Manufacturing and Testing in Support of Aerospace Structural Design Projects

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Abstract

This paper describes the experience with two projects conducted by students in the senior *Aerospace Structural Design* course in the Department of Aerospace Engineering at Mississippi State University. One project involved the design, fabrication, and testing of columns with unstable cross sections while the other involved the design, optimization, fabrication, and testing of stiffened panels under axial compression. An overview of each project, the specific activities performed by the students, and the lessons learned in the process are described in this paper.

I. Introduction

Design experience has traditionally been identified as an important component of engineering education. The engineering faculty and administrators are constantly reminded by industry about the importance of design and the need for students to learn about various elements that collectively constitute a good product design. The primary complaint is that most engineering graduates propose product designs that cannot be produced, and that their knowledge about manufacturing and the importance of cost in product development is minimal at best.

The universities and colleges are forced to comply with the demands of various constituencies, which are often in conflict. While industry would prefer engineers with greater understanding of all facets of product design and development, graduate programs favor students with greater scientific skills, as thesis and dissertation topics have become more and more theoretical and computational in scope.

In view of these concerns, the curriculum of the *Aerospace Structural Design* course was modified to include topics related to manufacture of aircraft structures. At present, four lectures are devoted entirely to the discussion of various design paradigms, such as design for manufacture and assembly, design to/for cost, integrated product and process development, etc., highlighting the importance of early design decisions on manufacturability, cost, and overall product quality. In addition, many of the assignments include design problems that require the students to propose alternatives that would result in a better performance at a lower cost.

The issues related to manufacturing and cost are addressed in this course by focusing primarily on designer-controlled elements that influence product design complexity, efficiency, and quality. Many of these issues have been a subject of research by the first author[1-3] for several years, and have made a natural transition from research to education arena.

The design activities culminate in this course with a fairly comprehensive design project with design analysis, manufacturing, and testing making up its major components. The hands-on experience with fabrication and testing provides students with the opportunity to learn about the importance of design for manufacture and assembly, as well as the importance of testing for design validation. Students also get a chance to practice collaborating with others on a design-build-test project, improve their written and oral communication skills, and gain better awareness of the importance of multidisciplinary design requirements. This paper describes the experience with two specific design projects that were conducted by students taking this course in two different years.

II. Project 1: Design of a Thin-Walled Column

In most airplanes, the wing, fuselage, and tail surfaces are made of metal sheets or plates that are stiffened in the axial direction with the help of stringers as shown in Fig. 1. When the wing or fuselage undergoes bending, these stringers are put in axial compression or tension. When in compression, stringers act as series of columns with end supports provided by ribs or frames. Since weight is of great concern in airplane design, stringers are usually designed as thin-walled sections. With buckling and crippling forming the main failure criteria, the designer has to select a material and design a cross-sectional geometry that lead to a light weight stringer with an acceptable margin of safety.

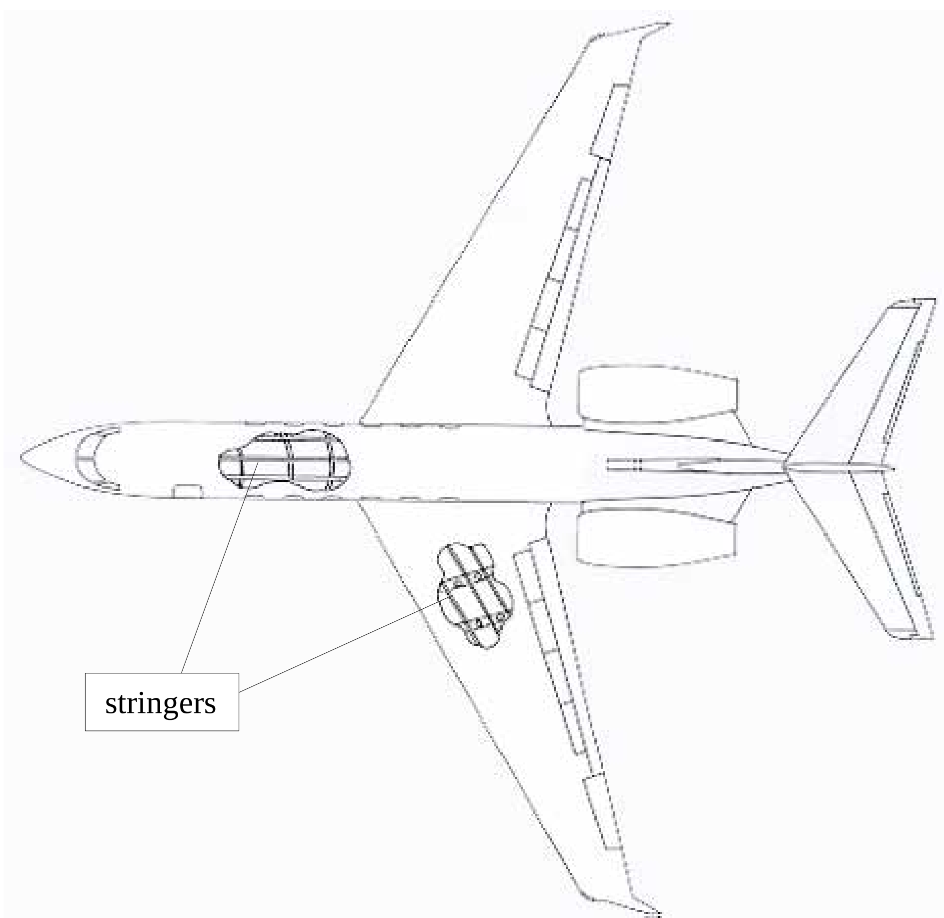


Fig. 1 Cutout sections showing the stringers in wing and fuselage structures

In addition to structural requirements, the designer must ascertain the manufacturability and affordability of the design. He or she has to know what manufacturing process is the most suitable and cost effective, and when options are limited, what process is available to produce the stringers. The lack of proper attention to manufacturability and affordability could lead to a design that cannot be produced. If, for example, the stringers were designed to have a variable wall thickness, then machining would be the recommended process for their production. However, when the wall thickness is constant and thin, the preferred process would be sheet metal forming. Against this backdrop, we proceed with the discussion of the thin-walled column design project.

The focus of this project is on the design of a thin-walled column (stringer) with a cross-sectional geometry that can be produced by break forming a 4.5" x 16" x 0.032" rectangular sheet of 2024 aluminum. The choices of material and thickness are consistent with the goal of reducing the likelihood of cracking the sheet metal in the forming process. The objective is to maximize the compressive load carrying capability of the column with the predicted failure load verified through fabrication and testing of a column specimen with the same specifications. This assignment was given to students as an individual design project in 1998.

A column of this kind can fail in crippling, buckling, or combination of the two. For very short thin-walled columns, crippling (crushing) is the mode of failure, and for a multi-corner section its corresponding stress is found from the semi-empirical formula[4]

$$\sigma_{cs} = 0.56\sigma_{cy}\left[\left(\frac{gt^2}{A}\right)\left(\frac{E_c}{\sigma_{cy}}\right)^{0.5}\right]^{0.85} \tag{1}$$

where t is the wall thickness, A is the cross-sectional area, E_c is the modulus of elasticity of the material in compression, σ_{cy} is the compressive yield strength of the material, and g is the shape parameter determined by dividing the cross section into multiple angle elements. For multi-corner sections, σ_{cs} is generally limited to 80% of σ_{cy}, unless there are test results to justify the use of a higher limit.

For long columns, buckling instability is the mode of failure. The critical stress for elastic buckling is found using the Euler formula

$$\sigma_{cr} = \frac{\pi^2 E_c}{(L_e/\rho)^2} \tag{2}$$

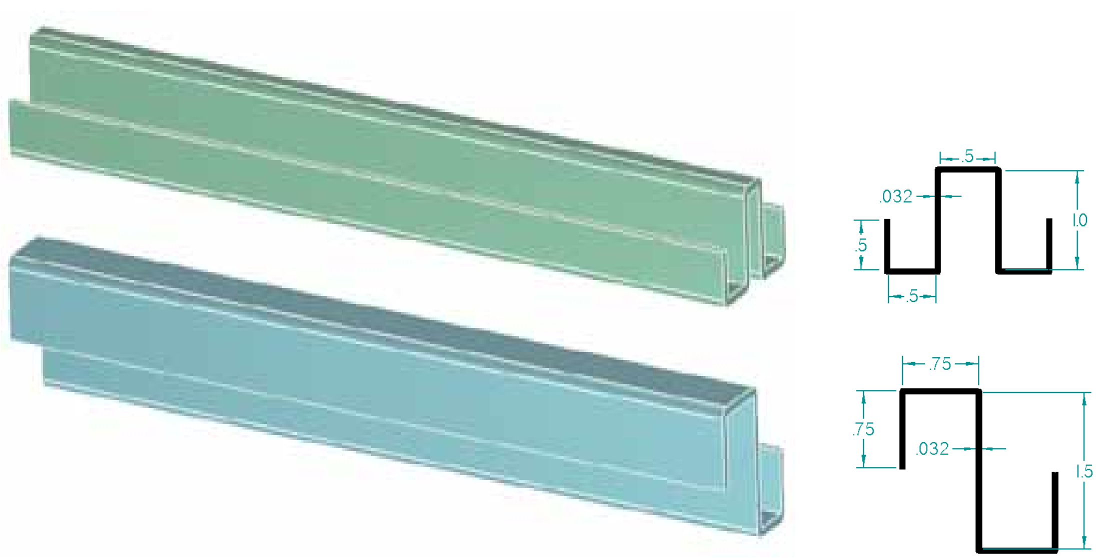
where L_e is the effective length of the column, and ρ is the radius of gyration about its bending axis (i.e., the axis with the smallest area moment of inertia). The effective length is determined based on the geometric length (L) of the column and its support condition. For example, if the two ends of the column are fixed, then $L_e = 0.5\ L$.

For columns of intermediate length, or more accurately, intermediate slenderness ratio (L_e/ρ), failure is governed by a combination of crippling and buckling with the corresponding stress obtained from the Johnson-Euler formula[4]

$$\sigma_f = \sigma_{cs} - \frac{\sigma_{cs}^2}{4\pi^2 E_c}\left(\frac{L_e}{\rho}\right)^2 \tag{3}$$

To predict the mode of failure and the corresponding stress, Eq. (1) is substituted into Eq. (3) and the Johnson-Euler stress is calculated. If this value is larger than one half of the crippling stress found from Eq. (1), then it is considered to be the failure stress; otherwise, the failure is due to buckling instability described by the Euler formula in Eq. (2). The preceding discussion basically summarizes the analysis procedure that students would use to evaluate a thin-walled column design.

To initiate the design activity, each student was asked to first analyze the two preliminary stringer design concepts shown in Fig. 2, which represented two possible configurations that could be produced using the specified strip of sheet metal. Concept 1 is a four-corner geometry consisting of two flanges and three webs while concept 2 is a six-corner shape made up of two flanges and five webs.



(2)

(1)

Fig. 2 Preliminary design concepts 1 and 2 for column cross-sectional shape

Following the analysis for predicting the failure load, each student had to fabricate a specimen consistent with the shape and dimensions specified for each concept. Prior to fabricating the columns, the students were introduced to the break forming process, which they had to use to make each column. They were also given the opportunity to get acquainted with the break forming equipment in our laboratory by forming several sections of various sizes and shapes. This training gave the students the basic knowledge and some hands-on experience with the sheet metal forming process.

For design concepts 1 and 2 the failure modes were predicted to be dominated by crippling resulting in ultimate loading capacity of 3,747 lb. and 4,112 lb., respectively. The student-manufactured stringers were then tested to failure using a computer controlled hydraulic testing machine. The attached load cell enabled the students to accurately measure the applied load from start to failure. The mode of failure in each case matched the predicted mode. The mean failure loads measured for concepts 1 and 2 were 3,278 lb. and 4,276 lb., respectively. The sample standard deviation for concept 1 was 96 lb. and was 324.2 lb. for concept 2.

The predicted results overestimated the strength of column 1 by an average of 14.3% and underestimated that of column 2 by an average of 3.8%. Although the discrepancy of this range between the predicted and measured results would be of concern at an aircraft manufacturing plant, it was to be expected in this project given the students' lack of manufacturing and testing experience. Nonetheless, in an attempt to identify the source(s) of discrepancy, students searched for possible clues in their analysis procedure and underlying theory as well as the possible anomalies with the fabrication process and the imperfections with the experimental setting.

The availability of multiple samples for each design concept provided an excellent opportunity to further elaborate on the statistical nature of such experiments involving multiple random variables. In this case the random variables included the specimen dimensions, support condition, loading eccentricity, and material properties. The discussion of statistics would not have been very meaningful without the fabrication and actual testing of multiple column samples.

By fabricating a column based on a given set of specifications, students learned about the importance of manufacturing considerations in design. Particularly, they recognized the effect of design complexity on production time and labor. This activity provided the students with important albeit modest experience as they proceeded to the next phase of the project.

Upon completion of the previous task, each student was challenged to design an alternative concept of his own that could outperform the two preliminary concepts in terms of compressive strength. In addition to performing a design analysis to provide evidence of design superiority, everyone needed to demonstrate the manufacturability of his design by actually fabricating (using the break forming equipment) a column with the same specifications. The individual column specimens would then to be tested to compare the predicted strength with that measured experimentally in each case.

Since the metal strip available to each student was of the same size and material as those used for concepts 1 and 2, and that they could not alter the support condition of the column (i.e., clamped at each end), the students were essentially left with two variables to control. One was the shape parameter g in Eq. (1), which in an open cross section of the type discussed here is primarily governed by the number of corners. For example, in design concept 1 (see Fig. 2), the shape consists of two free edges (f = 2) and four corners (c = 4) resulting in a $g = f + 3\ (c - 1) = 11$. In concept 2, there are two free edges and six corners resulting in a g of 17.

By setting the crippling strength equal to its maximum value of $0.8\sigma_{cy}$, Eq. (1) could be used to solve for the largest possible value that *g* has to have. Using the material properties of 2024 aluminum sheet ($E_c = 10.7\text{x}10^6$ psi and $\sigma_{cy} = 37$ ksi) along with the fixed cross sectional area ($4.5 \times 0.032 = 0.144$ in^2) and wall thickness (0.032 in), the largest value of *g* is found to be 12.6. Therefore, as far as the crippling strength is concerned any value greater than 12.6 would be unnecessary. However, for an open section with $g = 12.6$ and $f = 2$, the number of corners would be $c = 1 + (g - f)/3 = 4.53$, which is not possible. Hence, an open section with five corners resulting in a *g* of 14 would be needed.

If all students had used this approach and had found the same value for *g*, they could have still arrived at different geometric shapes for their columns. This fact is depicted in Fig. 3. Furthermore, the desired value for *g* had to be balanced against the minimum allowable distance between two adjacent corners as determined by the manufacturing process. This point represented a crucial design consideration that could have been very easily overlooked by the students if not for the requirement that their designs had to be manufactured using the break forming equipment in our laboratory. Consequently, students took time to very carefully test the equipment, and determined that the shortest distance they could incorporate between the corners was approximately 0.5".

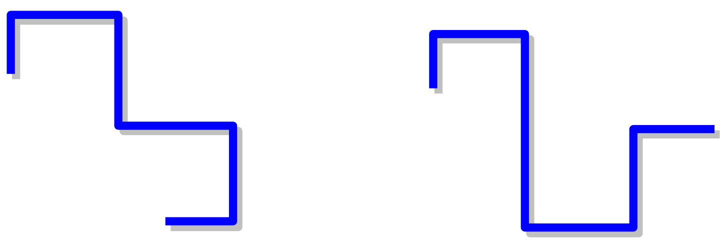


Fig. 3 Two geometric shapes with $g = 14$

The second variable that demanded a more careful consideration in the design was the radius of gyration ρ, which is defined as $\sqrt{I / A}$ with *I* representing the moment of inertia and *A* the area of the cross section. Because of fixed width and thickness of the metal strip, the cross-sectional area is fixed. However, the values of *I* and ρ can vary depending upon the shape of the cross section and the principal axis about which they are calculated. Since the column would buckle in the direction of least resistance, it is the minimum principal moment of inertia that is of main concern. A closer look at Eqs. (2) and (3) indicates that in order to improve the compressive strength of the column the radius of gyration has to be increased. All students realized this fact as they tried different shapes that would result in a sufficiently large value for the radius of gyration.

Students were also cognizant of the fact that for a given shape the sum of the moments of inertia about the two (perpendicular) principal axes is an invariant. This indicated that as they would try to increase the moment of inertia and radius of gyration about one principal axis, they would reduce those about the other. Ideally, if they could design a shape with two axes of symmetry, they would equalize the two principal moments of inertia and corresponding radii of gyration.

III. Assessment of Project 1

The concepts proposed by the students as alternatives to concepts 1 and 2 are shown in Fig. 4. These concepts vary in geometry and manufacturing complexity. The simplest one to manufacture is the four-corner section designated as (A) in Fig. 4. The more complex ones are those marked B and C. The majority of students suggested concept D, which was very similar to concept 2 but with different dimensions for flanges and webs.

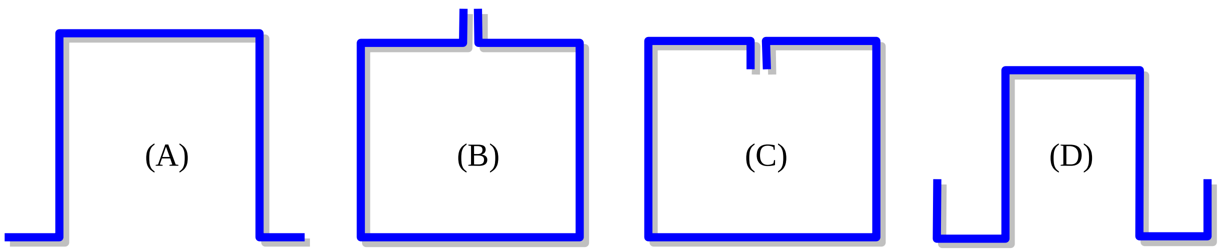


Fig. 4 Cross-sectional design concepts proposed by the students

Among all the proposed concepts one of those based on concept D in Fig. 4 provided the greatest strength with the measured failure load of 4,420 lb., which is roughly 3.4% higher than the mean value obtained for concept 2. The weakest design proved to be concept A in Fig. 4 with a measured failure load of 3,030 lb.

This project proved to be successful in that the hands-on experience with manufacturing and testing brought to light many important design issues that otherwise could have been easily overlooked by the students. It also initiated a general awareness for the importance of manufacturing considerations in design. In their evaluation of the course, students cited this project as the most interesting part of the course.

IV. Project 2: Design of Stiffened Panels

A stiffened panel describes a section of the airplane skin supported by several longitudinal stiffeners (or stringers). As such, it represents a larger and more significant portion of the airplane structure than a single stringer. Stiffened panels are typically designed based on a combination of in-plane bi-axial and shear loading condition with longitudinal stiffeners designed for axial compression and tension.

The factors affecting the structural performance of stiffened panels include the thickness and engineering properties of the skin material as well as the shape, size, quantity, and material properties of the stringers. As for the manufacturability and production cost, the complexity of the stringer shape, the quantity of stringers, and the number of fasteners used for skin-stringer assembly make up the significant factors. As always, low weight is a major design requirement.

In this project, students were asked to design a stiffened panel that could support an axial compressive force of 18,000 lb. representing the design ultimate load. They also had to optimize their designed panels for minimum weight. Similar to the previous project, students had to validate their design concepts by manufacturing and testing panel specimens with the same specifications. This assignment was conducted as a group project in spring of 1999 with each team consisting of two to three students. Although the members of a team worked together on design, analysis, and optimization, each individual member was required to manufacture a separate specimen for testing with the aim of providing all students with some hands-on experience as well as increasing the number of samples for a better statistical assessment.

The panel was defined to be a 24" x 18" x 0.032" rectangular sheet of 2024 aluminum that had to be stiffened by a set of identical stringers formed from a 0.032" thick sheet of 2024 aluminum. The loaded edges were simply supported while the unloaded edges were free. Except for the thickness, each team was free to decide on the shape, size, and the quantity of stringers as well as the number of 1/8"-diameter 5052 aluminum rivets needed for skin-stringer assembly. In addition to the constraint that the panel should support a compressive force of18,000 lb. distributed uniformly along the 24" edge, the number of stringers was limited to a minimum of 2 and a maximum of 6. Each team was provided an 18" x 48" sheet of aluminum that they could use to fabricate their stringers. This also included the contingency material needed to replace defective stringers.

The objectives of this project were as follows:

- Develop viable panel design concepts (with adequate attention to manufacturability and cost)
- Apply pertinent failure analysis techniques
- Optimize the design to minimize panel weight subject to a set of constraints
- Manufacture panel specimens to design specifications
- Validate the design by testing the manufactured panels

Consistent with the above objectives, the three quality measures established as evaluation criteria for determining the best panel design were *strength*, *weight*, and *manufacturability* or *manufacturing cost*.

A stiffened panel of this kind is susceptible to a compressive failure dominated by local failure or crippling. The unsupported skin between adjacent stringers usually buckles before the panel reaches its ultimate compressive load. Beyond this initial buckling, the load is supported by individual skin-stringer units forming a series of parallel columns. The effective width of the skin attached to each of the interior stringers is determined as

$$2w = 1.9t\sqrt{E_c / \sigma_{st}} \qquad (4)$$

while for skin attached to the stringer next to the free edge of the panel, the effective width is determined as $w + w^*$ where

$$w^* = 0.62t\sqrt{E_c / \sigma_{st}} \qquad (5)$$

In Eqs. (4) and (5) t is the skin thickness, E_c is the modulus of elasticity of skin material in compression, and σ_{st} is the compressive axial stress in stringer. Accordingly, as σ_{st} increases, the effective skin width decreases with the smallest value corresponding to the maximum value of σ_{st} found from Eq. (3). Thus, for a stiffened panel with N identical stringers the ultimate compressive axial load that it can theoretically support is found as

$$F_{c_{ult}} = \sigma_{\max}\left[NA_{st} + (N - 2)(2wt) + 2(w + w^{*})t\right] \quad (6)$$

where A_{st} is the cross-sectional area of each stringer and σ_{max} is the maximum stress that could be supported by the panel. The maximum stress is determined by using Eqs. (1) to (3) with one exception in that the crippling strength is the minimum of the values found for the stringer alone and the stiffened panel as a whole.

The panel design in this case had to be optimized for minimum weight such that its ultimate load capacity would be greater than or equal to the specified applied load of 18,000 lb. The design optimization problem would be formulated as

$$\begin{aligned} \text{Min} \quad & W(X) = 18[0.032(24) + NA_{st}]\gamma \\ \text{S.T.} \quad & F_{c_{ult}} \geq 18{,}000 \text{ lb} \\ & (N + M)A_{st} \leq 0.032(48) \text{ in}^2 \\ & X^l \leq X \leq X^u \end{aligned} \quad (7)$$

where W is the panel weight (excluding the rivets), γ is the specific weight of aluminum, X is the vector of design variables describing the stringer geometry with the lower and upper bounds (side constraints) given by X^l and X^u, respectively. The quantity M in the second constraint represents the number of defective stringers allowed in the manufacturing process. Since each member of a team was given a fixed amount of material for fabricating the stringers, each team needed to decide what value of M to use based on the level of confidence the team members had in forming the stringers they had designed. Prior to making this decision, each student was given an opportunity to practice forming various shapes using the break forming equipment at our laboratory.

V. Assessment of Project 2

The skin-stringer concepts proposed by student teams 1, 2, and 3 are shown in Fig. 5. All three teams developed a symmetric multi-corner design for their individual stringers. Team 1 developed a six-corner section described by four design variables (x_1 to x_4) while teams 2 and 3 considered a less intricate four-corner concept controlled by three design variables as shown in Fig. 5. While teams 1 and 3 used a single row of rivets for attaching each stringer to the skin, team 2 used two rows. This arrangement does improve the load carrying capability of the stringers but at a potentially higher manufacturing cost depending on the number of stringers used.

With the shapes of the stringers and corresponding design variables defined, each team proceeded to optimize their design concept to obtain the lightest panel that could satisfy the design constraints. By deciding on the stringer shape and skin-stringer assembly configuration, students for the most part had determined the manufacturing cost of their panels. The unknown factors that had to be determined through the optimization process were the size and number of stringers that would result in the lowest possible weight for the stiffened panel.

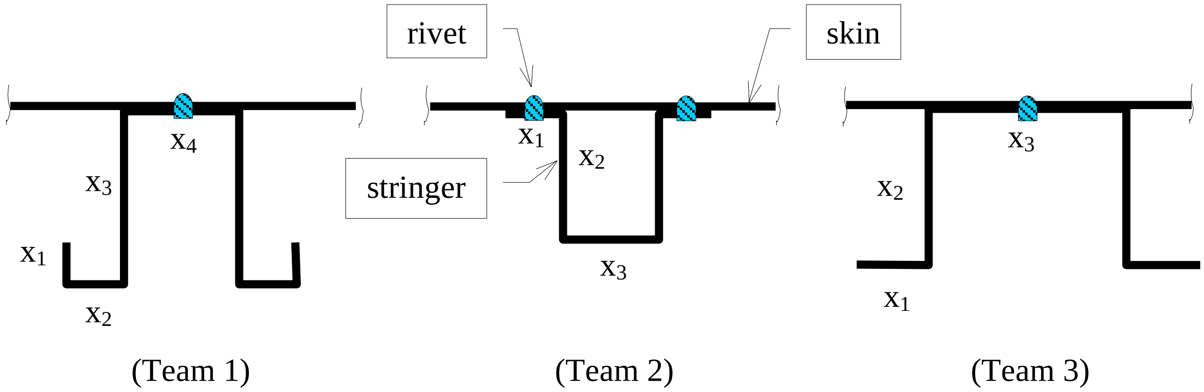


Fig. 5 Skin-stringer design concepts proposed by student teams

In support of this project, each student team first developed a computer code for the panel analysis that they then coupled with DOT[5], a general-purpose optimization program. Using the modified method of feasible directions, each team determined an optimum design for a given number of stringers, which ranged from two to six. By examining the weight versus the number of stringers, each team was able to determine the "best" combination of stringer size and quantity that would result in the lowest panel weight.

As is the case with all gradient based optimization techniques, the solution usually converges to a local versus the global optimum design. Without the use of an exhaustive search technique, students chose two to three different sets of initial design variables and solved for an optimum solution based on each initial set. The "best" design was determined by comparing the optimization solutions.

The optimum dimensions of stringers found by the three teams are shown in Table 1. With only 3 stringers, team 1 produced the design with the lowest part and rivet counts. With 4 stringers and two rows of rivets per stringer, team 2 had the highest rivet count at 144. Team 3 produced a design with 4 stringers and 72 rivets.

Table 1. Optimum design variables for the three panel concepts

Design Variable, in.	Team 1	Team 2	Team 3
x_1	0.30	0.375	0.30
x_2	0.50	1.00	1.25
x_3	1.39	0.75	1.50
x_4	1.00	-	-

With the best combination of stringer size and quantity identified, each student proceeded to manufacture a specimen with roughly the same specifications as those found in the optimization process. All students were able to produce the required quantities of stringers using the limited material provided to them.

For assembling the stringers and skin, students used the same size and type rivets at a conservative longitudinal spacing of 1 in. The rivet spacing was specified in the project based on a previous analysis for inter-rivet buckling of skin between two adjacent rivets. Part and rivet counts and design intricacy were used as parameters that determined the manufacturing cost of each panel. Design intricacy was determined based on the number of corners in the stringer geometry as the most dominant feature. The quantity and complexity of stringers would determine the cost of stringer manufacture while the part and rivet counts would determine the cost of assembly. The cost associated with the skin was not included, as it was constant for all panels. The properties of each panel specimen along with the corresponding measured failure load are shown in Table 2.

Table 2. Measured panel properties

Quality Measures	Team 1		Team 2		Team 3		
	I	II	I	II	I	II	III
Strength, lb	10,308	10,800	11,240	9,090	6,640	7,620	6,600
Weight, lb	2.300	2.302	2.216	2.227	2.412	2.445	2.438
Part Count	4	4	5	5	5	5	5
Rivet Count	51	51	144	144	72	72	72
Intricacy	6	6	4	4	4	4	4

Because of the relatively wide web sections, stringers in concepts 1 and 3 underwent local buckling prior to crippling and collapse of the panel. Because of skin-stringer attachment method and relatively narrow web sections, stringers in concept 2 did not suffer from local instability. The skin in all three cases underwent local buckling prior to the final collapse of the panel.

The variation in results for the same concept is primarily due to differences in the quality of panels produced by different members of the same team. In all cases students had to be careful to make sure that the stringers were spaced evenly, and that they were parallel to each other and perpendicular to the loaded edges of the panel.

In searching for the cause(s) for the significant difference between the predicted and actual failure loads, two factors were identified. For failure analysis students had to use Eq. (1) in two ways. They first needed to calculate the crippling strength of a single multi-corner stringer. Then they had to calculate the crippling strength for a monolithic skin-stringer section that incorporated the same stringer geometry. The lowest value would be the one to use in the design. The difference between the two values could be as much as 25%. Students determined the crippling strength based on stringer properties alone, which turned out to be larger than that for the stiffened panel. Secondly, some students did not make proper adjustment to the jig that was used to distribute the load uniformly over the edge of the panel. Therefore, it is possible that some panels were loaded in an eccentric fashion causing them to be put in bending as well as in compression, resulting in a premature failure. These two factors coupled together could account for a significant portion of the difference between the predicted and measured failure loads. Certainly the next time this project is conducted, the students will be more vigorously warned about these and other factors that could affect the design analysis as well as the manufacture and testing of their panel concepts.

To determine the best panel design concept, a datum was established for each quality measure. For strength, the limit was set at 18,000 lb. For the weight, the maximum value was set at 3 lb. based on the material given to each student. The maximum part count was set at 7 based on the upper limit of six stringers, and the maximum rivet count was set at 216 based on the maximum stringer quantity with each having two rows of rivets at 1-in. spacing. The maximum intricacy was set at 8 based on the maximum number of corners in the stringer. The values in Table 2 were normalized according to the specified limits. The largest normalized value in each category was given a score of 10, as highlighted in Table 3, with the rest determined accordingly. The three factors affecting the manufacturing cost (i.e., part count, rivet count, and intricacy) were combined into one item identified as cost in Table 3. Although the design concept produced by member I of team 2 earned the highest score in terms of strength and weight, it was not the best overall design because of the significantly higher rivet count, which lowered its score in terms of cost. The design concept produced by team 3 earned it the best score for having the lowest cost, but it suffered in terms of strength and weight. The best overall design concept was found to be that produced by member II of team 1 with a total quality point of 28.45 out of possible 30.

The technical report along with the effort in fabrication and testing of the panels made up the remaining 70% of the credit that could be earned by each student in this project.

Table 3. Scores for design quality

Normalized Quality Measures	Team 1		Team 2		Team 3		
	I	II	I	II	I	II	III
Strength	9.17	9.61	10	8.09	5.91	6.78	5.87
Weight	8.93	8.91	10	9.86	7.50	7.08	7.17
Cost	9.93	9.93	7.70	7.70	10	10	10
Total	28.03	28.45	27.70	25.65	23.41	23.86	23.04

Overall, this proved to be a highly educational and successful project. The premature failure of the panels served an important purpose in that it made students realize the consequences of improper design analysis, manufacturing and testing. The learning of such lessons in a more benign laboratory setting should help these future engineers as they get involved in much more elaborate design projects with mistakes and oversights having far greater consequences.

The students also had the opportunity to apply the principles of design for manufacture and assembly in addition to design for performance in this project. This activity also provided them with a chance to realize the effort and labor involved in mechanical assembly of aircraft parts, and the influence the designer exercises in not only establishing the performance of the designed structure but also its manufacture and quality. They also became better familiar with the principles of design optimization as they applied some of its techniques in this project.

V. 1 Summary of Students' Assessment of Project 2

At the end of the semester, the students were asked to provide their personal assessment of the project. Here are some excerpts of what the students had to say:

"The applying of concepts to real life applications was fantastic."

“I believe that if you allow the students to choose their own groups, the work atmosphere would be better.”

“Building the panel proved challenging when the stage of riveting was reached. The rest of the fabrication process besides riveting went quickly, even if it was mildly tedious and error-prone.”

“I learned that the spacing of the stiffeners will make a difference in the failure characteristics of the stiffened panel.”

“My teammate and I learned many important things from the various phases entailed in the stiffened panel project.”

“Troubles with riveting the stiffeners to the drilled panels brought to mind the necessity for keeping track of the assembly process and thinking about the little details.”

“The panels not being perfectly square (at the corners), and thus loading up unevenly, made me realize how much a little variation—such as a sixteenth of an inch—could affect manufacturing results. In my case, it caused my panel to fail at a much lower stress than it had been designed for.”

“I did enjoy the project because of the ‘hands on’ nature. I think the design load should be lowered so a wider variation in stringer cross-sections could be made.”

“The designer should consider the manufacturing process of his design. We had that experience through this project.”

VI. Conclusions

This paper described two student design projects that incorporated fabrication and testing as means of reinforcing the importance of manufacture, cost, and quality in design of aircraft structures. The students—participating in the first project—designed, fabricated and tested stringer sections with fairly good agreement between the predicted and measured results for failure in axial compression. In the second project, the students had to deal with a more difficult task that involved the design, optimization, fabrication, and testing of a built-up structure. In both projects students were able to successfully design and develop their own structural concepts based on the topics learned in the course.

The hands-on experience with rudimentary sheet metal fabrication and mechanical assembly helped students in better understanding the process through which design concepts come to realization and the degree to which the manufacturing complexity and cost are rooted in the design of the structure.

By testing multiple samples of the same design concepts, students were also able to observe the effect of manufacturing quality and the statistical nature of experimental results as influenced by random variables. They also learned the impact of improper analysis and testing procedure that led to the premature failure of the stiffened panels in the second project.

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