Numerical Studies on Low Velocity Impact Behavior of Monolithic and Layered Material

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Abstract: Low velocity impact is a critical factor in determining the durability and safety performance of structural materials used in various engineering applications, including aerospace, automotive, defense, and civil structures. Monolithic materials, characterized by their uniform composition, and layered materials, which consist of multiple bonded layers of differing properties, exhibit distinct responses under impact loading conditions. This study presents a comprehensive numerical investigation into the low velocity impact behavior of both monolithic and layered materials using finite element analysis (FEA) techniques. The primary objective is to understand the influence of material configuration, geometric parameters, and interface characteristics on energy absorption, and propagation under low velocity impact conditions. The numerical simulations were performed using explicit dynamic solvers in finite element software such as ANSYS LS-DYNA and ABAQUS/Explicit. The findings of this study can inform the development of advanced multi-material systems for critical structural applications where impact resistance is a key requirement**.**

INTRODUCTION

In aerospace and marine applications, structures are often exposed to impact forces and plastic deformations due to operational demands. To develop resilient and efficient designs, it is essential to study impact loads and material response. While a significant body of work has addressed ballistic limit velocity prediction, comparatively fewer investigations have focused on low-velocity impacts, generally defined as those occurring at velocities between0and50 mm/s. Such impacts can arise in situations like vehicle collisions, tool drops, cargo handling incidents, or maintenance-related damage. Nonetheless, analytical models remain of academic interest for predicting structural responses to low-velocity impact events. For instance, Langseth and Larsen applied both analytical and numerical approaches to examine the behaviour of mild steel square plates subjected to blunt circular impacts. Using the virtual energy method, they developed an analytical framework capable of estimating the maximum deflection of plates under impact conditions.

NEED OF THE STUDY

In various situations, such as aircraft engine nacelles, which may be impacted by birds, hailstones, and runway debris, the sandwich plate is continuously exposed to projectile impact. The sandwich panel may sustain damage ranging from a slight indentation on the factsheet to a whole perforation. The ballistic limit is a crucial metric that describes a plate's resistance to projectile contact. The highest bullet velocity that a plate can withstand before being punctured is known as the ballistic limit. This metric offers a numerical assessment of the plate's ability to withstand collisions. The study of perforation and penetration of materials by projectiles has been crucial in understanding the impact behavior of various target materials, particularly for military and engineering applications. This review focuses on key works that examine how different factors—such as material properties, target thickness, and projectile geometry—affect the perforation behavior of targets. The studies selected for this review represent significant contributions to the field, spanning arrange of experimental and predictive methods to understand the interaction between projectiles and targets.

METHODOLOGY

3.1 Creating a Plate

3.2 Applying Boundary conditions

Boundary conditions are essential for identifying and resolving issues in mathematical physics. By providing constraints on the system under analysis, they guarantee that solutions to differential equations are distinct. Boundary conditions, when combined with beginning conditions, give a thorough explanation of the behavior of a system, including its initial state, its changes over time, and its interactions at boundaries. The boundary conditions in this simple example force the value of the simulated physical quantity to take a particular value at the box's edges. To imitate the behavior of an actual physical system, boundary conditions are selected and specified.
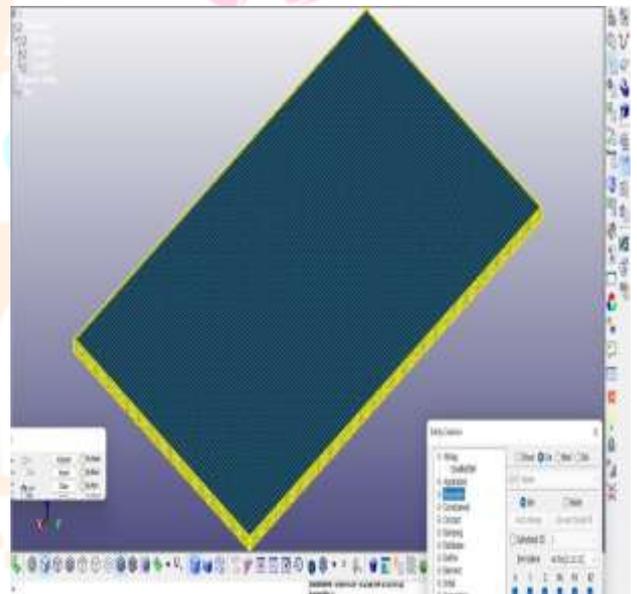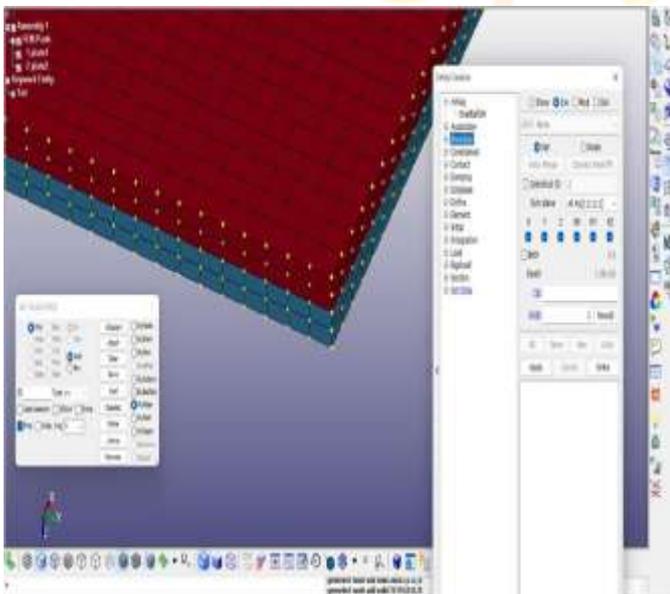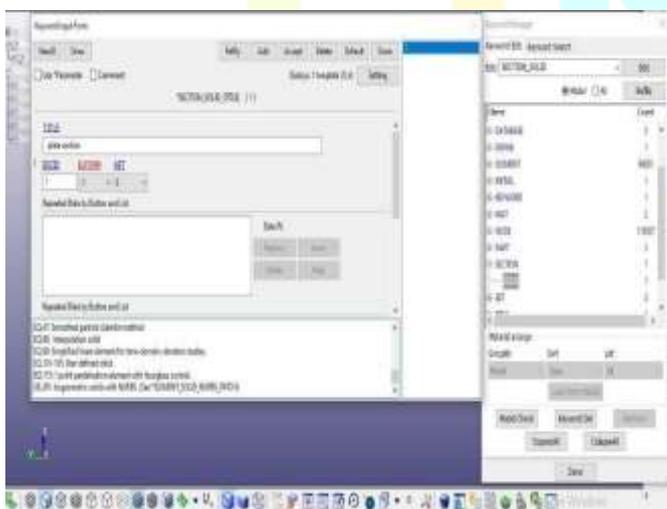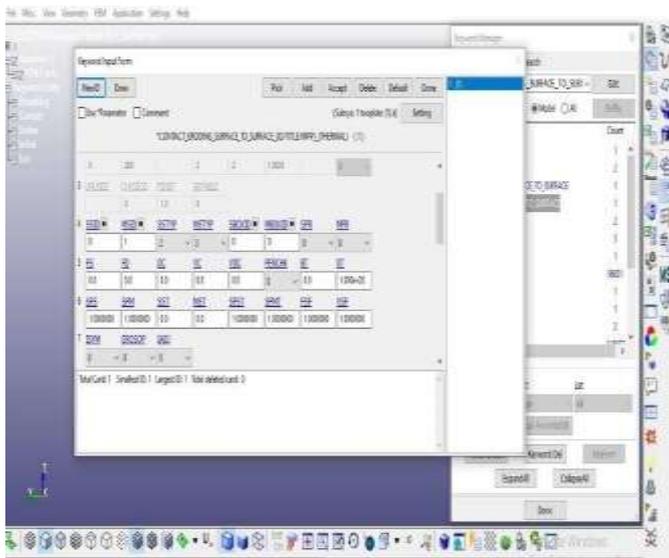

3.3 Section Solid   **3.4 Part Formation**
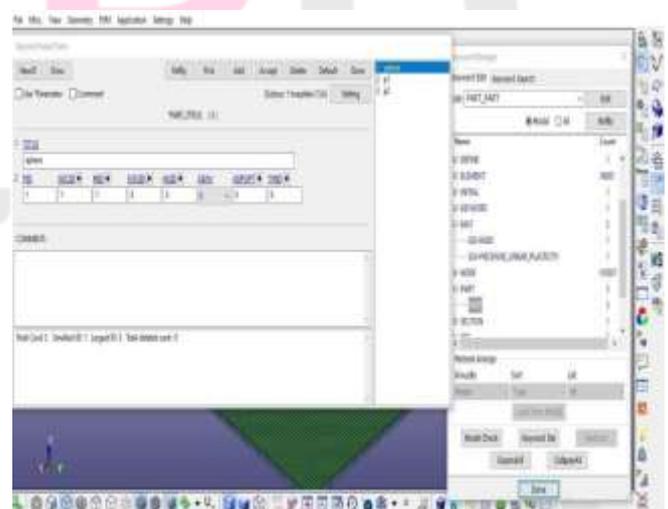
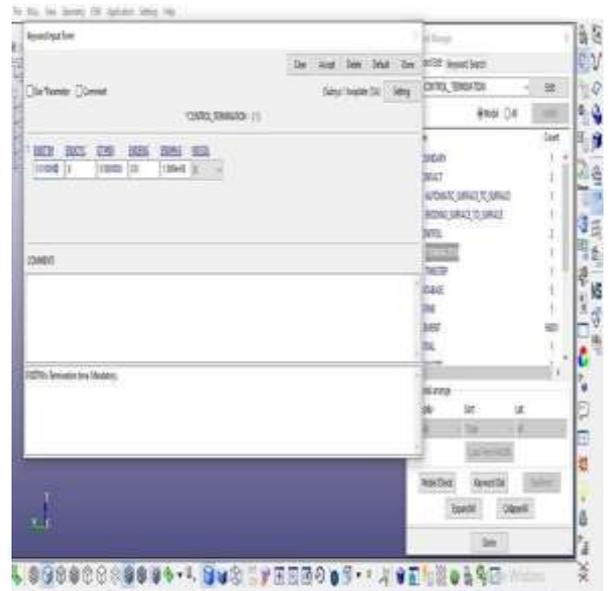**3.5 Contact Eroding Surface to Surface**

3.6 Control Terminations

Table - **Load curve ID or Table**

VARIABLE	DESCRIPTION
CMO:	Centre of mass constraint option, CMO:
EQ.+1:	Constraints applied in global directions,
EQ.0:	No constraints
EQ.-1:	Constraints applied in local directions (SPC constraint)
CON1:,	If CMO=+1.0:
EQ.0:	No constraints,
EQ.1:	Constrained x displacement,
EQ.2:	Constrained y displacement,
EQ.3:	Constrained z displacement,
EQ.4:	Constrained x and y displacements,
EQ.5:	Constrained y and z displacements,
EQ.6:	Constrained z and x displacements,
EQ.7:	Constrained x, y and z displacements.

LCSS: **LOAD CURVE ID OR TABLE**

Effective Stress against Effective Plastic Strain Is Defined By the Load Curve Id. Eps1- Eps8 And Es1-Es8 Are disregarded If defined:

The table ID specifies a load curve ID that shows the stress vs effective plastic strain for each strain rate value. If the strain rate is less than the minimal value, the stress against effective plastic strain curve for the lowest value of strain rate is applied. Similarly, if the strain rate is higher than the maximum value, the stress against effective plastic strain curve for the greatest value of strain rate is utilized. If specified C, P, curve ID, LCSR, EPS1-EPS8 and ES1-ES8 are ignored.

RESULTS AND DISCUSSIONS

In this research, the numerical study was conducted on the low-velocity impact behavior of monolithic and layered material systems demonstrates that increasing the number of plates in a layered configuration significantly enhances structural performance

### SINGLE PLATE DIFFERENT VELOCITY

Force vs. Time
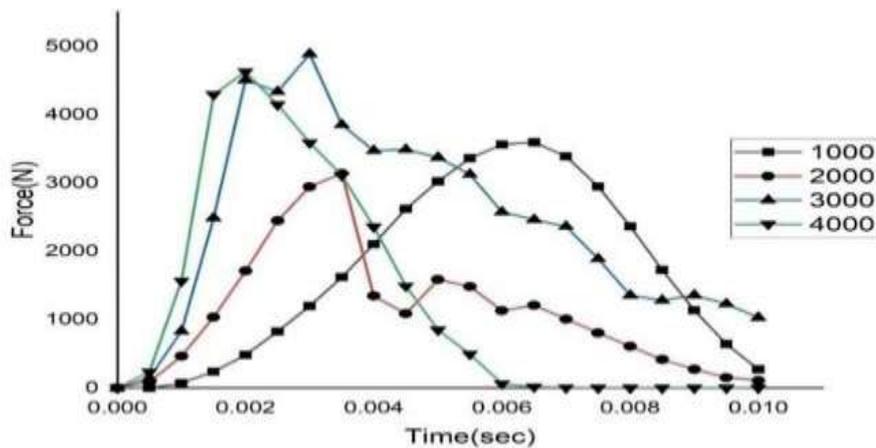
The graph illustrates the relationship between force (in Newton's) and time (in seconds) under four conditions—1000, 2000, 3000, and 4000. Each curve represents a distinct condition, showing how force varies over time for different loads, materials, or speeds. The X-axis corresponds to time, ranging from 0 to 0.01 seconds, while the Y-axis represents force, from 0 to 5000 N. As the conditions increase from 1000 to 4000, the peak force also rises, with the 1000 condition showing the lowest maximum force and the 4000 condition exhibiting the highest. This trend suggests that greater applied forces correlate with higher conditions. Additionally, the time taken to reach maximum force differs for each condition. Higher conditions, such as 4000, display steeper curves, indicating a quicker rise in force and a faster peak, whereas lower conditions, like 1000, show more gradual increases and longer force application durations. The curves' steeper slopes and more rapid declines following the peak in higher conditions suggest faster force application and dissipation, typical of dynamic loading scenarios such as material response analysis or impact testing. Interestingly, failure occurs at3000 and 4000 mm/s velocity, while no failure is observed at 1000 and 2000 mm/s velocities, highlighting the effect of velocity on force behavior and system stability.

Displacement vs. Time
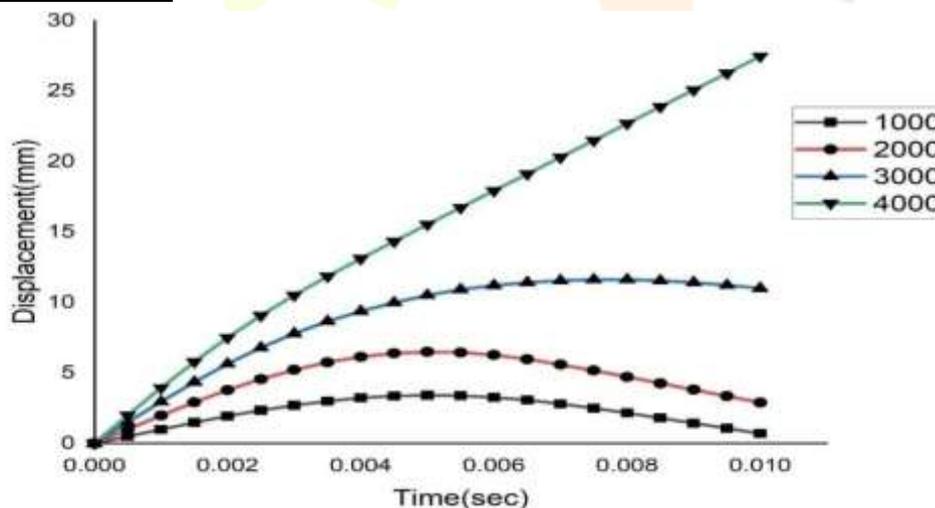
The graph represents the relationship between displacement (in millimeters) and time (in seconds) for four velocities—1000, 2000, 3000, and 4000 mm/s. It shows how displacement changes over a brief period, ranging from 0 to 0.01 seconds, with the Y-axis displaying displacement from 0 to 30 mm. The graph reveals that displacement increases over time for all conditions, but the rate and magnitude of this increase vary. Higher velocities, such as 3000 and 4000 mm/s, produce larger displacements, with 4000 mm/s peaking at around 30 mm, while 1000 mm/s only reaches less than 5 mm. The displacement rise is steeper for higher velocities, as seen in the 3000 and 4000 mm/s curves, while the 1000 and 2000 mm/s curves show slower growth. Lower velocities plateau after an initial rise, suggesting that motion slows or halts, while higher velocities maintain continuous displacement. This likely represents dynamic motion scenarios, such as compression or impact testing, where displacement reflects how an object moves under varying loads. The analysis indicates that higher conditions result in larger, sustained displacements, while lower conditions cause limited motion. Comparing this with the force-time graph, higher forces correspond to larger, longer- lasting displacements, showing how force affects motion and deformation.
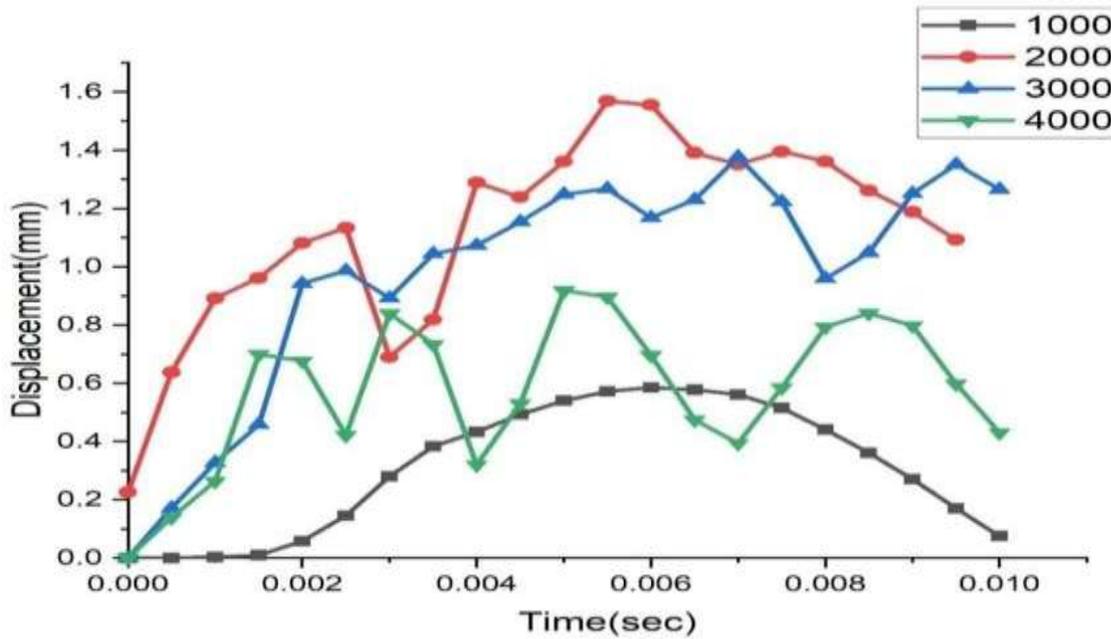
Internal Energy vs Time
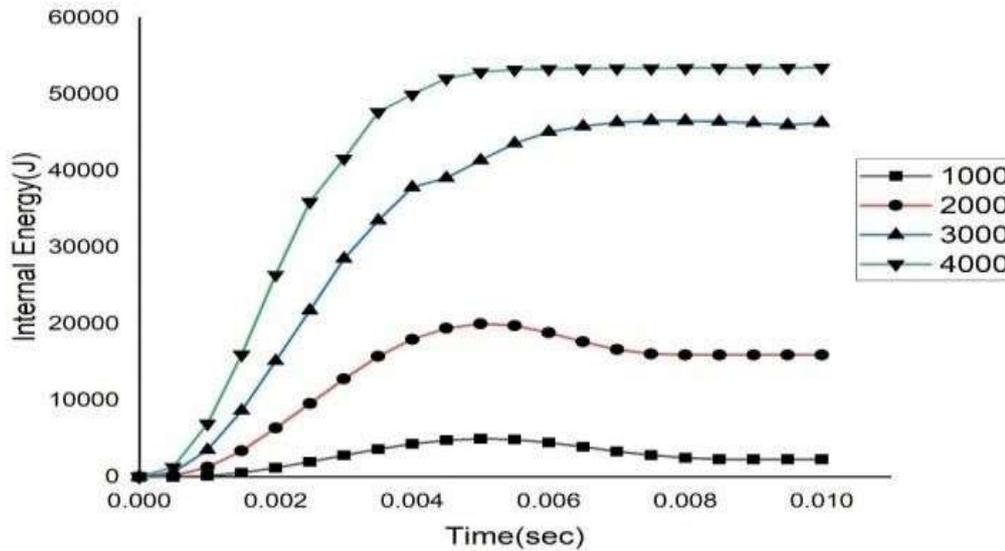
The third graph shows the relationship between internal energy (in joules) and time (in seconds) for systems under four conditions:1000,2000,3000,and 4000 mm/s. The x-axis represents time, ranging from 0 to 0.01 seconds, while they-axis measures internal energy from 0 to 60,000 J. The 1000 series accumulates the least internal energy, peaking at about 10,000 J at 0.004 seconds, followed by a slight drop, indicating energy dissipation. The 2000 series accumulates more energy, peaking at 20,000J,while the 3000 series reaches 40,000 J, showing a sharp rise in energy before stabilizing. The 4000 series absorbs the most energy, reaching about 60,000 J and steadily increasing until stabilization. As the parameter value increases from1000 to 4000, the system absorbs more energy, with steeper accumulation curves indicating more significant stress and deformation. Higher parameter systems, such as 4000, store more energy, potentially risking fatigue, while lower systems, like1000, show better energy dissipation, reducing the risk of material failure.
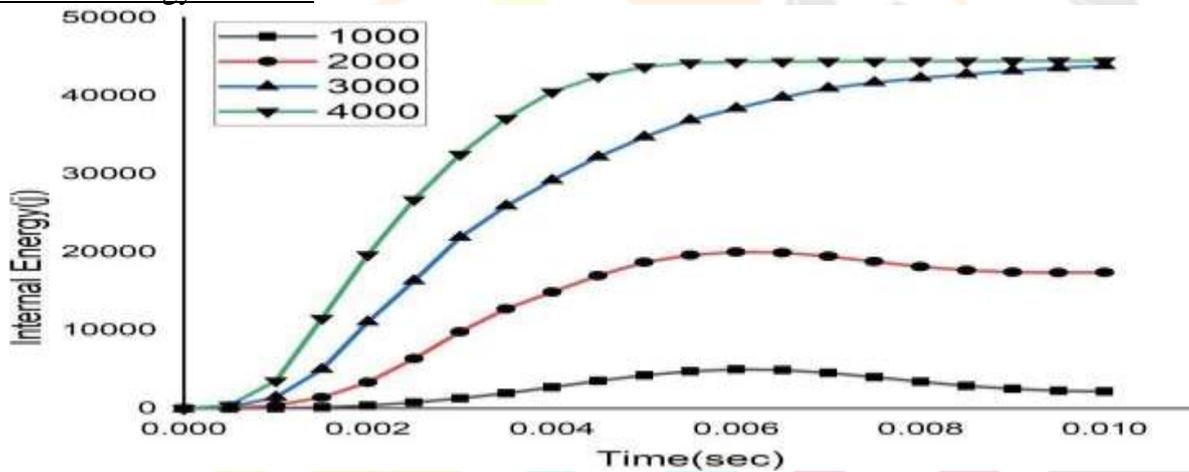
Two plates at different velocities
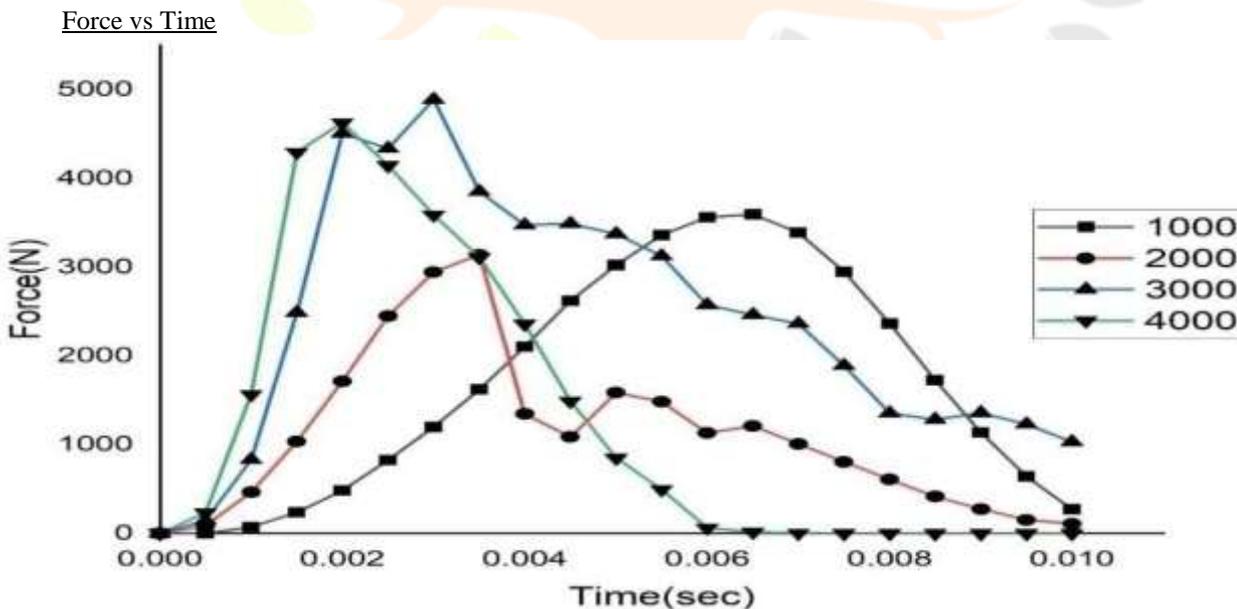
Force vs Time

The graph depicts the relationship between force (in Newton's) and time(in seconds) for four conditions—1000, 2000, 3000, and 4000 mm/s—shedding light on how force behaves under dynamic loading scenarios like impact or quick force applications. The x- axis represents time from0to 0.01seconds,while the y-axis measures the applied force from 0to5000N. In the 1000 condition, the force increases gradually to a peak of 2500N at 0.005 seconds, then drops steadily, indicating a slower rate of application and dissipation. The 2000 condition shows a steeper rise to 3500 Nat 0.003 seconds, with a quicker decline, while the 3000 condition reaches 4500N at 0.003 seconds, with a sharper rise and fall. The 4000 condition reaches the highest peak of 5000 N in the shortest time (around 0.0025 seconds), with a rapid rise and dissipation. As the velocity increases, the rate of force application becomes steeper, with higher conditions achieving greater peak forces and shorter peak times. The displacement graph, showing material deformation over time, follows a similar trend, with lower conditions (1000) exhibiting more stability and less displacement than higher conditions (3000 and 4000), which show more significant displacement and instability. This suggests that systems with higher velocities experience More significant stress and potential fatigue, while those with lower velocities offer better resistance to deformation.

Displacement vs Time

The graph illustrates the relationship between internal energy (J) and time (seconds) under four conditions -1000, 2000,3000, and 4000 mm/s velocities .The X-axis shows time, ranging from 0 to 0.01 seconds, while the Y-axis represents internal energy, peaking at 50,000 Joules. In the 1000 mm/s condition (black squares), internal energy gradually increases to about 10,000 J in 0.005 seconds before stabilizing, indicating energy absorption and equilibrium. In the 2000 mm/s condition (red circles), energy rises more steeply, peaking at 20,000 J by 0.004 seconds before stabilizing. The 3000 mm/s condition (blue triangles) sees a faster rise in energy, reaching 40,000 J in 0.003 seconds. Finally, the 4000 mm/s condition (green inverted triangles) exhibits the quickest and most significant energy rise, peaking at almost 50,000 J in just 0.0025 seconds before stabilizing, indicating highly efficient energy absorption and dissipation

Internal Energy v/s Time

The graph illustrates the relationship between internal energy (J) and time (seconds) under four conditions -1000, 2000,3000, and 4000 mm/s velocities .The X-axis shows time, ranging from 0 to 0.01 seconds, while the Y-axis represents internal energy, peaking at 50,000 Joules. In the 1000 mm/s condition (black squares), internal energy gradually increases to about 10,000 J in 0.005 seconds before stabilizing, indicating energy absorption and equilibrium. In the 2000 mm/s condition (red circles), energy rises more steeply, peaking at 20,000 J by 0.004 seconds before stabilizing. The 3000 mm/s condition (blue triangles) sees a faster rise in energy, reaching 40,000 J in 0.003 seconds. Finally, the 4000 mm/s condition (green inverted triangles) exhibits the quickest and most significant energy rise, peaking at almost 50,000 J in just 0.0025 seconds before stabilizing, indicating highly efficient energy absorption and dissipation.

FOUR PLATES AT DIFFERENT VELOCITY
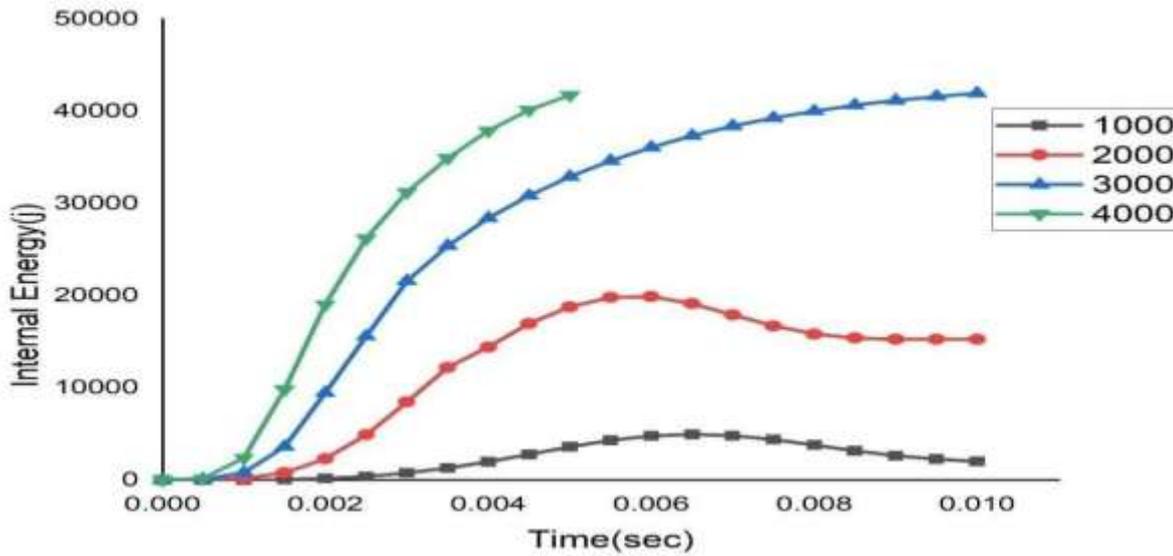
Force vs velocity
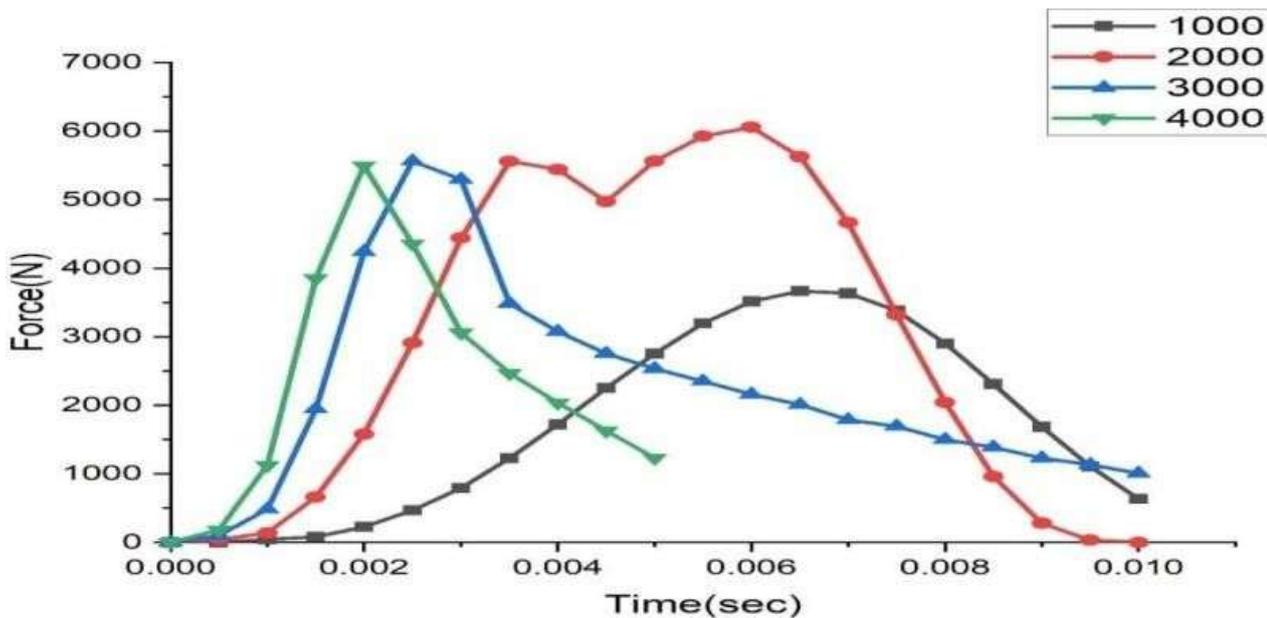
The graph depicts the relationship between Force (N) and Time (seconds) for four conditions—1000, 2000, 3000, and 4000. It illustrates the dynamic response of a system under varying applied loads or impact velocities, with the X-axis representing time (0 to 0.01 seconds) and the Y-axis indicating force (in Newton's). Condition 1000 shows a gradual force buildup, peaking at about 3000 N at 0.006 seconds before dropping to zero. In condition 2000, the force reaches 6000 N at 0.004 seconds and then sharply declines. Condition 3000 sees a peak of 5000 N at 0.003 seconds, with rapid dissipation to zero by 0.007 seconds. The steepest rise occurs in condition 4000, peaking at 4000 N in just 0.002 seconds before quickly dissipating. As the condition values increase, the force application period becomes shorter, and the rate of force buildup accelerates. Higher conditions lead to faster force application and quicker dissipation, indicating effective but localized energy handling. This behavior demonstrates how materials respond differently to varying force levels and the efficiency of energy.

Displacement vsTime
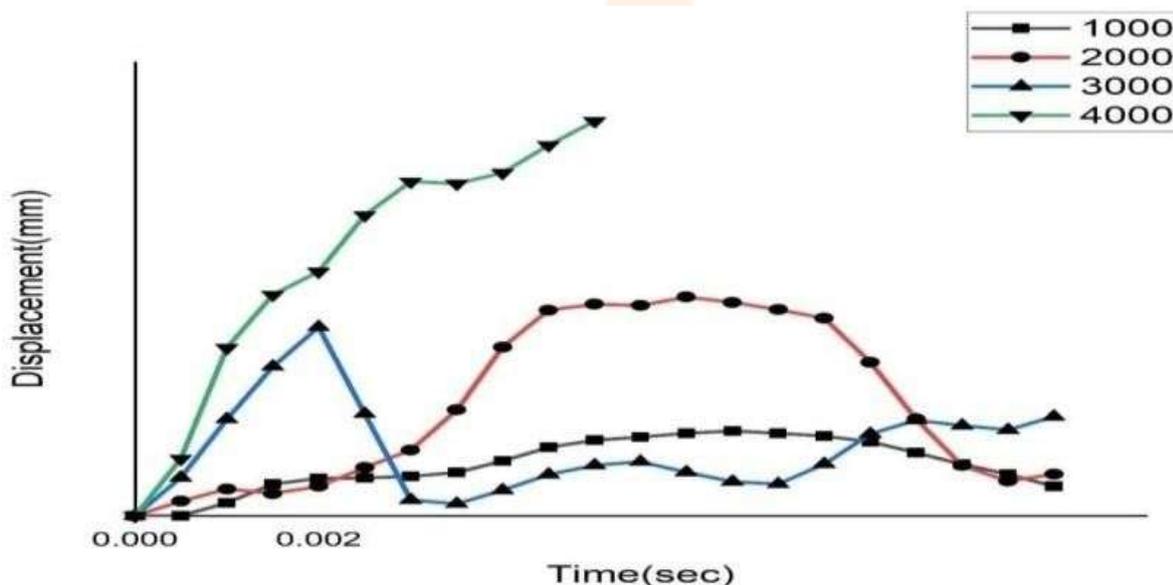
The graph depicts the relationship between displacement (in millimeters) and time (in seconds) under four conditions—1000, 2000, 3000, and 4000—highlighting how a system or material's displacement evolves under varying dynamic circumstances such as applied loads or velocities. The X-axis represents time, from 0 to 0.01 seconds, reflecting the rapid nature of events in dynamic studies like stress or impact tests. Displacement trends differ across the conditions. In Condition 1000, displacement increases gradually, peaking at approximately 0.7 mm at 0.006 seconds, suggesting a slower and more stable response. For Condition 2000, the displacement curve is steeper, reaching a peak of 1.5 mm at 0.005 seconds before steadily decreasing, indicating a more dynamic response. Condition 3000 exhibits the most rapid displacement, peaking at 1.2 mm at 0.003 seconds and sharply declining to zero.

Internal energy vs. Time

The graph illustrates how internal energy (measured in joules) changes with time (in seconds) for four conditions: 1000, 2000, 3000, and 4000. It compares the internal energy variations over a short period under different intensities of applied forces, such as pressures or loading rates. The X-axis, ranging from 0 to 0.01 seconds, reflects the quick, dynamic nature of the process, while the Y-axis shows the accumulated internal energy, reaching up to 50,000 joules. For condition 1000, the internal energy gradually increases, peaking at around 12,000 joules at 0.007 seconds before stabilizing. Condition2000 shows a steeper rise, reaching 18,000 joules at 0.004seconds, followed by stabilization. In condition 3000, energy climbs rapidly, peaking at 40,000 joules before stabilizing, while condition 4000 shows the highest increase, peaking at 50,000 joules at 0.003 seconds. The data indicates that more significant conditions, such as 3000and4000,exhibit faster energy accumulation, highlighting more intense processes and larger input forces

1000 VELOCITY AT DIFFERENT PLATES

Force vs Time
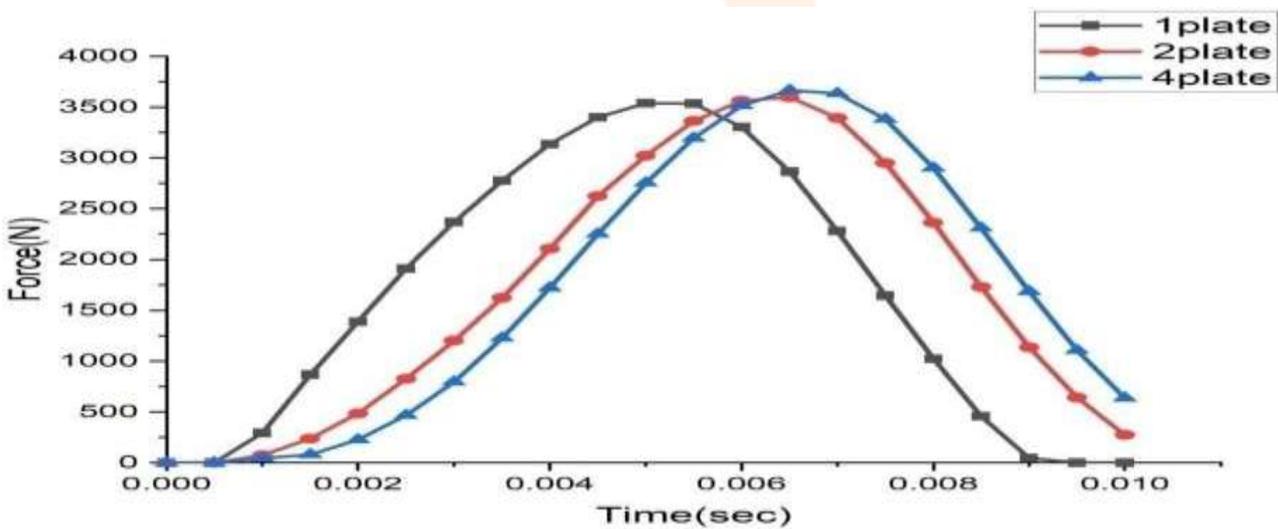
The graph illustrates how the number of plates in a system affects energy absorption during dynamic loading conditions at various speeds. It shows the fluctuation of force(N) with time (seconds) for one-plate, two-plate, and four-plate configurations. The Y-axis represents the force magnitude, with the four-plate setup peaking above 20,000 N, and the X-axis shows the time range from 0 to 0.01 seconds. For the one-plate system (black squares), the peak force reaches around 6,000 N at 0.004 seconds, with a symmetric rise and fall. The two-plate design (red circles) exhibits a lower peak force of about 4,000 N, with a broader curve and slower force variation. The four-plate system (blue triangles) reaches the highest peak force, exceeding 20,000 N at 0.005 seconds, with a sharp rise and longer duration. As the number of plates increases, peak force rises, and the system's load-bearing capacity improves. The four-plate arrangement is best for high-stress applications, while the single-plate design suits less demanding conditions

Displacement vs. Time
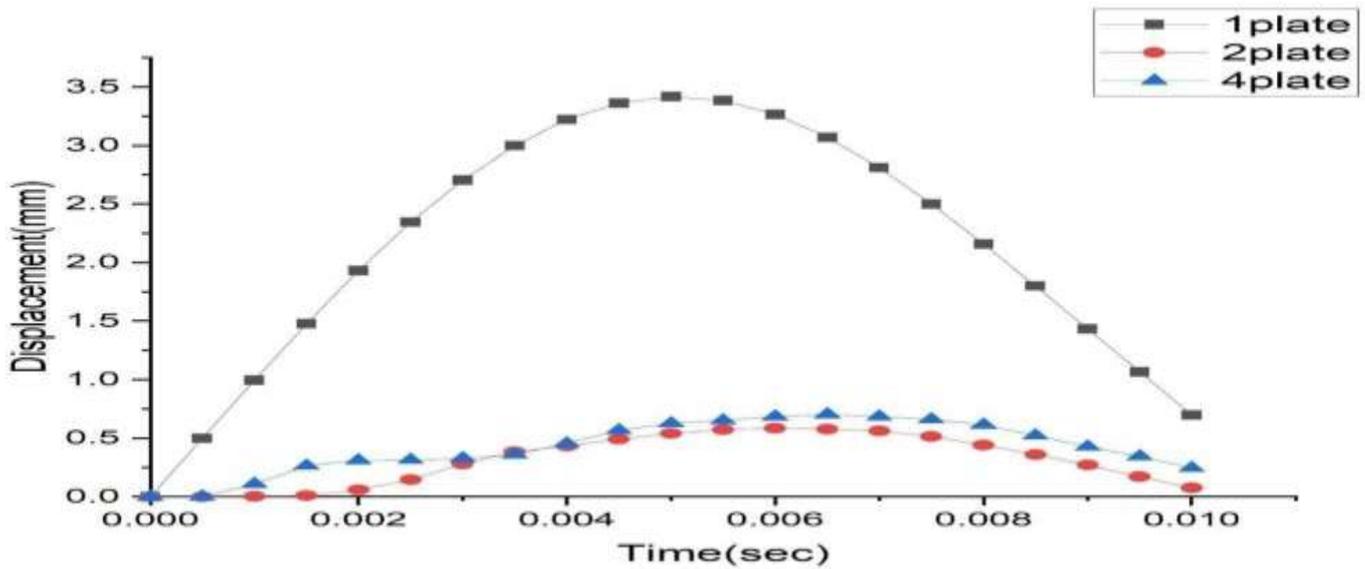
The graph illustrates the relationship between displacement (mm) and time (seconds)for systems with one, two, and four plates under conditions marked 1000, 2000, 3000, and 4000. The X-axis represents time, ranging from 0 to 0.01 seconds, reflecting the quick nature of the analyzed processes. The Y-axis shows displacement, with the peak displacement for one-plate setups reaching approximately 3.5 mm, while systems with more plates exhibit progressively smaller displacements. The one-plate design shows the most significant displacement, peaking at3.5 mm at 0.005 seconds, with a sharply rising and gradually declining curve, indicating an elastic response but lower structural rigidity. The two-plate configuration reduces the displacement to about 0.75 mm, reflecting improved structural integrity and resistance to deformation, as shown by its flatter and more stable curve. The four-plate setup results in minor displacement, peaking at roughly 0.5 mm, and exhibits the most stable curve with minimal changes over time, indicating better rigidity and energy absorption. As the number of plates increases, displacement decreases, with the most significant displacement occurring at 0.005 seconds for all configurations. The symmetry of the curves suggests that all systems behave elastically, returning to their initial state after deformation

Internal Energy vs Time
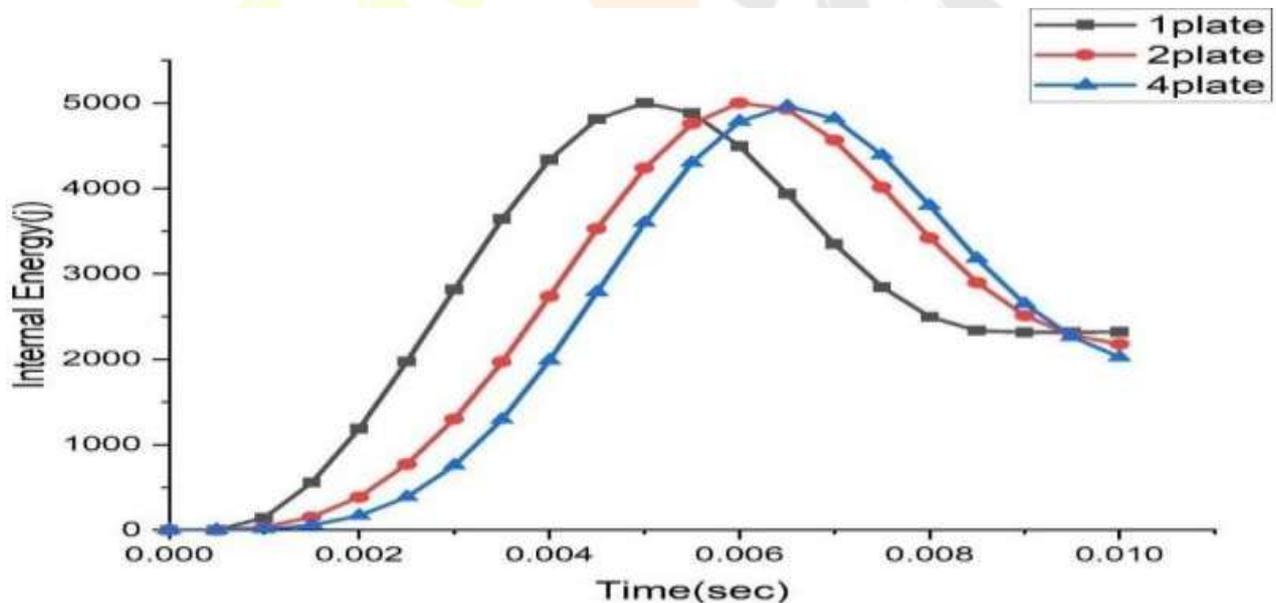
The graph illustrates the relationship between internal energy (measured in Joules) and time (measured in seconds) for one-plate, two-plate, and four-plate systems under similar loading conditions. It highlights how the internal energy changes over time and how adding more plates affects energy dynamics. The Y-axis shows internal energy, peaking at around 5000 Joules for the one-plate setup, while the X-axis represents time, ranging from 0 to 0.01 seconds. The single-plate system exhibits the highest internal energy, reaching about 5000 Joules at 0.005 seconds, with a sharp rise and slow decline. The two-plate system peaks at around 4500 Joules, and the four-plate system shows the lowest internal energy, peaking at approximately 4000 Joules. This trend indicates that adding more plates increases structural resistance, reducing energy absorption. The peak energy for all configurations is reached at0.005 seconds, with each curve displaying elastic behavior.

2000 VELOCITY AT DIFFERENT PLATES
Force vs Time
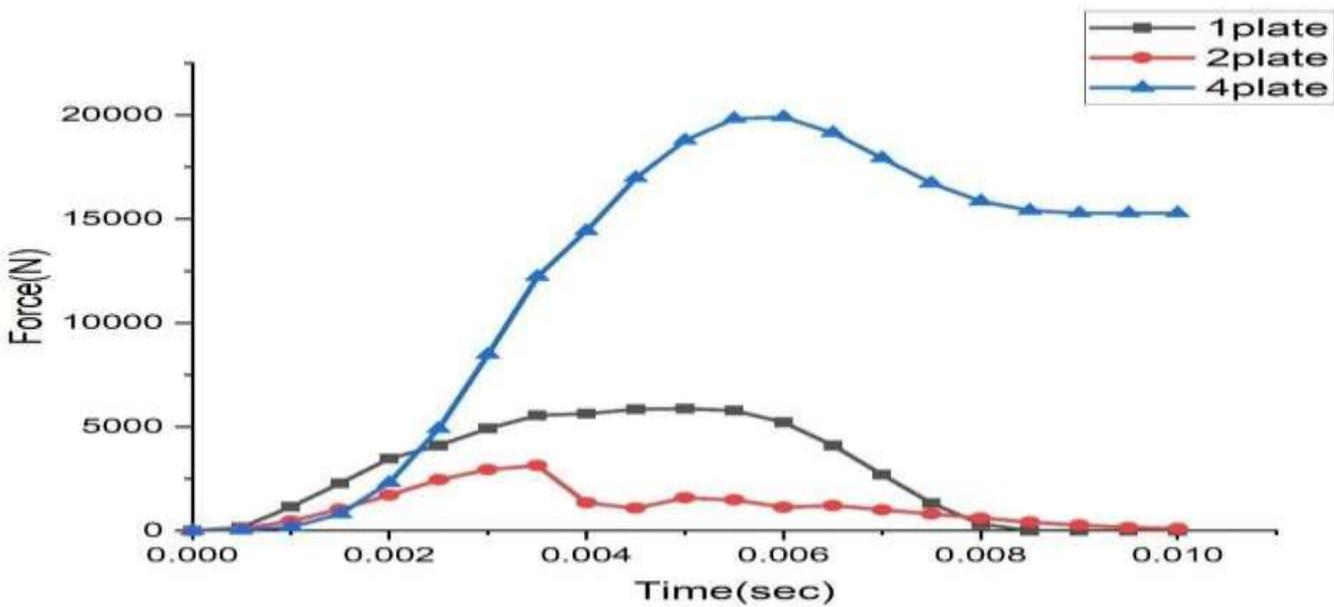
The graph illustrates the dynamic response and force transmission characteristics for systems with one, two, and four plates under applied loads over a brief time interval(up to 0.01 seconds). The Y-axis shows force, with the one-plate system experiencing a peak force of over 6,000 N at 0.0035 seconds, followed by oscillations during unloading, indicating instability. In contrast, the two-plate system shows a smoother force drop, peaking at about 5,000 N at 0.004 seconds, with moderate oscillations. The four-plate system has the lowest peak force, around 4,000 N, at 0.004 seconds, followed by a steady decline, suggesting superior energy absorption and structural stability. The analysis shows that as the number of plates increases, the peak force decreases, and the time to peak force slightly increases, reflecting better load distribution. The four-plate system is the most stable and ideal for applications requiring steady force transfer and energy dissipation, while the two-plate system offers a balanced performance.

Displacement vsTime
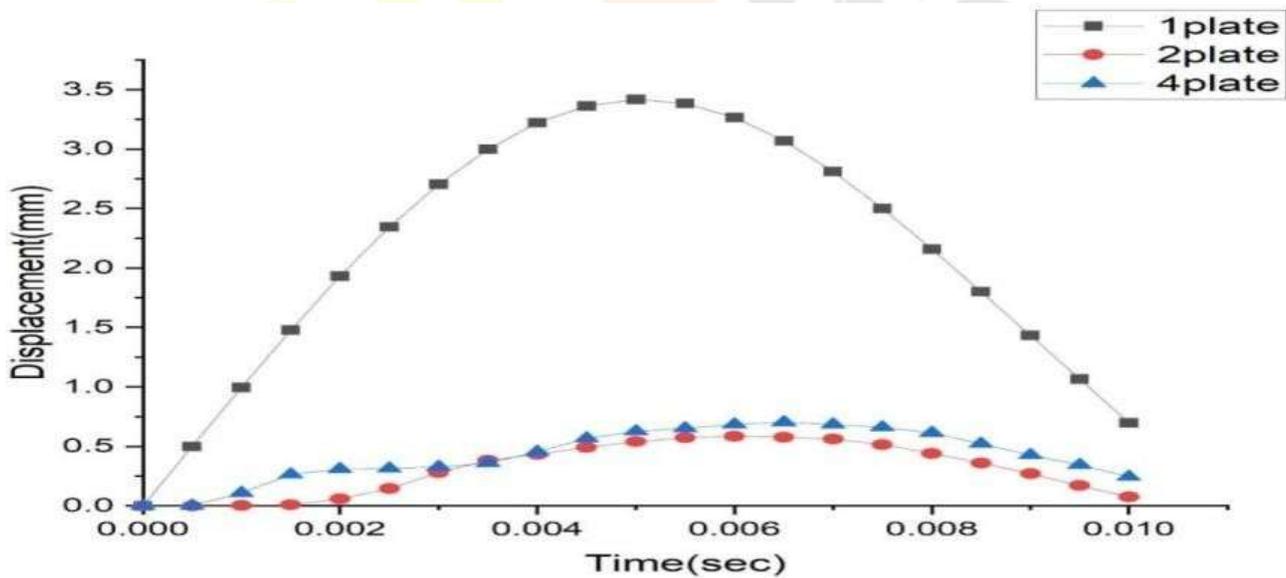
The graph illustrates show the number of plates in a system influences displacement under dynamic loading conditions. It compares systems with one, two, and four plates, showing displacement in millimeters on the Y-axis and time in seconds on the X-axis. The one-plate system experiences the most significant displacement, peaking at 6mm at 0.005seconds, with a broad, symmetric curve indicating substantial deformation. The two-plate system shows are deuced displacement of 1.5 mm, while the four-plate system experiences the least displacement, peaking at around1mm,with an arrow curve and quicker recovery. As the number of plates increases, displacement decreases, signaling increased stiffness and reduced deformation. All systems reach peak displacement between 0.004 and 0.005 seconds. With its more significant displacement, the one-plate system is more flexible but less rigid, making it suitable for lower-stress situations. In contrast, the four-plate system offers excellent stability and resistance to deformation, making it ideal for high-stress applications.

Internal Energy vs Time
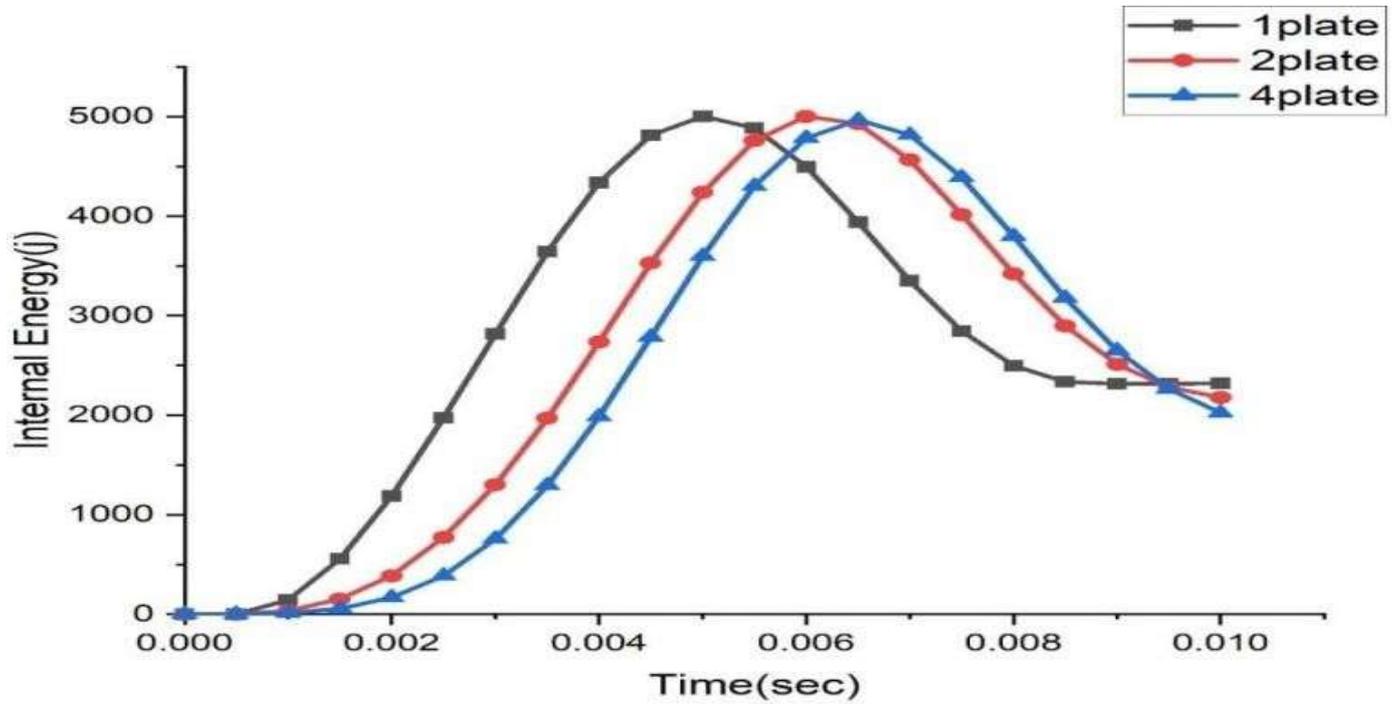
The graphs provide insights into the structural reaction and dynamic performance under applied loads by examining displacement and force behavior overtime for systems with one, two, and four plates. The left panel shows displacement for these configurations, revealing that the one-plate system experiences the most deformation, with a peak displacement of about 6.5 mm at 0.004 seconds, indicating low structural rigidity. The two-plate system exhibits a reduced peak displacement of around 1.5 mm at 0.005 seconds, signifying improved stability and rigidity. The four-plate arrangement shows the least displacement, peaking at approximately 1 mm, reflecting high structural rigidity and resistance to deformation.

3000 Velocities at Different Plates

Force vs Time
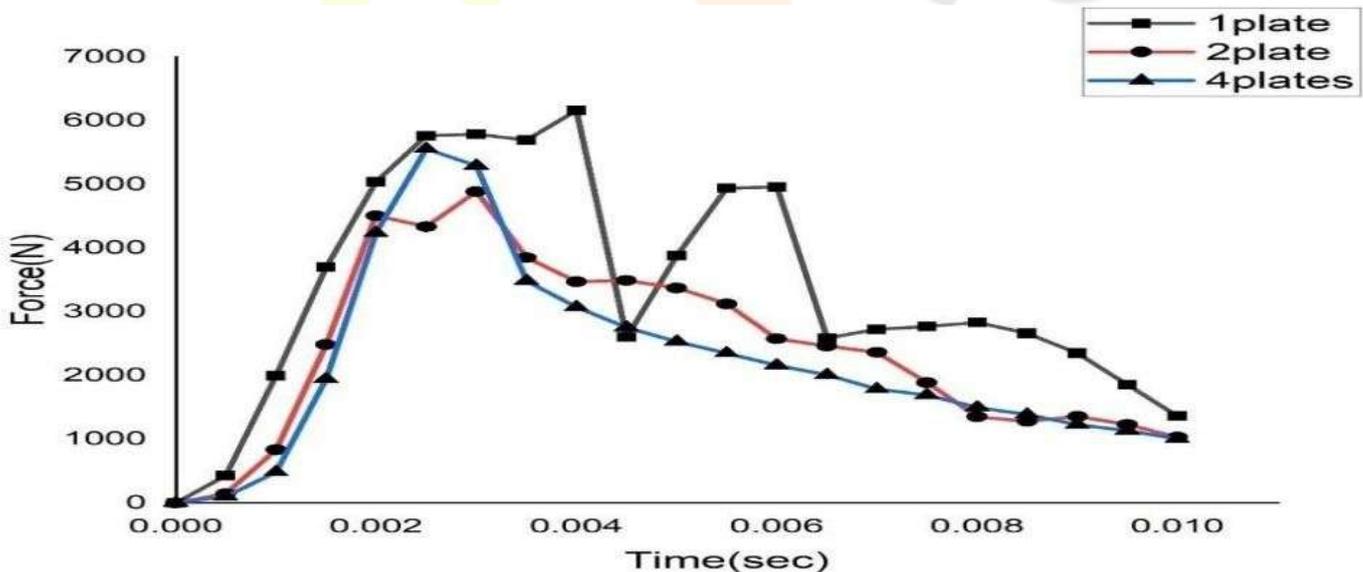
Under dynamic loading, the force-time relationship is analyzed for one, two, and four plate systems. The single-plate structure reaches the highest peak force of approximately 6,500 N at 0.0035 seconds but exhibits significant oscillations and instability during unloading. The two-plate system demonstrates improved force dissipation with fewer oscillations, peaking at 5,000 N at 0.004 seconds. The four-plate configuration, with the lowest peak force of 4,000 N at 0.004 seconds, displays the most stable response, superior energy absorption, and minimal oscillations. Comparative analysis reveals that increased plate count enhances structural stiffness, reduces displacement, lowers peak force, and improves stability. Conversely, fewer plates result in higher displacement, greater peak force, and increased instability. Physically, higher plate counts, especially in the four-plate system, offer superior energy management, stability, and rigidity, making them ideal for high-stress applications. These insights guide structural engineers in balancing stability, flexibility, and load-bearing capacity in design decisions.

Displacement vs Time
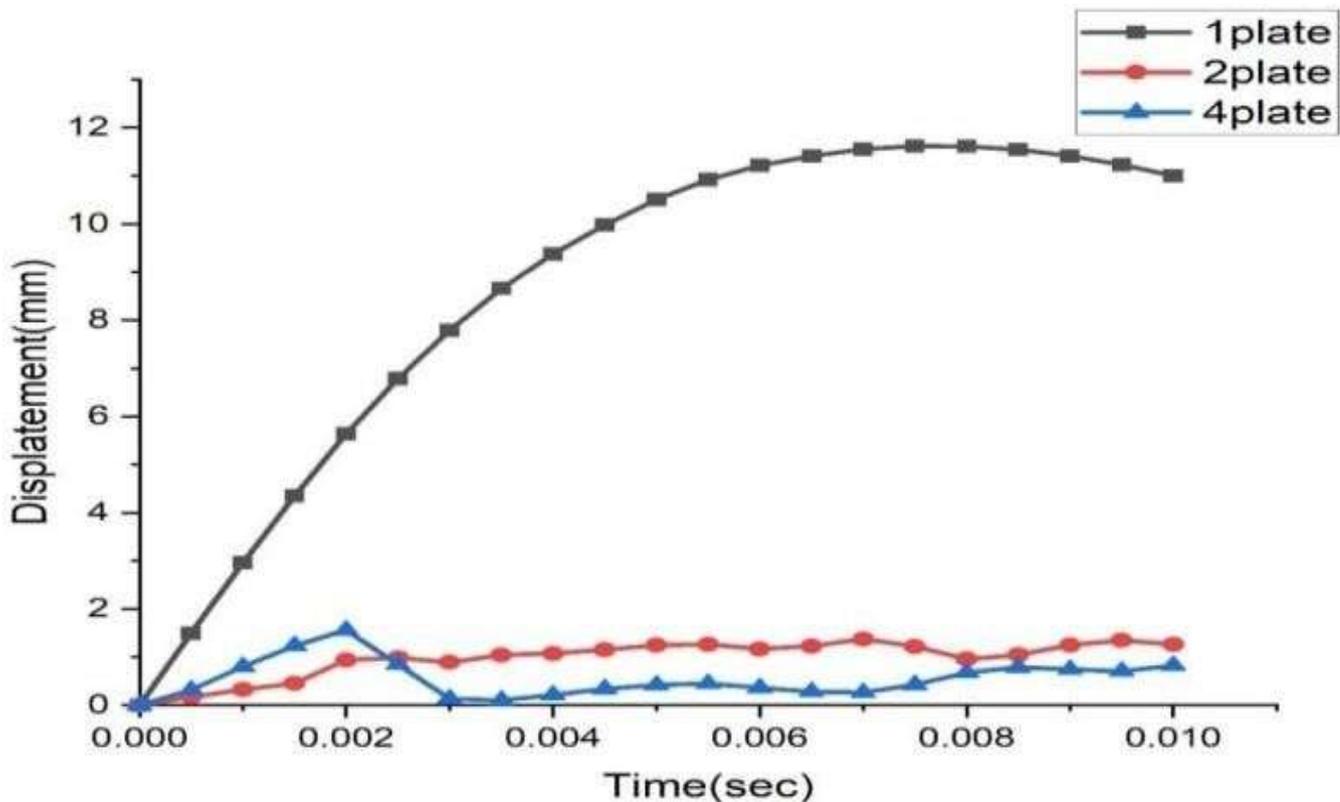
The study examines the relationship between displacement and time under dynamic loading conditions over a short interval of up to 0.01 seconds for systems with one, two, and four plates. The graph highlights the influence of plate count on system deformation. The one-plate design exhibits the highest displacement, peaking at about 12 mm at 0.007 seconds, indicating increased deformation and poor dynamic control. The two-plate system shows reduced deformation, peaking at 2 mm, with a steady curve. The four- plate design demonstrates the lowest displacement, about 1.5 mm, and the most stable response. Increasing plate count enhances load distribution, stability, and deformation control, making the four-plate system ideal for structural applications.

Internal Energy vsTime
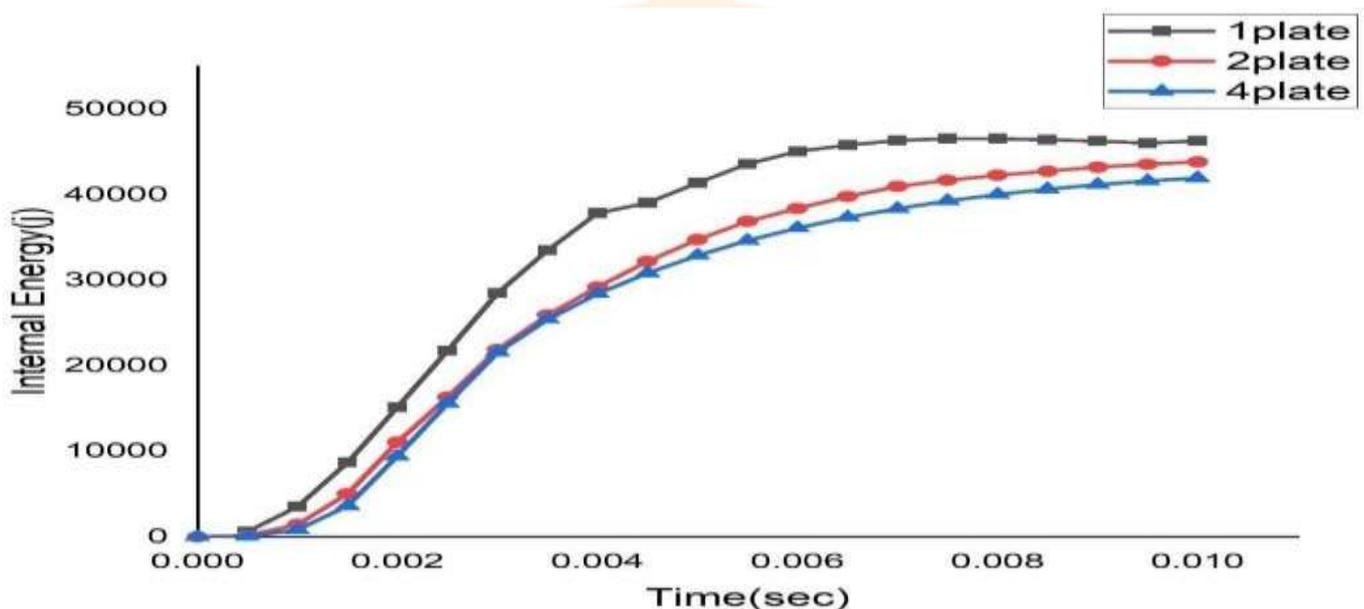
The study explores energy absorption in single and multi-plate systems, revealing variations in internal energy accumulation overtime. The graph shows internal energy (y- axis) peaking near 50,000J for the one-plate design, with time progression (x-axis) upto 0.01 seconds. The single-plate system reached approximately 47,000 J, showing rapid energy absorption but poor dissipation, leading to higher stress concentrations and dynamic instability. In contrast, the two-plate and four-plate systems peaked at 43,000J and 40,000 J, respectively, demonstrating improved energy distribution and stability

Key findings include:

Displacement Reduction: Systems with a higher number of plates exhibit reduced displacement under dynamic loading, indicating improved structural rigidity and resistance to deformation.

Energy Dissipation: Multi-plate configurations show lower internal energy peaks than single-plate systems, highlighting better energy distribution and dissipation capabilities.

Force Response: The increase in plate count improves load-bearing capacity and reduces peak force magnitude, ensuring excellent stability and lower stress concentrations.

The four-plate system consistently displayed the most favorable characteristics, such as minimal displacement, superior rigidity, and efficient energy management. It is ideal for applications requiring high-stress resistance and dynamic stability. Conversely, while more flexible, the single-plate system is less stable and suitable for low-stress scenarios. These results offer valuable insights for structural engineers and designers, emphasizing the importance of plate layering in enhancing impact resistance and overall structural integrity. To build upon these findings, further Investigations could explore material variations, boundary conditions, and impactor shapes.

Comparative Analysis

The higher slopes of the curves show that as condition values rise, the energy absorption rate gets faster. With Condition 1000 peaking at around 10,000 J, Condition 2000 at around 20,000 J, Condition 3000 at around 40,000 J, and Condit ion 4000 at around 50,000 J, greater condition values likewise translate into more significant peak internal energy levels. Higher conditions also result in a shorter time needed for energy stabilization: approximately 0.005 seconds for Condition 1000, approximately 0.004 seconds for Condition 2000, approximately 0.003 seconds for Condition 3000, and approximately 0.0025 seconds for Condition 4000.

Physical Implications

The system absorbs energy gradually under lower conditions (1000 and 2000), and slower redistribution or dissipation is indicated by longer stabilization times. These circumstances may reflect situations involving less intense impacts or lower energy inputs. On the other hand, higher circumstances (3000 and 4000) show speedy stabilization, which suggests a robust dynamic response, along with rapid and efficient energy absorption. These circumstances might be associated with high-energy impacts or forces, where the system exhibits resilience and can manage a sizable amount of energy well. This analysis provides valuable insights into system behavior under varying conditions, helping design and evaluates materials and systems for impact resistance and energy management. The above graph represents that there is more energy absorption at a velocity of 4000mm/s.

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