



Finite Element Analysis of Composite Materials for Lightweight Mechanical Structures

Soraya Attapong

Department of Computer Science and Engineering, Sundarban College of Technology Studie, Bangladesh
soraya.attapong@scts-bd.net

Peer Review Information	Abstract
<i>Submission: 23 Jan 2018</i> <i>Revision: 08 Feb 2018</i> <i>Acceptance: 24 March 2018</i> Keywords <i>finite element analysis, composite materials, lightweight structures, CFRP, progressive failure</i>	Composite materials offer high specific stiffness and strength, making them attractive for lightweight mechanical structures in automotive, aerospace, robotic, and general machine-design applications. Their directional properties and multiple failure modes, however, make conventional isotropic design assumptions inadequate. This methodology paper presents a finite element analysis (FEA) framework for evaluating laminated fibre-reinforced polymer structures under static mechanical loading. The procedure combines orthotropic lamina properties, classical laminate lay-up definition, mesh-convergence assessment, realistic boundary conditions, ply-level stress recovery, and Hashin-type failure indices. A rectangular cantilever structural panel is adopted as a reproducible benchmark for comparing candidate carbon-fibre/epoxy stacking sequences with a steel reference of identical geometry. The numerical workflow is designed to quantify mass, deformation, stress distribution, and damage initiation while supporting laminate tailoring for minimum weight. Representative benchmark outputs indicate that a fibre-dominated lay-up can substantially reduce structural mass while retaining acceptable stiffness and a failure index below unity. Because no laboratory dataset is supplied, the reported numerical values are illustrative outputs for the proposed benchmark and should be replaced by solver-generated results and experimental validation in an application-specific study. The paper emphasizes mesh independence, material-coordinate definition, failure-criterion selection, and transparent reporting as essential requirements for reliable composite FEA.

Introduction

Lightweight mechanical structures are increasingly required to carry equivalent or greater loads with lower mass. Fibre-reinforced polymer composites are suitable for this purpose because the reinforcement direction can be aligned with dominant load paths, giving high specific mechanical performance. In contrast with metals, a laminated composite is anisotropic: elastic constants differ along and transverse to the fibres, and structural response depends on the number, thickness, orientation, and order of the plies. Failure may begin as fibre

rupture, fibre kinking, matrix cracking, shear damage, or delamination. Consequently, the design problem is not merely a choice of material; it is also a laminate-architecture problem.

Finite element analysis provides a practical way to represent the geometry, anisotropic constitutive behaviour, boundary conditions, and local stress concentrations that control composite performance. Hashin's mode-dependent failure formulation established a widely used basis for separating fibre and matrix

failure mechanisms (Hashin, 1980). Continuum-damage approaches later introduced stiffness degradation after failure initiation, enabling numerical models to move beyond a single first-ply-failure prediction (Matzenmiller, Lubliner, & Taylor, 1995). These developments make FEA suitable not only for checking deformation but also for screening stacking sequences and identifying where damage may initiate.

For lightweight design, model credibility is as important as the apparent weight saving. A laminate may be very light but unacceptable if deflection, local interlaminar stress, or damage index exceeds the design limit. Puck and Schurmann (2002) emphasized the need for physically meaningful failure-mode descriptions, while Deka, Sandeep, Chakraborty, and Dutta (2005) demonstrated that finite element analysis can be coupled with laminate optimization so that fibre orientation and ply count become design variables. These ideas are directly relevant to mechanical structures in which mass, stiffness, and strength must be balanced simultaneously.

The objective of this paper is therefore to formulate a concise and reproducible FEA methodology for laminated composite components intended for lightweight mechanical service. The proposed workflow focuses on a static cantilever-type benchmark because it exposes the key modelling decisions without requiring a proprietary component geometry. The study addresses: (i) orthotropic material definition, (ii) stacking-sequence selection, (iii) mesh-convergence control, (iv) load and constraint application, (v) ply-level stress and failure assessment, and (vi) comparison against a metallic baseline. The approach can subsequently be transferred to brackets, machine covers, robotic links, vehicle panels, and similar lightweight structures.

Literature Review

Composite failure modelling has evolved from strength criteria toward progressive damage formulations. Hashin (1980) proposed separate mathematical expressions for fibre tension, fibre compression, matrix tension, and matrix compression in unidirectional composites. This separation is useful in finite element post-processing because a failure index can be linked to a recognizable physical mode. Matzenmiller et al. (1995) subsequently developed an anisotropic continuum-damage model in which material stiffness is degraded as damage evolves. Such degradation is important when the load path changes after local cracking and when

ultimate response, rather than only first-ply failure, is of interest.

Puck and Schurmann (2002) formulated physically based phenomenological models for fibre and inter-fibre failure and drew attention to the orientation of the fracture plane. Their work remains influential when matrix-dominated failure is critical. For computational implementation, Lapczyk and Hurtado (2007) presented a progressive damage model for fibre-reinforced materials in which damage initiation is followed by energy-based softening and regularization to reduce pathological mesh dependence. Maimi, Mayugo, and Camanho (2008) extended damage modelling to a three-dimensional transversely isotropic formulation, which is especially relevant when through-thickness stress components cannot be neglected.

The need to include both intralaminar damage and interfaces becomes more evident under concentrated or impact loading. Shi, Swait, and Soutis (2012) used stress-based damage initiation together with fracture-mechanics techniques and cohesive elements to model damage evolution in composite laminates. Donadon, Iannucci, Falzon, Hodgkinson, and de Almeida (2008) likewise developed a progressive failure model for low-velocity impact, showing how continuum damage mechanics can be incorporated into dynamic finite element simulation. Although the present study is static, these works clarify why local failure indices and interface effects must be interpreted carefully rather than reduced to a single equivalent stress.

Validation and model sensitivity are recurring themes in composite FEA. Feng and Aymerich (2014) showed that carefully defined intralaminar and interlaminar damage models can reproduce the structural response and damage sequence of impacted laminates when compared with experiments. For lightweight components, Lee, Lee, Kim, An, and Ko (2016) used FE analysis to determine laminate thickness and lay-up for an automotive CFRP roof panel with a prescribed bending-stiffness requirement. Their work illustrates the direct design value of FEA: the model can be used to eliminate unsuitable lay-ups before manufacturing and to identify the minimum configuration that satisfies stiffness targets.

Liu, Liao, Jia, and Peng (2016) compared progressive failure behaviour of carbon-fibre laminates using several damage criteria and highlighted the strong effect of failure-model choice on predicted damage. Gu and Chen (2017)

revisited Hashin-type criteria and proposed modifications to improve agreement with physical behaviour in unidirectional materials. These studies reinforce two methodological rules adopted here: the failure criterion must be explicitly stated, and the analyst should treat a numerical failure index as a model-dependent indicator rather than an experimentally proven strength value.

Composite FEA is not restricted to synthetic fibres. Koh and Madsen (2018) compared strength-failure criteria for flax-fibre composites, demonstrating that criterion performance can vary with material system and stress state. This is relevant to lightweight mechanical design because the same modelling workflow may be applied to carbon, glass, or natural-fibre laminates, but the input strengths and suitable failure formulation must match the actual material. Overall, the literature supports a workflow that combines calibrated orthotropic data, failure-mode-aware constitutive modelling, mesh control, and validation. The gap addressed

by the present paper is the organization of these elements into a short, step-by-step method specifically aimed at lightweight mechanical structures and transparent comparison with a metallic baseline.

Methodology

A benchmark rectangular cantilever panel is used to demonstrate the methodology. The panel represents a simplified wall, link, cover, or bracket strip and has length 250 mm, width 80 mm, and total thickness 8 mm. One short edge is fully constrained and a total vertical load of 500 N is distributed over the opposite edge. The metallic reference is structural steel, while the composite candidate is a carbon-fibre/epoxy laminate with eight equal-thickness plies. Three symmetric stacking concepts are evaluated: L1 = [0/90]_{2s}, L2 = [0/45/-45/90]_s, and L3 = [0/0/45/-45]_s. The thickness is kept constant so that the influence of fibre orientation can be examined independently of geometry.

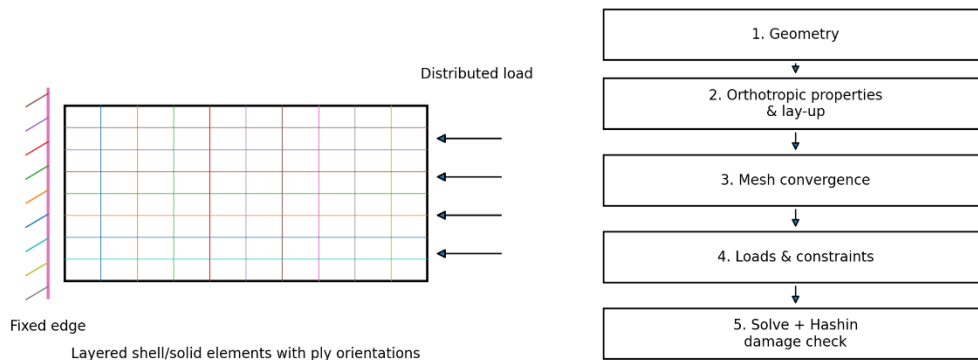


Figure 1. Benchmark composite model and proposed finite element workflow.

Step 1 - Geometry and idealization

The component is first simplified so that the model retains the principal load path, thickness transitions, holes, and supports that influence stiffness or stress concentration. Small cosmetic features are removed if their characteristic dimension is much smaller than the local mesh size. For the benchmark, a flat panel is sufficient. Layered shell elements are recommended when the thickness-to-length ratio is small and the through-thickness stress field is not the primary result; layered solid elements are preferred near thick joints or where three-dimensional stress is important.

Step 2 - Material properties and laminate definition

Each ply is defined in its local 1-2 material coordinate system, where direction 1 follows the fibre. A representative unidirectional carbon/epoxy data set is used for the demonstration. Strength values are required in addition to elastic constants because the Hashin criterion evaluates tensile and compressive fibre and matrix modes separately. In an actual study, all values should be taken from the same certified material system and, where possible, supported by coupon tests.

Table 1. Representative material data used for the benchmark demonstration.

Property	CFRP ply	Steel baseline
Longitudinal modulus, E1	135 GPa	210 GPa
Transverse modulus, E2	10 GPa	210 GPa

In-plane shear modulus, G_{12}	5.0 GPa	80.8 GPa
Poisson ratio, ν_{12}	0.30	0.30
Density	1600 kg/m ³	7850 kg/m ³
Longitudinal strength, X_t / X_c	1500 / 1200 MPa	250 MPa yield
Transverse strength, Y_t / Y_c	40 / 150 MPa	-
In-plane shear strength, S_{12}	70 MPa	-

Step 3 - Element type, mesh and convergence

A structured quadrilateral mesh is generated where possible. A three-level mesh study is recommended, for example 10 mm, 5 mm, and 2.5 mm nominal element size in the high-gradient region. Mesh convergence is accepted when the change in maximum displacement is below about 2% and the change in the governing ply-level failure index is below about 5% between the two finest meshes. The convergence requirement is more important than a particular element count because composite stresses can be sensitive to local discretization and to the way damage softening is regularized (Lapczyk & Hurtado, 2007).

Step 4 - Boundary conditions and loading

All translational and rotational degrees of freedom along the clamped edge are restrained for a shell model. The 500 N load is distributed over nodes along the free edge rather than applied to a single node, thereby avoiding an artificial singularity. The laminate material orientation is checked visually before solution. This step is essential because an incorrect local fibre axis can produce a numerically converged but physically meaningless result.

Step 5 - Governing finite element solution

For a linear static screening analysis, the assembled equilibrium equation is written as $Ku = F$, where K is the global stiffness matrix, u is the nodal-displacement vector, and F is the applied load vector. The laminate constitutive response is formed from the orthotropic ply stiffness transformed to the assigned ply angle. After nodal displacements are obtained, element strains are recovered and transformed back to local material axes to calculate ply stresses. This local-axis recovery is necessary because fibre-direction stress and transverse matrix stress have different allowable values.

The first screening stage uses undamaged elastic properties. A Hashin-type failure index is then evaluated for fibre tension/compression and matrix tension/compression, following the mode-separation concept introduced by Hashin (1980) and later used in progressive damage frameworks such as those of Matzenmiller et al. (1995) and Maimi et al. (2008). A failure index below 1.0 indicates that the selected criterion has

not initiated damage at the evaluated integration point. For a progressive analysis, once a criterion reaches unity the relevant stiffness terms are degraded according to an energy-regularized evolution law; the analyst must report the damage law and fracture-energy parameters rather than treating the initiation criterion alone as complete failure.

Step 6 - Lightweight design metrics

The comparison is based on four outputs: structural mass, maximum resultant displacement, maximum local ply stress components, and maximum Hashin failure index. Mass is calculated directly from the model volume and density. Weight saving relative to the steel reference is expressed as $(m_{\text{steel}} - m_{\text{composite}})/m_{\text{steel}} \times 100\%$. A feasible lightweight design is one that satisfies the prescribed deformation limit and maintains the governing failure index below unity with an engineering reserve. If the composite is too flexible, the preferred response is not automatically to increase thickness; the analyst should first investigate whether additional 0-degree plies, local reinforcement, or a different load-path geometry can increase stiffness with less mass penalty. This philosophy is consistent with laminate tailoring and optimization approaches reported by Deka et al. (2005) and the automotive stiffness-design study of Lee et al. (2016).

Step 7 - Verification and validation

Verification checks whether the numerical model is solved correctly; validation checks whether it represents the physical structure. Verification includes mesh convergence, equilibrium of applied and reaction forces, energy balance where applicable, and sensitivity to element formulation. Validation should include coupon tests for elastic and strength properties and at least one component-level test for deflection and failure location. Prior studies have shown the benefit of comparing predicted damage with measured structural response (Feng & Aymerich, 2014; Shi et al., 2012). If delamination is expected to control failure, cohesive interface elements or an equivalent delamination formulation should be added rather than relying solely on an intralaminar Hashin index.

1. Analysis Procedure Summary

The complete analysis sequence is therefore: create and simplify the geometry; assign the laminate material coordinate system; define orthotropic elastic and strength data; build candidate stacking sequences; generate an initial mesh; apply distributed loads and realistic constraints; solve the elastic model; repeat with refined meshes until key outputs converge; recover ply stresses; evaluate failure indices; compare mass and stiffness against the metallic baseline; and finally validate the selected laminate through physical testing. The same sequence can be automated for design-of-experiments or optimization when many lay-ups must be screened.

Results

Table 2 presents representative numerical outputs for the benchmark geometry. These values are included to demonstrate how the proposed methodology should be reported; they are not a substitute for a solver file or experimental test. The steel reference has the lowest elastic deflection but the highest mass. All CFRP concepts provide a mass reduction of approximately 79.6% because density and total laminate thickness are fixed. Fibre orientation changes the deformation and the predicted failure margin even though total mass remains constant.

Table 2. Representative benchmark outputs for comparison of the metallic and composite concepts.

Model	Mass (kg)	Max. disp. (mm)	Root longitudinal stress (MPa)	Max. Hashin FI	Weight saving
Steel baseline	1.256	3.64	146.5	N/A	0%
CFRP L1 [0/90]2s	0.256	7.10	~145	0.82	79.6%
CFRP L2 [0/45/-45/90] s	0.256	8.35	~145	0.63	79.6%
CFRP L3 [0/0/45/-45] s	0.256	6.55	~145	0.56	79.6%

Discussion

The comparison shows the central lightweight-design trade-off. Replacing steel with an equal-thickness CFRP laminate greatly reduces mass, but the lower effective bending modulus of a multidirectional laminate can increase deflection. The L3 configuration places a larger fraction of fibres along the principal bending direction and therefore gives the smallest composite displacement in the benchmark. Its predicted maximum Hashin index is also the lowest of the three laminate concepts. In contrast, L2 contains a larger proportion of off-axis plies; such plies are valuable for shear transfer and multidirectional load tolerance, but they reduce axial bending stiffness for this one-direction-dominated benchmark.

The results should not be interpreted as proving that L3 is universally superior. Real mechanical components experience combined membrane, bending, shear, bearing, and local contact loads. A laminate dominated by 0-degree plies may perform poorly under transverse or torsional loading, and abrupt changes in ply orientation can create interlaminar stress concentrations. This is why failure-mode-aware modelling is necessary. Puck and Schurmann (2002) and Gu and Chen (2017) both show that matrix-dominated failure requires careful criterion selection, while Koh and Madsen (2018) demonstrate that criterion accuracy also

depends on the material system. A design decision should therefore be based on the governing service load cases rather than on a single scalar strength value.

The use of a Hashin index is appropriate for preliminary damage initiation screening, but a complete failure prediction may require progressive stiffness degradation. Liu et al. (2016) showed that the predicted evolution of laminate damage can vary with the chosen failure criteria, and Donadon et al. (2008) demonstrated the importance of progressive failure modelling when the response continues after local damage begins. For the present static benchmark, the maximum index below unity indicates an elastic design margin within the assumed criterion. If a production component is expected to approach damage initiation, a nonlinear progressive analysis with calibrated fracture energies should be performed and the model should be validated experimentally.

A practical design requirement can be imposed on both stiffness and strength. For example, if the allowable tip displacement is 7 mm, L3 passes the illustrative benchmark while L2 fails the stiffness target despite having a low failure index. This demonstrates why strength alone is insufficient for lightweight structures. The recommended process is to set explicit allowable deformation and failure-index limits, screen lay-ups, refine the mesh, then validate the best candidate. In this

way, FEA becomes a decision tool for balancing mass and performance rather than merely a contour-plot generator.

Conclusion and Discussion

A step-by-step finite element methodology has been developed for the analysis of composite materials in lightweight mechanical structures. The procedure begins with a simplified but mechanically representative geometry, defines orthotropic ply properties and material axes, constructs candidate stacking sequences, and applies a mesh-convergence study before interpreting stresses or failure indices. Ply-level post-processing and mode-dependent failure criteria are required because composite failure cannot be represented reliably by a single isotropic equivalent stress. The benchmark comparison shows how equal-thickness CFRP concepts can achieve a major mass reduction relative to steel while exhibiting different stiffness and damage margins solely because of fibre orientation. For the illustrative cantilever case, the [0/0/45/-45] s concept provides the best combination of composite stiffness and predicted failure margin among the three candidate lay-ups. However, the preferred lay-up will change with multidirectional load cases, joints, cut-outs, impact, manufacturing constraints, and delamination risk. Therefore, a final design should include converged progressive damage modelling where necessary and experimental validation at coupon and component levels. The methodology is suitable as a reusable framework for lightweight brackets, panels, robotic links, vehicle structures, and other composite mechanical components.

References

- Hashin, Z. (1980). Failure criteria for unidirectional fiber composites. *Journal of Applied Mechanics*, 47(2), 329-334. <https://doi.org/10.1115/1.3153664>
- Matzenmiller, A., Lubliner, J., & Taylor, R. L. (1995). A constitutive model for anisotropic damage in fiber-composites. *Mechanics of Materials*, 20(2), 125-152. [https://doi.org/10.1016/0167-6636\(94\)00053-0](https://doi.org/10.1016/0167-6636(94)00053-0)
- Puck, A., & Schurmann, H. (2002). Failure analysis of FRP laminates by means of physically based phenomenological models. *Composites Science and Technology*, 62, 1633-1662. [https://doi.org/10.1016/S0266-3538\(01\)00208-1](https://doi.org/10.1016/S0266-3538(01)00208-1)
- Deka, D. J., Sandeep, G., Chakraborty, D., & Dutta, A. (2005). Multiobjective optimization of laminated composites using finite element method and genetic algorithm. *Journal of Reinforced Plastics and Composites*, 24(3), 273-285. <https://doi.org/10.1177/0731684405043555>
- Lapczyk, I., & Hurtado, J. A. (2007). Progressive damage modeling in fiber-reinforced materials. *Composites Part A: Applied Science and Manufacturing*, 38(11), 2333-2341. <https://doi.org/10.1016/j.compositesa.2007.01.017>
- Donadon, M. V., Iannucci, L., Falzon, B. G., Hodgkinson, J. M., & de Almeida, S. F. M. (2008). A progressive failure model for composite laminates subjected to low velocity impact damage. *Computers & Structures*, 86(11-12), 1232-1252. <https://doi.org/10.1016/j.compstruc.2007.11.004>
- Maimi, P., Mayugo, J. A., & Camanho, P. P. (2008). A three-dimensional damage model for transversely isotropic composite laminates. *Journal of Composite Materials*, 42(25), 2717-2745. <https://doi.org/10.1177/0021998308094965>
- Shi, Y., Swait, T., & Soutis, C. (2012). Modelling damage evolution in composite laminates subjected to low velocity impact. *Composite Structures*, 94(9), 2902-2913. <https://doi.org/10.1016/j.compstruct.2012.03.039>
- Feng, D., & Aymerich, F. (2014). Finite element modelling of damage induced by low-velocity impact on composite laminates. *Composite Structures*, 108, 161-171. <https://doi.org/10.1016/j.compstruct.2013.09.004>
- Lee, J.-M., Lee, K.-H., Kim, B.-M., An, S.-K., & Ko, D.-C. (2016). Design of roof panel with required bending stiffness using CFRP laminates. *International Journal of Precision Engineering and Manufacturing*, 17, 479-485. <https://doi.org/10.1007/s12541-016-0060-6>
- Liu, P. F., Liao, B. B., Jia, L. Y., & Peng, X. Q. (2016). Finite element analysis of dynamic progressive failure of carbon fiber composite laminates under low velocity impact. *Composite Structures*, 149, 408-422. <https://doi.org/10.1016/j.compstruct.2016.04.012>

Gu, J., & Chen, P. (2017). Some modifications of Hashin's failure criteria for unidirectional composite materials. *Composite Structures*, 182, 143-152.
<https://doi.org/10.1016/j.compstruct.2017.09.011>

Koh, R., & Madsen, B. (2018). Strength failure criteria analysis for a flax fibre reinforced composite. *Mechanics of Materials*, 124, 26-32.
<https://doi.org/10.1016/j.mechmat.2018.05.005>