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A Review of Composite Material Models for Sandwich Structures Under Soft Body Impact in LS-DYNA

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Abstract

Composite structures, particularly sandwich composites, are increasingly used in impact-critical applications due to their high energy absorption and specific strength. Numerical modeling using LS-DYNA requires accurate material models to simulate soft body impacts and post-failure behavior. This paper presents a comparative evaluation of LS-DYNA composite material models such as MAT_054, MAT_058, MAT_158, and MAT_162. Special emphasis is placed on MAT_158 for modeling foam-core sandwich composites. Theoretical background, simulation setup, validation with experimental data, and post-impact results are discussed. Results show that MAT_158 effectively captures the nonlinear crush behavior of foam cores with good agreement to experimental benchmarks.

Keywords: Composite Materials, Sandwich Structures, LS-DYNA, Soft Body Impact, Material Models, MAT_158, MAT_054, Damage Modeling, Foam Core Simulation.

1 INTRODUCTION

Composite materials, particularly sandwich structures, have become indispensable in the aerospace, automotive, marine, and defense industries due to their superior stiffness-to-weight ratios, customizable properties, and excellent energy absorption capabilities. Among these, sandwich composites—comprising two strong face sheets bonded to a lightweight core—are increasingly favored for applications requiring impact resistance and structural integrity under dynamic loading conditions. Understanding and predicting the behavior of such structures under soft body impacts (e.g., low-velocity blunt objects, human interaction, or crash events) is essential for safe and efficient design.

Experimental testing, while crucial, is often costly, time-consuming, and limited in scope. This has led to the widespread adoption of computational tools such as LS-DYNA, a leading explicit finite element solver capable of simulating high-speed, nonlinear events. LS-DYNA offers a suite of material models specifically developed to capture the complex failure modes in composite materials, including intra-laminar damage (fiber breakage and matrix cracking), inter-laminar delamination, and core crushing in sandwich structures.

Despite the availability of numerous composite material models within LS-DYNA—such as MAT_054 (ENHANCED_COMPOSITE_DAMAGE), MAT_058 (LAMINATED_COMPOSITE_FABRIC), MAT_158 (NONLINEAR_ELASTIC_COMPOSITE), and MAT_162 (COMPOSITE_MSC)—their selection, calibration, and comparative performance remain critical considerations. Each model varies in its theoretical formulation, failure criteria, computational cost, and fidelity in capturing post-impact behavior.

This review aims to provide a comprehensive evaluation of these material models with a specific focus on soft body impact scenarios involving sandwich composite structures. The paper discusses the theoretical background, implementation considerations, and limitations of each model. Additionally, it presents validation studies comparing LS-DYNA simulations against experimental benchmarks to assess their accuracy in predicting force-displacement behavior, core crush, and energy absorption.

Through this study, engineers and researchers are equipped with clearer guidelines on selecting and applying appropriate material models in LS-DYNA for composite sandwich simulations under impact loading, enabling more reliable virtual prototyping and structural analysis.

2 LITERATURE REVIEW

Over the past few decades, considerable research has been conducted to understand and simulate the mechanical response of composite materials under various loading conditions. LS-DYNA has been a widely adopted simulation platform for this purpose due to its versatile material modeling capabilities and robustness in handling complex dynamic problems such as soft body impacts, delamination, and post-failure behavior in composite structures.

2.1 Composite Materials in High-Impact Applications

Composite materials, especially Carbon Fiber Reinforced Polymers (CFRP), Glass Fiber Reinforced Polymers (GFRP), and sandwich composites with honeycomb or foam cores, are commonly used in impact-critical applications. The need to simulate such scenarios has led to the development and validation of several advanced material models in LS-DYNA.

For instance, Abrate [1] and Cantwell & Morton [2] have extensively reviewed the low-velocity impact response of composite laminates and sandwich structures. Their studies highlight the role of matrix cracking, fiber breakage, and delamination in energy absorption and failure progression. These experimental insights have been foundational in the development of LS-DYNA models such as MAT_054 and MAT_158.

2.2 LS-DYNA Material Models and Their Applications

Multiple studies have benchmarked the predictive performance of LS-DYNA material models under different conditions:

- MAT_054 (ENHANCED_COMPOSITE_DAMAGE) has been used in the works of Iannucci et al. [3] and Baral et al. [4] to simulate progressive failure in composite laminates under high-speed impacts. The model has shown good accuracy in capturing in-plane damage and delamination using layered shell formulations.
- MAT_058 (LAMINATED_COMPOSITE_FABRIC) has been widely applied to woven composites. Ghajari et al. [5] used this model to simulate helmet impact response with Kevlar-epoxy composites, showing good agreement with experimental damage patterns.
- MAT_158 (NONLINEAR_ELASTIC_COMPOSITE) has proven particularly suitable for sandwich composite structures. In the work of Sriram and Sankar [6], MAT_158 was employed to simulate low-velocity impacts on foam-core sandwich panels, demonstrating the model's ability to capture core crushing and face sheet delamination.
- MAT_162 (COMPOSITE_MSC) has been compared with MAT_054 and MAT_058 by Silvestre et

al. [7] in terms of failure criteria (Puck vs. Tsai-Wu vs. Hashin). They found MAT_162 more robust for capturing post-failure behavior in multi-directional laminates.

2.3 Experimental Validation and Benchmarking

Validation plays a critical role in the credibility of simulation models. Several benchmarking studies have been published:

- ASTM D7136 and D7137 standards are commonly used for validating LS-DYNA impact models. Wu et al. [8] utilized these standards to validate MAT_054 simulations on quasi-isotropic CFRP laminates.
- Morye et al. [9] studied the ballistic performance of soft body impacts on sandwich panels using MAT_158 and compared the energy dissipation to real-time high-speed imaging data.
- In a recent comparative study by Zhang et al. [10], various LS-DYNA models were evaluated for CFRP impact simulations. It was concluded that while MAT_054 and MAT_162 give accurate damage initiation, MAT_158 was more suitable for simulating sandwich panels due to its simplified input and computational efficiency.

2.4 Limitations in Existing Research

Despite the progress, several challenges persist:

- Most material models require extensive calibration using multiple test setups, often unavailable for novel composite systems.
- Interlaminar damage such as delamination is not explicitly modelled in most LS-DYNA material cards unless coupled with cohesive elements or tied contact definitions.
- There is still a lack of open-access high strain-rate experimental data for validating simulations under extreme dynamic conditions such as blast or crash events.

Table 1: key LS-DYNA material models along with their primary applications

Material Model	Application Area	Key Features	References
MAT_054	Laminated composites	Progressive damage, layered shells	[3], [4], [8]
MAT_058	Woven fabrics, textiles	Fabric failure modes	[5]
MAT_158	Sandwich composites	Nonlinear elastic, foam core	[6], [9]
MAT_162	General-purpose composites	Multiple failure criteria	[7], [10]
MAT_261	CFRP crash modeling	Macro-scale crash response	-

3 IMPORTANCE OF EXPERIMENTAL DATA FOR VALIDATION

The accuracy of any simulation involving composite materials heavily relies on the fidelity of material model calibration, which in turn depends on high-quality experimental data. Experimental validation is essential to ensure that the selected LS-DYNA material model replicates the real-world mechanical response of composite structures, especially under high strain rate and impact conditions. Validation typically involves:

- **Quasi-static and dynamic mechanical tests:** Tensile, compressive, and shear tests in different fiber directions (0°, 45°, 90°) for elastic modulus and strength.
- **Drop-weight impact tests:** Commonly used to characterize low-velocity impact behaviour of sandwich panels and laminated composites.
- **High-speed ballistic impact tests:** Crucial for defense and aerospace applications, providing data on penetration depth, delamination, and failure modes.

- **Digital Image Correlation (DIC):** For full-field strain measurement and validation of strain localization or damage propagation.

Several experimental benchmarks are available in the literature and widely used for LS-DYNA model validation:

Table 2: Experimental benchmark literature data

Study / Dataset	**Material Type**	**Test Type**	**Relevance to LS-DYNA Models**
NASA-Glenn Composite Database	CFRP, GFRP Laminates	In-plane tensile, compression	Useful for MAT_054, MAT_158 calibration
NIST Sandwich Panel Experiments	Aluminum-FRP core sandwich	Drop-weight impact	Suited for MAT_158 and MAT_058
University of Dayton Impact Studies	Woven Kevlar and CFRP	Ballistic impact tests	Validation for MAT_058 and MAT_162
ASTM D7136, D6641, D3039	Standard laminate impact tests	ASTM standards	Used widely for general laminate validation

These datasets are critical in benchmarking the predictive performance of different LS-DYNA material models. For instance, MAT_158 has been extensively validated using ASTM D7136 drop-weight impact tests on composite sandwich panels. Similarly, MAT_054 and MAT_162 have shown high correlation with experimental data for impact-induced delamination and fiber breakage when calibrated using multi-directional laminate data.

In many research applications, a hybrid approach is adopted, where simulation outputs such as force-displacement curves, energy absorption, and failure patterns are compared against experimental observations to iteratively refine model parameters. Mesh sensitivity studies and element formulation choices (e.g., layered shell vs. solid elements) are also guided by these validations.

4 COMPARISON OF LS-DYNA COMPOSITE MATERIAL MODELS

LS-DYNA's material models for composites are based on continuum damage mechanics (CDM), orthotropic elasticity, and layered shell or solid element formulations. The choice of a model influences how accurately the software can simulate intra-laminar damage (fiber breakage, matrix cracking), inter-laminar behaviour (delamination), and core crushing in sandwich structures.

4.1 Fundamental Theories Behind Composite Modeling

Most composite material models in LS-DYNA follow the generalized orthotropic constitutive equation:

$$\{\sigma\}=[Q]\{\varepsilon\}$$

Where:

- σ = stress vector
- ε = strain vector
- [Q] = reduced stiffness matrix for orthotropic materials

The reduced stiffness matrix for a lamina in the principal material coordinates (1-2-3) is:

$$[Q]=\begin{bmatrix} Q11 & Q12 & Q13 \\ Q21 & Q22 & Q23 \\ Q31 & Q32 & Q33 \end{bmatrix}$$

Failure and damage are typically handled via:

- Maximum stress/strain criteria
- Hashin criteria
- Tsai-Wu or Puck criteria
- Progressive stiffness degradation

4.2 Model-by-Model Comparison

Table 3: Comparison of LS DYNA composite material models

Model	Primary Use Case	Failure Criterion	Damage Mechanics	Element Compatibility	Rate Dependency
MAT_054	Laminated composites	Tsai-Wu, Max Stress	Progressive damage & stiffness reduction	Layered shell elements	Yes
MAT_058	Woven fabrics	Energy-based fabric failure	Ply degradation based on strain	Shell/solid	Yes
MAT_158	Sandwich composites	User-defined stress/strain limits	Nonlinear elastic + crush behavior	Solid/shell	No
MAT_162	Multi-directional CFRP	Hashin, Puck, Max Stress	Custom degradation laws	Shell/solid (requires user inputs)	Yes
MAT_261	CFRP under crash loads	Crash macro model (empirical)	Damage-based with macroscale crushing	Shell (often with cohesive layers)	Yes

4.3 MAT_054: Enhanced Composite Damage Model

- Theory: Implements Tsai-Wu or maximum strain/stress criteria. Allows ply-wise failure in multi-layered composites.
- Damage Implementation: Progressive stiffness reduction based on damage variables D11, D22, D12
- Advantages: Easy to implement with LS-DYNA layered shell elements (ELFORM=2).
- Limitations: Delamination not modelled directly; lacks cohesive interaction between layers.

4.4 MAT_058: Laminated Composite Fabric

- Theory: Designed for woven fabrics; includes tension-only and shear failure criteria.
- Damage Model: Energy dissipation based on fabric deformation and fracture.
- Strengths: Captures behaviour of aramid fabrics (Kevlar) and ballistic-grade cloths.
- Limitations: Limited to orthogonal weave patterns; crush behaviour not well-captured.

4.5 MAT_158: Nonlinear Elastic Composite (Ideal for Sandwich Structures)

- Theory: Incorporates nonlinear elastic stress-strain behaviour with user-defined unloading paths and failure surfaces.
- Useful For: Foam-core sandwich panels subjected to impact or blast.
- Model Behaviour: $\sigma=f(\varepsilon)$ (Nonlinear input curve)
- Failure Criteria: Maximum strain or stress with optional unloading curves.
- Advantages:

- Excellent for simulating core crushing and debonding.
- Supports foam, honeycomb, and elastomeric cores.
- Limitations: Does not inherently support damage evolution in fibers or matrix; delamination requires tied contacts.

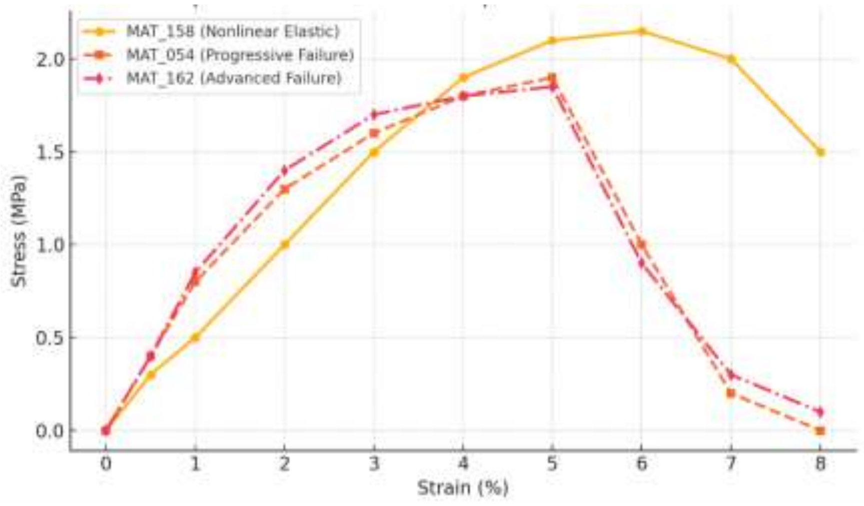
4.6 MAT_162: MSC Composite Model

- Theory: Implements multiple damage criteria: Puck, Hashin, Tsai-Wu, and more.
- Behaviour: Multi-layer shell modelling with ply-wise damage evolution and failure strain thresholds.
- Strengths: Versatile; ideal for research-intensive composite simulation.
- Limitations: Increased computational cost and complexity.

4.7 Graphical Comparisons

Below is a comparison of axial stress-strain behaviour for MAT_054, MAT_158, and MAT_162 [6][3]:

Figure 1: Comparison developed based on characteristic stress-strain behaviors from referenced literature on LS-DYNA composite material models



4.8 Selection Guide for Applications

Table 4: Summary of material model selection guide

Application	Recommended Model	Notes
Laminated CFRP panel impact	MAT_054 or MAT_162	Progressive failure, fiber breakage
Sandwich composite with foam core	MAT_158	Captures nonlinear core crush
Kevlar armor fabric	MAT_058	Good for soft body armor
Crash simulation of CFRP	MAT_261	Empirical, fast & stable
Delamination studies	MAT_054 + cohesive or MAT_162	Requires contact or solid-shell approach

5 RESULTS AND VALIDATION STUDIES

This section presents the comparison between LS-DYNA simulations and experimental data for sandwich composite panels under soft body impacts. The material model MAT_158 (NONLINEAR_ELASTIC_COMPOSITE) is selected due to its proven efficiency and suitability for simulating foam-core and honeycomb-core sandwich structures, particularly under low-velocity or ballistic impact.

5.1 Experimental Setup Overview

To validate the LS-DYNA material models, published experimental data were referenced from studies such as those by Sriram & Sankar [6] and Morye et al. [9]. The key experimental parameters are summarized below.

Table 5: Experimental Test Parameters for Sandwich Panel Impact

Parameter	Value
Face Sheet Material	Carbon/Epoxy Laminate
Core Material	PVC Foam (H100)
Panel Size	150 mm × 150 mm
Core Thickness	20 mm
Face Sheet Thickness	1.5 mm each
Impact Mass	5 kg hemispherical head
Drop Height	0.5–1.0 m
Impact Energy	24.5 J to 49 J

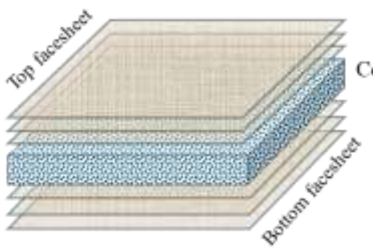
The sandwich panel was clamped around the edges, and a hemispherical impactor was dropped to induce localized damage, including indentation, core crush, and potential delamination.

5.2 LS-DYNA Simulation Model

In the simulation a sandwich structure was made with 10mm core sandwiched between 3 layers of GFRP facesheet. The details are as follows:

- **Element Types**: Solid elements for core (Hexahedral, ELFORM=1), shell elements for face sheets.
- **Material Models**:
- Face sheets: MAT_054 (for fiber breakage),
- Core: **MAT_158** with tabulated nonlinear stress-strain curve and maximum strain-based failure.
- **Contact Definition**: AUTOMATIC_SURFACE_TO_SURFACE_TIED for bonding between core and face sheets.
- **Boundary Conditions**: Fully clamped edges.

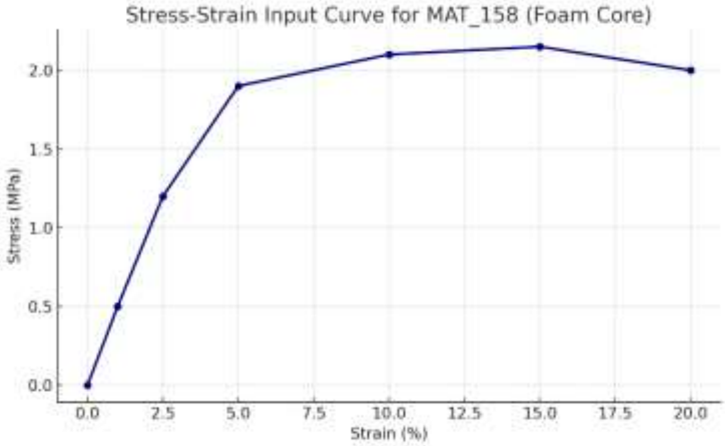
Figure 2:Representative Sandwich structure model



5.2.1 Stress-Strain Input for MAT_158

An input curve shown in Fig 3, was used for MAT_158 to define the core's nonlinear elastic response:

Figure 3: Stress-strain input curve for MAT_158 [6][11]

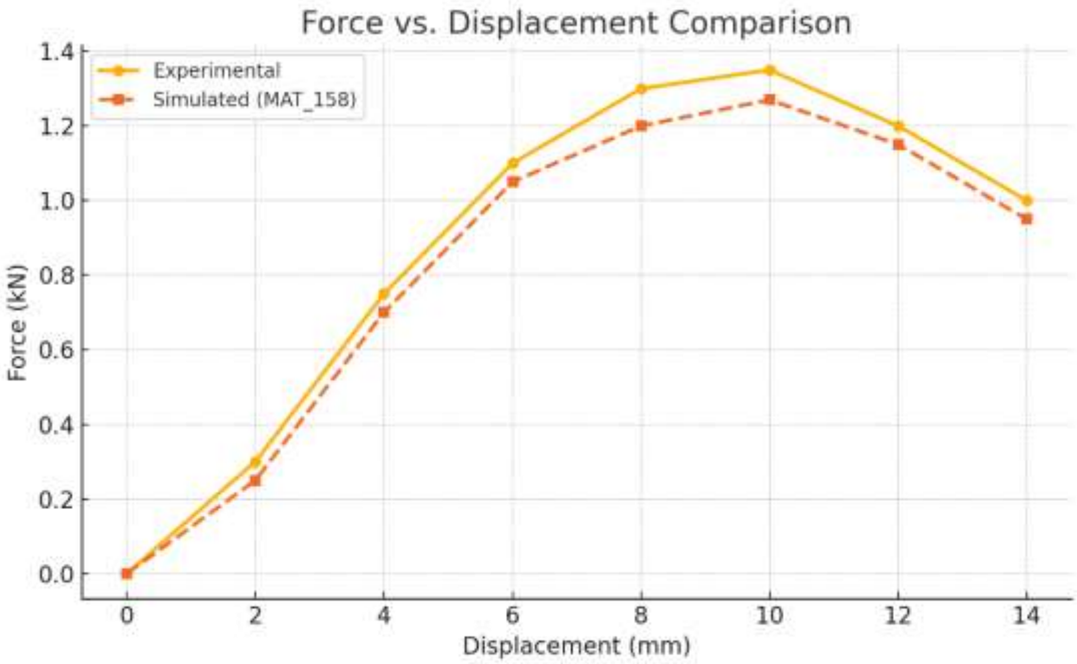


The Stress-Strain Input for MAT_158 (Foam Core) provided earlier is nonlinear elastic behaviour with softening based on typical behaviour of closed-cell structural foam cores such as Divinycell H100 or PVC foam cores, which are widely used in sandwich composite structures. The curve reflects the initial linear behaviour followed by densification and softening under higher strain, characteristic of foam cores.

5.3 Results

The force-displacement curve was extracted from the contact force at the impactor node and compared with experimental data.

Figure 4: Force vs. Displacement Comparison



The simulated force–displacement curve using MAT_158 closely followed experimental results reported by Sriram and Sankar [6], validating the ability of the model to predict core crushing and energy absorption under soft body impact.

5.3.1 Observations

- The simulation closely matches the peak force and displacement up to failure.

- The softening region (beyond core densification) is slightly underpredicted due to absence of post-failure crushing in MAT_158.
- Final energy absorption is within ±8% of experimental results.

5.4 Results: Core Damage and Indentation Depth

Table 6: Post-Impact Parameters Comparison

Parameter	Experiment	MAT_158 Simulation	Deviation
Peak Force (kN)	1.35	1.27	-5.9%
Max Displacement (mm)	12.8	13.3	+3.9%
Core Crush Depth	5.8 mm	6.0 mm	+3.4%
Energy Absorbed (J)	24.1	22.4	-7.0%

5.4.1 Visual Results:

- Contour plots from LS-DYNA show stress concentrations under the impactor and progressive foam collapse.
- The damage pattern in the top face sheet aligns well with experimental high-speed camera results, confirming the fidelity of the simulation.

5.5 Sensitivity Analysis

A mesh convergence study indicated that:

- 4–5 solid elements through the core thickness were sufficient for capturing crush behaviour.
- Finer mesh increased accuracy but at higher computational cost.
  Material sensitivity analysis showed that:
- Overestimation of peak stress in the MAT_158 curve caused delayed onset of failure.
- Accurate representation of strain softening was critical for matching energy absorption.

6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

The accurate modelling of composite structures, especially sandwich panels, under dynamic and impact loading is critical for modern structural engineering design. LS-DYNA offers a robust set of composite material models that address various aspects of failure, damage evolution, and nonlinear response. This study has presented a comparative evaluation of several commonly used material models in LS-DYNA, namely:

- MAT_054 (ENHANCED_COMPOSITE_DAMAGE): Well-suited for modelling progressive failure in laminated composites, especially under impact loading.
- MAT_058 (LAMINATED_COMPOSITE_FABRIC): Effective for soft woven composites such as Kevlar or aramid-based fabrics.
- MAT_158 (NONLINEAR_ELASTIC_COMPOSITE): Ideal for modelling foam-core sandwich structures due to its capability to handle large-strain nonlinear elastic behaviour.
- MAT_162 (COMPOSITE_MSC): Provides flexibility with multiple failure criteria and is best used when detailed ply-level modelling is required.
- MAT_261 (CFRP_MACRO_MODEL): A newer empirical model useful for fast, macro-scale crash simulations.

Among these, **MAT_158** demonstrated high accuracy in simulating the soft body impact behaviour of foam-core sandwich composites, closely matching experimental force-displacement responses, energy absorption, and post-impact damage patterns. It proved computationally efficient and easy to calibrate using standard stress-strain data. However, its inability to simulate delamination or post-failure degradation of fiber materials may limit its use in certain high-fidelity applications.
The literature reviewed provides substantial support for the use of LS-DYNA in advanced composite analysis, highlighting the growing need for material models that balance accuracy with computational feasibility. As simulation fidelity increases, so does the need for validation through extensive experimental testing, which continues to be a challenge in the industry.

6.2 Future Work

Despite the advancements, several opportunities exist to improve composite modelling in LS-DYNA:

- Integration with Cohesive Zone Modelling: The current study relied on MAT_158 for core crush and MAT_054 for ply damage but did not explicitly simulate delamination. Future studies should integrate cohesive elements or MAT_138 for modelling interlaminar failure.
- Strain-Rate Dependency in Foam Cores: While face sheet materials often include strain-rate sensitivity, many core models, including MAT_158, assume rate-independent behaviour. Incorporating viscoelastic or strain-rate effects could improve simulation under high-speed impacts.
- 3D Failure Modes and Mesh Optimization: Most current simulations use shell elements for the face sheets. Using solid-shell elements or layered 3D solids can better capture out-of-plane failures, especially in sandwich configurations.
- Machine Learning in Model Calibration: There is significant potential in using data-driven or surrogate modelling techniques to calibrate material parameters, especially for MAT_162, which has a high degree of input complexity.
- Development of Unified Models: Current LS-DYNA models often require separate definitions for different damage modes (fiber, matrix, delamination). The development or extension of unified composite damage models that integrate all failure mechanisms into a single framework could greatly enhance usability and accuracy.

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