Can Interactive Finite Element Analysis Improve the Learning of Mechanical Behavior of Materials? A Case Study

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ABSTRACT

The paper describes an interactive Finite Elements Analysis (FEA) tool that aims to improve the learning of mechanical behavior of materials in industrial engineering schools. We implemented a "user in the loop" approach where students can explore the mechanical behavior of virtual specimens selected from a library of standard elements (cantilever beam, IPE beams etc.). The users can apply forces or displacements interactively by mouse or haptic device, and visualize and "feel" the structures stress configurations. We extended our previous work and compared this novel approach with respect to traditional FEA learning techniques. A test with twenty engineering students showed that learners following the interactive approach are faster in completing the given assignment showing a reduced error rate.

Keywords: real-time finite element analysis, engineering education, haptics, virtual reality.

1. INTRODUCTION

The increased availability of Human Computer Interaction (HCI) technologies and the steady improvement of computational power are leading to new and unexplored means of supporting learning processes [15].

In engineering education, learning the mechanical behavior of structures using theoretical models and analytical equations can be complex and frustrating for the students. Indeed, the use of Finite Elements Analysis (FEA) software, gives the students the possibility to simulate realistically the mechanical behavioral of structures. However, the traditional FEA approach is sequential and can be summarized as: load the target geometry, create the mesh, impose the constraints, define the external loads and finally run the simulation. The results are visualized at the end of this cycle that can take long time to be completed. The possibility to make these simulations more interactive and introducing virtual, mixed or augmented reality (VR, MR, AR) technologies can be beneficial in order to make the learning process of mechanical behavior of materials more intuitive and engaging. Several successful attempts to introduce MR interfaces in the learning phase are reported in literature for the medical [12] and the engineering fields [14].

In this paper, we present and test an improved real-time FEA application for learning purposes. The user can deform a set of structures or specimens by imposing displacements to nodes or applying forces, after easily defining initial conditions. Both displacements and forces can be applied interactively through a haptic device or a simple mouse. The user can visualize the results with color maps in a 3D view on a simple desktop monitor and perceive the reaction forces through the haptic interface, when available. In a previous work [8] the authors described the initial implementation of the tool, which was able to provide a proof of concept for interactive FEA solver [10]. The results were encouraging but the tool was limited to simple structure examples and constraints. The application needed to be improved to become a real engineering learning tool.

The goal of this work is the implementation and validation of our interactive tool in a real educational scenario. For this reason, we have improved the application interface for a better usability and extended the available cases with a set of examples commonly used in the mechanical engineering courses. The paper reports the tests performed with 20 engineering students, and discusses the results.

2. RELATED WORK

VR, AR and MR technologies combined with real-time simulation algorithms have been always considered the best candidates to support the learning and accomplishment of complex scientific tasks [5]. The main advantage compared to real experiments is the possibility to explore in a natural and direct way the cause-effect of different boundary conditions in short timespans. However, even with current computational power, one of the main limitations of current FEA approach is that complex simulations must be scaled down to provide real-time feedback. This is not a primary issue when learning the mechanical behavior of materials in the context of engineering schools. In this specific case, the user needs to “learn by doing” and understand the governing laws of stress and strain by quickly evaluating different configuration of the geometry and the constraints. At present time, there are few approaches in this direction with an attempt to mix interactive and VR, AR and MR technologies.

In fact, despite most of the research in the scientific visualization technology is addressed to the visual stimuli (colormap, isolines, glyphs etc.), the haptic research nowadays provides a different and very powerful approach to the exploration of scientific phenomena. The project GROPE [2], for example, is one of the first attempts to use haptic displays as a support for scientific visualization. The idea at the basis of the GROPE system is to represent 6DOF force fields in interacting protein molecules. In the following years, several haptic devices have been used as a support for teaching and training in medical disciplines [6]. In the engineering field some examples of VR environments based on haptic systems as a support for teaching can be found in chemistry [16]. However, we can affirm that, to date, the use of haptics as a support for teaching, and in particular in the engineering schools, is rare.

The sense of touch, combined with other sensory modalities, in a multimodal/multisensory way can give the possibility to facilitate the creation of the enactive knowledge [3], generally indicated as “learning-by-doing”. In this logic, the introduction and exploitation of multimodal and multisensory environment for teaching engineering disciplines can be an interesting means to improve the learning process. The sense of touch does not necessarily require a specific device to be reproduced, and a simple mouse associated to specific visual stimuli can produce a haptic cue. This illusory effect is also known as pseudo haptic effect [13].

Another interesting technology that can be useful as a support for learning and teaching scientific/engineering phenomena is augmented reality. AR allows us to enrich the real environment with additional digital information. In this way the results of simulation can be projected onto the real experimental setup. For example, some attempts to represent computer aided engineering (CAE) data in AR are reported in [10,11]. Further works have introduced the possibility to modify initial conditions to structural FEA (finite element analysis) [9] and to CFD (computational fluid dynamics) analyses [1,4] in an interactive way.

Although literature reports several applications of haptic renderings, few of them are specifically addressed to active learning and assessment of the mechanical behavior of materials in mechanical engineering education. One of the main contributions of this work is the user validation of this novel learning experience in terms of raised interest and motivation in the students. In particular, the authors have improved the usability and the contents of the real-time FEA visual\haptic simulation loop. The students can now start to interact with simple structures and learn by increasing the complexity gradually. In the next section, we provide the details of the improvements of the approach compared to system reported in [8], followed by its validation and testing with industrial engineering students.

3. DESCRIPTION OF THE APPLICATION

The interactive application works as follows:

- The application provides the user with a “natural response” in a multisensory action-perception loop. The user can play with a set of specimens using two different input controls: a mouse or a haptic device. In particular, s/he is able to apply both forces and displacements to specific nodes of the specimen. The main feedback is visual. If the haptic device is available, the user can also feel the reaction as force feedback on her/his hand. The setup is illustrated in Fig. 1.

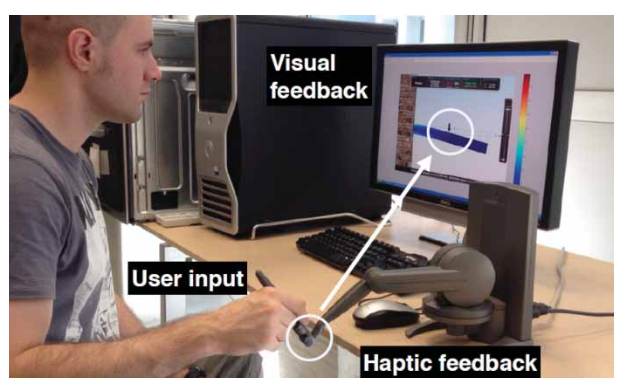

Fig. 1: The setup for the proposed approach.

- The user can interact with two types of specimens: planar or three-dimensional, as illustrated in Fig. 2. Tab. 1 reports the number and the types of elements used for each model. The maximum number of elements, therefore the complexity of the model, is limited by computational constraints to achieve real-time feedback with a minimum designated refresh rate of 15Hz (by using a standard laptop equipped with Microsoft Windows 8, CPU Intel I7 2.6 GHz, 8GB of RAM).
- The user can also select and evaluate different constraints for the same specimens as well as change the specimen thickness or length (depending on the specimen) as shown in Fig. 3.
- After choosing the node where to apply the force or the displacement, the user can play with the simulation and see the results as illustrated in Fig. 3. In addition to the classic color map visualization, the relevant engineering data are summarized in a specific box. This panel gives a quick highlight of the structural integrity of the model. The user can modulate the intensity of the external input in real-time on the basis of the feedback provided. If a haptic device is available and plugged to the computer, the user can apply a load or a displacement through it. Alternatively, the user can control the displacement or force value through a slider bar (visible on the right side of both pictures in Fig. 4).

The application has been implemented in MATLAB environment (www.mathworks.com). MATLAB is a programming platform widespread in industrial engineering schools. The application is flexible and the test cases are easily extendible. Our idea is that the set of case studies implemented in the initial release of the application should be extended and shared by an online community of both students and instructors. The FEA solver is COMSOL (www.comsol.com) connected to MATLAB through the bundled LiveLink tool. The haptic device, a Phantom Desktop device (www.sensable.com) in our case, is controlled through the MATLAB environment via the HaptikLibrary [7]. HaptikLibrary provides the 3D position of the user input (the haptic device end effector), and returns a force feedback according to the specimen internal stresses status.

We tested the application for usability with experts in interactive applications and FEM simulation. The collected suggestions have been implemented in the final release of the system.

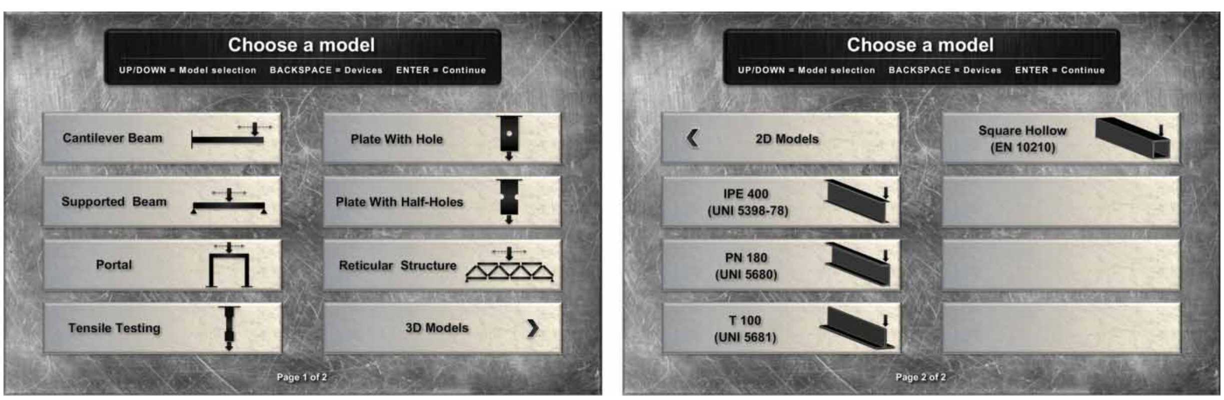

Fig. 2: The library of the implemented specimens: planar structures (left) and three dimensional ones (right).

Specimen	Elements	# of Elements	Solver
Cantilever Beam	Normal (ps plane stress, pn plane strain)	160	Quadratic
Supported Beam	Normal (ps plane stress, pn plane strain)	160	Quadratic
Portal	Normal (ps plane stress, pn plane strain)	276	Quadratic
Tensile Testing	Normal (ps plane stress, pn plane strain) ADAPTIVE	130	Quadratic
Plate with hole	Normal (ps plane stress, pn plane strain)	636	Quadratic
Plate with half holes	Normal (ps plane stress, pn plane strain)	834	Quadratic
Reticular Structure	Normal (ps plane stress, pn plane strain)	1760	Quadratic
IPE 400	Solid smsld (Extremely coarse or coarser)	1268	Linear Lagrange
PN 160	Solid smsld (Extremely coarse or coarser)	3373	Linear Lagrange
T 100	Solid smsld (Extremely coarse or coarser)	501	Linear Lagrange
Square Hollow	Solid smsld (Extremely coarse or coarser)	3352	Linear Lagrange

Tab. 1: List of elements, number of elements and solver used for each specimen.

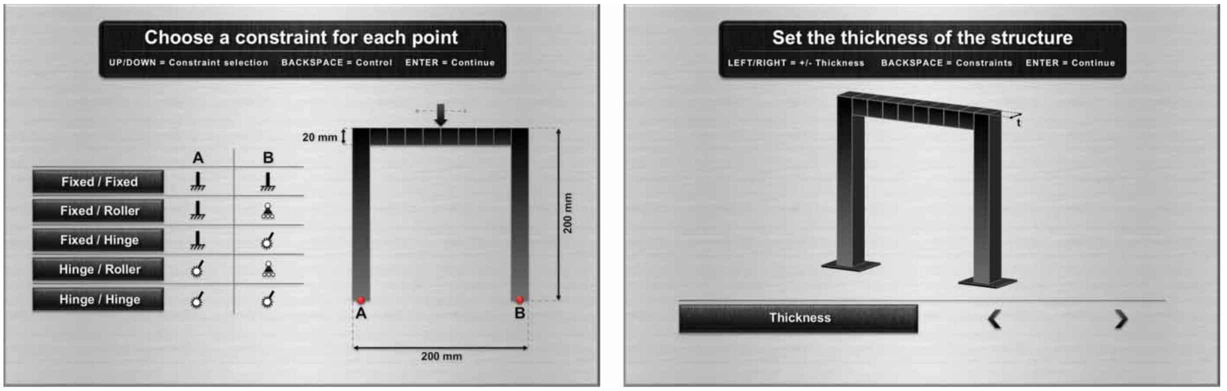

Fig. 3: The constraints selection window (left) and beam\structure thickness control (right).

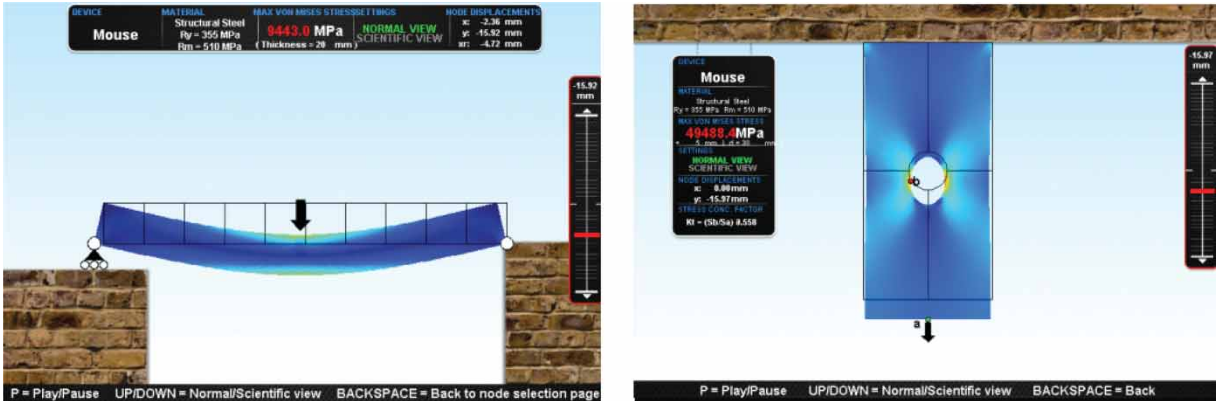

Fig. 4: Examples for cantilever beam (left) and plate with hole (right).

4. USER TESTS

The aim of the test was to compare the proposed interactive application with traditional FEA learning.

4.1. Procedure

Twenty students from the mechanical engineering school, aged between 21 and 28 (mean 24.3, STD 2.1), 15 males and 5 females, have been selected to participate to the testing session. Three of them had previous general knowledge of FEA. This was a between-group test design, therefore we split the participants randomly into two different groups. The first group performed the test first using the classic FEA interface (COMSOL has been selected for this purpose), and then on the new interactive interface while group two did the opposite. Users were initially invited to familiarize with the software interface they were supposed to use, i.e. the traditional FEA interface or the new interactive one, until they felt confident in using it. During this phase, they could ask questions to an expert operator until they felt sufficiently confident with the interface. There was no time limit during this training process.

When ready, participants were asked to play with the software tools. Specifically a specimen was chosen and they were asked to apply some initial conditions and displacements or forces to specific nodes (for example in Fig. 5 the specimen chosen is the portal). They were asked to learn and memorize as much information as possible on the specimen behavior at different loading conditions. Also in this case there was no time limit to complete this task and an operator could answer to participants' questions.

When they felt confident about what they learnt, they were asked to fill out a questionnaire (Google Forms have been used to collect the results). The questionnaire was composed by ten questions with multiple choices (five) and was structured in the following way:

- users were asked to imagine to apply some constraints and loads to specific nodes of the same specimen they had used in the training phase;
- they were asked to answer to questions on points of major stress, or major deformation or to indicate the more appropriate shape deformation. Fig. 6 illustrates, as an example, one of the specimens selected for the test (left) and the

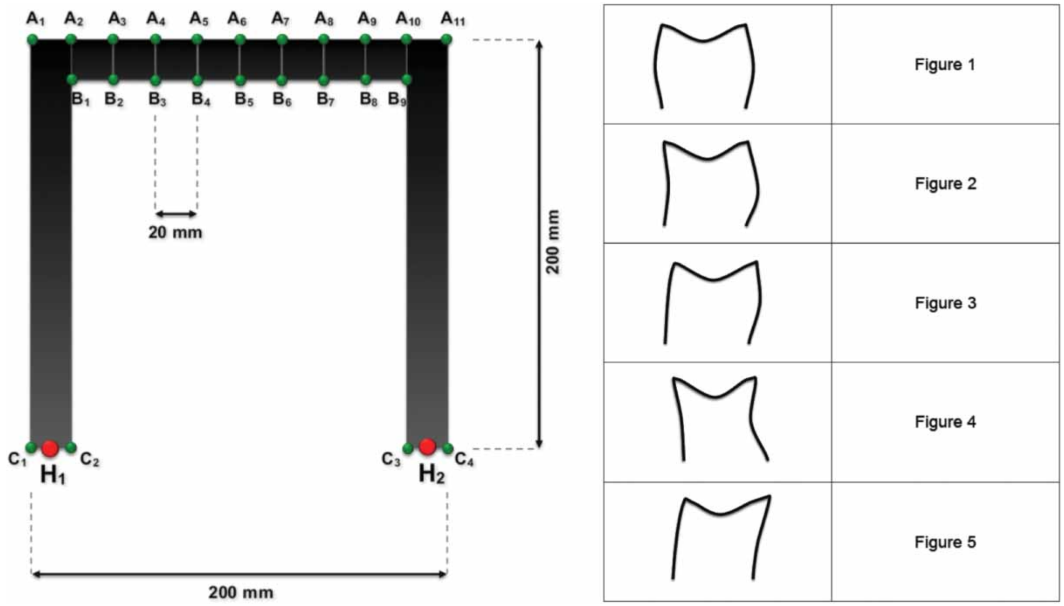

Fig. 5: One of the specimens used for the testing activity and deformed shapes the users had to select as answers for different loading and constraint conditions.

deformed shapes (right) the users could indicate as answer;

- there were 5 questions based on the understanding of loads and 5 questions on the understanding of constraints.

Users had a time limit of 1 hour to fill the entire questionnaire.

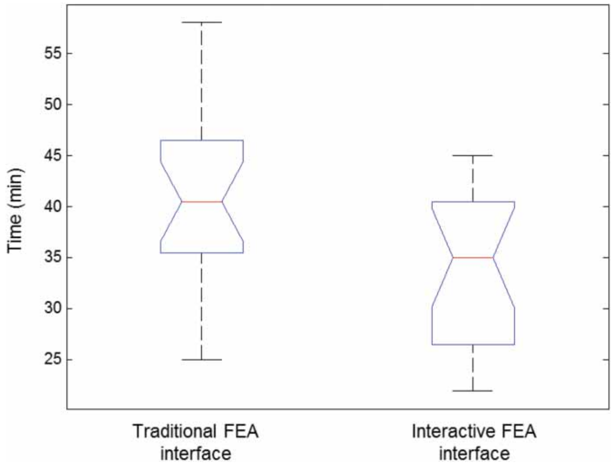

Fig. 6: Performance time for the two interfaces.

We collected, as dependant variables, the response time, i.e. the time to complete the questionnaire, as a measure of the learning time performance, and the number of wrong answers, i.e. error rate as a measure of the accuracy performance.

4.2. Results and Discussion

To evaluate the main effects of the interface, we verified that the response time samples followed a normal distribution, using the Shapiro-Wilk normality test, AS R94 algorithm. Usually short task completion times do not pass this test because they follow a log normal distribution, therefore a log10-transform to the original data is needed. In our case, the data passed the normality test, maybe because of the long task time, i.e. about 30 minutes. Then we executed an outlier detection for the samples using the Tukey's method, based on the interquartile range. We observed no outlier detected for both the interfaces proposed.

Before mean comparison analyses we assessed normality of the samples to be compared, with Shapiro-Wilk normality test. Then we evaluated homoscedasticity of the samples, applying Levene test that does not require equal dimensions for all the groups. Since all samples were normal and homoscedastic, we used one-way ANOVA.

As to the error rate, the faults considered in our analysis are wrong users' answers. We used the method of "nx2 contingency tables" to do statistical inference ($p = 0.05$), on error data. We used the following error rate definition:

$$ER\% = \frac{n.errors}{n.targets}.100$$

The first main result obtained is that there is a statistically significant difference on time performance between interfaces $F(39) = 7.567$, $p = 0.009$. Fig. 6 shows the box plot of the completion times. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the extreme data points. The average time to complete the questionnaire for users that had used the traditional interface for the learning phase was 41.15 minutes while it was 34.05 minutes for those who had used the new interactive interface.

Another main result is a significant statistical difference on error rates between the traditional (ER = 53.00%) and the interactive interface (ER = 30.50%) with $\chi 2(1) = 20.817$, $p<0.001$ (Fig. 7).

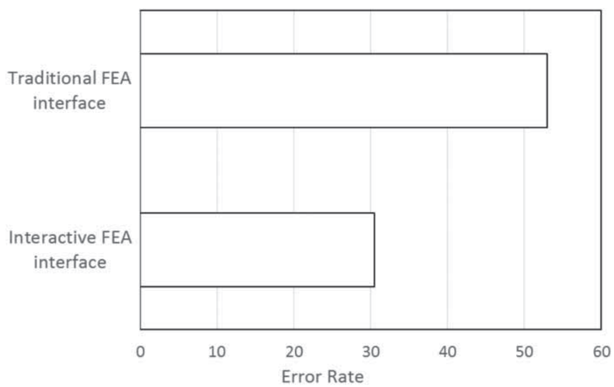

Fig. 7: Error Rate with the traditional FEA interface (top) and with the interactive one (bottom).

We then analysed deeply the results to evaluate the effect of the participant group and of the questionnaire sub-section. We found no significant differences on time performance between users who made the task first with traditional and those who made the task first with the new interface. This validated also the design of the experiment we made. Moreover, we found no significant differences on accuracy performance between the questions on loads and those on constraints.

It is evident that the proposed approach improves the learning for all participants. The questionnaire completion time is improved by 17%. This is a very good result, but the most important one is the improvement in the error rate by 42%. In designing an educational project, we are more interested in an effective learning more than in a fast learning.

5. CONCLUSIONS

We developed an interactive Finite Elements Analysis tool to improve the learning of mechanical behavior of materials in industrial engineering schools, to make the learning phase more engaging and effective. The tool allows students to play interactively with a set of specimens that are commonly used in mechanical engineering courses. The tool allows also students to create easily custom specimens. Through the GUI of the proposed tool, students can easily choose one of a set of common specimens, set materials and choose among different constraints. After the initial conditions have been setup, users can apply loads and/or displacements to specific nodes through a haptic interface, or by using a simple mouse, and see in real-time how specimens behave. To this aim, we interfaced a FEA solver with a haptic device, or with a mouse, through the MATLAB environment. This makes the application easily extendible, being MATLAB largely used in industrial engineering schools. The specimen elements have been chosen in order to allow the FEA solver to grant a minimum refresh rate of 15 Hz, which can be considered real-time. The usability of the tool has been refined during the development on the basis of the comments of experts.

The main novelty of the proposed approach is an effective integration of FEM code with haptic display of results in real time (i.e. 15 Hz). Finally, we compared this novel approach with learning techniques based on traditional FEA tools with twenty engineering students. Results clearly show that the interactive approach improves the learning capability with a significant reduction of the error rate (42%), and with faster learning times (17%).

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