Proceedings of the ASME 2015 International Design Engineering Technical Conferences &
International Conference on Design Education
IDETC/DEC 2015
August 30-September 2, 2015, Boston, USA

DETC2015-46978

BRIDGING THE GAPS: AUGMENTING DESIGN LEARNING THROUGH COMPUTER-AIDED EXPLORATION

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ABSTRACT

In helping students learn engineering design, it is very important that they explore complex scenarios that are realistic, and fall outside the domain of standard and over-simplified textbook problems that typically have an answer. A majority of the current educational methods and computer-based tools do not bridge this gap and lack affordances for design exploration. Although computational methods such as Finite Element Analysis have this potential, they are hard to use requiring the users to spend a significant effort. Also, several instructors have identified significant knowledge gaps in concepts related to structural design and strength of materials when the students reach their senior year. To this end, we have developed a problem-based framework to allow for rapid design exploration within engineering design curricula using an easy-to-use, simplified and constrained version of finite elements for stress analysis and exploration. Our framework makes it possible for users to rapidly explore various design options by incorporating a Finite Element Analysis (FEA) backend for design exploration. Our approach uses a constrained design problem for weight minimization that incorporates elements of structural topology optimization but does not automate it. Instead we provide the user the control on decision making for changing the shape through material removal. Using this framework, we explore the decision making of users, and their methodology in the course of the activities that provide a context of control, challenge and reflection. Using video and verbal protocol analysis we integrate assessment in ways that are important and interesting for learning. Our framework demonstrates that the ability of computational tools that are transformed for learning purposes can scaffold and augment learning processes in new ways.

1. INTRODUCTION

For students to succeed in engineering design and practice they must be able to make design decisions that are grounded in data and analysis. To make such design decisions confidently, a firm grasp of basic engineering concepts such as in Mechanics of Materials is important. Several instructors have expressed their disappointment with students' general lack of understanding and inability to apply these concepts in a real world scenario as well as in subsequent higher level classes [1-3]. This highlights the need to modify existing educational methods to ensure better understanding of the basic concepts of Mechanics of Materials and in turn, develop better design practices.

Kolodner *et al.* [4] posit that new mechanisms of learning would be triggered by critical exploration and a problem-based learning (PBL) approach. Simulations can be considered to be a variant of cognitive tools in that they allow students to test hypotheses and explore "what - if" scenarios [5]. Simulations can also vastly enhance learning as they offer an interac-

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tive and visual medium and thus promote critical exploration and thinking. Simulation tools like Finite Element Analysis (FEA) have tremendous potential in providing affordances for learning through design exploration because of their wide applicability in solving problems in a variety of domains. The use of simulation tools in practice is more as an analytical tool for confirming design feasibility rather than as a design synthesis tool [16]. This is partly because these tools have a steep learning curve and modeling directly on them is a very tedious process [6]. The use of these tools is thus, largely restricted to trained analysts performing specialized analysis after a design cycle. This creates a significant gap between engineering design and design engineering within engineering education.

With the above points in mind, we have developed a problem-based framework for two dimensional structural FEA problems that address this gap by facilitating rapid iterations in the design process. Our framework provides affordances for rapid design iterations and allows students to pose 'what-if' questions at the early stages of design. Within this paper we aim to discuss the following research questions related to the learning of concepts in Mechanics of Materials using our framework:

RQ1: How does our framework which incorporates easy geometry creation and on-the-fly FEA simulation impact the students' understanding of concepts in Mechanics of Materials and structural design?

RQ2: How does using our framework to explore a constrained design problem aid the students' learning of certain target concepts in Mechanics of Materials?

The current paper discusses a prototype implementation of our framework and a corresponding pilot user study to evaluate the learning impact of using our framework conducted with students in the School of Mechanical Engineering at Purdue University.

2. MOTIVATION AND NEED IDENTIFICATION

Engineers must have the ability to both perform analysis and engage in design thinking when making design decisions. In undergraduate engineering education, these skills are often taught in a discrete manner: taught in completely separate classes and often handled by different and completely separate groups of faculty. Students are then forced to reconcile their understanding of these skills through independent application opportunities.

The potential danger in introducing analysis and calculations too early in the design process is that this may lead the designer to get fixated on the current design [7,8] and not explore other, potentially better design solutions. This is problematic as engineering education endeavors to teach students to be more innovative.

Early introduction of engineering analysis can not only cause fixation; it can lead to knowledge gaps which can lead to misapplication of concepts and lower innovation in design [9,10]. Students may face challenges when prompted to recall and apply theoretical knowledge learned from their related coursework. Furthermore, students who do not have a strong understanding of how to apply theoretical knowledge to diverse real world contexts, which may differ from what is described in their textbooks, might not explore alternate design solutions given a design task because of their limited knowledge and their inability to form a connection between concepts learned earlier.

To ensure applicability of concepts being learned by students, a change at the "conceptual level" has to be enabled [31]. Presenting information and knowledge inconsistent with existing mental models and conceptual structures leads to the formation of misconceptions about the concepts being taught. It is therefore necessary to adopt an approach which enables a smooth experience in terms of learning new concepts/addressing knowledge gaps.

In a Problem - Based Learning (PBL) approach, software and online applications can facilitate students' learning by helping to ground their understanding of concepts and theories. By taking advantage of the visualization capabilities of simulations, affordances can be provided for design exploration.

Finite Element Analysis (FEA) has wide applicability in solving problems in structural, dynamic, thermal, fluid and electrical engineering problems [11-14], and the ability to demonstrate a wide variety of concepts effectively, for example, applying FEA to a common truss problem can help the student visualize the bending of truss members and deformation in a way previously not possible. Use of FEA for studying engineering concepts is similar to the inclusion of laboratory experiments in lecture courses, to provide reinforcement of core lecture material more effectively than a textbook [15]. Also, FEA can be used to bridge the gap between traditional learning through textbooks, which typically incorporate standard geometry, and applying those concepts to realistic design problems with complex geometry, where knowledge gained from textbooks alone is not sufficient.

Though powerful with advanced graphics and animation capabilities, these commercial tools do not lend themselves to use in engineering education as they were primarily developed for the industry [16]. The student must, therefore, become familiar with the software or application itself before using it as a medium for exploration. The complexity of a software application that will help students explore more design alternatives may actually serve as a hindrance to the student until they:

1) Improve their understanding of the needed engineering concepts and/or 2) become familiar with the software application.

There is thus, a need for a simplified framework that enables users to take advantage of advanced simulation software for design exploration.

3. RELATED LITERATURE

There has been considerable research towards addressing knowledge gaps in fundamental concepts of Mechanical Engineering such as in Mechanics of Materials. Egelhoff et. al [17] have identified and detailed several approaches followed by instructors and educators to augment the learning of fundamental concepts and to address knowledge gaps that exist in students understanding of fundamental concepts of Mechanics of Materials.

Extensive work has been done by [1,3,12,14,15,26 - 30] in using a variety of methods like physical models, computer programs, research on concept inventory, active learning strategy development and introducing FEA early in the curriculum to aid learning in the classroom.

Our approach is a Problem - Based Learning (PBL) approach that leverages the capabilities of commercial FEA software to assist in exploration of the problem design space. We use FEA as a metaphor for exploration. In our framework we enable the student to engage in simulation directly without having to learn how to use the FEA software. A detailed explanation of our framework follows in the next section.

4. FRAMEWORK DESCRIPTION

Based on the risk of low design exploration and the existence of knowledge gaps in students' understanding, we developed a framework which is designed to allow for more opportunities for learning of principles of Mechanics of Materials and would allow for increased ease of design exploration. The framework was designed to meet the following objectives:

- Stimulate an environment for design-analysis exploration, in which questions like 'what-if', 'why', 'what' and 'how' will be more effectively answered through on-the-fly simulation and visualization.
- Incorporate a visual approach to allow better understanding of practical situations through solving problems, where conventional equations do not apply, and also beyond "toy" textbook problems.
- Enable the transition from a passive, teacher-centered model of education to one that is student-centered [18] and emphasizes active-learning [19].
- Enable self-learning in students through critical exploration of engineering concepts.
- Empower the student designers to analyze and explore different concepts for stresses, deformation and failure during the early stages of design, rather than the conventional way of analyzing after detailed design.

To meet the above objectives, we developed a problem-based exploratory framework that uses a Finite Element Analysis backend to aid exploration. We removed the control on meshing and other FEA parameters from the participant and set default parameters that ensured an accurate solution without compromising on solving time. Also, by constraining the design problem, we ensured that the participants did not have control over the boundary conditions of the problem. By taking the above steps, we ensured that the participants did not have to focus on any other aspect of the problem other than the exploration and importantly, ensured that participants did not require any expertise in FEA to solve the design problem.

For the design task, we used a constrained design problem for area minimization that incorporates elements of structural design optimization. Structural design optimization is a challenging design problem because it can encompass a broad range of qualitative and quantitative objectives [20]. From a geometric perspective, it involves the selection of an appropriate topology for a member to satisfy certain constraints. The design space can be further narrowed by imposing additional constraints such as weight, stress and deformation limits. Constraining the design space in exploration is important because not all learners exhibit proficiency in unconstrained exploration and this can severely restrict their learning in such an environment [21].

Papalambros and Chirehdast [22] observed from a structural design optimization study conducted in 1990 that students for the most part, used their intuitive knowledge and in some cases, used low fidelity prototyping and FEA for a design task. Structural design optimization thus fits the bill as a fairly complex exploration framework to enable discovery learning. We provided the user with control on decision making for changing the geometry of a provided member. To impose constraints, we allowed only material removal operations by combining three shape primitives in any manner using Boolean operations. The shape primitives provided to the user were the rectangle, the circle and the rectangle with filleted corners. Fig. 1 shows a screenshot of the interface of our framework. For future portability, we developed the framework to run on a Web browser.

5. METHODS

In this section, we briefly introduce and discuss the theory which informed the design of this framework. The results from this work represent results of a preliminary pilot study conducted to evaluate the learning impact of our new framework and to further develop the framework based on participant feedback. Situated learning environments have been shown to support knowledge transfer from more decontextualized theoretical knowledge to more authentic contextual application [23]. Our focus is to provide a simple yet meaningful context for the students as they are learning, to apply mechanical engineering principles to solve design problems. By situating the design task in a context which differs from that presented in traditional textbook problems, the student engineers are given an opportunity to exercise their knowledge transfer ability and gain experience using tools and engaging in practices which may resemble those used by professional engineers.

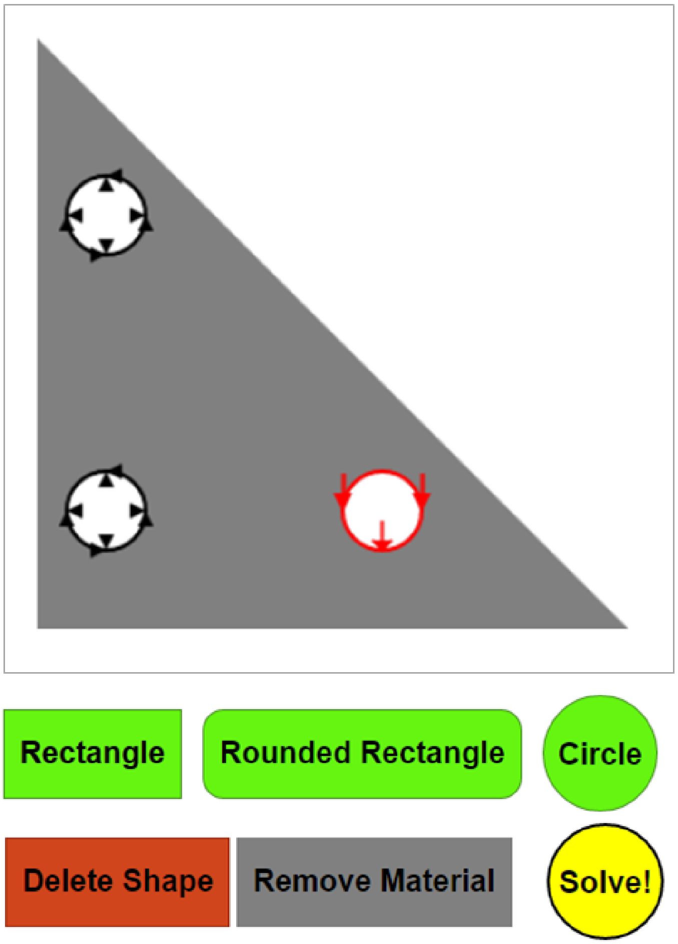


FIGURE 1. Screenshot of the interface of our framework. The green buttons are the different shape primitives available for material removal. The Delete Shape button enables the user to delete any of the primitive shapes created and the Remove Material button enables the user to get a visualization of how the member would appear with material removed at the places specified by the user. The Solve button runs the FEA simulation.

In order to impact learning, both context and content must be well-integrated. In this study, we presented students with a design task that is different in both context and content from any previous design tasks typically experienced by them in their coursework. The primary objective of the user study was to use our framework to aid the learning of three fundamental principles (target concepts) in Mechanics of Materials, the knowledge of which is essential for good design. These target concepts will be introduced later in this paper.

Our framework allowed for students to explore diverse pathways to accomplish the stated goal. It is important to develop strategies that effectively assess student learning and that assessment should be a "multidimensional process involving diverse measures and standards related to student thought, behavior or performance" [22]. For this study, it was important for us to understand what the students learned, where misconceptions existed and how they used the framework to complete the design problem.

Assessment in this study is multidimensional in that it includes pre-task and post-task questionnaire data and verbal justification (by the student) of their decisions. The pre and post-task questionnaires included the same six questions in the same order and it was designed to measure learning gains of our targeted concepts. After completion of the design tasks, students were asked to review their responses and make changes as necessary. For each question the students selected their response from the multiple choice options and provided an explanation. Assessment during the study required the student to provide justification at each solution iteration as well as think aloud about their process. This allowed the student to verbalize their thoughts and understanding and for the facilitator to gain insights into the student's understanding of a given concept and solution process.

5.1 Target Concepts

The target concepts that we outline below are rules of thumb and guidelines for synthesizing machine parts. They are well established in the engineering literature and are a part of undergraduate curriculum [23], [24]. The target concepts are listed below (P1 to P3). From these principles, we derived corollaries that extended their range of applicability(CP1-CP3.2).

P1: *For a member in bending, there exist regions of very low stress.*
CP1: *Remove as much material as possible from the regions of low stress.*

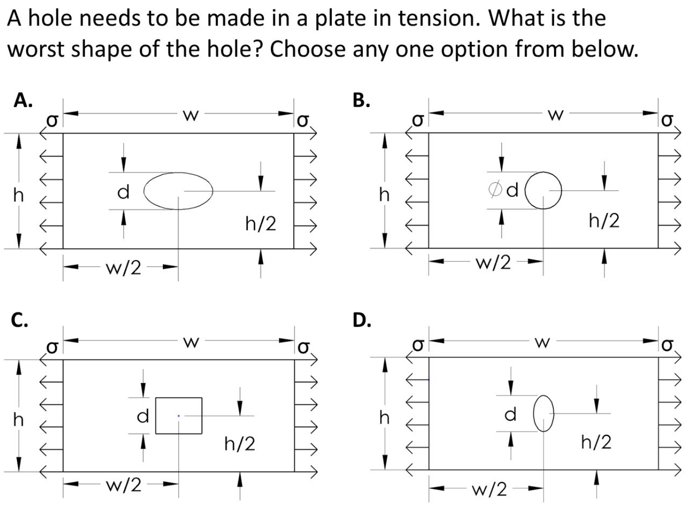
P2: *Material must be retained along lines of tensile/compressive loading.*
CP2: *Shrink voids/holes along lines of tensile/compressive loading.*

P3: *Sudden changes in geometry along the line of tensile/compressive loading result in high stress concentration.*
CP3.1: *Avoid sharp corners in design.*
CP3.2: *Increase the radius of curvature of notches.*

5.2 User Study

The user study was conducted in three stages.

Stage 1: Pre-Task
In order to evaluate the learning impact of our framework, we framed a questionnaire with six multiple choice questions with only one correct answer that tested the knowledge of



A hole needs to be made in a plate in tension. What is the worst shape of the hole? Choose any one option from below.

FIGURE 2. Sample of the Pre-task questionnaire. The same questionnaire was administered after the design task.

the design principles listed in Sec 5.1. The participants were given 15 minutes to answer the questions. The pre task questionnaire was administered on paper and the participants were given the freedom to make sketches and rough calculations as they desired. A sample of the questionnaire is shown in Fig. 2. The questionnaire in full is included in Appendix A. To minimize the chances of guesswork and gain a better sense of students' conceptual understanding, we provided space for the participants to explain their answers. Participants were also informed that it was mandatory for them to provide an explanation.

Stage 2: Design Task
The design task as mentioned before, was a structural design optimization problem which involved the minimization of the total area of the member with a constraint on the maximum stress that could be induced in the member. We used FEA to plot the equivalent Von Mises stress distribution in the member. Before starting the design task, we provided a short tutorial to the participants to train them to identify the value as well as location of the maximum and minimum stresses in the member.

We conducted our study on a Desktop PC. Participants used our framework for creating two-dimensional geometric models of their design. For conducting FEA on the designs and for meshing, we used ANSYS 14.0. The stress intensity distribution from the Tresca criterion of the designs created by the participants was displayed on a separate window. Users were given 30 minutes for the design task. Each participant was closely monitored by a facilitator who asked questions and took down observation notes at regular intervals (after every design iteration) on their design rationale. The facilitator refrained from providing any assistance to the participants except on using the framework.

Stage 3: Post-Task
We gave the participants the same questionnaire as the pre-task questionnaire in order to directly evaluate the learning impact of using our framework. The participants were also given their responses to the pre-task questionnaire for reference. The participants were asked to indicate whether or not they would like to change their answer or their reasoning. A survey related to possible learning outcomes, comments regarding the study and the task load was administered at the end of the design task. Observations made from the various recordings and notes were cross-checked with the post-task questionnaire results and user comments from the survey to assess the learning impact of our framework.

5.3 Participants

We recruited 8 paid participants (all male), aged between 18 and 30 years. Among them, 1 participant was in the graduate program and the rest (3 juniors, 3 seniors and 1 sophomore) were in the undergraduate program within the School of Mechanical Engineering. Since our study aimed to address knowledge gaps existing in Mechanics of Materials concepts, we ensured that all the participants had already taken a course that taught concepts of Mechanics of Materials. Among them, 2 participants had prior experience using Finite Element Analysis. A leaderboard detailing the final area of the member of the top three participants was displayed in the study area. However, to discourage unnecessary competition and to promote learning through exploration, the leaderboard was not brought to the attention of the participants until they had nearly completed the design task. The scores on the leaderboard motivated some participants to further minimize the area of the member.

5.4 Design Task Description

Participants were required to minimize the total area (and therefore the volume) of a triangular member made of Structural ASTM A-36 Steel in constrained loading such that it satisfied a primary design constraint that involved the maximum allowable stress of the member i.e. the allowable equivalent Von Mises stress was not to exceed 16700 N/cm^2 (derived from typical Factor of Safety guidelines for structural members). The loading condition of the member is illustrated in Fig. 3.

To measure the outcomes of the user study, a 'think-aloud' protocol was implemented wherein participants were asked to vocalize their thoughts while working on the task. Participants were also probed with questions related to significant observations we made during the user study. Three recording media were setup to capture this data audio, video and screen recordings.

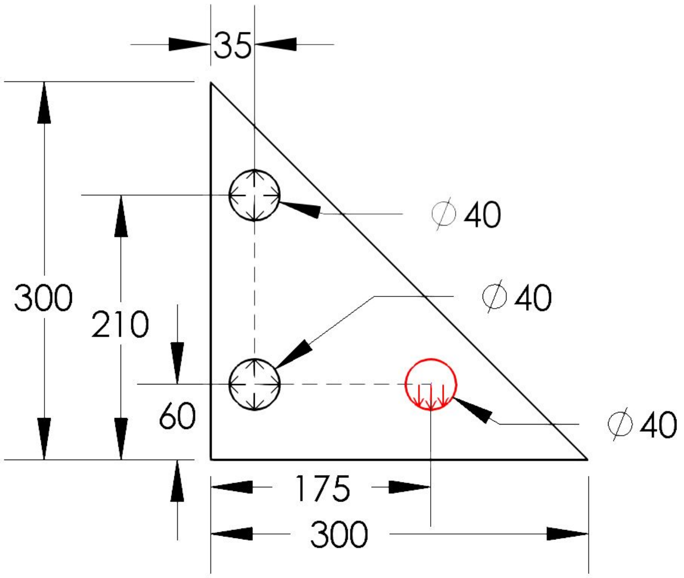


FIGURE 3. Loading condition for the design task in the user study. The triangular member is 300cm x 300cm. The circles with the black arrows illustrate that the member is completely constrained at that location. The red circle indicates that a downward concentrated load of 2.5 kN acts on the lower half of the hole.

Along with these, we also made detailed observation notes for every study session. Our intent was to conduct a post-hoc analysis for understanding heuristics used to generate solutions and to study if the target concepts we aimed to help the participants learn were successfully learned by the participants.

6. RESULTS

In this section, we detail the results of the pilot study we conducted using our framework. We evaluated the learning impact of our framework by analyzing the results of the pre and post-task questionnaire and by analyzing the different exploration pathways taken by the participants.

6.1 Pre and Post-Task Questionnaire Results

As mentioned before, to evaluate the learning impact of using our framework, we compared the responses and explanations provided by the participants to the questions in the pre and post-task questionnaires. The questions that we used in the questionnaires were selected to expose the knowledge or lack thereof of the target concepts that we aimed to help the participants understand better. Fig. 4 shows our observations from the participants' responses.

However, it was not possible to draw convincing conclusions about the learning impact of our framework from the pre and post-task questionnaire data because of the small size of the participant pool. We instead relied on analyzing the different exploration pathways followed by the participants by studying their different iterations.

6.2 Exploration Analysis

To further evaluate the learning impact of using our framework, we analyzed the exploratory paths taken by every participant by analyzing their different iterations. Based on inferences drawn from the think-aloud data and our observations during the study, we were able to summarize the design rationale of the different participants and derive common themes based on the explorations.

Some common themes that we were able to observe from the explorations of the participants are as follows:

- Most of the participants (7 out of 8) relied on an intuitive understanding of how stress is distributed in the member to make a preliminary decision on where to remove material from. In all cases, participants steered clear of the regions of where the loading and constraining occur. The common reasoning they came up with for this is that stress is most likely to manifest itself in regions where there is a direct force being applied.
- Some of the participants (3 out of 8) were aware that sharp corners act as stress risers and therefore used only the circle and the filleted rectangle to remove material. Two of the other participants were aware that sharp corners are 'bad' for structural design but were not able to provide a solid reasoning for why they thought it was so.
- A majority of the participants (5 out of 8) exceeded the allowable maximum stress value during the course of their exploration and were able to draw insights on how excessive material removal in certain regions leads to very high stresses being induced in the member.

In addition to the common themes that we observed above, we were also able to observe a few themes that are unique to individual participants.

- Only one participant did an initial solve to determine the stress distribution in the member before proceeding to remove any material. However, this participant did not interpret the stress plot as expected but proceeded to remove material in a random fashion. This participant also had not used FEA before. This was an interesting observation as it motivates us to investigate how students form mental models about engineering analysis results.
- One participant used the approach of removing material in regions as far away from the point of highest stress as possible as opposed to the usual approach followed by other participants of removing as much material as possible from

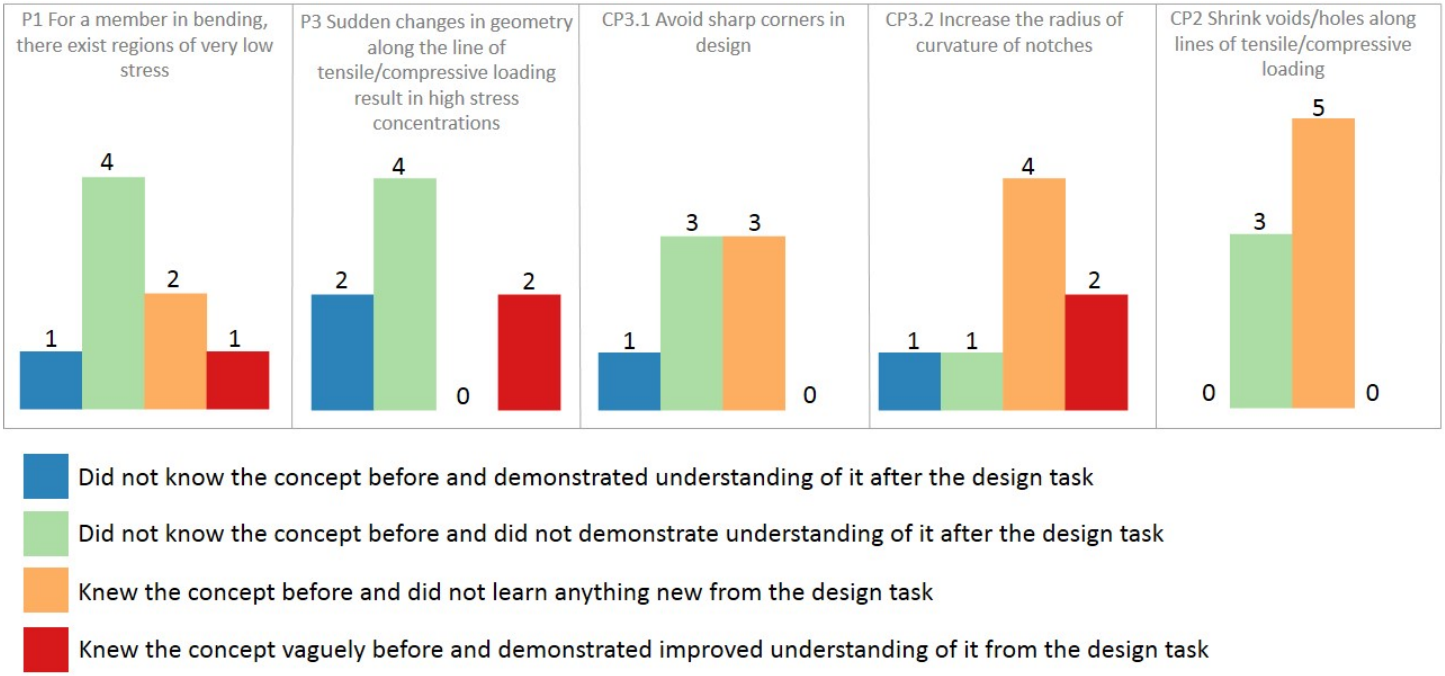


FIGURE 4. Concept-wise Learning Impact of the Framework based on Participants' responses to the pre and post-task questionnaires

regions of low stress only. This is different in that the participant did not recognize that regions of low stress can sometimes occur in regions moderately far away from the load.

These observations provide us with a solid platform upon which we can ground future studies. Fig. 5 shows a process map with stress plots that captures the different iterations followed by the participant who had the least area at the end of the design task. The stress plot with final iterations for the other participants are displayed in Fig. 6.

7. TAKEAWAYS

Based on the insights we developed from the pre and post-task questionnaires and the user study using our framework, we address the research questions that we put forward at the start of this paper.

RQ1: *Does our framework which incorporates an FEA backend to aid exploration impact the students' understanding of target concepts in Mechanics of Materials? If so, how?*

A1: As the results from the previous section show, for some cases, the framework has been successful in helping the students demonstrate correct understanding of some of the target concepts.

Learning as a result of using our framework has been of three forms 1) Participants did not know a certain concept to begin with and demonstrated a correct understanding of it after using our framework, 2) Participants knew a certain concept vaguely (not a complete understanding) to begin with and had their mental model validated after using our framework, and 3) Participants were already familiar with a certain concept and were able to solidify their understanding after using our framework. Conducting a similar study with a larger participant pool and more problems to explore would be very helpful to deeply evaluate the learning impact of our framework.

Further, by means of our iteration analysis for every participant, we were able to gain insights into the rationale followed by the participant and draw inferences about how they interpreted the results of the FE Analysis with respect to the design task and make design decisions.

RQ2: How does using our framework to explore a constrained design problem aid the students' learning of certain target concepts in Mechanics of Materials?

A2: The exploratory nature of the design task augmented the learning experienced by the students. In the 30 minutes that were provided for the design task, the minimum number of iterations was 5 and the maximum was 24.

Data from the Task Load Index and the Usability Scale administered at the end of the study indicated that the participants

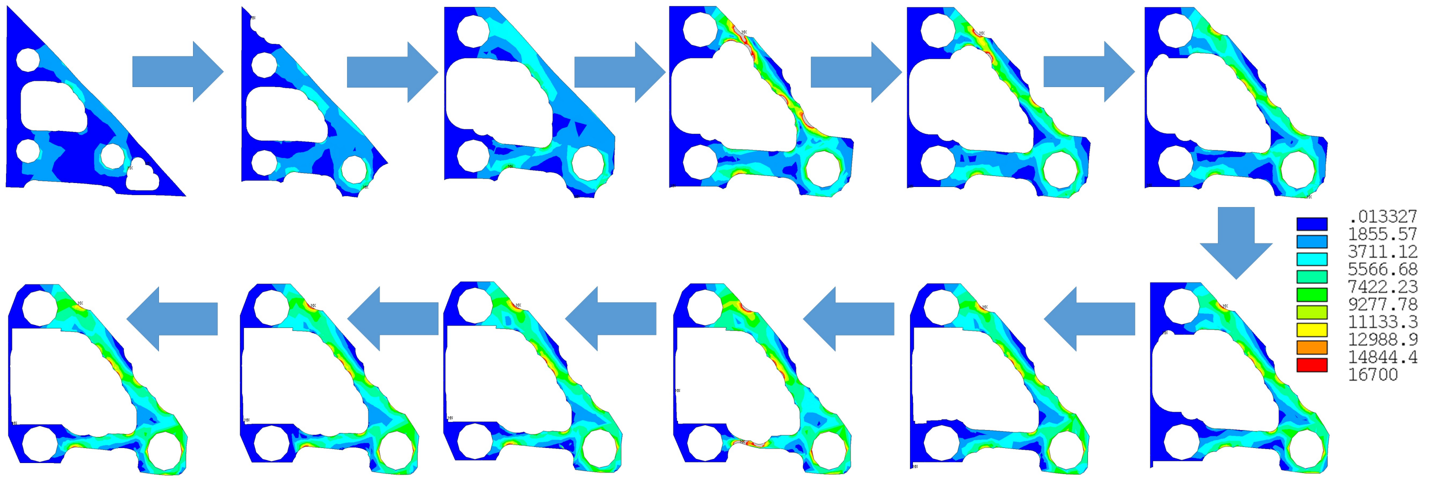


FIGURE 5. Process map with stress plots (SINT) for participant with least area of the member at the end of the study. Units of stress are Newtons per square centimeter.

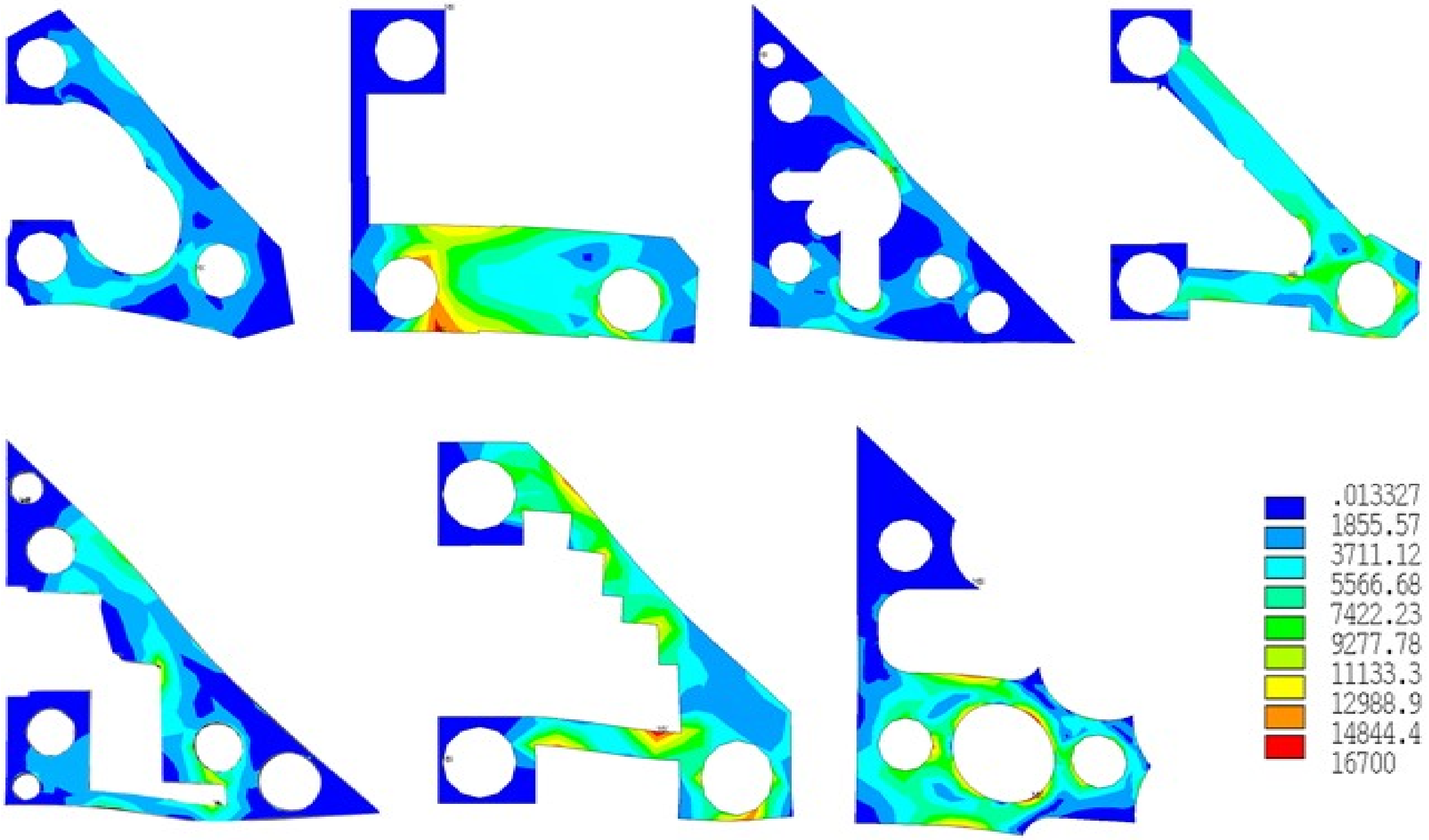


FIGURE 6. Stress plots (SINT) of final iterations for all other participants. Units of stress are Newtons per square centimeter.

felt that the framework was easy to use and enabled them to conveniently accommodate the changes that they were asked incorporate during the task with the framework.

After the study, students had the following comments on using our interface:

- ∗ *"I was able to learn from the study that there can be parts in a design that sort of act as zero-force members and carry no stress at all-sharp corners are incredibly bad for max stress in most cases."*
- ∗ *"I was able to understand how material removal affects stress distributions in the presence of discontinuities in areas."*
- ∗ *"The task helped me learn about where I could remove material ME323 does not really teach me that, it just tells me where the stress concentration will occur."*

ME323 is an undergraduate course in Mechanics of Materials taught at Purdue University.

8. LIMITATIONS AND FUTURE WORK

This paper has detailed the prototype implementation of an exploratory framework that incorporates an FEA backend to aid exploration through rapid design iterations. Based on our observations and results from a pilot study we conducted with a small sample population of students we have measured the learning impact of using such a framework.

- Our user study was limited to a participant pool of eight as the primary objective was to make detailed observations of user behavior to lay the foundation for a more detailed study in the future. We believe that by expanding the study to a bigger participant pool, we can better quantify the learning impact of our framework. We are planning on an extended version of this study with more participants.
- We plan to explore the impact of using our interface over an extended period of time to solve a design problem. With this approach, we can also investigate the learning impact of our framework when there is no temporal demand imposed due to a set time limit.
- We also plan to incorporate our framework as a teaching aid in courses that teach concepts of Mechanics of Materials. Among the participants in our study, most of them were of the opinion that such a framework and associated design task would be a very good supplement to augment their learning of the material covered in class.

  Some participant comments on our study and framework are as follows:

    - ∗ *"It will be very useful if I use this in class. Instead of a Professor telling me that this is where low stress would occur, it would be great if I could visualize it like I did here."*
    - ∗ *"I think this kind of a design task is very important. In my previous courses, we realize the importance of failure analysis and fatigue failure on all kinds of materials. I think that once you get into design, it is very important to know where your design can fail and where you can optimize certain parameters without compromising on other important parameters."*
    - ∗ *"I would love to see this interface in 3-D. It was pretty easy to see where stress manifested itself using the interface-the iterative process was very pretty natural."*
- We envision our current framework to lead to an environment that facilitates the integration of engineering analysis and engineering design by allowing users to explore different design options in early stages even before the detailed designs are made.
- Finally, to extend our work and to make it more accessible, further studies will focus on developing and disseminating a more intuitive framework using a natural user interface (NUI) based software platform.

ACKNOWLEDGMENT

Thanks go to Senthil Chandrasegaran and Devarajan Ramanujan for contributing towards the user study and providing feedback on the document. This research is partially supported by NSF under grant DUE 1245780. The contents of this manuscript do not necessarily reflect the views or opinions of the funding agency.

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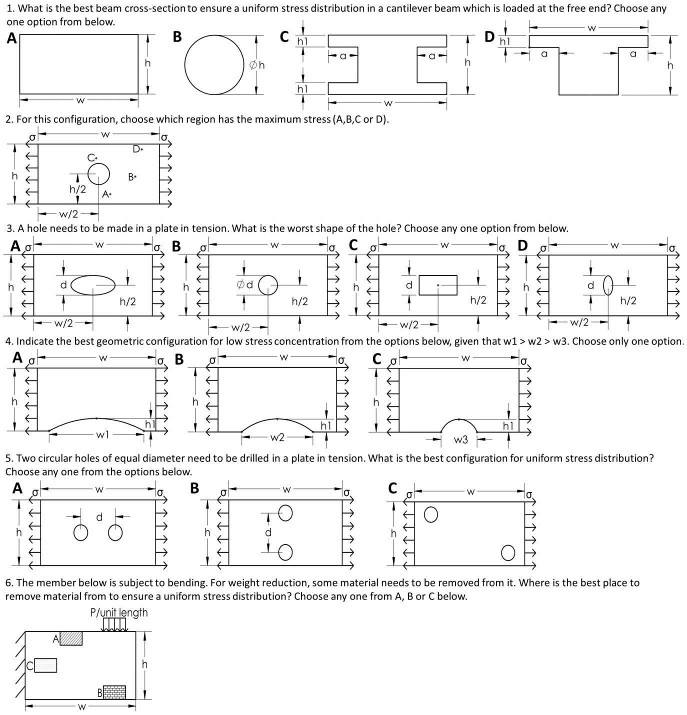
Appendix A: Pre and Post - Task Questionnaire

Fig. 7 details the pre and post - task questionnaires.



1. What is the best beam cross-section to ensure a uniform stress distribution in a cantilever beam which is loaded at the free end? Choose any one option from below.

2. For this configuration, choose which region has the maximum stress (A,B,C or D).

3. A hole needs to be made in a plate in tension. What is the worst shape of the hole? Choose any one option from below.

4. Indicate the best geometric configuration for low stress concentration from the options below, given that w1 > w2 > w3. Choose only one option.

5. Two circular holes of equal diameter need to be drilled in a plate in tension. What is the best configuration for uniform stress distribution? Choose any one from the options below.

6. The member below is subject to bending. For weight reduction, some material needs to be removed from it. Where is the best place to remove material from to ensure a uniform stress distribution? Choose any one from A, B or C below.

FIGURE 7. All questions of the Pre and post task questionnaire.