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Usability of a Mobile Augmented Reality Application to Teach Structural Analysis

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Introduction

Structural Analysis is an introductory course for structural engineering, which is taught in every undergraduate civil engineering program at about 300 institutions in the U.S., and also in most architectural and construction programs, as a core and required course. Structural analysis incorporates the fields of applied mechanics, materials science and applied mathematics to compute a structure's deformations, internal forces, stresses, support reactions under prescribed loads and/or other external effects [1], [2]. Despite its critical role in the curriculum, most novice learners in this course do not appear to have a sound understanding of fundamental concepts, such as load effects and load path; and in general, they lack the ability to visualize the deformed shape of simple structures, a necessary skill to conceptualize structural behavior beyond theoretical formulas and methods [1], [2]. In particular, students have difficulty in relating basic structural members, including trusses, beams, frames, and others, to more complex structural systems, such as buildings and bridges. Such learning deficiencies can be largely attributed to the ineffectiveness of the traditional lecture-mode of teaching during which much effort is spent on the analysis of discrete members, while less emphasis is devoted to understanding the behavior of the entire structure in a three-dimensional (3D) structural context.

In this study, we explore the potential of augmented reality (AR) to facilitate the teaching of structural analysis concepts. AR combines the real world with the virtual content so that it conserves users' awareness of the real world environment in a 3D space [3]. It enables users to visualize virtual objects and to interact with both real and virtual objects in the same context [4] thus extending their perception of the real world [5]. Through tracking technology, AR provides an accurate and consistent spatial relation between virtual and real objects, while sustaining the illusion that they coexist in the augmented space [6]. Rapid developments in computer hardware and software have made AR technology more accessible and user friendly. Mobile devices seem to be the most appropriate for educational use because of the increasingly ubiquitous nature of mobile devices (e.g. tablets, smartphones).

In Architecture, Engineering and Construction (AEC) domain, AR has been implemented to support planning, design, construction, and maintenance phases of a project [7], [8], visualization of construction graphics [9]; creation of virtual immersive job-sites to avoid safety-related concerns [10], [11] construction defect management [12] construction site visualization and communication [13] and damage prevention and maintenance of underground utilities [14]. Although these implementations indicate the promising potential of AR to enhance productivity and safety in civil engineering practice, the integration of such technologies into undergraduate teaching practices has been very limited despite the evidence that it facilitates learning of abstract and difficult-to-understand topics [15]. This work-in-progress is the first step of developing a new teaching pedagogy using mobile and interactive AR and advanced 3D technology to transform the way structural analysis is taught and test the usability of a prototype application.

Description of the AR App - iStructAR

iStructAR aims to supplement teaching traditional structural analysis concepts by helping students better visualize how structures behave under certain loading conditions. A pedestrian skywalk connecting two campus buildings was selected as the structure to teach the concepts of loads (specifically, live and dead load) and the resulting reaction forces and deflections for typical beam-type structures. iStructAR utilizes vision-based AR as defined by Dunleavey [16], with both indoor and outdoor targets to provide flexibility for the users and instructors. Using an iPad, students are able to project structural information onto either an inherent picture of the skywalk, a printed or digital photo of the skywalk, or the real structure itself. They can then modify the structural load, changing both its magnitude and distribution, to observe the effects on the structure, as seen in Figure 1.

In developing the application, we used the standard iOS user interface framework (UIKit) so the controls would be more familiar to users. Tracking for the indoor target is accomplished with Vuforia, an off-the-shelf AR toolkit. Because it is only designed to handle flat, two-dimensional targets, we developed a custom tracking approach for the outdoor target. Briefly, this involves extracting the planar surface of the structure to be tracked, then executing a typical 2D image tracking pipeline using ORB feature descriptors [17]. Currently, the outdoor tracking is too computationally intensive to perform in real time on older iPad models, so we provide a "Pause" button which freezes the video and locates the object in the frame. Future work will involve optimizing the outdoor tracking so that a real-time augmentation can be shown.

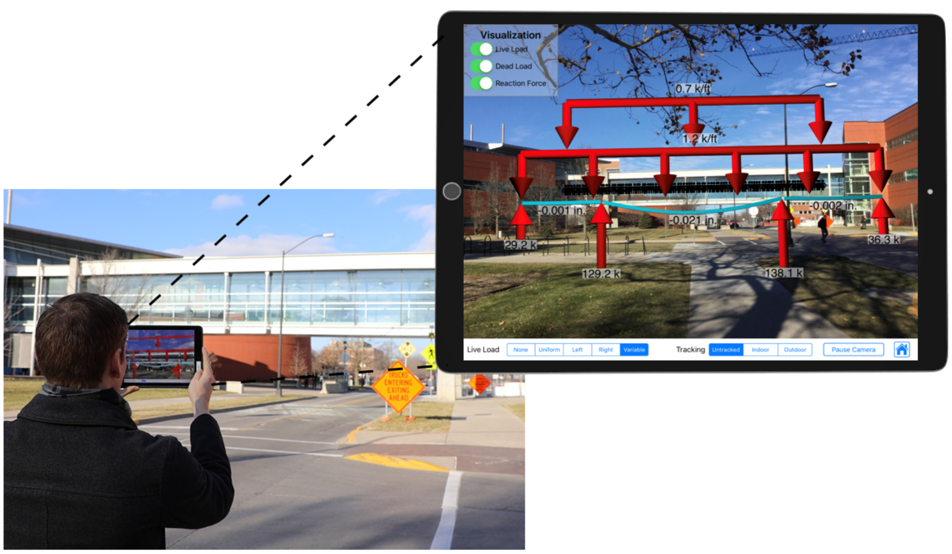

Figure 1: A student holds an iPad in front of the on-campus skywalk structure, projecting various loading conditions through AR while observing effects in real-time.

Figure 2 below defines the various functionalities of the application, referenced throughout the remainder of this paper.

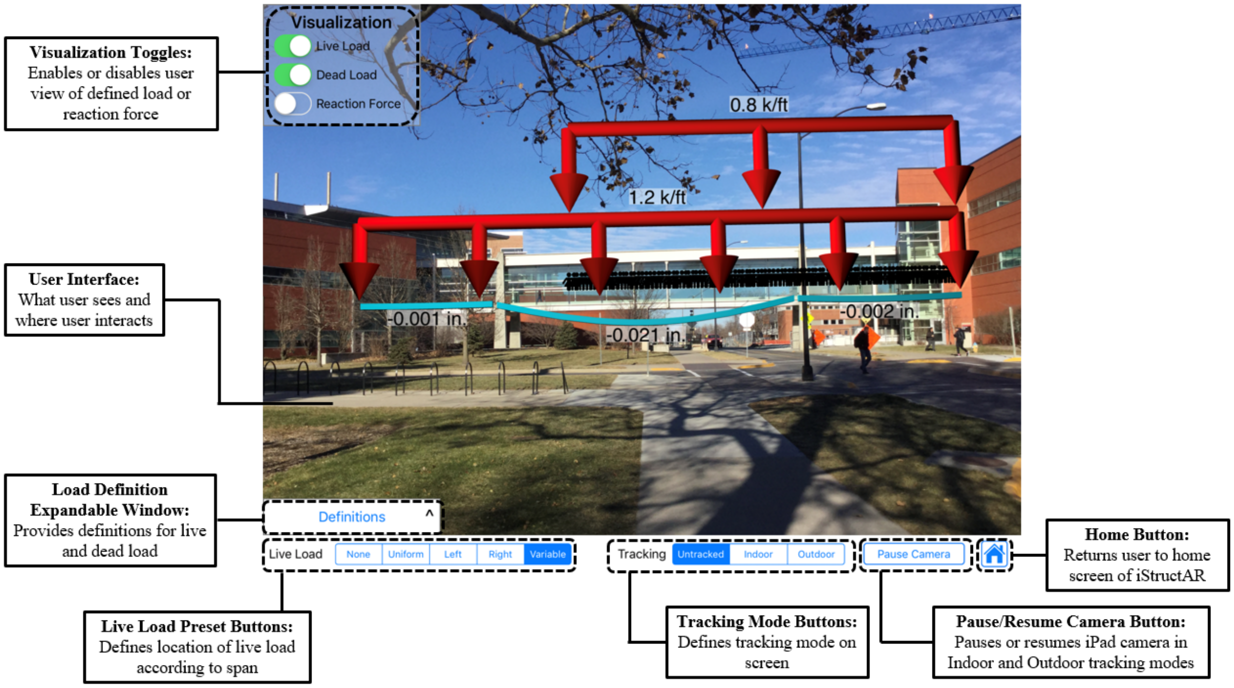

Figure 2: Functionality nomenclature and definitions within skywalk scenario

Methodology

Usability testing is a systematic process that evaluates users' ease of use of a tool to achieve a certain goal. Testing, therefore, focuses on the end user of a particular product, the results of which inform the systematic refinement of the product by identifying usability issues at an early stage and quickly rectifying them before full implementation [18]. For the purposes of this particular study, the goal was to discover if the provided AR interface was user-friendly, with functions meaningful and easy to locate and use.

For the above described skywalk model, two versions - "guided" and "unguided" - were created, one objective of the usability tests being to decipher which version was preferred by users. The guided version of the app module included step by step text guidance, describing the visualization of loads, reaction forces, and deflection. Within this version, certain functions were enabled during preliminary steps, encouraging students to understand concepts before using the full functionality of the application, as seen in Figure 3. This screenshot from the guided version shows Step 3 of a six step procedure, describing the application of dead load and resulting deflection values - note that the different live load preset buttons in the bottom left of the screen are disabled, as the procedure has not yet described the application of live load.

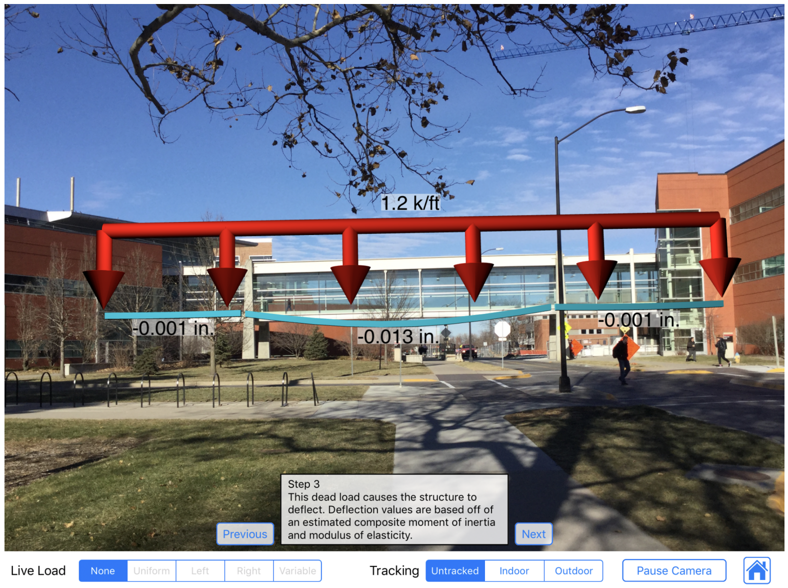

Figure 3: Guided version of skywalk application, with an example procedural step explaining deflection values.

The "unguided" version, shown in Figure 4, differs from the guided version simply in that procedural directions are not provided within the application at any time. While different visualizations of loading and options appear at different steps in the guided version, all visualization options are enabled at all times throughout the unguided version.

Figure 4: Unguided version of the current skywalk application, with enabled visualization of dead and live loading conditions.

Participants

As previously stated, the purpose of this current study was the evaluate the usability of the application, rather than the teaching impact (which will be investigated in a later study). Therefore, it is acceptable to have a small set of participants to provide feedback on various usability issues [18]. One student (student 1) participated in an initial usability test. After this particular test, small modifications were made to the overall testing protocol. The test results from this student are included with data throughout this paper, however, are not included in final survey results, as questions were altered too much to be accurate. After the initial test period, three students (students 2, 3, 4) participated in the study. Overall, two students interacted with the "guided" version and two students interacted with the "unguided" version.

Table 1 below shows preliminary information gathered on the students. Students 1 and 2 used the guided version for testing, while students 3 and 4 used the unguided version for testing. Of the four students, only one owned an iPad that he used once a week. No students had experience with AR. All students had previously taken a structural analysis class.

Table 1: Background information on student participants

Student #	Gender	Major	Year of Study	iPad Possession	Experience with AR
1*	Male	Civil Engineering	Senior	Yes, uses once per week	No
2	Male	Civil Engineering	Graduate Student	No	No
3	Male	Civil Engineering	Senior	No	No
4	Male	Civil Engineering	Graduate Student	No	No

**Testing protocol experienced minor modifications after testing with student 1*

Data Collection Materials, Procedures, and Analysis

A mixed-method approach was adopted where multiple data sources were included in order to identify issues from varying perspectives. Main data sources for each test included a background survey, a think aloud protocol, a functionality timeline, structural analysis example problems, and a survey at the conclusion of the testing. The background survey asked students to identify their year in school, major, and experience with tablets and augmented reality. The think-aloud protocol asked students to verbalize their thought processes while completing predefined tasks within iStructAR. Any verbally expressed areas of concern and/or enjoyment by students were notated. Participant audio and interaction with the app interface was recorded using a GoPro action camera (example video shot seen in Figure 5 below), as well as elevated camera. The functionality timeline was utilized to track participant interactions with the app on a timescale. Time-related tasks such as the duration for students to answer structural analysis questions, find a particular function on the screen, or manipulate loads to certain locations were all measured. Structural analysis example problems were given at the end of the main body of the usability test. These questions tested whether students understood the connection between classroom structural analysis concepts and the application, and whether students relied on, referenced, or ignored the app during problem solving. All questions given to students could be solved without the use of the app or a calculator, so use of the app for solving was a user-defined choice.

Finally, at the end of all interaction and tasks with iStructAR, students were asked to complete a survey, containing specific questions pertaining to each functionality that the app contained.

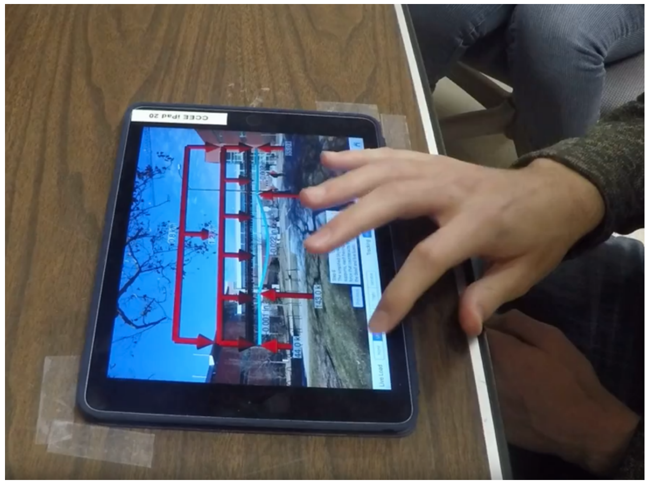

Figure 5: GoPro filming student interact with iStructAR during usability test

Qualitative data analysis approaches were used to analyze the data. Report results will be utilized to refine the application before full implementation.

Results and Discussion

Guided vs. Unguided

As described above, a guided version of the app provided step by step text descriptions of structural analysis concepts, while an unguided version provided no guidance and allowed users to explore all functionality of the app at any time. Table 2 below collates the main distinctions between the guided and unguided versions of the application. These distinctions provided points of focus during usability tests, in order to note if student performance was aided, deterred, or maintained consistent through the two different app versions.

Table 2: Distinctions of functions between guided and unguided versions of app, and points of focus during usability tests

Function	Guided	Unguided	Point of Focus
Description of structural analysis concepts	Provided through procedural steps	Provided through expandable window defining dead and live load	Necessary instructional guidance needed
Live load preset button enabling	Unlocked at end of procedural steps, encouraging students to read all text before interaction	Always unlocked, allowing students to interact from start to end of app interaction	Controlled interaction with location of live load

Load and reaction force visualization	Going forwards and backwards through steps enables and disables visualization of loads and reaction forces	Utilization of visualization buttons enables or disables load and reaction force symbols	Ease of visualization of load and reaction forces

Two students utilized the guided version of the application, while two students utilized the unguided version of the app. Points of focus could be observed through the think-aloud protocol, the functionality timeline, and responses to the structural analysis example problems.

Function: Description of structural analysis concepts

Accuracy of responses to structural analysis example problems given can be seen in Table 3. Problems 1 and 2 focused on deflection concepts, while Problem 3 focused on reaction force concepts and values. Overall, an increased dependence was seen on those students answering questions with the guided version of the application – rather than utilizing the app to check a solution that the student had written or verbalized, Students 1 and 2 directly manipulated loads on the app to find the answer, then answered the question.

Table 3: Results of structural analysis problems for students using the guided version and unguided versions of iStructAR

Structural Analysis Problem	**Guided**		**Unguided**	
	Student 1	**Student 2**	**Student 3**	**Student 4**
1	Correct; Uses app to find solution	Correct; Uses app to find solution	Correct; References app to check solution	Partially Correct; References app to check solution
2	Correct; Uses app to find solution	Correct; Uses app to find solution	Correct; References app to check solution	Partially Correct; References app to check solution
3	Correct; Uses app to find solution	Correct; Uses app to find solution	Correct; Uses app to find solution	Incorrect; Uses app to find solution

The amount of time that students took to respond to structural analysis problems was fairly consistent between all students, and there were no distinct timing differences between those students using “guided” versus “unguided” versions.

Only one student answered a problem incorrectly. The incorrect answer was due to an incorrect manipulation of location of live load, whch was not related to differing function with the guided or unguided versions.

Three questions were given to students on the survey regarding the specific functions in the unguided and guided versions of the app. These include questions 5, 6, and 8, and can be seen in

Table 7. As shown, there was no distinct difference between ratings of students in these questions.

Function: Live Load Preset Button Enabling

Live load preset buttons were disabled until Step 4 of 6 on the guided version, as seen in Figure 2. The unguided version had live load preset buttons enabled at all times. Both students using the guided version experienced confusion during steps 1 through 3 as to why live load preset buttons were disabled. Although procedural steps had not yet described live load, students still tried to push disabled buttons, showing that the procedural steps did not provide a controlled and focused flow as intended.

Function: Load and Reaction Force Visualization

The unguided version contained visualization buttons that created the appearance or disappearance of loads and reaction forces on the screen. To produce the same effect, the guided version required students to go forwards or backwards through steps. Overall, the structural analysis questions given at the end of the general usability test were answered more easily by the students with the unguided version of the application, as shown in Table 4 below. On average, those students using the guided version of the app (students 1 and 2) clicked the user interface almost three times more than those students using the unguided version of the app (students 3 and 4).

Table 4: Number of clicks/drags used by students when solving structural analysis problems

Question #	**Clicks/Drags Per Problem**			
	Student 1	**Student 2**	**Student 3**	**Student 4**
1	3	3	0	1
2	4	10	0	2
3	1	2	2	3
Total	8	15	2	6

Question number 7 on the survey asked students to rate the ease of enabling the visualization of the load, as seen in Table 7. All students responded positively, although student 2 did respond one rating lower. This response correlates with the data seen above, as visualization options for this student was clumsier in the guided version.

Preset Buttons vs. Dragging

In order to manipulate the location of the live load, students had two main functionality type choices: one, use of predefined live load preset buttons, or two, use of dragging the load directly (direct manipulation). Students were forced to make a decision between these two choices whenever directions given by the test facilitator indicated to move the live load to either just the right span, the left span, or all spans of the structure. This option arose four times within the usability test procedure. As seen in Table 5 below, the average student chose to utilize a preset button, allowing the application to self-direct the live load to either the left span, right span, or all spans. As mentioned previously, testing protocol experienced minor changes after usability testing with student 1; choice numbers 2 and 3 from the table were not included in this preliminary procedure.

Table 5: Student preference of live load location preset buttons vs. dragging (direct manipulation)

Choice #	Student 1	Student 2	Student 3	Student 4
1	Drag	Preset	Preset	Preset
2	-	Preset	Preset	Preset
3	-	Preset	Preset	Preset
4	Drag	Preset	Preset	Drag

While students chose preset buttons on average over dragging when redirecting loads to particular spans, all students were forced to drag load locations directly at one point within the usability test. Students did not experience any issues or concerns moving the load directly from a usability standpoint. Student 4, although choosing to drag loads rather than directly relocate via preset buttons for choice 4, expressed concern over inaccuracy of load location. Users were not given any datum or span lengths, so students could not be positive of the accuracy of where they dragged the load. Within all individual tests, all students expressed similar concerns over the lack of a datum of any kind within the application.

Questions 14 and 15 in the given survey pertain to the use of preset buttons vs. dragging when manipulating the live load, as seen in Table 7. Overall, students responded that they could easily change the load location, but had no preference in how this was achieved.

Augmentation

Within the usability procedure, students were forced to change tracking modes from an “untracked” to an “indoor” tracking. Outdoor tracking was not utilized in the study in order to minimize testing time for relocation, as well as to control the testing environment. Within the indoor tracking mode, students were asked to complete tasks similar to those asked in the previously used untracked mode, while holding up the iPad to a printed picture of the skywalk as shown in Figure 6. Loads could be manipulated in the same way as the untracked mode. Testers looked for any problems related to misunderstanding of loads projected onto the skywalk image, handling of the iPad, and technical malfunctions. The “Pause Camera” and “Resume Camera” functions were also tested during this time.

Figure 6: Student changes the magnitude and location of the live load on a printed photo of the skywalk through augmentation

All students encountered difficulty when taking a screenshot of the app during the augmentation, due to awkwardness of hand placement. This correlates with the result of question 12 on the survey, as well as with verbal confirmation of students. As seen in Table 7, question 12 received the lowest rating by students.

Overall, testers noticed an increased level of interest when students used the augmented reality functionality of the application. Perceived enjoyment of the users increased, many students commenting that this feature was their favorite functionality of the application.
No problems were encountered with the Pause Camera or Resume Camera functionalities.

Other Functionalities

Within usability testing, all students were asked to take screenshots of the user interface, in both “Untracked” and “Indoor” tracking modes. In future classroom use, professors may ask students to take a screenshot of a current loading situation to reference in following lectures. While the normal screenshot key combination is inherent to the tablet rather than iStructAR, testers wanted to confirm that users could easily complete the task. However, all students, regardless of previous iPad or tablet experience, encountered trouble taking a screenshot. Two out of four students had to be instructed of the correct key combinations after extensive time.

Conclusions and Future Direction

Overall, no problems were encountered through usability testing that disabled students from completing assigned tasks or caused extreme frustration. Main focuses centered on differences of student performance when using “guided” versus “unguided” versions, utilization of preset buttons over direct manipulation (dragging) of live load locations, and student interaction with augmentation.

Instructional guidance provided by the guided version did not increase accuracy when solving structural analysis problems, or giving verbal answers related to structural analysis concepts in the think-aloud protocol. However, the guided version proved to cause confusion and added clumsiness when interacting with live load preset buttons and visualization of loads and reaction forces. Based on listed results, testers have decided to proceed with making modifications to the "unguided" version only.

Students utilized both preset buttons and direct manipulation (dragging) when moving the location of the live load. Testing showed the necessity for both options. However, the presence of a datum or numbered axis would aid in load location when dragging the live load. Student interaction with augmentation was positive, met with increased user interest and enjoyment. No problems were encountered with the current user interface. However, students did struggle to take a screenshot of the interface while in Indoor tracking mode. To increase ease of taking screenshots, a single button will be added to the user interface that will make the application take a picture of the current screen.

Table 6 collates all functions of the application, any problems seen during usability testing, and if necessary, suggested modifications to be made. Although students had initial confusions about the tracking mode options within the app, the iPad cameras were initially blocked, creating a black screen when Indoor or Outdoor tracking modes were selected. Testers decided no additional modifications were needed.

Table 6: Summarized functionality problems and suggested modification from usability testing

Function	Problem Severity*	Problem Description	Suggested Modification
Visualization Toggles	None	-	-
Load Definition Expandable Window	None	-	-
Live Load Location Preset Buttons	Minor	Misunderstanding of "Variable" preset button; when pushed, live load shows no change	Remove "Variable" live load preset button; no functionality of application will be lost
Tracking Mode	Minor	When camera is blocked by item, students do not understand Indoor and Outdoor tracking modes	None
Pause/Resume Camera Button	None	-	-
Home Button	None	-	-
Direct Manipulation of Live Load Location (Dragging)	Minor	Unknown exact location of live load; imprecision when relating to hand calculations	Add datum showing dimensions of loads and spans
Direct Manipulation of Live Load Magnitude (Dragging)	None	-	-
Take Screenshot of iPad	Minor	Student unawareness of proper controls on iPad to take screenshot; awkward when in Indoor tracking mode	Add single button in interface that will take screenshot

**Problem Severity Types: Severe: problem type prevented students from completing a task or interacting with the application; Moderate: problem caused interaction with the application to be difficult or undesirable; Minor: problem type did not create barrier from completed tasks, but caused annoyance in users*

Table 7: Compiled results of usability test survey

Number	Question	Choice/Rating			Compiled Results	
		Student 2	Student 3	Student 4	Average Rating	Std. Deviation
1	I could identify the functionality of the available options through icons	3	5	4	4.00	1.00
2	I could select the desired function on the app all the time	4	5	5	4.67	0.58
3	I could easily undo/redo any action if I felt to do it	5	5	5	5.00	0.00
4	I could easily figure out what to do next given the instructions	4	5	5	4.67	0.58
5	I could understand the messages that appeared in the app	5	5	5	5.00	0.00
6	I was not confused or lost while performing the tasks	4	4	4	4.00	0.00
7	I could enable the visualization of the load	4	5	5	4.67	0.58
8	I could easily distinguish the different types of load on the screen	5	5	5	5.00	0.00
9	I believe the arrows are appropriate representations of loads on the structure	5	5	5	5.00	0.00
10	I believe the curved line is a good representation of the structure's deflection	4	5	5	4.67	0.58
11	I could easily read the load/force/deflection values on the screen	5	5	5	5.00	0.00
12	I could easily take a screenshot of the app screen	3	4	3	3.33	0.58
13	I could easily change the load to a certain magnitude given by the test facilitator	4	5	5	4.67	0.58
14	I could easily manipulate the location of distributed load to a position	5	5	4	4.67	0.58
15	I prefer dragging the load over clicking button icons	3	3	5	3.67	1.15
16	The definitions (...) helped me to understand the different types of load	5	3	5	4.33	1.15
	Average Rating	4.25	4.63	4.69		

*Student Ratings are on a 5 point scale: 1: Strongly Disagree; 2: Disagree; 3: Neutral; 4: Agree; 5: Strongly Agree

Table 7 compiles results from the survey given to students at the end of testing. Ratings were based on a 5 point score, with 5 correlating to “strongly agree”, and 1 correlating to “strongly disagree”. As seen, the lowest average rating pertained to the ability of the user to take a screenshot (number 12 in the survey), with an average score of 3.33 points. This data correlates with the qualitative data gained from the “think-aloud” protocol, as well as the functionality timeline. This issue is addressed in the above table as well.

Users also gave a lower rating to number 15, referring to preference of manipulation of live load. With an average score of 3.67, users did not strongly prefer dragging the live load over the use of preset location buttons. This data correlates with other data collected during testing; both load manipulation functionalities will be kept.

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