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Linking Targeted Undergraduate Research with Capstone Design Projects: A Framework for Composites Fabrication by Resin Infusion

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Abstract:
Several capstone mechanical engineering projects use composites as a structural material. A few examples are student competitions such as American Institute of Aeronautics and Astronautics (AIAA) Design–Build–Fly (DBF), Formula SAE (FSAE), Shell Eco-Marathon, etc. However, students participating in these projects often have limited background in composite fabrication techniques, leading to a trial-and-error approach during manufacturing and design integration. With the extensive use of composites in student design competitions, a framework for composites fabrication will be beneficial. Supported by the funding from Indiana Space Grant Consortium (INSGC), two junior mechanical engineering undergraduate students at Trine University were hired to explore composites fabrication by 'Resin Infusion' with the intention of creating a checklist for fabricating high-quality aircraft components for the AIAA DBF competition. This project spanning the 2025–26 academic year involves (a) PI/advisor-led training on basic composites fabrication, (b) working with the capstone team to learn aircraft design and fabrication for the AIAA DBF competition, and (c) students-led exploration of the resin infusion method to generate the wings, fuselage and other critical components of the RC aircraft for the competition. While basic composites fabrication method of wet layup and vacuum bagging have been traditionally used to fabricate RC aircraft components for the AIAA DBF competition, there are significant drawbacks with this method with respect to quality and consistency of parts. With resin infusion (or vacuum infusion) being the best alternative to overcome these drawbacks, this project will enhance the understanding of this method for future implementation. By the end of this project, students will produce a checklist in the form of a booklet that will include (a) layup schedule, (b) sketch/image of the molds, (c) infusion equipment checklist, (d) infusion process checklist, and (e) infusion postprocessing checklist. This checklist can serve as a practical guide for fabricating critical aircraft components—such as the wing and fuselage—for future AIAA Design–Build–Fly (DBF) competitions. In addition, it can be used as a reference resource for other capstone design projects and student competitions that incorporate composites as primary structural material. This paper will outline the process of mentoring undergraduate researchers in advanced composites fabrication, present lessons learned from implementing resin infusion in student-built aircraft components and highlight how this experience informs future capstone design and manufacturing courses. The project demonstrates how targeted undergraduate research can be linked with capstone design projects.

1. Introduction

Composite materials are increasingly used in undergraduate mechanical engineering capstone projects, particularly in student design competitions that demand lightweight and high-performance structures [1-4]. As a result, fiber-reinforced polymer composites have become common structural materials for aircraft wings, fuselages, and other load-bearing components. These projects require students to consider not only structural design, but also manufacturability, material selection, and fabrication quality. Despite this increased use, composite fabrication techniques are often not covered in depth within the core mechanical engineering curriculum. As aerospace programs continue to expand and engage more students, there is a growing expectation that graduates develop a functional, hands-on understanding of composite manufacturing processes, in addition to theoretical knowledge. Many students encounter composite manufacturing for the first time during capstone projects, where learning occurs concurrently with design and fabrication. While this experiential learning is valuable, the absence of a structured fabrication framework can lead to inconsistent part quality, inefficient manufacturing practices, and limited transfer of knowledge to future student teams.

This work is informed by experiential and scaffolded learning principles, in which students progress from instructor-led training to independent application in an authentic engineering context. This paper presents a structured educational framework that links targeted undergraduate research with capstone design through composite fabrication by resin infusion. The framework emphasizes PI-led training, student-led exploration, and the development of a detailed fabrication checklist to support consistent and high-quality composite manufacturing outcomes. Although demonstrated using composite manufacturing, the underlying pedagogical approach is broadly applicable to other technical areas within mechanical and aerospace engineering.

2. Project Context and Objectives

Beginning in Fall 2025 and extending through the 2025–26 academic year, the project engaged two junior-level mechanical engineering students at Trine University whose work was supported by funding from the Indiana Space Grant Consortium (INSGC). The students were selected based on their interest in composites and aerospace structures and their involvement in student design projects. The two students were not enrolled in the senior capstone course and were not responsible for capstone design deliverables.

The objectives of the project were to:

1. Provide PI-led training in basic composite fabrication techniques.
2. Introduce resin infusion as an advanced composite manufacturing method suitable for aircraft components.
3. Develop a structured fabrication checklist to guide future AIAA Design–Build–Fly and capstone teams.

The project was coordinated with a senior capstone aircraft design team participating in the AIAA Design–Build–Fly competition, allowing undergraduate researchers to understand aircraft design requirements and fabrication constraints**.** This structure created a pipeline model in which junior students developed manufacturing expertise early while supporting capstone teams and improving continuity between cohorts.

3. PI-Led Training in Basic Composite Fabrication

The initial phase of the project focused on PI-led instruction in composite materials and fabrication fundamentals. Training consisted of short, on-the-spot lectures and instructor-led demonstrations conducted for approximately two hours per week. Lectures were limited to essential concepts directly related to the fabrication tasks being performed. This instructor-led phase was intentionally limited in duration and designed to prepare students for independent fabrication work later in the project, ensuring sufficient time remained for capstone fabrication activities. The student-led phase aligned with capstone fabrication timelines and did not replace required capstone design or build activities. The instructor-led training comprised lectures and demonstrations related to wet layup, vacuum bagging, and resin infusion methods, as described below.

3.1 Wet Layup

Students were trained in wet layup fabrication, including fabric cutting, resin mixing, manual wetting of fibers, and laminate preparation. Emphasis was placed on fiber orientation, resin control, and surface finish.

3.2 Vacuum Bagging

Following wet layup, students were trained in vacuum bagging techniques. They learned to assemble vacuum bag stacks, select consumables, verify vacuum integrity, and troubleshoot leaks. This phase highlighted both the benefits and limitations of traditional fabrication methods.

3.3 Resin Infusion

After completing foundational training, students transitioned to resin infusion as an advanced fabrication method. Activities included basic mold preparation, dry fiber layup, placement of peel ply and flow media, setup of infusion lines, vacuum integrity checks, and controlled resin flow. The PI-led instruction included hands-on demonstration of fabricating a flat carbon fiber composite plate using resin infusion, during which students documented key observations in order to subsequently apply the learned fabrication skills to more advanced aircraft components.

4. Student-Led Exploration of Resin Infusion

After completing foundational training in resin infusion, students progressed to fabricating the critical components (wing, fuselage, tailplane, etc.) of the fully designed AIAA DBF competition aircraft based on the design presented by the senior capstone team. In order to aid in the fabrication, students also carried out mold-making for these components using the on-campus CNC router, with only minimal guidance provided to encourage independent problem-solving and hands-on learning. Fig. 1 illustrates the student-led resin infusion process used to fabricate one half of the AIAA DBF competition aircraft wing-skin, with the approximate material and consumable cost for the wing-skin estimated at $100–$120, excluding molds and capital equipment.

5. Development of the Resin Infusion Fabrication Checklist

The primary deliverable of the project was a resin infusion fabrication checklist in the form of a booklet designed to function as both a manufacturing guide and an educational resource. The checklist is intended as a training tool for novice fabricators rather than a standardized industrial protocol. In addition to outlining the fabrication steps, the checklist requires students to record key details such as vacuum readings, resin mixing ratios, and observations during the process. This encourages students to think carefully about how each step affects part quality instead of relying on trial and error. The checklist also helps future capstone teams by preserving fabrication knowledge and reducing repeated mistakes from year to year. The sections of the checklist are presented in Table 1.

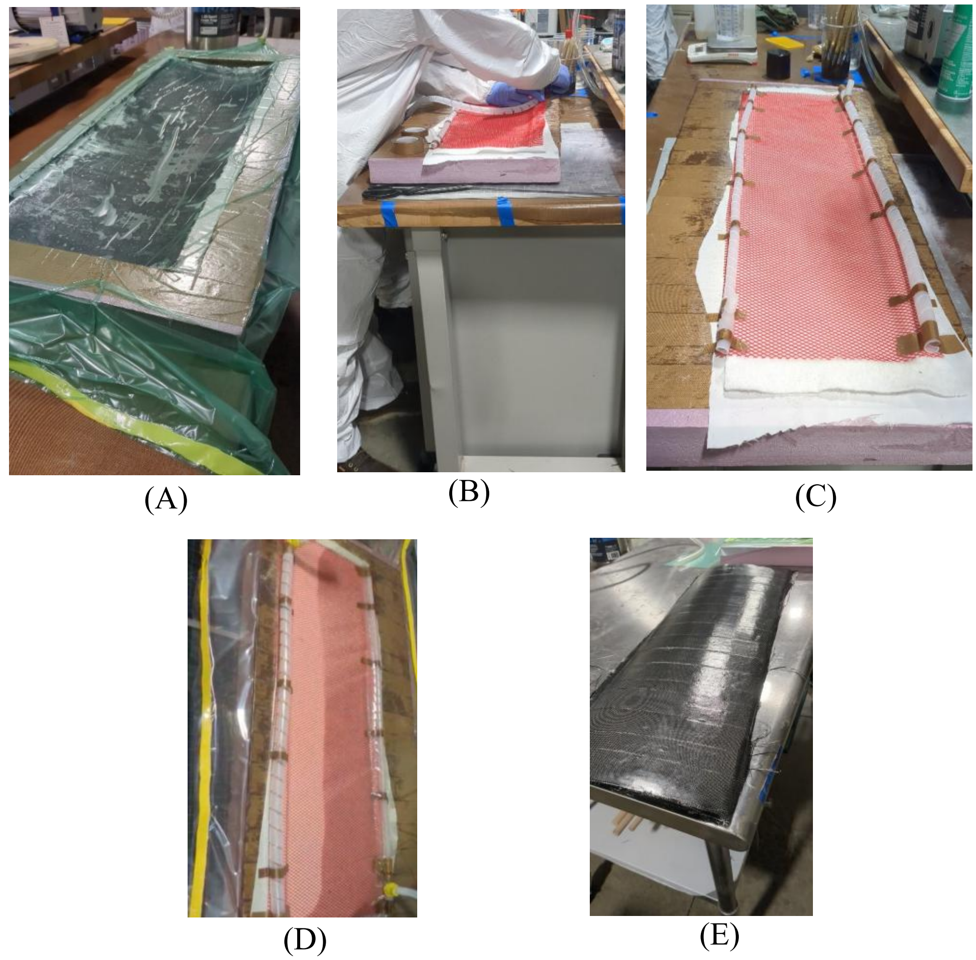

Fig. 1. Student-led resin infusion exploration for creating one-half of the AIAA DBF aircraft wing skin including: (A) wet lay-up and vacuum bagging trial; (B) resin infusion preparation; (C) completed resin infusion setup; (D) resin infusion process with resin flowing from the inlet to the outlet side, and (E) completed one-half of the AIAA DBF aircraft wing.

Table 1. Resin Infusion Checklist

Checklist Section	**Brief Description / Purpose**
Part Identification	Records the part number and brief description of the component being fabricated, establishing traceability between the fabricated part, aircraft design, and documentation.
Infusion Checklist (General Information)	Captures the fabrication date, part number, and part description at the start of the infusion process to ensure all data are associated with the correct component.
Sketch/Image of the Mold and Link to the Part File	Provides visual documentation of the mold and a reference to the digital part file, clarifying mold geometry, orientation, and tooling intent.

Sketch/Image of the Layup (Including Consumables)	Documents the planned layup configuration, including fiber layers and consumables such as peel ply and flow media, to support correct sequencing and setup verification.
Infusion Setup Checklist	Verifies readiness of the infusion system, including vacuum lines, pump condition, gauge calibration, and confirmation that no fabric or bag bridging is present prior to vacuum pull.
Vacuum Integrity Check Data	Records vacuum pressure over time and pressure decay behavior to assess system leakage and vacuum stability before resin introduction.
Infusion Process	Confirms resin and hardener condition, cleanliness of mixing tools and containers, and readiness of timing equipment to ensure proper material handling.
Resin and Hardener Mixing	Documents resin-to-hardener weight ratios, additional resin allowances for consumables, room temperature, target and actual weights, and mixing times to reinforce precision and process control.
Sketch of the Infusion Path	Captures the intended resin flow path, including inlet and outlet locations, promoting planning of resin distribution during infusion.
Infusion Time	Records infusion start and end times, allowing students to relate process duration to resin flow behavior and part quality.
Infusion Post-Process	Verifies that vacuum and resin inlet lines are properly clamped after infusion.
Curing and Demolding Time	Documents curing start and end times and demolding completion to emphasize controlled curing and careful part removal.
Notes on Mold Quality After Demolding	Provides space for qualitative observations regarding mold condition and part release, encouraging reflection on tooling and surface preparation.
Weight Fraction of the Part	Records the final weight fraction of the fabricated part, offering a quantitative indicator of material usage and fabrication efficiency.

6. Assessment Instrument: Retrospective Pre–Post Survey

To assess student learning and the educational impact of the project, a retrospective pre–post survey was administered to the two participating students at the conclusion of the project. The two students involved in this project rated their perceived level of knowledge and skill before and after participation using a five-point Likert scale:

1 = Very Low / Poor
2 = Low
3 = Moderate
4 = High
5 = Very High / Excellent

It is important to note that the small sample size (n = 2) limits the generalizability of the survey results. Accordingly, the survey is used as a formative and exploratory assessment rather than a summative evaluation. In addition, retrospective pre–post surveys rely on self-reported data and are known to be susceptible to student bias when compared to direct assessment methods. These limitations are considered when interpreting the results presented in this paper. The different categories of the survey are presented below.

Category 6.1: Knowledge and Understanding

Survey Item   Before (1–5)   After (1–5)

1. Your understanding of composite materials
2. Your understanding of the differences between wet layup and resin infusion
3. Your familiarity with the equipment used in resin infusion (vacuum pump, resin trap, lines, flow media)
4. Your ability to describe the resin infusion process clearly
5. Your understanding of why resin infusion may improve composite quality

Category 6.2: Hands-On Skills and Application

Survey Item   Before (1–5)   After (1–5)

1. Your ability to prepare molds correctly before layup
2. Your ability to set up, seal, and verify an effective vacuum system
3. Your confidence in placing peel ply, flow media, and infusion mesh correctly
4. Your ability to identify and troubleshoot vacuum leaks
5. Your ability to carry out resin infusion steps with minimal guidance

Category 6.3: Project Integration and Learning Impact

Survey Item   Before (1–5)   After (1–5)

1. Your understanding of how fabrication decisions affect aircraft design
2. Your ability to interpret DBF aircraft component requirements during fabrication
3. Your ability to collaborate effectively with a capstone aircraft design team
4. Your ability to apply classroom concepts to hands-on composite fabrication

Category 6.4: Checklist Development and Educational Outcomes

Survey Item   Before (1–5)   After (1–5)

1. Your contribution to developing the resin infusion checklist booklet

2. Your understanding of how the checklist will guide future DBF or capstone teams
3. Your ability to document fabrication steps accurately and clearly
4. Your understanding of the full resin infusion workflow after creating the checklist
5. Your ability to identify best practices for resin infusion and include them in the checklist

Category 6.5: Reflective Questions (Open-Ended)

1. Describe one major skill you gained or strengthened during this project.
2. What part of the resin infusion process did you find most challenging, and how did you learn to overcome it?
3. How did collaborating with the aircraft design team influence your understanding of composite fabrication?
4. Which section of the checklist did you contribute to the most, and why is it important for future users?
5. How will the knowledge and skills gained from this project support your future engineering work?

7. Results and Discussion

On the retrospective pre–post scale (1-5), the largest gain a student can report for any question is a 4-point increase in score. In this analysis, this 4-point change represents the maximum possible gain in understanding and corresponds to a normalized average of 1.0 (or 100%). The Normalized Average Gain (NAG) percentage for each question is calculated using the following expression: $NAG\ \% = \frac{Average(Score_{after} - Score_{before})}{4} \times 100$

The NAG % for the 19 Likert-scale questions is presented in Fig. 2 as data bars — reported as the percentage of the maximum possible gain in understanding. For sake of conciseness, the survey questions are abbreviated.

Category	Question #	Question (abbreviated)	NAG (%)
6.1	1	Understanding of composite materials	62.5
	2	Differences between composite materials	87.5
	3	Familiarity with resin infusion equipment	75
	4	Ability to describe resin infusion process	87.5
	5	Understanding why resin infusion is used	75
6.2	1	Mold preparation before infusion	50
	2	Vacuum setup, sealing, and verification	75
	3	Confidence with peel ply / flow media	87.5
	4	Troubleshooting vacuum leaks	50
	5	Carrying out resin infusion steps	100
6.3	1	Impact of fabrication decisions	50
	2	Interpreting DBF aircraft components	37.5
	3	Team collaboration effectiveness	37.5
	4	Applying classroom concepts hands-on	75
6.4	1	Contribution to infusion checklist	75
	2	Understanding role of checklist	75
	3	Documenting fabrication steps	37.5
	4	Understanding full infusion workflow	25
	5	Identifying best practices	62.5

Fig. 2. NAG % for each survey question

From Fig. 2, the highest gains were seen in outcomes related to performing the resin infusion process**.** Students showed the greatest improvement in carrying out resin infusion steps (100%), indicating strong confidence in executing the process after repeated practice. High gains were also observed in describing the resin infusion process, confidence with peel ply and flow media, and understanding differences between composite materials (87.5%). These results show that working directly with materials, equipment, and molds helped students clearly understand both how and why resin infusion is used.

Moderate gains (75%) were observed in familiarity with resin infusion equipment, vacuum setup and verification, understanding why resin infusion improves composite quality, and applying classroom concepts hands-on. Checklist-related outcomes also showed strong gains (75%), demonstrating that developing and using the fabrication checklist helped students stay organized and follow the process more effectively.

Lower gains were found in outcomes that require deeper thinking beyond following steps**.** Skills related to mold preparation, troubleshooting vacuum leaks, and understanding the impact of fabrication decisions showed moderate improvement (50%). This suggests that while students could perform tasks correctly, they were still developing experience in diagnosing problems and understanding how early decisions affect final part quality.

The lowest gains were seen in understanding the full resin infusion workflow (25%), documenting fabrication steps, interpreting DBF aircraft components, and team collaboration effectiveness (37.5%). These results indicate that students tend to focus on individual fabrication tasks rather than the complete manufacturing process or team coordination. This finding supports the need for structured documentation and workflow tools, such as the resin infusion checklist developed in this project.

Overall, the results show that hands-on resin infusion is highly effective for teaching composite fabrication skills. At the same time, the findings highlight the need for additional emphasis on documentation, process integration, and teamwork to help students develop a more complete understanding of composite manufacturing in capstone design projects.

8. Educational Outcomes and Lessons Learned

The structured progression from basic composite fabrication methods to resin infusion strengthened student confidence and process understanding. Checklist development reinforced documentation practices, systematic thinking, and awareness of fabrication best practices. The combination of PI-led training and student-driven exploration proved effective in supporting experiential learning.

9. Broader Impacts and Future Work

The fabrication framework and checklist developed in this work are transferable to other capstone projects and student competitions that incorporate composite materials. More broadly, the educational structure presented—early undergraduate research engagement, scaffolded training, and development of reusable instructional resources—can be applied to other technical areas such as additive manufacturing, robotics, thermal systems, and experimental testing.

The scope of this paper is limited to the development and documentation of a resin infusion fabrication checklist based on a targeted undergraduate research experience. Future work will focus on evaluating the effectiveness of the checklist through repeated implementation with additional student cohorts, including assessment of its impact on fabrication consistency, student learning outcomes, and reduction in trial-and-error during composite manufacturing. In addition, the checklist will be refined based on user feedback and integrated into formal manufacturing and composites coursework.

10. Conclusions

This paper presented a structured framework for linking targeted undergraduate research with capstone design projects through composite fabrication by resin infusion. Two INSGC-funded undergraduate students progressed from basic fabrication methods to advanced resin infusion and produced a practical checklist to support consistent manufacturing of aircraft components. While the survey results are based on self-reported data and a limited sample size, they provide useful insight into student learning in an authentic, hands-on fabrication environment. The project demonstrates how undergraduate research can enhance experiential learning while directly supporting capstone design outcomes.

11. Acknowledgment

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