shown sample side was measured with the SLDV, while the impacted side is the bottom one at which the piezoelectric sensor was bonded.

3. Results and conclusions

The result of damage assessment for the sample from Fig. 1 is shown in Fig. 2. The damage imaging was made for a 80-120 kHz frequency range that includes the excitation frequency that was 100 kHz. Two impact locations were clearly indicated. These were the impacts made with the highest energy: 8J and 16J. The impacts for the lower energies 1.5, 2 and 4 J are barely visible in this visualization. Investigating the repaired samples at 175°C it was observed that no damage indication is seen indicating effective repair process.

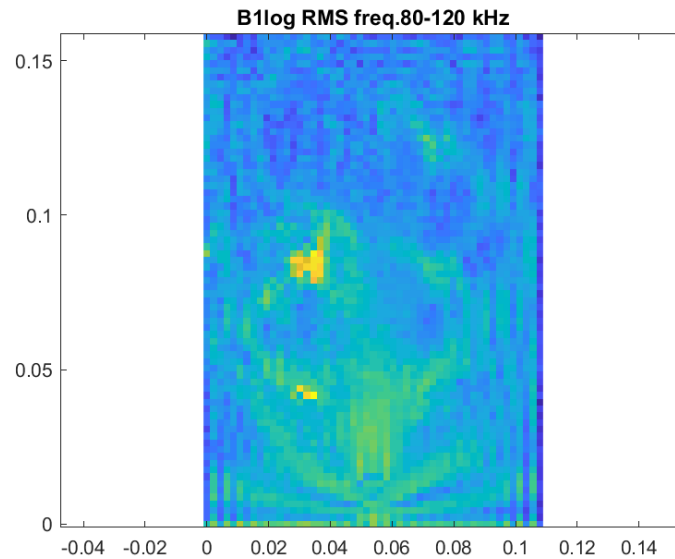


Fig. 2. Photo of SLDV of the impacted samples from figure 1.

In the EMI method the spectra of electrical quantities were analyzed (example in fig.3 shows conductance curves). The changes in the curves for impacted samples (B1-B11) were compared against the non-impacted (ref) sample. The preliminary study did not show clear sensitivity to the repairing of the sample.

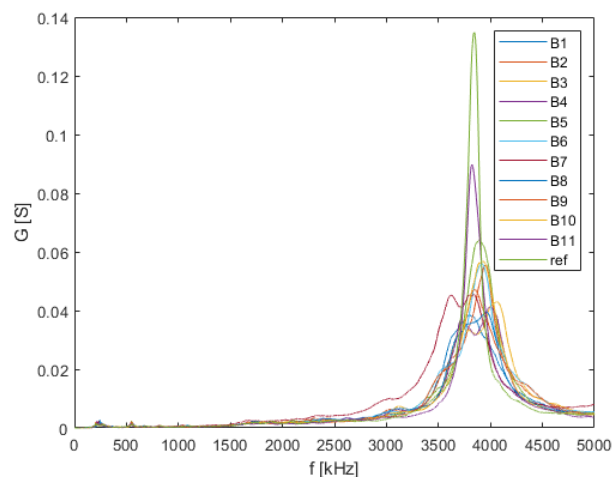


Fig. 3. Conductance curves registered in the EMI method for the investigated samples.

4. Acknowledgments

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Simulating an experimental setup for short-duration impacts on structures with Ti3C2-MXene sensors.

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Abstract: With the rising demand for high-performance structures in industries such as aerospace, automotive, and space, the monitoring requirements increase alongside. A recent experimental investigation [1] reveals that Ti3C2-MXene sensors exhibit response times approximately one order of magnitude faster than commercial piezoceramic sensors, significantly enhancing measurement capability on short-impact events. This study proposes simulating the experimental setup described in [1] using the FEM software Abaqus to assess measurement outcomes and potentially uncover novel physical phenomena. The study reports experimental findings on both an aluminum plate and a composite plate.

Introduction

Structural health monitoring (SHM) is crucial for ensuring the operational integrity of engineering structures throughout their life cycles. SHM relies on various sensors to measure field variables like displacement, strain, pressure, or temperature. Available sensing solutions, impact sensors play a vital role in detecting sudden loads acting on structures. This study is dedicated to simulating short-duration impacts on structures, with a focus on evaluating the performance of Ti3C2-MXene sensors, which revealed strong potential for impact detection in prior research [1]. Ti3C2-MXene sensors exhibit distinctive advantages, notably compactness and high sensitivity, rendering them promising candidates for structural health monitoring applications.

To establish an experimental framework conducive to repeatable short-time impact simulations, an experimental setup was devised. An inclined aluminum rail was installed to guide steel spheres onto a vertically mounted cantilever plate. The initial position of the sphere was controlled using an electromagnetic mechanism, ensuring its retainment in place before each experiment. Spheres of varying sizes were utilized, resulting in different radii and masses. For comparison against the proposed Ti3C2-MXene sensors, commercial piezoceramic sensors were affixed to the plate to capture the impact events. Following the sensor preparation protocol outlined in [1], the Ti3C2-MXene sensors were strategically positioned near the anticipated impact zone, away from the clamped side, to mitigate potential interference with end-effects.

The following assumptions are put in place for modeling of the phenomenon: It is assumed that the spheres neither slip nor bounce along the rail, with any rolling resistance neglected. Additionally, the collision between the sphere and the plate is assumed to be fully elastic, disregarding any thermal effects. Linear mechanics is further assumed, yielding small strains and deformations. Furthermore, air resistance acting on the moving ball and any vibration or swaying of the plate were neglected, resulting in the assumption of a parabolic trajectory for the sphere upon detachment from the rail. The plate dynamics are assumed to lie within the plane of the plate, neglecting any three-dimensional effects. By simulating the experimental setup, our aim is to test these simplifying assumptions and to enhance our comprehension of the dynamics of impact, improving the ability of interpretation of the obtained measurement results.

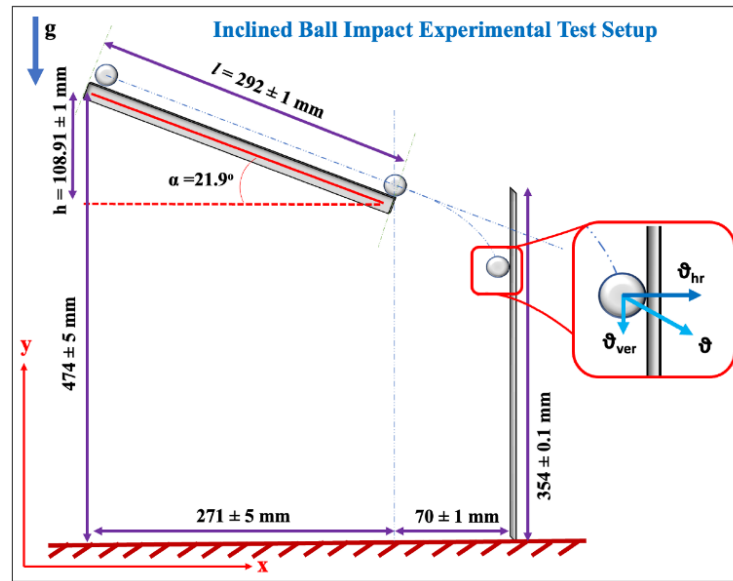


Fig. 1. Illustration of the table-top experimental structural impact test setup. [1]

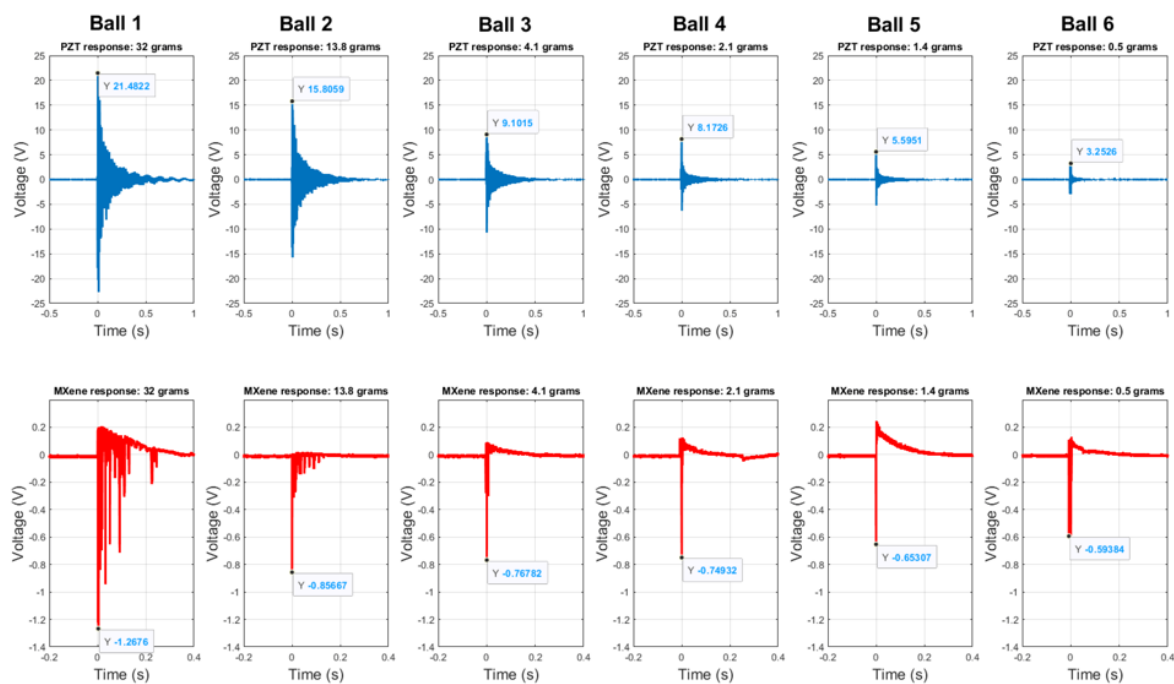


Fig. 2. Comparison of the response of Ti3C2-MXene and piezoceramic sensor raw data for the balls 1 to 6 (single trial plotted) [1].

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Considering Tensile Resistance of Scot pine-MDF Joint Connected with 3D Printed Single Dovetail Fastener

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Abstract: The mechanical strength of the joints representing the front and side members of cabinet drawers, which is one of the units of furniture used for storage purposes, was considered. Therefore, Scotch pine and MDF members were connected with a single dovetail fastener without glue, tensile strength was measured and compared between 3D Printed tough PLA dovetail fastener and injected PA dovetail fastener. Results showed that the average tensile strength values of dovetail joints produced from tough PLA by 3D additive manufacturing did not show a statistical difference compared to those produced from PVC by injection method but they were mathematically higher.

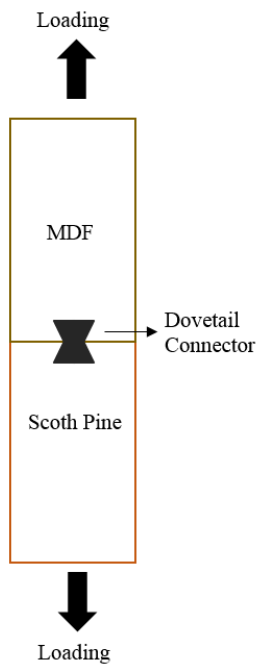
1. Introduction

Two critical phenomena exist in furniture structure. One is member either solid wood or wood composites such as MDF or particleboard, the other one is joint. Joint is the focus part of this study because it holds member in a furniture structure. Today several types of joint fastener used in furniture frames such as dowel, dovetail or minifix. Dovetail is one of the most preferred fastener type in drawers due to its tighter tensile strength when pulled in a frame. Therefore. In this study, tensile strength of drawers' joint connected with dovetail fastener were evaluated.

2. Materials and Methods

In this study, PA dovetail joints with 8 mm top-bottom width, 5 mm middle width, 10 mm height, 15 mm top-bottom depth and 12 mm middle depth, produced by the injection method, were obtained from the market. In addition, using the Tough Poly Lactic Acid (PLA) material, dovetail fasteners were produced with 3D technology or additive manufacturing method in the same dimensions as those obtained from the market.

5 static tensile loading for market samples and produced 3D connections were loaded on the BESMAK Universal test device in accordance with ASTM-D 143-94 standard [1]. Dovetail joints were made of 150×50×18 mm Scots



pine and MDF materials in an edge-to-edge shape as shown in the figure and joined together to represent the drawer front and side parts. 10 of these samples were prepared, 5 of which will be commercial products produced by PA injection, and the other 5 were produced from 3D printed dovetail fasteners. Figure 1 shows tensile loading.

a) b) c)

Figure 1 a) Tensile loading directions for dovetail joint b) Tensile loading side view on BESMAK Universal machine, c) b) Tensile loading front view on BESMAK machine.

3. Results

Figures 2 and 3 show the load-displacement graphs of furniture joints produced by the injection and 3 D methods, respectively. As shown in Figures 11 and 12, the load-displacement curves of the joints constructed by both fasteners resemble the typical of wood joints behavior under load.

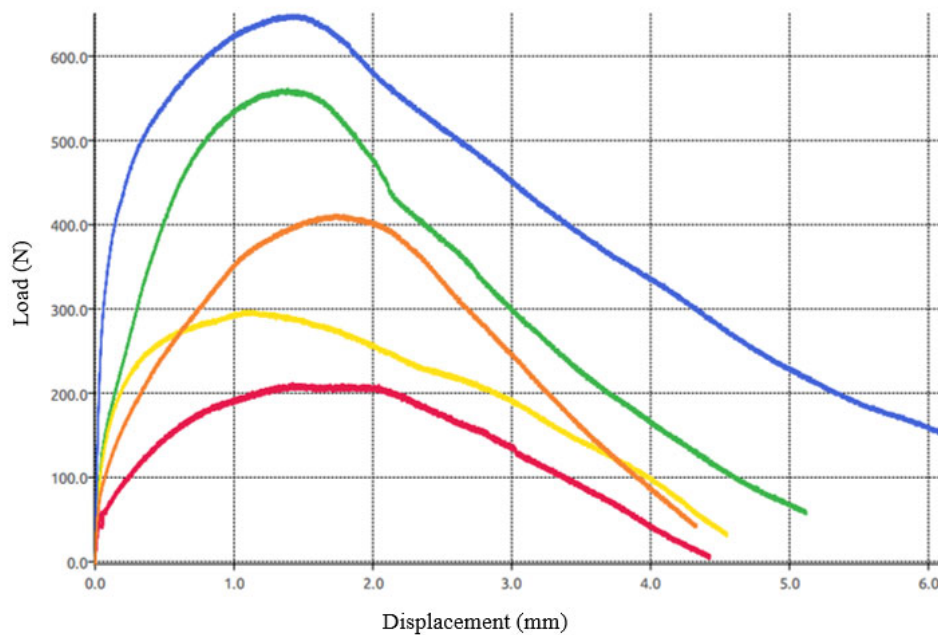


Figure 2. Load-displacement graphs of dovetail furniture joints produced by injection method.

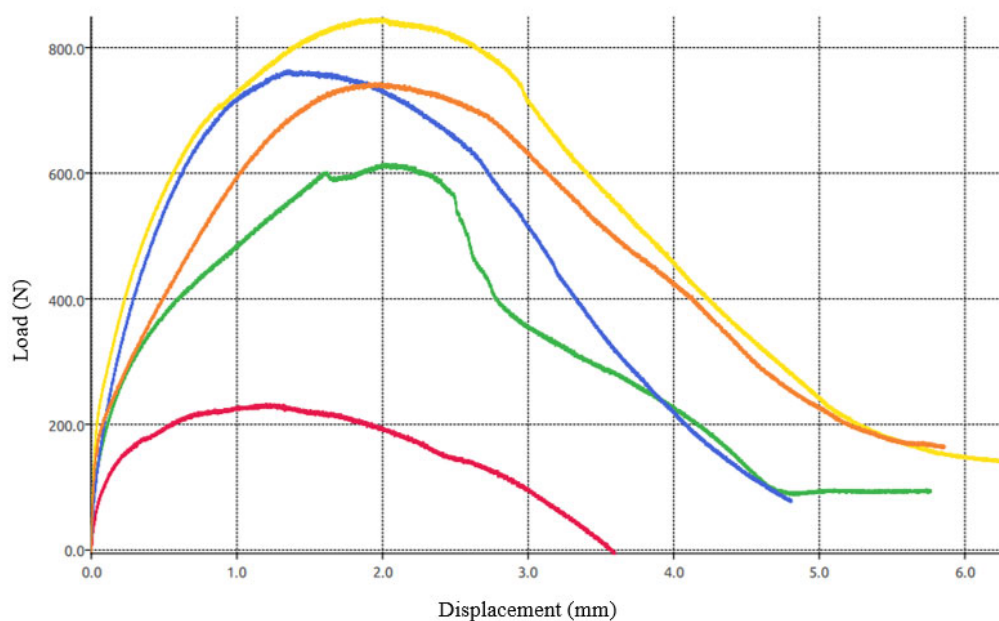


Figure 3. Load-displacement graphs of dovetail furniture joints produced by 3D additive manufacturing method. Margins and type size will be as set by the abstract template.

Table 1 gives the results of the maximum static tensile loads of both PA market dovetail joints produced by the injection method and tough PLA dovetail furniture joints produced by the 3D additive manufacturing method.

Table 1. Maximum static tensile strength values of dovetail joints

	Injection	3 D
Number of sample	Tensile Strength (MPa)	
1	212	233
2	562	616
3	298	848
4	650	764
5	412	743
Average	427 (A)	641 (A)

As a result of the statistical analysis performed at the 5% significance level between the production methods values of dovetail fasteners, the most significant difference value (LSD) was determined as 312.17. Therefore, there was no statistical difference between the static tensile strengths of dovetail joints produced with two different production methods. However, as seen in Table 1, PA dovetail tensile values produced by injection are mathematically lower than those produced by 3D injection method. The reason for this can be said that tough PLA material has a higher density than PA material. In Wen and Wang [2] study, tensile strength was applied to T-type dovetail joints made of maple and the average values were found to be 140 MPa. Here, the dovetail was obtained from the wood material itself and no plastic/PA dovetail was used, but lower tensile values were obtained than in current study. Again, Dalvand et al. [3] determined the tensile load value applied to the corner joints of fir wood elements using single beech dovetail connections as 176 MPa. Glue was also applied to the corner joint here. Again, the values in this study were lower than the values of current study. As failure mode, generally stripping is observed from pine member. The reason could be density of MDF is higher than that of pine.

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Mxene Fibers as Strain Sensors for Fiber Reinforced Composites

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Abstract: Fiber-reinforced polymer (FRP) composites, crucial in aerospace engineering for their strength, present challenges in structural health monitoring (SHM) due to their anisotropic nature and susceptibility to failures. Current non-destructive testing (NDT) methods are costly and lack precision, leading to undetected issues between inspections. Addressing this, our study explores piezoresistive MXene fibers, integrating them into FRP laminates for real-time strain sensing. Unlike prior research focused on high strains, we optimize for practical aerospace conditions, achieving high sensitivity (0.9 at 0.13% strain) and reliability under various loads. This advancement promises enhanced SHM, enabling early detection of damage and reducing maintenance costs in aerospace structures.

1. Introduction

Fiber-reinforced polymer (FRP) composites are vital in modern structural engineering due to their high stiffness, notably in aircraft components. However, their anisotropic behavior, with superior tensile strength, makes them prone to various failure modes such as fiber fracture and delamination, challenging to detect visually [1]. To address this, non-destructive testing (NDT) techniques have been employed, but they often come with drawbacks like high costs and suboptimal resolutions [2]. Structural health monitoring (SHM) methods, incorporating sensors like acoustic and piezoelectric devices, offer promise in enhancing safety and reducing maintenance expenses [3]. Advanced composites with integrated self-sensing capabilities, like piezoresistive MXene fibers, are gaining traction for their ability to monitor strain in real-time [4]. This paper explores the fabrication and integration of MXene fibers into FRP laminates for in-situ strain sensing, aiming to address challenges in aerospace applications and pave the way for advanced sensing solutions with broad societal impact.

2. Experimental

2.1. Wet Spinning of MXene Fibers: MXene fibers were produced using a computer-controlled wet spinning unit. MXene colloids were injected into a rotating aqueous chitosan coagulation bath. The positively charged chitosan induced polyelectrolyte complexation, resulting in the solidification of MXene fibers [5]. After being kept in the coagulation bath, the fibers were extracted, rinsed with a water-ethanol bath, and dried.

2.2. Composite Laminate Fabrication: Carbon fiber reinforced composites were manufactured from unidirectional reinforced prepreg containing carbon fiber grade T700SC 12K and E722 epoxy resin. The prepreg was subjected to a curing cycle in an autoclave, followed by machining to the final dimensions.

2.3. Material Preparation for Sensing Measurements: MXene fibers were characterized for current-voltage (I-V) characteristics using a source measure unit. Composite samples were prepared by attaching MXene fibers to the laminate surface using copper ports and epoxy adhesive, with strain gauges applied for comparison.

2.4. Mechanical Tests: The strain-sensing characteristics of MXene fiber-attached composite samples were evaluated through cyclic tensile and hammer tap impact tests. Cyclic tensile tests were conducted using a universal testing machine, while hammer tap tests assessed piezoelectric behavior under low-velocity impact loading. Measurement setups included NI PXI acquisition systems to record electrical resistance and impact force data.

3. Results and discussion

CFRP samples with MXene fibers underwent cyclic tensile tests to assess their mechanical properties. MXene fibers' piezoresistive behavior was analyzed within the early-elastic range of CFRP (maximum strain of 0.13%) during cyclic tensile testing, pertinent to aerospace applications [6].

The composite specimen underwent cyclic tensile loading with a stress ratio (R) > 0 and a maximum stress of 60 MPa (up to 0.13% strain), operating within the purely linear elastic regime (Figure 1a,c). MXene fiber sensors accurately tracked the elastic region of the composite, demonstrating their adhesion feasibility. FL3 closely followed the strain gauge signal, albeit with a slight discrepancy in resistance change rate (Fig 1a). Cyclic loading altered MXene fibers' piezoresistive characteristics, reflecting dimensional changes under tension. FL1 showed less distinctive resistance change, likely due to inconsistent adhesion or interface imperfections. FL4 exhibited an incomplete, noisy signal with poor resolution.

The gauge factor (GF) is a crucial indicator of sensor sensitivity, calculated from the slope of the curve. GF varies with strain and reaches a maximum of 0.6. This sensitivity enables detection of fatigue loading even at low tensile strain.

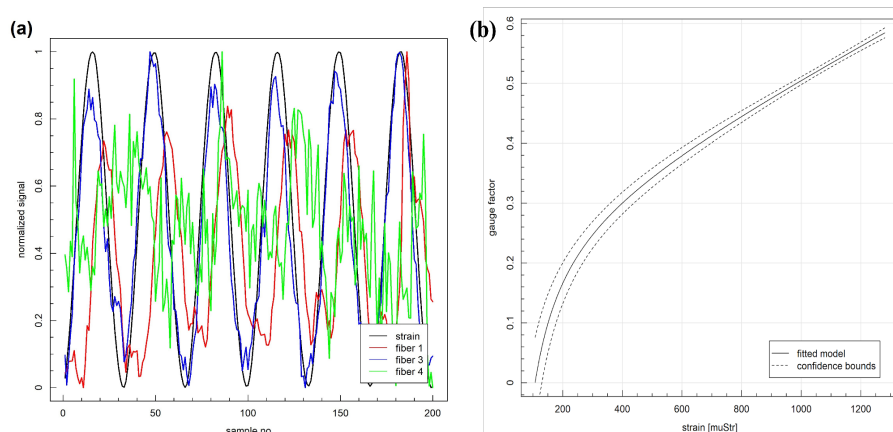


Fig. 1. a) Example of normalized signals acquired during cyclic loading with sensors aligned with the applied force direction, b) The response of FL3 aligned with the applied force direction with respect to the strain level in this direction

This study extensively explores MXene-based fibers for sensing, focusing on synthesis, characterization, and application in composites. Key findings include successful synthesis of MXene sheets, characterization of their morphology, and production of aligned MXene fibers. Electrical properties reveal their potential as strain sensors, with varying resistance among fibers. Electromechanical analysis confirms piezoresistive behavior, while sensitivity to low-velocity impacts suggests impact-sensing applications. Despite variations in response, MXene fibers show promise for diverse sensing applications, offering insights for future research in advanced sensing technologies.

Acknowledgments

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Comparative study of fiber Bragg sensors in remote and direct configuration for impact detection

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Abstract: Fiber Bragg grating (FBG) sensors offer several unique features and are widely regarded as ideal sensors for structural health monitoring (SHM). They have been widely employed for static and quasi-static strain monitoring. However, their application for high strain rate applications is limited due to insufficient sampling rate. As a solution, an edge-filtering approach has been proposed. This study investigates the suitability of FBG in direct and remote configuration impact detection. The response of the FBG sensors are compared to determine the relative merits of the configurations. The tests are performed on a carbon fiber-reinforced polymer plate subjected to hammer impacts.

1. Introduction

Fiber Bragg grating (FBG) sensors offer several advantages such as low weight, small size, electromagnetic neutrality, ability to be embedded, ability to be multiplexed, etc. [1]. Hence, they are seen as ideal sensors for structural health monitoring (SHM). Typically, off-the-shelf interrogators limit the sampling rate up to 50 kHz and can not be used for monitoring the structure in dynamic high-strain rate events. There have been few studies that report the use of FBG sensors for impact detection [2]. However, these impact events are low-speed impacts that result in a low frequency of excitation. High-speed impacts that cause damage in structures typically have large bandwidth and to study the material and the structure under such impacts higher sampling rates are necessary. The Edge-filtering approach allows very high sampling rate signal acquisition (range of GHz), where a tunable laser is tuned on the linear part of the FBG reflectivity slope, and the change in the amplitude of the reflected light is recorded using a photodetector [3]. In this study, the FBG sensors are interrogated in the edge filtering approach. Two configurations, namely, the direct configuration where the FBG sensor is directly bonded onto the structure and the remote configuration where the optical fiber is bonded to the structure at a location away from the sensor are studied. The remote configuration has been shown to increase the sensitivity and also enhance the applicability of the sensors in extreme environments [4]. Furthermore, the remote bonded sensors with acoustic coupling can reduce the deployment cost of the SHM system and hence are attractive. The study is carried out on a carbon fiber-reinforced polymer (CFRP) plate subjected to impacts. The acquired signals in the two configurations are compared.

2. Experimental Setup

For the impact study, 2 CFRP plates with dimensions $300 \times 150 \times 6 \text{ mm}^3$ plate were instrumented each with 4 FBG sensors and 1 PZT sensor at the locations shown in Fig. 1.

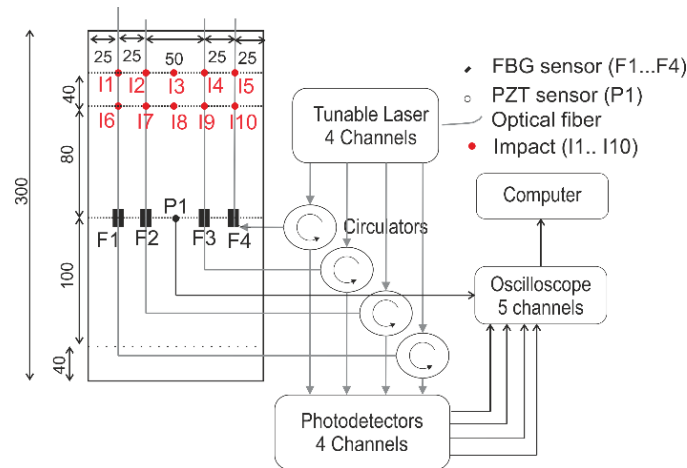


Fig. 1. Schematic of the sample and the experimental setup.

In the first case the sensors were bonded in the direct configuration, while in the second case, the sensors were deployed in the remote configuration. Ten impacts were introduced at the marked locations with a hammer. The impact forces were not measured, as in real in-service conditions are not measured as well. The CFRP plate was clamped at one end (cantilever). The FBG sensor responses were collected in the edge-filtering configuration using a tunable laser and photodetector setup shown in Fig. 1. The data was collected using an oscilloscope.

3. Results

Fig. 2 (a) shows the time signals for the direct and remote bonded FBGs as well as the PZT sensors under the two impacts. Firstly the guided wave created by the impact arrives at the sensor around the same time keeping in mind the similar distance from the impact location to the sensors. Also the direct bonded FBG gets saturated as the strain wave moves the FBG reflectivity by beyond the reflectivity slope. As a result the high frequency, low amplitude effects are not captured by the sensor in the direct bonded configuration. On the other hand the remote bonded FBG does not get saturated and can capture the high frequency low amplitude signals. As can be seen in Figure 2 (b), in the frequency domain, FBG in the remote configuration filters out the low frequency component and hence is not saturated. The two PZT sensor signals and the direct configuration FBG are very similar and have a significant low frequency component.

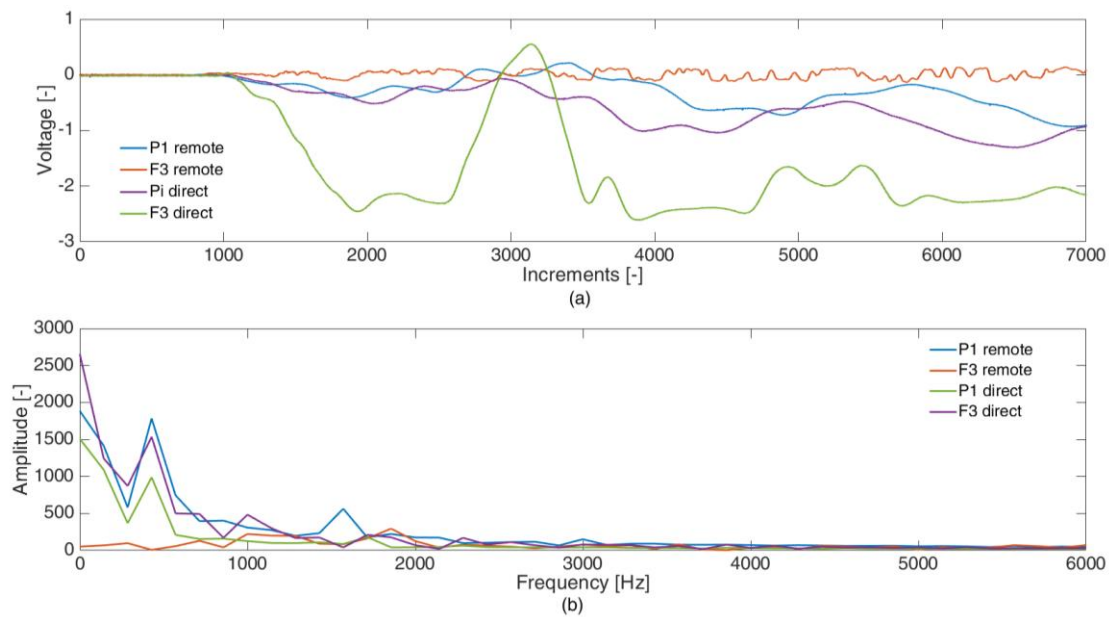


Fig. 2. (a) Time signals for FBG under remote and direct configuration and PZT (b) FFT of the signals.

4. Conclusions

As shown in Fig. 2, the responses of FBG sensors in remote and direct configurations are different under impact loading. The fact that the remote configuration does not get saturated can be used to detect the phenomenon occurring in the material at high strain rates. The time of arrival for the different sensors for the impact aligns well with the expectation and may be used for impact localization if the velocities of propagation are known.

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Acknowledgements

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*Advanced Composites under High Strain Rate
Loading A Route to Certification-by-Analysis*

2024 Conference
5TH - 6TH JUNE 2024

**Session 4 - Advanced testing and
instrumentation for composites
under high strain rates (WG6)**

Optical instrumentation for high strain rate testing of composite materials: maximising the value of measurements

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Abstract: This presentation summarises the recent developments and best practices in optical instrumentation for high strain rate testing of composite materials. This work was done within the HISTRATE COST Action. The main objectives of this presentation are to align and steer the recent developments in optical instruments to establish collaboration with materials modelling and experimental researchers.

1. Advanced testing and instrumentation for composites

Composite materials are vulnerable to extreme dynamic loadings such as impact, blast, and crash, where there is limited knowledge of material behaviour at very high strain rates. The development of new instruments to reconstruct extreme dynamic events provides key insight into the understanding of the behaviour of composites. These challenges are addressed in a recently established COST Action CA21155, Advanced Composites under HIgh STRAin raTEs loading: a route to certification-by-analysis (HISTRATE, 2022-2026) [1].

This presentation reviews the recent developments within HISTRATE workgroup #6 “Advanced testing and instrumentation for composites under high strain rates”. This workgroup focuses on the characterisation of wave propagation, shock loading and damage initiation in composite materials, as well as evolution and failure under multi-axial and high-speed loading. This includes specimen design, the use of advanced optical measurement techniques, embedded sensors and non-destructive testing (NDT) tools. WG6 brings together academic partners to collaborate on the coupling of techniques to advance real-time monitoring and the selection of high-strain rate testing. Expertise from industrial partners will direct the developments with a prospect of joint proof-of-concept experiments to demonstrate the potential usefulness of coupled characterisation tools.

2. Optical instrumentation for high strain rate testing of composite materials

This presentation will give an overview of the state-of-the-art optical instrumentation for the high strain rate testing of composite materials [2, 3]. Specific examples include recent developments in new specimen geometries for split Hopkinson bar assisted with high-speed digital image correlation [4] and EXTREME high-speed shearography for full-field wave characterisation during an impact event [5]. All these recent developments are summarised in Table 1.

Table 1. Overview of optical instrumentation for high strain rate testing

Imaging	In-plane displacement u, v	Out-of-plane displacement w	Velocity $\frac{dw}{dt}$	In-plane strain $\frac{du}{dx}, \frac{dv}{dy}$	Shear strain $\frac{dv}{dx}, \frac{du}{dy}$	Out-of-plane strain $\frac{dw}{dx}, \frac{dw}{dy}$	Stresses σ_{xx}, σ_{yy}	Resolution
Photoelasticity								
Marker tracking								1/10..1/100 pixel size
Moire imaging								Grating pitch/10
2D Grid tracking								1/10..1/100 pixel size
2D Digital image correlation (DIC)								1/10..1/100 pixel size
3D/Stereo DIC and grid tracking								
Holography & Interferometry								
VISAR								
Classical interferometry								
Digital speckle photography								
Stereo digital speckle photography								
Speckle interferometry								
Electronic speckle pattern interferometry (ESPI)								
Shearography								

Measured directly

Can be calculated

$\lambda/5...50$ strongly depending on the optical setup and phase processing approach

0.1..0.4 λ /shear distance

The EXTREME high-speed shearography instrument is a relevant example of an advanced optical technique used for the experimental validation of numerical models [5]. Fig. 1 shows the in- and out-of-plane components ($\partial u/\partial x$, $\partial w/\partial x$) captured during 3-4 microseconds after the impact of a hard projectile on the blade at around 55 m/s. The in-plane surface strain component ($\partial u/\partial x$) reaches values of $-400 \mu\text{strain}$ around the location of point A (Fig. 1(a); averaged area 10×10 pixels), $+250 \mu\text{strain}$ around area B. These results with captured wave propagation are unique in terms of the temporal and spatial resolution (1 microsecond and more than 1500×1500 pixels)

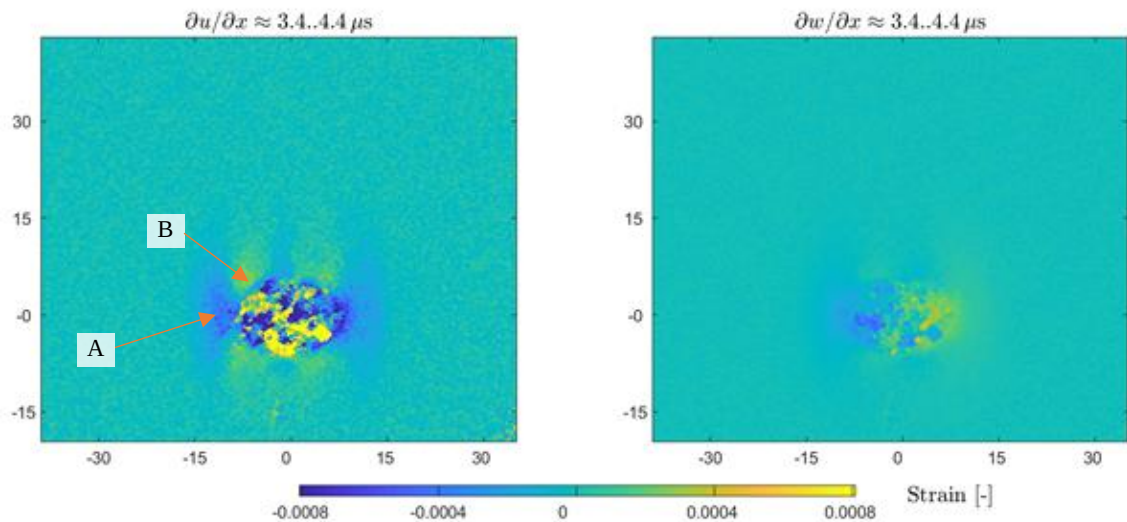


Fig. 1. Surface strain components ($\partial u/\partial x$, $\partial w/\partial x$) captured with EXTREME shearography instrument during the first 3-4 μs of the impact on a prototype of a fully composite fan blade (axes units mm).

3. Conclusion

A particular focus is made on what needs to be measured and how, during high strain rate testing, valuable information for material science, numerical modelling, and design points of view is obtained rather than isolated advancing optical techniques.

This overview of the recent developments and challenges also describes how the HISTRATE COST Action will steer the research and development of new optical instrumentation for high-strain rate testing and involve new academic and industrial partners. This Action will be one of the steps towards the application of certification by analysis of high strain rate loaded composite structures.

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Mechanical properties of basalt fiber-reinforced epoxy composites modified with star-like polymers

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Abstract: The mechanical properties of basalt fiber-reinforced epoxy composites modified with star-like polymers were evaluated. To analyze their environmental stability, hydrothermal ageing was performed on the investigated materials. The preliminary research results showed the increase of the storage modulus with the increase of the star-polymer content, revealing higher resistance to the dynamic loading at all temperatures.

1. Introduction

Basalt fiber reinforced composites (BFRC) offer a sustainable alternative, bridging the performance and cost-effectiveness gap between glass fiber reinforced composites (GFRP) and carbon fiber reinforced composites (CFRC). Moreover, BFRC exhibit notable resistance to water, acids, and other chemically active agents, enhancing the longevity of FRPs in outdoor environments compared to CFRC and GFRP [1,2]. Considering these advantages, there is significant anticipation for BFRC to become a staple in structural materials for outdoor applications. The interfacial adhesion between the matrix and fiber is pivotal in facilitating efficient stress transfer and achieving high mechanical properties. Star-like polymers, for instance, enhance adhesion by linking carbon fiber plies within the laminate [3], thereby boosting mechanical properties by adding low-weight percentages.

Dynamic mechanical analysis (DMA) is widely used to explore the viscoelastic properties of polymers that occur as a response to the application of oscillating forces and to draw conclusions about the mobility of polymer chains and their thermomechanical properties. An essential application of DMA is evaluating the glass transition temperature of polymers. Amorphous polymers have different glass transition temperatures, above which the material will have rubbery properties instead of glassy behavior, and the material's stiffness will drop dramatically along with a reduction in its viscosity.

However, the durability of fiber-reinforced composites is a multifaceted issue, contingent upon the deterioration of both the polymer matrix and fibers and their interfacial bonding behavior [1]. Typically utilized epoxy resins for impregnating FRPs may undergo alterations in their physical and chemical properties due to environmental factors such as moisture, temperature variations, and UV radiation exposure, resulting in plasticization, chemical reactions, and post-curing effects [4].

This work aimed to investigate the effect of star-like polymers on the mechanical properties of a bio-based epoxy matrix and BFRC laminates subjected to hydrothermal ageing.

2. Materials and methods

The additive in the form of star-like polymers, specifically poly(n-butyl methacrylate)-(glycidyl methacrylate) block copolymer, were incorporated into a biobased epoxy matrix reinforced with basalt fibers to enhance the mechanical properties. SR Greenpoxy 33 (Sicomin, France) and LITE 2401 (Cardolite, Belgium) sourced from biobased carbons and cashew nutshell liquid were mixed to create a matrix of bio content of approx. 33%. The solid star-like polymer was dissolved in a solution of 51% tetrahydrofuran and combined with the resin over 24 hours at 80 °C to produce a masterbatch with a concentration of 10 wt. %. This masterbatch was then diluted to create samples with concentrations of 0.25, 0.5, and 1 wt.% for comparison with the neat matrix. Unidirectional basalt fiber fabric (Basaltex, Belgium) was used to fabricate the laminate plates, which were impregnated with the same content of star-like polymer as the epoxy.

DMA was implemented to study the effect of filler content on the epoxy's viscoelastic properties. DMA tests were performed in tensile configuration at a force of 2 N using a Mettler Toledo (Columbus, OH, USA) DMA/SDTA861 instrument to evaluate the thermomechanical properties of the investigated materials. All experiments were performed at a frequency of 1 Hz from 30 to 180 °C with a 3 K/min heating rate to ensure slow heating, thus avoiding any temperature gradient. The maximum peak of the loss modulus vs. temperature plots was used to identify the α -relaxation associated with the glass transition, and the corresponding temperature was assumed to evaluate the glass transition temperature for all tested samples.

For the developed BFRC laminates, mode I interlaminar fracture toughness tests were performed according to ASTM D5528 to study the effect of star-like polymers on mechanical properties. The tests were performed by using Zwick 2.5 testing machine with a crosshead speed of 1 mm/min at RT and Canon EOS40D to record photos every 3 s for the analysis of the crack propagation until a failure occurred. ImageJ 1.38x software was used to estimate the delamination length in double cantilever beam (DCB) samples. At least five DCB samples per star-polymer content in the epoxy resin-impregnated unidirectional BFRC laminates were tested.

Thermogravimetric analysis was used to determine the fiber content ratio, which is imperative to create a viable comparison between the composites' properties. Scanning electron microscopy was performed to check the interlaminar damage created post-impact.

Water absorption tests were performed at 50 °C to evaluate the effect of star-like polymers on the kinetics of water absorption. The elevated temperature was used to increase the rate of water absorption. Mechanical tests were performed on the moistened samples at equilibrium water content.

3. Preliminary results and conclusions

The representative DMA curves for the storage and modulus of the neat epoxy and epoxy filled with star-like polymers (poly(n-butyl methacrylate)-(glycidyl methacrylate) block copolymer at different filler content (0.25, 0.5 and 1 wt.%) is shown in Fig. 1. It can be noticed from Fig. 1 that besides the epoxy filled with 0.25 wt.% of the star-like polymers, the storage modulus increases with the increase of the star-polymer content, revealing higher resistance to the dynamic loading at all temperatures. The highest storage modulus was registered for epoxy filled with 0.5 wt. % of the star-like polymers.

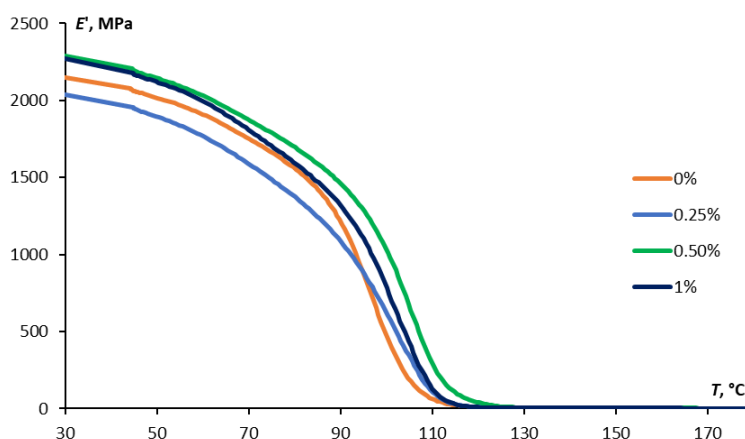


Fig. 1. Storage modulus vs. temperature for the epoxy resin and epoxy filled with 0.25, 0.5 and 1.0 wt. % of the star-like polymers.

Figure 1 shows that the storage modulus decreased dramatically at the glass transition. Thus, evaluated at the maximal value of loss modulus, the glass transition temperature as a function of the star-like polymer content slightly increased by 7.6 °C, proving some reinforcement effect of the filler particles. Small data scattering was obtained for the identical material specimens, proving the repeatability of the results and sufficient quality of the test specimens.

Acknowledgements

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Multiphysics Characterization of Composite Materials at High Strain Rates

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Abstract: The need to join the structural properties of the materials with their multi-functional ones leads to revisiting the traditional techniques for material characterization. Consequently, material properties need to be explored in terms of mechanical-thermal-electrical interaction during the loading application instead of simply mechanical response. Among all materials, composite materials are getting more attention because of their strong potential as structural materials with valuable self-sensing properties. Therefore, the multiphysics characterization of these materials requires special attention; this study provides a simple approach to evaluate these properties of composite materials at high strain rates through an advanced Split Hopkinson Bar setup.

1. Experimental Setup

Multiphysics characterization of composite materials at high strain rates needs to determine the electrical, mechanical, and thermal properties during an impact loading. To evaluate all these properties simultaneously, the traditional mechanical characterization testing apparatus at high strain rates, direct Split Hopkinson Bar (SHB) was equipped with further measurement instruments, as shown in figure 1. The SHB system consists of three aligned steel bars (Pre-stressed, Input and Output) of 18 mm in diameter and 3.0, 7.5, and 4.0 m long, respectively. Between the input and output bars, the samples were recorded with a high-speed camera (Fast-cam 150 kHz), for local strain evaluation, and a high-speed thermocamera (Flir X6900 10 kHz) for local change in temperature evaluation. The electrical properties were indirectly determined on the sample by monitoring the change in electrical resistance between the compressive plates, compression test, or along the gauge length, in a tensile test. The piezoresistivity measurement technique uses the basic principles of identifying an unknown electrical resistance in series circuit in which the samples are the unknown resistance. A known electrical resistance R is connected between the NI PCI-6120 and the sample end so that the R resistance is in series with the tested sample. Both resistance R and sample were powered by the NI PCI-6120 with a constant tension, i.e. 5 V. This set-up ensures measuring of the unknown electrical resistance, i.e. the sample resistance R_U , through the simple relationship:

$$R_U = \frac{\Delta V_U}{\Delta V_R} R$$

where ΔV_U is the potential measured by the instrument between the sample edges. ΔV_R is the potential measured between the known electrical resistance R . Since the electrical measurement is strongly dependent on the environment, the bars were insulated from the other components through cylindrical support in PTFE, as figure 1 shows. Strain gauges and voltages signals were acquired by NI PCI-6120 at 1 MHz and the signals were triggered on input strain waves signal so the acquisition starts at the same time with cameras recording.

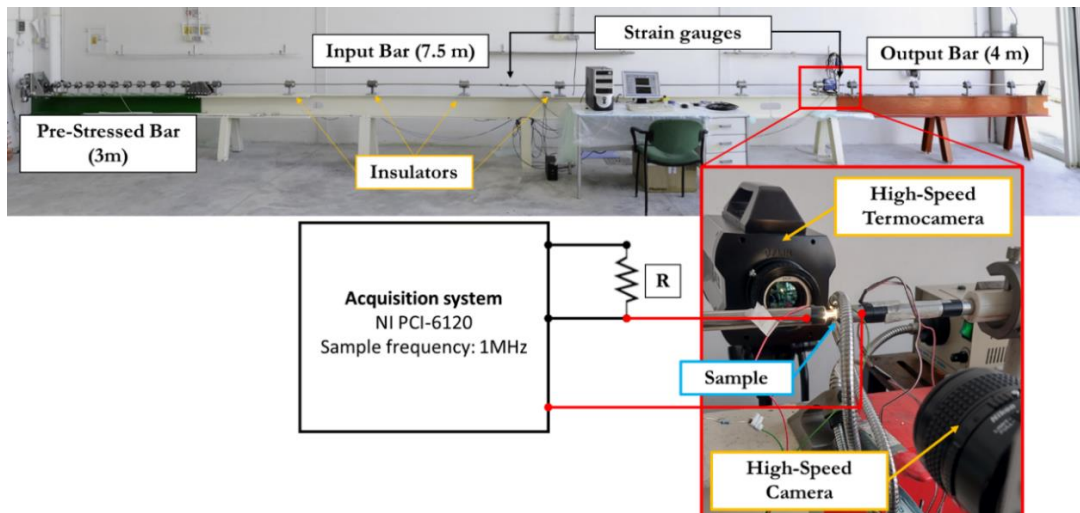


Figure 1: Set-up of Split Hopkinson Pressure Bar for high strain rate multiphysics measurement [1].

A compression test on piezoresistive composite materials was proposed as an illustrative example. The cylindrical sample was compressed at a high strain rate of approximately 400 1/s. Figure 2 depicts the strain and electrical resistance signals observed during the test. The transmitted and reflected waves were shifted based on the position of the strain gauge along the bars as well as the electrical resistance signal. The analytical shifting procedure highlights the dynamic equilibrium achieved during the compression test. Initially, the electrical resistance increases due to the stretching of the pre-stressed bar, causing a slight loss of compressive pre-load. However, once the normal stress waves propagate along the input bar, the electrical resistance stabilizes. Subsequently, the electrical resistance decreases only after the compressive wave reaches the sample. Furthermore, an increase in electrical resistance is evident after the sample undergoes fracture, as depicted in Figure 2, occurring at approximately 600 μs . The history of electrical resistance provides insights into the timing of failure occurrence in addition to material piezoresistivity property, providing an alternative strategy to determine material fracture at high strain rates.

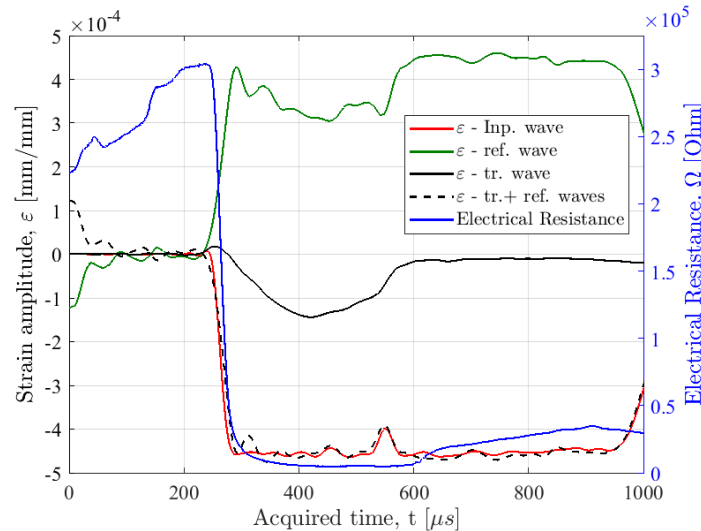


Figure 2: Strain waves signals into input and output bars coupled with electrical resistance signal [1].

The high strain rate affects the sample temperature, consequently impacting the piezoresistivity and mechanical properties, which are inherently temperature dependent. Figure 3 illustrates the temperature distribution captured by the high-speed thermocamera during high-speed compression tests. Initially, the temperature remains uniform up to the stress peak, showing the thermoelasticity phenomenon. Subsequently, as the cylinder begins to fracture, the apparent temperature in the fractured zone increases rapidly from 15°C at 0.065 mm/mm to 58°C at 0.13 mm/mm. It's noteworthy that before reaching the peak load, the temperature change can be considered negligible as the thermoelastic effect is about 1°C, attributing the temperature effects predominant in the plastic regime. However, after the peak stress, the fragmentation of the sample complicates the temperature assessment and how temperature might influence the piezoresistive and mechanical response.

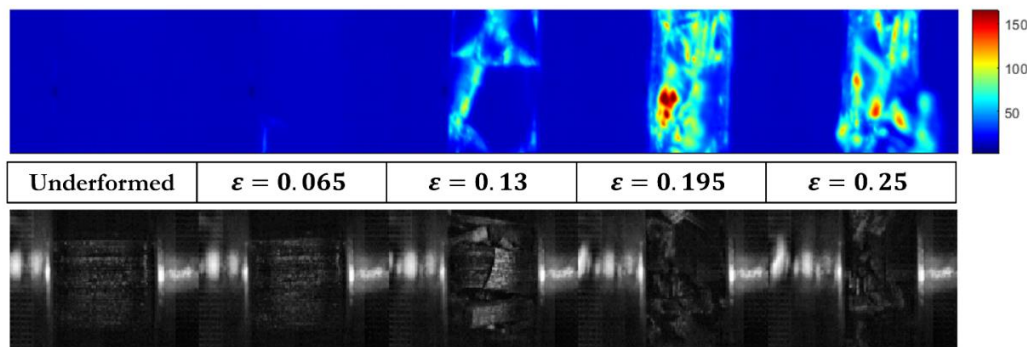


Figure 3: High speed thermocamera results vs deformed shape of FFF-printed sample in high strain rate compression test[1].

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Enhancing Impact Resistance and Tensile Properties of 3D-Printed Biobased Photopolymers with Ultra-Low Nanocellulose Content

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Abstract: Ultraviolet (UV) light-assisted additive manufacturing (AM) needs biobased resins capable of rivalling traditional petroleum-based alternatives. This study introduces a resin derived from vegetable oil, filled with nanofibrillated cellulose (NFC), which boosts mechanical properties at extremely low NFC concentrations (0.1 – 1 wt%). Remarkably, adding just 0.1 wt% NFC resulted in a 2-fold increase in elongation at break and a 1.5-fold enhancement in impact resistance. Furthermore, incorporating 0.5 wt% NFC led to an almost 3-fold rise in tensile modulus and a 6-fold improvement in material toughness.

1. Introduction

Additive manufacturing (AM) originated with vat photopolymerization [1], employing photocurable thermoset polymers, and to this day, such resins remain a focus of research due to their ability to reduce energy consumption and achieve higher print resolutions, up to 2 μm [2]. Vegetable oils, owing to their inherent unsaturation, have been identified as promising raw materials for creating bio-based AM resins [3]. Photocurable resins commonly utilize acrylates and epoxides as their primary components [4]. However, epoxides are somewhat limited in their applicability to 3D printing technologies because their photocuring process is mostly cationic, taking minutes rather than seconds, unlike acrylates [5]. Moreover, while bio-based photocurable resins are more sustainable, they often fall short of the mechanical performance provided by traditional petroleum-based resins [6]. The introduction of fiber reinforcement, particularly using discontinuous fibers, can enhance mechanical properties by facilitating crack bridging, thereby imparting ductility and impact resistance [7]. Sustainable alternatives, such as cellulose nanofibers, offer not only excellent mechanical properties but are also abundantly available. For effective stress distribution and resistance to crack propagation, fibers must be strongly integrated and bonded within the matrix.

2. Methods

This resin composition was formulated from acrylated epoxidized soybean oil (AESO) (65 wt%), trimethylolpropane triacrylate (TMPTA) (35 wt%), and 1,6-hexanediol diacrylate (HDDA) (5 wt%). Afterwards, photo-initiator diphenyl(2,4,6-trimethyl ben-zoyl)phosphine oxide (TPO) (3 wt%) was added. Filter paper-based nanofibrillated cellulose (NFC) suspension was prepared using a LM 20 Microfluidizer (200 μm diameter z-shaped chamber, Microfluidics, USA) and solvent transferred to acetone from water. Using a high-shear mixer, NFC was added in the desired amount (0.1–0.5 wt%), and acetone was removed via evaporation. To print samples from the CAD models, a PRUSA SL1 printer was used, with a 5.5" LCD mask and a 25 W LED with a UV wavelength of 405 nm. After printing, all parts were washed in isopropanol and post-cured in a Prusa Curing and Washing Machine (CW1). According to EN ISO 179-1, Charpy impact resistance tests were carried out on a Zwick IPM-8 testing machine (USA) using unnotched 3D printed rectangular specimens whose dimensions met EN ISO-178 requirements. A 2 J impact hammer was used with five parallel measurements. As per the EN ISO 527-1BA standard, tensile tests were conducted on dog-bone-shaped samples, which had dimensions of 30 $\times$ 5 $\times$ 2 mm. Tensile modulus and tensile strength measurements were conducted at testing speeds of 1 mm/min and 5 mm/min, respectively, using a 5kN S-type load cell and a Tinius Olsen 25ST universal testing machine (USA) using five parallel measurements for each sample.

3. Results and Discussion

Data pertaining to the tensile characteristics is depicted in Fig. 1 (a). Notably, the inclusion of 0.1 wt% NFC marked a pronounced elevation in tensile strength, which increased by 2.3-fold. Additionally, elongation at break experienced enhancement by almost 2-fold at the highest loading of 0.5 wt% of NFC. The determination of material tensile toughness can be achieved through the integration of the area beneath the stress-strain curve up until the point of fracture during tensile testing, as outlined in reference. As illustrated in Fig. 1 (b), the incorporation of NFC as a reinforcement enhances the material's capacity to dissipate energy per unit volume

before reaching fracture. This enhancement is quantitatively reflected in the toughness values, which demonstrate the most significant augmentation at a 0.5% NFC concentration, registering a 6.2-fold increase in comparison to the neat resin. The Charpy impact strength (unnotched) for both the neat and NFC-filled composites is detailed in Fig. 1 (c), demonstrating a pattern that mirrors the outcomes observed in tensile testing. The incorporation of a minimal amount of NFC results in enhanced impact strength, showing a 1.5-fold increase when compared to the neat resin. Conversely, at higher NFC concentrations, the impact strength approximates that of the neat resin, a phenomenon attributable to the agglomeration of NFC. This result in 0.5 and 1.0 wt% samples is typical in filled polymer composites where there is inadequate dispersion of the filler within the polymer matrix. These findings affirm the remarkable capacity of NFC to serve as a reinforcing agent in bio-based UV-curable 3D printing resins.

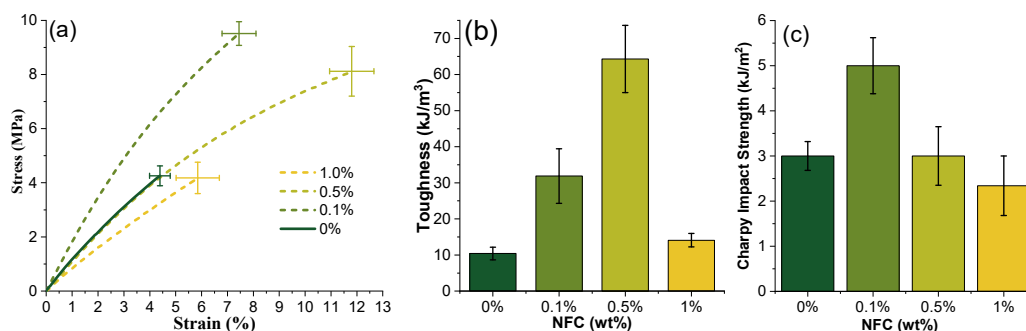


Fig. 1. 3D-printed sample (a) Tensile test stress vs. strain curves, (b) Toughness, and (c) Charpy impact resistance.

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Impact toughness and tensile properties of Polylactic acid/Polyhydroxyalkanoate/Poly(butylene succinate-co-adipate) blends

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Abstract: Biodegradable and bio-based melt-extruded binary and ternary polymer blends of polyhydroxyalkanoate (PHA), polylactic acid (PLA), and poly(butylene succinate-co-adipate) (PBSA), stand out as sustainable alternatives to traditional petroleum-based plastics for a wide range of consumer applications. This study is a preliminary investigation of the impact fracture behavior for the blends. Using the Ternary plot or Gibb's triangle the thirteen binary and ternary biopolyester blends were used. The impact testing method employed in this study includes the notched Charpy impact test. In addition, tensile tests, dynamical mechanical testing, and density measurements were prepared.

1. Introduction

1.1. Background

Petroleum-based polymers have become an essential part of the modern world. However, the limited availability of oil resources and fluctuating oil prices are causing concern for the long-term production of synthetic polymers. Additionally, the environmental impact of petroleum-based polymers as non-degradable waste is a major concern [1]. To address these issues, research is being focused on developing biodegradable polymers from renewable agricultural resources [2]. There are many fossil-based polymer grades available with a wide range of properties, but the options for biodegradable polymers are limited to a small number per producer [3]. Polymer blends are combinations of two or more polymers, which can enhance properties such as strength, toughness, and thermal stability [4]. In many cases, the cost of the final product is an important factor to consider, particularly in commodity and engineering applications, in addition to the quality of the final product. Polymer blends offer a range of options and are cost-efficient, whereas copolymer synthesis is geared towards specialized applications where cost is less of a concern like in biomedical applications [5], [6]. Biodegradable polymers, also known as bioplastics, have gained attention in recent years as a potential replacement for traditional commodity plastics. These polymers, such as polylactic acid (PLA), poly(butylene succinate) (PBS), and polyhydroxyalkanoate (PHA), aim to be more environmentally friendly [7]. PLA, which has a relatively high market share of around 20%, is known for its high elastic modulus and tensile strength, but can be brittle and lack toughness [8]. To improve these properties, it is often blended with other polymers or plasticizers [9].

1.2. Methodology

The materials used were poly(butylene succinate-co-adipate) (PBSA) FD92PM, polyhydroxyalkanoate (PHA) grade PHI002, and Polylactic acid (PLA) 6201D pellets. The blends were prepared using the Thermo Electron PRISM TSE 16 TC bench-top twin-screw extruder. The compositions of the blends used are detailed in Figure 1(a). The mechanical testing was carried out using Tinius Olsen 25S with a crosshead speed of 1 mm min^{-1} and an S-type load cell with a capacity of 5 kN. The V-notched Charpy impact test was performed on a Zwick IPM-8 testing machine. Dynamic mechanical analysis was performed utilizing a dynamic mechanical analyzer DMA/SDTA861e from Mettler Toledo (USA) at a temperature range from $-70 \text{ }^{\circ}\text{C}$ to $100 \text{ }^{\circ}\text{C}$. The testing protocol entailed a heating rate of $3 \text{ }^{\circ}\text{C min}^{-1}$, an applied force of 10 N, a displacement amplitude of $20 \text{ }\mu\text{m}$, and a frequency of 1 Hz.

1.3. Result and conclusion

As demonstrated in Figure 1(b), PBSA is the most significant component to increase the impact strength both for binary and ternary biopolyester blends. Neat PBSA demonstrated 2.2- and 2.7-fold higher values compared to PHA and PLA, respectively. Considering the binary blends, it can be clearly said that the strength increase of PHA/PBS blends is much less compared to PLA/PBSA blends. Ternary systems showed somewhat similar results indicating that PBSA content must be above 50 wt.% to achieve notable improvements.

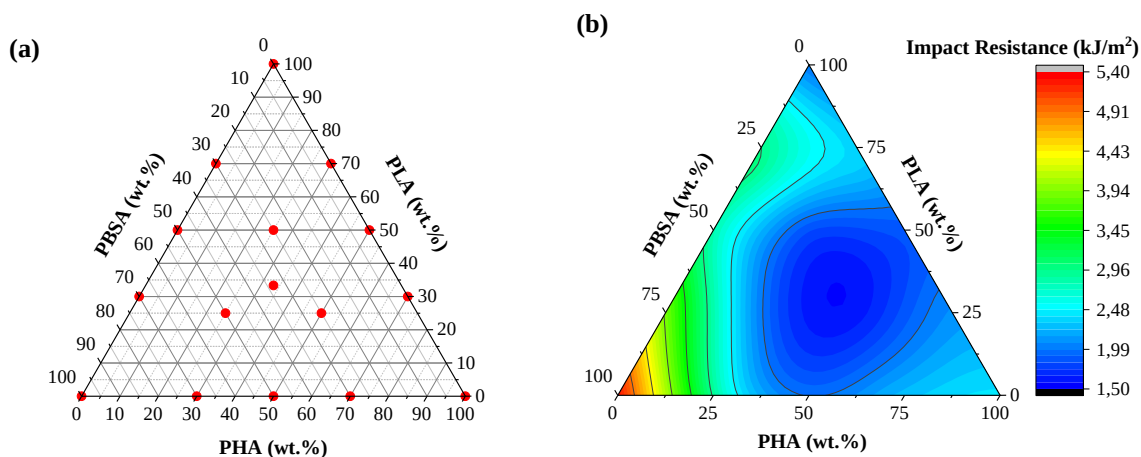


Fig. 1. Binary and ternary PBSA, PHA and PLA blends (a) compositions and (b) impact resistance.

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Graphene nanoplatelets and carbon nanotubes as effective high-strain property enhancers of an epoxy matrix

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Abstract: This work compares the tensile strength, Charpy toughness, and fracture toughness of two-component epoxy composites filled with 0 – 0.5 vol.% of multiwall carbon nanotubes and graphene nanoplatelets. A neat sample and eight composites were prepared using high shear mixing and mold casting techniques. The mechanical tests (tensile testing, Charpy impact testing, K_{1c} bending testing) permitted the evaluation of the extent of interaction between the carbon nanotube and graphene nanoplatelets via a regression model, and their influence on the overall high strain properties of the composites. Critical filler concentrations are estimated around 0.25 %, where the highest property increases are seen.

1. Introduction

1.1. Background

The addition of carbon nanoparticles stands out as a simple and compatible solution for modifying polymer materials while maintaining desirable properties, such as mechanical strength, chemical resistance, and low density. Nanocomposite properties widely depend on the nanoparticles used, filler concentration, and processing methods. The most promising and widely researched nanofillers for the enhancement of both mechanical and functional properties (such as electric conductivity) are multi-walled carbon nanotubes (CNT) and graphene nanoplatelets (GN). The covalently bonded crystalline structure of the fillers imparts them with extremely high mechanical properties and elastic modulus [1], while the high length-to-diameter ratios impart them with very high specific surface areas, which allow efficient contact and stress-strain transfer to and from the composite matrix. The main problem of their application is the efficient dispersion, distribution, and alignment within the matrix, which is complicated by their nano scale and tendency to agglomerate [2].

Epoxyes are widely used in the fiber reinforced composite industry due to their ease of use, high heat deflection temperatures, and very high mechanical properties. By further improving their mechanical-dynamical properties via carbon nanofillers, it's possible to make composite materials more economical and effective.

In this paper we created novel epoxy and carbon nanoparticle binary composites with CNTs and GNs as nanoscale reinforcement. The aim is to combine two different nanoparticle morphologies in order to optimise composite properties for dynamic high-strain and static mechanical applications. The combination of two different types of nanoparticles could give property synergies, which arise from the interaction of platelike and fiberlike particles, and their interaction with the crosslinked epoxy network [3].

1.2. Methodology

The materials used were Peran STC (Flowcrete) two part liquid epoxy, multiwall carbon nanotubes NC7000 (Nanocyl), and graphene nanoplatelets xGnP-750 (XG Sciences). The nanofillers were mixed into the A component at 0, 0.25, 0.5 vol.% in a full factor experiment using a high-shear mixer, followed by combination with the B component, and casting in standard silicone molds. The mechanical and fracture toughness testing was carried out using a Zwick ProLine FB020 TN with tensile and bending attachments. Charpy impact testing was carried out using a Zwick 5102 on notched samples. The data were evaluated using regression analysis.

2. Results and conclusions

Figure 1 shows the surface response models of elastic modulus (Fig. 1a), strain at yield (Fig. 1b), and tensile strength (Fig. 1c) of the composites depending on the concentrations of CNT and GN. It can be seen that the elastic modulus and yield strength reach their maximums around critical values with GN:CNT at 0.25:0.25 and 0.25:0.0 respectively. In the case of E, both fillers synergistically interact to stiffen the composite up to 0.25 vol.%. At higher concentrations filler agglomeration likely causes structural defects, which reduce the modulus. In the case of σ_Y , increasing the GN content up to 0.25 vol% provides a strengthening effect, after which the effect diminishes. In both cases, GN can act like a molecular mobility enhancer or a plasticiser due to inter-plate slippage. However, at higher concentrations, the thin planar structure could act as a matrix stress concentrator. Both fillers could restrict polymer network mobility due to their large specific surface areas and high level of entangling with the network. The addition of fillers reduces the yield strain significantly.

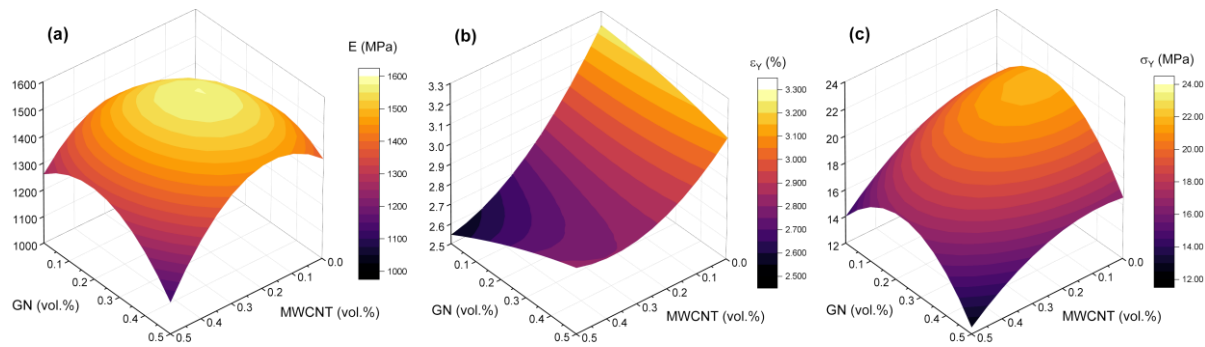


Fig. 1. Regression analysis of (a) elastic modulus E , (b) yield strain ϵ_Y , and (c) yield strength σ_Y .

Figure 2 shows the surface response models of (Fig. 2a) fracture stress intensity factor, (Fig. 2b) fracture strain energy release rate, and (Fig. 2c) notched Charpy impact toughness. A similar response can be seen in both K_{1C} and G_{1C} – the addition of 0.25 vol.% of GN drastically increases the fracture toughness, likely due to the previously mentioned plate morphology of graphene, as plate slippage and particle mobility absorbs energy. At higher loadings agglomeration occurs and the opposite effect of mobility restriction occurs, thus reducing the fracture toughness. The increase of CNT concentration further reduces the fracture toughness. In the case of impact toughness, however, individual CNTs act as high strain and stress diverters, increasing the impact toughness over the pristine epoxy. GN decreases impact toughness as the nanoplatelets enhance crack propagation along their planes.

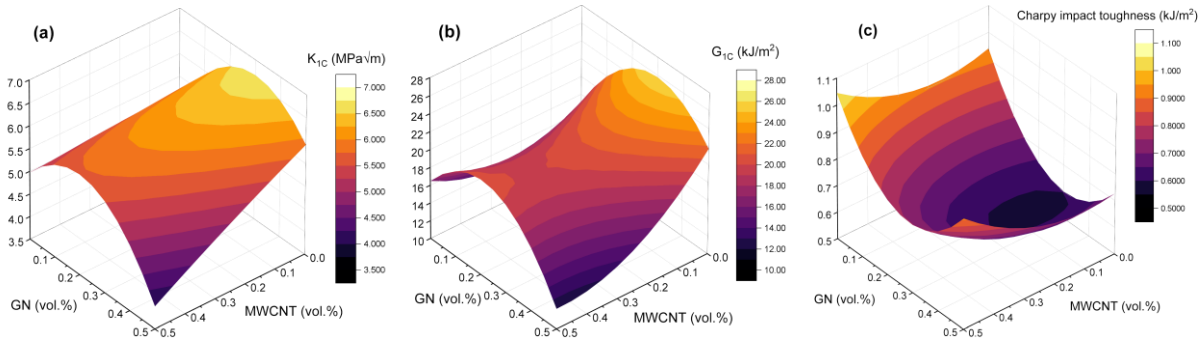


Fig. 2. Regression analysis of (a) fracture toughness K_{1C} , (b) fracture energy release rate G_{1C} , and (c) Charpy impact toughness.

The addition of carbon nanofiller interacts with the mechanical properties of the epoxy composites in a complex way- enhancing tensile modulus and strength, fracture toughness, charpy toughness, while reducing strain at yield. Further investigations into the nanoscale structure of the composites would be useful to explain the interaction between the individual filler particles, as well as their dispersion and distribution within the composite. Carbon nanofillers are an effective tool to increase the high strain properties of engineering polymers.

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Static Thermographic Method for Fatigue Limit Assessment of Composite Materials

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Abstract:

The current paper focuses on determining the fatigue limit of short fiber reinforced polycarbonate using the static thermographic method. The method used for this investigation was proposed by Risitano&Risitano [1] to determine the fatigue limit by tensile testing. The specimens were subjected to tensile tests to obtain stress over time and surface temperature was monitored with a FlirA40 thermographic camera to determine temperature variations. Fig.1 presents a measurement of a specimen using the STM. The fatigue limit values obtained were compared with the fatigue curves [2]. As presented in Fig. 2, the Zwick/Roell Z005 was engaged to perform the tensile tests with two different test speeds, 5 mm/min and 10 mm/min. Thermographic measurements were taken at a frame rate of 50 Hz in the fracture area. The temperature was filtered to eliminate noise to have a smoother curve.

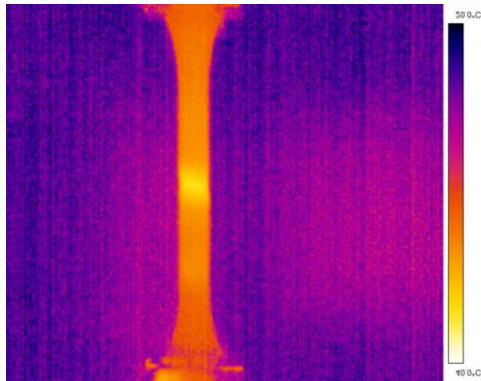


Fig. 1 – Thermographic measurement



Fig. 2 – Test setup for measurements

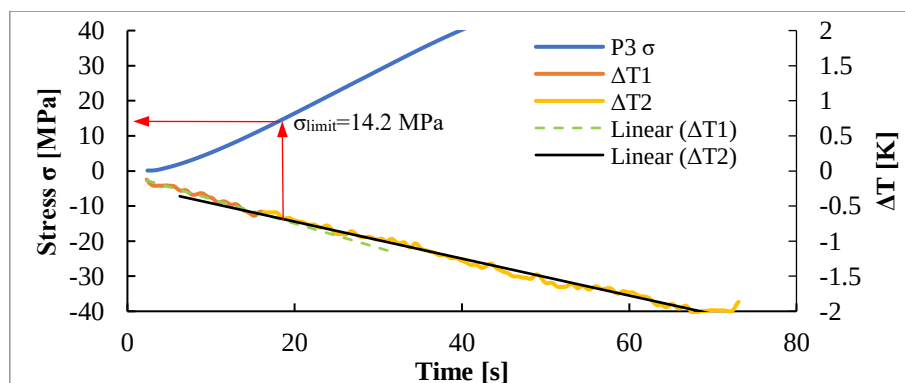


Fig. 3 – Surface temperature vs time

In Fig. 3 the stress and the temperature variation are plotted over time. Temperature variation was determined by taking the difference between instantaneous temperature and initial surface temperature at time zero ($\Delta T = T_i - T_0$) according to [1]. The value of the fatigue limit σ_{limit} corresponds to the time when the linear interpolations of the temperature variations intersect [3].

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Speckle techniques with a high-speed camera for deformation evaluation of composites during impact testing

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Abstract: The paper presents the implementation of two speckle techniques with a high-speed camera acquisition for the characterization of composites during impact testing. The first technique is digital image correlation (DIC) based on the correlation of printed or painted speckle patterns captured before and after the deformation to calculate the displacement field. The second technique is intensity-based dynamic speckle imaging (DSI), which enables the detection of defects and visualization of speed distribution for processes developing in an object. We proved that the DSI can be used as a complementary source of information with the DIC method.

1. Introduction

The DIC and the DSI have proven their efficiency in evaluation of deformations and monitoring of processes. The DIC relies on finding the maximum of the correlation array between pixel intensity subsets on two or more corresponding images. The method involves image acquisition, placement of printed speckle, subset selection, correlation calculation, sub-pixel registration, and obtaining full-field displacement and strain maps. The DIC is applied in material testing, biomechanics and civil engineering to study material behavior, structural deformation, and mechanical properties [1-3]. The intensity-based DSI is a single-beam coherent optical method for non-destructive testing and monitoring of processes in industrial and biomedical applications. Through statistical processing of speckle patterns formed on the surface of a laser illuminated object, the DSI extracts an activity map which presents areas with different scales of intensity fluctuations in time [4-6]. High sensitivity of the method is due to the strong impact of micro changes in topography, refractive index or reflectivity of the tested object on speckle formation. The activity map reflects the temporal correlation in the raw speckle data and can be built by averaging in the temporal or spatial domains.

The paper compares the DIC and DSI implementation with a high-speed camera acquisition for the deformation characterization of composites during impact testing. One motivation for comparing both DSI and DIC was the fact that, in some cases, the deformation of the object is measured at temperatures at which the printed speckle is not able to adhere to the surface. Then, the speckle pattern has to be created by alternative methods, such as laser beam illumination, which is the basis of the DSI method. The other motivation was to prove the applicability of the DSI for impact testing while capturing images with a high-speed camera.

2. Material impact testing with DSI and DIC methods

The experimental setup consisted of a Coherent Verdi 6 W (532 nm) laser, white light sources, two high-speed cameras, Photron FASTCAM Mini AX200 and FASTCAM NOVA S6 for image capturing and a gas gun with an impact speed of 55 m/s. We used three types of samples of size 200×200 mm for impact testing: 1) Aluminum plate 3 mm thick; 2) Woven thermoplastic CFRP 3 mm thick; 3) Cyttec 977-2 CFRP 4 mm thick.

Table 1. List of experiments

Number	Method	Sample, plate	2D or 3D	Speckle
1 - 3	DIC	Aluminum	3D	printed
4	DIC and DSI	Aluminum	3D	Laser
5	DIC	CFRP woven thermoplastic 3mm	3D	printed
6	DIC	Cyttec 977-2 CFRP 4 mm	3D	printed
7	DIC	Aluminum	3D	Laser
8	DSI	Aluminum	2D	Laser
9	DSI	Cyttec 977-2 CFRP 4 mm	2D	Laser
10	DSI	CFRP woven thermoplastic 3mm	2D	Laser
11	DSI and DIC	CFRP woven thermoplastic 3mm	2D	printed

For contrast enhancement, the surface of the samples was covered with white acrylic paint. During the experiments, the surface of the test objects was covered with a printed speckle pattern using Speckle Pattern Application Kit or a laser speckle was created by illuminating the surface with an expanded laser beam. All the experiments performed are listed in Table 1, where column “2D or 3D” means usage of either one or two high-speed cameras respectively. Images were captured at 10 μ s time intervals or 100.000 fps frame rate.

For the DSI experiments, we estimated activity by pointwise calculation of the absolute value of intensities, $|I_{ij,n} - I_{ij,n+m}|$, at time lag, $\tau = m\Delta t$, from two images, where $I_{ij,n}$, is the intensity at pixel (i,j) at instant $n\Delta t$, and n varies from 1 to $N-m$, where N is the number of the acquired images. The activity map at increasing n allows following the state of the test object for a certain period of time. Figure 1 a) shows the deformation of the Cytec 977-2 CFRP plate. One may notice waves propagating inside the object. Figure 1 a) was obtained by subtracting 4th and 5th frames captured after the projectile contact with the sample. In this figure, the values vary from 0 to 60. Globally, values change in the range of 0 – 255 in the case of working with 8-bit images. Contrast enhancement is achieved by averaging in the spatial domain. The higher the estimated value, the higher the activity. The activity map, however, is not sufficient to describe deformation or to obtain the parameters provided by the DIC during impact testing. This is the main drawback of the DSI. Application of the DIC method with VIC-3D software (figure 1 b) does not allow visualization of the sample behavior similar to figure 1 a), but it gives estimation of displacement Z in mm and strain during deformation. Figure 1 b) shows the change of the 3D shape of Cytec 977-2 CFRP from 40 to 50 μ s after the projectile contacted the sample.

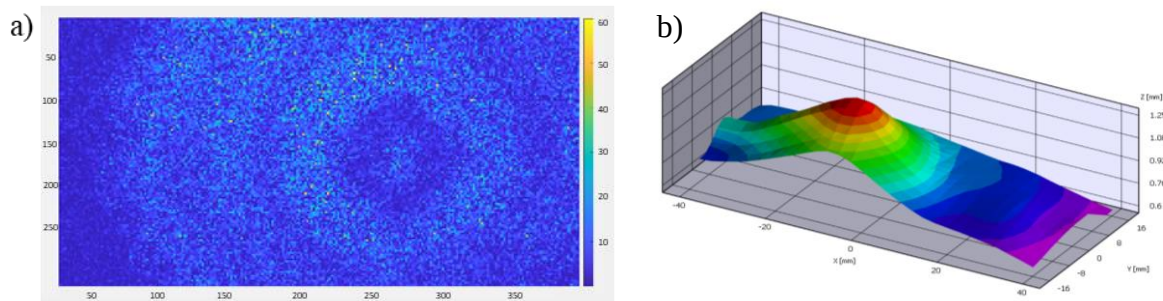


Fig. 1 a) Moment of Cytec 977-2 CFRP sample deformation detected with the DSI method; b) Moment of Cytec 977-2 CFRP sample deformation detected with the DIC method

3. Conclusion

In summary, we compared advantages and disadvantages of DIC and DSI methods for impact testing while capturing images with high-speed cameras. The DSI gives better visualization of strain within the sample, but method information about strain or displacement values is missing. The DIC method, in its turn, allows the calculation of these values. However, it contains less visual information, especially after the stage when the projectile has fully penetrated the test sample. Both methods can be combined together in order to fully interpret the impact testing experiment.

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HISTRATE

*Advanced Composites under High Strain Rate Loading
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Yıldız Technical University

Vineta Srebrekoska, Predicting the ballistic strength of composite laminates subjected to a perpendicular impact by a solid projectile
Goce Delcev University Stip

Nikoloz Chikhradze, Experimental Study of the Explosion Resistant Ability of Low Carbon Steel Plates with Intermediate Aluminum Sheet Layers
Mining Institute Georgia

Amine Haj Taieb, A review of textile Composite Structures under High Strain-Rate Loading Conditions
University of Sfax

Aleksandre Vanishvili, Development of basalt based Fiber-Metal Laminate with advanced mechanical properties
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Yang Zhang, Polish Simulation and Quantification Method of Crack Propagation Damage of Adhesively Bonded Composite Structures under High Strain Rates
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Müslüm Kaplan, Bartın Poly (Vinylidene Fluoride)/Carbon Nanotube/Semiconductor Inorganic Nanoparticles Composites for Piezoresistive Sensing
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Elena Stoykova, Hidden defects detection under tensile loading by laser speckle photometry
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Maraym Viqar, Laser speckle photometry with binary patterns
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Tomasz Waldowski, FBG based lamb wave mode separation for damage localisation
Polish Academy of Sciences

Violeta Madjarova, Hilbert transform method for electronic speckle pattern interferometry to study plastic deformation of materials under tensile stress
Bulgarian Academy of Sciences

Petros Gkertzos, Machine learning based damage localisation utilising finite element modelling, intended for tinyML applications
University of Patras

Svetlana Risteska, Influence of strain rate and type of matrix on mechanical properties of carbon thermoplastic laminates under dynamic compression produce with LATP/LAFP
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Material Model Development from Quasi Static to High Strain Rate for Thermoset Polymers

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Abstract:

Material modeling of thermoset polymers from quasi-static to high strain rate loading requires accounting for the unique characteristics of crosslinked structures, nonlinear viscoelastic behavior, residual stresses, brittle fracture behavior, and thermal effects. Among these unique characteristics, adiabatic heating which is observed at high strain rates is taken into account in the development of cooperative viscoplasticity theory based on overstress for high strain rate applications. The thermal strain is included into the total rate of deformation formulation and compression behaviors at quasi static and high strain rate loading are simulated for various strain rates. The influences of thermal strain on the stress-strain behavior are depicted.

1. Introduction

Thermoset polymers play a pivotal role in numerous industrial applications due to their desirable mechanical properties and thermal stability and serve as the matrix material in composites. Understanding their behavior across various loading conditions and developing accurate material models for thermosets particularly in dynamic scenarios, are essential for optimizing their performance in diverse engineering applications. This study focuses on the development of material models capable of accurately predicting the response of thermoset polymers over a wide range of strain rates, from quasi-static to high strain rates. The research methodology encompasses experimental characterization and modeling techniques tailored to capture the complex behavior of thermoset polymers under dynamic loading conditions. The experimental data serve as the foundation for developing constitutive models capable of capturing the strain rate-dependent behavior of thermoset plastics, [1].

In this work, the Cooperative Viscoplasticity Theory based on Overstress (CVBO) for thermoset polymers modified to account the thermal effects observed in high strain rate loading [2] is used to simulate the compression behaviors of thermoset polymers at quasi static and high strain rate loadings. Rate dependency is depicted in addition to the influences of thermal effects on high strain rate behaviors.

2. Thermal Effects in High Strain Rate Loadings

In high strain rate loadings, thermal effects refer to the phenomenon where the rapid deformation of a material leads to an increase in temperature due to the conversion of mechanical energy into heat. When a material undergoes rapid deformation, such as during impact or explosive loading, a significant portion of the mechanical energy is converted into heat due to internal friction and viscous dissipation. This conversion of strain energy into thermal energy contributes to a rise in temperature within the material. This temperature rise can have significant implications for the material's mechanical behavior and performance. The mechanical properties of materials, including stiffness, strength, and viscosity, can be highly sensitive to temperature changes.

3. The Cooperative Viscoplasticity Theory Based on Overstress (CVBO)

CVBO is a material modeling approach specifically designed to capture the behavior of polymers under high strain rate loading conditions, [2]. This theory builds upon the traditional concepts of viscoplasticity while incorporating the notion of overstress. Overstress represents an additional stress state that evolves dynamically during deformation, reflecting the cooperative interactions among material elements. The details of the CVBO model can be found in the work by Colak et al. [3] and . Here, only the part related to adiabatic heating will be introduced. To simulate the influences of adiabatic heating observed at high strain rate loadings, the thermal strain is included into the total rate of deformation formulation. Then, the rate of deformation tensor becomes,

$$\mathbf{D} = \mathbf{D}^e + \mathbf{D}^{vp} + \mathbf{D}^{th}$$

Where $\mathbf{D}^e$, $\mathbf{D}^{vp}$ and $\mathbf{D}^{th}$ elastic, viscoplastic and thermal part of the rate of deformation tensor respectively. Thermal strain is, $\mathbf{D}^{th} = \alpha(\theta)\dot{\theta}\mathbf{I}$

where $\mathbf{I}$ is identity tensor and α is thermal expansion coefficient for the material. The rate of change of temperature is, $\dot{\theta}$

$$\dot{\theta} = \omega \frac{\Gamma \dot{\gamma}^{vp}}{\rho c}$$

Where ω is Taylor and Quinney coefficient, Γ is overstress invariant, $\dot{\gamma}^{vp}$ viscoplastic strain rate, ρ is density of the material and c is specific heat capacity. The details of the model can be found in the work [3].

4. Simulation Results for Epoxy

Compression stress-strain behavior of epoxy is simulated at different strain rates from under quasi static loading to high strain rate loadings and depicted in Figure 1.

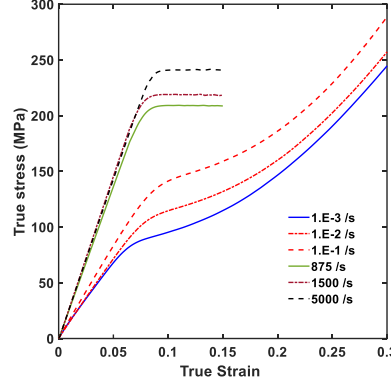


Figure 1. Compression stress-strain behavior of thermoset epoxy at different strain rates

As seen from Fig. 1 rate dependency from quasi static to dynamic can be captured by the proposed model. The behavior at quasi static and high strain rate loadings are quite different. Rate dependent hardening behavior at viscoplastic region under quasi static loading is prominent. At high strain rate loading, due to thermal effects, hardening is not observed. By including and excluding the influence of adiabatic heating, the simulations are performed and the stress-strain behavior results are given in Figure 2.

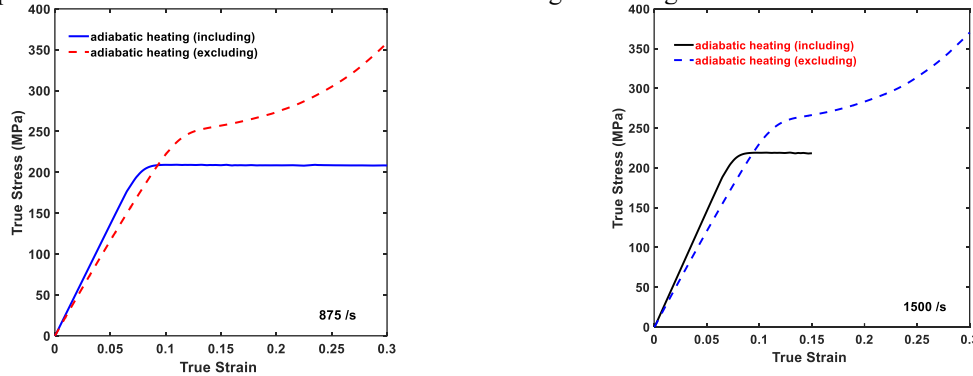


Figure 2. The influences of adiabatic heating on the compression behavior of thermoset epoxy.

5. Conclusions

Thermal effects in high strain rate loadings can significantly influence the mechanical behavior, failure mechanisms, and performance of materials. Understanding and accurately modeling these thermal effects are essential for predicting the response of materials under dynamic loading conditions and optimizing their performance in applications such as impact resistance, crashworthiness, and ballistic protection. The influences of the thermal effects on the stress-strain behavior of thermoset polymers are shown for different strain rates from quasi static to high strain rates by using CVBO model.

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Predicting the ballistic strength of composite laminates subjected to a perpendicular impact by a solid projectile

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Abstract: In the paper, the attempt was made to assess the applicability of the full factorial experimental design in predicting the ballistic strength of nylon fiber/ phenolic composite laminates when subjected to a perpendicular impact by a solid projectile. In the study we used a number of ballistic composites (20 cm x 20 cm) with different areal weight (thickness) and fiber/resin ratio. The composites were made with an open mold high pressure, high-temperature compression of prepreg layers made of plain woven ballistic nylon fabric and polyvinyl butyral modified phenolic resin of the resole type. The preparation of the composite experimental samples was conducted in accordance with the 2² full factorial experimental design. The areal weight of the composites was taken to be the first factor and the second was the fiber/resin ratio. The influence of each individual factor to the response function was established, as well as the influence of the interaction of the two factors. We found out that the estimated first-degree regression equation with the interaction gave a very good approximation of the experimental results of the ballistic strength of composites within the study domain.

Fiber/resin composites are mainly used as structural materials. Because of their very high strength-to-weight ratio these materials have substituted many traditional materials in applications where the strength and weight are of crucial importance, especially in military and aerospace industries [1, 2].

The impact damage mechanism of composite materials can be categorized as either being a low velocity impact or a high velocity impact, which essentially pertains to the kinetic energy state of the impacting projectile. However, regardless of the categorization, the impact damage as a whole is defined as the application of a high strain rate on the material [3]. The low velocity impact damage can be defined as an event that applies a quasi static load to the material, which is an event that has the duration sufficiently long enough for the entire composite structure to respond to the impact. However, a high velocity impact can be defined as an event where the composite structure does not have time to respond to the impact loading, which is usually characterized by the stress wave propagation through the material with the majority of damages being inflicted in a localized area. The energy-absorption characteristics of a laminate subjected to the ballistic impact depend on constituent material properties (fiber and resin), laminate and projectile parameters and impact conditions [4, 5]. The influence of some of these parameters on the perforation of laminate plates has been studied. One of the main parameters affecting perforation i.e. ballistic strength is laminate thickness. An alternative and related parameter is the areal weight of the laminate; the other main parameter is fiber/resin ratio into the composites which greatly affects overall mechanical properties of the laminate including the impact resistance.

Ballistic composites are traditionally developed by using the legacy knowledge, and their development relies extensively on the use of fabricate-and-test approach. Since this approach is not only economically unattractive, but is often associated with significantly longer lead times, it has gradually become complemented by the appropriate cost- and time-efficient Computer Aided Engineering (CAE) analyses [3,4]. Based on the empirical knowledge, in this study we tried to find a mathematical correlation between two main factors affecting the ballistic strength of nylon/phenolic composites - the areal weight and the fiber/resin ratio of the composites.

The thermosetting phenolic resin with the dry content of 76 % and gel time at 150 °C of 120 s was used as a matrix. The resin was modified with polyvinyl butyral with the dry content >98 %, supplied by Plasta Erkner, Germany. The purpose of the modification was to make the intrinsically brittle phenolic resin more flexible. It is a well-known fact that the flexibility of the matrix system better contributes to the kinetic energy absorption of high- and low-velocity impact and its dissipation in the adjacent layers [2]. As reinforcement, a plain woven nylon fabric was used. The impregnation of the fabric was carried out on a semi-industrial vertical impregnating machine. The laminated composites were produced by an open-mold compression at high pressure and the temperature of 155 °C within 150 minutes for fully curing i.e. cross-linking of the resin. No post-curing treatment was conducted.

All tests were conducted with a standard 1.1g chiselnosed, a fragment simulating projectile which is non-deformable, made of quenched and tempered steel with a flat rectangular tip. Figure 1 shows the ballistic test setup. V50 measurement is based on measuring the time for which the projectile passes through two photo-sensitive frames which are positioned at a fixed distance, L. The ballistic limit velocities, V50, are calculated in accordance with the NATO standard STANAG 2920 calculation method [6]. V50 property presents 50 % probability of the penetration i.e. non-penetration of the projectile into the test specimen (composite plate) and is

a statistical measure developed by the US military. In accordance with 2^2 full factorial experimental design procedure, 4 (2^2) trials are needed i.e. all possible combinations of the variables are tested. The first factor low and high levels were set at 2 kg/m² and 9 kg/m², respectively, and for the second factor – at 80/20 and 50/50, respectively. To approximate the response i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m² x (80/20 – 50/50) fiber/resin ratio, the first-order linear model with the interaction was used.

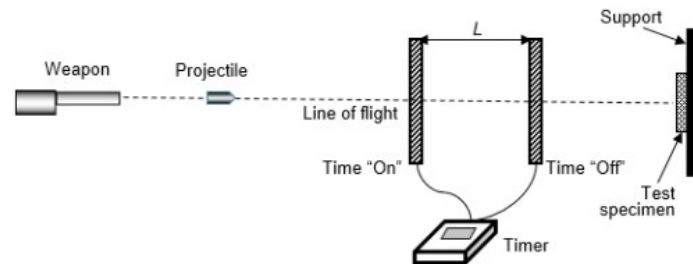


Fig. 1 Ballistic test setup

Weave patterns typically used for ballistic application are plain and basket. When a projectile strikes a layer of fabric, the fabric deflects transversely and the mesh of yarns is distended, resulting in the enlargement of the spaces between yarns as shown in Fig. 2. If the fabric is not too tight and the projectile is relatively small and impacts at an angle, only a few yarns ahead of projectile break, the projectile can slip through the opening or “wedge through” by pushing yarns ahead instead of breaking them. The number of broken yarns is less than the number of yarns that intersect the projectile. Therefore, lateral movement of the yarns results in less energy absorption [2-5].

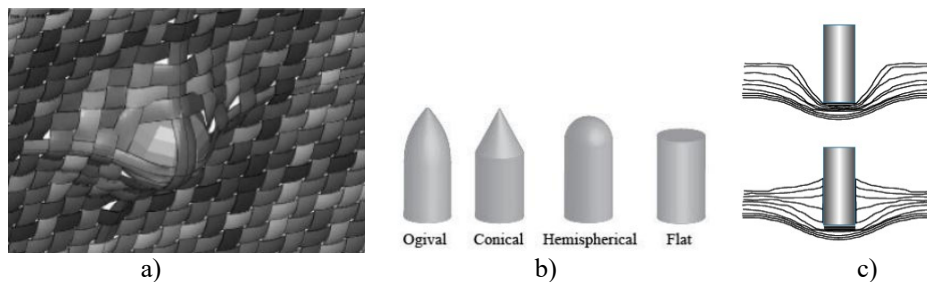


Fig. 2 a) Wedge-trough phenomenon; b) Projectiles with different geometries; c) Cutting actions with flat-tip projectile

The predominant mechanisms that led to perforation of the fabric are highly dependent on the shape of the projectile. With the perforation of plain woven nylon fabric laminates by four different tipped projectiles: flat, hemispherical, ogival and conical. with the same caliber and with the same mass, the flat-tipped projectile cut the laminate through a shearing action whereas hemispherical projectiles perforate the laminates by stretching the fibers to failure. Conical and ogival projectiles perforated the laminates by stretching the fibers to failure. Conical and ogival projectiles perforate the fabric with least amount of yarn pull-out, indicating these projectiles were able to slip through the weave. The V50 velocity decreases in the following order of the projectile geometry: hemispherical, flat, ogival, and conical. But, the effect of projectile geometry decreases with the thickness of the laminate [3-6].

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Experimental Study of the Explosion Resistant Ability of Low Carbon Steel Plates with Intermediate Aluminum Sheet Layers

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Abstract: The war in Ukraine has shown that the protection level of armored vehicles is not adequate to anti-tank weapon capabilities. It is therefore expected that the improvement of ballistic and blast resistance of vehicles will be one of the key challenges within the following years [1-4].

The present paper assesses the efficiency of different energy-absorbing layers under equal conditions. It presents the results of experiments conducted to study steel plate deformation and acceleration under blast impact when a protective layer is made of material with strong suppressing properties. Comparative analysis of cellular panel and aluminum as a suppressant for ensuring higher effectiveness of steel plate protection has been conducted.

1. EXPERIMENTAL SETUP

1.1. Steel plate and protective layers

Was tested steel plate without a protective layer, with a protective layer of an aluminum plate 3 mm thick and with aluminum honeycomb plates. An aluminum honeycomb panel with a thickness of 10mm, 20mm and 30 mm was used for shock wave energy absorbing (Fig. 1). The panel consists of aluminum skins (bottom, top) with a thickness of 0.8 mm and the core of aluminum honeycombs with hexagonal cells. The panel weight is 6.7-7.7 kg/m², compressive stabilized strength - 2.9 MPa and skins elastic modulus – 68 MPa.



Figure 1. Steel plate with an aluminum honeycomb layer

During testing, a model of an armored vehicle was used, which corresponds to the real armored vehicle in terms of its geometric dimensions, mass, and mass distribution. The model contains supporting elements, steel I-beam construction, in which the test plates are rigidly fixed and extra mass in the form of sandbags. The total weight of the model is 8 tons (Fig. 2). The dimensions of the test plates were 1124 mm x 765 mm.

Experimental conditions: TNT explosive charge mass $W = 1.950\text{-}2.475\text{ kg}$, distance from charge to the plate $R=0.63\text{m}$, scaled distance $R/W^{1/3} = 0.500\text{-}0.465\text{m/kg}^{1/3}$.



Fig. 2. Principal scheme of experimental set-up on car model

2. Results of experiments under high loads

Seven experimental explosions were performed on an armored vehicle under critical loads, including: 1. Steel plates 2 mm + 1 mm thick without protective layer; 2. Steel plate 2 mm thick + aluminum plate 3 mm thick; 3. Steel plate 2 mm thick + aluminum plate 3 mm thick; 4. Steel plate 2 mm thick + aluminum plate 3 mm thick + steel plate 3 mm thick; 5. Steel plate 2 mm thick + aluminum honeycomb plate 10 mm thick + steel plate 3 mm thick; 6. Steel plate 2 mm thick + aluminum honeycomb plate 10 mm thick + steel plate 3 mm thick; 7. Steel plate 2 mm thick + aluminum honeycomb plate 20 mm thick + steel plate 3 mm thick.

Figures 3 show deformations of steel plates with and without a protective layer respectively. The image of test results is shown in fig. 3.

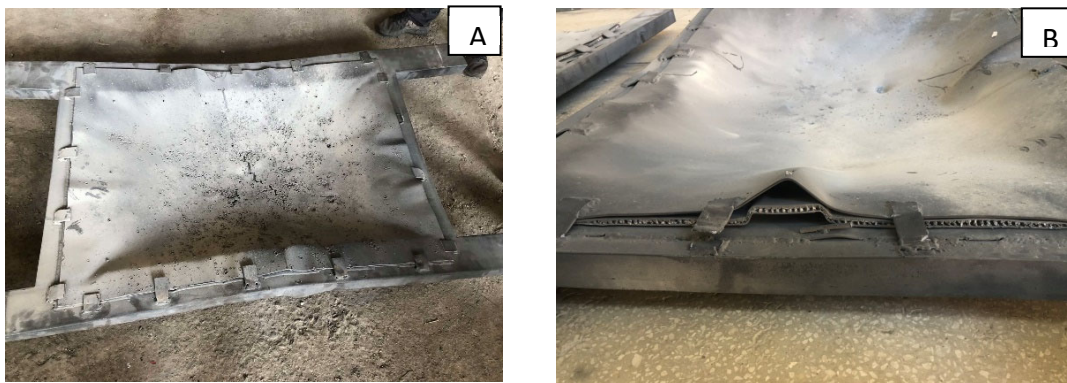


Fig. 3. images of protective sheets after the explosion. A – Steel plate of 2mm thickness+3mm thickness aluminum plate, scaled distance $R/W^{1/3} = 0.504 \text{ m/kg}^{1/3}$; effect: plate bending without breaking. B - Steel plate of 2mm thickness+3mm thickness aluminum plate, scaled distance $R/W^{1/3} = 0.465 \text{ m/kg}^{1/3}$; effect: plate bending without breaking

CONCLUSION:

Experiments conducted on an armored vehicle model under high dynamic loads showed that sandwich composites containing a 3mm thick aluminum plate retain integrity when scaled distance is more than $0.50 \text{ m/kg}^{1/3}$. Of the tested composites, the sandwich containing an aluminium cellular plate showed the highest strength. Such sandwich can resist relatively high dynamic loads when $W=0.46 \text{ m/kg}^{1/3}$.

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A review of textile Composite Structures under High Strain-Rate Loading Conditions

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Abstract

For many years now, various branches of industry such as automotive, aerospace or sports equipment extensively using fiber-reinforced composite materials for innovative and high-performance products. They offer specific mechanical properties, low weight and high-design freedom. In contrast to classical composites based on thermosetting matrices, fiber- and textile-reinforced composites with thermoplastic matrices recently gaining greater interest.

Textile-reinforced thermoplastics exhibit high specific mechanical and an improved damage tolerance, enhanced impact resistance as well as the recyclability and feasibility for a low-cost rapid production. In this paper, a review of the textile Composite Structures under High Strain-Rate Loading Conditions will be presented.

1. Introduction

Textile structures include weaving, knitting, and braiding which are the three basic performs. Compared with conventional two-dimensional fabric, three-dimensional textile structural composites have become more and more popular nowadays due to their high performance structures such as high strength-to-weight ratio and high resistance to corrosion and abrasion [1]. These kinds of composites often are used under impact loading in the practical applications. For example, among all the composite materials, Kevlar finds its major application in body/vehicle armors as it exhibits an improved impact resistance with lightweight. As the necessity increases, it is very important to understand the effect of high strain rate on the impact performance of Kevlar composite laminates. The response of the material under different strain rates should be clearly known for the effective use of materials [2]. Through-the-thickness loading is one of the crucial conditions in the ballistic impact applications. The compressive properties of composite armor materials under high strain rate conditions are highly desirable to assess the ballistic impact response. The textile reinforcement is then impregnated by a resin and cured forming a lamina. It is also possible to stack several lamina in a laminate or stitch several textile layers together before impregnating and curing them. Generally, the fibres have transversely isotropic elastic properties and the matrix material is non-linear isotropic. Composite materials are being used in various fields including aerospace industries where aircraft structures may undergo high strain-rate dynamic loading. Examples of these loadings are bird strike or foreign object impact against wing leading edges, propellers, and engine rotor containments. Therefore, if the engine casing is made of the composite materials, it needs to be strong enough to contain broken blades and also should be damage-tolerant to withstand the impact of a loose blade-turned-projectile [3].

2. Methods

In this study a comparison review of the three-dimensional textile and 2D composites will be presented.

The studied composite structures combine the desirable properties or behaviour of two or more identifiable constituent materials in order to achieve improved strength, stiffness, and toughness at reduced weight. Composites are gradually replacing traditional metallic materials due to their high specific modulus, high specific strength, high stiffness to weight ratio, and their capability of being tailored for a specific application. These properties can be altered or modified by varying the constituents of the composite, i.e., the matrix and the fibres. Among the different types of composite materials, the class of woven fabric composites has received attention in many structural applications because of the balanced in-plane properties, manufacturability, and high impact resistance. Reinforcement in all directions within a single layer, better impact resistance, better toughness and lower cost of fabrication are some of the reasons that the woven fabric composites have been recognized as more competitive than the unidirectional composites. Those properties make the woven fabric composites attractive for structural applications. The ability to simulate the material behaviour and to predict the survivability of structures becomes more and more important at the stage of the structure design [4].

Woven composites are fabricated from strong and light fibres such as graphite, carbon, aramid, glass, nylon or other advanced polymeric fibrous materials. The fibres form yarns, which are woven in different textile architectures such as plain weave, twill, satin or crowfoot. Similar architectures could be achieved if the yarns are braided. In this review, the development and features of different types of textile structures, including weaving, knitting, and braiding have been introduced, and the current and future potential applications of these kinds of textile structural composites have been described. The impact tension behaviors and the damage mechanisms of textile structural composites have been introduced. The future development of impact tension behaviors of textile structural composites is also introduced in this review.

3. Results

The compared composite textile structures have excellent advantages of impact resistance, owing to their more integral microstructure and higher interlaminar shear strength than those of laminated composites. The composites are frequently used under impact loading in the practical application. Researches on the impact behaviors can help in the development and optimization of design for textile structural composites.

Three-dimensional braiding is the first kind of textile structure which is employed as the reinforcement of composites, this kind of composites has high failure stress and failure strain under high strain rate impact tension. Three-dimensional weaving including orthogonal woven fabrics and angle-interlock woven fabrics is widely used to prepare the composites, which are obviously strain rate sensitive. Three-dimensional knit can be employed to manufacture the complex shape structural and high energy absorption composite due to its excellent deformability. Despite the three-dimensional textile structural composites have wide variety of demonstration components and high impact resistance properties, these materials currently have few commercial application, which are used in some top fields like aeronautics and astronautics areas. Only the multi-axial warp knitting fabrics are used widely in the wind power and plane manufacture in the past five years. Designing the high performance fabrics and their composites with high impact damage tolerance, high impact resistance is the further key research. At the same time, the damage mechanism of textile structural composites under impact also is the other key research.

4. Conclusion

Finally, we highlighted the importance of designing of novel three-dimensional textile structures which have higher impact damage tolerance and higher impact resistance, furthermore the manufacturing process of textile structures should be simpler and the manufacturing cost also should be lower.

We can improve the interfacial properties by chemical and physical methods to modify the fiber surface and increase the impact resistance of textile structural composites.

The impact features of textile structural composites under various extreme weathers which include extreme high temperature and extreme low temperature environments need to be more studied.

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Development of basalt based Fiber-Metal Laminate with advanced mechanical properties

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Abstract: For the past 20 years worldwide, intensive efforts have been underway to develop shock-resistant polymer composites, commonly known as Fiber-Metal Laminates (FMLs). FMLs are hybrid composite materials constructed from thin metals and fiber-reinforced adhesive layers. The research area of this scientific work is exploring the potential of using basalt fibers to enhance the capacity of FMLs in withstanding dynamic loads. Basalt fiber, selected for its local availability, outstanding mechanical and chemical properties, and low cost, proves to be an ideal candidate for study. The ongoing research includes the process of developing FML and the associated testing experiments, which are discussed here.

Introduction

A composite is a material that is made up of two or more discrete materials that are combined in such a way as to achieve desirable properties. Commonly, the composite consists of a matrix material and some kind of reinforcement [1]. Such composite materials include Fiber-Metal Laminate (FML) which consists of layers of metal and polymer bonded together and reinforced with some fibers. FMLs offer several notable advantages over traditional metal structures. By utilizing thin metal layers supported by polymer materials, these laminates achieve lighter structures without compromising strength FMLs deliver significant weight savings compared to solid metal counterparts. This weight reduction is particularly valuable in industries where improved weight saving is essential [2-3]. Improved weight savings are particularly valuable in various industries, including aerospace, automotive, shipping and maritime, defense, and military applications. In these sectors, materials science and engineering advancements contribute to enhanced efficiency, performance, and cost-effectiveness.

The choice of basalt is strategic, given its local availability and outstanding chemical composition. Basalt fiber originates from igneous rock found plentifully in the Earth's crust. The benefit of basalt lies in its abundance and the simplicity of its mining process, rendering it comparatively inexpensive [4-5].

FMLs are designed with a broad spectrum of multifunctional applications in mind. This includes the reinforcement and rehabilitation of buildings, the repair, and preservation of motor vehicles, the construction of temporary defensive structures, the development of defense equipment for law enforcement officers personnel, road management, urban construction, and the establishment of specialized chemical production zones.

The scientists at the Laboratory Polymer Composites and High-Tech Materials of the G. Tsulukidze Mining Institute are utilizing basalt fibers and advanced fabrication techniques to create FMLs with exceptional mechanical properties. The primary goal of research is to produce a laminate boasting specific physical-mechanical characteristics, including a density not exceeding 1.4g/cm³; tensile strength along fibers of no less than 520 MPa, and across fibers of no less than 12 MPa; elasticity module along fibers at 30 GPa, and across fibers of no less than 4 MPa; compressive strength not less than 150 MPa; bending strength not less than 300 MPa; tensile strain within the range of 1.5 to 2.5%; and interlayer shifting strength of not less than 20 MPa.

Samples preparations:

FMLs were fabricated using two techniques: first, RFI (Resin Film Infusion) Technology, which involved resin injection in a low-pressure environment (vacuum of 0.03 MPa) in layers of fiber components; and second, direct compression of composites (load: 0.5kg/cm²). The process involved the preparation of basalt fiber prepreg and surface treatment of the steel plate, followed by bonding and curing of both plates. The vacuum infusion method was employed to create the basalt fiber plate. After being placed in a vacuum for 20 hours, it underwent an additional 48-hour drying period at room temperature.

Basalt fiber was provided by “LLC Basalt Fibers, Georgia” and was used as a reinforcement. epoxy resin (XRL - ER80AB two-component transparent epoxy resin) was used as a polymeric matrix. The structures of FMLs are shown in Figure 1.

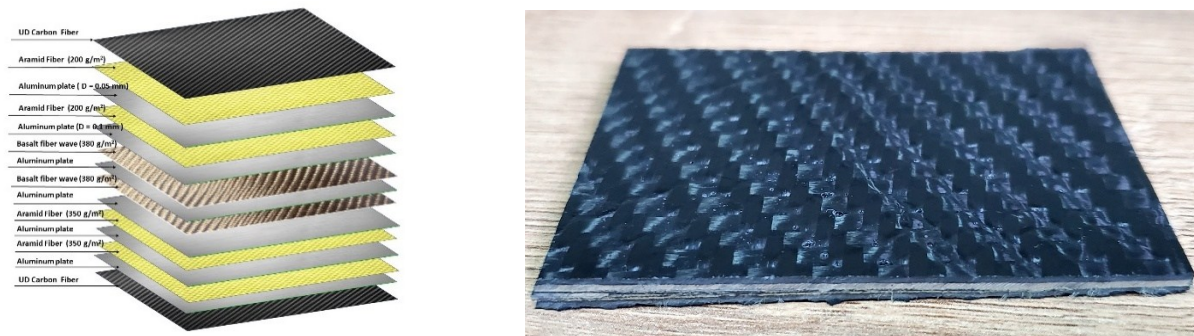


Figure 1. Schematic illustration and depiction of laminate testing sample

Dynamic assessment: Blast and impact Testing

FMLs undergo testing at the laboratory of polymer Composites and High-Tech Materials laboratory at the Mining Institute, equipped with all necessary tools, instruments, and equipment. The blast explosion test was conducted on a special test stand in the explosion chamber. The G. Tsulukidze Mining Institute has an underground experimental base containing: a system of tunnels with a total length of 225 m; 1500 m³ explosion chamber; explosive substances storage; and controlling station properly equipped (sensors, digital oscillographs, and computers for registration and analyses of dynamic processes); ventilation system, water supply, and power supply systems. Low-velocity impact testing was conducted using the Charpy impact tester. The samples were prepared according to ISO 179-2 standard.

Conclusion

A preliminary dynamic assessment was conducted on impact and shock resistance. The material underwent explosion testing, during which data on acceleration and pressure were gathered. During the dynamic loading experiment, specifically investigating the effects of shock waves generated by explosions, a noticeable contrast surfaced between the aluminum sheet standard and the FML. The deformation of the FML decreased by 15%, while the acceleration decreased by 20%. Further investigations are necessary to evaluate the properties of the current materials.

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Simulation and Quantification Method of Crack Propagation Damage of Adhesively Bonded Composite Structures under High Strain Rates

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Abstract: The increasing use of bonded composites has increased interest in detecting potential defects. In this study, we examined the structural integrity of the bonded zone of the single lap joint under high strain fatigue cycles and characterized the associated crack propagation by using the extend finite element method (XFEM) technique. Furthermore, a guide waves-based approach is employed to quantify the damage extent of the structure. Our findings provide valuable insights into assessing the health condition of bonded composites and can aid in developing effective maintenance strategies for ensuring long-term safety and reliability.

1. Introduction

Composites have been extensively employed in various modern industries, such as aerospace, automotive, and military industries, due to their excellent material properties for reducing weight and enhancing tensile stiffness. [1] Compared with mechanical rivet joints, the adhesive bonding of composite structures has the advantage of uniform force distribution between connectors. It is an essential work to ensure long-term service for the bonded composite structures that employing structural health monitoring (SHM) techniques to detect damage under fatigue loads, especially for the crack that occurs in bonded zone in the early stage. In this paper, a framework of damage diagnosis based on guided waves and remaining useful life (RUL) prognosis [2,3] based extend finite element method (XFEM) is proposed, which main contribution for bonded composite is to obtain the extent of damage and predict the propagation of progressive damage crack. The framework calibrates the fatigue crack propagation (FCP) simulator by quantifying uncertainties and simulating the multi-direction crack propagation in fatigue model parameters using the damage extent data (DED) [4]. The more common approach used in predicting the RUL is to obtain DED via a cohesive model, which only can simulate the crack growth along with the element pre-set by a user based on traction-separation law (T-S). Therefore, considering the FCP simulator and damage propagation with uncertainty, it is proposed that DED are collected by using XFEM without setting the growth path of damage. Simultaneously, the comparison between XFEM and the cohesive method is presented to illustrate the difference in calculating and predicting crack propagation. Because of the randomness of the DED obtained via XFEM, this paper considers interlaminar cracks in addition to simulating the through cracks. The received signals include the information on bonded zone and substrate, which is used to verify the damage extent data collected from the simulation model. The single lap joint and mixed mode joint under variable fatigue loads as specimens are used to introduce the damage simulation and quantification.

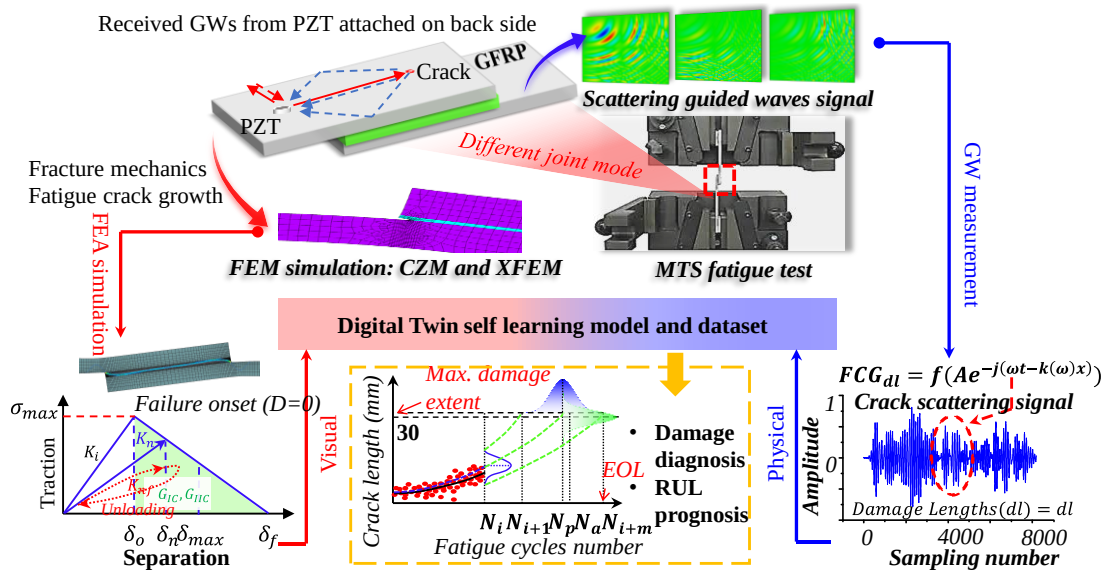


Fig. 1. Schematic representation of crack propagation in the bonded area.

2. Methodology

The main principle of XFEM for crack propagation is to add the enrichment function of crack surface and crack tip displacement on the basis of single finite element method, as shown in Fig. 3, which is described as Eq. (1).

$$u = \sum_{i=1}^n N_i (u_i + H a_i + \sum_{j=1}^4 Q_j b_{ij}), \quad (1)$$

where u denotes the displacement approximation function, N_i is the FEA shape function, u_i , a_i and b_{ij} are classical and additional degree of freedom, Q_j represents displacement function at area of crack tip, i and j express number of nodes for whole region and nodes of a crack tip. H is defined as Heaviside function that crossing the level of crack. The horizontal enrichment function used to describe the crack tip is described by Eq. (2).

$$\mu_i = (x - x_i) \frac{v_i}{\|v_i\|}, \quad (2)$$

Utilising the maximum principal stress criterion as the initial cracking condition:

$$f = (\sigma_{I0}/\sigma_{max}^I) + (\sigma_{II0}/\sigma_{max}^{II}) = 1, \quad (3)$$

The constitutive model of the adhesive material in the bonding area adopts the criterion of traction separation law.

3. Conclusion

It can be seen from the Fig. 2 that there is a big difference in period between cohesive zone model (CZM) and XFEM, especially in the problem of simulating cracking in the bonded zone. If the experiment does not pay attention to the damage details of the bonding area, the CZM method is recommended instead of the time consumption XFEM, but if it pay attention to the specific damage path of the zone, then the XFEM method will have more advantages than the CZM method. When predicting the RUL at later stages, the CZM may yield RUL predictions deviation from actual material life. As the primary aim of this study is to predict RUL in the bonded area, the study employs the XFEM to simulate the crack growth process. This decision is based on the fact that the XFEM method can more accurately model the actual crack propagation process in the bonded area, thereby facilitating more reliable RUL predictions.

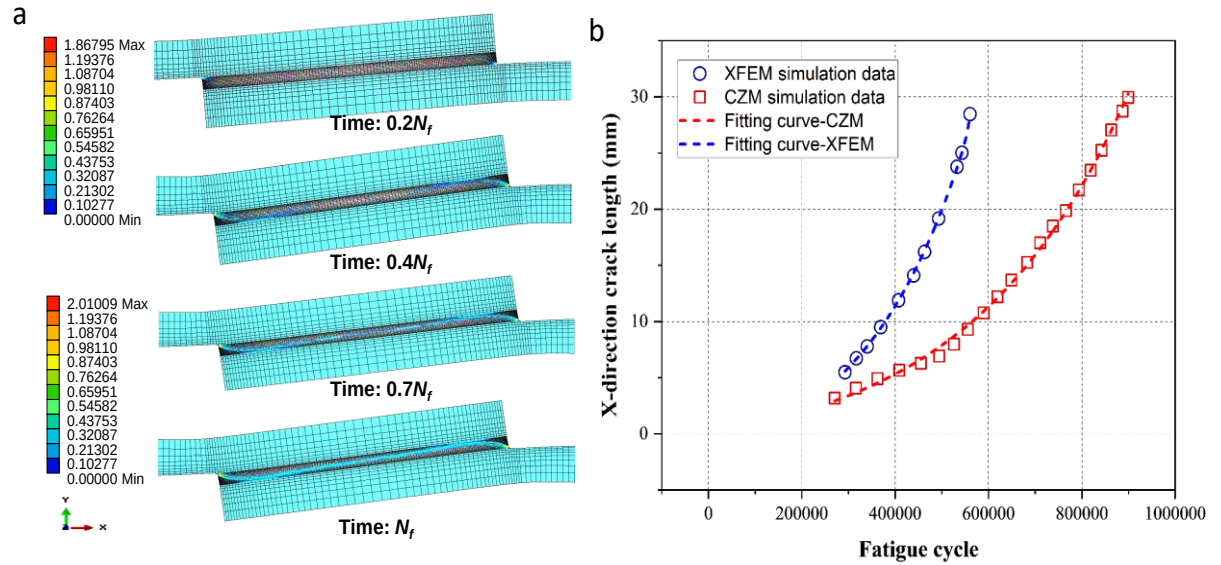


Fig. 2. The FEA simulation results by employing XFEM and CZM methods.

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Poly (Vinylidene Fluoride)/Carbon Nanotube/Semiconductor Inorganic Nanoparticles Composites for Piezoresistive Sensing

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Abstract: Conductive polymer composites (CPCs), obtained by incorporating conductive nanofillers into a polymer matrix, are suitable for fabricating strain sensors for structural health monitoring in infrastructure. Here, the effect of the addition of zinc stannate (ZnSnO₃) and zinc sulfide (ZnS) inorganic semiconductor nanoparticles (INPs) of different structures and morphology to a poly(vinylidene fluoride) (PVDF) composite filled with multi-walled carbon nanotubes (MWCNTs) on the piezoresistive behaviour is investigated.

1. Introduction

In recent years, semiconductor metal oxide inorganic nanoparticles such as ZnO [1], ZnSnO₃ [2], and ZnS [3] have attracted considerable attention due to their piezoresistive properties and environmental friendliness. This work introduces a strategy to combine MWCNTs and INPs as a hybrid filler system with varying morphologies, sizes, and phases. The aim is to fabricate PVDF-based responsive piezoresistive strain sensor materials. For this purpose, INPs with various morphologies and sizes were synthesized using a hydrothermal method. The influence of the incorporation of these INPs on the structural properties and piezoresistive behaviour of melt-mixed PVDF/MWCNT composites was examined.

2. Experimental Section

The INPs were synthesized via the hydrothermal method. The polymer matrix used to fabricate the composites was PVDF, specifically Kynar™ 720, procured from Arkema Inc., Paris, France. The conductive fillers were non-functionalized short-thin MWCNTs designated as NC3150, obtained from Nanocyl, S.A., Sambreville, Belgium. The microstructural and morphological properties of the INPs were investigated via a TESCAN™ MAIA XMU field emission gun scanning electron microscope (FESEM) (TESCAN, Brno, Czech Republic). The PVDF/1 wt% MWCNT/ INPs composites were produced through a one-step melt-mixing process using a twin-screw micro compounder (Xplore, Geleen, The Netherlands) with 15 cm³ capacity (Fig. 1-a) at a mass temperature of 210 °C, a rotation speed of 200 rpm, and a mixing time of 10 minutes.

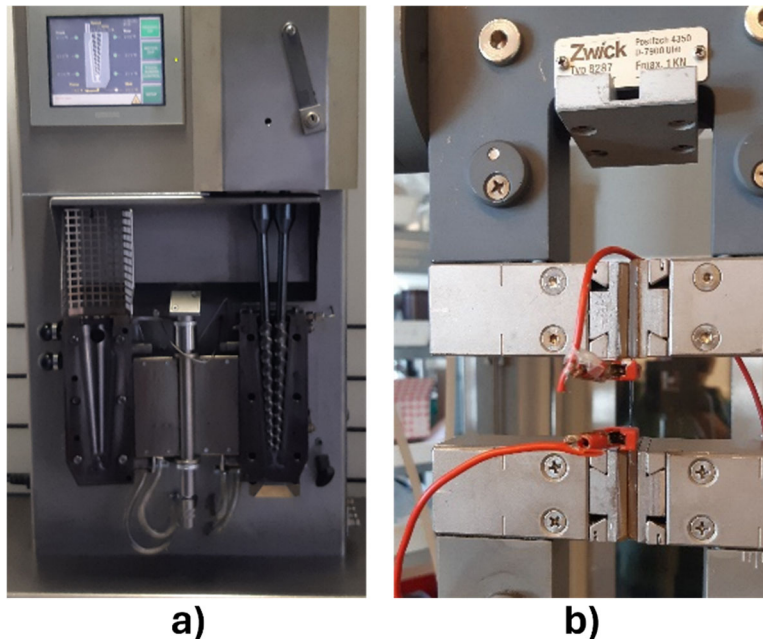


Fig. 1: a) Conical twin-screw micro compounder DSM Xplore15 b) Cyclic testing of composites in a universal testing machine 1456 Zwick

Cyclic piezoresistivity measurements of PVDF/MWCNT/INP composites were determined following DIN EN 527-2/S2/1 [4] using a universal testing machine 1456 Zwick (Zwick Roell, Ulm, Germany) connected to a

Keithley 2000 electrometer (Fig. 1-b). The relative resistance was measured as $\Delta R/R_0$, where R_0 stands for the initial electrical resistance, and ΔR stands for the change in electrical resistance after compressing the specimen in the specimen holders. The cyclic test was conducted at a 1 mm/min speed with a maximum loading strain of 3% for 15 cycles.

3. Results

The structures and morphologies of various INPs were characterized using FESEM. The FESEM images of a ZnSnO_3 sample (Figure 2-a) and a ZnS sample (Figure 2-b) are shown in Figure 2. ZnSnO_3 exhibits thin plates, while ZnS -based INPs appear spherical.

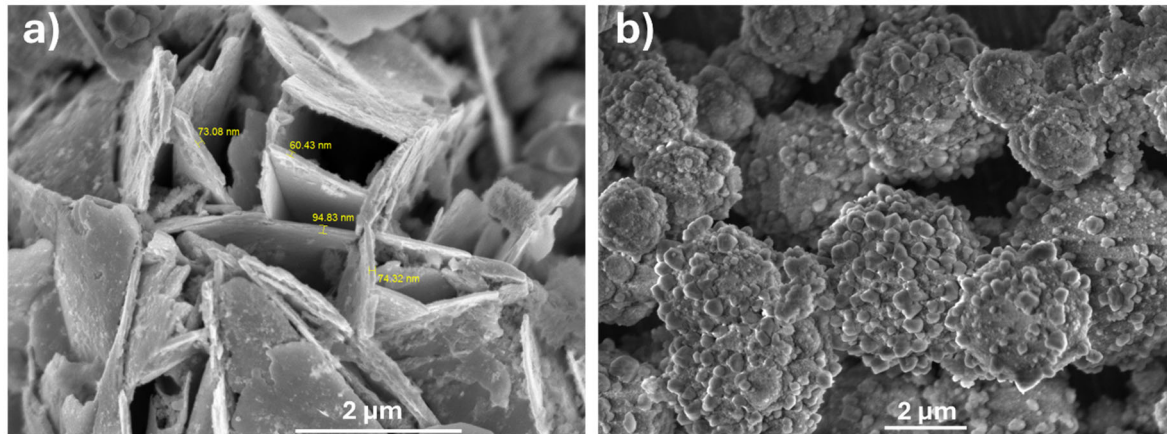


Fig. 2: Microstructural features of the synthesized nanoparticles. a) ZnSnO_3 b) ZnS

Cyclic piezoresistivity measurements were conducted on all composites to assess their piezoresistive behaviour under load. The piezoresistive behaviour of these composites was compared with that of a reference sample containing only 1 wt% MWCNT. Both composite series, either with ZnSnO_3 or with ZnS , show a higher piezoresistive sensitivity in cyclic strain sensing with 15 cycles up to 3% strain than the reference sample. The piezoresistive sensitivity of the reference sample was measured between 2-2.5% $\Delta R/R_0$. The maximum and minimum $\Delta R/R_0$ values gradually decreased with increasing cycles after loading and unloading of the composite. The highest piezoresistive sensitivity was initially observed for composites containing 3 wt% ZnSnO_3 nanoplatelets with 4.5 wt% $\Delta R/R_0$ and composites containing 1 wt% ZnS nanospheres with 4 wt% $\Delta R/R_0$. It was also observed that the $\Delta R/R_0$ values of ZnSnO_3 and ZnS loaded composites remained more stable as the number of cycles increased.

Enhancing complex and adaptable composites with inorganic semiconductor nanocrystals enables the fabrication of customizable sensors for diverse applications and offers exciting prospects for future studies by exploring the correlation between piezoresistive properties and the microstructure of conductive polymer composites.

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Hidden defects detection under tensile loading by laser speckle photometry

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Abstract: Laser speckle photometry (LSP) is single-beam coherent optical technique with potential of defect detection. The LSP relies on different speckle dynamics within the area of the defect and the surrounding region. Speckle dynamics is estimated through correlation-based statistical processing of the speckle patterns formed on the surface of the tested sample. During the capture of the correlated in time images of these patterns, excitation of speckle variation is provided by various means. In this work, we studied the LSP ability to detect a hidden defect in a sample subjected to tension at a certain tensile speed.

1. Introduction

Laser speckle photometry (LSP) is a full-field non-destructive intensity-based method which relies on high sensitivity of speckle to micro-changes in the tested surface characteristics. A source of polarized laser light, a beam expander and a 2D optical sensor are the components required for creation and capture of speckle patterns. Statistical processing is elaborated to reveal the rate of speckle evolution across the tested sample. Speckle evolution in time may be due to ongoing processes on the surface or in the bulk of the sample, as e.g. in monitoring the paint drying or performing food quality assessment [1]. In industrial inspection, dynamic speckle is excited by illuminating the sample with another laser or by heating [2,3]. The LSP measurement output is an activity map which is the contour map of the statistical parameter chosen to evaluate the speckle dynamics.

In this work, we studied the LSP application to samples under tension at increasing tensile speed and, more specifically, we checked detection of a hidden defect by dynamic speckle analysis. Speckle excitation was achieved by stretching the tested sample in time using a test machine.

2. Hidden defect detection

The LSP set-up for controlling a sample under tensile loading is shown in Fig.1. As a light source we used a He-Ne laser (LASOS Lasertechnik) emitting at 632.8 nm. Polarization of the laser light was adjusted using a half-wave plate with a fast axis oriented at $(-\pi/4)$ to the loading axis of the tested sample. After the 4f spatial filter, the light beam was expanded and illuminated normally the sample. A CMOS camera (BASLER acA4096-30um) with the objective optical axis inclined at 9.6 degrees with respect to the laser beam propagation axis, acquisition rate $1/\Delta t$ equal to 30 frames per second and exposure time 0.01 s acquired a sequence of images of the speckle patterns formed on the sample. A test machine (AMETEK LRX PLUS) was used for extension of a rubber sample from a Land Rover Sport fender liner part with thickness of 5 mm. The length of the sample was 200 mm and the width – 50 mm. The defect represented a depression created by melting the rubber using a soldering iron at a temperature of 340°C. The defect was located within the borders of a rectangle of size 30 mm along the vertical (extension) direction and 10 mm in horizontal direction. The depth of the depression varied from 0.5 mm to 2 mm. The stretching of the sample continued for 30 seconds and was performed at different extension speeds starting from 1 mm/min and going up to 20 mm/min.

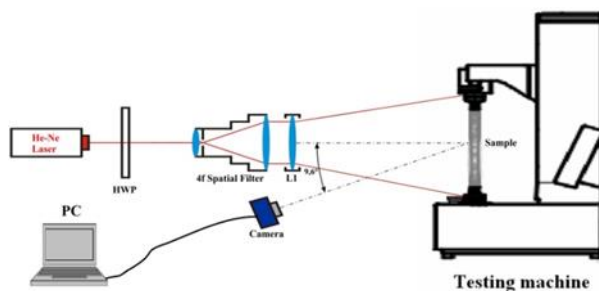


Fig. 1. Experimental set-up for laser speckle photometry of a sample under tensile loading.

For statistical processing, a sequence of N intensity values, $I_{kl,n}$, $n = 1..N$ was formed for each camera pixel (k, l) , $k = 1..N_x$, $l = 1..N_y$, where n indicates the instant $n\Delta t$ and $N_x \times N_y$ is the size of the images. The size of the captured speckle images was 724×1584 pixels. Due to the big size of the sample, the captured images were characterized with noticeable non-uniformity of illumination. This entailed normalization of the activity estimate to avoid incorrect interpretation due to spatially variable speckle statistics. We used the following estimate:

$$\hat{S}(k, l, m) = \frac{1}{N} \sum_{n=1}^{N-m} |I_{kl,n} - I_{kl,n+m}| (I_{kl,n} + I_{kl,n+m})^{-1} \quad (1)$$

The estimate (1) increases with activity and the time lag, $\tau = m\Delta t$, where m is an integer.

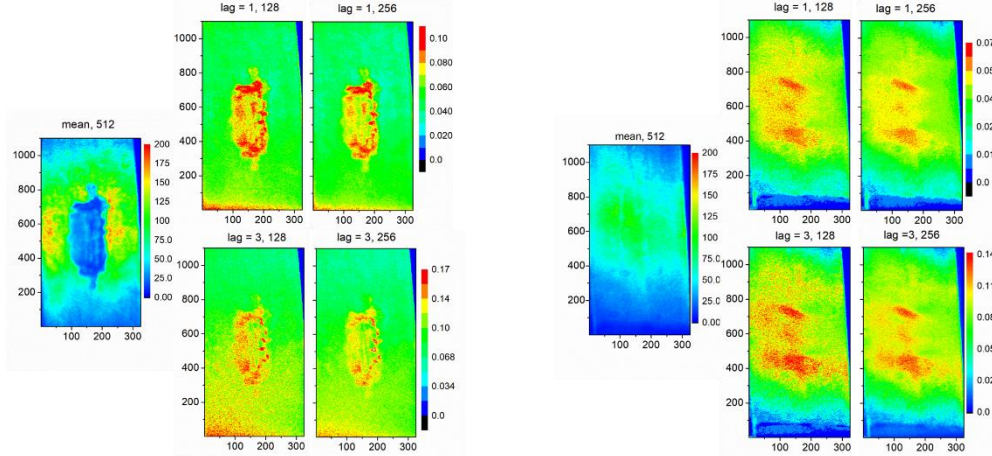


Fig. 2. Mean intensity distribution and activity maps for images captured from the side of the depression (left) in a rubber sample subjected to tensile loading and from the other side (right).

As a first task, we established that LSP shows high sensitivity even at small tensile speeds as 1 mm/min when the extension of the upper border of the sample between two consecutive frames is less than a micrometer. As a second task, we checked the LSP potential to detect a region which differs in its surface properties from the other parts of the sample. We captured images of the rubber sample with the depression region in both the case of facing the depression and the case when it was not visible. The results of processing the images for both cases are presented in Fig.2. The shown maps were obtained by averaging over 128 and 256 images or for the time intervals corresponding to 4 s and 8 s respectively. The rubber stretching at a tensile speed of 10 mm/min was applied for dynamic speckle excitation. The used small time lags of 0.033 s and 0.1 s guaranteed lack of decorrelation. The mean intensity distribution in Fig.2 (left) shows much lower intensity in the region of depression. Nevertheless, activity in this region is higher than on the remaining rubber surface. The maps obtained for the other rubber side definitely reveal an area of higher activity corresponding to the defect location within the sample. The same experiment was conducted for a rubber sample with three smaller in size defects created in the same manner. The activity maps calculated from the images taken for the side of the sample where the defects are not visible also exhibit three spots of higher activity. In summary, we demonstrated LSP applicability to tensile loading experiments performed at a certain tensile speed. We plan to apply the LSP to fast developing processes by using a high-speed camera for capture of the speckle images and to develop a processing algorithm based on two images but providing high spatial resolution.

Acknowledgements

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Laser speckle photometry with binary patterns

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Abstract: Application of laser speckle photometry for industrial inspection usually encounters a problem of non-uniform sample illumination. This renders difficult extraction of correct measurement output due to signal-dependent nature of the input data. The additional critical issue is the big volume of data to be stored. We propose binary representation of the recorded speckle patterns using a pointwise threshold. Efficiency of the proposed compressed data format for processing data acquired under non-uniform illumination is proven by comparison to results obtained in a tensile loading experiment with normalized processing of 8-bit encoded speckle images.

1. Introduction

Laser speckle photometry (LSP) is a robust full-field cost-effective method for monitoring of processes and impact detection in industrial inspection [1-3]. This single beam illumination method relies on high sensitivity of speckle as an interference phenomenon to micro changes of topography or refractive index of the objects. Correlation based processing of a temporal sequence of speckle patterns formed on the tested object surface under laser illumination yields a 2D activity map visualizing areas with different speckle dynamics [1]. There are two problems when interpreting the built activity map: i) strong fluctuations of the map entries and ii) non-uniform illumination of large samples that leads to spatially varying speckle statistics. Storage of big amount of data when monitoring processes is also a challenge. The aim of this study is to prove that solution of the non-uniform illumination problem can be combined with effective compression. For the purpose, we conducted a tensile loading experiment and transformed the recorded speckle images into binary ones. The activity maps obtained from the transformed data are practically similar to those built from 8-bit encoded images with normalization.

2. Processing of bmp and binary images in tensile loading experiment

We applied LSP to a sample subjected to tensile load. The sample was illuminated by a He-Ne laser (LASOS Lasertechnik) at a wavelength 633 nm. The laser light passed through a half-wave plate with a fast axis at $-\pi/4$ to the loading axis of the test sample. After the 4f spatial filter, the light beam is expanded with the lens to illuminate the whole sample. The speckle patterns formed on the object surface were captured sequentially by a CMOS camera (BASLER acA4096-30um) with camera lens optical axis at 9.6 degrees to the laser beam propagation, acquisition rate $1/\Delta t$ equal to 30 frames per second and exposure time 0.01 s. For the tensile stress of the sample, a universal material testing machine (Amitek LRX PLUS) for tension, compression and cycling loading was used. We prepared a rectangular rubber sample with length 90 mm, width 30 mm and 1 mm thickness. In the center of the sample a circular hole with 10 mm diameter was made as a source of stress concentration in order to obtain an activity map with a more complicated structure. For the same reason, we used a tensile speed of 20 mm/min. Duration of the loading was 30 seconds and 900 frames in total were captured. The size of the captured speckle images was 1204×2172 pixels. A part of an exemplary speckle image (700×1200 pixels) is shown in Fig.1.

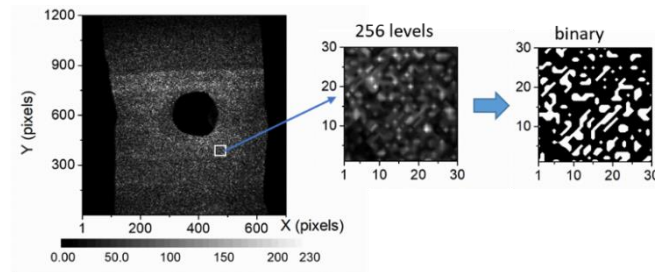


Fig. 1. Speckle pattern on the sample surface as an 8-bit encoded bmp image and a binary image.

The input data for statistical processing were formed for each camera pixel (k, l) , $k = 1..N_x$, $l = 1..N_y$ as sequences of N intensity values, $I_{kl,n}$, $n = 1..N$, where n corresponds to the instant $n\Delta t$ and $N_x \times N_y$ is the size of the images. Intensity-based algorithms are used to obtain the speed-related statistical parameter. For patterns with strong non-uniformity of illumination, normalization must be applied to avoid distortions as follows:

$$\hat{S}(k, l, m) = \frac{1}{N} \sum_{n=1}^{N-m} |I_{kl,n} - I_{kl,n+m}| (I_{kl,n} + I_{kl,n+m})^{-1} \quad (1)$$

The estimate (1) is calculated for a given time lag $\tau = m\Delta t$. This estimate increases with activity. In intensity-based pointwise LSP implementation, the rate of temporal variation of speckle intensity is a quantity of interest. This enables lossy data compression of the data. Among coarse quantization techniques, binarization offers the advantage of avoiding normalization. We used a mean intensity value, A_{kl} , as a threshold for each pixel (k, l) , $k = 1..N_x, l = 1..N_y$ and formed sequences consisting of $\vartheta_{kl,n} = \mp 1, n = 1..N$ depending on $I_{kl,n}$ value being less or larger than A_{kl} . The activity estimate is composed in this case as $\hat{S}_b(k, l, m) = \frac{1}{N} \sum_{n=1}^{N-m} |\vartheta_{kl,n} - \vartheta_{kl,n+m}|$.

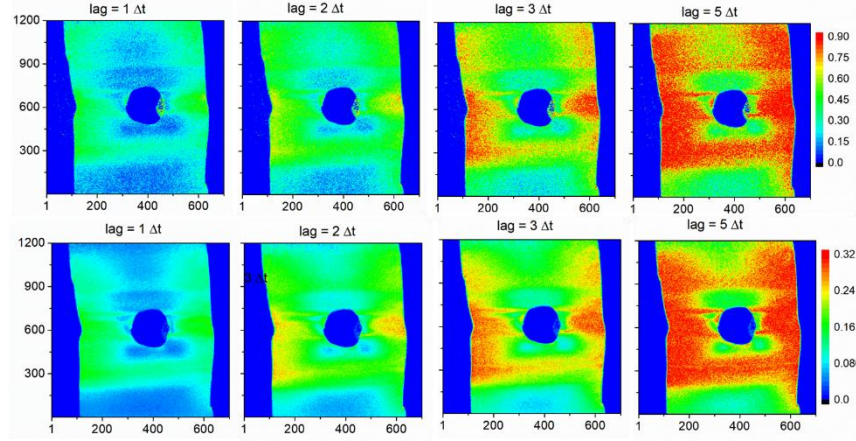


Fig. 2. Activity maps for a tensile loading experiment at increasing time lags: top – binary images, bottom – 8-bit encoded images, $N = 128$.

Small patches of an 8-bit encoded image and the corresponding binary image are shown in Fig.1. The random character of the binary pattern and its change in time successfully encode the speed of the observed process. The results of processing binary images are presented in Fig.2 (top). The maps were obtained by averaging over 128 images which corresponded to approximately 4 s. The rubber stretching at a tensile speed of 20 mm/min created dynamic speckle with observable variations across the sample. The obtained activity map exhibits a rather complicated structure around the hole. The higher the estimate values, the faster the intensity fluctuations. As it should be expected, the estimate increases with the time lag. For proving adequacy of the built maps, the activity maps for estimate (1) are also presented in Fig.2. Note that the scales of the maps for both estimates are different. Nevertheless, the graphical representations of activity for both estimates practically coincide. Instead of calculating the 2D distribution of the mean intensity, intensity distribution in the first image in the processed sequence can be used as a threshold.

In summary, we demonstrated efficiency of binarization in the LSP applied to tensile loading experiments performed at a certain tensile speed. We intend to check the LSP applicability for monitoring fast developing processes by using a high-speed camera for capture of the speckle images. Another task of interest is to relate the activity map to the stress concentration.

Acknowledgements

This work is supported by COST Action CA21155 HISTRATE and has received funding from Bulgarian National Science Fund under project КП-06-KOCT/19. M.V. thanks the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956770. V.M. and E.S. thank CoE "National center of Mechatronics and Clean Technologies" BG05M2OP001-1.001-0008. N.B. and L.N. acknowledge the funding provided by the European Union-Next Generation EU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.004-0002, "BiOrgaMCT".

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FBG-based Lamb wave mode separation for damage localisation

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Abstract: In this paper analysis of phenomenon of elastic guided wave sensing using fibre optic strain sensors based on Bragg gratings (FBGs) and piezoelectric transducers (PZTs) are presented. Waves excitation is based on piezoelectric transducer. The PZTs are very popular in applications related to elastic wave generation and sensing. The FBG strain sensors are more and more utilized in field of elastic wave sensing. In the case of FBG sensors the edge filtering method is utilized. Attention in this research is focused on possibility of symmetric and antisymmetric guided wave mode sensing with the possibility of mode separation. For this purpose pairs of sensors located on the top and bottom surface is utilized. Moreover, mode index was introduced in order to distinguish fundamental symmetric and anti-symmetric wave modes. Moreover authors performed elastic guided wave-based damage localisation in plate-like structure. Damage localisation is based on delay-and-sum algorithm. In this paper experimental results are presented.

1. Introduction

Among various SHM techniques, the elastic guided waves (Lamb waves) is getting very popular nowadays. The main problem with guided Lamb waves-based technique is complex signal processing due to wave dispersion and multimodal propagation. The piezoelectric ceramic transducers (PZTs) are most commonly used sensors. However, they are prone to electromagnetic interferences (EMI) and due to the utilization electrical signals they cannot be utilised in explosive hazard areas. In order to overcome these problems elastic wave sensing using fiber Bragg grating (FBG) sensors is proposed. These sensors can be multiplexed, have small diameter and could be embedded in the structure. Due to these advantages they are promising choice for guided wave sensing [1]. In most popular approach of FBG wave sensing, the sensor is directly bonded to sample in order to sense the elastic waves [2]. The sensitivity analysis of FBG wave sensing of Lamb waves was performed in the case of aluminum plates in [3]. Damage assessment in based on algorithms such as delay and sum. The delay and sum passive imaging in composite plates using FBG sensors was proposed in [5]. For the improvement of the damage localization simplifying the signal processing is a key. This can be achieved by identifying the sensed guided wave mode as the symmetric (S) and antisymmetric (A) mode. To this effect, parallel placed sensors on the top and bottom surface of the plate. In order to perform the identification automatically, a mode indicator (MI) was introduced. The further part of research is related to damage localisation using delay-and-sum algorithm in plate-like structure.

2. Experimental Setup

The investigated specimen was in the form of square panel with dimensions: 1000 mm × 1000 mm × 1 mm (Fig. 1). Elastic wave excitation was performed by PZT actuator (PZT A). The elastic wave sensing was conducted based on a pairs of piezoelectric sensors (PZT S) and FBG sensors (Fig. 1). Sensors were located on the top and bottom surfaces of the panel. The distance between the sensors and the wave actuation point was 250 mm. Artificial damage in the form of additional mass (M1 - Fig. 1) was investigated. The measurement set-up consisted of: signal generator, signal amplifier, oscilloscope card, tunable laser, optical signal circulator, photodetectors, PZT and FBG. In the case of FBG the edge filtering method was utilized. The excitation signal was in the form of five cycles of sine modulated by the Hann window applied to the piezoelectric actuator.

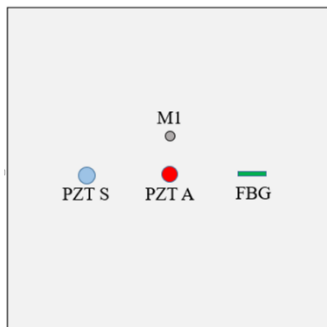


Fig. 1. Schematic of the investigated sample.

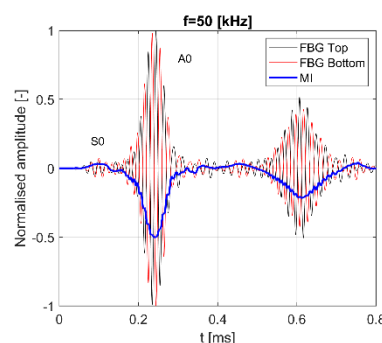


Fig. 2. Signals registered by FBG on the top and bottom surface of panel and mode indicator MI; frequency 50 kHz

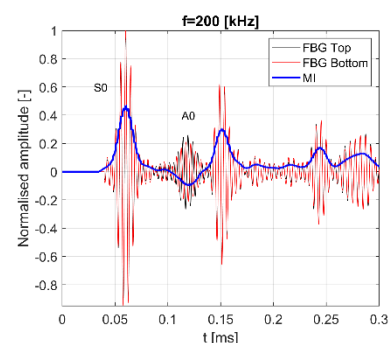


Fig. 3. Signals registered by FBG on the top and bottom surface of panel and mode indicator MI; frequency 200 kHz.

3. Results

In Fig. 2 and Fig. 3 signals registered by FBG on the top and bottom surface of panel for frequencies 50 kHz and 200 kHz were presented. The wavepackages of first arrivals of fundamental S0 and A0 mode were marked in the signals. For the frequency 50 kHz (Fig. 2) amplitude of S0 mode is very low comparing to A0 mode. In the case of frequency 200 kHz (Fig. 3) amplitude of S0 mode is larger than A0 mode. Moreover, for both frequencies wave signal are in-phase for S0 mode and out of phase for A0 mode. This is by the configuration of sensors located on top and bottom surface. Phase of signals gathered by pair of sensors (on the top and bottom side of panel) and its multiplication could be utilised for the purpose of distinguish symmetric and anti-symmetric fundamental Lamb wave modes. Mode indicator (MI) index was proposed for mode separation. The MI is calculated based on signals multiplication for pair of sensors and filtration of resulting signal based on moving averages. The results in the form of MI were presented in Fig. 2 and Fig. 3. The MI achieves the positive values for symmetric S0 mode (signal in-phase) and negative for A0 mode (signals out of phase). This could be utilised for mode identification in wave signals for the damage localisation purpose what could improve the localization results.

Next part of research was related to damage localisation based on the delay-and-sum algorithm [5]. Results in the form of damage map for S0 wave mode at frequency 150 kHz for summation of signals gathered by both FBGs was presented in Fig. 4. Damage map indicates waves reflections from the edges and the location of additional mass with significantly lower amplitude that for edge reflection (Fig. 4). In the second step the fusion of signals gathered by pairs of FBG as well as PZT sensors was conducted. The fused map for S0 mode at frequency 150 kHz based on FBG and PZT sensors was presented in Fig. 5. There is large number of ellipses cross-sections caused by wave reflections from edges of panel and sensors. However, there are also cross-sections indicating the location of additional mass.

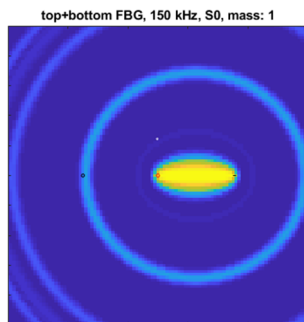


Fig. 4. Damage map for artificial damage

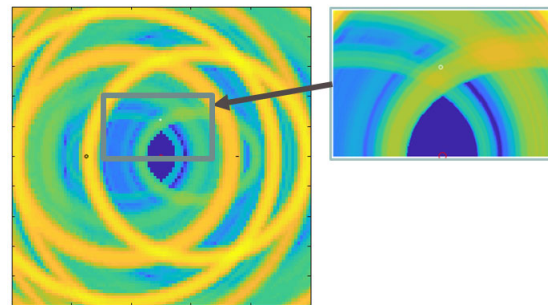


Fig.5. Fused damage map for dual PZT and FBG in panel with artificial damage (additional mass).

4. Conclusions

The study showed that the FBG sensors can effectively sense high frequency signals corresponding to the propagating elastic waves. The symmetric mode (S0) allow to indicate the presence of discontinuity (mass) on the sample surface. The utilization of fusion of signals improved the localization results. The placement of two sensors at one location allows for mode separation. The application of mode indicator will be further investigated by its implementation in damage localization algorithm. The A0 wave mode has larger amplitude than S0 mode for low frequencies while as situation is opposite for higher frequencies.

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Hilbert Transform method for Electronic Speckle Pattern Interferometry to study plastic deformation of materials under tensile stress

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Abstract: In this study we propose Electronic Speckle Pattern Interferometry (ESPI) for studying plastic deformations in aluminum alloys under tensile stress. A robust to vibration in-plane sensitive Dynamic ESPI system with Hilbert transform for phase and deformation analysis was applied. The method allowed for constructing temporal history of whole-field (x-y) in-plane plastic deformation of the sample. An area of concentrated deformation and the velocity of propagation of this area along the sample was studied.

1. Introduction

Electronic Speckle Pattern Interferometry (ESPI) is a commonly used technique in the realm of Non-Destructive Testing (NDT) for diffusely scattering samples due to its high sensitivity [1]. It offers an appealing approach to approximate the micro displacements on the surface without actual physical contact by an immediate, comprehensive depiction of object deformation across the entire field. The quantitative ESPI signal processing for deformation analysis is in most of the cases hindered by the speckle that modulates the correlation fringes, thus making the task of phase unwrapping extremely difficult [1-2]. The acquired interference images as temporal sequences can be considered as a 3D matrix and the processing of the data to be considered in time domain. Let us represent the interference signal using (x,y) as spatial co-ordinates and t-time in 3D-space as follows:

$$I(x, y; t_i) = I_o(x, y; t_i) + I_m(x, y; t_i) \cos\{\vartheta(x, y; t_i) + \phi(x, y; t_i)\} \quad (1)$$

where bias intensity is I_o , modulation intensity is I_m , speckle phase $\vartheta(\cdot)$ and the deformation phase ϕ . We can link every real signal to the analytical signal [3]. Hence, we use the Hilbert Transform in temporal domain [4] to extract the phase information of this analytic signal as:

$$\vartheta(x, y; t_i) + \phi(x, y; t_i) = \tan^{-1} \left(\frac{HT\{I(x, y; t_i) - I_o(x, y; t_i)\}}{I(x, y; t_i) - I_o(x, y; t_i)} \right) \quad (2)$$

where Hilbert transform represented as $HT\{\dots\}$. We analyze this phase information in time-domain and we get the 3D representation of phase in time and spatial domain. As the phase contains the random signal component, so first using the HT we obtain the phase information and after unwrapping, we extract the deformation phase in following manner. The phase-plane at a time instant ($t+k$) is subtracted from the plane at instant (t). In this manner, the random speckle phase is removed as it is time-independent. Following the 2D spatial median filtering for removing the spiky is applied.

2. Method

In this work, we study the plastic deformation process and an in-plane sensitive ESPI system was applied. The experimental system is illustrated in Fig.1. The light source is a YAG laser 2nd harmonic generation, with an output power of 200 mW, and a wavelength of 532 nm. After being reflected from mirrors M1 and M2 the light emitted from the laser is expanded by an objective lens L1 to illuminate the specimen. In this setup, the object is illuminated directly at an angle $\alpha = +45^\circ$ on the upper half, and after reflection from mirror M3 at $\alpha = -45^\circ$. The sensitivity vector lies within the x-y plane. Primarily we focus on the y-component of the in-plane displacement. The deformation per unit fringe spacing is expressed as $\lambda/2\sin\alpha$ and it equals to 380nm. The CCD camera was set perpendicular to the specimen's surface, continuously capturing interference speckle patterns at a consistent acquisition rate. Subsequent subtraction of the captured images yields correlation fringes, with the subtraction time interval determined based on experimental conditions. For the experiment the tensile speed of 0.5 $\mu\text{m/s}$, the (a) time rate was set to 2 fps. Nevertheless, at some (b) instants in time at the plastic stage of deformation

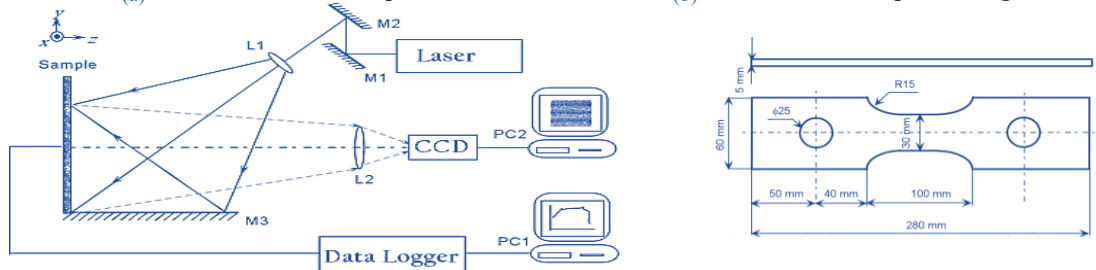


Fig. 1. (a) The scheme of the optical set-up for in-plane deformation measurement. M1, M2 and M3 – mirrors, L1-objective lens, L2 camera lens, CCD – camera, PC1, PC2 – computers, (b) test sample

a Localized Strain Band (LSB) at 45° to y-axis with high frequency of the fringe that couldn't be resolved will appear. For this reason, a 30 fps acquisition rate was also simultaneously applied, and executed only at those time instants. In the tensile experiment a dumbbell-shaped plate of aluminum alloy A2017 with the effective length of 80 mm, width of 30 mm, and thickness of 5mm (Fig.1 (b)) was prepared.

3. Results

The LSB will appear several times in the sample during the plastic stage of deformation and will sweep along the sample. We estimated the velocity of LSB propagation and by polynomial approximation could distinguish two stages of plastic deformation. These two stages of plastic deformation can also clearly be distinguished on the stress curve in function of time on Fig.2.

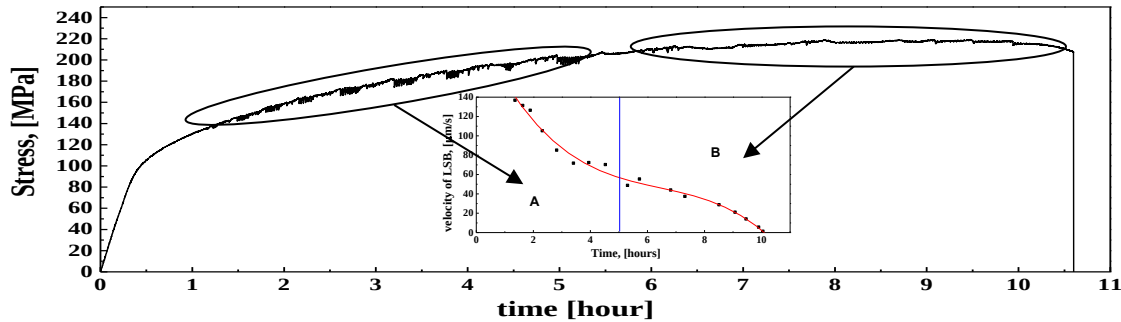


Fig. 2 The stress curve in function of time, illustrating the two different plastic deformation stages

We implemented the HT method for the deformation during the LSB shifting of angle from $+45^\circ$ to -45° to y-axis results are illustrated in Fig.3. The accuracy of the method was estimated in our previous study [4] by comparing the obtained deformation values with the theoretically estimated values, which is $\lambda/10$.

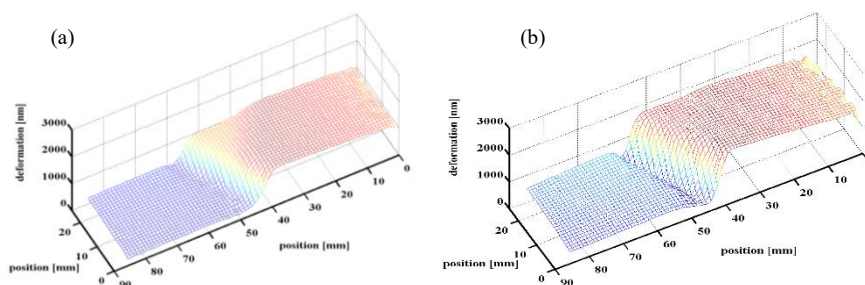


Fig. 3 Deformation at the beginning (a) of the LSB shifting and the end (b) of LSB shifting.

4. Conclusions

The Plastic deformation of aluminum alloy sample under tensile stress was studied with ESPI. The quantitative deformation was analyzed by applying HT method in time domain on the interference signal. Using the correlation fringes and estimating the velocity of the LSB, two different stages of plastic deformation can be distinguished. The temporal development of deformation during the LSB was analyzed with temporal HT method with estimated error of $\lambda/10$.

Acknowledgements

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Machine Learning based damage localization utilizing finite element modelling, intended for TinyML applications

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Abstract: In this study, we explore the use of Piezoelectric Transducers (PZTs) attached to a plate for both generating and detecting signals, simulating various damage scenarios. The generated data is then utilized to train Machine Learning (ML) algorithms aimed at pinpointing the location of damage. The objective is to pinpoint features that provide high accuracy with minimal computational resources, making them suitable for Tiny machine learning (TinyML) applications. The findings suggest that the most effective features include descriptive statistics, summed values of the absolute Fourier transform, and the linear trends of the peak and trough values in the time series data.

1. Introduction

The necessity for prompt detection of faults in structural systems is paramount to prevent severe failures, streamline maintenance operations, and eliminate unscheduled inspections, as underscored in reference [1]. The discipline of Structural Health Monitoring (SHM), which encompasses both algorithm development and the strategic deployment of sensors, has gained substantial traction, evidenced by a plethora of over 6000 publications in the last decade focusing on "composites SHM" [2]. Among the diverse methodologies in SHM, such as vibration analysis, strain monitoring, guided wave techniques, acoustic emission, and Electrical Impedance Tomography [3], the advent of lightweight structural designs [4] has propelled the use of Piezoelectric Transducers (PZTs) for SHM. These devices, serving dual roles as actuators and sensors, are particularly suited for plate-like structures due to their non-invasive nature, ease of implementation, widespread availability, and cost-effectiveness [5, 6]. Positioned as intermediate solutions within the SHM spectrum [2], these PZT-based methods necessitate sensor arrays that, in extensive structures, pose challenges related to energy consumption, data transmission, latency, and the complexities of cloud integration, not to mention the initial setup and ongoing operational costs [7].

Emerging as a potential solution to these hurdles is Tiny Machine Learning (TinyML), particularly within the Internet of Things (IoT) framework, heralded for its ability to reduce latency, optimize bandwidth, bolster data security, enhance privacy, and cut down expenses [8]. The integration of TinyML with advanced algorithms for damage localization could markedly enhance efficiency in inspection and maintenance procedures. However, the inherent constraints of TinyML in terms of processing power and memory [8] necessitate the careful selection and extraction of computationally light features, alongside the deployment of memory-efficient models.

Given the need for extensive datasets to train robust ML models for intricate damage localization tasks, which could lead to impractical experimental designs [9], this study advocates for the use of sophisticated (physics-based) simulations to enhance the experimental datasets. By simulating a thermoplastic plate equipped with PZTs for both excitation and detection across various damage scenarios, this approach circumvents the issues associated with limited experimental datasets. This dataset then informs the training of ML models aimed at addressing classification and regression challenges in damage localization, with a clear focus on identifying computationally efficient features conducive to TinyML applications, thereby advancing the field of SHM.

2. Methodology

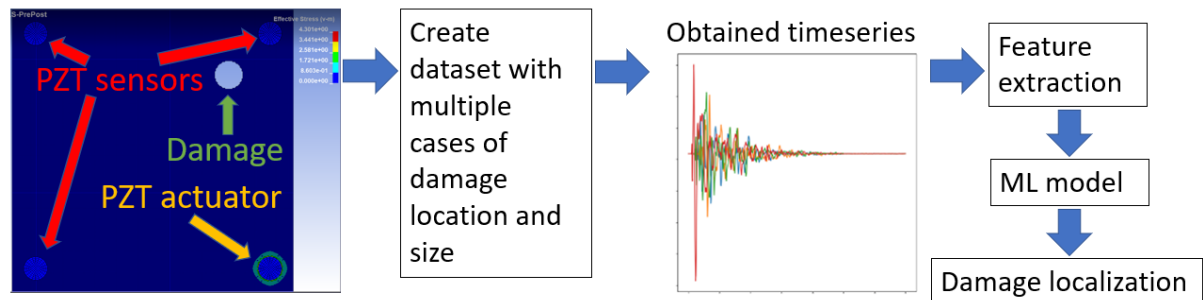


Figure 1: Simplified workflow of the current study

The methodology of the current study can be viewed in Figure 1. A finite element model of a thermoplastic plate mounted with PZTs acting as both actuators and sensors is simulated in LS-DYNA, with a 5-cycle Hanning excitation at 200 KHz. Different damage cases are simulated and combinations of features are extracted from the obtained time series, using the tsfresh python package[10]. These are used in ML models with low memory size (≤ 256 KB), as they are intended for TinyML embedded intelligence use in IoT devices.

3. Results

Figure 2 provides the error of a Random Forest (RF) model for different combination of features. Aggregate expressions of the Fourier transform and linear trend of the maximum and minimum values of the time series significantly improve the error, as the model can't handle sequential data (e.g. Fourier coefficients). Finally, a comparison between different models (RF, XGBoost, Gradient Boosting) is presented in Table 1 in terms of memory usage and error performance. RF provides the best damage localization, while XGBoost exhibits slightly lower performance but with smaller memory requirements.

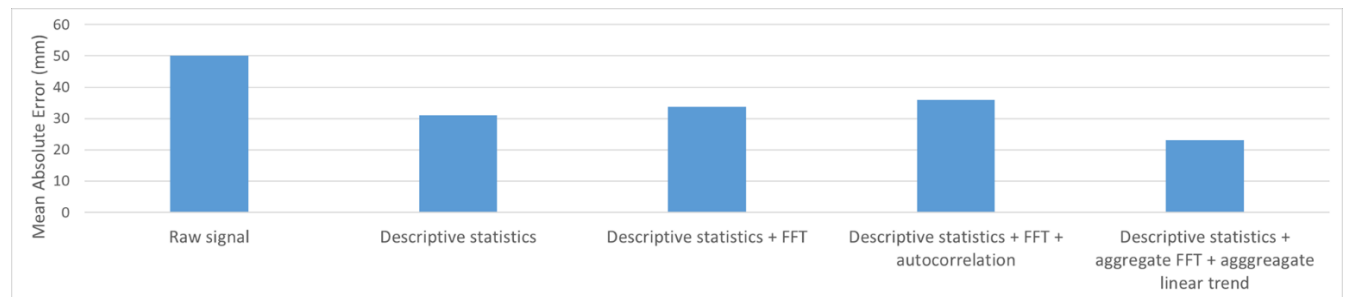


Figure 2: Comparative model performance for different feature combinations

Table 1: Comparative model performance and memory size

Model	Mean Absolute Error (mm)	Model memory size (MB)
Random Forest	23	0.18
XGBoost	26.6	0.1
Gradient Boosting	40	0.24

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Influence of strain rate and type of matrix on mechanical properties of carbon thermoplastic laminates under dynamic compression produce with LATP/LAFP

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Abstract: Thermoplastic composite materials are used for heavier-duty applications like aerospace, space and medical industries. Thermoplastics composite materials systems are generally considered as substitutes for thermoset materials defense applications to take advantage of fabrication cost reductions afforded by consolidating without an autoclave. Production of composites from carbon thermoplastic tapes with different matrices PEEK, PPS, PEKK using LATP/LAFP consists of consists of three main steps: impregnation, consolidation and crystallinity. Impregnation is a parameter that cannot be controlled by automatic fiber / tape laying while consolidation and crystallinity can be controlled. Consolidation consists of two sub-processes: intimate contact and autohesion. To achieve better final characteristics of the thermoplastic composite it is necessary to achieve a good degree of intimate contact and good self-connection.

This paper examines the impact of new design of compaction roller on several types of thermoplastic matrices that have different flows after melting. The aim is to reduce the percentage of pores in the lamina that is present in the material itself, because process parameters cannot reduce the voids in the tape that has the raw material itself. The results show that the new design of the compaction roller in the LATP / LAFP process for given materials reduces the percentage of pores present in the laminate of the raw material. This is another reason that the impregnation of the prepreg used in this technology is a key part of the final product It is because, the thermoplastic UD prepregs rely on a powder-based application process that is more difficult to control and can create resin-rich and dry areas. Such non-uniformity can lead to problematic interplay porosity. The key point is that high-quality tapes, with low void content, are an enabler of fast, automated processing of high-quality composites. Tapes with high levels of voids will require longer consolidation cycles to produce high-quality parts [1-10].

The carbon fiber volume fraction is 60% in the CF/PPS laminate/ CF/PEEK laminate and CF/PEKK laminate. After a good selection of technological processes, the composite laminates were manufactured using LATP (in-situ Laser assisted tape placement Fig 1.) technology according to quasi-isotropic lay-up sequence: [0/45/-45/90]2s. Then the composite laminates were cut into a cube specimen by a water-cooled diamond saw, and the size of 10 mm (length) x 10 mm (width) x 4.5mm (thickness) for high-strain-rate compression tests. To avoid the size effects in the impact tests, the specimens in all tests had the same dimension.

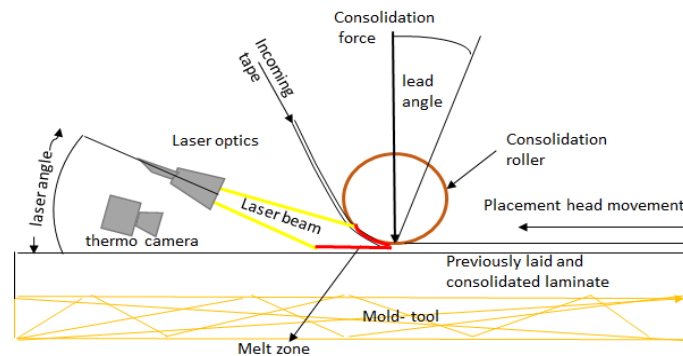


Fig. 1 In situ consolidation of flats and pipe with LATP/LAFP head

In this paper, we investigated the dynamic compressive behaviour of thermoplastic polymer composites in the in-plane and out-of-plane directions over a different matrix (PPS, PEEK, PEKK) and strain rates (~0.01, 10, 1000–5000/s) with a Split Hopkinson Pressure Bar (SHPB) apparatus (Fig.2)[8-10].

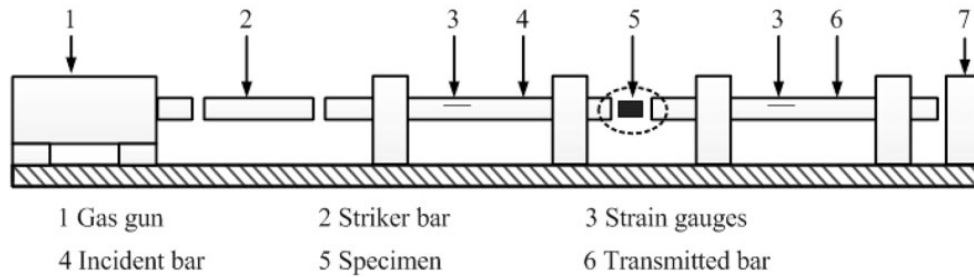


Fig. 2. Schematic diagram of a compressive split Hopkinson Pressure bar.

The dynamic stress-strain behaviours and mechanical properties were discussed. Following the experiments, the damage and fracture morphologies of composite specimens after failure were examined by optical and scanning electron microscope (SEM). The dynamic failure mechanisms were comprehensively characterized at different strain rates and different matrix (PPS, PEEK, PEKK) in the in-plane and out-of-plane directions (table 1.).

Table 1. Samples for tests

Sample No.	CF/PPS laminate	CF/PEEK laminate	CF/PEKK laminate
in the in-plane directions [0/45/-45/90]2s			
Strain rate (s⁻¹)	0.01/s	0.01/s	0.01/s
	10/s	10/s	10/s
	1000/s	1000/s	1000/s
	5000/s	5000/s	5000/s
out-of-plane directions [0/45/-45/90]2s			
Strain rate (s⁻¹)	0.01/s	0.01/s	0.01/s
	10/s	10/s	10/s
	1000/s	1000/s	1000/s
	5000/s	5000/s	5000/s

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