MULTISCALE MODELLING AND FAILURE PREDICTION OF BRAIDED METACOMPOSITE

Rohit Raju Madke, Rajib Chowdhury

Computational Mechanics Research Group, Department of Civil Engineering (Structural Engineering Group), Indian Institute of Technology Roorkee, Uttarakhand - 247667

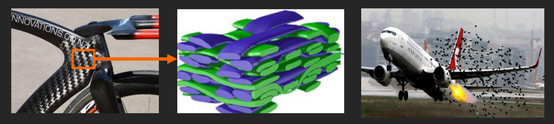
1. Abstract

This research proposes an innovative braided metacomposite design integrating semi-auxetic braided composite with auxetic and negative stiffness (NS) mechanical metamaterials.

The computed effective properties at lower scales serve as input for static progressive damage analysis and dynamic impact simulations of semi-auxetic braided composite.

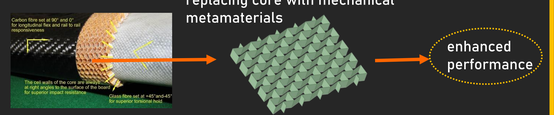
The novelty lies in the proposed lightweight metacomposite with dual negative metamaterial for a coupled effect to mitigate ballistic impact loads and their shocks, simultaneously, are useful in NIJ level IV protective body armor applications.

2. Problem Statement



The complicated architecture in textile composites leads to anisotropy – model in 3D space necessary

Defense and aerospace components are subjected to very high in-plane and out-of-plane static and dynamic loads



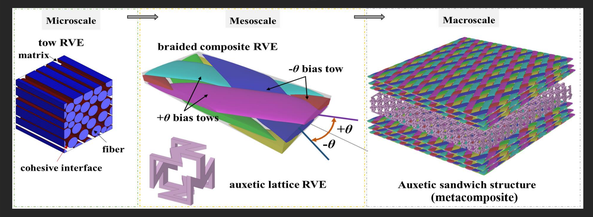
Indian defense systems face unique challenges in developing protective armor systems for mitigating both low and high-frequency ballistic loads and shocks due to conventional designs

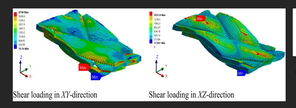
3. Aims & Objectives

- Multiscale mechanical modelling of woven and braided composite
- Analytical and numerical homogenization of woven and braided composites and mechanical metamaterials
- Anti-impact design of metacomposite with application to body armour

3. Methodology and Findings

(i) Multiscale modelling of textile composite

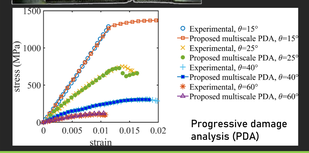




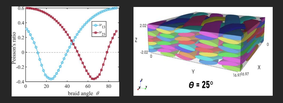
Carbon fibers and yarns – Transversely isotropic
Epoxy matrix - Elasto-plastic epoxy resin (J_2 - plasticity)
Failure criteria – Hashin's (yarn) and von Mises (matrix)

Semi-auxetic braided composite
braid angles 15 - 40° = nu_{13}
braid angles 55 - 80° = nu_{23}

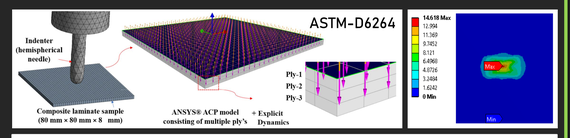
- Semi-analytical Mori-Tanaka & double inclusion homogenization
- Mechanics of structure genome (MSG)
- Multiscale FE analysis



Progressive damage analysis (PDA)

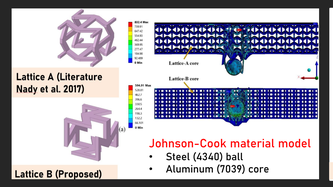


(ii) Low-velocity impact behaviour

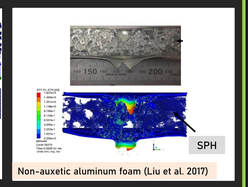


Semi-auxetic braided composite – Orthotropic Equation of State (*ANSYS® Explicit* and *Autodyn*)

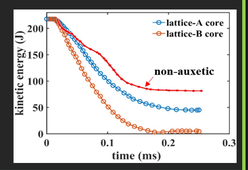
indentation depth (deformation) and maximum stress produced is least in semi-auxetic braided composite

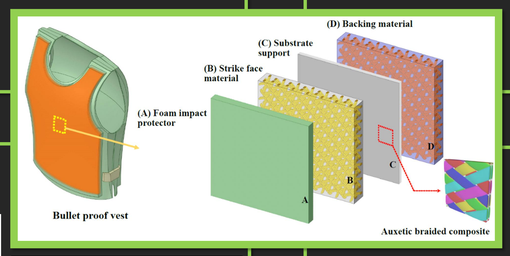


Johnson-Cook material model
- Steel (4340) ball
- Aluminum (7039) core

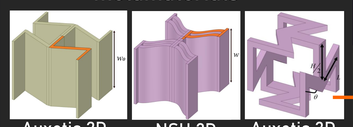


lattice-B core absorbed 49% more kinetic energy

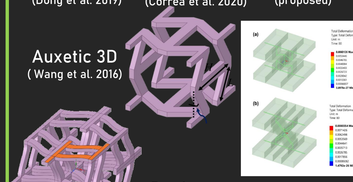


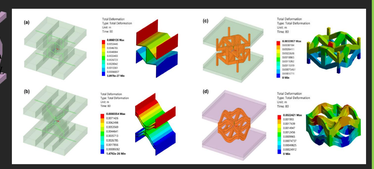


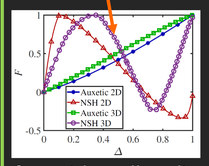
(iii) Tunability in mechanical metamaterials



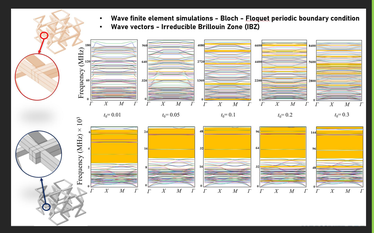
$\nu_{12} = -0.4080$
$\nu_{13} = -1.3814$
$\nu_{23} = -1.3814$
negative Poisson's ratio in all the three orthogonal symmetry planes







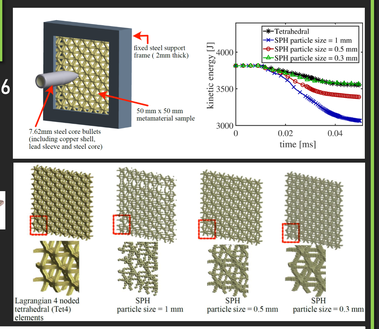
Geometric nonlinearity



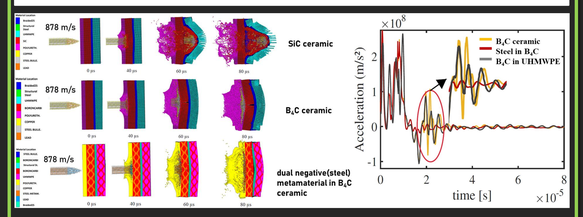
(iv) Ballistic impact behaviour

NIJ Standard-0101.06 (Body Armor Performance Standards – U.S.)

7.62 mm (copper shell + lead sleeve + steel core)



SiC ceramic – Polynomial EOS - Johnson Holmquist constitutive strength and failure model (JH-1)
B_4C ceramic - Johnson Holmquist (JH-2)



4. Discussion

The research proposes two configurations of braided metacomposite one with auxetic 3D lattice B and the second with dual negative lattice C.

The first configuration is useful for withstanding impact with intermediate velocities below 200 m/s like a bird strike or foreign object strike. Whereas the second metacomposite system helps to mitigate the ballistic impact and shock loads in body armor plate.

In the case of textile composites, homogenization in conjunction with finite element analysis is a precise and consistent way to analyze their behavior. The microstructure's cohesive zone modeling can consider factors pointing to failure initiation, such as surface defects, imperfections and voids, and built-in residual stresses for realistic behavior of the tows

5. Major Conclusions

Braided composite with braid angles 25° has the most negative through-the-thickness Poisson's ratio value and 25° ($\nu_{13} = -0.1676$) shows enhanced mechanical properties and better energy absorption.

Bandgap analysis using wave FE reveals a slight alteration in the geometrical topology of metamaterial leading to noteworthy variations in their band structures, signifying their tunability and promising engineering application potentials of vibration isolation.

SPH is an efficient meshless method and when applied prudently to the actual microstructure gives reliable results. It can aid the designers in the selection and analysis of metamaterials with complex architectures and curvatures.

Metacomposite with steel-based dual-negative metamaterial embedded inside B_4C ceramic displays preeminent performance for simultaneous impact and shock mitigation.

6. Future Directions

Simulations on the thermal shock effect of the ballistic performance

Systematic design of multifunctional metamaterials by topology optimization (TO) + additive manufacturing

Fracture and fatigue studies on braided metacomposites – XFEM & phase-field techniques

Contact Information

Rohit Raju Madke, Ph.D.
Indian Institute of Technology Roorkee
Email: rvmadkey@gmail.com, rmadke@ce.iitr.ac.in
Website: https://computationalmechanics.in/rajib_teams/rohit-raju-madke/
Phone: 9503995154, 8979535004

Journal & Conference Publications

1. R. R. Madke and R. Chowdhury (2019), A multiscale continuum model for inelastic behavior of woven composite, *Composite Structures*, 226, 111267.
2. R. R. Madke and R. Chowdhury (2020), Anti-impact behavior of auxetic sandwich structure with braided face sheets and 3D re-entrant cores, *Composite Structures*, 236, 111838.
3. R. R. Madke and R. Chowdhury, *Numerical scheme for the prediction of elastic properties of textile composite*, International Conference on Composite Materials and Structures (ICCMS 2017), IIT Hyderabad, India, 27-29th December 2017.
4. R. R. Madke and R. Chowdhury, *Multiscale analysis of a triaxially woven fabric composite*, International Conference on Advances in Construction Materials and Structures (ACMS-2018), IIT Roorkee, India, 7-8th March, 2018.
5. R. R. Madke and R. Chowdhury, *Multi-objective optimization of a fabric reinforced composite*, 2nd National Conference on Multidisciplinary Design, Analysis (NCMDAO-2), RUAS Bengaluru, India, 22-23 March 2019.
6. R. R. Madke and R. Chowdhury, *Numerical characterization of auxetic composite exhibiting multiscale heterogeneity*, 7th International Congress on Computational Mechanics and Simulation (ICCMS 2019), IIT Mandi, India, 11-13 December 2019.

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शिक्षा मंत्रालय MINISTRY OF EDUCATION
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