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IMPACT ANALYSIS OF COMPOSITE LAMINATE STRUCTURES IN TRADITIONAL *JALOE KAYOH* BOAT HULLS

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ABSTRACT

This study investigates the impact response of a composite laminated structure applied to the hull of a traditional Jaloe Kayoh boat using a glass and ramie-reinforced polyester (GRRP) configuration. The GRRP laminate, which consists of three sequential layers, was engineered to enhance impact resistance in structural marine applications. A series of impact tests were conducted at controlled velocities of 2.4 m/s, 4.4 m/s, 6.4 m/s, 8.4 m/s, and 10.4 m/s, and the results were analysed using both experimental methods and Finite Element Analysis (FEA) simulations. At a baseline impact velocity of 2.4 m/s, experimental strain measurements were closely aligned with FEA predictions, showing a deviation of only 4.7% toward the pendulum impact. However, the strain results in the reverse direction indicated larger discrepancies, highlighting the limitations of predicting asymmetric deformation behaviour. At higher impact velocities, particularly beyond 10.4 m/s, the simulation results revealed that the composite structure begins to approach its elastic threshold, especially on the non-impact (transverse) side, resulting in significantly increased strain levels. The GRRP laminate demonstrated reliable elastic performance in the impact direction, whilst exhibiting vulnerability to transverse deformation under high-energy loading. These findings confirm the effectiveness of the GRRP structure under low-to-moderate impact conditions and suggest the need for reinforcement in the opposite direction, to improve transverse resilience at higher speeds. Overall, this study underscores the value of combining experimental testing and numerical simulations to understand the mechanical behaviour of hybrid composite structures and guide structural design improvements for traditional boat hulls.

Keywords: composite laminate structure; impact response; finite element analysis; *Jaloe Kayoh* traditional boat

INTRODUCTION

Traditional boats used by coastal communities around the world reflect a rich diversity of local traditions, functional requirements, and cultural values. Each vessel embodies unique craftsmanship, locally available materials, and philosophies passed down through generations, resulting in innovative forms of maritime design. For instance, the *Dhow* boats on the Middle East and East African coasts are recognised for their distinctive triangular lateen sails [1]. In the Arctic, the Inuit *Kayaks* are highly adapted to harsh environmental conditions and are traditionally constructed from wooden or whalebone frames covered with sealskin [2]. The *Hokule'a* canoes of Hawaii and Polynesia were instrumental in long-distance Pacific migrations, relying on celestial navigation techniques that used stars, winds, and ocean currents [3]. In Scandinavia, Viking longboats—with their slender hulls and dual rows of oars—were designed for speed and versatility and capable of navigating both open seas and shallow coastal waters [4]. In West Africa and the Caribbean, the *Pirogue* is a multipurpose vessel often carved from a single log and decorated with vibrant, symbolic ornamentation [5]. Traditional boats in Asia hold substantial historical and cultural value because coastal communities have adapted to their environments and developed distinctive vessel designs. The *Sampan*, widely used across China and Southeast Asia, has long served as a utility boat for rivers and shallow coastal waters [6]. Its design has evolved through regional influences and local maritime techniques [7]. The *Jukung*, which originates from Bali and Lombok in Indonesia, features twin outriggers (stabilisers) on both sides, providing excellent stability when navigating waves and shallow areas [8]. In the Philippines, the *Banca* (or *Bangka*) also incorporates dual outriggers to enhance balance. Modern adaptations have equipped the *Banca* with outboard motors to improve its propulsion efficiency, although many of these motors are still operated manually with oars [9]. The *Jong*, a traditional Malay vessel, was historically used for long-distance maritime trade, extending into India and China. Built from durable hardwood, the *Jong* was capable of withstanding strong ocean currents, making it a reliable vessel during the Nusantara kingdom era [10].

The *Jaloe Kayoh* is a traditional Acehnese rowing boat, handcrafted from solid woods, such as Meranti, Damar, and Ulin, and often adorned with traditional Acehnese carvings. Characterised by its elongated and narrow hull, the *Jaloe Kayoh* is well-suited for manoeuvring in rivers and shallow waters. Due to the abundance of marine resources in Aceh, this vessel has played a vital role in the daily lives of coastal populations. However, several challenges exist in its current form. The absence of standardised design criteria, combined with its narrow structure, limits its transverse stability, particularly in deeper waters and during rough sea conditions. Additionally, the use of dense ironwood makes the boats relatively heavy, which affects their ease of transport. The vessel also demands frequent maintenance due to wear and the increasing cost of high-quality timber has reduced its practicality and affordability for everyday use. The study of traditional boats provides critical insights into hull design, material selection, and hydrodynamic performance. For example, Prabowo et al. [11] analysed the resistance of indigenous Indonesian woods to marine corrosion, while Çamll et al. [12] and Semedi et al. [13] evaluated the stability of Balinese *Jukung* vessels in shallow waters, demonstrating the effectiveness of outriggers for balance. Akhmad et al. [14] examined the structural strength of traditional boat hulls and identified areas that could benefit from reinforcement. Juhl et al. [15] applied Computational Fluid Dynamics (CFD) to optimise a traditional canoe hull design for reduced hydrodynamic resistance. Similarly, Lacsina et al. [9] found that outriggers improved the transverse stability of Philippine *Banca* boats under varying wind and sea current conditions. A study by Kamaruddin et al. [16] showed that the hull design of Malay *Jong* contributed significantly to its efficiency in open sea navigation, supporting its historical role in long-distance trade. These studies highlight how modern analytical tools can be integrated into traditional boat construction to preserve cultural heritage while enhancing structural performance, reliability, and durability in contemporary marine environments.

In this study, the use of E-glass and ramie fibres as reinforcement and polyester resin as the matrix in the laminated composite structure of the *Jaloe Kayoh* traditional boat hull was motivated by the need to withstand harsh marine environments, improve durability, and reduce lifecycle maintenance costs. Traditional wooden boats, commonly used in coastal regions, are highly susceptible to degradation in seawater, including saltwater-induced corrosion and mechanical damage from wave impacts and floating debris, which significantly reduce their service life and increase maintenance demands [17]. In contrast, hybrid composites made from E-glass and ramie fibres offer high tensile strength, superior corrosion resistance, and improved energy absorption under impact loading, thereby enhancing the overall structural performance of the hull [18]. Moreover, the laminated composite configuration allows for the personalised placement of fibre layers throughout the structure, promoting the uniform distribution of impact loads and maintaining structural integrity under varying marine conditions [19, 20]. From an economic and sustainability standpoint, ramie fibres are both renewable and locally available, making them a cost-effective and environmentally friendly reinforcement option [21, 22]. Functionally, the use of lightweight composite materials has contributed to improved vessel stability, increased fuel efficiency, and extended operational range [23, 24]. Therefore, the integration of fibre-reinforced composites into traditional boat construction offers significant advantages, in terms of durability, cost-effectiveness, and operational reliability, while enhancing the vessel's ability to endure the demanding conditions of marine environments.

Recent studies have focused on the development of composite materials for maritime structures, particularly in the redesign of traditional boat hulls to improve their durability and toughness under harsh marine conditions. These efforts often integrate experimental testing with Finite Element Analysis (FEA) to provide comprehensive validation of the mechanical response of composites, particularly strain behaviour under impact loading [25–27]. The findings suggest that laminated composite materials not only perform well under low-velocity impacts [28] but, also, exhibit significant resistance at higher impact energies—performance levels that are difficult to achieve using traditional materials such as wood [29]. Such data can serve as a foundation for designing more impact-resistant hull structures that can be designed specifically for the operational demands of coastal maritime environments. The objective of the present study was to evaluate the impact resistance of a laminated composite structure composed of glass and ramie-reinforced polyester (GRRP) applied to the hull of a traditional *Jaloe Kayoh* wooden boat. The research methodology involves experimental impact testing using a pendulum-driven cement ball, followed by structural simulation using Finite Element Analysis. Strain measurements from the physical tests were used to validate the simulation results. In addition, various loading conditions were applied in the simulations, to assess the structural performance of the GRRP hull under a range of realistic impact scenarios.

METHODOLOGY

This research involves both experimental testing and numerical simulation, to evaluate the impact response of the glass and ramie-reinforced polyester (GRRP) composite laminate used in the hull structure of the traditional *Jaloe Kayoh* boat. Two composite boat wall specimens were fabricated and subjected to controlled impact testing to assess their physical behaviour under dynamic loading, followed by validation through FEA.

EXPERIMENTAL SETUP

The experimental setup involved dropping a 405.1 g concrete ball (7 cm diameter) from a height of 178 cm onto the GRRP laminate, producing an impact velocity of 2.4 m/s. Velocity was measured using a Nikon J5 camera and analysed using a Vernier Logger Pro. Strain gauges (Omega SGD-3/350-LY11) were attached to the composite surface and connected to an NI-9237 data acquisition system. Strain data were recorded at 2 kHz using SignalExpress and each test was repeated at least three times for consistency. This test aimed to evaluate the laminate's response to a sudden impact, which is relevant to marine applications where resistance to localised loading is critical. In parallel, relevant hydrodynamic considerations were drawn from Iqbal [30], who analysed hull performance at various operating speeds. At a forward speed of 4 knots (approximately 2.06 m/s), the study reported a significant increase in the vessel's dynamic response, particularly in the heave, pitch, and roll motions compared to stationary conditions. The Response Amplitude Operator (RAO) analysis showed that this speed influences vertical motion and roll amplitude, with greater sensitivity observed when the vessel has a higher centre of gravity (KG) due to reduced damping. Moreover, wave conditions with natural periods of 2–3 seconds were found to induce resonance, potentially amplifying motion amplitudes and compromising stability. Under beam sea conditions (waves at 90° incidence), the same speed resulted in the highest RAO roll peaks, indicating a critical interaction between wave direction and vessel speed. Iqbal's study concluded that, although 4 knots is generally a safe operational speed for typical Java Sea conditions (wave periods of 3–5 seconds), careful navigation and load distribution are essential for avoiding resonance and maintaining stability. These insights support the experimental framework of the current study by emphasising the importance of impact and motion resistance in small-scale traditional vessels. A schematic of the experimental setup is presented in Fig. 1.

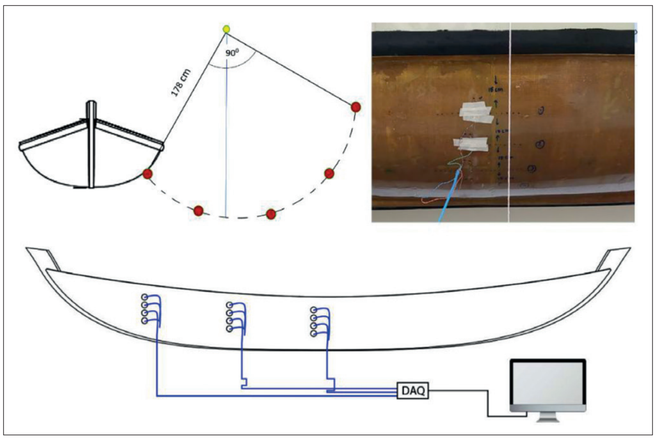

Fig. 1. Schematic view of experimental set-up

FINITE ELEMENT MODELLING

The strain data recorded during each repetition was averaged and compared with the FEA simulation results to validate the model's accuracy and obtain representative values. This data processing also analysed deeper statistics to determine whether the variation in the test results was within accepTable tolerance limits. This method consisted of a ball pendulum impactor system, constructed and employed for simulating the impact point on a boat's hull and often used in impact testing of composite materials, as explained by Reiner et al. [31]. Reiner et al. stated that the repeatability of measurements and average calculations are important in studies involving the dynamic response of materials [32]. The analysis results validated the FEA simulations and ensured that the numerical model predictions followed the experimental results. The simulation phase of this research began with the generation of a computer-aided design CAD model of the hull form for the *Jaloe Kayoh* boat. The obtained 3D model reflected the geometric dimensions of the traditional boat hull used in the experiment, which was moulded from a GRRP laminated composite material. This model was exported to the Abaqus FEA program for impact simulations after the geometry design. The meshing process was applied to the 3D model to divide the whole geometry for more detailed numerical analysis. The mesh size was then gradually tuned to 4.8 mm but the focus was on the influence zone, which plays a critical role in enriching the outcome of the analysis phase. The FEA simulation stages in this study consisted of several systematic steps to replicate and validate the impact conditions on the hull of the traditional *Jaloe Kayoh* boat made of laminated composite GRRP. The simulation process, described below, used the FEA software Abaqus to provide analysis results that are close to the experimental conditions. A geometric boat hull was modelled using CAD software. The boat had a length of 4398 mm, width of 1233 mm, and height of 596 mm, at a scale of 1:1. Furthermore, after the image creation process was saved in STEP format (so that it could be imported into CAE Software), this model was designed to reflect the shape, dimensions, and thickness of the material corresponding to the real specimen, with the composition of GRRP laminate material on the hull structure. The model was precisely designed to ensure that the simulation results reflected the physical response to the original boat hull. The *Jaloe Kayoh* boat design model is shown in Fig. 2.

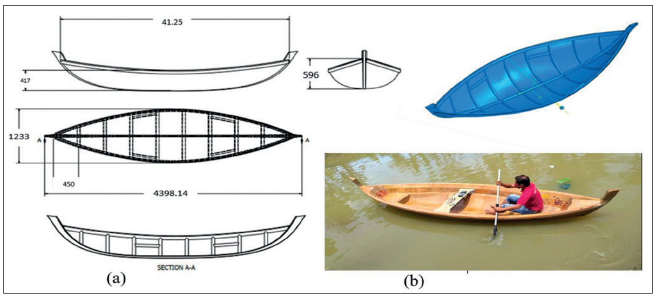

Fig. 2. (a) Jaloe Kayoh Boat Design Model (b) Jaloe Kayoh Products

Following the completion of the geometric model, material properties were assigned to each layer of the GRRP composite laminate. The material properties of both E-glass/polyester and ramie/polyester laminates were sourced from experimental data and validated literature. The detailed material properties are summarised in Table 1. In this simulation, each layer was modelled as being anisotropic, ensuring that the mechanical response corresponded to its specific fibre direction and material composition. The GRRP laminate consisted of an E-glass/polyester layer with a thickness of 0.65 mm and a ramie/polyester layer with a thickness of 1.30 mm. The meshing process was carried out to discretise the geometry into interconnected finite elements suiTable for numerical analysis. To ensure higher accuracy around the impact zone, a locally refined mesh was applied near the contact area. In flatter regions, quadrilateral or hexagonal elements were used; whereas, triangular elements were used in more complex geometries. The selected mesh size for the analysis was 4.8 mm, with refinement concentrated around the impact point to effectively capture localised strain gradients. The meshed models of both the pendulum impactor and the *Jaloe Kayoh* boat section are shown in Fig. 3.

Tab. 1. Material properties of the E-Glass/polyester laminate and ramie/polyester

	E_1 (GPa)	E_2=E_3 (GPa)	ν_{12}=ν_{13}	ν_{23}	G_{12}=G_{13} (GPa)	G_{23} (GPa)
E-Glass/polyester [33]	34.7	8.5	0.27	0.27	4.34	2.83
Ramie–polyester, computed by the Microscale RVE plug-in [34, 35]	10.5	6.3	0.25	0.25	2.78	2.84

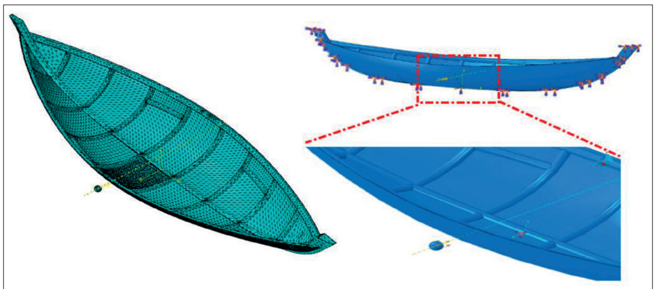

Fig. 3. Meshing pendulum, Jaloe Kayoh boat and boundary conditions

To replicate realistic operational conditions, appropriate boundary conditions were defined by fixing specific regions of the boat hull that represented immovable areas when the vessel was in contact with water. These constraints allowed the simulation to capture realistic deformation and strain distributions during impacts, whilst minimising rigid body motion. The impact load was applied in the form of a prescribed initial velocity, which represented the speed of the concrete ball at the moment of contact with the hull surface. The velocity input was derived directly from the experimental observations and assigned to the designated impact location in the numerical model, as illustrated in Fig. 3. Parameters such as impact velocity, direction, contact position, geometry, and mass properties of the concrete ball were all incorporated into the simulation setup, to ensure accuracy in replicating the physical test conditions. In addition, specific solver settings were configured to support the dynamic nature of the impact analysis. A short time step was used in the explicit dynamic simulation, to improve the precision of capturing rapid changes in stress and strain across the mesh during a transient impact event. These numerical controls maintained the simulation stability and ensured that the peak response of the structure was accurately recorded.

The primary objective of this simulation analysis was to evaluate the stress and strain distribution on the surface of the GRRP composite laminate used in the traditional *Jaloe Kayoh* boat hull. The relationship between stress (σ), elastic modulus (E), and strain (ε) forms the foundation of this analysis, where the elastic modulus varies according to the material properties of each laminate layer, namely E-glass and ramie fibres. Modelling the laminate using these layer-specific properties yields a more accurate representation of its mechanical behaviour. Using this constitutive relationship, stress distributions were computed across mesh elements and not only at the point of impact and the surrounding regions, where stress wave propagation induces secondary strain. The simulation assumed a linear elastic material model, as described in [36], which is appropriate for studying laminate behaviour under impact loading conditions before the onset of permanent deformation. This model assumed a proportional relationship between stress and strain within the elastic regime of the material.

To validate the FEA model, strain data were recorded in physical impact tests using strain gauges placed around the impact zone. The experimental results were then compared with the simulation output, to evaluate the accuracy of the numerical model. The impact tests were performed at five distinct velocities: 2.4 m/s, 4.4 m/s, 6.4 m/s, 8.4 m/s, and 10.4 m/s, to assess the influence of impact speed on the stress–strain response of the GRRP laminate. These variations allowed the model to simulate a range of dynamic impact conditions which were representative of real-world scenarios. The impact force generated by the concrete ball was derived from its mass (0.4051 kg), rope length (178 cm), and release angle (90°), resulting in an initial velocity of 2.4 m/s. The initial potential energy of the ball was calculated using Eq. (1):

$$E_p = mgh \quad (1)$$

where *m* is the mass of the ball, *g* is the gravitational acceleration, and *h* is the drop height.

The impact force was further estimated based on Newton's Second Law, considering deceleration during contact. The stress results were extracted from the mesh elements located in and around the impact region, to evaluate how the material reacts at different impact speeds. These results were then directly compared to experimental strain gauge data for model validation. Throughout the simulation, the modulus of elasticity used in each element was assigned based on the specific fibre-reinforced layer (E-glass or ramie) and the stress results were interpreted within the linear elastic domain. This simulation approach follows the methodology found in the classical mechanics of laminated composites [37] and provides a reliable prediction of how GRRP laminates respond to dynamic impacts. After the simulation, the stress and strain distributions at various nodes were recorded for each impact velocity. These values were then analysed and matched with the corresponding experimental data, with a particular focus on the strain distribution around the impact zone. The results offer insight into the mechanical performance of GRRP composites under impact and provide a valuable basis for future improvements in the composite design of traditional vessel hulls.

MESH CONVERGENCE

A mesh convergence study was conducted to determine the optimal element size for the FEA of the GRRP composite laminate structure. The goal was to ensure that further mesh refinement would not significantly affect the simulation results, thereby balancing the computational efficiency and accuracy. In this study, the total number of elements was varied across four levels: 59,960, 68,476, 73,770, and 81,535 elements. For each mesh configuration, the maximum strain values were extracted from four critical nodes (Node 1 to Node 4) near the impact area. As shown in Fig. 4, the results indicate that the strain values begin to stabilise beyond approximately 73,770 elements, with only marginal differences observed when increasing to 81,535 elements. This behaviour demonstrates that mesh convergence was achieved at approximately 73,770 elements, beyond which further refinement had a negligible impact on the accuracy of strain predictions. Therefore, an element distribution of approximately 73,770 elements was selected for all subsequent simulations to ensure computational efficiency but without compromising the fidelity of the results.

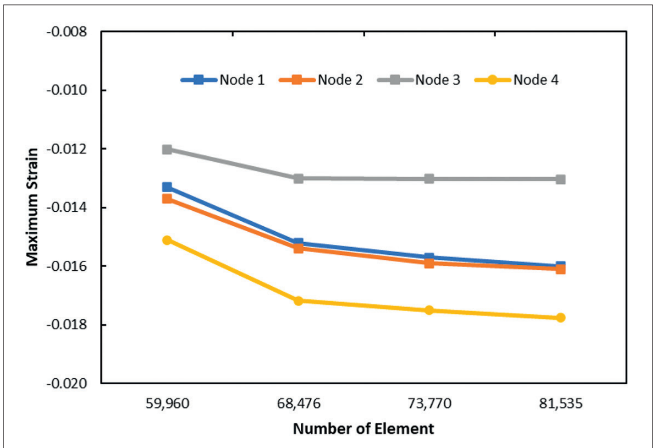

Fig. 4. Mesh convergence study results

RESULTS AND DISCUSSION

An impact testing approach was implemented using a pendulum-driven concrete ball to assess the structural response of the GRRP composite laminate applied to the *Jaloe Kayoh* traditional boat hull. Finite Element Analysis was conducted in parallel, to simulate the same impact conditions and to compare the resulting strain values. The primary objective was to investigate how increasing impact velocities influence the strain behaviour on the composite surface and to validate the reliability of the simulation against experimental data.

The experimental and simulation procedures were performed at an impact velocity of 2.4 m/s. At this baseline speed, the strain values obtained from the physical test were used to validate the FEA model. Upon confirming the strong correlation between the two datasets, additional simulations were conducted at higher velocities of 4.4 m/s, 6.4 m/s, 8.4 m/s, and 10.4 m/s to analyse how increasing impact energy affects the stress and strain distribution in the composite laminate. The experimental results indicate that both tensile and compressive strain responses are present on the laminate surface following impact. These observations were supported by the FEA simulation, which provided consistent strain values at the corresponding impact speeds. The simulation further enabled the exploration of deformation behaviour at higher speeds, which are challenging to replicate experimentally, as noted in prior studies [18, 38]. The simulated results closely matched the experimental data reported in similar studies, thus validating the FEA approach for composite impact analysis [39, 40]. As the impact speed increased, the strain magnitude also increased significantly, especially in the layers directly in line with the direction of impact. Maximum strain values were recorded in both the impact zone and the opposite direction, highlighting the effect of stress wave propagation through the laminate. These trends align with findings from previous research on both synthetic and natural fibre-reinforced composites, which reported increased elastic–plastic responses under high-energy impact conditions [41, 42]. At 2.4 m/s, the measured strain towards the impact was 0.02120, whereas the strain in the opposite direction was −0.00890, indicating localised tension and compression effects. The FEA simulation yielded the same strain values: 0.02120 in the impact direction and −0.00890 in the opposite direction. The calculated deviation between the experimental and simulated data was minimal, with only a 4.7% difference in the impact direction and 1.2% in the opposite direction, demonstrating high agreement and model accuracy, as shown in Fig. 5. These findings validate the effectiveness of the GRRP composite structure in absorbing impact energy and demonstrate that the integration of experimental testing and FEA modelling offers a comprehensive method for analysing the dynamic behaviour of laminated composites used in marine applications.

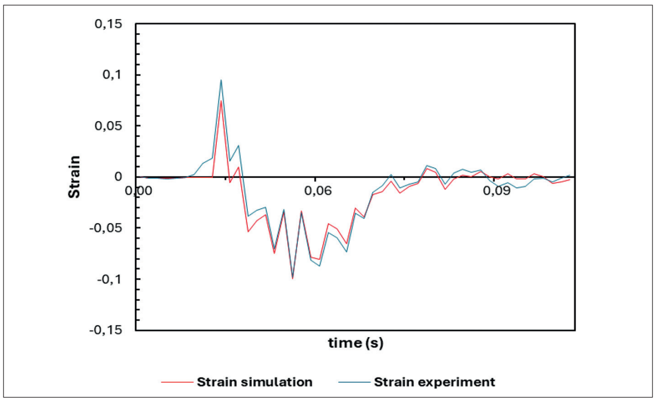

Fig. 5. Experimental and simulation test graphs at a speed of 2.4 m/s

These results demonstrate that the FEA model can reliably estimate the mechanical response of GRRP composite materials under low-velocity impact conditions, with correlation factors (e.g. Scarlett numbers) approaching unity, indicating strong agreement with the experimental data. The accurate prediction of strain behaviour at lower impact speeds confirms the validity of the FEA approach for capturing first-order deformation characteristics of laminated GRRP composites. Prior studies have shown that FEA simulations validated under low-energy impact conditions can be extrapolated to evaluate the structural integrity of composite systems under higher loading scenarios [43]. In this study, the linearity of the composite's response under impact was preserved, confirming that the GRRP laminate behaves predictably within the elastic range. This is an important feature for marine structures such as boat hulls that are frequently exposed to dynamic forces from wave impacts or collisions with submerged objects. The simulation output for the pendulum impact at 2.4 m/s on the *Jaloe Kayoh* boat wall is illustrated in Fig. 6, which visualises the localised deformation pattern and stress propagation across the GRRP laminate.

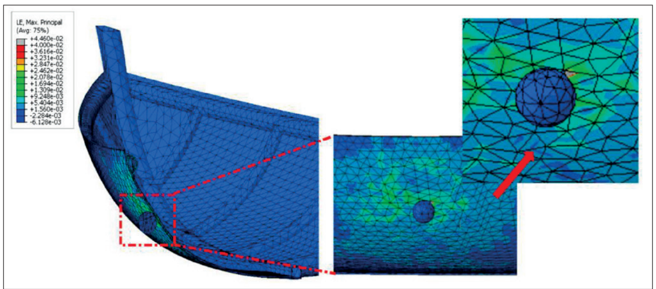

Fig. 6. Strain distribution at a speed of 2.4 m/s

This small deviation, between the experimental and simulation results at low-speed impacts, is sufficient to confirm that the FEA model can reliably represent the actual mechanical behaviour of the GRRP composite. Such minor differences are typically attributed to environmental influences and inherent material variability, which are difficult to fully replicate in numerical models. The previous work by Novak et al. [44] also reported that FEA simulations of hybrid composites, such as GRRP, are generally accurate under low-impact loading, where the stress–strain relationship remains within the linear elastic regime. At 2.4 m/s, the stress distribution in the laminate indicates that the outer E-glass layers absorb most of the impact stress, while the central ramie layer functions as an energy-dissipating zone. This observation supports the intended design of the hybrid composite: the E-glass layers act as structural shields, while the ramie core provides damping capability. This laminate architecture is well suited for boat hull applications, which frequently encounter impacts from wave slamming or collisions with submerged objects.

Further simulations were performed at higher impact velocities: 4.4 m/s, 6.4 m/s, 8.4 m/s, and 10.4 m/s. As the impact speed increased, more noticeable differences emerged in the simulation results, particularly in terms of the stress concentration and distribution within the ramie layer, which became increasingly susceptible to localised deformation. The complete strain data for all impact speed variations, comparing the experimental and simulation outcomes, are illustrated in Fig. 7. At an impact speed of 4.4 m/s, the FEA model recorded a strain of 0.0219 toward impact and −0.0347 in the opposite direction [Fig. 7(a)]. These values suggest that the laminate was still able to distribute the impact energy effectively, with the outer E-glass layer continuing to resist high stress levels, and the ramie layer operating efficiently as a damper without excessive deformation [45]. At 6.4 m/s, the strain increased to 0.0312 toward impact and −0.0949 in the opposite direction [Fig. 7(b)]. The stress concentration became more pronounced in the ramie core, which exhibited lower elastic modulus than the surrounding E-glass layers. This trend aligns with the findings of Chandgude and Salunkhe [46], who reported that natural fibre-based composites typically possess lower elastic thresholds, making them more vulnerable to deformation under increasing loads.

In Fig. 7(c), the simulation results at 8.4 m/s show a strain of 0.0392 in the impact direction and −0.112 in the opposite direction. At this stage, the stress distribution across the laminate becomes increasingly uneven, particularly in the ramie layer. This behaviour indicates a growing risk of delamination or interlayer separation, a well-known failure mode in composite materials subjected to high impact loads—especially those with nonuniform elastic properties between layers [47]. This finding suggests that special attention is required when designing boat hulls using GRRP laminates that are expected to endure medium to high-speed impacts because structural failure may initiate in the form of interlaminar stress buildup.

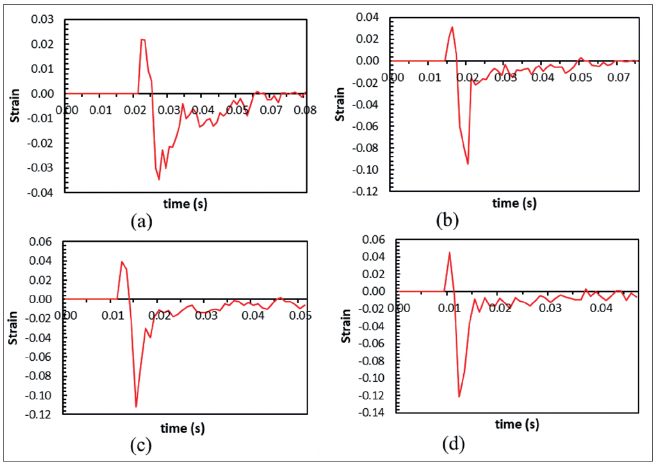

Fig. 7. Simulation test strain data at speeds of (a) 4.4, (b) 6.4, (c) 8.4, and (d) 10.4 m/s

At the highest impact speed of 10.4 m/s, as shown in Fig. 7(d), the FEA simulation yielded a strain value of 0.0449 toward impact and −0.122 in the opposite direction. These elevated strain values suggest that the ramie core layer has reached its critical deformation limit. The stress distribution at this speed reveals a high concentration within the central ramie layer, indicating the onset of significant fibre deformation and potential mechanical failure. At this stage, the likelihood of delamination between the ramie and E-glass layers increases substantially. This is consistent with the findings of [48], who reported that natural fibre composites under high-velocity impacts are prone to microdeformation, fibre rupture, and interfacial delamination, primarily due to the lower elastic modulus of natural fibres. These microfailures lead to energy dissipation through cracking and interlayer separation.

The FEA results of the *Jaloe Kayoh* boat model under progressively increasing impact velocities (4.4 m/s, 6.4 m/s, 8.4 m/s, and 10.4 m/s) are visualised in Fig. 8, showing the stress propagation and deformation zones for each velocity scenario. At the lowest impact speed of 2.4 m/s, the experimental results confirmed that the GRRP laminate structure exhibits a sTable and elastic response to both the impact and its rebound effect. The strain measured in the impact direction was 0.0202, which matches the value predicted by the simulation. This close agreement confirms that FEA can accurately capture the mechanical response of hybrid laminates at low strain rates. These results are in line with studies by Shahirul et al. [49] and Prasad et al. [50], who observed that hybrid composites containing E-glass and ramie fibres maintain structural stability under low-velocity impacts, where the stress–strain response remains within the linear elastic region. However, in the opposite direction from the impact, a noTable discrepancy was observed between the experimental strain (−0.00890) and the simulation result (−0.00879). Although small in magnitude, this difference may point to limitations in the simulation's ability to differentiate between tension and compression behaviours in hybrid composites. As described in [51], laminated composites with heterogeneous elastic moduli across layers, such as the stiffer E-glass and more compliant ramie, can exhibit asymmetric mechanical behaviour, especially under multi-directional stress fields. The tensile and compressive properties of each layer interact differently with the polymer matrix, which may not be fully captured in simplified elastic FEA models.

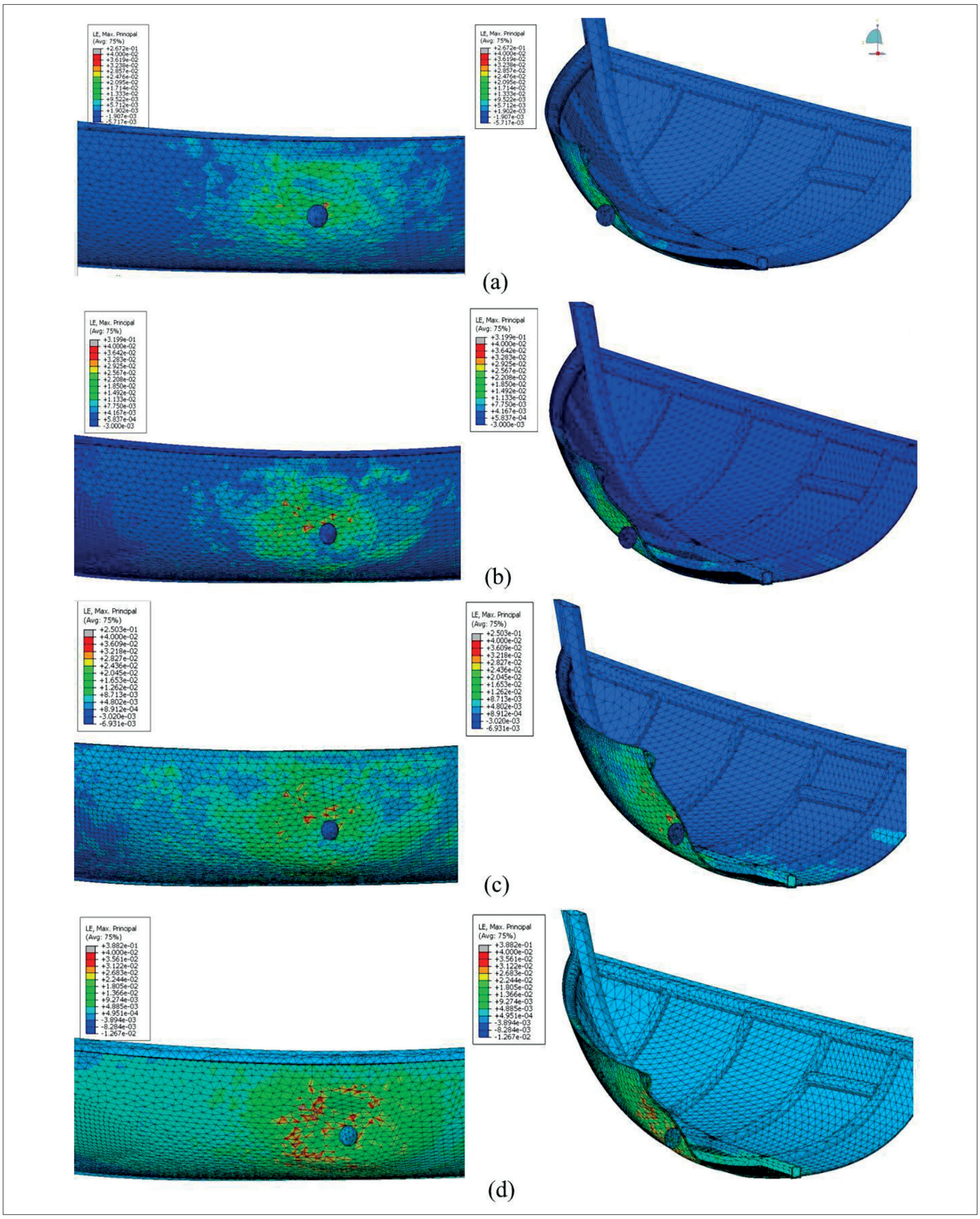

Fig. 8. FEA Simulation image at speeds of (a) 4.4 m/s, (b) 6.4 m/s, (c) 8.4 m/s, and (d) 10.4 m/s

As the impact speed increases, the simulation results reveal a tendency for strain to increase linearly towards impact. However, this linear relationship begins to diverge at higher velocities. For instance, at 10.4 m/s, the simulated strain reached 0.0449, suggesting the onset of non-linear deformation behaviour. This deviation can be attributed to the strain-rate effects that are not fully captured by the current simulation model, which assumes linear elastic material behaviour. In hybrid composites, such as GRRP, the interaction between fibre and matrix becomes increasingly complex under dynamic loading, particularly in natural fibre layers like ramie, which exhibit different mechanical characteristics compared to synthetic fibres such as E-glass [52]. High-speed simulations also show a pronounced increase in deformation, particularly in the direction opposite to the impact direction. For example, at an impact speed of 8.4 m/s, the simulation recorded a strain of −0.112, indicating an imbalance in the stress distribution across the laminate. This phenomenon suggests that differences in the structural resistance of each composite layer become more significant with increasing impact velocity increases [53]. This behaviour can be explained by the contrasting mechanical properties of the constituent fibres. The E-glass outer layers, which have a higher elastic modulus, absorb more of the direct impact energy. In contrast, the middle ramie layer exhibits greater deformation, due to its more compliant nature, primarily due to the increased mobility of natural fibres. As a result, deformation in the opposite direction becomes more significant at higher speeds because ramie does not offer the same level of impact resistance as E-glass [54].

At such high impact speeds, the peak loads are likely to exceed the elastic limit of the GRRP laminate. The simulation data suggest that microstructural damage may begin to occur in multiple directions, particularly in the negative direction, where a strain of −0.122 was recorded. These values imply that the composite layers are approaching their damage threshold and that phenomena such as delamination and matrix debonding may occur due to stress wave interactions at the interface of materials with different moduli [55]. Overall, the results show that, while the GRRP composite exhibits a predicTable and linear mechanical response at low impact velocities, the structure begins to display non-linear effects at higher speeds, including strain-rate sensitivity and the risk of interlaminar failure. These findings underscore the need for more advanced simulation models, such as those incorporating progressive damage modelling or strain-rate dependent material properties, to more accurately predict the behaviour of hybrid laminates under dynamic impact loading.

CONCLUSIONS

This study demonstrated that the GRRP composite laminate structure exhibits strong impact resistance, particularly at low to medium impact velocities. The integration of experimental testing and Finite Element Analysis provided a reliable approach for understanding the mechanical behaviour of the GRRP laminate and validating its performance under dynamic loading conditions. The key conclusions of this study are as follows:

1. The GRRP laminate structure applied to the hull of a traditional *Jaloe Kayoh* boat showed good impact resistance at low speeds (2.4 m/s), particularly towards the pendulum strike. Validation of the FEA model against experimental results at this speed showed high correlation, with only a 4.7% difference in the impact direction and 1.2% in the opposite direction, confirming the model's predictive accuracy under low-energy impacts.
2. At higher impact velocities (10.4 m/s), the laminate structure exhibited elevated strain values, especially in the direction opposite to the impact direction. This indicates that the GRRP composite approaches its elastic limit at higher speeds. While the structure performs well in dispersing impact energy at moderate velocities, it becomes increasingly susceptible to deformation and possible interlaminar stress imbalances under high-speed conditions.
3. To enhance structural resilience at high velocities, it is recommended to consider modifications to the laminate configuration, such as incorporating additional layers or adjusting the material properties, to improve energy absorption and flexibility. This study provides both practical experimental data and validated numerical modelling techniques that can inform future design optimisation of traditional composite boat hulls.

Further research should include simulations under more complex impact scenarios. These investigations will provide deeper insight into the long-term performance and durability of hybrid natural–synthetic composites in maritime applications and offer design recommendations for the next generation of lightweight, impact-resistant traditional vessels.

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