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WIP: Enhancing Student Engagement in the Matrix Stiffness Method through Web-Based Interactive Documentation

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Abstract

The matrix stiffness method is the workhorse for modern structural engineering, integrating principles from statics and solid mechanics together to allow for the scalable analysis of indeterminate structures. Furthermore, it serves as an introduction to the finite element method, which enables high-fidelity computational analysis of complex and multi-physics behavior based on principles from continuum mechanics. However, the matrix stiffness method is frequently challenging to understand, requiring the integration of lower-division mechanics classes with principles from linear algebra.

To aid in the process of mastering the matrix stiffness method, an interactive web-based framework is created through the assistance of generative artificial intelligence (AI) and deployed to demonstrate foundational concepts of the matrix stiffness method for trusses and to clarify how each of these components is integrated into the full analysis of a truss. Discussion surrounding the resources used in the creation of this tool is presented to demonstrate the potential of generative AI in the creation of interactive documentation. In the final product, users can select a member of a provided truss and follow, through the entire method, the contribution of the truss member to the global stiffness matrix, as well as the underpinning element stiffness matrices in both local and global configuration based on principles from Hooke's Law. Furthermore, the framework serves as a tool for engineers to engage with an entire solved example of the stiffness method, and to reference for analyses on alternative trusses.

The proposed tool will be integrated into Brigham Young University's Civil Engineering Structural Analysis (CE 321) course. Discussion is presented about the kinds of evaluations that will take place in the future to assess the value of the proposed interactive learning tool from various stakeholders, including students and other faculty. Future work will more thoroughly investigate both stakeholder perceptions and student understanding of the matrix stiffness method based on use of this tool.

Introduction

As civil and mechanical structures become larger and more complex, the use of computer-aided analysis tools has become critical for accurate assessment of proposed designs. However, without sufficient technical background, engineers may be reluctant to apply these software techniques, may struggle to validate provided output, and may lack ability to discern errors (e.g. in input or processing output). Consequently, it is imperative that engineers develop fundamental training in these methods, building upon concepts learned in courses such as statics and solid mechanics [1].

In structural analysis, the force method, the stiffness method, and the finite element method apply and extend concepts from these fundamental courses to enable the analysis of statically indeterminate structures (i.e. more general structures that cannot be assessed simply using principles from statics). While the finite element method [2, 3] subsumes both the force and the stiffness method in generality, direct access to the finite element method is often challenging because it requires knowledge and application of theory from advanced mathematics, including linear algebra, multivariable calculus, functional analysis, and numerical methods for linear systems of equations and partial differential equations. The force method [4, Chapter 9], instead, provides a simple alternative for analysis of structures with low levels of static indeterminacy, but may be complicated to apply for more complex structures with higher indeterminacy. Conversely, the stiffness method [4, Chapters 14-16] allows for the analysis of both statically determinate and indeterminate structures following a prescriptive and general framework, but at the cost of introducing linear algebra and basic concepts from finite element analysis. Because of its generality and relative simplicity, the stiffness method may be seen as either the culmination of an undergraduate structural analysis course or the initial method for graduate-level structural analysis, enabling unfettered access to linear structural analysis on structures composed of beams, frames, and trusses while simultaneously acting as a stepping stone to more general finite element methods [5].

A full understanding of the stiffness method, nonetheless, requires mastery of principles from statics, application of laws from solid mechanics, and competency with linear algebra. The method is not easily discussed in a single class period, involves many steps, and requires creation of ancillary indexing schemes for solution and interpretation of results [5]. As a result, students frequently struggle to understand and apply the stiffness method [6], impeding their ability to engage with modern structural analysis computer software and their capacity to progress in their structural mechanics education to finite element methods. Simply treating the stiffness method as a black box [5] used in software inherently impedes an engineer’s ability to engage with a host of other aspects of advanced structural analysis.

This work aims to enhance student abilities to understand and employ the matrix stiffness method by creating a novel interactive web-based framework to explore the stiffness method on planar trusses [7]. Similar interactive frameworks have received attention as educational tools to better engage student interest and increase understanding [8, 9], but traditionally require enormous amounts of time to create [10, 11]. Supported by generative AI, however, the interactive visualization tool developed herein required only a fraction of the typical time required for resource development, and provides in a single webpage information aimed to support student learning of the stiffness method. While a thorough assessment of the web-based software created still needs to be performed, it is hypothesized that these resources will support student learning based on preliminary communications with stakeholders and documented studies surrounding similar visualization tools.

The rest of this document will be organized as follows. First, background information will be provided, including an overview of the stiffness method and a discussion of how the proposed work is contextualized against current research and resources. Subsequently, methods for creation of the web-based interactive tool are discussed, followed by an illustrative use of the visualization software. Preliminary discussion regarding how to ultimately assess the value of this tool as an educational resource by various stakeholders will then follow. Finally, conclusions and future work will be presented.

Background Information and Related Work

The matrix stiffness method enables the analysis of both simple and complex structures using tools from matrix analysis. For trusses, the stiffness method is exactly equivalent to structural finite element analysis under the assumption that each truss is comprised of a single element and that structural loads are only applied at nodes of the truss [3, Chapter 5]. Both of these assumptions typically hold true for idealized structural analysis. While the matrix stiffness method can be used to operate on space trusses, this paper will only speak to and use planar truss analysis.

The steps of the matrix stiffness method for trusses are outlined in Table 1, and are discussed in detail in [4, Chapters 14]. Particularly, the second step involves defining an auxiliary numbering convention at each node of the truss, and all subsequent steps make use of both this indexing convention and tools from linear algebra to solve a system of equations for unknown displacements, reactions, and axial loads. Students frequently express dismay at the large number of steps, confusion at the indexing scheme, and frustration with material related to linear algebra. Because of the significant amount of data required for computation, analyses are typically performed using software such as Excel, Python, Matlab, or MathCAD [5, 12] rather than by hand.

Relatively few studies regarding effective teaching of the matrix stiffness method have been published to date. Welch and Ressler [5] described the approach taken at the US Military Academy in teaching the matrix stiffness method using a combination of Excel and MathCAD, after which students were asked to validate their results using a commercial solver to understand that the technique is foundational to modern structural engineering. Instructors indicate that use of software such as Excel or Matlab helps better facilitate student learning [5, 12]. Others found that providing preliminary scaffolding for applying the method and then gradually removing this introductory support assisted in student success [6]. Overall, students indicate an appreciation of understanding commercial solvers based on the tools used [5].

Table 1: Steps for the Stiffness Method for Trusses

Steps	Operation
(1)	Idealize the structure as a planar truss
(2)	Number degrees of freedom with unknown displacements first
(3)	Define local stiffness matrices for all truss members
(4)	Transform member stiffness matrices into global coordinates
(5)	Assemble global stiffness matrix based on member contributions
(6)	Define prescribed loads and displacements
(7)	Decompose into a block system of equations
(8)	Solve for unknown nodal displacements and nodal forces
(9)	Compute axial loads in truss members

More broadly, however, numerous studies explore effective teaching of statics and mechanics, as well as the use of computer-based and multimedia tools in this learning. Recent studies show that the use of virtual reality in statics instruction may improve student retention [13] and keeps student engagement levels high [14]. Both student motivation and understanding may increase when using interactive computer tools regarding gearbox mechanics compared to more traditional methods [15]. Often students perceive interactive modules to be more engaging than alternative methods [16, 17]. Indeed, researchers found that use of animated and interactive textbooks tends to get much greater viewing and use than traditional textbooks [18]. However, the instructional efficacy of interactive methods is still unclear: while some report significant student learning improvements when using interactive methods [19], others indicate that no significant differences were found between multimedia methods and other traditional instruction methods [16]. Furthermore, module development typically takes a significant amount of time [17, 19, 20].

Despite a relative lack of study particularly surrounding the stiffness method, a variety of online and multimedia resources have been created to support student learning through its use. The Engineering Skills website gives a comprehensive overview of the truss stiffness method using a detailed numerical example and videos [21], but all content is static, limiting interaction. A variety of free online tools are available to help in using the stiffness method for trusses and/or frames, including Truzme [22], EduBeam [23], TrussAnalysis [24], CivilCalc [25], and STRIAN [26] but many of these tools come with little or no explanation about the underlying method and none of them allow for interactive understanding of the underpinning components of the stiffness method (including element stiffness matrices, transformation matrices, and system of equations setup and solution). The SkyCiv [27] toolset offers free tools and static picture and movie-based learning resources, with a paywall for more advanced features, but instructional resources for truss analysis only cover the method of joints and the method of sections, rather than the stiffness method. The website created herein [7], conversely, creates software that allows students to easily interact with the underpinning fundamentals of the matrix stiffness method, including each of the steps described in Table 1, on a member-by-member basis while providing instruction about how operations fit into the overall framework. In particular, the purpose of this website is not to solve an arbitrary analysis on a truss, as is the case with many of these software, but instead to train students in how the components of the stiffness method combine to facilitate analysis of arbitrary planar trusses.

Methods

An interactive website was created using the Quarto publishing system. Quarto is “an open-source scientific and technical publishing system” with the ability to “create dynamic content” using Python, R, and Julia while also being able to publish both websites and static documents [28]. Because the intent of the created material is to enable interactive exploration of the stiffness method on example trusses, Quarto was employed to enable interactivity by integrating Markdown, Python, JavaScript, and CSS in the creation of a professional publication.

Despite extensive experience with the Python programming language and some previous experience with Quarto, knowledge of web development languages including HTML, JavaScript, and CSS was extremely limited, making the development of such interactive documentation ambitious. However, after observing similar kinds of content created under the assistance of generative AI tools, efforts were undertaken to develop the interactive documentation using ChatGPT Edu [29], which is available to faculty at Brigham Young University.

Content was created in a piecemeal manner with high levels of specificity in prompts [30]. Functionality was developed gradually, beginning with some level of interactivity (which was the primary desired functionality of this framework); building to highlight both element-level and structure-level features of the stiffness method; and ultimately extending to incorporate loads, displacements, alternative structures, and a basic matrix solver. Example prompts used in interactive document generation are shown in Table 2.

Functionality created by generative AI initially contained approximately 300 lines of code using programming languages including HTML, Markdown, LaTeX, CSS, JavaScript, JSON, and Quarto’s YAML. Preliminary content displayed member-specific versions of the local stiffness matrix in which the length of the member, L, would change numeric value based on the length of the truss member that the user hovered over. Content was built and previewed using VS Code to enable debugging and visualization without the need to publish content online. Output HTML files resulting from the compilation allowed visualization and interactivity using software such as Google Chrome or Apple Safari.

Using this foundational starting content, additional prompts were provided both to debug and to extend content. Due to limited prior experience with HTML, JavaScript, and other web-based programming languages, many of the initial prompts asked for assistance in debugging content that was improperly formatted or in receiving guidance about choice of programming architecture for the generated content.

Occasionally, issues arose that the generative AI tools were unable to adequately address given the provided prompts, such as on one occasion, when some of the interactivity of the content broke due to the AI tools referencing content that was deleted based on earlier guidance. Frequently, all code content had to be submitted for review to either help in debugging or to ground the generative AI chat-bot to the current content being used. On rare occasions, starting a fresh chat in ChatGPT with a new prompt accompanied by all code pasted into the software aided

Table 2: Sample Generative AI Prompts for Website Development

Desired Functionality	**Generative AI Prompt**
Document Initialization	"I want to make a website that shows a picture of a truss. Whenever someone hovers over a truss member, I would like a matrix underneath that says EA/L *[1 -1, -1 1] to change the value of L based on the length of the member hovered over. I'd like this created using Quarto. Could you please make that for me?"
Improved Interaction	"Thank you! How can I keep a member active if I click on it but remove it from being active if I click off of it (e.g. on nothing)?"
Better Visualization	"I'd now like to make another display under the current one that, given a selected member, redisplays it in isolation from the others."
	"This is great! How can I make another display under this one that rotates the selected member to be in the x direction and displays the resulting member?"
Compilation Issues	"I found the issue—it was with numericSubEl [a function created by ChatGPT], which had been recommended that I delete earlier, but was reinserted in the latest fix. I got rid of it and now things behave as I would like. Thanks!"
Content Annotation	"This is great! Thank you! How can I annotate the angle from the positive x direction to the bar in the oriented (not aligned to the x direction) view? I would like the origin of this to start at the start node and then be in the positive x direction from there"

in creating the desired content by getting the chat-bot out of a rut in its pattern searching.

Resulting Software

The resulting interactive stiffness method visualization software (excluding additional content containing narrative describing the visualized material) contains approximately 4600 lines of code, the vast majority of which were created under the direction of prompts using ChatGPT and generative AI. To facilitate student learning from this software while preventing use of this resource as a crutch in subsequent evaluations, only a small set of prescribed truss configurations are allowed. However, arbitrary loads, settling, Young's modulus, and cross-section area are permitted thereafter.

An example of the use of the generated interactive visualization resource is displayed in Figures 1 through 7. After selection of the problem setup, including the truss for analysis, material and section properties, applied forces, and settling (as displayed in Figure 1), an indexing convention is prescribed as seen in Figure 2. Thereafter, a truss member can be selected, whereupon graphics depicting the indexing convention for this particular member and the member's near and far nodes are created as seen in Figure 3. Element stiffness matrices for the member are also

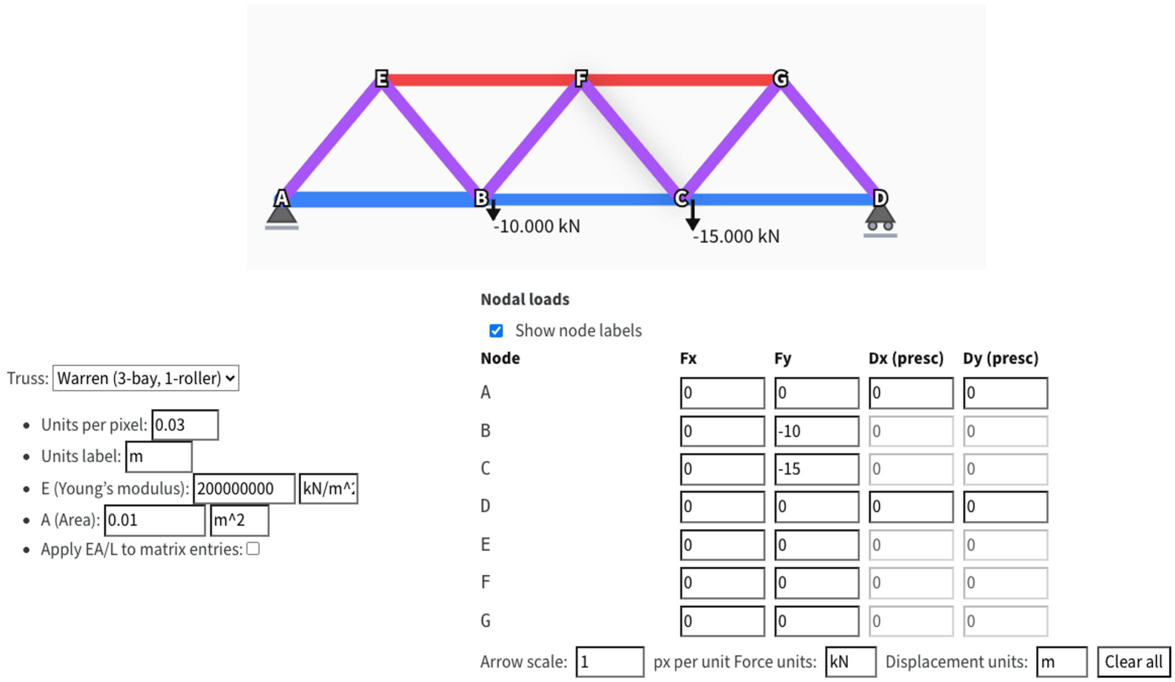


Figure 1: The setup configuration for a prescribed truss is displayed, with flexibility to choose scale, Young's modulus, cross-section area, and applied loads/displacements. Prescribed loads are depicted on the resulting structure.

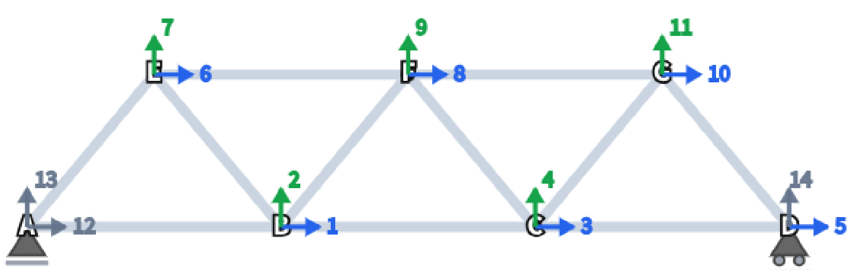


Figure 2: Example indexing for the stiffness method is shown for a statically determinate Warren truss with one pin on the left and one roller on the right. Note that each node is assigned two directions, each of which has two indices. Directions for nodes in which movement is constrained are indexed last, while unconstrained directions at nodes are indexed first.

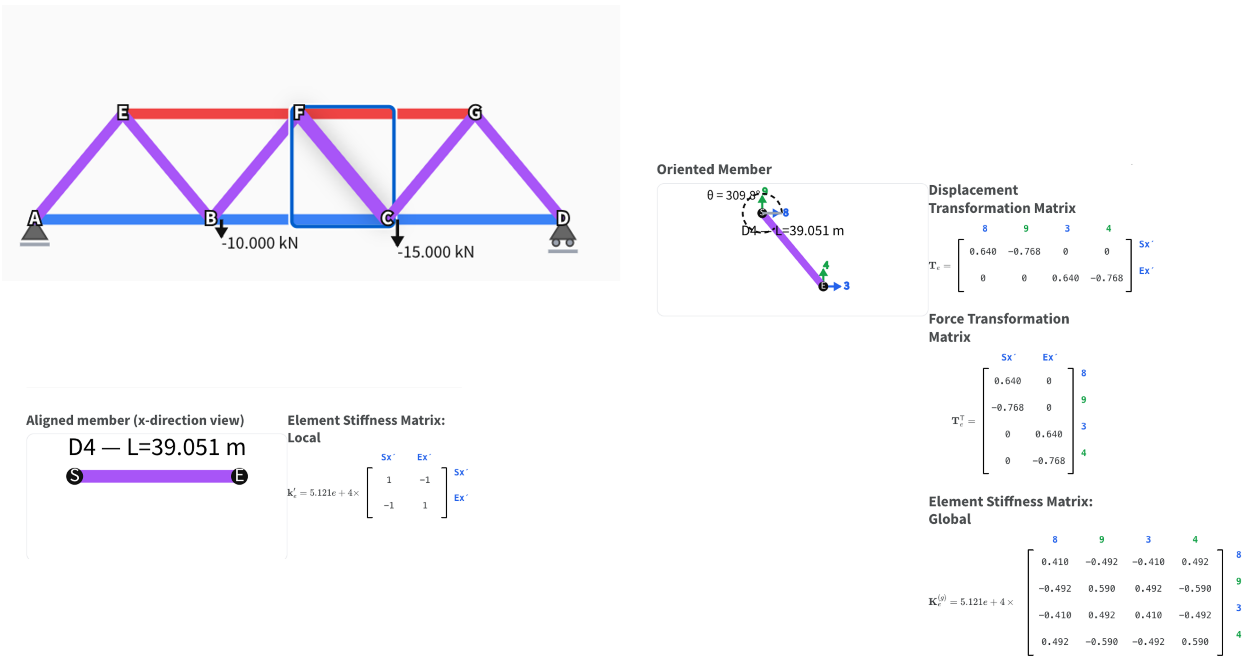


Figure 3: Upon selecting a member of the given truss, images isolating the truss member are created and data relevant to the truss including element stiffness matrices are automatically populated.

Member Contributions

$\mathbf{K}^{(g)} =$

1	2	3	4	5	6	7	8	9	10	11	12	13	14	
2.033e+6	0	-6.667e+5	0	0	-3.498e+5	4.198e+5	-3.498e+5	-4.198e+5	0	0	-6.667e+5	0	0	1
0	1.008e+6	0	0	0	4.198e+5	-5.038e+5	-4.198e+5	-5.038e+5	0	0	0	0	0	2
-6.667e+5	0	2.033e+6	0	-6.667e+5	0	0	-3.498e+5	4.198e+5	-3.498e+5	-4.198e+5	0	0	0	3
0	0	0	1.008e+6	0	0	0	4.198e+5	-5.038e+5	-4.198e+5	-5.038e+5	0	0	0	4
0	0	-6.667e+5	0	1.016e+6	0	0	0	0	-3.498e+5	4.198e+5	0	0	-4.198e+5	5
-3.498e+5	4.198e+5	0	0	0	1.366e+6	0	-6.667e+5	0	0	0	-3.498e+5	-4.198e+5	0	6
4.198e+5	-5.038e+5	0	0	0	0	1.008e+6	0	0	0	0	-4.198e+5	-5.038e+5	0	7
-3.498e+5	-4.198e+5	-3.498e+5	4.198e+5	0	-6.667e+5	0	2.033e+6	0	-6.667e+5	0	0	0	0	8
-4.198e+5	-5.038e+5	4.198e+5	-5.038e+5	0	0	0	0	1.008e+6	0	0	0	0	0	9
0	0	-3.498e+5	-4.198e+5	-3.498e+5	0	0	-6.667e+5	0	1.366e+6	0	0	0	4.198e+5	10
0	0	-4.198e+5	-5.038e+5	4.198e+5	0	0	0	0	0	1.008e+6	0	0	-5.038e+5	11
-6.667e+5	0	0	0	0	-3.498e+5	-4.198e+5	0	0	0	0	1.016e+6	4.198e+5	0	12
0	0	0	0	0	-4.198e+5	-5.038e+5	0	0	0	0	4.198e+5	5.038e+5	0	13
0	0	0	0	-4.198e+5	0	0	0	0	4.198e+5	-5.038e+5	0	0	5.038e+5	14

Figure 4: Entries of the assembled global stiffness matrix to which a selected member contributes are highlighted.

Global system

K × d = F

$$\left[\begin{array}{cccccccccccccc}
2.033e{+}6 & 0 & -6.667e{+}5 & 0 & 0 & -3.498e{+}5 & 4.198e{+}5 & -3.498e{+}5 & -4.198e{+}5 & 0 & 0 & -6.667e{+}5 & 0 & 0 \\
0 & 1.008e{+}6 & 0 & 0 & 0 & 4.198e{+}5 & -5.038e{+}5 & -4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 0 & 0 & 0 \\
-6.667e{+}5 & 0 & 2.033e{+}6 & 0 & -6.667e{+}5 & 0 & 0 & -3.498e{+}5 & 4.198e{+}5 & -3.498e{+}5 & -4.198e{+}5 & 0 & 0 & 0 \\
0 & 0 & 0 & 1.008e{+}6 & 0 & 0 & 0 & 4.198e{+}5 & -5.038e{+}5 & -4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 0 \\
0 & 0 & -6.667e{+}5 & 0 & 1.016e{+}6 & 0 & 0 & 0 & 0 & -3.498e{+}5 & 4.198e{+}5 & 0 & 0 & -4.198e{+}5 \\
-3.498e{+}5 & 4.198e{+}5 & 0 & 0 & 0 & 1.366e{+}6 & 0 & -6.667e{+}5 & 0 & 0 & 0 & -3.498e{+}5 & -4.198e{+}5 & 0 \\
4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 0 & 0 & 1.008e{+}6 & 0 & 0 & 0 & 0 & -4.198e{+}5 & -5.038e{+}5 & 0 \\
-3.498e{+}5 & -4.198e{+}5 & -3.498e{+}5 & 4.198e{+}5 & 0 & -6.667e{+}5 & 0 & 2.033e{+}6 & 0 & -6.667e{+}5 & 0 & 0 & 0 & 0 \\
-4.198e{+}5 & -5.038e{+}5 & 4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 0 & 0 & 1.008e{+}6 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -3.498e{+}5 & -4.198e{+}5 & -3.498e{+}5 & 0 & 0 & -6.667e{+}5 & 0 & 1.366e{+}6 & 0 & 0 & 0 & 4.198e{+}5 \\
0 & 0 & -4.198e{+}5 & -5.038e{+}5 & 4.198e{+}5 & 0 & 0 & 0 & 0 & 0 & 1.008e{+}6 & 0 & 0 & -5.038e{+}5 \\
-6.667e{+}5 & 0 & 0 & 0 & 0 & -3.498e{+}5 & -4.198e{+}5 & 0 & 0 & 0 & 0 & 1.016e{+}6 & 4.198e{+}5 & 0 \\
0 & 0 & 0 & 0 & 0 & -4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 0 & 0 & 4.198e{+}5 & 5.038e{+}5 & 0 \\
0 & 0 & 0 & 0 & -4.198e{+}5 & 0 & 0 & 0 & 0 & 4.198e{+}5 & -5.038e{+}5 & 0 & 0 & 5.038e{+}5
\end{array}\right] \times \left[\begin{array}{c}
d_{(1)} \\ d_{(2)} \\ d_{(3)} \\ d_{(4)} \\ d_{(5)} \\ d_{(6)} \\ d_{(7)} \\ d_{(8)} \\ d_{(9)} \\ d_{(10)} \\ d_{(11)} \\ 0 \\ 0 \\ 0
\end{array}\right] = \left[\begin{array}{c}
0 \\ -10.000 \\ 0 \\ -15.000 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ F_{(12)} \\ F_{(13)} \\ F_{(14)}
\end{array}\right]$$

Figure 5: The assembled global system of equations is computed on the fly, with faint coloration separating the blocks of the system of equations.

computed on the fly as indicated in Figure 3, while the indices of the global system of equations to which these values contribute are also highlighted (see Figure 4). These intermediate steps aim to help students visualize how information is populated and transferred in the context of the stiffness method.

A global system of equations based on the prescribed truss, its loads, and its section/material data is then computed on the fly, as shown in Figure 5, with coloration used to emphasize the block structure separating known forces from unknown ones (or equivalently unknown nodal displacements to known ones). These block matrices are then extracted to compute the unknown forces and displacements (see Figure 6). Finally, axial loads of the selected member are computed based on the nodal displacements of the truss, as shown in Figure 7. Altogether, the visualization tool graphically depicts the methodology for the stiffness method on a truss while allowing users to understand how angles, members, and loads affect final results and how information is transferred in the stiffness framework.

Forthcoming Evaluations

To date, efforts have predominantly focused on the creation of the interactive visualization tool for the truss stiffness method. Consequently, future work needs to be used to assess the value of the created interactive documentation in learning and in gaining comfort and competency with the

Free-DOF solution

$$
\begin{bmatrix} 1.458e-5 \\ -1.360e-4 \\ 4.583e-5 \\ -1.455e-4 \\ 6.250e-5 \\ 6.111e-5 \\ -7.409e-5 \\ 3.194e-5 \\ -1.538e-4 \\ -1.389e-6 \\ -7.971e-5 \end{bmatrix}
=
\begin{bmatrix}
1.500e-6 & -8.333e-7 & 1.500e-6 & -4.167e-7 & 1.500e-6 & 1.250e-6 & -1.042e-6 & 1.250e-6 & -6.250e-7 & 1.250e-6 & -2.083e-7 \\
-8.333e-7 & 6.582e-6 & -2.083e-6 & 4.680e-6 & -2.500e-6 & -2.778e-6 & 3.638e-6 & -1.111e-6 & 6.152e-6 & -2.778e-7 & 2.514e-6 \\
1.500e-6 & -2.083e-6 & 3.000e-6 & -1.667e-6 & 3.000e-6 & 2.000e-6 & -1.667e-6 & 2.000e-6 & -2.500e-6 & 2.000e-6 & -8.333e-7 \\
-4.167e-7 & 4.680e-6 & -1.667e-6 & 6.582e-6 & -2.500e-6 & -2.222e-6 & 2.514e-6 & -1.389e-6 & 6.152e-6 & 2.778e-7 & 3.638e-6 \\
1.500e-6 & -2.500e-6 & 3.000e-6 & -2.500e-6 & 4.500e-6 & 2.250e-6 & -1.875e-6 & 2.250e-6 & -3.125e-6 & 2.250e-6 & -1.875e-6 \\
1.250e-6 & -2.778e-6 & 2.000e-6 & -2.222e-6 & 2.250e-6 & 2.768e-6 & -1.910e-6 & 1.768e-6 & -2.813e-6 & 1.268e-6 & -1.215e-6 \\
-1.042e-6 & 3.638e-6 & -1.667e-6 & 2.514e-6 & -1.875e-6 & -1.910e-6 & 3.246e-6 & -1.076e-6 & 3.336e-6 & -6.597e-7 & 1.344e-6 \\
1.250e-6 & -1.111e-6 & 2.000e-6 & -1.389e-6 & 2.250e-6 & 1.768e-6 & -1.076e-6 & 2.268e-6 & -1.563e-6 & 1.768e-6 & -7.986e-7 \\
-6.250e-7 & 6.152e-6 & -2.500e-6 & 6.152e-6 & -3.125e-6 & -2.813e-6 & 3.336e-6 & -1.563e-6 & 7.926e-6 & -3.125e-7 & 3.336e-6 \\
1.250e-6 & -2.778e-7 & 2.000e-6 & 2.778e-7 & 2.250e-6 & 1.268e-6 & -6.597e-7 & 1.768e-6 & -3.125e-7 & 2.768e-6 & 3.472e-8 \\
-2.083e-7 & 2.514e-6 & -8.333e-7 & 3.638e-6 & -1.875e-6 & -1.215e-6 & 1.344e-6 & -7.986e-7 & 3.336e-6 & 3.472e-8 & 3.246e-6
\end{bmatrix}
(
\begin{bmatrix} 0 \\ -10.000 \\ 0 \\ -15.000 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
-
\begin{bmatrix}
-6.667e+5 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -4.198e+5 \\
-3.498e+5 & -4.198e+5 & 0 \\
-4.198e+5 & -5.038e+5 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 4.198e+5 \\
0 & 0 & -5.038e+5
\end{bmatrix}
\times
\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
$$

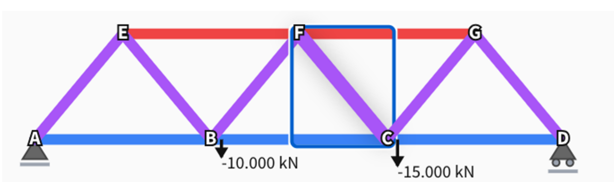
$$\mathbf{d}_u = \mathbf{K}_{11}^{-1} (\mathbf{F}_k - \mathbf{K}_{12}\, \mathbf{d}_k)$$

Net Forces at Supports

$$
\begin{bmatrix} 0.000e+0 \\ 11.667 \\ 13.333 \end{bmatrix}
=
\begin{bmatrix}
-6.667e+5 & 0 & 0 & 0 & 0 & -3.498e+5 & -4.198e+5 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -4.198e+5 & -5.038e+5 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -4.198e+5 & 0 & 0 & 0 & 0 & 4.198e+5 & -5.038e+5
\end{bmatrix}
\times
\begin{bmatrix} 1.458e-5 \\ -1.360e-4 \\ 4.583e-5 \\ -1.455e-4 \\ 6.250e-5 \\ 6.111e-5 \\ -7.409e-5 \\ 3.194e-5 \\ -1.538e-4 \\ -1.389e-6 \\ -7.971e-5 \end{bmatrix}
+
\begin{bmatrix}
1.016e+6 & 4.198e+5 & 0 \\
4.198e+5 & 5.038e+5 & 0 \\
0 & 0 & 5.038e+5
\end{bmatrix}
\times
\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
$$

$$\mathbf{F}_u = \mathbf{K}_{21}\, \mathbf{d}_u + \mathbf{K}_{22}\, \mathbf{d}_k$$

Figure 6: Using the block matrix structure depicted in Figure 4, unknown displacements and forces are computed using linear algebra.



By global DOF indices (no evaluation):

$$
\mathbf{f}_e = 8.536e+5 \times \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \times \begin{bmatrix} 0.640 & -0.768 & 0 & 0 \\ 0 & 0 & 0.640 & -0.768 \end{bmatrix}
\times \begin{bmatrix} d_{(8)} \\ d_{(9)} \\ d_{(3)} \\ d_{(4)} \end{bmatrix} = \begin{bmatrix} f_S \\ f_E \end{bmatrix}
$$

With current displacement values substituted:

$$
\mathbf{f}_e = 8.536e+5 \times \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \times \begin{bmatrix} 0.640 & -0.768 & 0 & 0 \\ 0 & 0 & 0.640 & -0.768 \end{bmatrix}
\times \begin{bmatrix} 3.194e-5 \\ -1.538e-4 \\ 4.583e-5 \\ -1.455e-4 \end{bmatrix} = \begin{bmatrix} -2.148 \\ 2.148 \end{bmatrix}
$$

Figure 7: Axial forces of a selected member are computed on the fly, both using numerical values and using indexing of the computed displacements.

Table 3: Sample Questions to Assess the IVT for Various Stakeholders

Student Stakeholders

○ Would you describe yourself as a visual, auditory, kinesthetic, or reading/writing learner?

○ Please rate how well you feel that you understand the truss stiffness method.

○ On a scale from 1–10, how effective is the interactive resource at helping you synthesize/visualize the stiffness method for trusses?

○ Do you feel that being presented with this resource is helpful after learning the material in class?

○ Do you feel that this resource would have been helpful in learning material concurrently with class instruction?

○ What percentage of your time doing homework did you spend using this interactive document to assist you in homework?

○ Do you feel like this kind of a visualization tool would be helpful in other aspects of the class? If so, which ones?

○ How could this document better connect with your learning needs?

Instructor Stakeholders

○ Rate your knowledge of structural analysis from 1–10, with 10 being very high.

○ Based on your knowledge, how effective do you feel this interactive documentation is at teaching the matrix stiffness method?

○ How valuable would you consider a similar interactive document for use in the material you teach?

○ What material in courses you teach would benefit from this kind of documentation?

stiffness method. Preliminary conversations with stakeholders, including students, teaching assistants, and faculty, give mixed feedback about potential benefits. Some stakeholders strongly feel that these kinds of interactive tools will greatly enhance learning, while others have a more muted response. Nonetheless, it is anticipated that this tool will be of high value to at least a subset of learners.

Future work will involve more rigorous assessment pending Institutional Review Board (IRB) approval. Sample kinds of questions to help evaluate the perceived value of the proposed method for various stakeholders are shown in Table 3. Beyond understanding the perceptions of the software, additional effort will be devoted to determining the efficacy of the interactive tool in teaching the stiffness method compared to educational methods that use static pictures and/or videos. This will likely involve randomly separating structural analysis student volunteers into a control group that uses the traditional methods for learning and an experiment group that uses the interactive documentation and then assessing student performance based on these groupings.

Conclusions

This work describes the creation of a web-based interactive visualization tool to help instruction about the matrix stiffness method for trusses. The visualization tool is available for use online, and was created using Quarto through the assistance of generative AI. While rigorous assessment of the merits of the tool need to be evaluated, preliminary conversations and educational literature about related resources indicate that it may be a valuable tool for some learners. Future work will further investigate the use of this resource by stakeholders in the teaching and learning process.

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