Composite Battery Enclosure for High-Performance Electric Vehicles

MAE 4131 Senior Design Project
Spring 2025
Ata Zavaro

Abstract

This project develops a lightweight battery enclosure for EVs using composite materials, aiming to reduce vehicle weight while meeting the standards required from sheet steel. Targeting luxury performance vehicles that prioritize performance over cost, the design employs an Epoxy/Carbon Fiber laminate, which is significantly lighter than sheet steel. The design process utilized Ashby's methods for material selection, with an emphasis on stiffness and strength per unit mass. ANSYS FEA was employed to optimize design choices and confirm adequate stiffness and crashworthiness. A quasi-isotropic layup was selected to create a balanced laminate capable of handling complex loading scenarios in a battery enclosure. Manufacturing methods to optimize cost and post-processing for corrosivity and electrical insulation were considered, recommending a polyurethane coating. Results demonstrate significant weight savings, up to 80%, and compliance with crash and standard use conditions; however high material costs restrict immediate adoption to the performance EV market. The design process reveals a trade-off between performance and manufacturing costs, but scalability and affordability are expected to improve with advancements in manufacturing technology, positioning this innovative enclosure as a promising solution for enhanced EV performance with potential for broader adoption.

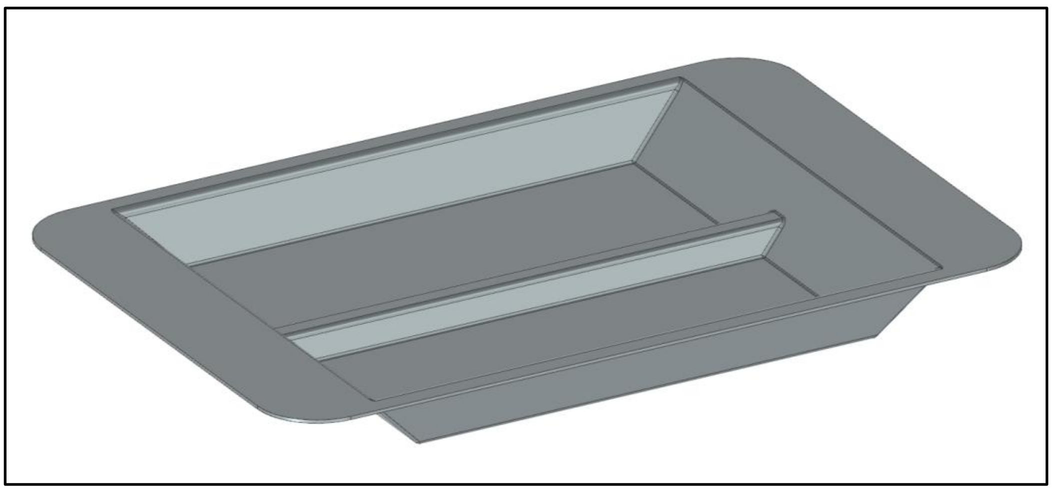

Table 1: CAD of Battery Platter. Dimensions: 2.52m x 1.7m x 0.21m

1. Background

Introduction

Electric vehicles (EVs) are increasingly prominent in the high-performance segment, with models like the Porsche Taycan, Rimac Nevera, Tesla Model S, and Lucid Air Sapphire pushing the boundaries of speed, handling, and range. A critical component in these vehicles is the battery enclosure, which safeguards the battery pack, ensures safety, and often contributes to structural integrity. Traditionally, enclosures are made from steel or aluminum; materials that, while robust, add significant weight and are susceptible to corrosion in harsh environments, such as salted roads in cold, humid regions.

For daily-use vehicles, sheet metal enclosures work great as they are easy to manufacture, cheap, and highly scalable. However, its weight limits its suitability for performance EVs. A perfect example of this fact is that 85% of Formula 1 car's volume is composites, specifically carbon fiber. With EV technology improving rapidly, along with the increasing demand, there is high motivation for producing an electric super car[1] where every kilogram of mass saved influences the acceleration, cornering ability, and top speed of a vehicle.

Material Properties

Composites can be as strong and stiff as traditional steel, while being significantly lighter, positioning them to be used in battery enclosures for EVs, where a steel enclosure can weigh up to 150kgs. An example is carbon fiber reinforced polymers (CFRP), a common family of materials employed for high performance, high force applications, offering a yield strength up to 5000 MPa and Young's Modulus of ~400 GPa, far surpassing mild steel (250 MPa, 210 GPa) (Venkatesan et al., 2025). With a density of 1.55 g/cm^3 versus steel's 7.85 g/cm^3 (Avient, n.d.; Solitaire Overseas, n.d.), CFRP provides a superior strength-to-weight ratio. Such promising materials will be explored in this paper and assessed for suitability for enclosure applications.

Manufacturing Techniques

Resin Transfer Molding (RTM) balances cost and precision for low-volume production (Kopeliovich, 2023), while Advanced Fiber Placement (AFP) offers high precision at a higher cost. Furthermore, manufacturing technology in composites is improving rapidly, which will further reduce costs in the near future. Hence, the application of composites for high performance EVs is ahead of the curve, and it is possible that further decreases in costs can enable a more widespread adoption of composites in the automotive industry.

State of Current Research

There exist research papers on composite based battery enclosures such as Gupta et al. (2024), who explored aluminum and Sheet Molding Compound (SMC), achieving weight reductions through design changes, though with trade-offs in cost and complexity. Similarly, Venkatesan et al. (2025) demonstrated a carbon fiber reinforced polymer (CFRP) enclosure for two-wheelers, reducing deformation by 39-50% and weight by 73% compared to steel, highlighting composites' potential. However, Gupta didn't have an emphasis on performance vehicles and manufacturability, and Venkatesan et al. (2025) worked on two wheelers, lacking verification for vehicles.

[1] Supercar: a street-legal sports car with race track-like power, speed, and handling (Wikipedia)

2. Problem Statement

High-performance EVs require lightweight structures to maximize acceleration, handling, and energy efficiency—key metrics where every kilogram impacts performance. Current steel battery enclosures, weighing 50-160 kg (Bharodiya et al., 2023; Kopeliovich, 2023), limit performance and efficiency, and may not offer optimal corrosion resistance, compromising long-term durability.

Functions

- Protect the battery pack during standard use conditions (e.g., transient road frequency, static loading)
- Protect the battery pack during crash scenarios (e.g., side impact, penetration)

Objectives

This project aims to:

- Design a lightweight, crash-resistant battery enclosure using fiber-reinforced composites.
- Reduce enclosure weight by at least 20% compared to steel benchmarks.
- Optimize structural integrity and energy absorption via finite element analysis (FEA).
- Limit cost premium to 50% over steel, targeting the luxury EV market.

Constraints

The design must:

- Meet SAE J2464 crash standards (Bharodiya et al., 2023)
  - Side crush: Penetration by 150 mm diameter rigid pole for a crush speed of 10mm/min. Termination force should be above 100kN.
  - Shock: 25g acceleration vertically; no component failures
- Maintain structural integrity under operational and crash loads
  - Deformations must be insignificant during regular use
- Achieve a first natural frequency >40 Hz (Gupta et al., 2024).
  - A lower first natural frequency can resonate with other vehicle parts and systems.
- Be electrically insulating to prevent short circuits
- Exhibit high corrosion resistance as platter can also be the underbody for some vehicles

Scope

This project focuses on designing and selecting materials for a composite battery enclosure, validated through FEA simulations. Manufacturing considerations will be explored, though physical prototyping is beyond the current scope.

3. Design Concept

Proposed Solution

This project proposes a fiber-reinforced composite battery enclosure doubling as the vehicle's underbody for high-performance EVs. The design prioritizes weight reduction, crash safety, and structural integration. Only the platter was designed for this project as it's the important part for stiffness and structural integrity and carries the entirety of the load.

Rationale

Reducing weight enhances acceleration, handling, and range—critical for performance EVs. Composites like CFRP offer exceptional mechanical properties, corrosion resistance, and electrical insulation. Targeting the luxury market justifies higher costs, leveraging the premium buyers are willing to pay (e.g., $200K+ supercars).

Design

The enclosure will feature (refer to figure 1):

- Cross members for structural rigidity.
- Curved edges to prevent stress concentration
- Dimensions 2.52m(L) x 1.7m(W) x 0.21m(h) were determined based on an average sampling of wheelbase length and width of Sedans

Underbody Integration

By serving as the underbody, the enclosure simplifies design and manufacturing, getting rid of the necessity for an additional underbody component. This also further reduces the net mass of the vehicle

4. Material Selection

Criteria

Materials must exhibit:

- High yield strength-to-weight ratio.
- High Young's Modulus-to-weight ratio.

- Electrical insulation (with potential coatings).
- Corrosion resistance (with potential coatings).

Additionally, it would be advantageous if:

- The net cost of manufacturing and material is at most 50% more than sheet metal

Material Index

Using Ashby's method, materials will be evaluated based on specific stiffness,

$$M_1 = \frac{E^{\frac{1}{3}}}{\rho}$$

And specific yield strengthc(refer to appendix section A.1 for derivations),

$$M_2 = \left(\frac{\sigma_{yield}^{\frac{1}{2}}}{\rho} \right)$$

Other material constraints is the density ρ being less than steel (Eurocode Applied, n.d.).

$$7850 \frac{kg}{m^3} \geq \rho$$

For steel,

$$M_1 = \frac{(210\ GPa)^{\frac{1}{3}}}{7850 kg/m^3} = 7.57 \cdot 10^{-4} \frac{(GPa)^{\frac{1}{3}}}{kg/m^3}$$

$$M_2 = \frac{235\ MPa}{7850 kg/m^3} = 2.99 \cdot 10^{-2} \frac{MPa}{kg/m^3}$$

Material Selection

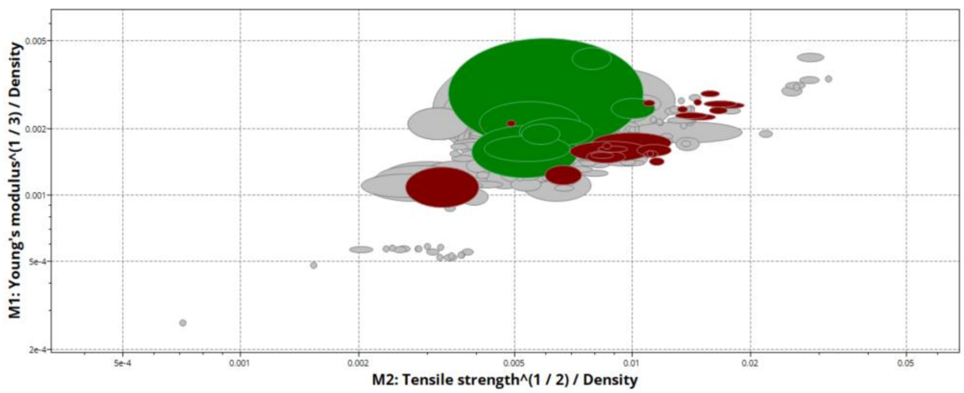

Figure 1: Ashby Material Selection Method

Based on material indices, price, and availability of data, prepreg Epoxy/Carbon fiber and prepreg Epoxy/High Strength Carbon fiber appear to be the best options for the battery enclosure. The higher strength carbon fiber will allow the use of a thinner laminate, which can allow further weight cuts. These materials will be compared with a benchmark sheet steel of 3.78mm (industry standard). Furthermore, both are established materials with well-developed manufacturing methods

Although there are other promising materials, they are either too expensive, not much lighter than steel, or lack data. For instance, there are titanium metal matrix composites which are both expensive and heavy. Zinc and Magnesium metal matrix composites (MMC) are lighter and promising; however, they are experimental materials that are being developed with high costs and scarce data, preventing calculations and simulations.

Justification

Parameters (taken from Granta):

	Structural Steel	Epoxy/Carbon fiber	Epoxy/HS Carbon fiber
$E_1 (GPa)$	200	121	209
$\sigma_{yield} (MPa)$	250	2231	1979
$\rho (kg/m^3)$	7850	1490	1540

Table 2: Steel, Epoxy/Carbon Fiber, Epoxy/HS Carbon Fiber material parameters

These material properties are in the fiber direction, and since we will use laminate with different angled layers, the average material constants of the laminate will be different.

Furthermore, EV batteries tend to operate around 35°C (EV Engineering Online, n.d.), and since Epoxy/Carbon Fiber has proven thermal properties, doing a thermal analysis at standard operating conditions is unnecessary

5. Laminate Design

For both materials, a $[0,90,\pm 45]_s$ layup will be used, resulting in a quasi-isotropic laminate. This will allow the laminate to handle the static loads, as well as be prepared for unexpected loading conditions that may be caused by crashes. For regular Epoxy/ Carbon Fiber, each lamina will be 0.4mm thick, while the high strength one will have 0.3mm thick layers.

6. Analysis and Simulation

FEA (ANSYS) will assess:

- Stress and deformation under static loading (2500N for battery pack, applied vertically).

- Acceleration (25g), applied along with the weight of the battery pack
- Safety Factor (static loading and acceleration)
    - Used a combination of Maximum Shear, Maximum Strain, Tsai-Hill, and Puck failure criterion for safety calculations
- Frequency response (>40 Hz).
- Penetration tests couldn't be performed due to a lack of licensing.

	Structural Steel (3.78mm thick)	Epoxy/Carbon fiber (3.2 mm thick)	Epoxy/HS Carbon fiber (2.4mm thick)
Max $\sigma_{vm}(MPa)$ (static)	13.4	25.4	46.3
Max Deformation (mm)	0.909	7.35	10.4
Factor of Safety (static)	18.7	6.29	4.75
Factor of Safety (25g)	2.84	6.60	6.14
First Natural Frequency	42.8	82.0	37.4
Mass (kg)	121.4	24.6	19.1

Table 3: Outcomes of Static and Frequency Simulations

Epoxy/HS Carbon fiber does not pass the frequency requirements. Thicker plies have almost the same thickness as Epoxy/Carbon fiber, but are more expensive. It can be concluded that for this application, the regular Epoxy/Carbon fiber will be sufficient; however, if company guidelines require higher factors of safety or the platter fails one of the proposed physical tests, the high strength carbon fiber can be substituted for an improvement in performance.

The discrepancy in factor of safety under acceleration is likely due to the difference in the weight of the platters, which directly affects the force felt under identical acceleration.

7. Comparison to Analytical Solution

Based on the analytical solutions using classical laminate theory, the average elastic modulus is 47 GPa for regular Epoxy/Carbon fiber, and the shear modulus is 18 GPa, similar to the ANSYS results which gave 47 GPa and 18 GPa for elastic and shear moduli respectively, indicating that our laminate has been defined correctly.

However, comparison between stresses isn't feasible as assuming the platter to be a plate is incorrect, and the loading is also too complex to simplify enough for applications of theory.

8. Manufacturing Considerations

Production Methods

- **Resin Transfer Molding (RTM):** Ideal for low-volume production, offering precision and moderate cost.
- **Advanced Fiber Placement (AFP):** High precision for premium applications, though costlier.

Given the layup being rather simple, it is more appropriate to use RTM or its variations for the production of the enclosure.

Scalability

RTM suits the luxury niche, with potential for mid-range EV adaptation as automation reduces costs. However, it does have higher initial costs of composites versus metals, along with higher costs for materials.

Epoxy/Carbon Fiber costs $65 per kilogram (Composite Envisions, n.d.), for $0.94 per kilogram for steel (Focus Economics, n.d.). This makes the steel platter cost $114 per unit, while the composite costs $1599 per unit, on material costs only.

Mitigation

Targeting the luxury market offsets costs initially. Hybrid manufacturing[2] techniques may balance performance and affordability. Improvements in composites manufacturing technology may enable scalability.

Corrosivity and Insulation

Due to its graphite structure, carbon fiber is inherently conductive and can suffer from galvanic corrosion if in touch with other metals. Although, the epoxy resin should offset this to a certain extent, a polyurethane coating, or an alternative, is required to reach the required insulation and corrosion resistance.

This is not necessarily a disadvantage as sheet steel also requires coatings for the exact same reasons.

9. Results and Discussion

FEA results, as discussed in section 6, indicate that the use of composites in the battery enclosure can save up to 80% in mass, or 96.8 kg for the platter alone. Assuming that the top enclosure weighs half as much as the platter, the approximate weight cut for a midsize vehicle is ~150 kg. Although this is an astounding weight cut, the premium is ~$1400, or 1300%, which is far above

[2] Hybrid manufacturing techniques combine multiple composite production processes. An example would be employing RTM for cost-effective large panels and AFP critical high stress areas, aiming to balance production costs and performance.

the initial objective. Nonetheless, for a high-end vehicle, this may be premium that is worth the performance boost.

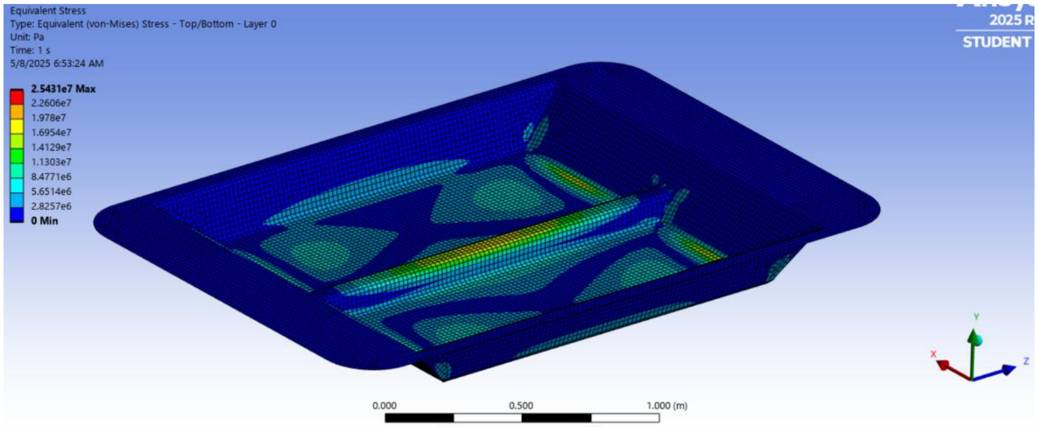

Figure 2: Epoxy/Carbon Fiber Von Mises Stress

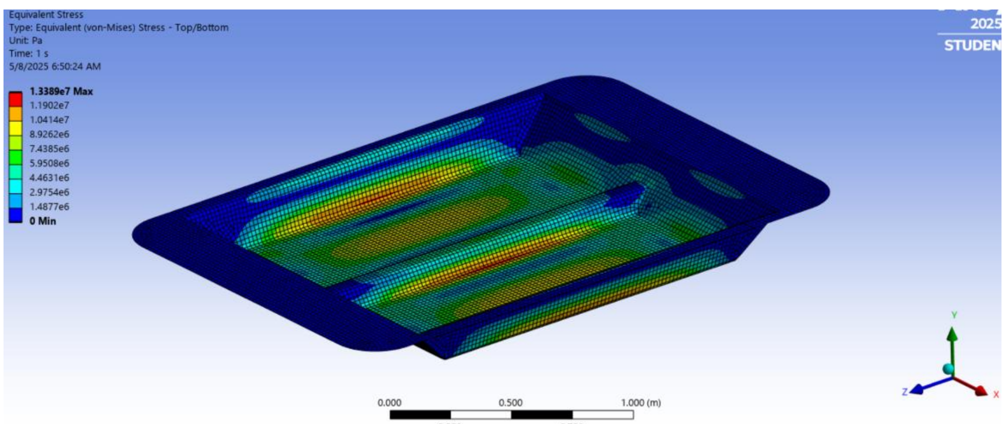

Figure 3: Steel Von Mises Stress

In the Von Mises Stress analysis, stress concentrations occur around bends and cross-frames most significantly. This is proof of design decisions as an alternative to using stronger or stiffer materials and implies that cross-frames should be utilized effectively when the battery platter is being designed for a vehicle.

This could also be an aspect where carbon fiber has an advantage against sheet metal as the latter goes through a series of bends and weldments, which may result in crack formation during production. On the other hand, RTM doesn't have these issues; however, composites themselves are anisotropic — often orthotropic, as was the case for the materials investigated. Therefore, composites require more thorough investigation prior to production to avoid any complications.

10. Conclusion

To compare to the objectives defined initially, the Epoxy/Carbon Fiber:

Objectives:

- Reduced enclosure weight by 80%, surpassing the 20% goal.
- Exceeded the 50% cost premium limit significantly (1300%).

Constraints

- Met the shock requirement per SAE J2464.
- Had small deformation (7.4mm).
- Had a first natural frequency of 82Hz (>40Hz).
- Is insulating and corrosion resistant with the application of coating.

Tests that still need to be performed include penetration tests, physical tests for acceleration and force, drop tests, and fatigue life tests. Furthermore, after coating is applied (e.g. Polyurethane), the electrical and corrosive properties must be verified through fuse tests and corrosion tests.

From a mechanical property standpoint, it is a superior alternative the sheet metal. However, from a manufacturing perspective, with current costs and technology, the price premium and production difficulty are likely not worth it for a sport or performance vehicle that will rarely, if at all, be used in a track setting.

Until either CFRP costs decrease or metal matrix composites (MMC)[3] that are cheaper and easier to manufacture in large quantities are discovered, it is likely that Epoxy/Carbon fiber will be used in race settings, such as F1 cars, or super cars that are priced at $500,000 or more.

[3] A group of materials that use metals as their matrix, which often have very high material costs. Promising experimental MMCs include Magnesium matrix, boron fiber reinforced, and Zinc matrix, titanium carbide particulate reinforced.

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APPENDIX

Section A.1

Index M_1 for light stiff plate

For a light stiff plate, stiffness is defined as (Ashby, 2017, p. 90),

$$S = \frac{F}{\delta} \geq \frac{C_1 EI}{L^3}$$

where the second moment of area I is,

$$I = \frac{bt^3}{12}$$

b is the width of the plate, and t is the thickness. Substituting into the stiffness results in,

$$S = \frac{F}{\delta} \geq \frac{C_1 Ebt^3}{12L^3}$$

The mass of a plate can be defined as,

$$m = \rho V = \rho btL$$

Using worst case scenario,

$$\left(\frac{S \cdot 12L^3}{C_1 b}\right)^{\frac{1}{3}} \frac{1}{E^{\frac{1}{3}}} = \frac{D}{E^{\frac{1}{3}}} = t$$

$$m = \rho bL \cdot \frac{D}{E^{\frac{1}{3}}} = H\left(\frac{\rho}{E^{\frac{1}{3}}}\right)$$

Where H is a geometric constant of the form,

$$H = \left(\frac{S \cdot 12L^3}{C_1 b}\right)^{\frac{1}{3}} \cdot bL$$

Hence, to minimize m, $\left(\frac{E^{\frac{1}{3}}}{\rho}\right)$ must be maximized

$$M_1 = \left(\frac{E^{\frac{1}{3}}}{\rho}\right)$$

Index M_2 for light stiff plate

$$\sigma_y \geq \sigma = \frac{My}{I} = \frac{My}{\frac{bt^3}{12}}\ , y_{max} = t/2$$

$$\sigma_y = \frac{6M}{bt^2}$$

$$t = \left(\frac{1}{\sigma_{yield}}\right)^{\frac{1}{2}} \cdot \left(\frac{6M}{b}\right)^{\frac{1}{2}} = P \cdot \left(\frac{1}{\sigma_{yield}}\right)^{\frac{1}{2}}$$

$$m = \rho V = \rho btL = \rho bP \left(\frac{1}{\sigma_{yield}}\right)^{\frac{1}{2}}$$

$$m = P' \cdot \left(\frac{\rho}{\sigma_{yield}^{\frac{1}{2}}}\right)$$

$$M_2 = \left(\frac{\sigma_{yield}^{\frac{1}{2}}}{\rho}\right)$$

Section B
Code that uses classic laminate theory to analyze the laminate. Used to check laminate engineering constants.

```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd

def read_csv(path: str):
    df = pd.read_csv(path, skiprows=1, header=None)
    arrays = []
    for col in df.columns:
        clean = df[col].dropna().to_numpy(dtype=float)
        arrays.append(clean)

    return tuple(arrays)

def T_1(theta):
    c = np.cos(theta)
    s = np.sin(theta)
    return np.array([
        [c**2,      s**2,        2*c*s],
        [s**2,      c**2,       -2*c*s],
        [-c*s,      c*s,   c**2 - s**2]
    ])

def T_2(theta):
    c = np.cos(theta)
    s = np.sin(theta)
    return np.array([
        [c**2,     s**2,      c*s],
        [s**2,     c**2,      -c*s],
        [-2*c*s,  2*c*s,  c**2 - s**2]
    ])
def clean_matrix(M):
    M_clean = np.where(np.abs(M) < 1e-14, 0, M)  # set noise to zero
    return np.round(M_clean, 1)  # Round to 3 significant digits

def ABD_nt(E1, E2, v12, G12, fiber_angles_deg,index_n,t_list):
    fiber_angles_deg = np.array(fiber_angles_deg)
    index_n = np.array(index_n, dtype = int)
    t_list = np.array(t_list)

    if len(E1) < max(index_n) + 1:
        raise ValueError("Number of materials and number of properties do not match!")
```

```
# Shift z positions by half of the total thickness, geometrically setting the midplane correctly
total_thickness = np.sum(t_list)
mid_shift = -total_thickness / 2.0
z_cum = np.concatenate(([0], np.cumsum(t_list))) + mid_shift

num_mat = np.arange(0,max(index_n)+1)

S = {}

for i in (num_mat):
    S[i] = np.array([
        [   1.0/E1[i],    -v12[i]/E1[i],   0.0      ],
        [  -v12[i]/E1[i],     1.0/E2[i],    0.0      ],
        [      0.0,            0.0,       1.0/G12[i] ]
    ])


Q = { i: np.linalg.inv(S_i)
    for i, S_i in S.items() }

#the +1 arranges for the z(k-1)
k_all = np.arange(len(fiber_angles_deg))+1

# Create empty array
Qbar_all = {}

for k,angle,n in zip(k_all, fiber_angles_deg, index_n):
    theta = np.deg2rad(angle)  # Convert fiber orientation to radians

    T1_theta = T_1(theta)
    T1_theta_inv = np.linalg.inv(T1_theta)
    T2_theta = T_2(theta)

    Qbar = T1_theta_inv @ Q[n] @ T2_theta
    Qbar_all[k] = Qbar

# Create empty matrix
A = np.zeros((3, 3))
D = np.zeros((3, 3))
B = np.zeros((3, 3))

for k,z in zip(k_all,z_cum):
    A += Qbar_all[k]*(z_cum[k]-z_cum[k-1])

    D += 1/3*Qbar_all[k]*(z_cum[k]**3-z_cum[k-1]**3)
```

```
    for k in k_all:
        B += 1/2*Qbar_all[k]*(z_cum[k]**2-z_cum[k-1]**2)

    return A , B , D

def clean_matrix2(M,rundi):
    M_clean = np.where(np.abs(M) < 1e-14, 0, M)  # set noise to zero
    if rundi: M_clean = np.round(M_clean, 1) # Round to 3 significant digits
    return M_clean

def compute_a_star(A, t_list):
    total_thickness = sum(t_list)
    a_star = np.linalg.inv(A/total_thickness)
    return(a_star)

def mat_constants(a_star):
    Ex = 1/a_star[0,0]
    Ey = 1/a_star[1,1]
    Gxy = 1/a_star[2,2]
    vxy = -a_star[0,1]/a_star[0,0]
    nxy_x = a_star[0,2]/a_star[0,0]
    nxy_y = a_star[1,2]/a_star[1,1]
    return(Ex,Ey,Gxy,vxy,nxy_x,nxy_y)

# t_list and fiber angles deg are the thickness and orientation of each layer
# row number 1 is the top
# index_n indicates which material each layer is. Since python, material of first row is 0 in
index_n
E1, E2, v12, G12, fiber_angles_deg, index_n, t_list = read_csv('Lam1.csv')

A,B,D = ABD_nt(E1, E2, v12, G12, fiber_angles_deg,index_n,t_list)

A_clean = clean_matrix(A)
B_clean = clean_matrix(B)
D_clean = clean_matrix(D)

print(f"\nA = t *\n{A_clean}")
print(f"\nB = (t^2) *\n{B_clean}")
print(f"\nD = (t^3) *\n{D_clean}")

a_star = compute_a_star(A,t_list)
a_star_clean = clean_matrix2(a_star, False)
print(f"\na* =\n{a_star}")

Ex,Ey,Gxy,vxy,nxy_x,nxy_y = mat_constants(a_star)
print(f"\nEx     = {Ex:.2f} MPa")
```

```
print(f"Ey     = {Ey:.2f} MPa")
print(f"Gxy    = {Gxy:.2f} MPa")
print(f"vxy    = {vxy:.3f}")
print(f"nxy_x  = {nxy_x:.3f}")
print(f"nxy_y  = {nxy_y:.3f}")


# Exploratory plot of Von Mises stress
def Stress_Distribution(E1, E2, v12, G12, fiber_angles_deg,index_n,t_list,M):
    fiber_angles_deg = np.array(fiber_angles_deg)
    index_n = np.array(index_n, dtype = int)
    t_list = np.array(t_list)

    if len(E1) < max(index_n) + 1:
        raise ValueError("Number of materials and number of properties do not match!")

    # Shift z positions by half of the total thickness, geometrically setting the midplane correctly
    total_thickness = np.sum(t_list)
    mid_shift = -total_thickness / 2.0
    z_cum = np.concatenate(([0], np.cumsum(t_list))) + mid_shift

    num_mat = np.arange(0,max(index_n)+1)

    S = {}

    for i in (num_mat):
        S[i] = np.array([
            [   1.0/E1[i],    -v12[i]/E1[i],   0.0      ],
            [  -v12[i]/E1[i],     1.0/E2[i],    0.0      ],
            [      0.0,            0.0,      1.0/G12[i] ]
        ])


    Q = { i: np.linalg.inv(S_i)
        for i, S_i in S.items() }

    #the +1 arranges for the z(k-1)
    k_all = np.arange(len(fiber_angles_deg))+1

    # Create empty array
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    for k,angle,n in zip(k_all, fiber_angles_deg, index_n):
        theta = np.deg2rad(angle)  # Convert fiber orientation to radians

        T1_theta = T_1(theta)
```

```
        T1_theta_inv = np.linalg.inv(T1_theta)
        T2_theta = T_2(theta)

        Qbar = T1_theta_inv @ Q[n] @ T2_theta
        Qbar_all[k] = Qbar

    # Create empty matrix
    A = np.zeros((3, 3))
    D = np.zeros((3, 3))
    B = np.zeros((3, 3))

    for k,z in zip(k_all,z_cum):
        A += Qbar_all[k]*(z_cum[k]-z_cum[k-1])

        D += 1/3*Qbar_all[k]*(z_cum[k]**3-z_cum[k-1]**3)

    for k in k_all:
        B += 1/2*Qbar_all[k]*(z_cum[k]**2-z_cum[k-1]**2)
    A_inv = np.linalg.inv(A)
    D_prime = np.linalg.inv(D)

    z_cont = np.linspace(z_cum[0], z_cum[-1], 100)
    sigma = np.zeros((len(z_cont), 3))  # Match sigma shape to z_cont

    # Compute stress for each z-coordinate
    for i, z in enumerate(z_cont):
        # Find which layer this z belongs to
        for k in k_all:
            if z_cum[k-1] <= z <= z_cum[k]:
                sigma[i] = z * Qbar_all[k] @ (D_prime @ M)
                break

    sigma = sigma * 1e-6  # Convert to MPa
    return z_cont, sigma

My = (2500/2*1.9/2)/1.7

M = np.array([0,My,0])
z_cont, sigma = Stress_Distribution(E1, E2, v12, G12, fiber_angles_deg,index_n,t_list,M)
sigma_1 = sigma[:,0]
sigma_2 = sigma[:,1]
tau_12 = sigma[:,2]

sigma_vm = np.sqrt(sigma_1**2 - sigma_1*sigma_2 + sigma_2**2 + 3*tau_12**2)
z_cont_mm = z_cont * 1000
```

```
plt.figure(figsize=(10, 6))
plt.plot(z_cont_mm, sigma_vm, 'g-', label=r'$\sigma_v$ (MPa)')

plt.xlabel('z (mm)')
plt.ylabel('Stress (MPa)')
plt.title('Von Mises Stress Distribution Through Laminate Thickness')
plt.grid(True)
```