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MULTISCALE STOCHASTIC INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIOUR OF HYBRID COMPOSITE LAMINATES

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This study investigates the probabilistic low-velocity impact behaviour of a hybrid composite plate composed of nitinol-based smart materials and a glass-epoxy composite. A multiscale framework was created by combining micromechanics and macromechanics models. At the micromechanics level, the effective material properties were derived from the different phases (nitinol fibers, glass fibers, and epoxy matrix) by means of homogenization schemes, which reflect the local stress and strain behaviour. At the macromechanics level, laminate theory and finite element methods were used to model the overall structural response under impact loading. A comparative analysis between micromechanics- and macromechanics-based results was performed to check the consistency, accuracy and computational efficiency of the two methods. The impact force and other related parameters were determined from a modified Hertzian contact model and the governing time dependent differential equations were numerically integrated utilising the Newmark method. Variability in the material and the geometric properties were handled with the help of a Monte Carlo simulation. Parametric analyses were performed to investigate the influence of the impactor mass, impact velocity and impact angle on the hybrid plate response. The results revealed that while both models capture the overall stochastic impact behaviour, micromechanics provides greater accuracy in reflecting local damage initiation, whereas macromechanics offers computational efficiency for global response prediction.

Keywords: **hybrid composite material, Hertzian contact model, Newmark time integration method, stochastic impact analysis, low-velocity impact analysis**

INTRODUCTION

Composites are engineered materials made from a combination of two or more different constituents, usually a matrix and reinforcement, in such a way that the resulting composite has properties superior to those achievable by the individual components. The matrix, which may be polymeric, metallic, or ceramic, serves to bond the reinforcement and distribute loads applied to the composite, while the reinforcement (e.g. fibers, particles, or whiskers) provides the strength and stiffness. Material selection, volume fraction and orientation play important roles in the final property of material. Composites possess some very attractive attributes, for instance, resistance to corrosion, a high strength-to-weight ratio or superior fatigue behaviour. Because of these benefits, composite materials are used extensively in a wide variety of applications in the marine, civil infrastructure, aerospace, automotive and sporting equipment sectors. They are also widely employed in biomedical devices, renewable energy systems and other advanced engineering applications.

Nonetheless, more advanced materials are required for aerospace, automotive, medical and other industries to fulfil the criteria or demands for materials like superior fatigue resistance or a high strength-to-weight ratio. Enhanced energy absorption capabilities and adaptive functionality are some criteria that often demand the development of hybrid, multi-functional and smart composite structures, such as the nitinol-based glass-epoxy composite studied herein. A hybrid composite plate is fabricated by embedding nitinol shape memory alloy (SMA) fibers into the base glass-epoxy composite structure. This hybridization capitalizes on the high strength and stiffness of the glass-epoxy material while taking advantage of the unique adaptive and damping properties of the nitinol fibers, which are critical for improved dynamic performance. The behaviour of this composite depends very strongly on key material specifications, which include the volume fraction of the constituents and laminate design features such as the ply orientation angle and stacking sequence [1].

Due to the complex nature of their structure, plus the occurrence of localized phenomena such as superelastic phase transformation in the nitinol reinforcements and gradual damage of the matrix under low velocity impact conditions, hybrid composite materials require the implementation of a detailed multiscale probabilistic framework of modelling. On the one hand, these materials exhibit significant constituent interactions at different scales, while microscale mechanisms can largely determine the overall structural response of the material. On the other hand, standard stochastic finite element methods are usually limited to defining uncertainty at the macroscopic level by means of assumed probability distributions and correlation structures. Nevertheless, those assumptions may not be able to fully account for the intrinsic heterogeneity, spatial variability and microstructural randomness characteristic of hybrid composite systems. As a result, the changes to the fiber-matrix interface caused by the different phases, the phase-dependent behaviour of the smart material, and the progression of damage at a given point may remain insufficiently predictable. This limitation implies a major issue for multiphase systems, in particular where the overall response is governed by fiber-matrix interactions and phase transformations.

However, that weakness is a strong argument for the adoption of a model which makes the link between the global stochastic response of composite structures and microscale uncertainties more accurate [2]. Recent studies combine atomistic simulations, representative volume element-based homogenization and continuum mechanics to establish the material behaviour connection across different scales [3]. These types of multiscale modelling frameworks are essential for high-end composite systems, for example, nitinol-based glass fiber-reinforced composites. With their strong material behaviour coupling at several scales, these methodologies allow less uncertain structural performance predictions, informed design optimization and effective material selection by directly accounting for the interactions and uncertainties at the different scales. By providing a systematic relationship between atomistic and microscale responses in addition to macroscale behaviours, multiscale frameworks limit the use of simplified assumptions that are generally characteristic of single scale models. Consequently, the uncertainty in modelling is reduced and the precision of the predicted structural responses is greatly improved. Such higher accuracy is especially important for accurately predicting the response of composites under complicated loading scenarios, including dynamic and impact conditions [4–6]. Different scales of modelling have been combined in a neatly organized stepwise manner resulting in a very effective approach to depict the complex mechanical behaviour of hybrid composite materials. By linking the atomistic microscale and the macroscale responses, detailed studies of these materials are made possible.

At the atomistic level, numerical simulations are used to investigate the fundamental mechanisms such as phase transformation, interfacial bonding and localized deformation processes, which essentially control the material behaviour, while at the microscale, representative volume elements along with homogenization techniques are implemented to determine effective material properties considering the interactions of the material components' heterogeneity and the development of progressive damage. The properties derived by homogenization are then utilised in macroscopic models, which comprise classical laminate theory and finite element based structural models. Such models help in predicting the overall behaviour of composite structures under dynamic as well as low velocity impact loading situations. Thus, hierarchical multiscale frameworks of this kind provide a trustworthy basis for the design analysis and performance improvement of advanced hybrid composite systems [7]. Vaishali et al. [8] conducted research on the stochastic free vibration and low velocity impact behaviour of functionally graded plates by means of a hybrid computational framework that combines finite element modelling with support vector machine based surrogate modelling. They employed Monte Carlo simulation to incorporate the material and geometric uncertainties in addition to sensitivity analysis, finding the elastic and shear moduli as well as the mass density as the major parameters influencing the properties. At the same time, they used the Halpin Tsai model for micro-macro property linkage. Their results showed that the natural frequencies and impact responses were greatly affected by stochastic variations, thus highlighting the necessity for probabilistic design. Furthermore, the surrogate model was able to make accurate predictions while significantly lowering the computational cost.

Karsh et al. [9] demonstrated that the RBF-based surrogate model can accurately and efficiently predict the stochastic low-velocity impact responses of FGM cantilever plates, with results closely matching Monte Carlo simulations. It highlights the significant influence of material randomness, temperature, and impact parameters on the contact force and displacements, confirming the effectiveness of surrogate modelling in reducing the computational cost while maintaining high prediction accuracy for probabilistic impact analysis. Kumari et al. [10] utilised multivariate adaptive regression splines (MARS) combined with the Monte Carlo simulation to study the dynamic response of porous functionally graded plates under uncertain conditions. Their method takes into account the nonlinear influence of porosity, the grading index, temperature as well as thickness, and is as accurate as a Monte Carlo-based finite element analysis but at a much lower computational cost. A sensitivity analysis shows that the main parameters affecting the natural frequencies are the shear modulus, elastic modulus, Poisson's ratio and mass density. Karsh et al. [11] proposed a finite element surrogate modelling approach that uses a polynomial neural network to model the parametric uncertainty of natural frequencies for laminated softcore sandwich plates. Latin hypercube sampling was employed to enable efficient training and the results demonstrated its capability to predict the effects of input uncertainties on the vibration characteristics at a lower computational cost than a Monte Carlo simulation. A multi-interface FE model considering both cohesive and friction damage was developed by Li & Qian [12] based on the pull-out tests of individual fibers, which was justified with the results of acoustic emissions. The process of failure at the interface can be well reproduced, which emphasizes the importance of the interfacial strength and the value of the energy release rate on the general performance of the composite.

Vaishali et al. [13] studied the low-velocity impact response of hybrid functionally graded sandwich structures by means of a probabilistic approach that combined MARS and finite element analysis. Geometric, material, and impact uncertainties were taken into account and the results showed a high sensitivity of impact response to uncertainties, thus underlining the importance of probabilistic modelling in hybrid composite design. Padhiyar et al. [14] studied the deterministic and stochastic free vibration behaviour of CNT-reinforced functionally graded cantilever plates using finite element analysis and Monte Carlo simulation. The results show that material uncertainty significantly affects natural frequencies, with CNT content, plate thickness and temperature playing dominant roles in the dynamic response. Most existing studies on the low-velocity impact of hybrid composite plates rely on deterministic or single-scale modelling approaches and do not adequately account for uncertainty in material and geometric properties. Moreover, the combined use of micromechanics and macromechanics frameworks to simultaneously capture local damage initiation and global structural response under stochastic impact loading remains limited. A comparative evaluation of the accuracy and computational efficiency between these two scales, particularly for SMA-based hybrid composites, has not been sufficiently explored in the literature.

Singh et al. [15] present an analysis of the vibration characteristics of hybrid composite plates embedded with shape memory alloy fibers. A numerical framework is used to analyse the influence of material and geometric uncertainties on the structural response. The composite plate behaviour is simulated utilising an advanced shear deformation theory in tandem with probabilistic modelling. Any random variation in the critical parameters is included to represent real operating conditions realistically. The results indicate that the addition of shape memory alloy fibers regulates the natural frequency response of the composite structure. Overall, this paper focuses on the importance of accounting for uncertainty effects to obtain accurate dynamic analyses of smart composite materials. Osfouri et al. [16] investigated nitinol SMA wire-reinforced glass- and carbon-fiber laminates and reported significant improvements in impact damage tolerance and energy absorption. Their experimental and numerical studies showed that SMA reinforcements reduce the peak impact forces, delay damage initiation, as well as enhance residual stiffness through superelasticity and phase transformation. Additionally, prestrained SMA wires improve stiffness, damping, and post-impact integrity, making such hybrid composites suitable for aerospace and transportation applications subjected to repeated impacts. Tian et al. [17] investigated the nonlinear dynamic behavior of thick hybrid composite laminates employed in railway vehicles. Their study showed that hybrid laminates can withstand both mechanical and impact loads while maintaining stable dynamic performance. The analysis considered the geometric nonlinearities and contact effects. The results revealed that frequency shifts, mode coupling, and damage progression are strongly influenced by the hybrid architecture and stacking sequence. These findings highlight the importance of using coupled vibration-impact models for the design of SMA-reinforced hybrid plates operating under multi-hazard loading conditions.

Thakkar et al. [18] integrated machine learning with finite element modelling to quantify uncertainties in hybrid composite plates. The technique uses machine-assisted stochastic analysis for estimating the probability distribution of the natural frequencies of hybrid laminates, thus reducing the computational costs for full Monte Carlo simulations. The application of radial basis function, MARS and polynomial neural networks, combined with finite element data, enables more accurate natural frequency estimates and understanding of the effects of the input parameters on the elastic modulus, shear modulus, mass density and layup configuration variations on the quantitative distribution of the modal properties of hybrid laminates; therefore, this research demonstrates the importance of including probabilistic models in the design of future hybrid composite materials with embedded smart materials.

Watanabe et al. [19] reported on advances in the multiscale modelling of carbon fibre composite processes by an integrated understanding of the connections between atomistic, mesoscale and structural responses to load(s). Specifically, their work used quantum chemical reaction path analysis, molecular dynamics and finite element analysis to develop methods to predict the off-axis failure of carbon fibre reinforced laminate structures by analysis of local interfacial debonding and matrix cracking failure mechanisms. Additionally, they developed methodologies based upon initial representative volume element (RVE)-based virtual testing of the shear performance and random nature of the response of cross ply laminate systems by employing RVE-based data to facilitate the scaling relationship between the local fibre/matrix architecture, fibre/matrix defect population and fibre/matrix material variability to predict structural level stiffness as well as strength distribution properties. Arora et al. [20] examine the recent developments in the multiscale modelling of natural and bio-based fiber composites, illustrating how microstructural characteristics, porosity, and fiber-matrix interfacial properties can be integrated into hierarchical simulations for analysing damage evolution and dynamic loading. These methodologies further endorse the application of microstructurally informed probabilistic models for multi-phase systems, such as Nitinol/glass-epoxy hybrids, where interfacial debonding, phase transformation, and matrix cracking interact across various length scales to influence low-velocity impact behaviour.

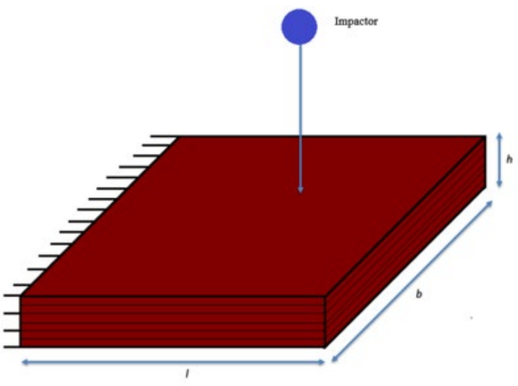


Fig. 1. Geometric view of hybrid composite plate subjected to low velocity impact loading

MATHEMATICAL EQUATIONS

The low-velocity impact between a rigid spherical impactor and a composite plate is modelled as a coupled two-degree-of-freedom dynamic system, representing the transverse motion of the plate and the impactor. The governing equations of motion are written as:

$$M_p \ddot{w}_p(t) + K_p w_p(t) = F_c(t) \tag{1}$$

$$m_i \ddot{w}_i(t) + k_i w_i(t) = -F_c(t) \tag{2}$$

Where, M_p and m_i represent the equivalent mass of the plate and impactor, K_p and k_i are the stiffness of the plate and impactor, while F_C is the contact force due to impact loading. The contact force is governed by a nonlinear Hertzian-type contact law, expressed as:

$$F_c(t) = k_c \delta(t)^{\frac{3}{2}} \tag{3}$$

$$\delta(t) = w_i(t) - w_p(t), \delta(t) \geq 0, \tag{4}$$

where, k_c is the effective contact stiffness, and $\delta(t)$ is the indentation. In Equation (3), if $\delta(t) < 0$, $F_c(t) = 0$. The properties of the constituent materials in a hybrid composite vary continuously and effectively throughout the thickness of the plate. There are various types of divergence laws governing the transition of material properties [21]. In this section, we will discuss the modelling of materials in hybrid composite plates using the micro model.

$$E_{11} = E_s(\zeta)V_s + E_{1m}(1 - V_s) \tag{5}$$

$$E_{22} = E_{2m} \left[\left[\left(1 - \sqrt{V_s}\right) + \frac{\sqrt{V_s}}{1 - \sqrt{V_s}\left(1 - \frac{E_{2m}}{E_{s(\zeta)}}\right)} \right]\right] \tag{6}$$

$$G_{12} = G_{13} = G_{12m} \left[1 - \sqrt{V_s} + \frac{\sqrt{V_s}}{1 - \sqrt{V_s}(1 - \frac{G_{12m}}{G_{s[\zeta]}}} \right] \tag{7}$$

$$G_{23} = \frac{G_{23m}}{1 - \sqrt{V_s\left(1 - \frac{G_{23m}}{G_{s[\zeta]}}\right)}} \tag{8}$$

$$\nu_{12} = \nu_{12s} V_s + \nu_{12m}(1 - V_s) \tag{9}$$

$$\alpha_1 = \frac{V_s \alpha_s E_s(\zeta) + (1 - V_s)\alpha_{1m} E_{1m}}{E_{11}} \tag{10}$$

where, V_s = the volume fraction of the hybrid composite, E = Young's modulus, G = shear modulus, ν = Poisson's ratio, and α = the thermal expansion coefficient. Equation 11 represents the calculation of the material properties of a hybrid composite by means of the macro model.

$$E_{macro} = \eta_{stacking} \eta_\theta E_{eff}, \tag{11}$$

where, E_{eff} is the effective modulus obtained from the micromechanical model, η_θ is the ply orientation factor, and $\eta_{stacking}$ is the stacking sequence efficiency factor. The constituent materials are assumed to exhibit linear elastic behaviour, with perfect bonding between the fiber and the matrix, and small deformation theory is considered. The micromechanical model is based on homogenization techniques to evaluate effective material properties assuming uniform distribution of the reinforcement. The macromechanical model employs classical laminate theory to predict the global structural response using equivalent properties. The impact interaction is modelled by means of Hertzian contact theory, assuming frictionless contact and local elastic deformation under low-velocity conditions. Uncertainty associated with material and geometric parameters is modelled employing Monte Carlo simulation, where the input variables are assumed to follow normal distributions with specified coefficients of variation.

RESULTS

A square SMA-based hybrid composite plate was considered for low-velocity impact analysis, as shown in Fig. 1. A hybrid composite plate of length *l*, width *b*, and thickness *h* was subjected to impact loading by a rigid spherical impactor as shown in Figure 1. The length and width of the plate were taken as 1 m each, while the thickness was varied stochastically. The material properties of the constituent materials, including the matrix, reinforcing fibers, and nitinol-based SMA, are presented in Table 1. The effective material properties of the hybrid composite, evaluated utilising the micromechanical formulations described in Eqs. (5-11), were used to calculate the material properties based on the macro model. The computational procedure adopted in the present study is illustrated in the flowchart shown in Fig. 2. The analysis begins with the identification and definition of the input parameters, such as the material properties, geometric dimensions, impactor characteristics, and stochastic variables.

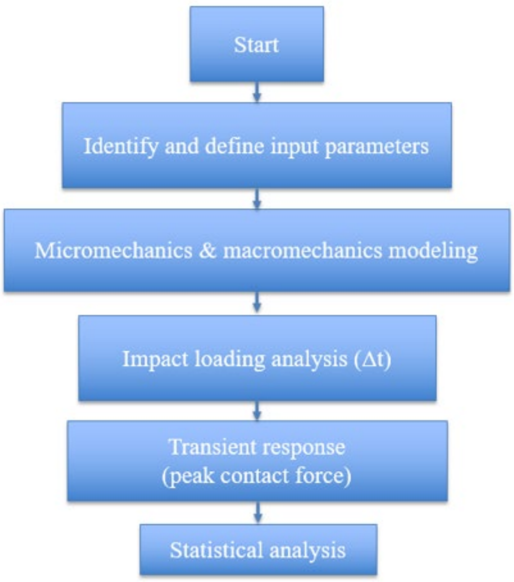


Fig. 2. Flowchart of stochastic low-velocity impact analysis methodology for SMA-based hybrid composite plate.

The micromechanical and macromechanical models were then employed to evaluate the equivalent stiffness and mass properties of the plate. Subsequently, the impact loading simulation was carried out using a time-stepping integration scheme (Δt) to capture the transient response of the system (contact force). A convergence check was performed at each time step to ensure numerical stability and accuracy; if convergence was not achieved, the solution process was iterated. Finally, statistical analysis was conducted on the Monte Carlo simulation results to quantify the uncertainty in the impact response. Table 2 presents the stochastic parameters adopted in the Monte Carlo simulation. The accuracy of the developed numerical model was validated by comparison with previously published results, as shown in Fig. 3. The specific volume of nitinol was considered as 0.1. Figure 4(a) shows the variation of the peak contact force as a function of the impact velocity for macro and micro models. For both models, the peak contact force increased significantly as the velocity rose from 1 to 3 m/s, indicating a strong velocity-dependent impact response. At all velocities, the micro model predicted higher peak contact forces than the macro model because of its detailed consideration of the constituent-level stiffness effects.

TABLE 1. **Material properties used in stochastic low-velocity impact analysis of SMA-based hybrid composite plate [1, 22]**

Constituent material	Property	Value	Unit
Nitinol (SMA)	Young's modulus (Austenite)	67	GPa
	Young's modulus (Martensite)	26	GPa
	Density	6450	kg/m³
	Martensite finish temperature	280	K
	Austenite finish temperature	320	K
E-glass fiber	Young's modulus	73	GPa
	Density	2600	kg/m³
Epoxy resin	Young's modulus	3.5	GPa
	Density	1200	kg/m³
Plate geometry	Length	1	m
	Width	1	m
	Thickness	0.005	m
Impactor	Mass	2	kg
	Radius	0.01	m
	Impact velocity	1	m/s

TABLE 2. **Stochastic parameters adopted in Monte Carlo simulation**

Parameter	Mean value	Coefficient of variation
Elastic modulus	Material-dependent	0.1
Density	Material-dependent	0.1
Plate thickness	0.005 m	0.1
Impact velocity	1.0 m/s	0.05
Temperature	300 K	0.1

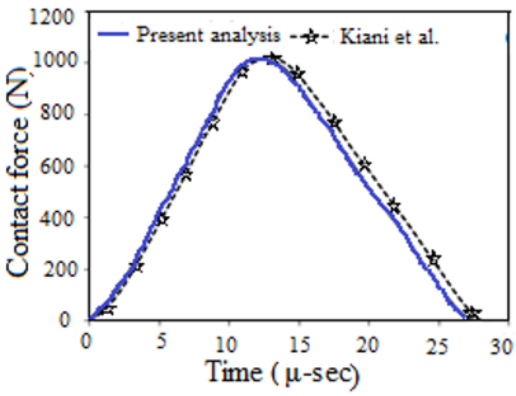


Fig. 3. Time histories of contact force for silicon nitride and stainless steel functionally graded beam clamped at both ends considering time step (Δt1) =1.0 µ-sec, length (Lo) =135 mm, width (b) = 15 mm, thickness (t) =10 mm, impactor of mass (mi) = 0.01 Kg, radius of impactor (ri) = 12.7 mm, velocity of impactor =1.0 m/s [23]

Figure 4(b) presents box plots of the peak contact force obtained from the macro and micro models at different impact velocities. The increasing spread at higher velocities reflects greater nonlinear and stochastic effects under severe impact conditions. In Figure 4(c), the mean of the probability density function plots rises as the velocity increases, indicating a clear velocity-dependent impact response. At all velocities, the micro model distributions are shifted to the right of the corresponding macro model distributions, reflecting higher predicted peak contact forces as a consequence of micromechanical effects. The observed growth in the peak contact force with impact velocity (Fig. 4) is consistent with earlier studies on hybrid and functionally graded composites, where higher impact energy leads to greater contact forces and damage initiation [8, 13]. Similarly, the increment in the peak contact force with impactor mass (Fig. 5) agrees with reported findings in the literature [27], confirming the direct dependence of impact response on inertial effects. The reduction in the peak contact force with increasing impact angle (Fig. 6) is also in line with established contact mechanics principles, where the normal component of impact force decreases under oblique loading conditions.

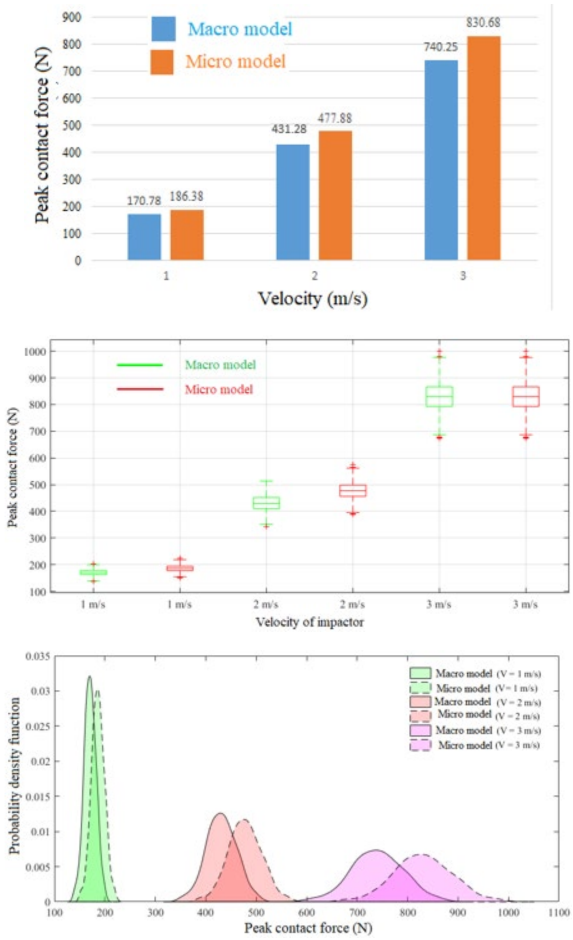
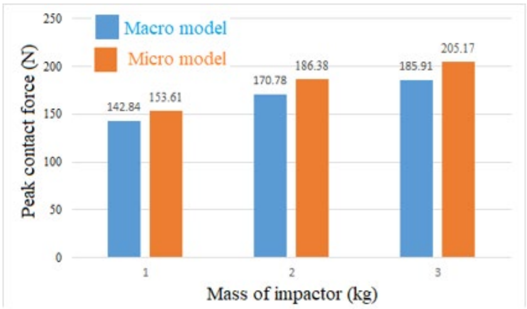
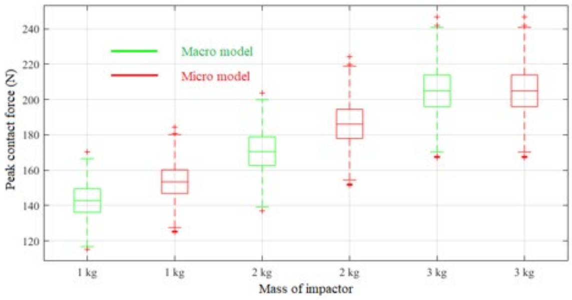


Fig. 4. Effect of impactor velocity on peak contact force of hybrid composite plate

Figure 5 illustrates the effect of the impactor mass on the peak contact force of the hybrid composite plate using macro and micro models. In Fig. 5(a), the bar chart shows that the peak contact force grows steadily with increasing impactor mass from 1 to 3 kg for both models, with the micro model consistently predicting higher forces than the macro model. Figure 5(b) presents the statistical dispersion of the peak contact force using box plots. An increment in impactor mass leads to more median values and wider upper ranges, with the microscale model predicting slightly larger forces and greater variability, indicating increased sensitivity to mass variation. The corresponding probability density functions in Fig. 5(c) indicate a systematic shift toward more force levels as the mass increases, with the micromodel distributions consistently surpassing those of the macro model. Figure 6 examines the effect of the impact angle on the peak contact force predicted by both modelling approaches. As shown in Fig. 6(a) the peak contact force dwindles steadily as the the impact angle increases from 0° to 45°, reflecting lower normal contact intensity during oblique impacts. Across all the angles, the microscale model yields higher force predictions.



a)



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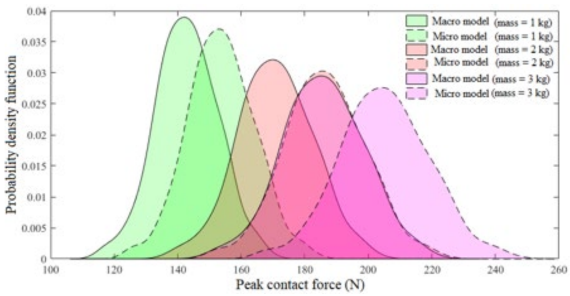
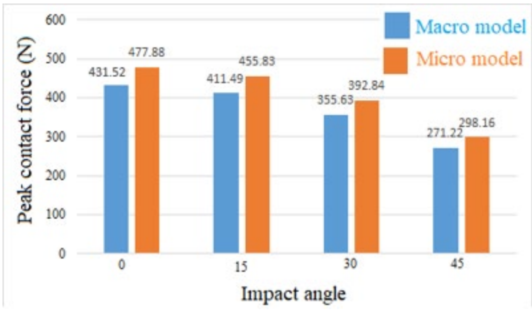
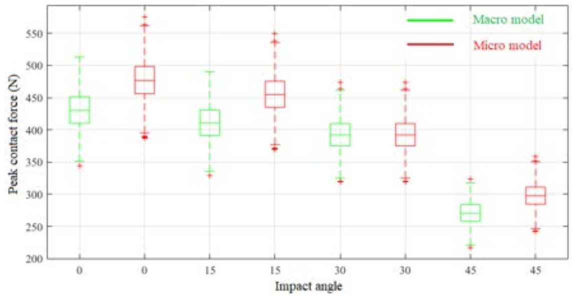


c)

Fig. 5. Effect of impactor mass on peak contact force of hybrid composite plate



a)



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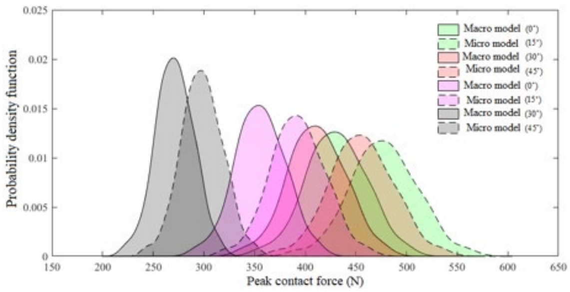

c)

Fig. 6. Effect of impact angle on peak contact force of hybrid composite plate

The box plots in Fig. 6(b) reveal a reduction in both the median values and dispersion with increasing impact angle, while Fig. 6(c) validates this trend with a leftward shift of the probability density functions, demonstrating the diminishing peak contact force with increasing obliquity. Nano-engineering holds the promise of revolutionizing hybrid composite laminates by the creation of multifunctional, damage tolerant, and self-monitoring materials with enhanced resilience to impact loads and robustness. Further research into the modelling of multiscale impact response and nano-reinforced composites will enhance the ability to predict and optimize impact performance for lightweight and intelligent composite structures [24-27].

CONCLUSIONS

In the current work, magnesium hybrid composites reinforced with 10 wt% This work represents a probabilistic low-velocity impact analysis for an SMA-based hybrid composite plate by means of an integrated multiscale modelling approach. The formulation integrates a modified Hertzian contact model with Newmark time integration. The uncertainties in the material properties, geometric parameters, and impact conditions are accounted for using Monte Carlo simulation. The findings shows that the peak contact force rises with the impact velocity and impactor mass but declines with increasing impact angle owing to reduced normal contact effects. In all the cases, the micromechanical model forecast higher peak contact forces than the macromechanical model, reflecting the influence of local stiffness and microstructural interactions. The statistical measures, including box plots and probability density functions, show increased response variability under higher impact, underscoring the importance of probabilistic analysis for reliable impact prediction.

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