

IN EMBRY-RIDDLE THE CAPSTONE PROJECT BRINGS CLOSURE TO STRUCTURES

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ABSTRACT

The Aerospace Engineering undergraduate program at Embry-Riddle Aeronautical University is capped by a semester-long aircraft detail design course in which the students, in line with CDIO philosophy, apply all their acquired knowledge and skills to a real problem provided by industry; specifically, the design of a wing for a business jet. They are expected to propose a structural concept that meets all the functional requirements, select a suitable material, size the structure with appropriate margins of safety and submit a thorough technical report that includes a stress justification dossier. They greatly benefit from a “real world” experience, being involved in a multifaceted engineering problem. However, the Implementation and Operation phases of the CDIO process could not be put into practice due to the complexity, cost and time demands of such a project. Thus we are confronted with a dilemma, should the project be limited to only something that can be manufactured and tested in the school semester and therefore be robbed of realism or should it be kept complex while accepting that it will not be built and operated? In the latter case the problem would remain in the realm of academic abstraction in which the students may think that a fundamentally unsound structure is a good design because they have generated tables of positive margins of safety, although perhaps not for the appropriate failure modes. In both situations something important is lacking. To deal with this issue a *miniature* design project has been introduced at the beginning of the semester in which the students conceive, design, build and test a cantilevered beam box out of aluminum foil and common glue. The key point of this activity is that the structure should be designed and adequately analyzed before being built. Furthermore, a complete technical report should be submitted. In this way the course objectives are met without sacrificing realism for practicability.

KEYWORDS

Capstone Design, Structural Design, Failure Modes, Aerospace, Engineering Judgment, Engineering Sense, Standards: 1, 5, 7, 8

INTRODUCTION

The undergraduate degree in Aerospace Engineering at Embry-Riddle Aeronautical University culminates with a semester-long Aircraft Detail Design course (Ae421) where students obtain actual experience in the design of aircraft components, in line with the principles contained in the CDIO Syllabus: “the product, process, or system lifecycle (conceiving-designing-implementing-operating), should be the context, but not the content, of engineering education.” (Crawley et al., 2011)

For the last years, the industry provided project has revolved around the design, structural sizing and systems integration of a business jet wingbox, closely following CDIO Standards 5, 7 and 8, i.e., Design-Build, Integrated and Active Learning Experiences. This seems to be the most effective way of preparing students to become effective engineers (Crawley et al., 2007 and 2008). Indeed, the design of a wing provides ample challenges that stretch the students' knowledge and capabilities. However, by its very nature (a large, expensive aircraft component), the last two letters of CDIO cannot be put into practice directly. One way to address this problem would be to simplify the project to something that can be designed and tested in the university labs in one semester. But this solution would strip the students from the real world experience and challenges that an authentic industrial problem entails. On the other hand, having the students only perform a *paper exercise* renders their education somewhat incomplete. Indeed, experience has shown that students can become good at solving “canned” problems, at reproducing—sometimes uncritically—problem solving algorithms without understanding of the underlying principles and, when confronted with open-ended design jobs, these approaches are insufficient or result in totally wrong answers. For example, when asked to design a structure to carry certain loads, a majority of students automatically tries to apply Von Mises' or Tresca's criteria without first stopping to reflect whether those are really the failure modes for that type of structure under those loads and with that type of fixity. In many cases, localized buckling will occur much earlier than yielding but the students could be completely satisfied that their structure will carry the loads because they have generated tables of positive “margins of safety” albeit based on the wrong failure criterion or false assumptions.

Another issue encountered in capstone projects is that the homework or test problems that the students have become familiar solving are always *clean* and well bounded; i.e., if it belongs to the “Beam Bending” chapter of the book it will not buckle, or vice versa. There are other simplifying assumptions that make the problem manageable and put the emphasis on the topic to be studied, for example, fixities and the way to achieve them are always assumed to be perfect and, in general, no consideration is given to joints (bearing, bypass, peaking, shear), clearances, St. Venant's zones where stress distributions vary from the theory being applied, and so on. Furthermore, in undergraduate structures courses it is quite rare to study how loads are transferred from one structural element to another, for example, how and why bonded joints work better in shear than in tension and the importance of the extent of the area necessary to distribute the loads and reduce the stresses. All this is reasonable since the best way to understand a phenomenon is to isolate it from its surroundings for clearer observation. However, in a real problem all of the above clearly need to be considered.

Thus when students are tasked with designing a wingbox they are usually unprepared and are prone to falling into all the pitfalls previously mentioned which would only become apparent to them if their designs were built and tested, something not possible as previously discussed. Therefore a new class activity has been introduced at the beginning of the term. In essence, it consists in a *miniature version* of the semester-long project (the *big* project) condensed into two weeks where the students design, build and test a cantilevered “wingbox” (110 x 14 x 5cm), using only kitchen aluminum foil and glue, loaded with distributed sand bags. In it they are required to *design* the box, i.e., trial and error are not acceptable, and to submit a written technical report *before* they start any construction. Only afterwards their designs are tested, thus demonstrating whether their assumptions and analyses were adequate (or not). There is a weight-not-to-exceed target and the students are in competition with their classmates. In more than one sense, this activity constitutes

perfect practice and complement for the *big* project, helping to heal the deficiencies of the original Ae421 and of previous structures instruction.

The mini-project was designed with the following specific expected learning outcomes (ELO) in mind:

- a) develop and demonstrate engineering design skill; conceive, design, build and test a lightweight structure responding to a stringent set of requirements and constraints,
- b) perform stress analysis and sizing with complex loading,
- c) recognition of diverse failure modes and associated criteria,
- d) propose technical solutions for structural response to identified failure modes,
- e) understanding of buckling instability and the mechanisms to prevent it,
- f) understanding of bearing failure and joint design,
- g) expansion of 2D problem thinking into 3D,
- h) development of engineering judgment, coping with uncertainty or incomplete information and implementation and use of factors of safety,
- i) understanding of concept of load path,
- j) physical experience and understanding of the concept that a given force can be transferred with lower stress levels by an increase in the area of action,
- k) improvement in technical report writing skills, and
- l) innovative thinking in light weight structural design.

DESCRIPTION OF THE ACTIVITY

The idea was to create an Active Learning Experience (CDIO Standard 8) that would represent, in a manageable and controlled scale the design of a minimum weight highly swept, fairly long and thin wingbox, subject to ultimate flight loads and geometrical constraints (the *big* project), with many of its challenges, requirements and pitfalls. In other words, due to the limited scope and relative simplicity of the activity it becomes easier to directly address ELOs a through d.

The statement of work for this mini-project called for the design of a “wingbox” with the outer mold line dimensions shown in Figure 1 weighing no more than 8 kg. This weight limit proved to be quite a generous target that will be tightened in future semesters.

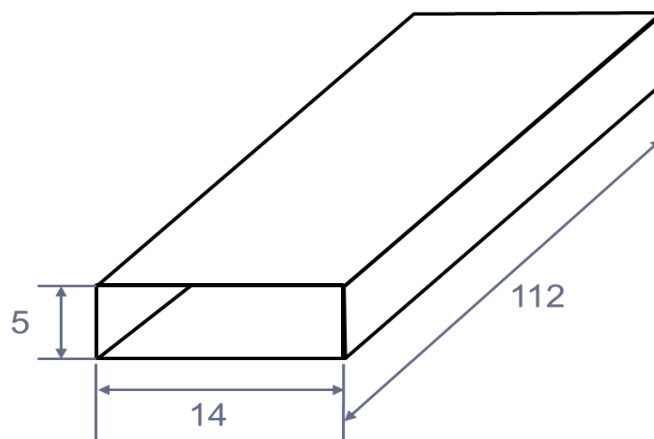


Figure 1. Outer mold lines for wingbox with dimensions in cm.

Students were free to choose any structural arrangement inside the box. They could even make it a solid beam if they so decided. However there was the weight constraint and an incentive to reduce the mass to the minimum since only the team with the lowest weight design would earn an “A” in that part of the task.

To render this activity more challenging and to force the students to deal with some of the intricacies of thin walled structures, the only materials allowed were conventional kitchen aluminum foil and common glue. These materials were also selected because they are readily available, at a relatively low cost. For any type of stress analysis mechanical properties are needed but for this material they are not immediately obtainable, something that pushes the students to conduct some research or to estimate or measure-test them while applying an appropriate safety factor to cater for errors or uncertainties (ELO *h*). Likewise, since “sizing” consists in determining the cross sectional areas that react the loads, those thicknesses could be created by the accretion of layers of aluminum.



Figure 2. The only materials allowed were kitchen aluminum foil and common glue.

The box would be cantilevered and subjected to a distributed load in the form of (7 × 18 cm) sand bags, each of 500 g, along the span and located in the front half of the chord as shown in Figure 3. This layout would subject the structure to torsion, shear and bending but the clever student could eliminate the torsion, for example, by placing the principal structural elements right under the line of action of the loads, thus merging the flexural and the elastic axes. An important lesson to learn here was the relevance of identifying where and how the loads are acting so that the design of the structure effectively accommodates them (ELO *i, j*). Some students tend to automatically idealize a beam as a one dimensional line on which shear and bending diagrams are drawn and therefore they miss the fact that, for example in a two spar design, the front and the rear spars do not carry the same loads and therefore do not need to have the same dimensions.

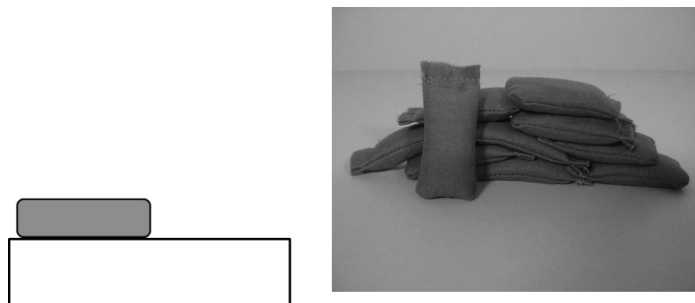


Figure 3. The box is loaded with 7 × 18cm sand bags along the span, each weighing 500g.

With the specified arrangement it is clear that the highest loads will occur at the root and that the integrity of the entire structure depends on its attachment. Mimicking the situation in real aircraft structures design, the students were allowed to use fasteners of any kind or even duct tape for the root attachment to a flat wooden board as long as they did not disturb the outer mold line (“aerodynamic profile”) and, in the case of duct tape, the extension of the tape spanwise into the wingbox did not surpass 3 cm in length.

Some of the lessons to be learned from the root attachment design were, for example, that it had to react the moment and the shear in a very constrained geometry. If duct tape was chosen, those loads had to be carried by the shear stress in the adhesive. If, on the other hand, fasteners were used, then the students got exposed to the phenomenon of pull-through or bearing loads (depending on their arrangement), the relevance of common design practice of preferably loading bolts only in shear and the need to increase the thicknesses in the joint area to react the bearing stresses, particularly in such a thin walled structure (ELO f).

For the entire semester the students were organized in teams of five and for the mini-project the specific deliverables were:

- a technical report or design note (1 week), and
- a working prototype to be tested (2 weeks).

One of principal learning outcomes of the entire course is precisely the development and demonstration of technical writing skills but experience has shown that students can be unprepared for this and, if the final report is the only one they write in the semester, some guiding principles or required standards of quality may be missing. This activity serves as an excellent help to set those standards (ELO k).

DISCUSSION

In most Aerospace Engineering curricula design, creativity and analysis are sometimes dissociated from one another. In freshman year students participate in design competitions where creativity is rewarded (CDIO Standards 4 and 7) but most of the times those designs are produced by trial and error, without any analysis, a technique that can be useful in simple applications but clearly inadequate for complex engineering endeavors. At the other end of the spectrum, in capstone design projects, structures are analyzed, aerodynamic models are created but, due to the complexity, student skills, cost and time constraints those products are seldom built or tested and therefore large amounts of numerical data are generated that could remain meaningless for the students involved. It was mentioned above that the first reaction when confronted with a beam structure and asked to size it tends to be to calculate its strength or yielding in the material whereas, in reality, it may buckle well before that material allowable is reached. If no tests are performed, the student could be perfectly content with a design that might be completely unsound. It should also be stated that computer simulation would be of little help here since most finite element codes, for example, will only provide solutions, say, for instability, if the models are expressly created and defined for that particular type of analysis and for that specific failure mode.

In order to restore that *touch* and *feel* that engineers should possess so that they recognize what the appropriate analyses are this activity was carefully conceived, planned and executed. It is a simple proposition: a cantilevered box beam with distributed loads, something they have analyzed plenty of times before. It could be designed, built and tested in a short period of time, providing significant learning in the process, particularly, helping the

students discover what they did not know that they did not know or did not consider important with regards to the problem. It also mimics, in a small scale, the actual work of sizing a wingbox in an industrial setting – the main focus of the actual term project.

An important aspect to underline is that they were required to *design*, i.e., not to just build something and hope it would work but to actually apply what they have learned in materials science and structure analysis courses. Therefore the students had to submit a technical report one week ahead of actual testing. In other words, before they would start building their prototype they should have designed it and conducted a detailed stress analysis to “proof” the structure. The final prototype tested should conform to the design specification in the technical report and any non-conformance had to be properly documented. The report should contain the following sections:

- requirements,
- information gathering,
- concepts generation and down selection,
- analysis, structural justification and
- engineering drawings.

The section on information gathering is one of the most important. It should contain all the information needed to successfully conduct the project, e.g., material properties, methods of analysis, types of fixity, prior art or examples of solutions to similar problems, etc. To be able to design the structure material properties are needed. These are normally not readily available for kitchen aluminum foil. This absence of data compels them to conduct some research or, possibly, testing and to establish adequate safety factors after recognizing the presence of unknowns and uncertainties (ELO *h*).

It was expected that all this groundwork would prepare them to generate their own concepts and to evaluate them so that a down selection of the best candidate could be performed. That would be the one concept to size, analyze, build and, ultimately test.

One of the objectives (ELO *k*) of this activity was to help establish the standards for technical report writing that would be demanded for the *big* project at the end of the semester. By receiving this miniature report graded and commented they would be able to better calibrate what to expect. This prevents the situation in which student groups submit a poor report at the end of the term because they had never written one before. At the end of the mini-project they would better know what details should be paid more attention to or what the elements of good technical communications are.

Also, experience has shown that some students, who have only been exposed to textbook problems, have difficulty thinking in 3D. In the problems they have been solving in previous courses they deal with 3D objects but, for example, in beam problems, they work on the cross sections and somehow lose sight that that 2D representation is only a *cut* of a 3D body. In building this beam some students created thorough analyses of those plane sections without worrying about the way those slices would be connected to the other slices of the beam and, obviously the structure failed. Thus this became a significant ELO (*g*) aiming at coping with that deficiency.

IMPLEMENTATION AND RESULTS

Up to this point the theory and objectives of this activity have been described. Now the results will be presented. The class was divided into five teams and each came up with original designs. There was the “brute force” approach in which a semi-monolithic aluminum bar was built positioned right under the sand bags, with a non-structural rectangular “fairing” built around it to form the profile. There were also more elegant solutions like one resorting to honeycomb structure or another, built in a multicell fashion. Another team tried a hybrid design with I-beams and honeycomb. Unfortunately their good intentions were not matched by equally good analysis (and prior testing) and it was the only one that failed during the final test. And there were also a three-spar and ribs structure, a multicell architecture and a sandwich construction (Figure 4). It should be said that the students chose fairly conservative designs, most of them following existing examples of wing construction without venturing into exploring more creative solutions. One of the reasons expressed for this conservatism was the fear of not knowing how to correctly analyze “unconventional” architectures. The time constraint was also cited as a motivation for keeping the design close to existing book examples. From that point of view, ELO 1 was not entirely achieved.

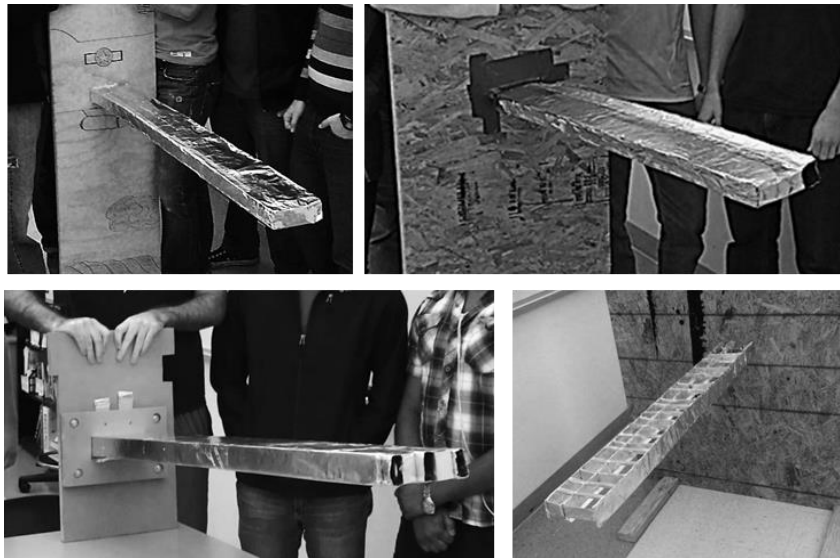


Figure 4. Four prototypes with different architectures: multicell, monolithic bar under loads with fairing, multispar.

All prototypes, with the exception of one were able to carry their loads without failure and without excessive deformation. No stiffness requirement was given other than that the sand bags should not slide off (friction enhancing devices were not allowed). Perhaps in the future stiffness and torsional rigidity limits could be set.

The box that failed did so at the root joint where the stresses were the highest, as it should have been expected. That joint was not properly analyzed and sized and it was therefore the weakest link. The whole class, but that team in particular, learned and experienced firsthand the importance of joint design (ELO f) and, even though, their structure analysis showed positive margins of safety, now they visually verified the significance of other failure modes (ELO d).

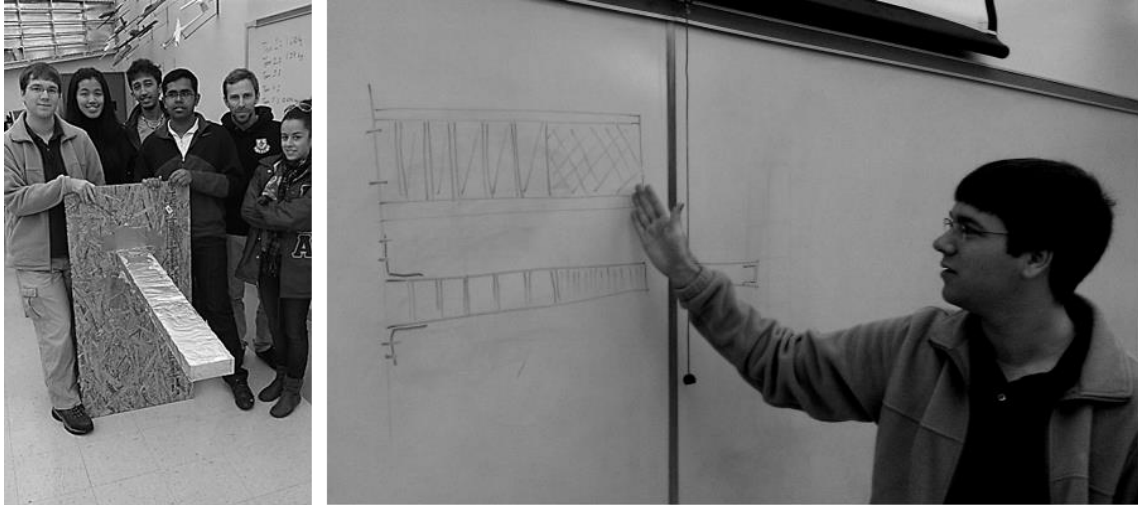


Figure 6. A team optimized its structure using honeycomb construction with different core densities depending on the load levels expected.

As previously mentioned, there was a degree of freedom in the root attachment design. In other words, in a situation similar to what exists in the design of large aircraft, the root joint did not need to be constrained by the same materials and adhesives as those of the outboard box structure. Any type of joining system was an accepted option (fasteners were allowed). Nevertheless, this would not help the students if they did not properly identify the load paths and therefore the appropriate arrangement to effectively transfer those loads from the structure to the wall (ELO f and i). The example shown in Figure 7 shows the solution adopted by one of the teams, where the students recognized that there would not be any load reversal (i.e., the structure was only loaded by the sand bags in the downward direction and they did not need to worry about “lift” or upward load) and therefore the root attachment could be simplified. The design chosen consisted of a pin through the spars above the neutral axis and the lower half of the spars abutting against the wall to react the bending moment. In both instances the critical condition would be bearing. For that reason the spars were padded up by adding layers of foil to obtain the necessary thickness. The pin was also needed for carrying the shear.



Figure 5. Test of multicell structure. Not only did it carry the specified loads but it also demonstrated a high level of rigidity.

The final prototypes were weighed before the test. All proved to be fairly conservative designs with masses between 1230 and 1980 g. The structure that failed (I-beam/honeycomb) had a much lower weight (650 g) but, as noted, its analysis was deficient, particularly, but not only, at the root joint. The not-to-exceed-weight requirement was clearly too high. In subsequent semesters a more challenging limit will be established to encourage creativity, demanding a more refined analysis.

All the prototypes were also measured before the test to verify that they met the dimensional requirements (in this occasion the students were allowed 10 % tolerances). All the structures were within those limits but not all of them displayed the same level of consistency. Clearly, in future courses, tighter tolerances will be demanded.

The students submitted their reports and, as anticipated, many corrections were in order, for example, with regards to formatting, appropriate referencing, with respect to the quality of the engineering drawings or of the analysis and how the information was presented. Weak areas were pointed out to them and all teams had the opportunity to resubmit the amended document one week later. As it will be explained further down, this contributed directly to the expected learning outcome *k* and the beneficial effects were verified in the final reports at the end of the semester.



Figure 7. Detail of the root attachment of one of the concepts. Notice how the spars have been padded up for the bearing loads of the pin and on the wall.

COMPARISON TO PREVIOUS METHOD OF INSTRUCTION

In previous semesters instruction consisted only of lectures and the semester-long design project of a large, complex aircraft component. Then certain deficiencies in the students' skills and preparedness were identified. These can be mapped to the list of expected learning outcomes for the mini-project activity. Since this task has been incorporated into the course the development of the *big* project and the final presentations and reports were positively impacted. In particular, the final reports of all the groups showed better coherence, more professional format, more logical argumentation and presentation of tables of margins of safety for the proofing of the structure including all the appropriate failure modes.

All groups now assessed various failure modes and were conscious of the importance of bearing and buckling failure, concepts that were completely overlooked in previous courses (ELO *c, d, e, f*).

One of the teams in the new course was an example of the two dimensional thinking

problem, not recognizing that the plane solutions in textbooks correspond to cross sections or slices of a 3D object and designed the aluminum box accordingly. They created “perfect” ribs or cross sections according to the theory they had learned in previous courses but ignored the fact that those slices were part of the continuum of the beam and, only joined those slices by non-designed discrete struts. Obviously that structure failed. A posteriori they understood their mistake, something that they would not have been able to identify without this activity.

ELO *h*, “development of engineering judgment, coping with uncertainty or incomplete information and implementation and use of factors of safety,” is something that would have hardly been addressed in the course as it used to be taught. In the past, they would design their structures using only the exact material values that they would find in a manual or catalog so there was no need to apply any engineering judgment or factors of safety for this aspect of the problem. With this activity they were forced to do it and a new way of looking at their *big* project was developed.

All groups in the semesters under the previous instruction method failed to incorporate buckling into their analysis, a situation that was reversed after the experience of the mini-project.

Also, in the new course, the majority of teams demonstrated an improved understanding of load paths and they designed structures that were more efficient. The concepts they proposed now also displayed that they grasped the need of increasing the areas of action of the forces to reduce the stresses.

OTHER FINDINGS

Not everything was perfect or ran smoothly in the implementation of this activity. As already mentioned, several groups limited their creativity out of fear of not being able to analyze the structure. They did not feel confident about their accrued knowledge and some tried to find the problem already solved somewhere else so as to only “plug in” numbers for their application. From that point of view, these students were still in the mindset that this activity precisely tries to break. At least they were nudged in the right direction.

Although the statement of work clearly required to *design* first and, only then, build the structure—no trial and error approach—, there were some teams that followed the opposite path: they constructed something out of trial and error and then tried to adjust some analysis to justify it. This was reflected in their reports and the quality of their analysis.

In the exposition of the statement of work to the students, the instructor proposed a reasonable way of tackling this activity, stressing the importance of observation of existing solutions to similar problems from all sorts of sources and required that the report included a section on “prior art.” Two of the teams included the section and even elaborated some conclusions about what the best type of structure would be only to proceed and ignore it in their design. In other words, they only incorporated that chapter in the report because *it was required* and failed to recognize that it was there as a significant help or stepping stone for their subsequent work.

Many of these findings point to preconceptions and acquired habits that the students bring along to this class and that need to be deconstructed or addressed in a more direct way and are being the focus of current efforts in that course. This activity in itself is a first step but, as can be seen, the task does not solve those problems infallibly and automatically; an active involvement of the instructor is needed.

STUDENT FEEDBACK

Students provided informal feedback, being in general quite positive and supportive of this new activity. Many expressed that it was fun and interesting *actually* building something. There was a healthy spirit of competition and expectation to see how their creations fared in comparison to those of the other teams. Others expressed their gratitude for finally understanding some concepts that, no doubt, they had studied before. Some students complained about the amount of time allocated for this task (two weeks in total), considering it insufficient. However, the mini-project was *compressed* in that way by design since the most important part of the course is the industrial project and there is where the majority of the effort should be concentrated.

The following are direct quotes taken from the end of course student evaluations of the course. One specific entry of that survey is “What elements in the course MOST helped you learn the course content? Please be specific.” Two different students wrote, “The aluminum wing box project was a great way to get our feet wet for the main event,” and “The aluminum side project was fun and useful. Made us think about structures and was a good introduction to what the course was all about.”

CONCLUSION

A novel educational activity has been incorporated into the final year course of Aircraft Detail Design at Embry-Riddle Aeronautical University. This task has been conceived to serve as a prop to the semester-long project which constitutes the core of the course and, specifically, to allow the conversion of a capstone design course from a “conceive-design” only activity to a full “conceive-design-implement-operate” one where otherwise the complexity and realism of the design project would preclude the inclusion of the last two phases of CDIO. The activity was designed with specific expected learning outcomes. After its implementation it could be concluded that those learning outcomes were achieved.

Its main objectives are to help the students understand, in a physical, visual and experimental form, the intricacies of structural detail design, the need to identify all the possible failure modes and then analyze them properly (e.g., that thin-walled structures are most likely to buckle before they yield). Other important concepts that students experienced and learned in this exercise were the never-to-be underestimated relevance of connections and joints—the strongest, stiffest structure will be only as strong and stiff as its joints—something that often is neglected or overlooked in most undergraduate structures courses. A simple and almost obvious fact that stress levels can be reduced by increasing the area over which they act, be it shear or direct stresses, is something that students came to realize and almost discovered when dealing with the aluminum foil and adhesives. The design of the root joint posed the challenge of reacting a fairly high moment in a very constrained space. For some students it was their first contact with bearing stresses or with panel buckling and is probably one of the first occasions in which they were exposed to the concept of load paths. In summary, all this gives back a certain innate sense for structures that only a few of them may already have possessed. In previous semesters the theoretical and conceptual foundations are laid by the materials science and structural analysis courses but it is in this course that everything “comes together,” and it can be said that the instruction of structures analysis and design achieves closure.

Other significant outcomes of this activity are the improvement in technical report writing and production of stress justification dossiers. Such documents are produced at the end of the term for the *big* design project and this “rehearsal” helps to set the standards and to allow

the students to identify their weak points in need of improvement. Along the same lines, it also serves as a primer in project management and, in summary, it is conceived to smooth the transition from “book problem” type of courses into the real engineering world.

Student feedback has been positive and encouraging and circumstantial evidence suggests that the activity has improved the level of engagement and enthusiasm in the class.

It would be recommended to incorporate similar activities upstream into the fundamental structures courses.

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VV.AA. CDIO Standards.

BIOGRAPHICAL INFORMATION

Luis Gonzalez, Ph. D. is an Assistant Professor in the Aerospace Engineering Department at Embry-Riddle Aeronautical University, specializing on Aircraft Preliminary and Detail Design. Prior to his appointment in the university he worked for close to ten years in the Structures Analysis group and the Future Projects Office of Airbus.

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