Design and Development of Arched Beam using Vacuum Infusion

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ABSTRACT

We manufactured beams using vacuum-infusion to fabricate and test carbon-fiber arched beams. Design 1 used discrete top plies and insufficient peel-ply sealing; rapid epoxy exotherm left the vertical walls dry, so its 564 g beam could not be mechanically tested. Design 2 adopted continuous C-shaped ±45°/0° layups, extended peel-ply, and a slower LAM-125/INF-2112 resin: the 884 g specimen (Beam 2) carried 2,907.90 lbf at 1.62 in mid-span deflection, displaying a plateau and then re stiffening curve that tripled the energy absorption of peer beams while failing in support-zone shear. Design 3 tapered the side walls for fixture clearance, reduced C-sections to cut mass, and added high-GSM ±30° wall fabric; its 615 g beam (Beam 3) reached 1,056.40 lbf at 0.32 in but failed abruptly from resin starvation near the supports. Across all teams, the strongest beam was Group 3 Beam 3 at 3200 lbf set the ultimate load ceiling, yet our Beam 2 matched that strength class while absorbing far more energy thanks to its progressive failure mode. Continuous fiber paths, full peel-ply sealing, controlled resin pot-life, and targeted ±45° wall reinforcement emerged as the key levers for achieving high strength, toughness, and manufacturing consistency in lightweight composite arches.

INTRODUCTION

Vacuum-infusion is a closed-mold process where fabric layers are laid dry, covered with peel ply, sealed under a flexible bag, and then saturated when resin is pulled in by vacuum. The pressure differential drives resin through the thickness while air is removed, so voids are minimized. Variations include Vacuum Assisted Resin Transfer Molding, which uses a single rigid mold under a bag, and full Resin Transfer Molding, which clamps fabric between two hard tools for higher pressure. Hybrid routes add flow media only in selected zones to speed wet out of thick parts. Each variant balances tooling cost, part size, and fiber volume fraction. No external autoclave heat or pressure is required, so large structures can be cured with simple ovens. Cycle times are longer than autoclave prepreg but capital cost is lower. As a result, vacuum-infusion is chosen for wind-turbine blades, boat hulls, and prototype airframes.

Arched composite beams are favored when a curved load path must resist bending while clearing internal space. The arch shape puts fibers in combined compression and tension, spreading stress more evenly than a straight beam. Carbon fabric is draped over a bowed core or mandrel, then infused to create a thin-walled, C-section shell. Flexural behavior is evaluated by a three point bending rig: the beam rests on two supports while a central punch applies load until failure. Force and mid-span deflection are recorded to plot stiffness, strength, and energy absorption. Failure often initiates as shear at the supports or local wall buckling near the load nose. The method is standard because it needs only simple fixtures and gives clear comparison data among layups.

Common infusion fabrics include plain-weave or ±45° stitched carbon at 200 to 600 gm^{-2} areal density. High-shear zones may use heavier triaxial or woven hybrids. Epoxy resins with low viscosity (200–400 mPa·s at 25 °C) and pot lives of at least 60 min are preferred, as they wet dense fiber stacks yet cure with minimal shrinkage. Toughened systems add rubber or thermoplastic particles to raise fracture toughness. Slow hardeners permit full impregnation before gel, while post-cure at 60–80 °C raises glass-transition temperature above expected service heat. Dry fiber mass, resin mass, and final void content are measured to compute the fiber-volume fraction that largely controls stiffness. Mechanical targets include bending strength, interlaminar shear, and impact resistance for service safety. These properties are captured by three-point bending, short-beam shear, and drop-weight impact tests.

Industry trends show rapid uptake of vacuum-infused carbon parts in aerospace, automotive, and space hardware. Single-piece wing covers and fairings are moving from autoclave prepreg to VARTM to cut cost on large tools. Automotive carbon use grows about five percent per year as electric cars seek lightweight structures. Space launch firms adopt out-of-autoclave prepreg and infusion to speed prototype tanks, driving the space-prepreg market above USD 270 million by 2032. Research continues on curved sandwich beams that absorb crash energy while staying light, and on automated tape-laying combined with in-situ infusion. Monitoring of resin flow with fiber-optic sensors is being trialed to reduce scrap. Sustainability pushes bio-based epoxies and recycled carbon fabrics into pilot lines. More digital twins now link flow simulation with bend-test data to close the design loop.

Products made with these methods span wind-turbine blades, boat hulls, automotive monocoques, and aircraft control surfaces. Infused carbon arches support drone landing gear, roll-over hoops in sports cars, and footbridges where corrosion must be avoided. Sandwich panels cured this way line refrigerated trucks and cryogenic tanks. High-stiffness camera booms and satellite trusses rely on thin-walled carbon arches to hold position while saving mass. Medical prosthetic blades, sports racquets, and bicycle frames also use vacuum-infused carbon shells for their stiffness-to-weight edge. In civil engineering, carbon arches reinforce masonry vaults without adding bulk. The same processes build custom molds and tooling plates for other composite parts. Thus vacuum-infusion and its variants enable a wide class of lightweight, high-performance structures across many sectors.

MATERIALS USED

1. Epoxy Resin (LAM-125)
   Purpose: Acts as the bonding matrix for the carbon fibers in the composite.

2. Epoxy Hardener (INF-2112)
   Purpose: Initiates the curing process to solidify the epoxy resin.

3. Precision Scale
   Purpose: Measures resin and hardener accurately to ensure correct ratios.

4. Stirring Stick
   Purpose: Mixes the resin and hardener thoroughly to form a uniform mixture.

5. Plastic Cup
   Purpose: Serves as a container for blending the resin and hardener.

6. X-Acto Knife
   Purpose: Cuts carbon fiber panels and other materials to the required shapes.

7. Carbon Fiber Panel
   Purpose: Provides the primary reinforcement for the arched beam structure.

8. Flow Media
   Purpose: Guides the resin through the composite layup for even distribution.

9. Peel Ply
   Purpose: Creates a smooth surface finish and improves resin flow during infusion.

10. Airtac 2 Mega High Tack Adhesive Spray
    Purpose: Bonds the flow media securely to the mold for proper resin transfer.

11. Vacuum Bagging Sealant Tape
    Purpose: Seals the assembly during vacuum infusion to maintain an airtight environment.

12. Release Film
    Purpose: Prevents the resin from adhering to the mold, ensuring clean demolding.

13. Vacuum and Catch Pot
    Purpose: Applies a controlled vacuum and collects excess resin during infusion.

14. Acetone Spray
    Purpose: Softens the foam mold during demolding to aid in the release of the composite.

15. Foam Mold Pieces (Quantity: 3)
    Purpose: Form the template for the arched beam layup during the vacuum infusion process.

16. Tubes for Beam Ends
    Purpose: Maintain the structure's shape and aid in resin flow control during infusion.

PROCEDURE

Below is the procedure for the current project. The process is divided into five sections. Each section presents the steps in bullet form, with each bullet representing one step written in passive voice.

1. Resin Preparation

- The epoxy resin (LAM-125) was measured using a precision scale.
- The epoxy hardener (INF-2112) was measured to achieve the required ratio.
- The measured resin and hardener were combined in a plastic cup.
- The mixture was stirred with a stirring stick until a uniformity was obtained.

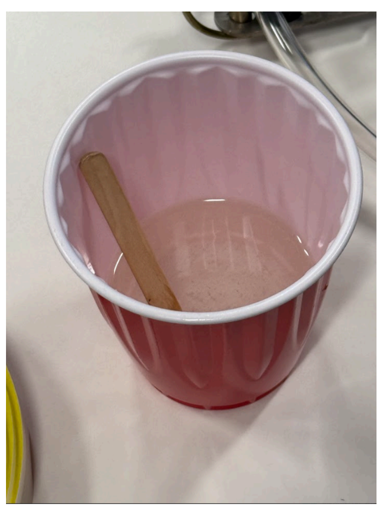


Figure 1: Resin Mixture

2. Material Preparation

- The required shapes were cut with precision using an X-Acto knife and a ruler.
- The carbon fiber sheet was cut to 3 different shapes for the beams.
- The dimensions were 28 in × 4 in, 28 in × 5 in, 10 in × 4 in for the first beam and 28 in × 7 in, 28 in × 4 in, 28 in × 5in for the second beam.

Figure 2: Curved Carbon Fiber Sheet Cutout for Beam 1 (28 in x 4 in)

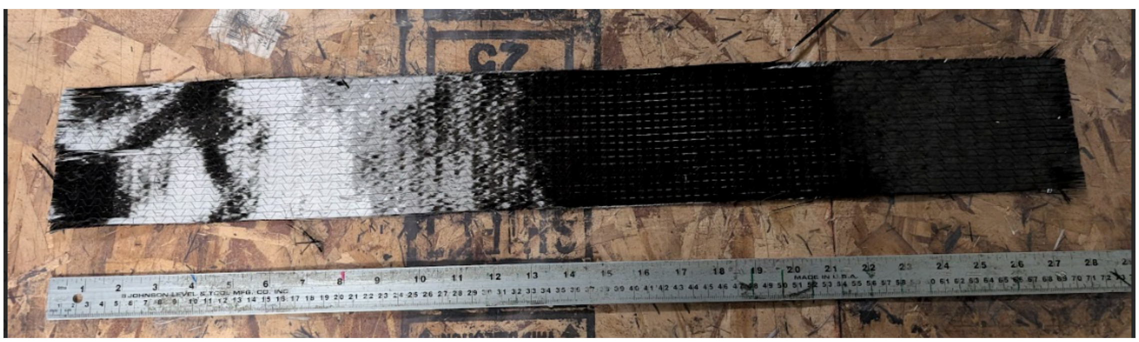


Figure 3: Carbon Fiber Sheet Cutout for Beam 1 (28 in x 4 in)

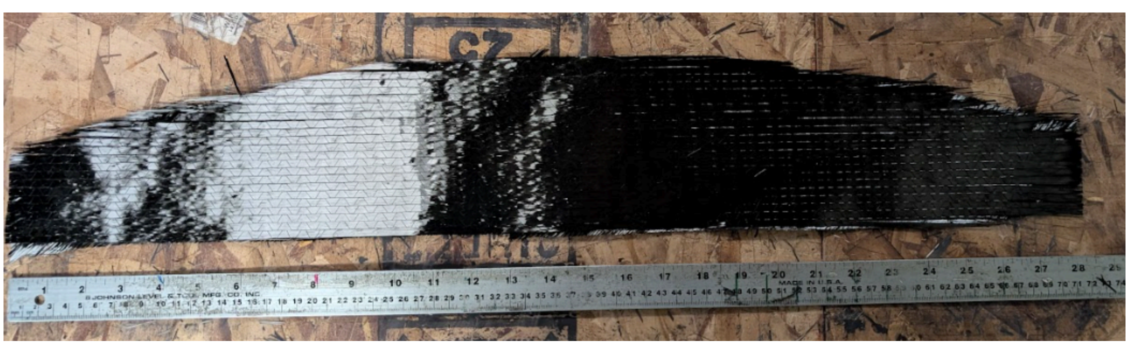


Figure 4: Carbon Fiber Sheet Cutout for Beam 2 (28 in x 5 in)

- The peel ply was cut to appropriate dimensions.
- The flow media was cut to appropriate dimensions.

- Three Foam molds were used to form the beam formation.

3. Layup

- The foam molds were arranged on a clean work surface for assembly.

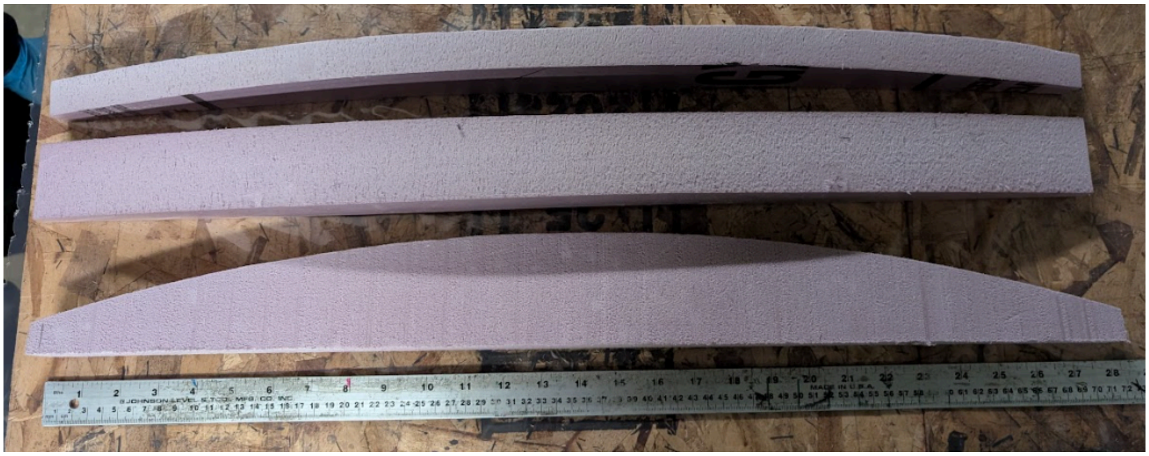


Figure 5: Foam Molds used for layup

- Airtac adhesive spray was applied onto the foam molds to secure the flow media.
- The flow media was then placed on each foam mold to form the base layer.
- The peel ply was laid onto the flow media to maintain a smooth surface.
- The carbon fiber sheets were positioned over the peel ply to form a continuous layup with mid-plane symmetry.

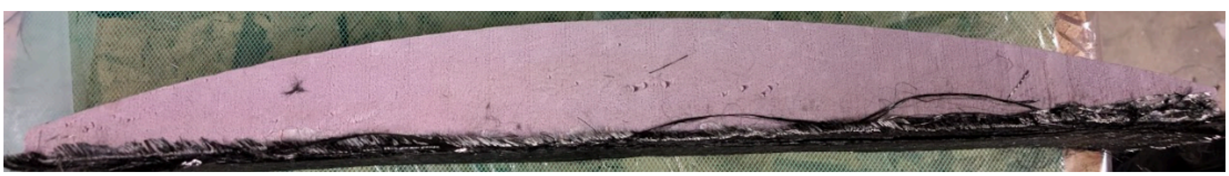


Figure 6: Carbon Fiber layup over mold (Side View)

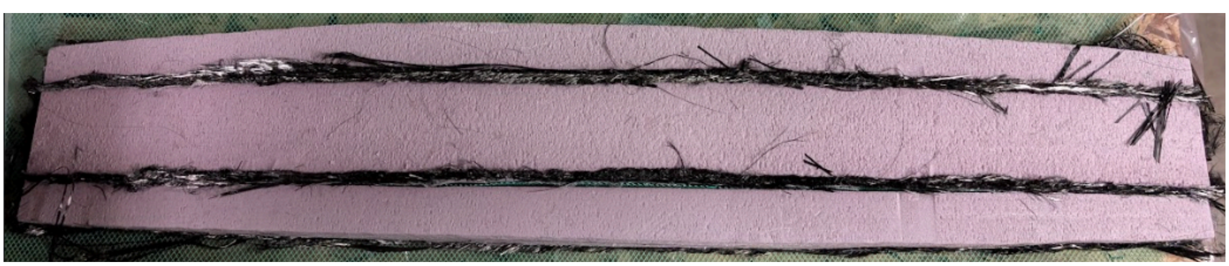


Figure 7: Carbon Fiber layup over mold (Top View)

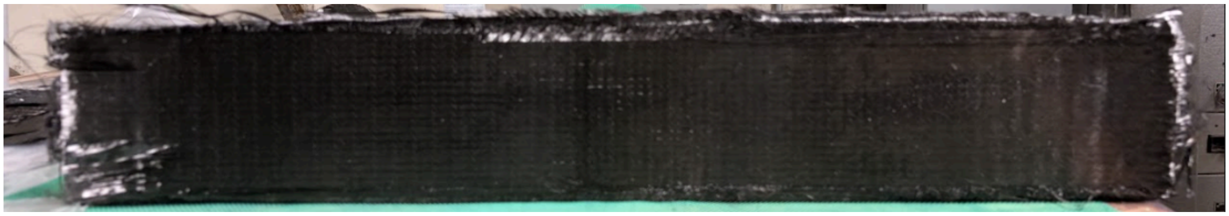


Figure 8: Carbon Fiber layup over mold (Bottom View)

- Finally the peel ply and flow media was placed over the carbon fiber sheets to complete the layup.
- Tubes were connected to the beam ends using tape, and a release film was set over the assembly to prepare for vacuum bagging.

4. Vacuum Infusion and Curing

- The vacuum bag was applied over the assembly and sealed with double-sided sealing tape.
- The vacuum was connected to the catch pot to one tube of the beam to remove excess air from the system.

Figure 9: Catch Pot used to retrieve excess resin

- The prepared epoxy mixture was introduced into the sealed bag from the other tube to initiate resin flow.
- The infusion process was maintained for 12 hours while the resin flowed through the composite layers.

Figure 10: Visible Resin Flow over the Peel Ply and Flow Media

- The assembly was left to cure for 24 hours to ensure full resin setting.

5. Demolding and Testing

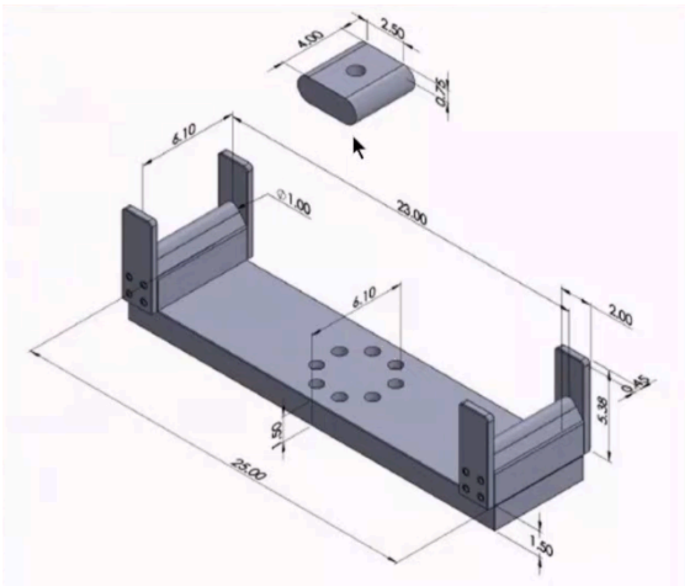
- The cured assembly was removed from the vacuum bag after the curing period.
- Acetone spray was applied to the foam molds to soften and dissolve them.
- The arched beam was demolded by carefully pulling out the softened foam and the peel ply.
- The beam was allowed to cool and stabilize after demolding.
- A three-point bending test was conducted to assess the structural integrity of the beam.

COMPETITION REQUIREMENTS

- Overall length must be at least 24 in and remain in one piece; splices are not allowed.
- Outer envelope of the square beam may not exceed 4 in × 4 in.
- Web layout shall include two or three separate webs with a minimum web‑to‑web gap of 0.75 in.
- Cap overhang beyond each web shall be no less than 0.50 in.
- Fillet radius where a web meets a cap shall not be larger than 0.50 in.
- Cross‑section may be open or closed but may not be solid along any portion of the span.
- Manufacturing methods are limited to wet lay‑up, compression molding, or resin‑transfer molding; filament winding is prohibited.
- Processing equipment may include an oven or autoclave; no other heat sources are specified.
- Material system must use carbon and/or aramid fibres with liquid resin; prepreg materials are not permitted.
- Design load for Category B testing is 7,200 lbf; the specimen must at least reach 1,500 lbf or it will not be ranked.
- Test span between supports is fixed at 23 in (Figure 11).
- Support rollers have a 1 in diameter (Figure 12).
- Loading block measures 4 in × 4.1 in × 1.5 in and contacts the top cap at mid‑span (Figure 9).
- Load‑application rate during testing shall be no less than 1 in min^{-1}.
- Maximum applied point load shall not exceed 25,000 lbf, and a distributed load of 6,250 lbf in^{-1} is the upper limit (Figure 8).

Figure 11 shows the full loading fixture. A 23‑in span is set between two fixed supports, and a recessed well in the base keeps the beam from sliding. Two side plates rise 2 in above the supports to prevent lateral movement, yet they leave room so the beam cannot brace against them.

Figure 12 details one lower contact point. A 1 in-diameter steel pin is seated 2.88 in above the base plate, giving a line contact to reduce stress concentration while still matching the 4 in web-to-cap envelop



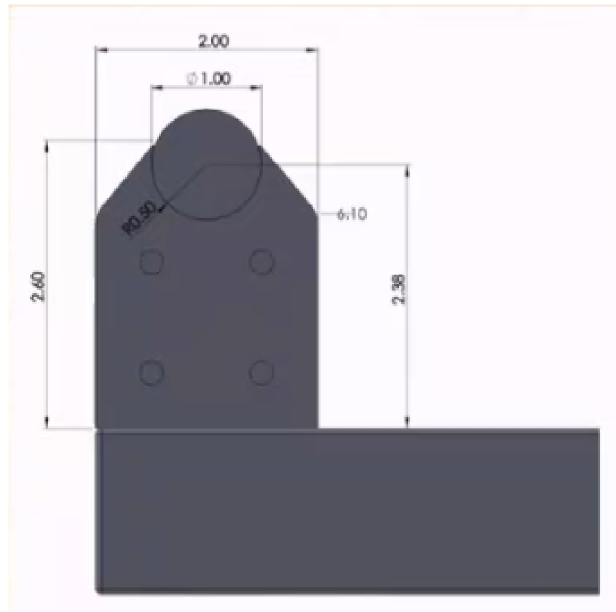
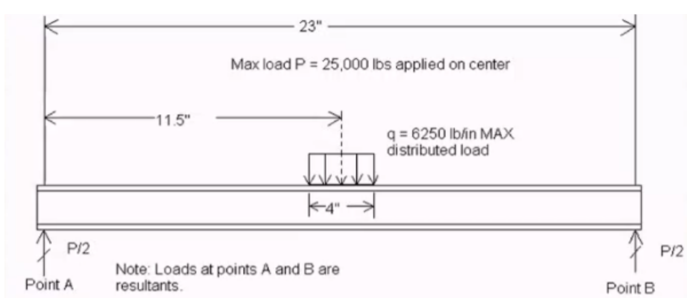


Figure 11: Loading Fixture with Bridge

Figure 12: Lower Contact Point

Figure 13 presents the free-body diagram for the modified three-point bend. A single point load, P, is applied at mid-span, while equal reaction forces act at the supports. An optional distributed load, q, is limited to 6,250 lbf per inch across a 4 in zone beneath the loading block.

Figure 14 gives the dimensions of the loading block. The block is 4 in long, 4.1 in wide, and 1.5 in thick with generous top-edge radii to avoid local crushing. A 2.5 in-deep central hole allows the load cell pin to seat without eccentricity.



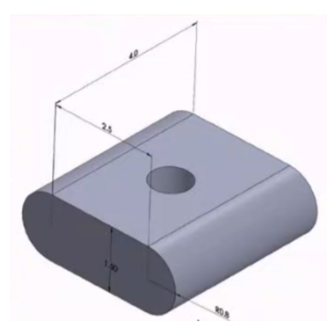


Figure 13: Load Case Free Body Diagram

Figure 14:Loading Block Dimensions

DESIGN 1 CONCEPT

This project marked our first attempt at fabricating an arched square beam using carbon fiber, epoxy resin, and vacuum infusion. The design was tailored to balance structural integrity and weight efficiency while conforming to the constraints of our foam mold system, which included one central mold and two side molds along the length of the beam.

Core Layup Strategy: Center Mold

The layup design began with 16 alternating cutouts designed to span the length of the center mold (28 inches) and wrap around the bottom surface. Each cutout had a width of 6 inches and was tailored to conform to the mold's arch: 4 inches high at the center, tapering to 3 inches at both ends, with an additional 2 inches extending to cover the mold's flat bottom. Alternating the side from which these cutouts folded helped balance the material distribution and fiber orientation throughout the cross-section.

Side Mold Reinforcement and Vertical Wall Formation

To build up the vertical walls of the beam between the center and side molds, additional cutouts were applied on the inner surfaces of the side molds. Two types of cutouts were used:

- **Bottom Coverage Only:** Rectangular pieces of 28 in × 1 in to cover just the bottom of the side mold.

- **Side and Bottom Coverage:** 28 in × 5 in cutouts shaped similarly to the center mold pattern but with only a 1-inch extension for bottom coverage.

These cutouts were alternated to form:

- **8 layers per vertical wall from the side mold**, and

- **8 layers per vertical wall from the center mold**,
  combining to produce **16 layers on each vertical wall** for improved shear resistance and structural uniformity.

The beam's bottom surface, after all alternating layers were placed, was additionally overlaid with a 28 in × 6 in rectangular carbon fiber cutout to ensure a continuous, smooth surface and edge finish.

Top Surface Layup

With the side molds secured, the top layup was completed using two types of cutouts to reduce overall weight while maintaining strength in load-bearing regions:

- A **full-length cutout** (29 in × 6 in), sized slightly larger to accommodate the arch.
- A **shorter reinforcement cutout** (14 in × 6 in), focused on the beam's center where maximum loading is expected.

These were alternated to form a total of **10 layers on the top surface**. To finalize the layup and improve outer smoothness and resin distribution, **two additional full-length top layers** were added across the entire surface.

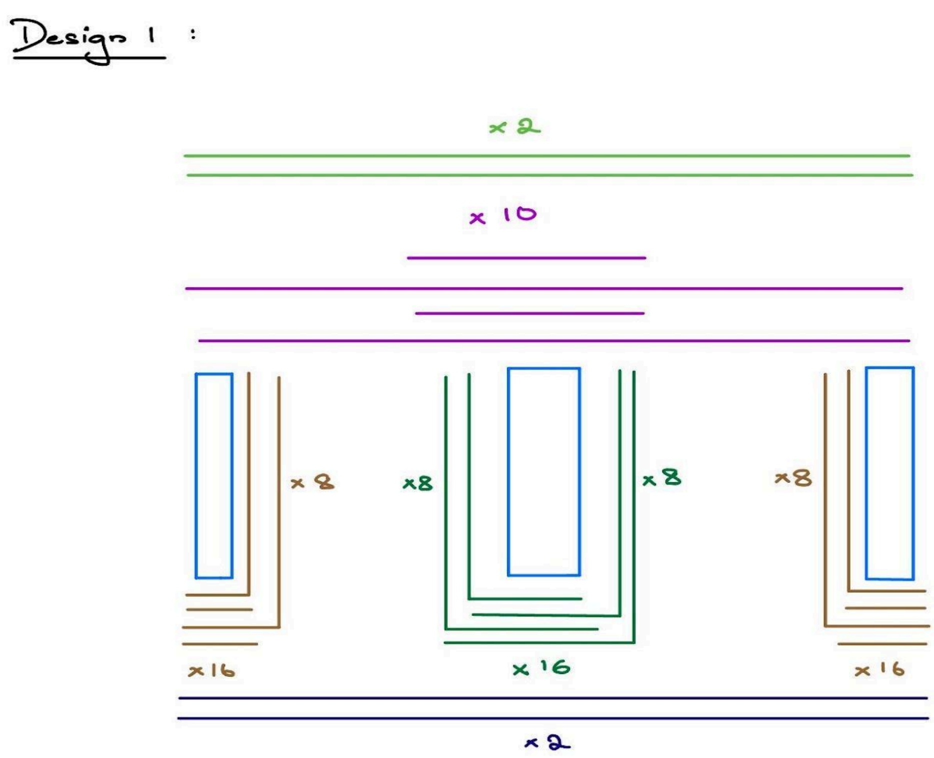


Figure 15: Design Concept for Beam 1

BEAM 1 RESULTS

- Infusion was not completed, so the beam could not be placed in the test rig.

- The inner vertical walls were left almost unattached to the top cap, so resin paths were blocked.
- A large heat rise occurred during cure, and the resin gelled early; flow stopped before reaching the walls.
- Dry fibre bundles were visible after demoulding, showing that air had stayed inside the lay‑up.
- Peel‑ply ended at the flange edge, so a small leak may have reduced vacuum and slowed resin pull‑through.

Figure 16: Beam Layup before Top Layer

Figure 17:Hardened Resin before Infusion

DESIGN 2 CONCEPT

Following the evaluation of our initial beam, we identified a critical flaw in the structural integration of the layup. The original method resulted in discontinuities between the top surface and inner vertical walls, leading to concerns about resin flow and the potential for delamination under load. To correct this, we redesigned the layup to create continuous structural paths and improve bonding during vacuum infusion.

C-Shaped Layup Geometry for Continuity

The revised design introduced **C-shaped layups** for both the center and side molds. Each cutout was shaped to wrap across the **top surface**, down the **vertical wall**, and beneath the **bottom surface**, forming a continuous channel when viewed in cross-section. This ensured structural integration and allowed for consistent resin flow across surfaces.

- **Center Mold Cutouts:**
  28 inches in length × 8 inches in breadth, these cutouts wrapped from the top, down one vertical wall, and under the beam to form the bottom surface.

- **Side Mold Cutouts:**
  28 inches × 6 inches, shaped similarly, these covered the top of the side mold, the outer vertical wall, and extended beneath the side mold.

By alternating these C-shaped cutouts from either side, the entire structure was built up symmetrically and without discontinuities, eliminating the need for independent top-surface layups used in Design 1.

Fiber Orientation Strategy

To further enhance mechanical performance, especially in resisting shear and axial loading, fiber orientation was carefully controlled for each layer:

- **Outer Layer:** 45° fiber orientation, facing outward, to improve resistance to torsion and off-axis loads.

- **Middle Layer:** -45° orientation, facing inward, to counteract shear forces.

- **Inner Layer:** 0° orientation, facing inward and aligned with the beam's axis, to ensure continuity with previously laid plies.

This sequence was repeated consistently, allowing for interlocking fiber paths across adjacent layers.

Layer Distribution

The updated layup maintained and improved upon the previous structural profile with the following distribution:

- **Top Surface:** 16 integrated layers formed from the alternating C-shaped cutouts, **plus 2 additional full-coverage top layers** for surface smoothness and load distribution.

- **Bottom Surface:** Also formed by 16 layers through the integrated layup, with **2 additional full layers** added underneath for reinforcement and edge continuity.

- **Vertical Walls:** 16 layers total, formed by overlapping center and side mold C-shaped cutouts (8 layers from each side).

This integrated strategy provided a significantly stronger, fully bonded composite structure with improved resin infusion, structural integrity, and performance under load.

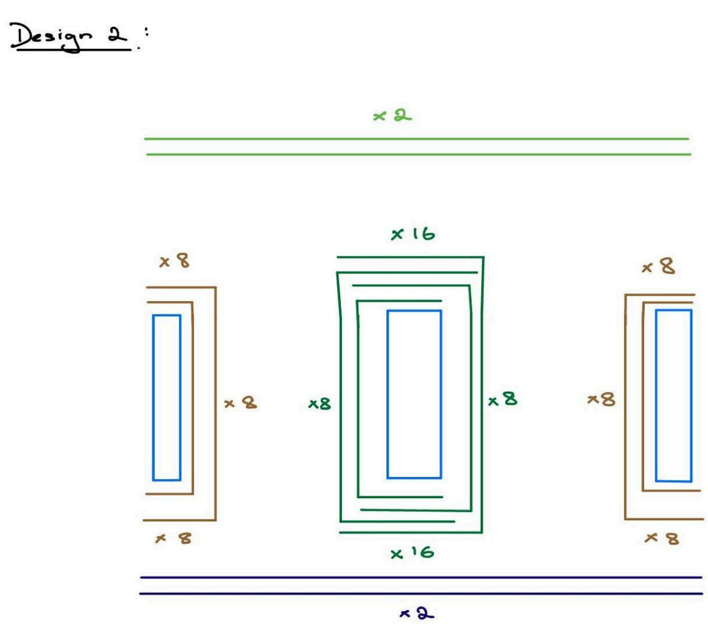


Figure 18: Design Concept for Beam 2

BEAM 2 RESULTS/TESTING

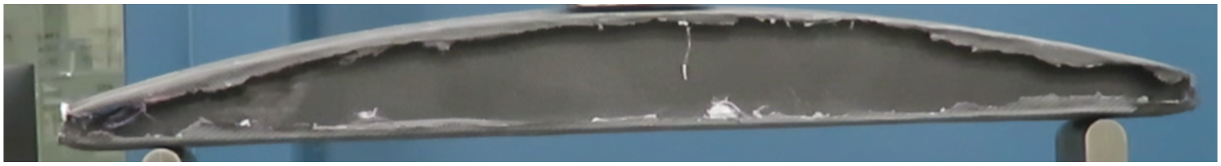


Figure 18: Beam 2 after Demolding

	Specimen ID	Thickness [in]	Width [in]	Length [in]	Max. Load [lbf]	Failure Mode	Notes
1		2.900	4.200	27.6	2907.9	*See Notes Below	
Mean		2.900	4.200	27.6	2907.9		
Std. Dev.		-----	-----	-----	-----		

	Specimen ID	Force at Maximum Load [N]	Displacement at Maximum Load [mm]	Displacement at Maximum Load [in]	Time at Maximum Load [min]
1		12935.20	41.09	1.618	0.90
Mean		12935.20	41.09	1.618	0.90
Min.		12935.20	41.09	1.618	0.90
Std. Dev.		-----	-----	-----	-----

Figure 19: Testing Results for Beam 2

- Beam dimensions were recorded as 27.6 in long, 4.2 in wide, and 2.9 in thick; its weight was 883.9 g.
- The weight matched the planned fibre-to-resin ratio, so gross over- or under-infusion was not expected.
- Patchy resin stripes were noted on both vertical walls before cure, so weak shear zones were anticipated.
- Under loading the force climbed to about 1,200 lbf by 0.8 in of mid-span deflection.
- Between 0.8 in and 1.2 in the load held near 1,200 lbf, which indicated that small cracks began where resin was thin.
- From 1.2 in to 1.6 in the load rose again, peaking at roughly 2,900 lbf as intact fibres carried the bending moment.
- At 1.6 in the force fell sharply to about 1,600 lbf, and the beam fractured without further warning.
- The first break was observed at the right support, confirming a shear failure in the wall-to-cap region.
- Sparse ±45° layers and the locally dry resin near the supports were identified as the chief causes of the failure.

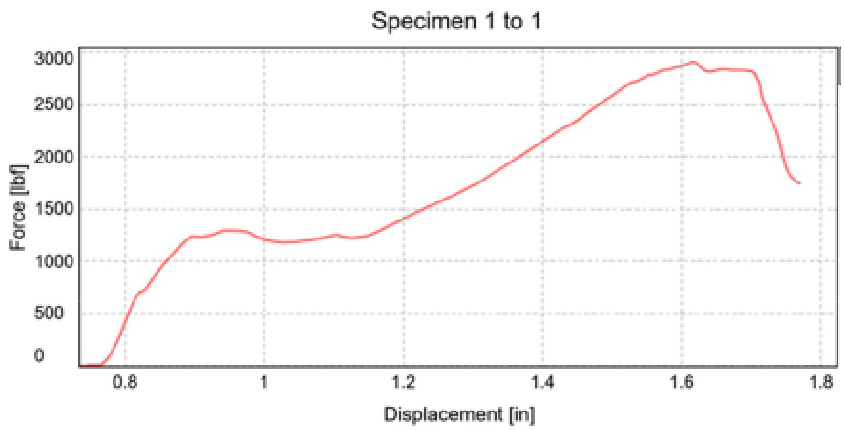


Figure 20: Force vs Displacement Curve for Beam 2

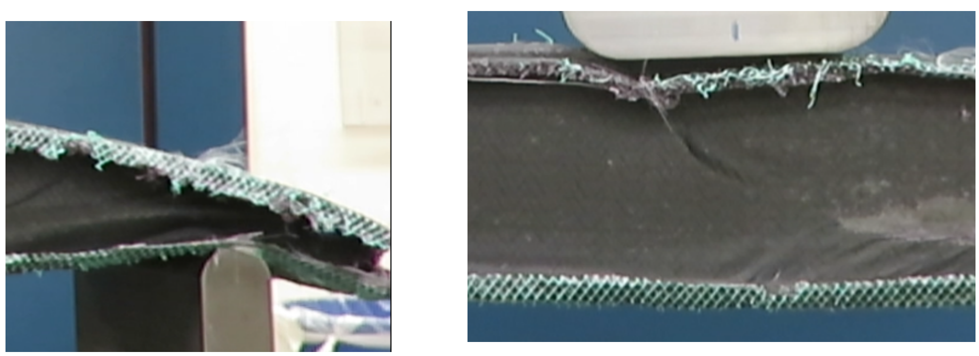


Figure 21: Failure Zones for Beam 2

DESIGN 3 CONCEPT

Following the testing of our second beam, we identified a flaw at the end support and there was no proper resin distribution. We redesigned the layup introducing tapered sections at the end supports to improve shear strength.

C-Shaped Layup Geometry

The revised design used **C-shaped layups** same as our second beam for both the center and side molds. Each cutout was shaped to wrap across the **top surface**, down the **vertical wall**, and beneath the **bottom surface**, forming a continuous channel when viewed in cross-section. This ensured structural integration and allowed for consistent resin flow across surfaces.

- **Center Mold Cutouts:**
  28 inches in length × 8 inches in breadth, these cutouts wrapped from the top, down one vertical wall, and under the beam to form the bottom surface.

- **Side Mold Cutouts:**
  28 inches × 6 inches, shaped similarly, these covered the top of the side mold, the outer vertical wall, and extended beneath the side mold.

- **Taper Sections for ends:**
  3 inches × 4 inches, 4 inches × 5 inches, 5 inches × 6 inches, 6 inches × 7 inches (each quantity of 4) cover the ends of side molds added after every C Section of 28 inches × 6 inches.

Fiber Orientation Strategy

To further enhance mechanical performance, especially in resisting shear and axial loading, fiber orientation was carefully controlled for each layer:

- **Outer Layer:** 45° fiber orientation, facing outward, to improve resistance to torsion and off-axis loads.

- **Middle Layer:** -45° orientation, facing inward, to counteract shear forces.

- **Inner Layer:** 0° orientation, facing inward and aligned with the beam's axis, to ensure continuity with previously laid plies.

- For tapered sections we used 30°/60° sheets.

This sequence was repeated consistently, allowing for interlocking fiber paths across adjacent layers.

Layer Distribution

The updated layup maintained and improved upon the previous structural profile with the following distribution:

- **Top Surface:** 10 integrated layers formed from the alternating C-shaped cutouts, **plus 2** rectangular pieces to create tapered structure, **plus 4 additional full-coverage top layers** for surface smoothness and load distribution.

- **Bottom Surface:** formed by 14 layers through the integrated layup, with **4 additional full layers** added underneath for reinforcement and edge continuity.

- **Vertical Walls:** 16 layers total, formed by overlapping center and side mold C-shaped cutouts, at the end to create tapered structure we added **plus 4** on each end.

This integrated strategy provided a significantly stronger, fully bonded composite structure with improved resin infusion, structural integrity, and performance under load.

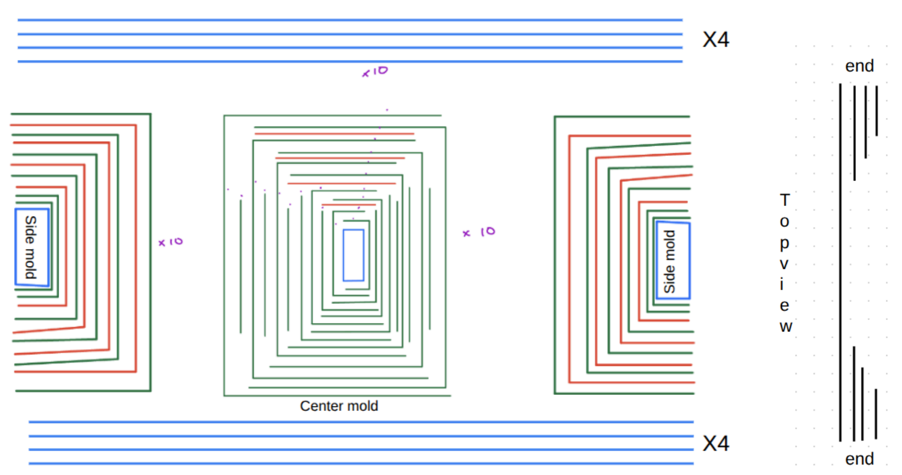


Figure 22: Design Concept for Beam 3

BEAM 3 RESULTS/TESTING

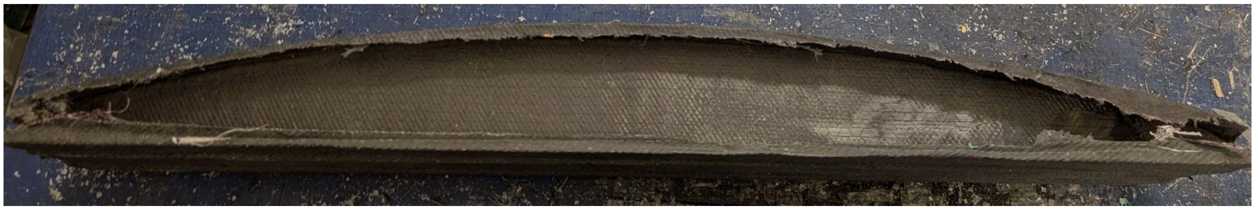


Figure 23: Beam 3 after Demolding

	Specimen ID	Thickness [in]	Width [in]	Length [in]	Max. Load [lbf]	Failure Mode	Notes
1		2.800	4.250	27.2	1056.4	*See Notes Below	
Mean		2.800	4.250	27.2	1056.4		
Std. Dev.		-----	-----	-----	-----		

	Specimen ID	Force at Maximum Load [N]	Displacement at Maximum Load [mm]	Displacement at Maximum Load [in]	Time at Maximum Load [min]
1		4698.96	8.23	0.324	0.41
Mean		4698.96	8.23	0.324	0.41
Min.		4698.96	8.23	0.324	0.41
Std. Dev.		-----	-----	-----	-----

Figure 24: Testing Results for Beam 3

- Beam length measured 27.2 in, 0.4 in shorter than Beam 2; thickness measured 2.8 in, 0.1 in thinner; width held at 4.25 in.
- Mass recorded at 615.0 g, which was 269 g lighter than Beam 2 and signalled a lower resin volume.
- Uneven flow lines were visible on the vertical walls before cure, so weak shear bands were expected.
- During loading the force rose smoothly to about 1,050 lbf by 0.30 in of mid-span deflection.
- A rapid peak of 1,056 lbf occurred at 0.32 in; no secondary stiffening stage was present.
- Force dropped at once to roughly 600 lbf within the next 0.20 in, indicating sudden structural loss.
- Fracture initiated at the left support; the break combined shear and compression in the wall-to-cap joint.
- Unsaturated fabric and scarce ±45° reinforcement near the supports were judged to be the main causes of the low load capacity.

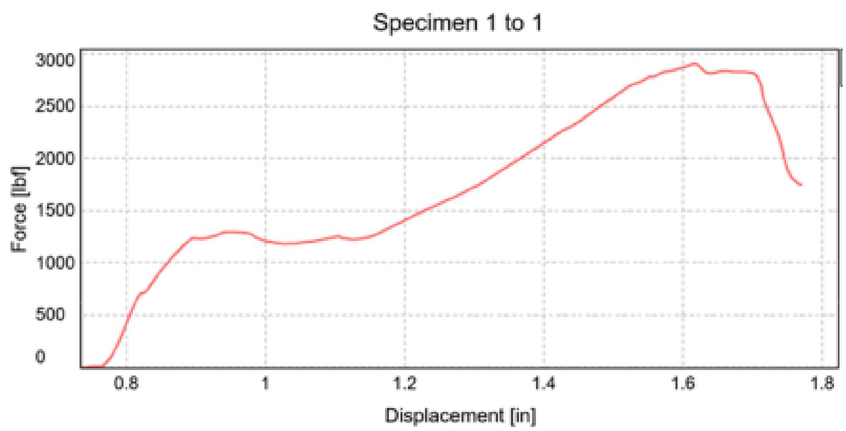


Figure 25: Force vs Displacement Curve for Beam 3

Figure 26: Failure Zones for Beam 2

HORIZONTAL COMPARISON

A comparative analysis of all three beams fabricated by our team reveals the progressive improvements in structural performance, resin infusion, and material efficiency across iterations.

- **Beam 1** could not be mechanically tested due to premature gelation and dry vertical walls. Inadequate peel ply sealing and rapid resin exotherm led to delamination risks and flow interruption.

- **Beam 2**, with an integrated C-shaped layup and ±45°/0° fiber orientations, exhibited the highest strength and energy absorption. It withstood a peak load of **2,907.9 lbf** with **1.62 in** mid-span deflection, albeit failing in shear near the support due to locally dry walls.

- **Beam 3** achieved significant weight savings (615 g), but at the expense of structural integrity. It failed abruptly at **1,056.4 lbf** due to inadequate wall reinforcement and incomplete infusion.

Beam Characteristics	Beam 1	Beam 2	Beam 3
Maximum Load Capacity (lbf)	**N/A**	**2,907.90**	**1,056.40**
Deflection at Peak Load (in / mm)	**N/A**	**1.618 in (41.09 mm)**	**0.324 in (8.23 mm)**
Beam Weight (g)	**564.12**	**883.91**	**615.04**
Length	**27.2**	**27.6**	**27.2**
Width	**4.1**	**4.2**	**4.25**
Thickness	**2.75**	**2.9**	**2.8**

The following bar chart compares the peak load each of our beams could withstand during testing. Beam 2 clearly outperformed Beam 3, reaching a maximum load of 2,907.9 lbf, while Beam 3 failed at 1,056.4 lbf. Beam 1 was not tested due to incomplete resin infusion.

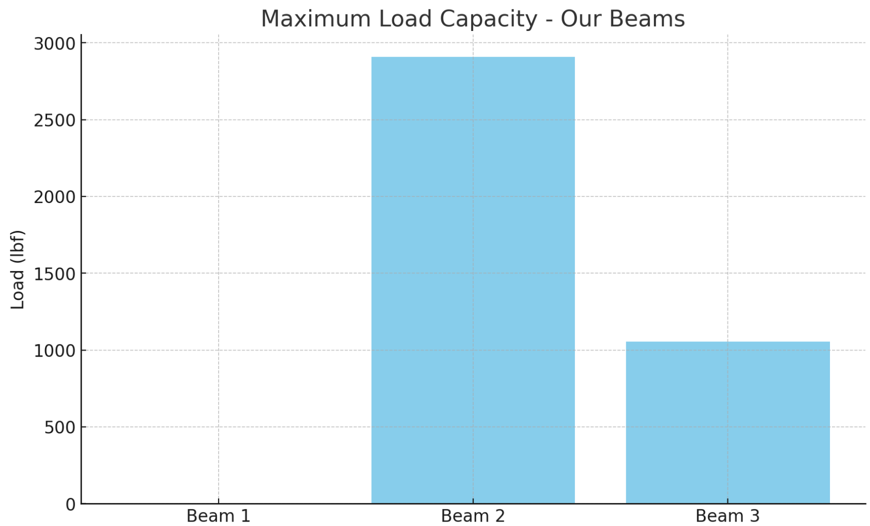


Figure 27: Maximum Load Capacity Group 2

The following graph displays the weight of each beam, highlighting the trade-off between structural strength and mass. Beam 3 was the lightest at 615 g due to reduced material usage and simplified geometry, while Beam 2 was the heaviest at 884 g. Beam 1 weighed 564 g but could not be tested. The graph illustrates how Beam 2's higher weight contributed to better load-bearing performance.

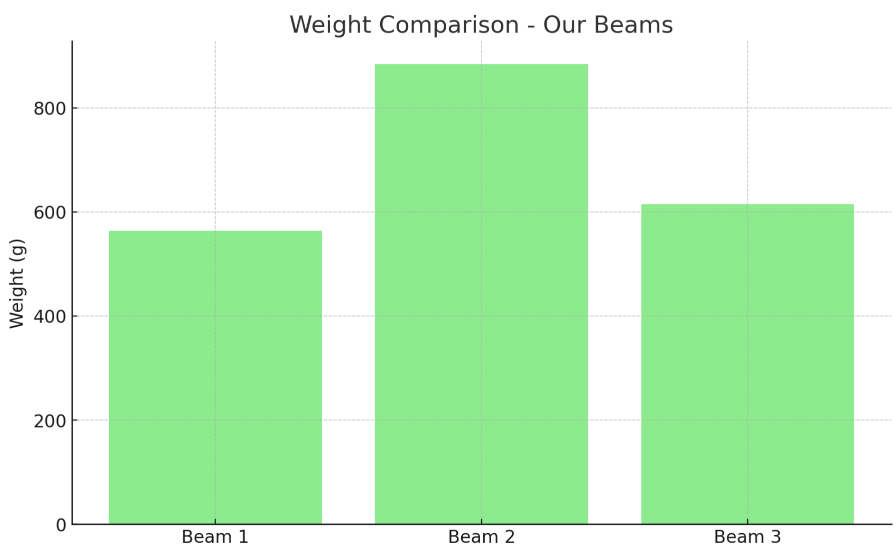


Figure 28: Weight of beam Group 2

The following line chart shows the relationship between deflection and maximum load for each tested beam. Beam 2 exhibited a significantly larger deflection at peak load (1.62 in), indicating a ductile failure and greater energy absorption. Beam 3 showed minimal deflection (0.32 in), reflecting a brittle failure mode. The chart highlights the enhanced toughness of Beam 2 due to its progressive failure.

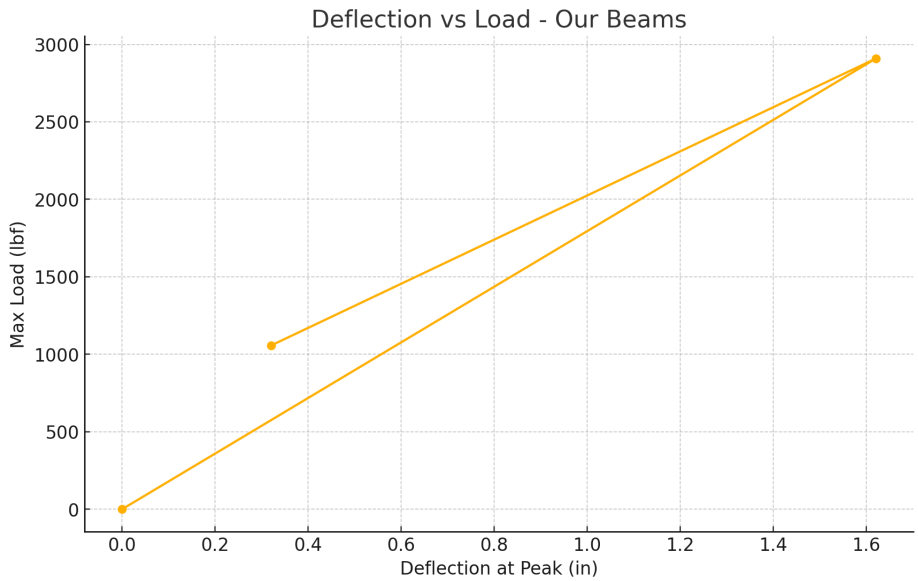
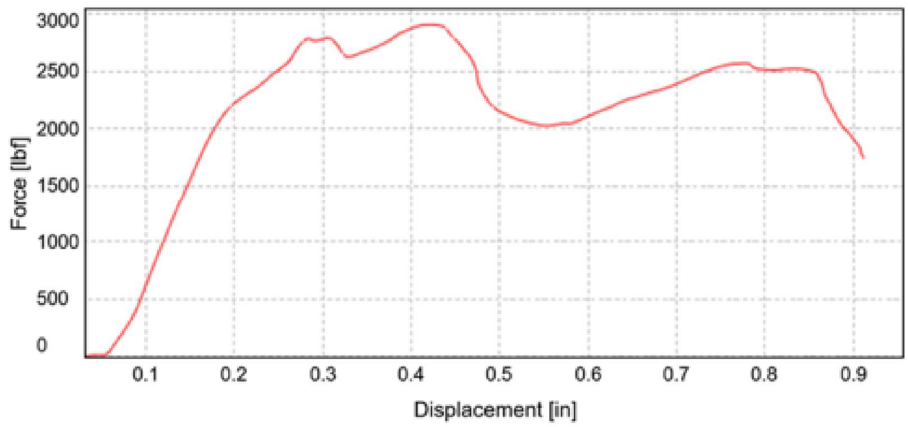
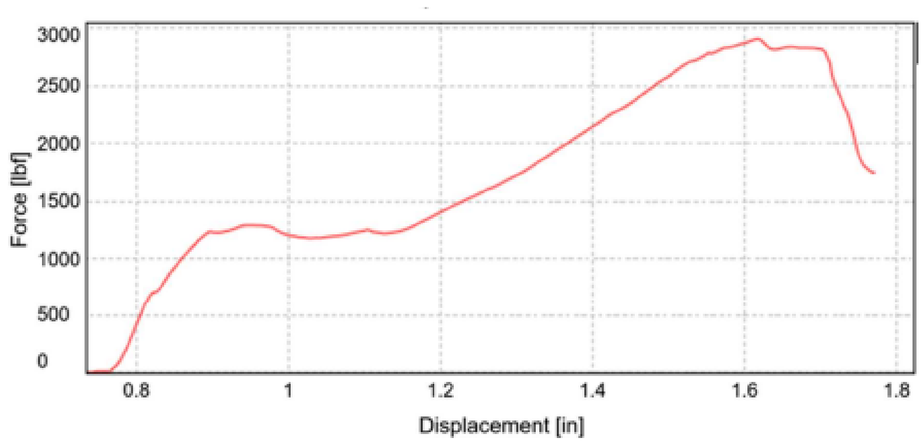
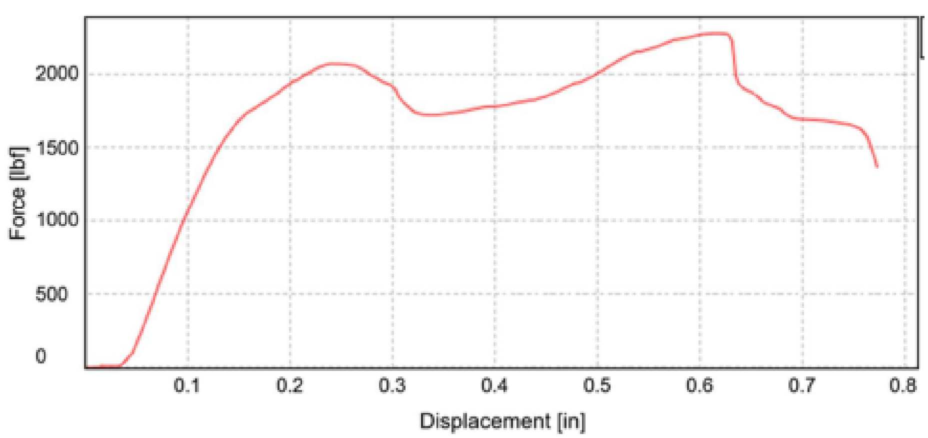


Figure 29 : Deflection v/s Load Group

VERTICAL COMPARISON WITH OTHER GROUPS

	BEAM #1
TEAM #1	
TEAM #2	
TEAM #3	

The comparative analysis of the force vs. displacement behavior across the three groups reveals distinct performance characteristics and failure modes. Group 1's Beam 1 exhibited a steep load curve, rapidly reaching a high peak of approximately 2,906 lbf at a relatively low deflection (~0.42 in). This indicates a high stiffness beam with minimal ductility, suggesting strong bonding but a brittle failure mode likely due to insufficient energy absorption and reinforcement at stress concentrations.

Group 2's Beam 2, in contrast, demonstrated a unique progressive failure pattern. After an initial climb to ~1,200 lbf, it plateaued, then surged to a peak of 2,907 lbf at 1.62 in deflection—the highest energy absorption among all. This behavior suggests the beam effectively redistributed stresses even after microcrack initiation. Its controlled resin infusion and integrated C-shaped layup likely enhanced interlayer bonding and toughness.

Meanwhile, Group 3's Beam 2 showed a rapid but limited load increase, peaking at 1,056 lbf with only 0.32 in deflection. This brittle response reflects localized shear failure and resin starvation near the supports, compounded by insufficient ±45° reinforcement layers. Although lighter than the others, it sacrificed structural resilience for weight, resulting in early catastrophic failure.

Group 2 had the most load endured and with high energy absorption, but it deformed quite a bit in the beginning, which is noticeable from the deflection values compared to the other teams.

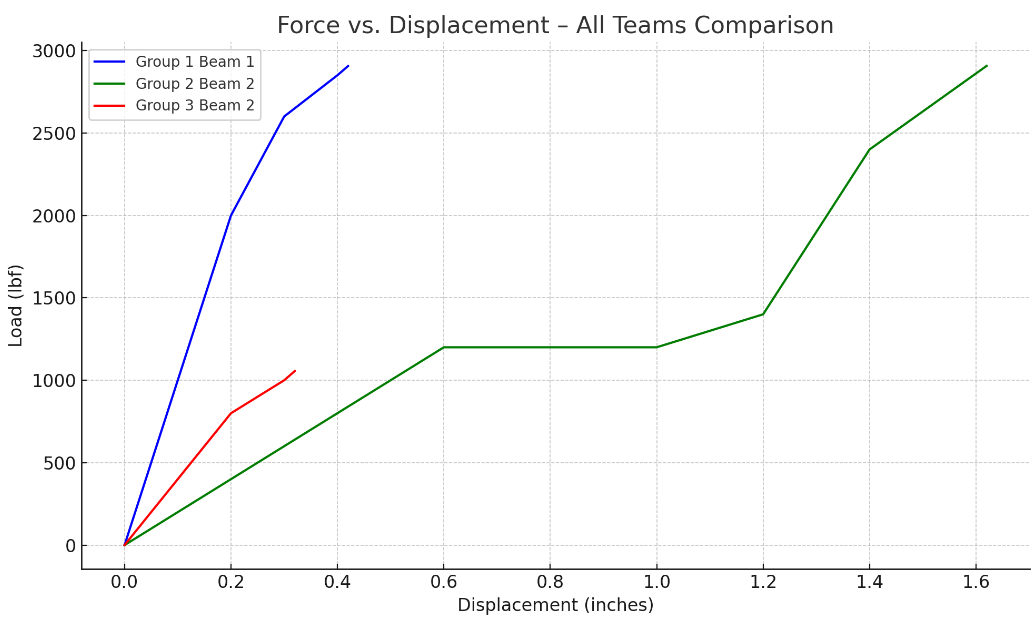
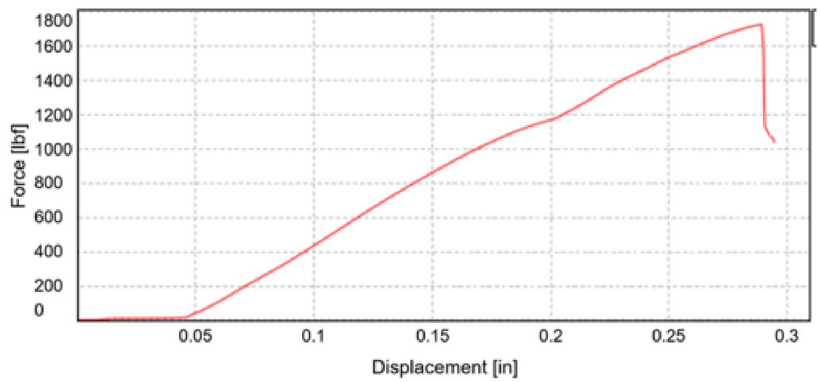
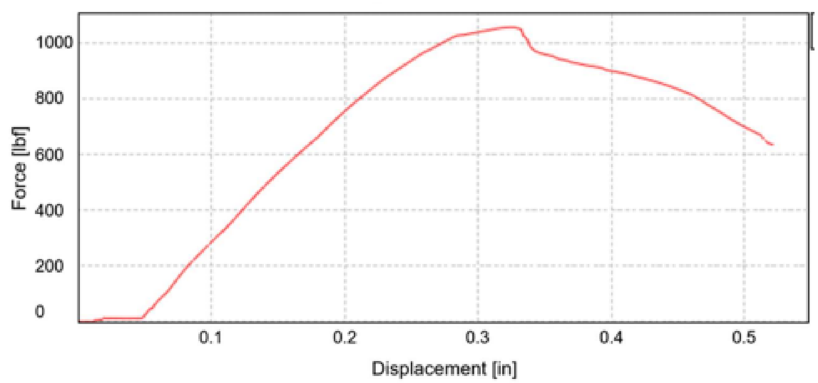


Figure 30 : Beam #1 of all teams

	BEAM #2
TEAM #1	
TEAM #2	

Both Group 1 and Group 2 beams reached nearly identical peak loads (~2,907 lbf), but their failure modes differed. Group 1 Beam 2 failed abruptly with minimal deflection (0.42 in), showing high stiffness and predictable performance—ideal for bridges where excessive bending is unsafe. In contrast, Group 2 Beam 2 deflected significantly (1.62 in) before failing, which shows toughness but risks structural collapse after prolonged sagging. For bridge applications, Group 1's beam is the safer and more reliable design.

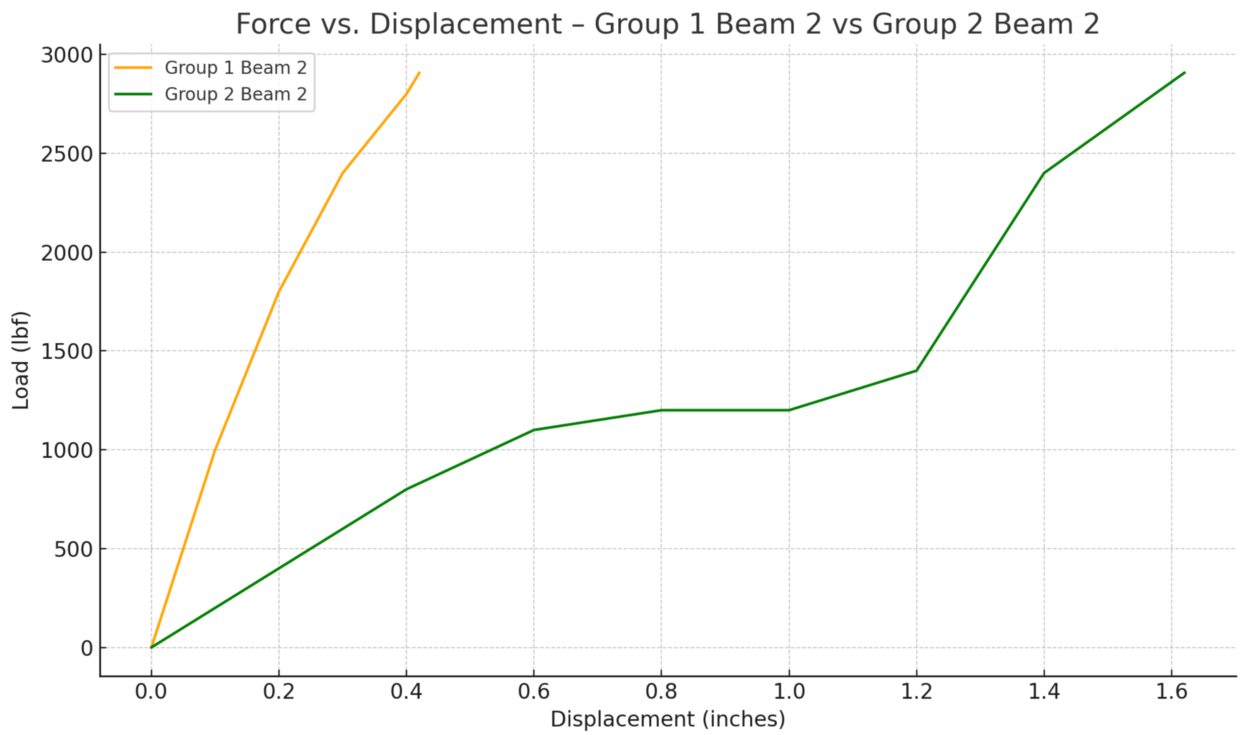


Figure 31: Beam #2 of all teams

PRO TIPS

- When cutting c-shaped sections for the center mold, cut out 0.5 inches less than what is required as it has the tendency to go beyond the edge and eventually create bumps during layup.
- Never place the mesh and the fiber together as it can get quite hard to separate them without damaging the fiber.
- Cut with the 45/-45 wave facing upward for a cleaner and easier cutouts.
- While laying up, always use minimal adhesive between layers as it can lead to patchy resin infusion.
- The mesh should always fit inside the edges of the foam mold while the side molds and the ends of the center mold need to have an extra inch of peel ply to grab onto while demolding.
- Always make sure that the resin is mixed well with the hardener before infusion.
- While vacuum bagging, notice pressure drops and listen for sounds indicating leaks.
- Ensure that the peel ply has no folds and is completely smooth during layup.

CONCLUSION

This project successfully explored the iterative design, fabrication, and testing of carbon fiber arched beams using vacuum infusion techniques. Across three beam iterations, our team progressively refined the layup strategy, fiber orientation, and resin infusion quality to meet structural performance goals and competition constraints.

The first beam had problems because the resin hardened too quickly and didn't fully reach all parts of the mold. This happened because we heated the resin too much and didn't control the resin flow properly. Also there was a detachment between the top surface and vertical walls. From this, we learned how important it is to manage the layup and resin process carefully. In the second beam, we used a better design with C-shaped carbon layers and planned the fiber angles more thoughtfully. As a result, Beam 2 was the strongest, reaching the minimum load of 1500 pounds (even though the graph shows 2,907.9 pounds there was an initial shear failure at around 1500 pounds).

Design 3 aimed to reduce weight (as the 2nd beam was 884g) while addressing known weak points with tapered wall sections and targeted ±30° reinforcement. Though significantly lighter, Beam 3 fell short in mechanical strength due to under-infusion near the supports, emphasizing that weight savings must not compromise critical reinforcement.

Comparative testing with other groups, the project underscored the importance of precise fiber placement, full resin saturation, and strategic layering in producing high-performance composite structures.

Ultimately, this hands-on study deepened our understanding of vacuum infusion processes and structural composites, equipping us with valuable insights into failure mechanisms, material behavior, and manufacturing challenges. These skills are directly translatable to aerospace, automotive, and structural applications where lightweight and high-strength composite solutions are in increasing demand.