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Conducting a column buckling test in 3D virtual reality

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Abstract
This paper summarizes an effort to apply recent advances in virtual reality technology to structural stability research and education. The demonstration project focuses on a simulated test, where flexural buckling deformation of a doubly-symmetric imperfect structural steel W-shape column is calculated with a recently developed open source software package *StructuresKit.jl.* This package solves for the column deformations from a nonlinear system of differential equations modeled in the Julia programming language. The solution output is a 3D animated rendering of the column test over time, with buckling deformations, the loading, and boundary conditions displayed. Instructions for viewing and interacting with this animated rendering with the Oculus Quest virtual reality headset will be provided. The paper concludes by describing how the animated column test could be used in a structural stability teaching module. Some thoughts are also provided on how virtual reality technology can augment physical testing in support of structural stability research.

1. Introduction
Virtual reality (VR) technology is rapidly improving and becoming more accessible. VR is realistic, engaging, interactive, and immersive. It allows the user to interact and explore their environment in new ways. Virtual reality technology is gaining popularity in the workplace. For example, structural and architectural design firms are now using VR technology to show clients and potential clients their designs. This rapidly growing technology will become more common in the workplace and students can benefit from VR use in their education.

A major benefit to the increase in availability of virtual reality technology is in the education sector. Previous studies have showed improvement in student learning and have indicated the beneficial use of virtual reality in structural engineering and structural engineering education (McCabe and McPolin, 2015; Leach and Fowler, 2016; Fogarty, McCormick, and El-Tawil, 2018). Virtual and mixed reality can assist in improving the visualization of complex concepts and can allow students to work on their own creative ideas. Additionally, the experience with using VR technology will be an asset to students looking to enter the workforce as this technology becomes more widespread.

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Virtual reality can help students to gain a better understanding of structural engineering concepts, such as framing of large-scale structures and load path distributions, results of finite element models, and stability of members and systems. Several goals of using virtual reality for education include (1) improved visualization of engineering concepts, (2) deepening of student understanding of complex concepts through immersive interaction, and (3) increased student interest and involvement with use of a non-traditional classroom.

This paper describes a virtual reality based teaching aid under development to illustrate column buckling. It is envisioned that the end product will enable students to study the effects of end conditions, material grade, and column height on the stresses and deflections of a column, in addition to experiencing a realistic column testing scenario.

2. Model Development

A W14x90 hot-rolled steel column with pinned-pinned boundary conditions is tested in load control to failure. The column has a length of 3962 mm and a half-sine wave imperfection of 4.0 mm, $\frac{L}{1000}$, in the weak axis direction. The simulated test is performed with *StructuresKit.jl*, an open-source software package written in the Julia scientific computing language.

The *StructuresKit.Column* module is used to perform an elastic second-order analysis of the column (Plaut and Moen, 2020). First yield of the column occurs in the flange tips at $0.90P_y$, where $P_y = 5984$ kN for ASTM A572 steel. It is assumed that at this compressive load, the column collapses. The load-deformation response for the simulated test is shown in Fig.1. Local buckling is not modeled in the simulated test.

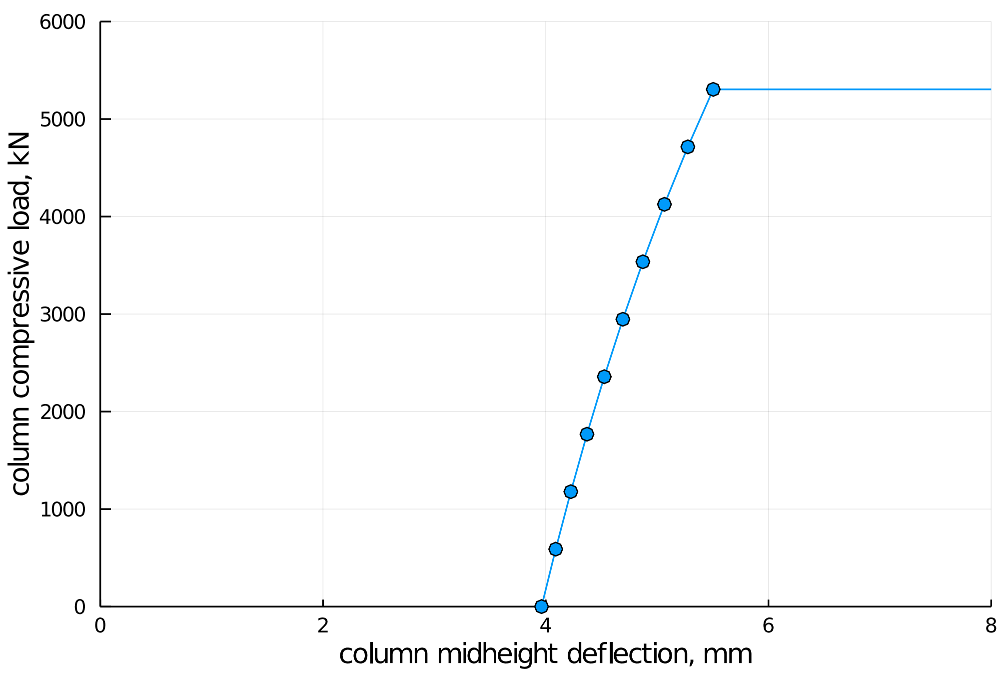

Figure 1: W14x90 simulated test load-deformation response

The *StructuresKit.CrossSection* and *StructuresKit.Mesh* modules are used to render the column 3D shape. The W14x90 cross-section is pulled from the AISC database with the *StructuresKit.Cross-Section.AISC* function, and the outside surface and column end face geometries are meshed with triangular elements using the *StructuresKit.Mesh.surface* function and the Julia package *Triangle.jl*. Meshed column models at load steps of $0.00P_y$, $0.10P_y$, $0.20P_y$, ... $0.90P_y$ are generated and then saved in Polygon File Format, i.e., as .ply files, using the Julia *FileI0.jl* package.

3. Conversion to Virtual Reality

Results from the the column analytical model are output in .ply file format. This file is then input into Blender, a free and open source 3D creation suite, to convert the model to a .fbx file format. The .fbx file format is needed to input the column model into Unity. Unity is a cross-platform game engine which can be used to create three-dimensional virtual reality games. The educational module is created in Unity in the form of a virtual-reality game.

An environment must be created, which will serve as the space for the user to move around in and interact with the column model. The environment can be designed as desired in terms of size, color, decorative elements, and background. To move and interact with a model, a first person controller must be created. Movement controls are also defined, and includes simulated walking, flying, and teleportation. The buttons on the virtual reality headset controller enables movement. The controller is also used to interact with the column model. Lighting is also added in the Unity model to ensure that the column can be viewed from multiple angles without dark regions.

To apply load, a slider is created where the user can slide to increase or decrease the load, as shown in Fig.2. The analysis is not conducted in the Unity model, rather each position on the slider corresponds to the output files at various load levels on the column model. The displacements at all nodes on the column model are stored in the data files and the relevant output is displayed with the applied load corresponding to each slider position.

Finally, the game in Unity is exported to be viewed in a VR headset using the Oculus Unity plugin. The same environment in Unity can be exported as an Android build for the Quest, and also a PC build for the Rift. This can be done by changing the final export settings, without having to change anything else in regard to the environment or controls. This module is designed to be viewed in Oculus Quest and Quest 2 headsets in standalone mode and does not require the additional GPU of a gaming PC.

4. Future Work and Implementation

At the time of writing, the work described in Sections 2. and 3. was completed, however, the authors continue to work on improving the module and implement new features.

The models initially included pinned end conditions. The model will be expanded to have fixed end conditions, including the option for a cantilever, and user-defined semi-rigid boundary conditions. Colored stress contours will be added to help indicate how stress levels vary along the column height and how stresses are affected by a change in boundary conditions. Several grades of steel will be added to the module. Furthermore, various height columns can be created so the user can explore how stresses and deflections change due to the column failure mode, such as between

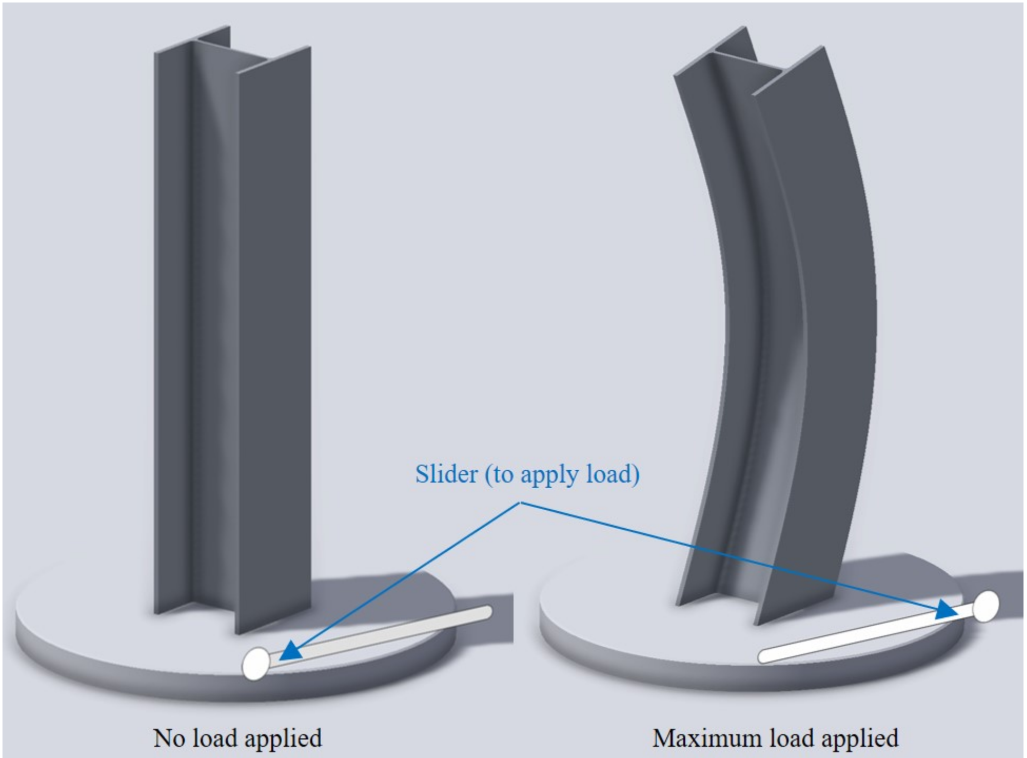

Figure 2: Column model with slider to apply load

failure due to squashing versus Euler buckling.

Later, the column buckling module can be expanded to frames. The user can specify boundary conditions at the frame ends, connection stiffness, and ratio of beam-to-column lengths in the frames. This will allow the user to get a better understanding of the effects of boundary conditions and frame geometry on the stresses and deflections in frames.

In addition to the updates to the column model, the representation of the column fixtures in the virtual reality space will be improved. Realistic end conditions will be created, such as an actuator to apply loads, and laboratory pin connections between the actuator and column and column and floor which show the rotation of the column ends. This will show realistic test conditions to the users. The background of the virtual environment can also be updated to look more aesthetically pleasing and include other informational stability items.

To help students understand the effects of boundary conditions, steel grades, and column height, the module will be expanded to allow several columns to be modeled together in the virtual space. In this manner, the students can view several columns simultaneously, which can have different properties. For example, three identical columns could be modeled, where one column has fixed ends, the other pinned ends, and the last semi-rigid ends. Students can walk around the virtual lab to see how the displaced shape and stresses are affected by only a change in boundary conditions.

It is envisioned that this educational module can be implemented into a steel design course. The module could be a standalone assignment, or a guided virtual lab exercise. Accompanying documents should be created, including learning objectives, directions, and related exercises for the students to complete.

Eventually, the authors would like to run *StructuresKit.jl* through the Oculus headset. In this manner, a user could create and define a model in virtual reality, have the model run, and view the output while still in the virtual environment.

5. Conclusions

This paper summarizes an effort to conduct an animated column test in virtual reality. The software package *StructuresKit.jl* is utilized to generate the flexural buckling deformation of a compact, doubly-symmetric imperfect column. The solution output is rendered in an interactive virtual reality module, and the process for converting the output to the virtual environment is described. Features to be implemented into the module are discussed and future possibilities for virtual reality in stability education.

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