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Structural Analysis and Laboratory Model of a U-Shape Pedestrian Bridge

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Abstract

This paper presents student work involving the structural analysis of the existing Clear Creek Pedestrian Bridge, as well as the design, construction, and laboratory testing of a bamboo bridge model as part of the Project Capstone course. The existing bridge conveniently located near the campus with easy access, comprises two pony trusses supporting the floor beams and concrete deck, forming a U-shaped cross-section, with dimensions of 130'-0" in length and 8'-0" in clear width. RFEM6® software is used for structural analysis and stability assessment, ensuring compliance with applicable codes.

The bamboo bridge model is designed and constructed using glued bamboo sticks for laboratory testing under ultimate loads to observe buckling behavior. The model, resembling the Clear Creek bridge, measures 6'-0" long, 4.0" high and 4.5" wide, and includes two pony trusses, floor beams, and a lower horizontal truss. Deflections, member loads, and buckling modes of the model are analyzed using structural software. The bamboo bridge model fails under a load of 290 pounds, exhibiting a buckling shape that closely aligns with theoretical expectation.

Student survey responses indicate that the project effectively meets the objectives of the Capstone course, as demonstrated by the application of acquired knowledge in the preliminary design of a new bridge.

Introduction

The project assigned to Capstone Design students of the Structural Analysis and Design Engineering Technology Program at the University of Houston Downtown consists of the structural analysis and design verification of the pedestrian steel bridge over Clear Creek, located in the city of Pearland, TX, and the design, construction, and laboratory testing of a scaled model of the bridge using bamboo sticks 0.10" by 0.38" in cross section and 15" long, glued and cut as necessary. Finally, the project requires students to develop a preliminary design of an alternative bridge with similar conditions as the constructed Clear Creek bridge, where the obtained knowledge is applied.

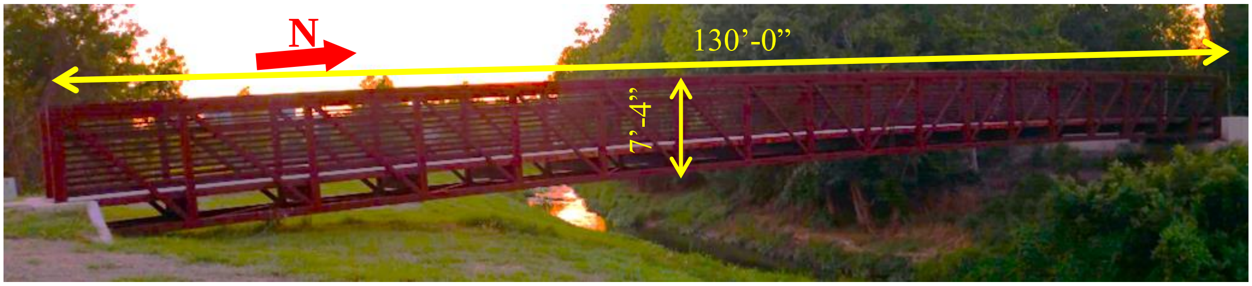
The selection of this bridge is based on several factors, including the availability of a comprehensive set of construction drawings provided by both the designer (Hulsey[1]) and the owner (City of Pearland[2]). Additionally, its proximity to the campus and its location within a public park ensure easy and safe access for students. This enables them to visit the bridge at their convenience, observe its structure, and compare its details with the provided construction drawings.

U-Shaped steel pedestrian bridges are frequently used in parks for trails due to their economy, aesthetics, and constructability. The structure of these bridges comprises two pony trusses, with floor beams connected to the vertical elements of the trusses to form a U-frame, lower horizontal diagonals connected with the bottom chord of the trusses, and a concrete deck supported by the floor beams. The handrails are affixed to the truss elements. The structural design of these bridges depends on the strength of the steel sections and the overall lateral stability. Specifically, the lateral stability of such bridges is influenced by several factors, including the stiffness of the U-frames providing horizontal bracing to the top chords, the horizontal stiffness of the top chords themselves, the bottom horizontal truss, and the quality of the connections. Additionally, the lateral stiffness of the bridge is further improved by the concrete deck, which is poured onto corrugated steel forms attached to the floor beams with self-drilling fasteners. However, this stiffness is not considered for the strength of the bridge because the type of form cannot develop composite action with the concrete.

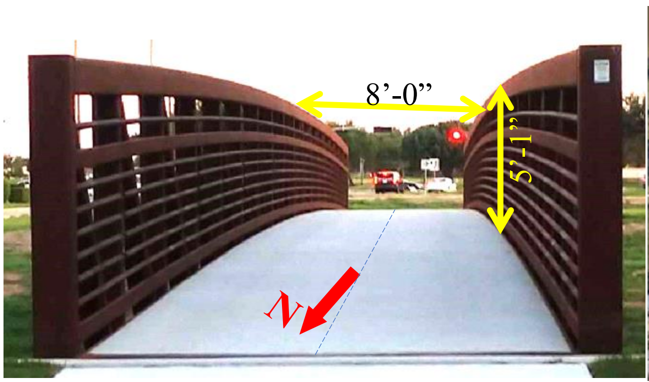
Past experience suggests that projects of this nature offer valuable hands-on experience that students typically respond well to. This approach allows for a deeper understanding of the structural analysis, including loading and interpretation of results. For instance, Palmquist[3] presents a case where students engage in the physical inspection and study of a truss bridge, demonstrating how working with a real structure facilitates learning of structural engineering concepts.

Clear Creek Pedestrian Bridge

Figure 1 shows the Clear Creek pedestrian bridge located in Pearland, TX. This bridge has a U-shaped cross section with a clear width of 8’-0”, a height of 5’-1”, and a total length spanning 130’-0”. The bridge superstructure consists of two pony steel trusses 7’-4” heigh, a 6” thick concrete slab on a metal deck supported by floor beams that are welded to the vertical elements making U-frames, and horizontal diagonals forming a truss with the bottom chord. For transportation purposes, the structure is divided into two modules, each with shop-welded connections. The modules are connected in the field using bolted splices. The concrete slab was poured after the steel structure is installed on the abutments. As non-structural elements, the bridge has safety railing connected to the vertical trusses, and electrical connections for lights. B. Hulsey representing Contech Engineered Solutions[1], engineered the original design for Lower Kirby Park at Ivy District, City of Pearland, TX[2].



a. Longitudinal view (looking west)



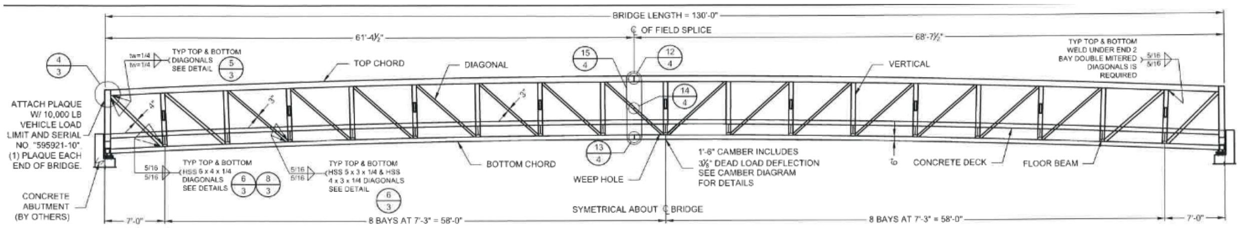
b. Transversal view (looking south)

c. Location of the bridge

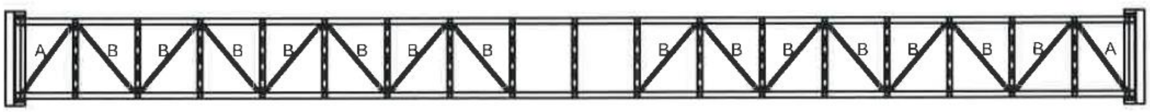
Figure 1: Pictures of the Clear Creek Pedestrian Bridge, Pearland, TX.

Figure 2 shows the elevation view of the pony truss, the bottom horizontal truss, a typical cross section, and the steel schedule extracted from the construction drawings. For better understanding of the drawings, students carried out the following activities:

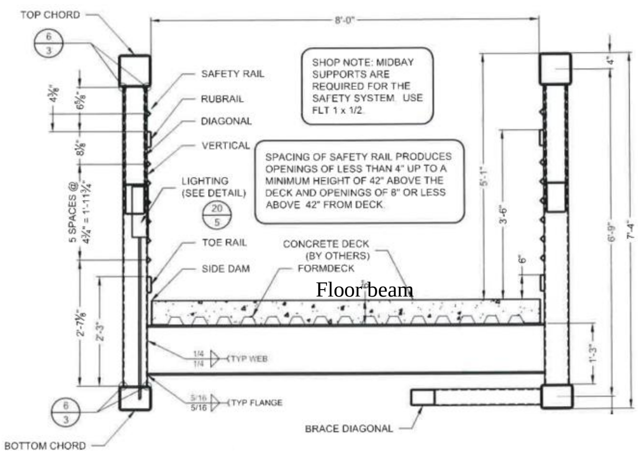
a) Field visit, comparing the design details with the actual construction. Figure 3 displays some comments gathered following this visit.
b) Redraw the main details using AutoCAD®[4].
c) Prepare the Material Take-Off (MTO), detailing the list of materials and the total weight of the bridge superstructure. These findings are then compared with the information given by the drawings to ensure accuracy. Additionally, the weight calculated in this MTO is used to verify the total dead load calculated by the structural software.



a. Elevation view



b. Bottom truss for horizontal bracing



c. Transversal section

TOP CHORD	HSS 8 x 8 x 3/8
BOTTOM CHORD	HSS 8 x 6 x 3/8
VERTICAL	HSS 6 x 6 x 1/4
END VERTICAL	HSS 8 x 8 x 3/8
DIAGONAL	HSS 4 x 3 x 1/4 ①
BRACE DIAGONAL	HSS 4 x 4 x 1/4
FLOOR BEAM	W 12 x 30
END STRUT	HSS 6 x 6 x 3/8
SIDE DAM	∠ 6 x 4 x 1 (R.F.)
END FLOOR BEAM	HSS 10 x 8 x 3/8 (STACKED)
TOE RAIL	C4 x 1 x 10 GA (R.F.)
RUB RAIL	C4 x 1 x 10 GA (R.F.)
SAFETY RAIL	∠ 1 1/4 x 1 1/4 x 1/8

① USE HSS 6 x 4 x 1/4 END 2 BAYS ONLY. USE HSS 5 x 3 x 1/4 3RD, 4TH. & 5TH BAYS, TYP EACH END. DOUBLE MITER ALL DIAGONALS.

d. Steel schedule

Figure 2: Details from the construction drawings[1].

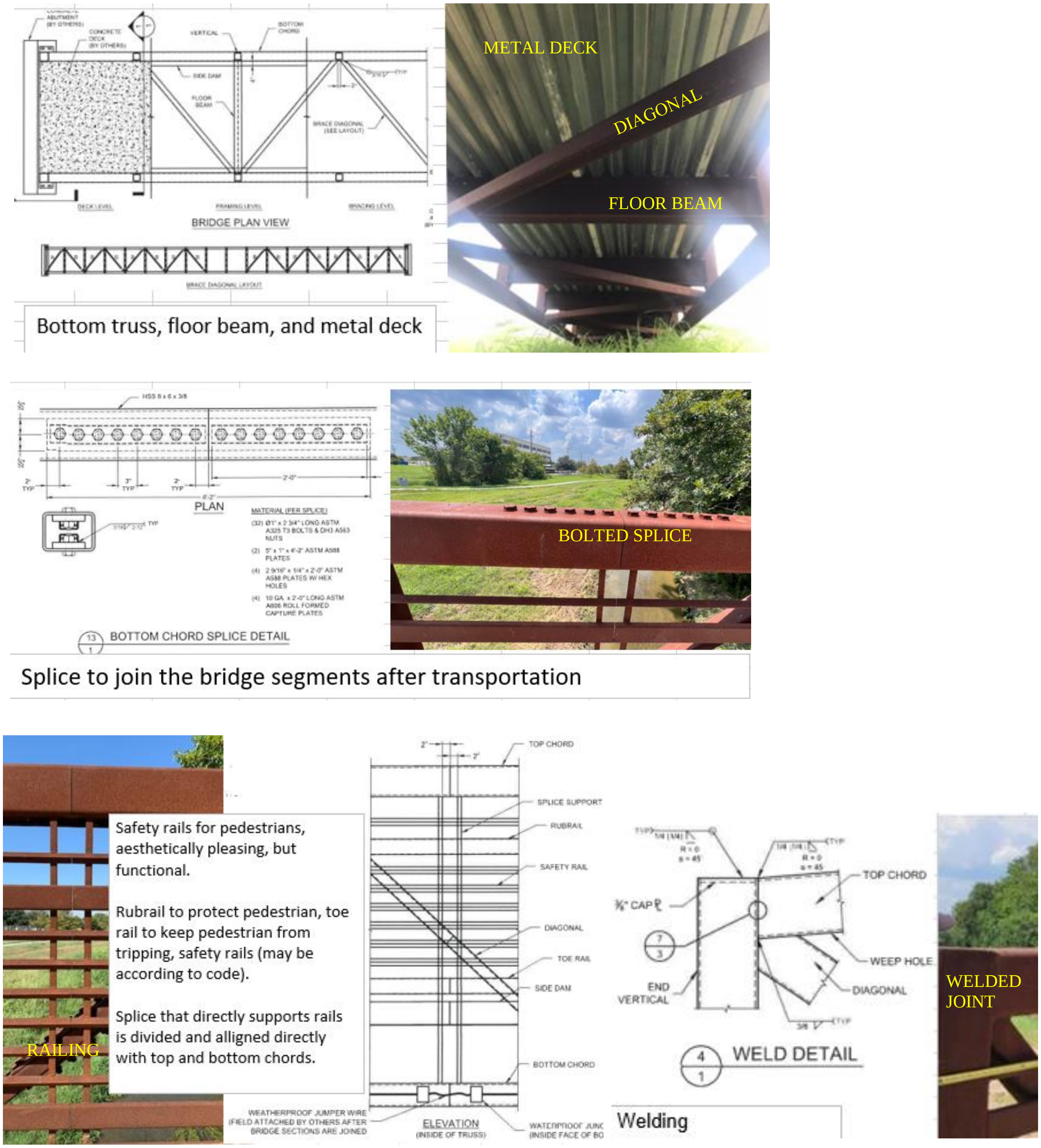
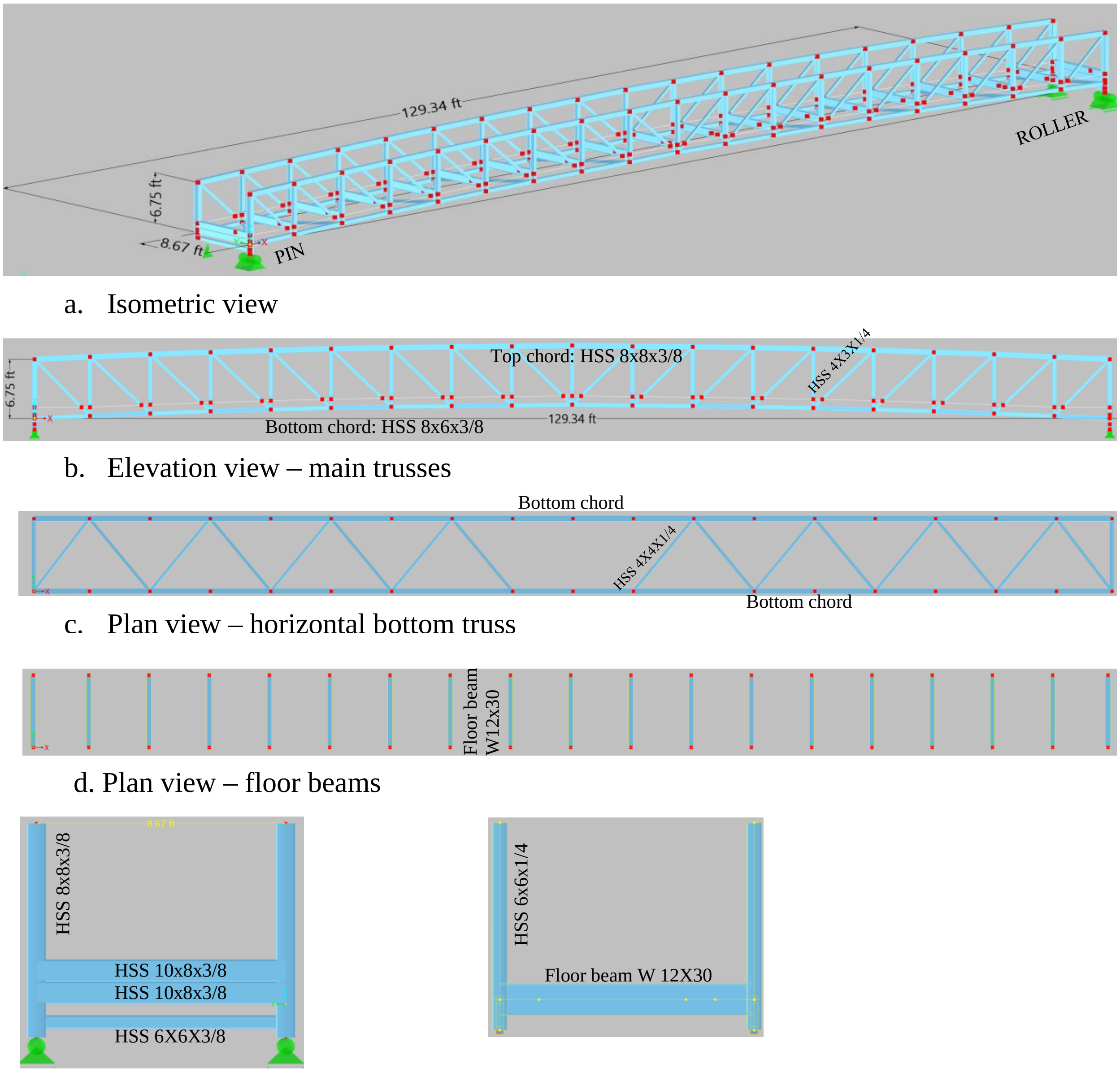


Figure 3: Details observed during the field visit.

For the structural analysis of the bridge, students utilize the finite element analysis (FEA) program RFEM6® from Dlubal Software[5]. Figure 4 displays the input of the bridge geometry following the dimensions and details given in the drawings.



a. Isometric view

b. Elevation view – main trusses

c. Plan view – horizontal bottom truss

d. Plan view – floor beams

e. End cross section

f. Central cross section

Figure 4: Structural model using RFEM6®.

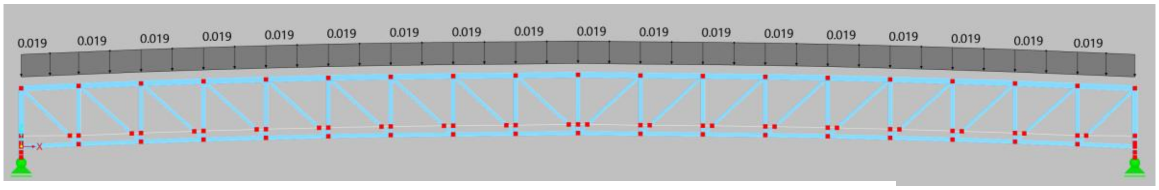
Figure 5 shows the load cases according to AASHTO Guide for Pedestrian Bridges[6] and ASCE/SEI 7-22[7], ensuring adherence to industry standards. The weight obtained from the MTO is utilized to adjust the input Dead Load (DL), as the software calculates only the weight of the structural elements. This adjustment ensures a more accurate representation of the total dead load acting on the bridge structure during the analysis. The concrete slab is included in the model; however, for strength purposes its stiffness is not considered because it is poured against the metal deck without studs to transmit shear loads. This model allows the loads applied on the slab to be transmitted to the bridge structure.

The Live Load (LL) is applied either as a uniform 90 psf on the full deck or as a single 10,000-pounds vehicle load, measuring 6'-0" wide and 10'-0" long, positioned at the critical location as specified by AASHTO[6] guidelines. This ensures that the bridge design adequately accounts for both standard distributed loads and concentrated vehicle loads at the most critical points.

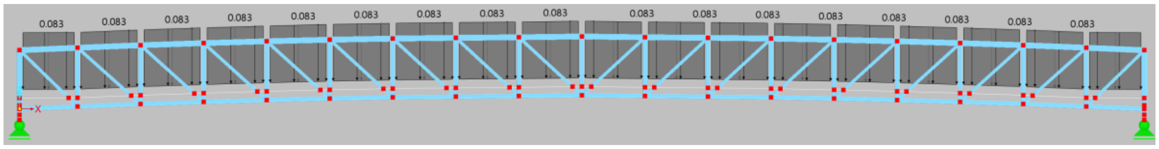
The design Wind Load (WL) is from the design wind velocity of 140 mph, corresponding to the site and Risk Category II, as shown by ASCE/SEI-7[7] and ATC[8]. The wind pressure is 35 psf applied across the entire height of the bridge as if it were enclosed, with an additional 20 psf upward pressure applied at the windward quarter point of the bridge's transverse width[1].
Input loads are rigorously verified by comparing the total reaction obtained from RFEM6® with the total load calculated through manual hand calculations. This meticulous cross-checking process serves to identify and rectify any potential input errors, ensuring the accuracy and reliability of the structural analysis.

The load combinations and steel verification are performed following ANSI/AISC 360-16[9] and using the effective lengths from the stability analysis performed by RFEM6®, as shown in Figure 6. The first buckling mode consisting in the lateral buckling of the top chord of the main trusses is shown in Figure 6a. The analysis shows that the bridge complies with the code.

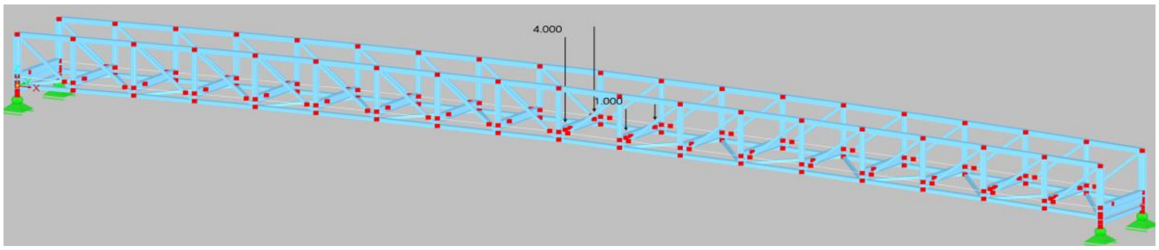
The structural analysis results obtained using RFEM6® allow students to observe the buckling modes obtained after the stability analysis. This aspect of the analysis is particularly crucial for structures like U-shaped bridges. AASHTO[6] also provides an equation to estimate the effective length of the top chord, which relies on factors such as the stiffness of the vertical elements and the location and stiffness of the floor beam.



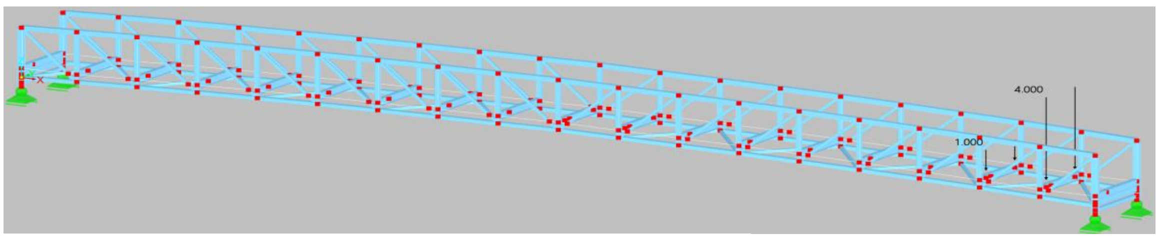
a. Dead load: self-weight + weight of non-structural elements



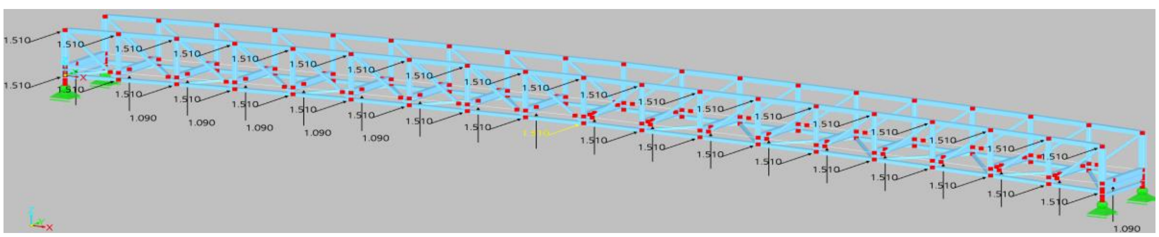
b. Live load: 90 psf applied on the slab.



c. Live load: vehicle load applied at bridge center.

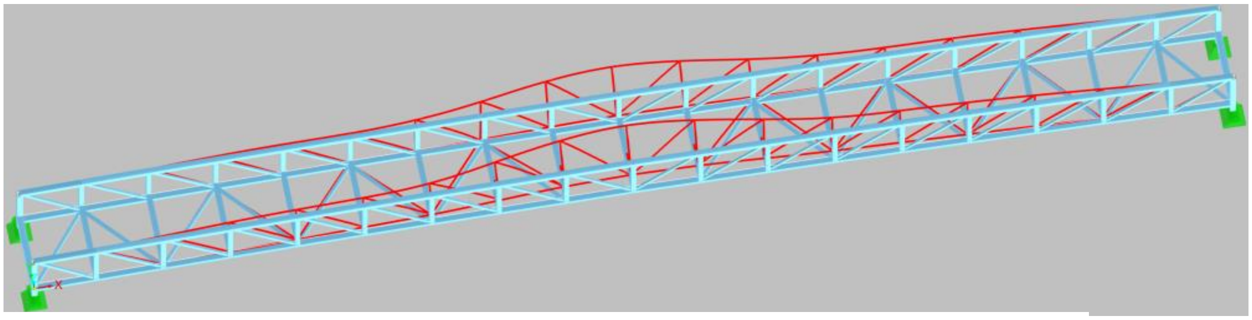


d. Live load: vehicle load applied close to supports.

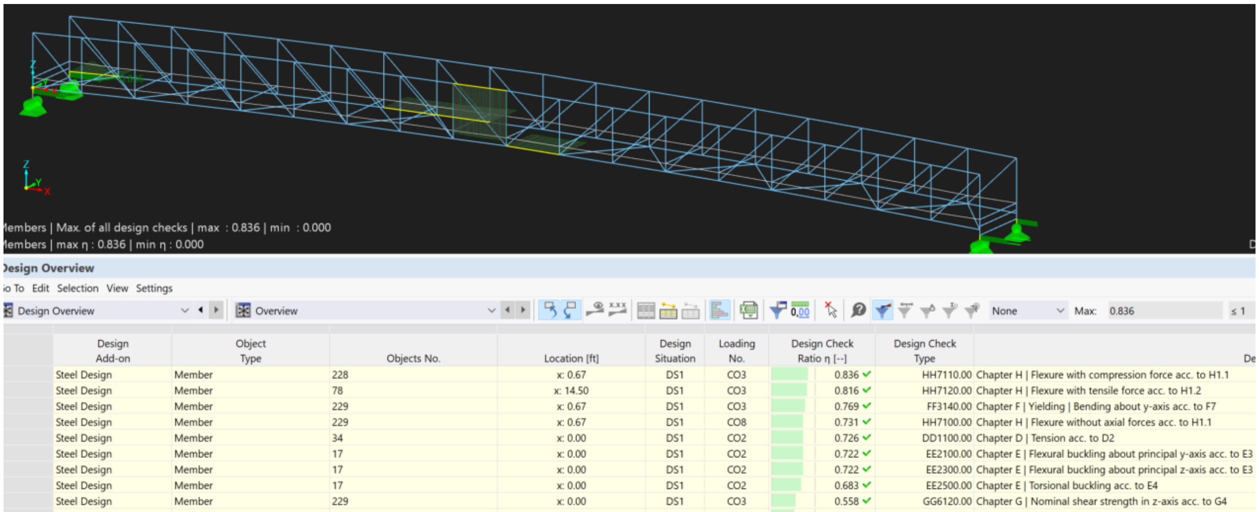


e. Wind load: 35 psf applied horizontally and 20 psf uplift applied at slab quarter.

Figure 5: Load cases applied to the RFEM6® model.



a. Stability analysis: buckling of bridge due the dead load multiplied by 10.8



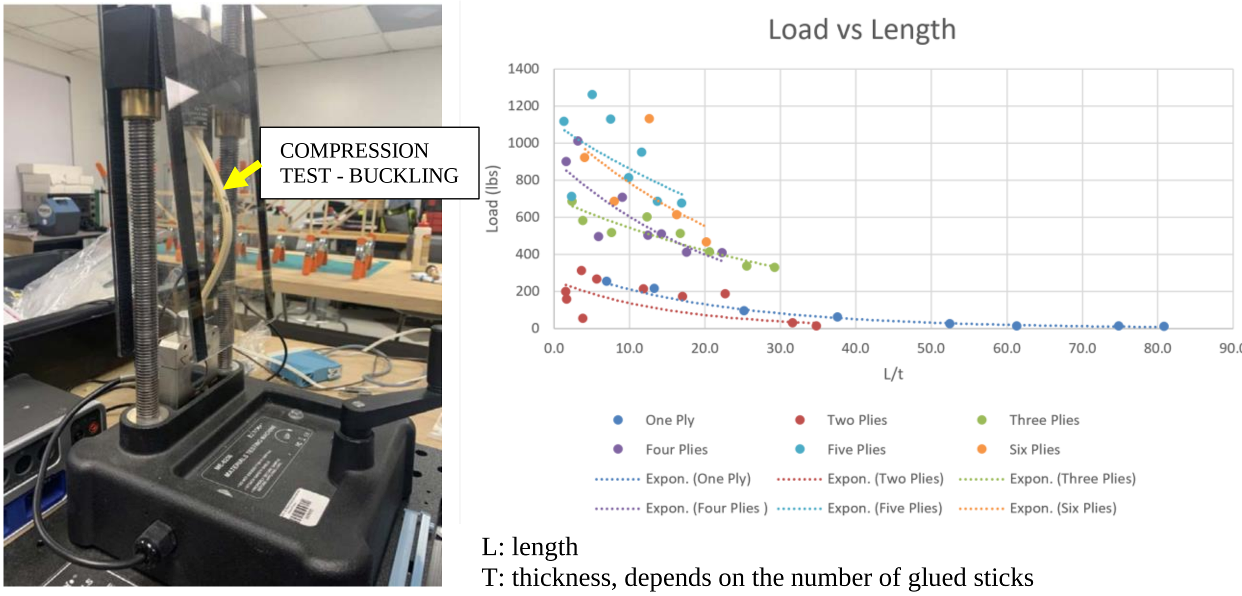
b. Stress ratio after structural analysis and design.

Figure 6: Clear Creek Pedestrian bridge - structural analysis using RFEM6®.

Pedestrian bridge model using bamboo sticks.

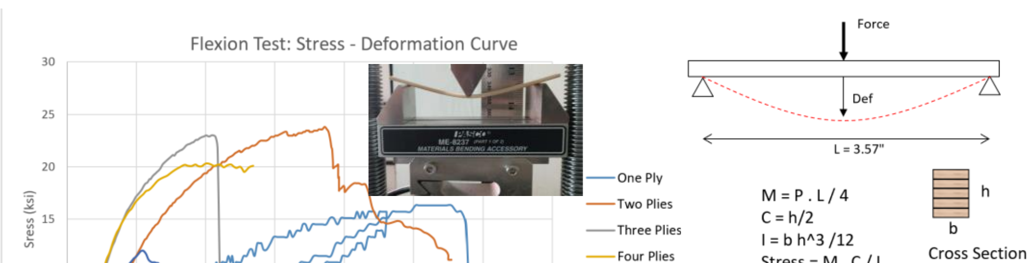
A reduced scale of the bridge is built with the main objective of allowing students to visualize the buckling failure of a bridge with a U-shaped cross section. The materials used are bamboo sticks 0.10” thick, 0.37” wide and 15.5” long, glued to obtain the desired cross section of each element.

The engineering properties of the bamboo sticks are determined through compression and bending tests. Compression tests involve various series of columns, each comprising columns of identical cross sections but varying lengths. From these tests, load-versus-slenderness curves are obtained, as shown in Figure 7. Slenderness, in this context, is defined as the ratio of the length to the thickness of the column.



L: length
T: thickness, depends on the number of glued sticks
L/t: slenderness

Figure 7: Compression test of bamboo sticks and curve load versus slenderness.



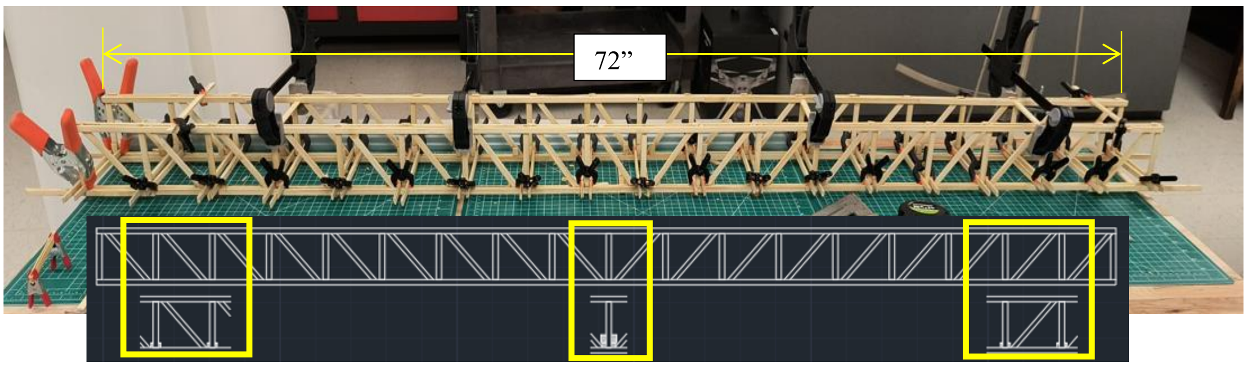
Cross Section	Width b (in)	Height, h (in)	Modulus of Elasticity (ksi)
One Ply	0.356	0.075	1030
Two plies	0.368	0.165	1172
Three Plies	0.361	0.250	1634
Four Plies	0.365	0.337	1295
Five Plies	0.381	0.430	739
Six Plies	0.381	0.537	386

Figure 8: Bending test of bamboo sticks.

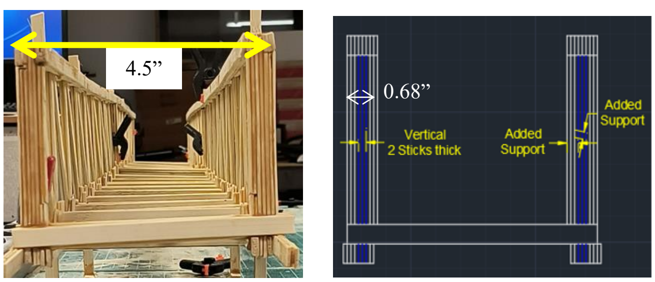
Figure 8 shows the setup for the bending test of bamboo sticks using beams constructed from one to six glued sticks. The beam has a span length of 3.57” and the load applied at their center. The modulus of elasticity obtained from these tests ranges from 386 ksi to 1634 ksi. Notably, samples composed of 5 or 6 glued sticks exhibit a lower flexural modulus of elasticity due to the presence of glue, which affects the overall stiffness of the composite beam.

The compression and bending tests are conducted using the compression machine from Pasco[10], which allows for the generation of load-versus-deflection curves. These curves are subsequently processed using MS-Excel[11], facilitating the analysis and interpretation of the test results.

The bridge model measures 72” long, 4.5” height and 4.5” wide and is designed to withstand 100 pounds applied at the center of its span. The number of glued bamboo sticks used in each cross section is defined using the axial forces in each element, the results from the compression tests, and to obtain rigid joints. Figure 9 shows some drawings made in AutoCAD®[4] of the model that permits planning the construction of the model.



a. Model during construction and longitudinal view using AutoCAD®



Member	# glued sticks	Dimensions (inch)
Top chord	8	0.68x0.38
Bottom chord	6	0.51x0.38
Diagonals	2	0.16x0.38
Verticals	4	0.33x0.38
End & Central Posts	8	0.68x0.38
Floor Beam	9	0.69x0.42
Bottom truss	1	0.38x0.08
Central loading beam	33	1.14x0.98

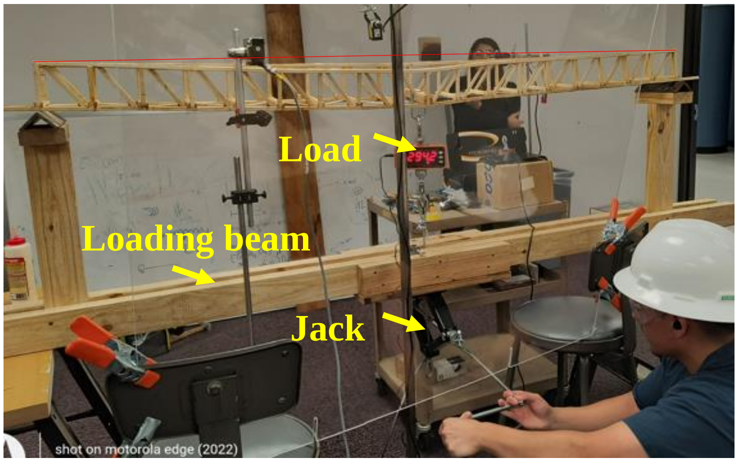
b. Transversal view

c. Number of glued sticks per element

Figure 9: AutoCAD® drawings and construction process of the bamboo bridge.

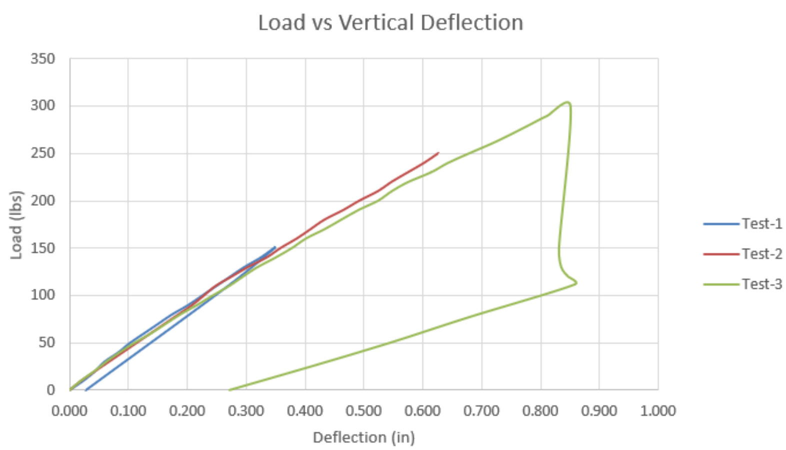
Figure 10a and 10b show the test setup. The load is applied at center of the bridge using a jack, which reacts with a timber loading beam. An electronic scale measures the load during this process. Vertical central deflections and lateral movements at one-third span are both monitored using laser deflectometers.

The load versus vertical deflection curves are presented in Figure 10c, revealing a linear behavior for all test loads. The initial loading test applies a load of 150 pounds, followed by a second test with a load of 250 pounds. However, during this second test, some elements of the bottom horizontal truss failed at the connection points. After repairs of the connections, a third test is conducted until the bridge exhibits horizontal buckling, as shown in Figure 10d. Upon unloading, the bridge regains its original shape. It is noted that the top chord detached due to the unbonding of the sticks.



a. Maximum load – lateral buckling and vertical deflection

b. Cross section before loading

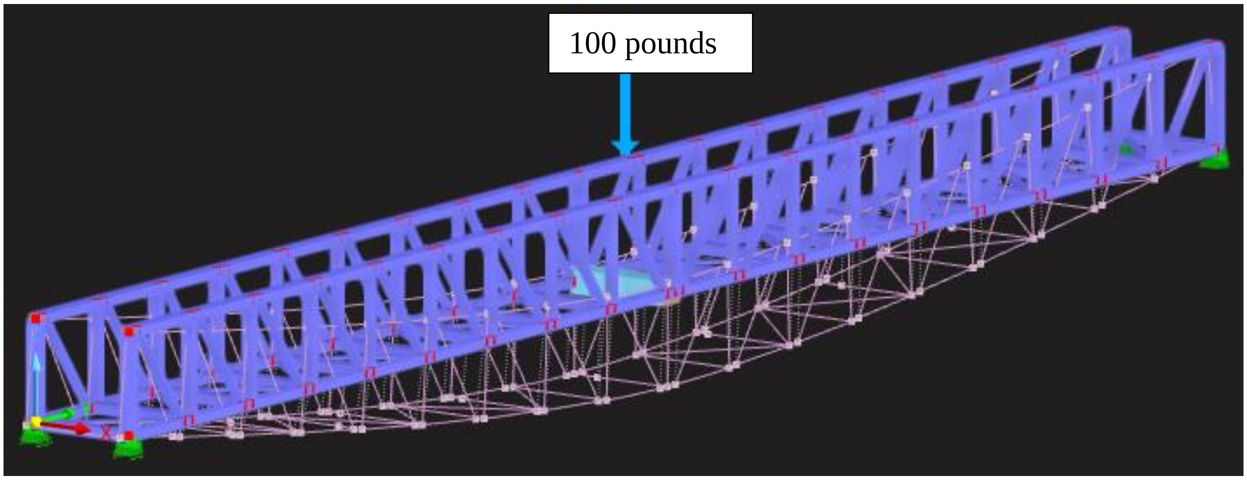


c. Load versus Deflection

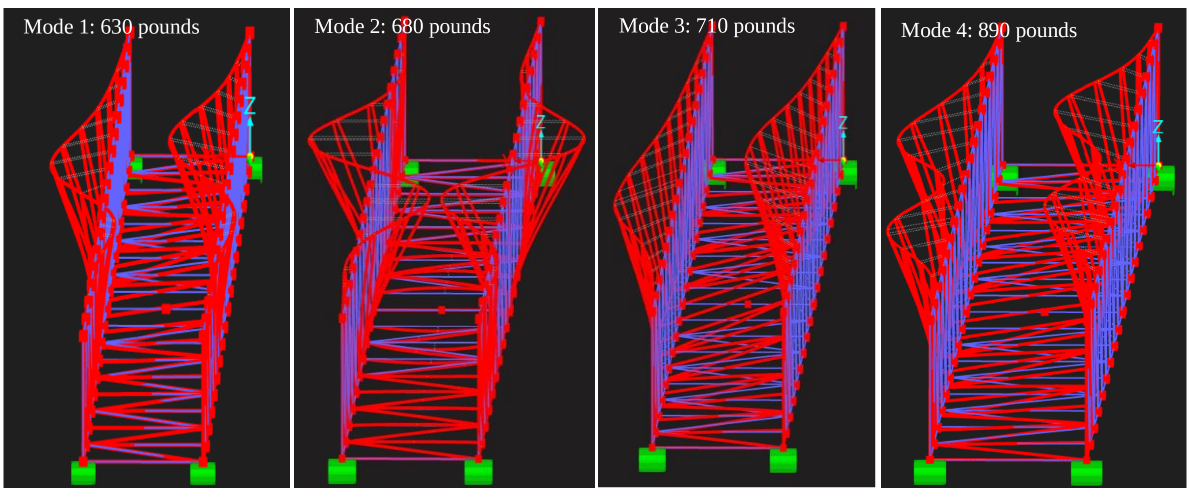
d. Lateral buckling

Figure 10: Bamboo bridge model - loading test.

Figure 11 shows the structural modeling of the bamboo bridge using the software RFEM6®. A load of 100 pounds is applied at its center, as shown in Figure 11a. For the structural modeling of the bamboo bridge, a modulus of elasticity of 1200 ksi is used. This value has been chosen because it results in a deflection of 0.24”, which aligns with the loading test and falls within the range of reported laboratory tests as documented in the work of Yang et al[12]. Using these parameters, the stability analysis indicates that the first mode of lateral buckling is produced with 630 pounds, as shown in Figure 11-b. The lateral buckling from the laboratory test occurs with 290 pounds, however the buckling shape is like the theory. The disparity between the predicted and observed loads is attributed to misalignment of the upper chord and other imperfections inherent in the construction process.



a. Deflections under 100 s applied at center



b. Stability analysis – Buckling

Figure 11: Bamboo bridge model - RFEM6® structural modeling of the bamboo bridge.

Academic assessment of the project

During this project, students are exposed to the evaluation of an existing pedestrian bridge with U-shaped cross section, where it is necessary to verify the serviceability, strength, and stability of the structure. For this reason, the bridge is modeled in RFEM6®, a professional Finite Elements software, obtaining important practice in the evaluation of a structure. Additionally, students designed, constructed, and tested a model using bamboo sticks, obtaining the engineering properties of this material using laboratory tests. The load test is important to verify the design for the service load and to observe the buckling mode, which basically was due the lateral stability of the top chords of the trusses. The students used this project to make a poster for a student conference. Figure 12 shows the course survey indicating that all the students agree that the course objectives are covered by the project.

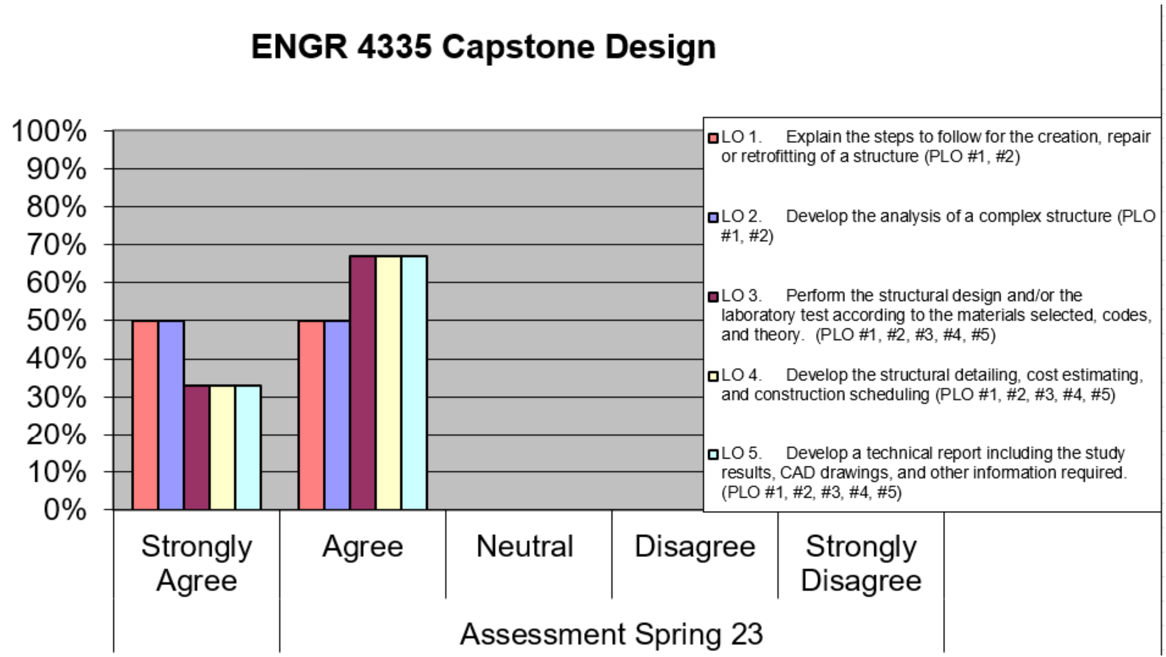
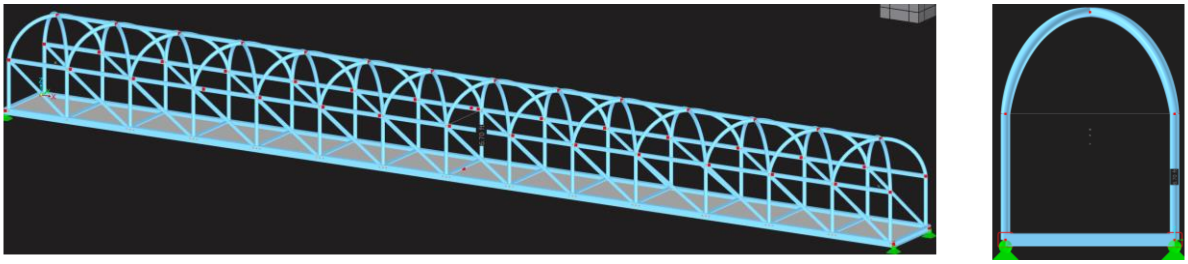
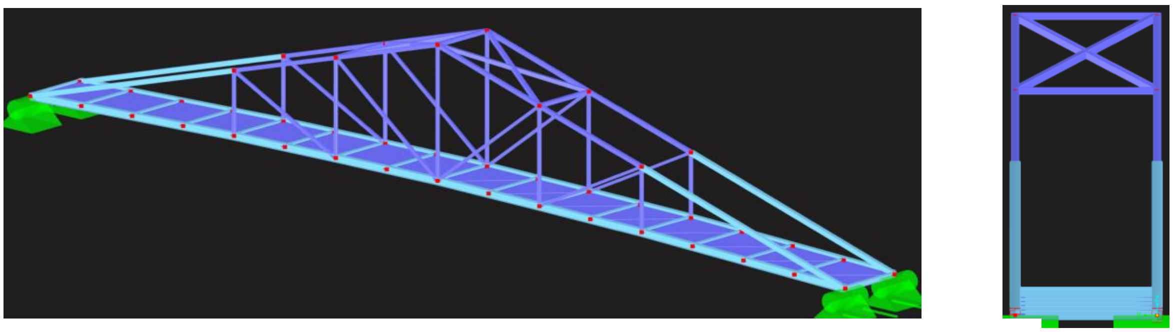


Figure 12: Assessment of capstone course using a survey of acceptance

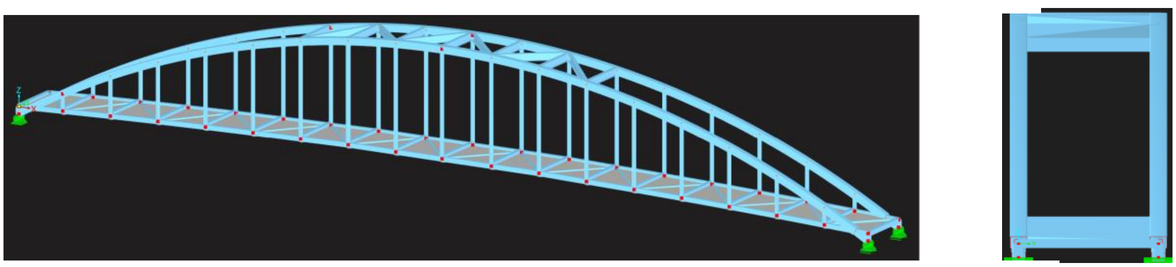
The experience acquired from this project is utilized by students to undertake the preliminary design and analysis of a new bridge under the same conditions as the original one. Figure 13 shows the bridges created and analyzed by three group of students using RFEM6® software. Figure 13-a depicts a bridge with small three-dimensional arches connected with a longitudinal tube at the top to bear the compression force. Figure 13-b shows a bridge with triangular vertical trusses and an additional top horizontal truss to ensure stability. Figure 13-c presents an arch bridge with the slab supported by hangers, supplemented by an upper horizontal truss for stability. These preliminary designs highlight how students the applied lessons learned from the project to a new structural endeavor.



a. Bridge with 3-D arches.



b. Bridge with triangular vertical truss and top-bottom horizontal trusses.



c. Bridge with vertical arches, hangers, and top-bottom horizontal trusses.

Figure 13: Preliminary bridge design as alternative to the Clear Creek Pedestrian Bridge.

Conclusions and Recommendations

Students conducted the structural analysis on the Clear Creek pedestrian bridge, confirming compliance with the strength and stability requirements outlined by the AISC code for the steel sections. Additionally, they designed and constructed a model using bamboo sticks, testing it to observe failure due to lateral buckling. Results were compared with theoretical calculations. Although the failure load was lower than theoretically estimated due to initial misalignments and construction imperfections, the buckling shape closely aligned with theoretical expectations.

The objectives of the Capstone course were successfully achieved through this project, with students demonstrating interest and active participation. Moreover, they developed a preliminary design for a new bridge with constraints similar to the original, effectively applying the experience gained from analyzing both the Clear Creek bridge and the bamboo bridge model.

Acknowledgements

The author extends sincere appreciation to Dlubal Inc. and Autodesk, Inc. for generously providing the professional versions of their software for educational purposes, greatly benefiting students. Additionally, the author expresses deep gratitude to the students of Capstone Design (Fall-2022 & Spring-2023) for their remarkable enthusiasm, dedication and professionalism demonstrated throughout the project.

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