Implementation of a Hands-On Aerospace Design Project During the COVID Pandemic

Prof. Rani W. Sullivan, Mississippi State University

Rani W. Sullivan is Professor of Aerospace Engineering at Mississippi State University (MSU) and the holder of the Bill & Carolyn Cobb Endowed Chair. She has teaching and research interests in the area of solid mechanics, aircraft materials and structures, and engineering education. Her research spans structural health monitoring, composite manufacturing, and mechanical and non-destructive testing of polymer matrix composites and large-scale structures for aerospace applications. She is the founder and adviser for the Women of Aerospace student organization at MSU. Prof. Sullivan is an Associate Fellow of the American Institute of Aeronautics and Astronautics. She is the recipient of the 2019 Hermann Oberth Award and the 2014 SAE International Ralph R. Teetor Educational Award. Prof. Sullivan is a member of the MSU Bagley College of Engineering Academy of Distinguished Teachers.

Shuvam Saha, Mississippi State University
Dr. Masoud Rais-Rohani, University of Maine

Masoud Rais-Rohani is Richard C. Hill Professor and Department Chair of Mechanical Engineering at the University of Maine. He is also Professor Emeritus of Aerospace Engineering at Mississippi State University. He has taught undergraduate and graduate courses in the areas of design optimization, aerospace structures, structural mechanics, and composites. He has made extensive use of experiential learning and computer applications in his courses, including the development of two websites, one devoted to analysis of aircraft structures and the other to statics. He has also led or contributed to the development or redesign of several courses in aerospace and mechanical engineering.

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Abstract
This paper discusses the successful implementation of a critical hands-on, semester-long team project in a senior aerospace structural design course during the COVID pandemic. This design course, required of aerospace undergraduates at Mississippi State University, focuses mainly on the failure mechanisms in thin-walled aerospace structures. The project covers topics of design, analysis, fabrication, and testing of an aircraft skin-stringer panel. Ordinarily, student teams would design their panels per the project specifications, resulting in students conducting all steps of the project during the last few weeks of the semester. This became an impossible task during the pandemic due to the imposed physical distancing and safety requirements. Thus, we modified the project so that the hands-on (manufacture and testing) aspects of the project occurred over a longer time period, thus allowing comfortable space and time for student teams to safely complete all aspects of the project. This was accomplished by giving the materials and the stiffened panel specifications, such as stringer geometry, spacing, number of rivets, etc. to each team, thus allowing students to begin fabrication at the beginning of the course and test all articles by mid-semester. The end of the manufacture and test phases coincided with the completion of the technical material in the course so that students could proceed with the full analysis and optimization of the panel design. The modified project format produced unexpected benefits. Post-project surveys show that students were able to gain a deeper understanding of manufacturability and design aspects since the technical material was presented concurrently with the hands-on manufacturing and testing of the panels. Students were also able to experience all aspects of the design process as an optimization module was required to improve upon their given panel geometry. Additionally, since different panel specifications were assigned to each team, the measured data set was used to develop a parametric evaluation, demonstrating the impact of changing stringer geometry.

I. Introduction

The novel corona virus (COVID-19) pandemic required faculty and students to quickly modify well-established classroom activities and projects [1, 2]. Challenges were especially present for the hands-on projects since these required on-site attendance by students and instructors [3, 4]. This paper describes the modification and implementation of an existing experiential learning project in a required senior-level aerospace structural design course in the Aerospace Engineering (ASE) Department at Mississippi State University. The learning outcomes of the course establish the expectations that students should achieve by the end of the course. Students should be able to

1. Demonstrate fundamental understanding of:
    - Design methods and criteria and the impact of design decisions on life cycle factors such as manufacturability and cost.
    - The influence of design on internal stresses due to compression, tension, shear, bending, and combined load systems.
2. Demonstrate the ability to:
    - Analyze thick and thin-walled columns for elastic/inelastic buckling and crippling.
    - Design columns and stiffened panels against compressive failure.
    - Determine the bending response of rectangular plates under lateral loads.

- Determine the buckling strength of rectangular sheets in compression, shear, in-plane bending, and combined stress systems, and to calculate effective skin width in stiffened panels.
- Build and test a stiffened panel and design and analyze for a specified compressive load.
- Design and analyze tensile loaded structures, such as pressure vessels, against yield and fracture failure. Estimate fatigue life under cyclic loading.

3. Demonstrate the ability to submit assignments as technical reports with clear and concise statements explaining the steps taken in solving a problem.
4. Demonstrate the ability to actively participate in teamwork with other students.

The original design-build-test "panel project" is described in previous studies [5-7]. The project involves design, fabrication, testing, analysis, optimization, documentation, and project presentation of thin-wall stiffened panels under uniaxial compression. This experiential activity enhances the understanding of topics studied in the course through analysis of panel design concepts and their performance characteristics. Students gain experience with sheet metal forming, hand tool operations, manual assembly, and acquire familiarity with laboratory testing as a means of design validation. The semester-long project allows students to improve their teamwork and communication skills.

Thin-walled structures play a key role in the design of modern aircraft [8]. Components such as wings and fuselage are designed to reduce as much of the structural weight as possible, thus, making compression-induced instability and failure a major design criterion. Buckling refers to a structural instability caused by a sudden out-of-plane deflection when the applied load places all or part of a structural member's cross-section under compression [9]. To prevent buckling, the thin skins of aerospace structures are supported or stiffened by stringers. The premise of the current panel project is to produce stiffened thin-walled panels within prescribed design criteria, observe the response of the structures during compression testing, compare with analytical predictions, recommend improved designs, and disseminate the findings.

II. The Panel Project Pre-and Post-Pandemic

Prior to the COVID pandemic, each student team was required to develop their panel design within a given set of constraints [6]. They were free to choose the cross-sectional shape of the stringers (kept the same for all stringers) and the form of attachment to the panel, with stringer quantity, spacing, and cross-sectional dimensions determined through the subsequent structural analysis and design optimization process. They also had the opportunity to practice bending sheet metal to establish practical limits on flange and web dimensions that would appear as side constraints in the optimization problem. However, this meant that the necessary course material had to be covered before students could begin the project. Thus, the panel project was given during the last third of the semester, with students having about three weeks to complete the design, fabrication, and testing of their panels and another week to submit the final report and give class presentations.

We considered eliminating the project due to the health concerns imposed by the pandemic. However, we also considered the learning benefits of the hands-on activity and the emotional isolation of the students. We decided to implement the panel project, but in a safe manner. Thus, the project was reframed to comply with safety regulations. The main considerations to accomplish this were to include safe distancing requirements and minimize student stress and anxiety. This was accomplished by (a) limiting the number of teams that could occupy the laboratory space (Fig. 1) at any given time and (b) allowing a longer period of time to complete the many steps in the project. Since the necessary course material had not been covered to enable students to design their panels, the panel geometry (stringer shape, size, quantity, spacing and form of attachment) was given to each team two weeks after classes began.

Figure 1. Students fabricating their panels (fall 2020).

Students reserved two-hour slots (non-consecutive) for fabrication of their team panels over a four-week period; testing occurred over a two-week period. The final project, which also included detailed analysis and sizing optimization of their panels, concluded with submission of the final report and team presentations about two weeks before the final examination. Thus, the complete project occurred over two months, instead of three to four weeks.

The Current (post-Pandemic) Panel Project

The panel project includes taking individual stringers and attaching them to a thin skin, resulting in a stiffened panel, as shown in Fig. 2. In each panel, the stringers are identical and parallel and equally spaced, with each team having a different stringer geometry. This section will describe the panel project format that was implemented during the pandemic in fall 2020, which had a class enrollment of 69 students. This resulted in (18) three or four-member teams, with each team fabricating three or four identical test specimens, respectively.

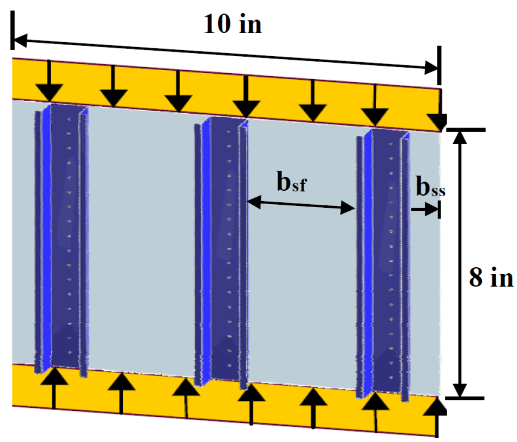


Figure 2. Schematic of stringer panel in compression

Project Description

A 10" × 8" × 0.032" rectangular sheet was stiffened in the short direction by three identical 8"- long formed stringers, made of 2024-T3 aluminum (bare sheet) of 0.032" thickness. Stringers were attached to the sheet using ten uniformly spaced 1/8 in. -diameter 5052 aluminum cherry rivets. A schematic of a skin-stringer panel loaded in axial compression is shown in Fig. 2.

Each team was assigned either a z-stringer geometry (Fig. 3a) or an open hat stringer (Fig. 3b) with dimensions in the ranges for each flange and web length: $(0.5 \leq X_1 \leq 1.0)$ in, $(1.0 \leq X_2 \leq 2.0)$ in, $(0.5 \leq X_3 \leq 1.5)$ in. The rivet spacing (Fig. 3c) and spacing of the stringers b_{ss} and b_{sf} (as indicated in Fig. 2) were also given. Each student was given a 24" × 24" 2024-T3 aluminum sheet, from which stringers and the skin were fabricated. A maximum permissible tolerance of 1/32" was assigned for all cross-sectional dimensions (except the sheet thickness).

Students were instructed to watch a panel fabrication video and practice bending and cutting using scrap aluminum prior to beginning the fabrication of their panels. Safety protocols were discussed regarding the use of shop equipment and each student was required to attend safety training to gain access to the necessary machines (sheet metal brake, drill press, router machine, rivet gun, etc.). Table 1 lists the tasks that students performed during the manufacturing phase of the project.

Following fabrication, each panel was loaded in uniaxial compression in a mechanical test frame (Fig. 4) to determine the ultimate load carrying capacity and to provide validation data for the design code. Each student was required to be present for their team's testing; students recorded all structural responses for later correlation with their load-displacement data. Testing was done by a graduate student trained on a 25-kip Instron servo-hydraulic test frame. Table 2 lists the testing tasks performed by students.

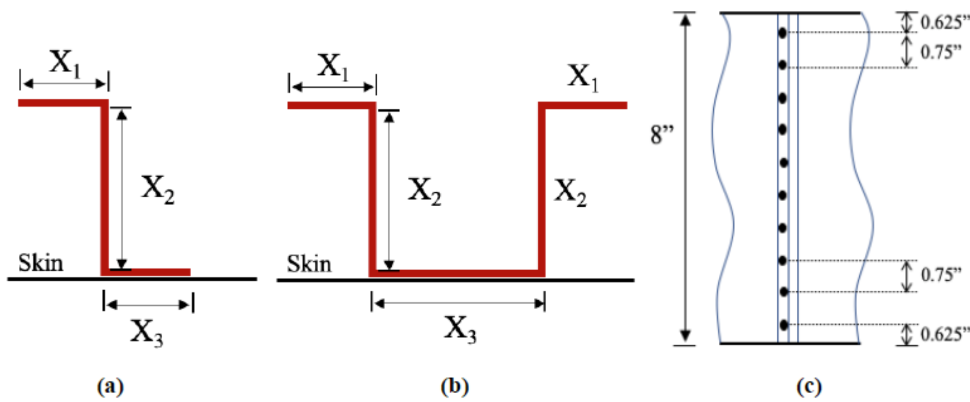


Figure 3. (a) Cross-section of a z-stringer, (b) cross-section of a hat stringer, and (c) a rivet spacing for each stringer.

Table 1. Fabrication Tasks

Task	Description
1	Complete safety training and watch fabrication video
2	Develop a manufacturing specification drawing that details the shape, size, and placement of the stringers and rivets.
3	Reserve a 2-hour fabrication slot for your team
4	Fabricate a skin-stringer stiffened panel to the manufacturing specification in #2. Each team member will be evaluated on the quality of each panel; the quality will be graded by evaluating the uniformity and alignment of the stringers and the uniformity of fastener spacing.
5	Record the time to fabricate each stringer. This data will be used to determine the learning curve and the learning curve parameter.
6	Verify that the loaded edges are parallel.
7	Drill rivet holes and attach the stringers to the skin
8	Weigh the panel
9	Rout the wooden end pieces and use plaster to pot the end caps to the stiffened panel, making certain that the ends of the stringers are flush with the loaded edges and the end pieces are level and square. All stringers must be parallel to each other and perpendicular to the loaded edges.
10	Complete the measurement worksheet and supplies checklist and return all tools. Leave space clean and organized.

Table 2. Testing Tasks

Task	Description
1	Use the Testing Data Entry Form to record test parameters such as loading rate. During the test, record all observations, such as loads where local buckling, inter-rivet buckling, and ultimate failure occur. Take videos and photos for your presentation and final report.
2	Aid the test machine operator in the correct alignment and setup of your panel.
3	Obtain your load-displacement data file and analyze your data. Plot and locate key points.

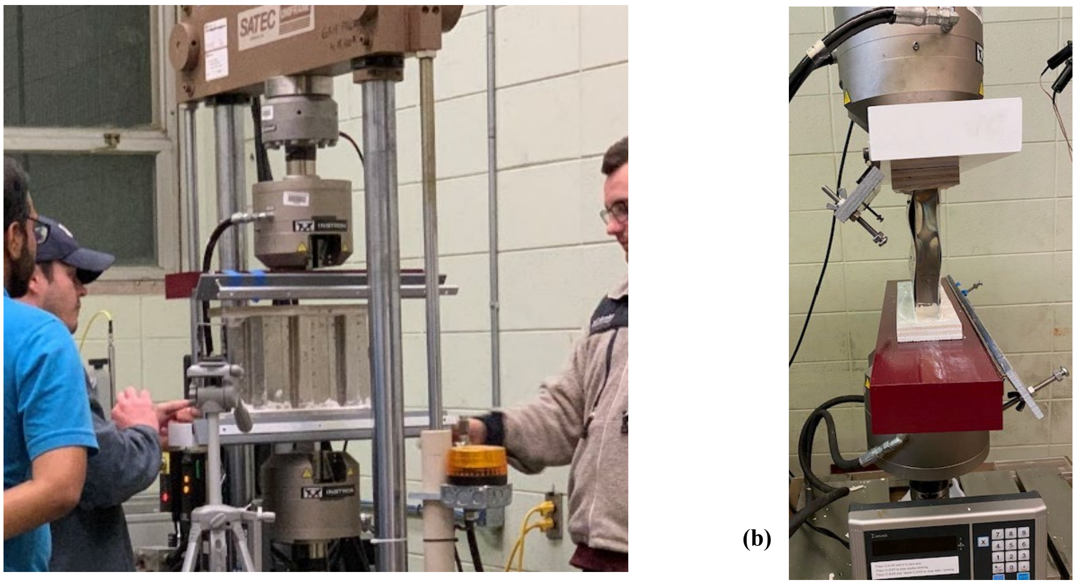


Figure 4. (a) Panel testing monitored by students and (b) panel buckling under axial compression.

Each team was required to develop a computer code to perform the structural analysis of their panel design using the theory and methods presented in the course. Students were required to evaluate the assigned stringer design concept analytically and propose a design to optimize the number of stringers and stringer cross-sectional dimensions to achieve the strength to weight ratio obtained from the experiments or exceed it by a maximum of 10%. For the optimized panel, the overall panel dimensions (10” × 8”), stringer length (8”) and material thickness (0.032”) were kept constant. The optimized panel was to be manufacturable, thus attention must be given to the choice of increments used to vary the stringer cross-sectional geometries. Table 3 lists the calculated panel properties that must be compared with the experimentally measured properties and the properties of the optimized stringer design.

Table 3. Stiffened Panel Properties

1	Panel weight
2	Panel volume
3	Skin buckling force
4	String local buckling force
5	Failure load (crippling)
6	Failure load (combined crippling and local buckling)
7	Failure load (column buckling)
8	Failure load (monolithic)
9	Failure mode
10	Strength to weight ratio

The final report contained the motivation of the project, descriptions of the manufacturing, analysis, and optimization processes. Each team presented their design in a virtual format, with faculty and graduate students submitting evaluation of each teams’ efforts.

III. Student Feedback Pre and Post-Pandemic

Students agree that the project is a serious undertaking, but by project's end, they express their enjoyment and satisfaction. They expressed an appreciation for the many elements that must be considered in designing a part and a particular understanding of what "manufacturability" means. Table 4 lists unedited comments from students regarding the panel project experience with regards to the timeline.

Table 4. Student Feedback

Pre-pandemic (2019)	During (2020) and Post Pandemic (2021, 2022)
Not sure how to change it, but Panel Project felt like it should have had one additional week to get all of it done.	*Dr. ____did a good job transitioning to online format. Having the panel project started earlier in the semester, as opposed to after the material is covered, was so much more beneficial*
Panel project was the best part of my aerospace classes this semester. I would recommend allowing more time for the project to help take the rush out of it.	*I think the panel project was the most beneficial aspect of the class since having the hands-on knowledge of the concepts learned in class helped us to see the relevance of the project in the industry. I liked how the project was broken up into two sections so that it wasn't all due at once and it helped to spread out the work throughout the semester.*
Design project at the end of the year was terrible and had very little time to do major things being required. *I work and have a family at home, this class was very very tough on me specifically because of how little free time I have in general. That being said, this project was fun and actually enjoyed building the panel.*	*I liked that the panel project was due before all of our finals. I think the timeline for that project was very reasonable and doable.*
	The course's primary project, the panel project, is one of the most important projects in the curriculum and covers all aspects of engineering in regards to design, fabrication, testing, and analysis.
	The panel project, while being a dreadful amount of work, did help teach concepts.
	Panel project was awesome!

Because of the additional time allotted for the fabrication and testing phases, students were able to reflect on their experience and discuss possible reasons why their predicted results were different from the measured values. This discussion was required as a part of their final report. Table 5 lists excerpts from student team reports that give possible causes for the discrepancies between experimental and analytical data.

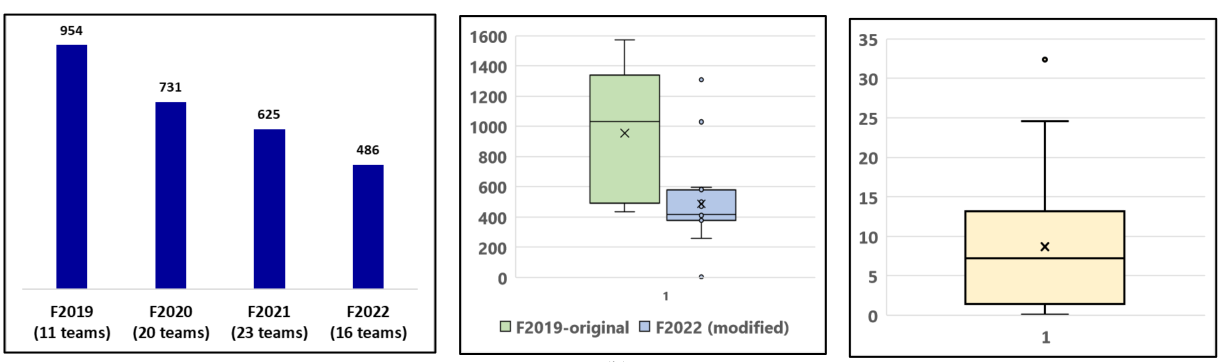
Table 5. Panel Project Report Excerpts Detailing Reasons for Differences in Measured and Analytical Data

The team were able to see how variations and discrepancies in the manufacturing, however small, can cause large variations in performance. Some of the reasons behind some discrepancies between the data are human error, manufacturing defects, and poor end cap construction.
Overall, the data collected from the experimental tests does not always closely compare to the predicted values generated from the algorithm. This error in the data can be attributed to a variety of factors including but not limited to human observation error during the test, panel fabrication impurities, and completed panel quality.
Small imperfections in our group's panels caused them to fail earlier than any simulation could have predicted, thus cementing just how important real world testing is in any design process.
These discrepancies that we encountered during fabrication were inaccurate measurements, loss of material while shearing, stretching during bending, cracks in the bends, and excessive bending while drilling.
The differences between each panel and the theoretical value can also be explained by precision and manufacturing errors. Specifically, differences can be observed with Panel 2 as each of the components fail prematurely compared to the other values. This is due to unevenness during the plastering and capping phase of fabrication. During this step, a small piece of hardened plaster stuck between the panel and the table surface

causing the cap to dry unlevel. This caused the press to work towards leveling the cap through compression and provides for failure due to manufacturing

IV. Results & Discussion

From informal interactions and student evaluations, we found there was increased student satisfaction in the modified version of the panel project. To obtain a more quantitative evaluation, we considered the experimental test data to evaluate the quality of the "build" or the fabrication of the panels. We expected that, with more time and with less academic responsibilities (at the beginning of the semester), the modified format of the project should produce panels of higher quality, and should also provide results that have a lower standard deviation of the panel failure load for each team. Teams had either three or four members and thus, each team tested either three or four panels (of identical specifications) to failure; the standard deviation of the failure load values was computed for each team. Fig. 5a shows the average standard deviation of the panel failure load of the original panel project (fall 2019) and the modified version implemented in fall 2020, 2021, and 2022. The variations in each team members' panel was reduced and thus produced a higher quality part. Figure 5b shows a box plot of the standard deviation of the panel failure load for the fall 2019 class and for fall 2022 for which the original format and modified format, respectively, were used. The figure clearly shows the larger distribution in the data for the fall 2019 group as compared to the 2022 group; there were only three outliers (out of 16 teams) for the fall 2022 class. Students expressed a deeper understanding of the importance of quality control in manufacturing and the need to design parts that could be manufactured. Also, it was noted from class discussions that students were able to better understand failure mechanisms of the skin and stringers since they had observed those in the laboratory before the technical material was covered in class lectures. To observe students' skill in developing their predictive model, Figure 5c shows a box plot of the percent difference between the average measured ultimate load and the student-predicted ultimate load for the fall 2022 class; this indicates a median value of 7.2% difference with the majority (11 out of 16 teams) of the data ranging from 0.1% to 9% difference between the average experimental and the team simulation data. These results indicate that, in general, the fall 2022 class had an increased appreciation of the importance of the quality control necessary for a successful design; this includes a better understanding of the manufacturing, testing, and simulation processes that were due to the longer time range allowed for the project.



(a) (b) (c)

Figure 5. Statistical project results showing (a) average standard deviation (STDV) of panel failure load for student teams (F2019-F2022), (b) box plot showing the distribution of the STDV for the F2019 (original project format) and the F2022 (modified project format) classes, and (c) box plot of the percent difference of the average panel failure load and the predicted value for each team in fall 2022.

V. Conclusions

n existing design-build-test panel project was modified to a build-test-validate design project to accommodate the health and safety concerns during the COVID pandemic. This hands-on activity, which replicates the stiffened thin-walled construction found in modern aircraft structures, is an integral part of the senior-level aerospace structures design course at Mississippi State University. To address the distancing regulations, a limited number of student teams could occupy the laboratory at any given time and were given a total of two months instead of the usual three-four weeks to complete the project. Student feedback showed increased satisfaction and engagement. The measured panel failure load test data showed better quality control in the manufacturing and test processes; a median value of 7% difference in the average measured and the predictive values of the failure load shows students' comprehension of the analytical concepts and simulation skills. All elements of the new format have been retained except for time and space requirements that were enforced during the pandemic. The project was modified to allow for safe distancing and comply with health regulations, but it continues to be implemented because of increased student engagement and understanding of key elements (manufacturing, simulation, optimization) of the design process.

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