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An Educational Framework based on Collaborative Reverse Engineering and Active Learning: a Case Study*

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This paper presents early results of a novel educational framework, currently in development. Incorporating Active Learning and Collaborative Reverse Engineering techniques, this framework aims to completely re-structure the learning system at Monterrey Tech., specifically in engineering courses. This is achieved through the assembly of an experimental, true-scale aircraft RV-10, focusing on the activities of a work-team of students in charge of the aircraft's structural analysis. In addition to obtaining numerical results, this assessment investigates the practical aspects of the developed methodology, such as the efficiency of the educational strategies in realising advanced learning concepts. In particular, it is shown how Reverse Engineering and Active Learning concepts can be successfully implemented as learning techniques, via carefully planned activities. During the latter, emphasis is given to the development of innovative, creative, self-learning, team-work and other desirable skills in students. Several evaluation methods (diagnostic, formative, summative, etc.) are considered, each measuring a distinctive feature of the students' performance. These show that the proposed strategies have a direct and positive impact on the student's ability to generate and synthesize knowledge. The case study described here represents an isolated cell within a larger educational project, thus future work will continue to explore educational issues arising from the aircraft's assembly, to be reported in forthcoming papers.

Keywords: collaborative reverse engineering; active learning; engineering education; engineering design; structural analysis; finite element method

INTRODUCTION

MONTERREY TECH.† is currently undergoing a major re-design of its learning system, in order to comply with its Mission towards 2015 and accreditation bodies such as ABET‡ and SACS§. Given this new challenge, the Engineering School has implemented a number of projects aimed at measuring the effectiveness of several educational techniques, particularly in courses related to design methodologies [1]. This work presents the preliminary results of the development and implementation of a novel educational framework, originally proposed by Ramírez-Mendoza *et al.* [2]. Taking off from well-established educational techniques, such as Active Learning [3–6], Collaborative Reverse Engineering [2,7–10] and others [11–14], the introduced framework provides a common ground and theoretical foundation for the educational strategies implemented here. Some background is given next.

Active Learning (AL) encourages students' involvement in their own learning process [3–6, 15]. It advocates hands-on learning; validating hypotheses through experimentation; socializing among peers in terms of sharing experiences and discussing what they learn [16–19]. Thus, students commit to intellectual activities within a factual framework. Reverse Engineering (RE) techniques [7–9, 17] are appealing as they pose open problems—quite common in engineering design—in terms of manageable components, and are thus an excellent vehicle for achieving insight into a subject. Collaborative Reverse Engineering (CRE) lets students 'get their hands dirty' by directly manipulating the subject of study, trying to deduce input information based on output phenomena [9, 19]. Although this experience could be partially replaced by expensive simulators [10], this alternative could never surpass the hypothesis' validation of a genuine CRE approach.

AL and CRE concepts are implemented here through a medium-term project represented by the assembly and re-design of an experimental, true-

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† aka ITESM ("Instituto Tecnológico y de Estudios Superiores de Monterrey", as in Spanish) is a leading Latin-American university based in México. See http://www.mty.itesm.mx and http://www.itesm.mx/2015/

‡ "American Board of Engineering and Technology", ABET Inc Board of Directors, Criteria for Accrediting Engineering Programs 2006–2007, 111 Market Place, Suite 1050. Baltimore, MD 21202 (2005).

§ "Southern Association of Colleges and Schools", http://www.sacscoc.org/

Fig. 1. Experimental aircraft, RV-10.

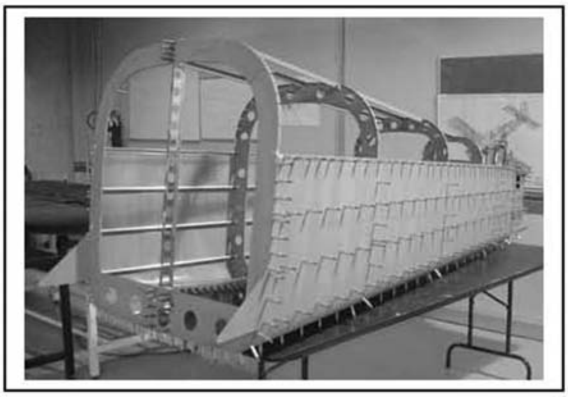

Fig. 2. Assembly of the aircraft.

scale aircraft RV-10, shown in Fig. 1.* This is a low wing airplane with aluminium for the primary structure and a composite cabin top and doors, designed to accept engines in the 200–260 hp range. The aircraft is sold as a kit with all the necessary parts unassembled, and it takes about 2000 man–hours of work to assemble. (Fig. 2 shows an assembled section of the plane, made by students.) Because of safety issues, this aircraft needs to be certified by some administrative and governmental Mexican bodies, e.g., DGAC ('Dirección General de Aeronáutica Civil'). However, it is not subjected to the strict FAA (Federal Aviation Administration) regulations usually imposed on larger aeroplanes, thus allowing one to focus on engineering and educational matters.

A typical design process (i.e., direct or forward-path) of an aircraft of this kind would require an extensive planning stage and a good deal of expertise in diverse engineering fields. It would also require highly reflexive and abstractive skills to evaluate, conceptualize and synthesize the body of knowledge generated during the process. One way to circumvent the obstacles encountered in developing these abilities is to use Reverse Engineering. Here, one would start by examining a (finished) physical prototype of an aircraft. Development would proceed backwards, disassembling the whole and experimentally discovering earlier assumptions made by the designer. Students can infer these assumptions without possessing the designer's skills. The reverse process should result in full comprehension and an enlarged picture of the design, possibly identifying those areas in which the design could be improved. Reassembling the physical prototype can also yield extended information about the manufacturing, ergonomic and other aspects of design. This is an efficient way of developing planning, reflexive, observational and abstractive skills, as well as obtaining 'hands-on' experience. The reverse engineering process of an aircraft is summarized in Fig. 3.

The main objective of this paper is to explore the efficiency of the implemented educational strategies in generating new knowledge, as well as provoking abstractive, creative, reflexive, and synthesizing mental processes. Other objectives include exploring the usability of several evaluation schemes for assessing students' performance. This paper proceeds as follows: first, the case study is described; second, the methodologies and strategies are outlined and thoroughly discussed (the main section); then, the evaluation methods used here are explained. Finally, our conclusions are given.

DESCRIPTION OF THE CASE STUDY

The case study focuses on the activities performed by the 'SA team', a group of four senior Mech. Eng. students in charge of the aircraft's structural analysis. The chosen component for performing the analysis was the Vertical Stabilizer, one of the first to be fully assembled (Fig. 4(a)). Owing to the lack of precise information regarding the loading conditions on this component alone, the analysis was restricted—for the time being—to assessing the reliability of a Finite Element (FE) model, a significant contribution often overlooked in practice. This can be achieved by comparing the Frequency Response Functions (FRFs) [20, 21] of the FE model and its physical counterpart, which must be fairly similar within a region of interest. Owing to the many approximations involved in typical FE formulations, these responses differ, thus a model updating [20, 21] procedure must be employed to identify modelling errors and produce a reliable FE model.

Following Fig. 3, the SA team started by measuring individual parts to produce a CAD† model of the Vertical Stabilizer, and then proceeded to generate an FE‡ model to calculate its frequency response at several points, considered the theoretical response. In parallel, an experimental modal analysis was performed on the physical component, measuring the frequency response at the same points as in the FE model. Because the

* http://www.vansaircraft.com. This aircraft was supplied by ICKTAR, a Mexican company, with the general objective of developing competences for providing high tech services to the Mexican aerospace industry.

† "Computer Aided Design". *Unigraphics®* *NX2.0* was used throughout this work for CAD generation.

‡ *Hypermesh®* was used throughout this work for FE analysis.

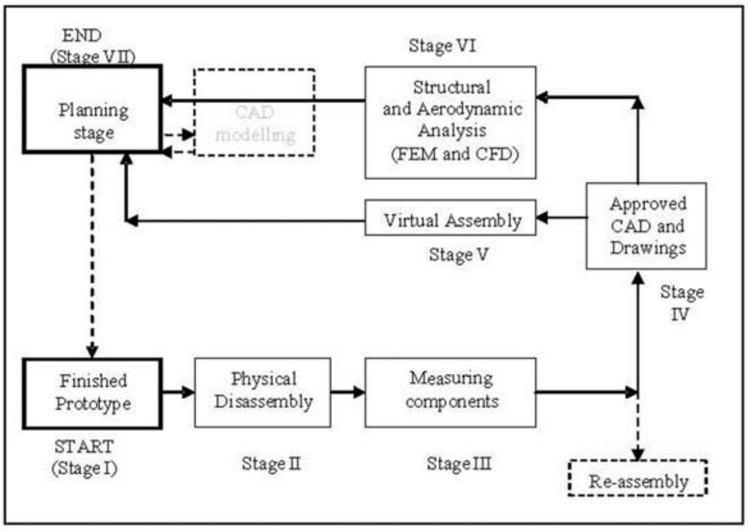

Fig. 3. Reverse-path for designing an experimental aircraft, RV-10.

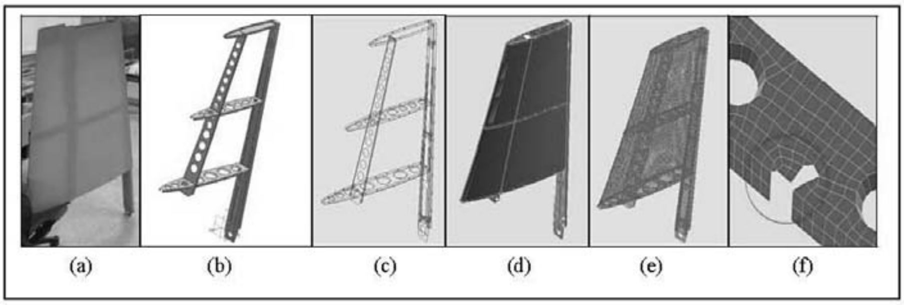

Fig. 4. (a) Vertical stabilizer (experimental or physical part); (b), (c) and (d), several stages of the construction of the CAD model; (e) meshed FE model; (f) mesh distortions due to relatively small geometric features compared with element size.

existing model updating techniques for correlating numerical and experimental FRFs [20, 21] are well beyond the scope of undergraduates, a trial-and-error approach was implemented here to achieve a reasonably match. Several evaluations were made of the team members throughout the project, not only to asses their levels of understanding, but also to create awareness of their own learning processes. One main issue to be measured was the efficiency with which Reverse Engineering (RE) and Active Learning (AL) techniques were implemented as educational strategies.

METHODOLOGY AND STRATEGIES

The methodology for implementing the educational strategies associated with AL and RE techniques are now outlined. The reader is reminded that this methodology does not necessarily represents an optimum path for performing a structural analysis, but rather ensures that students will face most of the problems commonly found in real-life analyses, as well as provoking planning, experiential, reflexive and abstractive mental processes. The latter are main objectives of the educational framework espoused here.

Educational strategies during measuring and CAD generation (Stages III and IV of Fig. 3)

Figure 5 shows the measuring of one of the aircraft's components, carried out in a ZEISS Coordinate Machine Measurement (CMM) system. This allows precise digital images of complex surfaces that can be directly exported to most CAD platforms via IGES*, to produce a virtual model (Fig. 4(b, c ,d)). After all the parts had been measured and exported, they were virtually assembled to produce the finished component (Fig. 4(d)). Digitalization of a physical component represents a reverse-path of a traditional (i.e. direct-path) CAD generation, the latter based entirely on the designer's modelling skills. Indeed, students required little or no CAD skills for measuring and exporting geometr—as these are highly automated procedures—but these skills were developed during the process and reinforced via simple tutorials. At the end of this stage, students were able to manipulate the obtained CAD models quite efficiently, even fixing uncertain measurements. This is an example of how new knowledge can be generated through Reverse En-

* "Initial Graphics Exchange Specifications", a neutral exchange format for 2- and 3D CAD models.

Fig. 5. Coordinate Machine Measurement (CMM) of one of the aircraft's components.

gineering. Another benefit of using a CAD system is that the team members could have individual access to a common database, thus allowing each member to work on a different part, at his or her own time and pace. This is an illustrative feature of Collaborative Engineering.

Educational strategies for learning FEM (Stage VI of Fig. 3)

Although it is a mature methodology nowadays, FEM is still regarded as an advanced technique. The team spent a week familiarizing themselves with it, via selected literature [22–24] (provided by the professor) and group discussions. Specifically, students were asked to translate an existing FEM code (available in [22], originally written in Mathematica®) to a different platform (i.e. Fortran), for learning purposes. Code-translation is standard practice in the software industry [25–26], where developers learn and improve existing algorithms by analyzing legacy code. This task requires a thorough comprehension of the original algorithm, and is thus an efficient technique for generating knowledge and insight. Such approach represents a reverse-path of the traditional (i.e. direct-path) software development, the latter entirely based on the designer's previous knowledge and programming skills, thus being an effective implementation of Reverse Engineering. Later, students were asked to use their newly-developed codes to solve a sample case (a truss-bridge, also described in [22]), and validate their results against commercial FE software. This validation provided a strong and meaningful purpose for learning, which is generally acknowledged as a powerful self-motivating tool.

Educational strategies during FE meshing and analysis (Stage VI of Fig. 3)

An essential feature of an accurate FE model is a high-quality mesh, and students spent some time manipulating the FE software to obtain this. It was noticed that small features—such as riveting holes and fillets—caused most of the problems (as shown in Fig. 4(f)), so it was decided to suppress them in the CAD model*. However, it was agreed that some of these features could be re-installed during a second analysis if it turned out that they were localized in critical regions of high stresses/strains. This required an iterative procedure that started by suppressing a few features in conflictive regions, then generating a new mesh and looking for errors, finally selecting new CAD features to be suppressed or reinstalled (the final mesh is shown in Fig. 4(e)). The iterative nature of this solution scheme ensured that students tried a large number of possible solutions in search of the optimum, thus undergoing planning, experiential, reflexive and abstractive mental processes. The aforementioned methodology also promoted intense decision-making sessions (moderated by the instructor) regarding the validity of FE models after major changes†. A final formative strategy was to produce a *Manual of Best Practices for FE Structural Analysis*, highlighting potential problems during an FE analysis.

Educational strategies during correlation of results (Stages VI and VII of Fig. 3)

A frequency response analysis was performed in both the FE model (via commercial FE software) and the experimental one (via a *CSI-2120* spectral analyzer). The obtained FRFs showed that the fundamental (first) natural frequencies were 65 Hz and 52 Hz for the FE and experimental models, respectively (Fig. 6(a)). A trial-and-error approach was used for correlating numerical and experimental responses. Arguably not a scientific method, it is otherwise an accepted engineering practice which can yield good results, provided an objective comparison tool is made (FRFs, in this case). It was found that the numerical (FE) response could be manipulated to some extent by varying Young's modulus and mass density, but beyond reasonable values. However, just a slight modification in the boundary conditions, e.g., freeing the rotational degrees-of-freedom at the fixed nodes, caused a dramatic change, in agreement with literature advice [22, 23]. This finding increased the students' self-confidence and also made them aware of the inhernt inaccuracies of typical FE models. After fine-tuning these boundary conditions‡, the numerical and experimental response matched reasonably well within the vicinity of the first resonance (Fig. 6(b)).

* This issue is acknowledged as good practice in the literature [22, 23], in spite of incurring in the so-called *discretization error* [2].

† On the other hand, students were promptly reminded of Einstein's famous advice, *"Models should be as simple as possible, not simpler"*, whenever essential geometry was ruled-out.

‡ As well as introducing a somewhat "artificial" structural damping factor of around 0.4%, four times greater than the recommended value for this material (aluminium).

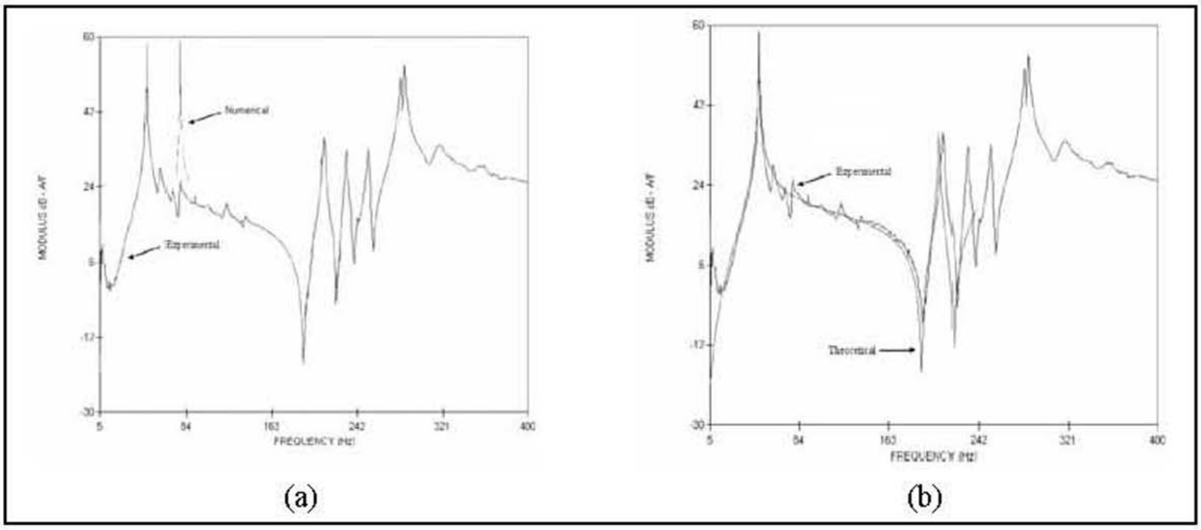

Fig. 6: Numerical and Experimental Frequency Response Functions (FRFs) in the vicinity of the first resonance, (a) before and (b) after the correlation procedure.

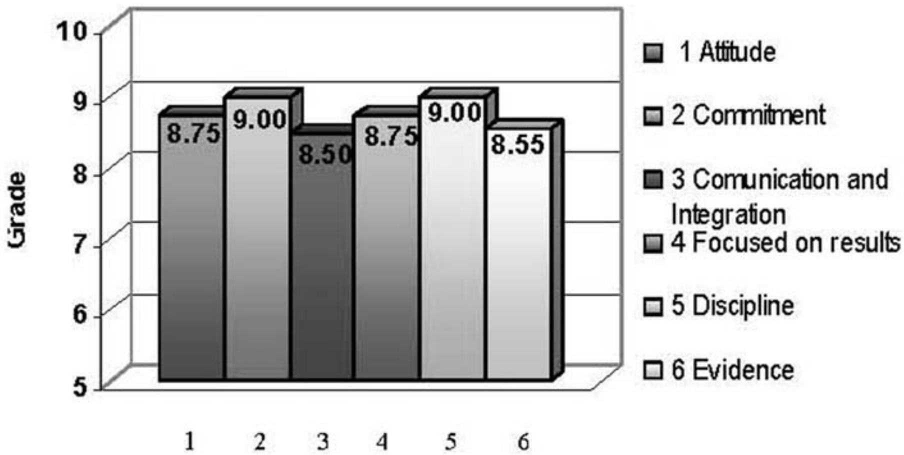

Fig. 7. Results of the evaluation of skills and capabilities for the SA team, evaluation applied by Professor Dr Hugo Elizalde and Eng. Daniel Meléndez . (Grades: 10 excellent, 9 very good, 8 good, 7 average, 6 poor performance)

EVALUATION METHODS

Several evaluation methods [17] were applied for assessing the strategies' effectiveness in reaching educational objectives. First, a diagnostic evaluation was applied to determine the previous background of the students. Second, formative evaluations were employed throughout the project to assess the students' progress. Third, summative evaluations were used to determine the final grade, based on major results and overall performance. More details are given below.

Diagnostic

- Oral and written examinations were applied to students at the beginning of the course, to determine their previous knowledge in materials science, mechanics of materials and structural analysis. Rather than assigning grades, the main objective here was to create awareness in students regarding their own weaknesses, previous to tackling the project.

Formative

- Each session was thoroughly documented in a log book, registering obtained results and commitments for future tasks. This provided a systematic formative evaluation tool, as students were aware of their own strengths and weaknesses at any time during the course, without feeling exposed.
- Code-translation and its applicability to a truss-bridge exercise [22] were adopted both as training and formative evaluation tools. By comparing results with commercial FE software, this turned out to be a self-evaluated exercise.
- Skills and capabilities, such as good attitude, discipline, commitment, communication and documenting were evaluated by one ITESM's faculty and one ICKTAR's engineer. Figure 7

Table 1. Compilation of ABET criteria

(A)	Ability to apply knowledge of mathematics, science, and engineering
(B)	Ability to design and conduct experiments, as well as to analyze and interpret data
(C)	Ability to design a system, component, or process to meet desired needs . . .
(D)	Ability to function on multi-disciplinary teams
(E)	Ability to identify, formulate, and solve engineering problems
(F)	Understanding of professional and ethical responsibility
(G)	Ability to communicate effectively
(H)	Broad education necessary to understand the impact of engineering solutions . . .
(I)	Recognition of the need for, and an ability to engage in life-long learning
(J)	Knowledge of contemporary issues
(K)	Ability to use the techniques, skills, and modern engineering tools . . .

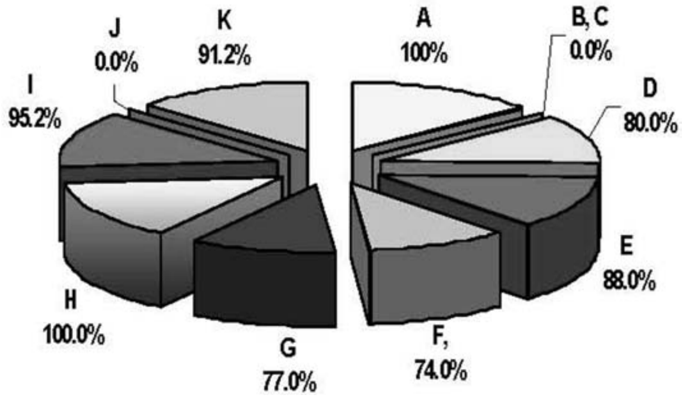

Fig. 8. Results of the evaluation for each ABET outcome (see Table 1).

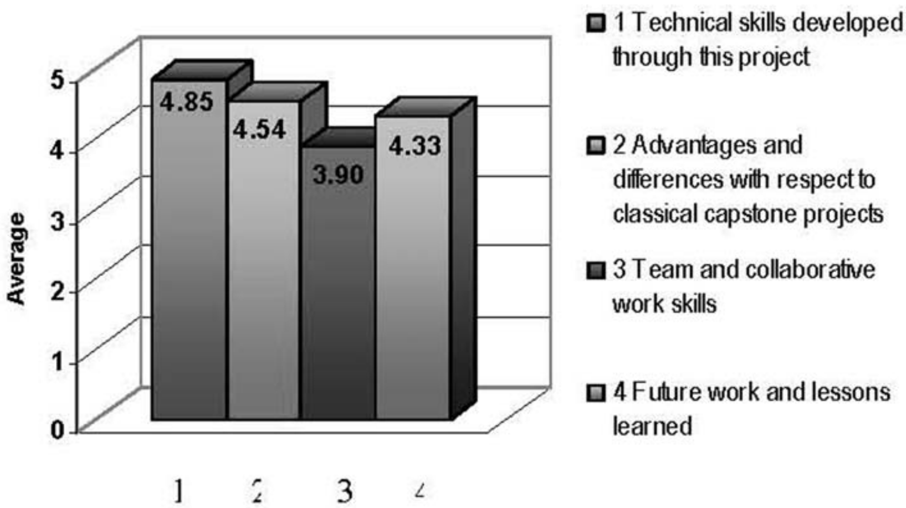

Fig. 9. Results from the ABET evaluation. Each topic in the graph was evaluated by members of the SA team. (1 completely disagree, 2 disagree, 3 undefined, 4 agree, 5 completely agree.)

shows the results of this evaluation, exhibiting some weaknesses such as communication among students and lack of documenting activities.

- Summative: In order to comply with accreditation criteria set by ABET (detailed in Table 1), graduates must demonstrate a sound knowledge of science (physics, mathematics, chemistry) and engineering's fundamentals. They should also possess communication, multidisciplinary team-work, and lifelong learning skills, along with a consciousness of social and ethical issues associated with their profession*. In this context, an evaluation was applied to asses the effectiveness of the proposed educational strategies in meeting some ABET outcomes. Figure 8 summarizes the average results for the SA team. It can be seen that results are satisfactory vis-à-vis the ABET criteria described in Table 2. Figure 9 shows relationships between ABET's

* Monterrey Tech. is currently certified by ABET

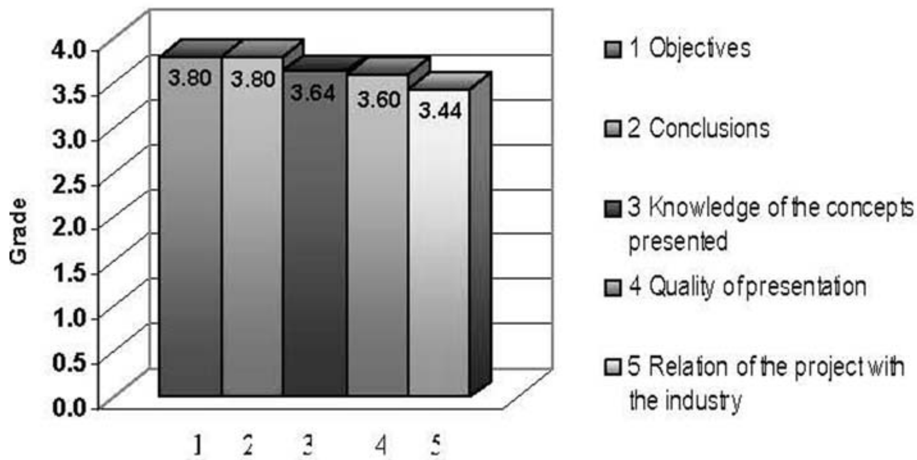

Fig. 10: Results of the evaluation of the final presentation and the posters for SA team. (Grade: 4 excellent, 3 good, 2 average, 1 poor performance.)

and project's outcomes. Most students obtained satisfactory results regarding developed technical skills. However, team-work and collaboration skills have room for improvements.

- Students were evaluated through a final presentation, a written report and a poster. These activities were most important in the learning process because the students were required to review, analyze and select relevant information. The SA team presented results to an audience of freshman students, professors and ICKTAR's engineers. Presentation and posters were evaluated by the audience through a survey, considering aspects such as presentation, organization, concise objectives, relation with the industry, etc. Figure 10 shows results of the evaluation, showing that students need to improve the quality of their presentations. Here, the relation of the project to the industry needs to be emphasized, to create awareness in the audience of this significant issue.

CONCLUSIONS

The main purpose of this paper was an assessment of some educational strategies, specifically those incorporating Active Learning (AL), Collaborative Reverse Engineering (CRE) and dedicated evaluation techniques. The main aspects of this assessment are highlighted below.

- CAD generation through digitalization of physical components was a practical example of Reverse Engineering. This allows a safe, fresh and fast approach for learning CAD systems, compared with the traditional method based on tutorials.
- The use of a common CAD database was also an example of Collaborative Engineering, allowing each team's members to work on different components, on his/her own time and pace. In fact, students rarely met physically during this stage—not until the final virtual assembly was required—and they fully appreciated the usefulness of this approach.
- Generating knowledge through code-translation was found to be an efficient Reverse Engineering technique. Although still relying on commercial software for the main analysis, students stopped perceiving FEM as a black-box.
- Associating learning to a meaningful purpose was demonstrated as a self-motivating technique. In this case, students learnt commercial FE software in order to validate results from their own codes.
- Implementing an iterative procedure to solve a difficult task ensures that the methodology will be repeatedly applied. Here, a correct FE mesh was eventually achieved by selective (a priori) suppression/re-instalment of small geometric features. This also stands as a Reverse Engineering technique, because it optimizes input parameters based on output results.
- A synthesising strategy and formative evaluation tool was to produce a *Manual of Best Practices for FE Structural Analysis*, written right after the SA team faced and committed almost every possible mistake. The team felt especially proud of this product, knowing that this manual would eventually be used by ICKTAR's engineers for training purposes. The latter is another example of associating learning to a meaningful purpose.
- The trial-and-error approach for correlating numerical and experimental results is yet another example of Reverse Engineering. This is a common engineering practice for finding out root causes through parameter manipulation. In this case, it promoted healthy discussions and even some fun due to unexpected results.
- Increasing a rise in the students' self-confidence, one of the main objective that were initially set, was achieved by allowing students to discover (for themselves) agreement between their own findings and advice in the literature's.
- In a different context, students experienced a

fact that is well-known but hard-to-grasp: most mathematical models are valid within a narrow range only. In the current implementation, this range occurred within the vicinity of the first resonance. Beyond this, a rapid deterioration of the model was evidenced by an increasing mismatching between the numerical and experimental responses.

- In spite of its daily use by the engineering community, a log book was a novelty for most students. As a formative evaluation tool, it allowed students to have immediate feedback about their own work, without feeling under scrutiny. The log book stood as a main documenting technique for the project.
- The students' final presentation provided a good opportunity for extending Collaborative Engineering concepts beyond the team limits, interacting with other teams. This interesting issue will be addressed in future papers.

This assessment has demonstrated the efficiency of the analysed educational techniques towards generating and synthesising knowledge, as well as enhancing desirable learning skills in students. The strategies will be incorporated within a larger educational framework, currently under development, aimed at a complete restructuring of the learning process in engineering courses at Monterrey Tech. Hopefully, these results will inspire educators elsewhere, who are well-aware of the ambiguities and pitfalls often found in classical engineering courses.

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