Predicting Ballistic Limit and Specific Energy Absorption of Bioinspired UHMWPE-Kevlar Armour Structure using Surrogate Modelling

M. Ghowtham[1a], Pradeep Seshadri[1] and Prashant Rawat[2]

[1]Department of Aerospace Engineering, Indian Institute of Technology, Madras

[1a]ae22d007@smail.iitm.ac.in,[1]pkseshadri@smail.iitm.ac.in, [2]prashant.rawat@iitm.ac.in

Abstract. This study develops a high-fidelity surrogate model to predict the ballistic limit and specific energy absorption of a novel bioinspired fish-scale inspired sandwich armour. The structure integrates Ultra-High Molecular Weight Polyethylene (UHMWPE) discs with a Kevlar fabric backing to absorb energy ballistic impact load. To ensure the surrogate model captures complex physical phenomena, a comprehensive material characterization was performed, incorporating viscoelastic-viscoplastic and strain-rate-dependent thermomechanical constitutive laws. The surrogate model was trained using a synthetic dataset generated from LS-DYNA ballistic impact simulations, which were rigorously validated against experimental impact tests. By coupling bioinspired structural parameters with advanced material modelling, the resulting analytical framework provides a computationally efficient alternative to traditional Finite Element Analysis (FEA). Results demonstrate that the surrogate model accurately captures the synergistic effects of geometry and rate-dependency, offering a rapid design tool for the development of lightweight, flexible, and high-performance ballistic protection system

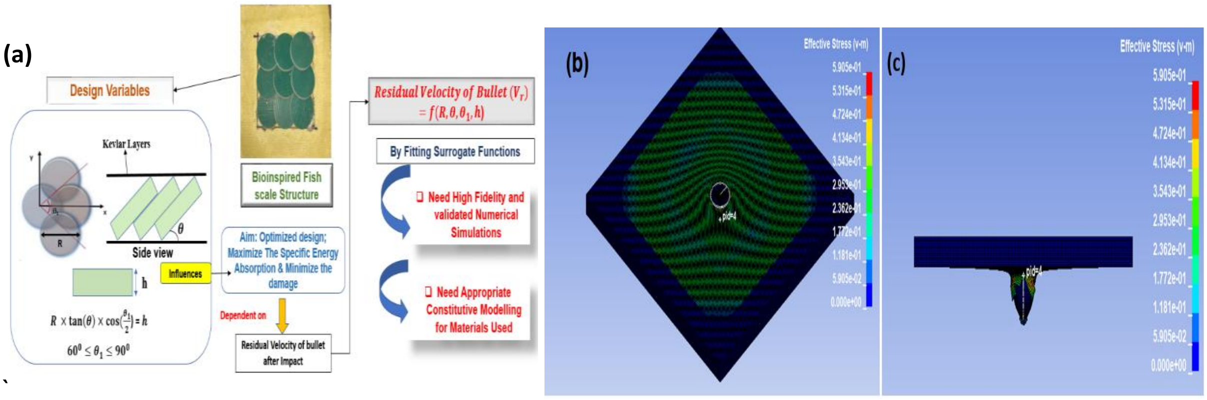

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Fig. 1. (a) Graphical Abstract **(b) & (c)** Preliminary simulation results showing the validation of experimental results

Introduction

From ancient times, body armours have been evolving catering to three prime requirements high specific energy absorption, flexibility and light weight. Conventional body armours, lack in flexibility and light weight properties, which are crucial for the wearer’s comfort. From literature, researchers [1, 2] have elucidated the deformation mechanisms of naturally evolved protective structures in fishes, armadillos and alligator etc. and provided conclusive evidences that these arrangement are effective in effective dispersion of indentation and impact loads. They have attributed these advantages to phenomenon called as strain stiffening effect [3 and 4]. Design variables associated with the fish scale bioinspired structures are overlapping angle of the discs θ_1 with adjacent, tilt angle θ with respect to backing layers, radius of disc (R) and thickness of the discs (h) (refer with: Fig. 1).The motivation of this work is to apply the concept of bio inspiration from fish scale structures to improve the existing conventional body armours design using innate impact resistant, lightweight materials like UHMWPE and Kevlar 49 Fabric. A multiobjective optimization problem is formulated to maximize the specific energy absorption and minimize the damage or deformation undergone by the bioinspired structure. As a precursor to it, in this work, fits a high fidelity surrogate model for the residual velocity of the bullet and ballistic limit of the bioinspired structure after impact with the design variables of fish scale inspired armour structure.

Research Gap and objective

The design values corresponding to the maximum specific energy or minimum residual velocity found in the past research works are result of fixing one or more design variables and varying rest that maximizes the energy absorption of fish scale inspired structures. But, it doesn't satisfy the geometrical constraints relation and leads to suboptimal solutions.Formulation of a Multi Objective optimization problem, will give us a global optimal solutions which can further increasethe ballistic limit and flexibility of the body. To achieve that a relationship between the residual velocity of bullet and design variables associated with the bio inspired structure is to be established. There exists several ballistic models for predicting residual velocity like Goldsmith (1971), Recht and Ipson (1963), but it involves target of simple geometry and materials. In this work, a surrogate model for predicting residual velocity of bullet and ballistic limit of an intricate bioinspired structure is established.

Methodology

To carry out surrogate modelling, data points of residual velocity corresponding to varied value of design variables is required. Achieving that, experimentally is costly in terms of time and resources used. So, using a high fidelity and validated numerical simulation model built in LS DYNA explicit software is used for this purpose in conjunction with appropriate material constitutive models sourced from literature for creating synthetic datasets for training the surrogate model.

Constitutive material Models. Selecting of appropriate constitutive material models for the material used in the fish scale structure is crucial to perfectly emulate the complex deformation process undergone by the target under ballistic impact. From [4], dry fabric material model is used for Kevlar fabric and based on [5], a user-defined code involving Generalized Maxwell, J2 plasticity radial return algorithm and Johnson cook hardening model was written for UHMWPE material.

Experimental tests for Numerical simulation validation. In order to ensure the correctness of selected constitutive material model incorporated in the numerical simulations, matching of residual velocity from experimental tests and numerical simulations is required. In this regard, high velocity impact experiments using two stage gas gun setup were conducted on a simple plate geometry of UHMWPE sandwiched between Kevlar 49 fabrics. Using Schlieren setup and post processing, the residual velocity of bullet was evaluated. The experimental and numerical residual velocities matched, confirming the validity of numerical simulation model created. Hence, used for data generation for surrogate modelling.

Conclusion

The surrogate model is fit for the governing design variables, by conducting appropriate design of experiments model.The accuracy of obtained surrogate model is checked by accuracy metrics, cross validation sets and experimental values did at unseen points.

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