Kathmandu University Journal of Science, Engineering and Technology, Vol. 15, No. 2, August 2021

Kathmandu University
Journal of Science, Engineering and Technology

Structural optimization of simple span bridge by adding truss structure

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Abstract

A truss is a structure that involves members assembled into connecting triangles so that the overall connection behaves as a single object. Its application is in industrial and building construction. This paper presents a study about optimizing a simple span bridge in terms of stress, the factor of safety, and maximum displacement by adding different structures. A simple span bridge having a span length of 12m was modeled using SolidWorks's finite element analysis approach. A uniform initial load of 5000N was applied to the beams in all cases to determine safety factors, which helps determine the maximum allowable force, the maximum displacement, and the ultimate yield stress. The result shows that a simple span bridge has an efficiency score, the maximum displacement of 24.17, and 749.9 mm, respectively. Upon design modification by adding Howe truss structure, floor beams, and lateral bracing, a considerable increase in efficiency score was observed with reduced displacement. Among all cases, the optimized bridge has an efficiency score and maximum displacement of 83.69 and 63.08 mm, respectively. This paper aims to find the optimized structure to its full capacity for the given material.

Keywords: Structural analysis; Finite Element Analysis(FEA); SolidWorks; Stress; Factor of safety; Displacement

1. Introduction

A truss is a framework that involves members assembled to behave as a single object. Most structures are the collection of these trusses to form a particular framework in engineering construction. The application varies from supporting a roof, bridges, or other forms and mostly in the machine parts. It is a practical and economical solution for engineering problems, primarily due to its unique features like simple fabricating techniques, minimal structural load, and shorter construction periods. These structures bear different horizontal and vertical loads, and the system loads themselves acting in their plane and have to consider as a two-dimensional structure. However, when the truss carries the concentrated and distributed load, the system requires a floor structure by which the joint bears the loads. Although the truss members are linked using a bolted or welded connection, it is conventional to presume that they are pinned together [1]. For complicated truss system, a three-dimensional structural analysis approach is gaining more popularity.

The structural optimization provides a simple, efficient, effective, and economical solution for truss design and installation. This technique helps to meet a particular design objective with a minimum amount of material and time. The trusses withstand various loads and may repeat over several spans in the same bridge [2]. Developing a high computing machine and different simulation tools help to optimize the system virtually before its installation. Structures are becoming cheaper, lighter, and more vital as well. Nowadays, industries are accepting a higher form of optimization techniques [3]. This paper aims to optimize the simple span bridge using simulation techniques. It seeks to find the optimized design by performing a linear static analysis in SolidWorks using Finite Element Method (FEM). The study focuses on analyzing the effect of adding the structures at a different location on a simple span bridge. The overall performance, displacement, and maximum load it can bear as a structure are the essential analyzing topics.

2. Materials and method

This study used Balsa wood for simulating truss structure for different cases. Balsa woods having properties, as shown in Table 1, are commonly available and are taken from SolidWorks property table.

The structural analysis predicts the effect of load on the structure using the sets of the mathematical equation. The groups of a complex equation that essentially defines the physical systems are solved using FEM. It is a numerical method used to obtain an approximate solution for a given boundary value problem. It converts the boundary value problem into a linear equation system, which is easy to solve and understand. The general approach is to discretize the domain using the lattice analogy. The formulation of the boundary value problem gives algebraic equations and approximates the unknown function over the domain. Combining these equations provides one sparse matrix equation through the connections among the elements, the property of material, the load, and the restraints. The solution of the engendered matrix equation controls the behavior of all the local components. The final result comes up with the data for stress and displacement [4].

Beam elements are the common choice to mesh structural members. By meshing curve, beam elements are created, which is commonly called wireframe geometry in CAD terminology. They do not have any physical dimension in the direction normal to their length. A beam element can be considered a line with assigned beam cross-section properties. It has six nodal degrees of freedom, meaning that restraints and load are in six directions [5].

The study using SolidWorks software involves three significant

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Table 1: Material properties of Balsa wood.

Property	Value	Unit
Elastic Modulus	2.99×10^9	N/m^2
Poisson's Ratio	0.29	-
Shear Modulus	2.99×10^8	N/m^2
Mass Density	159.98	kg/m^3
Yield Strength	1.99×10^7	N/m^2

steps: pre-processing, analyzing, and post-processing. The pre-processing involves creating geometry, adding necessary dimensions, and supplying information like material, external load, and fixtures. The second step is analyzing, meshing, and calculating for each element of the geometry. Post-processing involves representing the results in graphical format, identifying the problem area, modifying and optimizing the outcomes [2]. In this study, using this technique, the stress, factor of safety (FOS), and displacement were determined for the truss bridges in different cases. The design cycle involves the change in the model or pre-processing stage. The transformation includes changing the beam length, whereas pre-processing consists of the change in load and fixtures. Either change leads to the model to be re-analyzed, cycling until obtaining the best solution.

2.1. Model description

The model considers gravity. The red downward pointed arrow represents the gravity, Fig. 2–5. Among three fundamental element types in SolidWorks: beam element was used during the meshing. The structure has several joining points; each joining point of the system was considered as a joint. The bridge has simply supported joints in the two ends. These are the basic assumptions made during this study.

A detailed cross-section area is required while defining the beam element so that the software can calculate the moment of inertia, neutral axis, and other information [6]. A simple span bridge had bottom chords of cross-section 0.25 m × 0.25 m and floor beam of cross-section 0.25 m × 0.10 m, as depicted in Fig. 1. The stepwise modification was made by adding truss structures, a number of the floor beam, and lower lateral bracing.

In real cases, the members in the bridge are welded or bolted together. But the general consideration for designers is the load in the joints, instead of considering joint types. Each member of the structure is either compressed or tensed. So, the axial force is the only inner force developed in the members responsible for axial stress. It is uniform through the cross-section and constant along its length [4].

The first case of the study is the analysis of the simple span bridge. A bridge having a span length of 12 m and a breadth of 2.25 m was modeled in Solidworks. This bridge has 9-floor beams with a 1.5 m gap in between. A load was applied on all the 9-floor Beams, as shown in Fig. 2. The second case is a specific modification by adding the Howe truss configuration of height of 3.375 m, as depicted in Fig. 3. For the third case, the structure has eight more floor beams. The total of 17-floor beams are separated by a distance of 0.75 m, as depicted in Fig. 4. The uniform load of 5000N was applied to all the floor beams. For the fourth case, 7 pairs of lower lateral bracing were added to the bridge, as shown in Fig. 5. The study's basis was the linear static analysis that gives the ultimate yield stress, maximum displacement, and efficiency score.

Efficiency score is the ratio of the weight-bearing capacity to the system weight itself. It gives an idea about the structure's load-bearing ability, i.e., the construction with an efficiency score of 25 indicates the system can withstand 25 times more load than the system load. There is a general procedure for calculating the efficiency score. The basis of calculation was the general approach suggested by [2] for its analysis. The applied load of 5000 N per beam is indicated by the pink downward pointed arrows, as shown in Fig. 2–5. The FOS is an essential parameter to determine the maximum stress on the structure. The FOS value was calculated for all the cases accordingly, which gives an idea about the maximum load the structure can withstand. The mass property table provides the system mass, and the efficiency score was calculated for all cases.

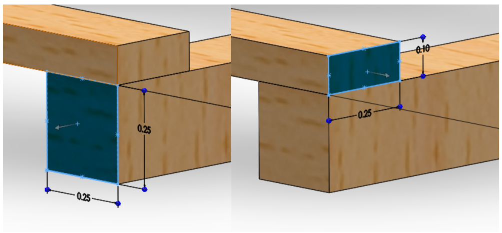


Figure 1: Cross-section area of the bottom chord and the floor beam of simple span bridge.

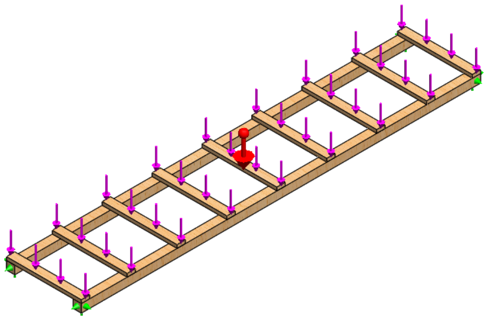


Figure 2: Simple span Bridge (Case-I).

3. Results and discussion

This section presents the results of different cases after the design optimization on the simple span bridge. The study splits into several cases, but the analysis approach is the same for all of them. The load of 5000N was applied to all cases to find FOS that gives an idea about the maximum load the system can handle, along with the efficiency score. All cases have the same general method for optimizing structural performance.

3.1. Case-I

As shown in Fig. 6, the simulation used SolidWorks for modeling the simple span bridge. The bridge has total elements of 354

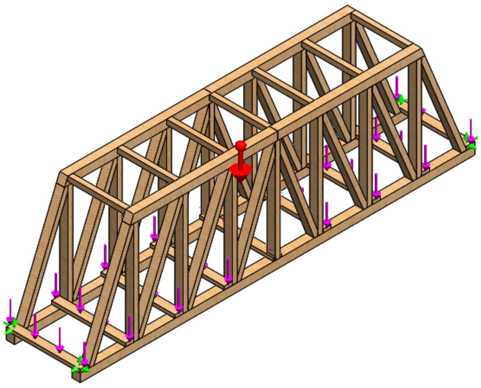


Figure 3: Adding Howe truss in the initial structure (Case-II).

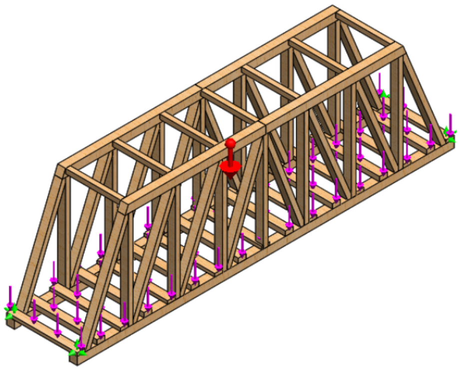


Figure 4: Adding more floor beams (Case-III).

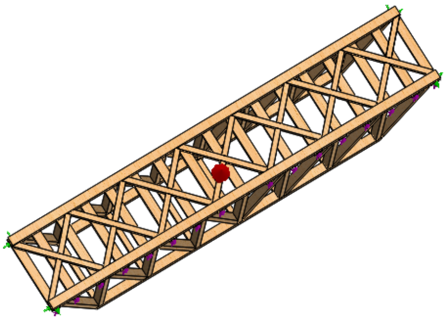


Figure 5: Bottom view showing lower lateral bracing (Case-IV).

and nodes of 350 to study the stress, displacement, and FOS. Considering the FOS value 1, the maximum allowable load per beam was 8450N. As all nine beams were under a load of 8450 N, the total load given to the structure was 76050 N. Although the provided load was on the floor beams, the yield stress is maximum in the middle of chords. The maximum stress value is 19.33 MPa, as depicted in Fig. 6 (a). There is moderate stress of 3.82 MPa in the center of the floor beam, and stress gradually decreases to minimum values toward the joint section. When the applied load per beam is above 8450 N, the bridge possibly crosses the elastic limits and causes plastic deformation. The failure may occur from the chords. The weight of the structure is 3145.6 N, obtained from the mass property table. The total allowable force for the system and the system weight gives an idea of the efficiency score. The value of the efficiency score for this case is 24.18. This value is lowest among all the cases and likely to bear lesser force than other structures. The bridge has a maximum displacement of 749.9 mm near the center, as shown in Fig. 6 (c). Unlike the yield strength, the displacement is uniform in the floor beams and the cords under loading. Fig. 6 (b) represents the FOS value in the bridge. The blue color indicates the structure is safe under the given load, which is the same for all the cases.

3.2. Case-II

This case has additional members named as Howe truss on the initial configuration. The structure has a total number of 781 elements and 787 nodes. In this case, the added structures have significant impacts on the bridge's load-bearing capacity. It has the maximum allowable load per beam of 50000 N, making 450000 N load in the system. This value is around six times greater than that of the previous case. The yield stress is distributed uniformly in the structure, as shown in Fig. 7(a). However, the stress value is high near the joint of chords and beam, with a maximum value of 19.12 MPa. These results indicate that if the allowable load applied per beam is greater than 50000 N, the bridge is expected to fail, particularly from the joint region. The structure's weight is 10973.88 N, and the efficiency score for this case is 41.01, as shown in Table 2. The efficiency score slightly increases than the previous one. The maximum displacement of the chord beams decreases drastically to around 21.9 mm. The simulation shows that the floor beam is about to displace more on applying the load, as shown in Fig. 7 (c). The value is 43.9 mm at the middle of the floor beam, and the value is in decreasing order toward the joint section.

3.3. Case-III

The second case gives the basis for further optimization. The allowable load-bearing capacity increases with reduced displacement in the chord. However, there is a considerable increase in displacement in the middle section of the floor beam. The structural configuration is obtained from the addition of eight more floor beams to the Case-II, making the numbers of floor beams 17 in which the force was applied to all of them. The mesh elements in the structure are 841, having 847 nodes. Fig. 8 (c) shows the simulation result; the displacement in-floor beam increases to 67.6mm. This increment in displacement may be due to an increase in the number of floor beams. However, the displacement in chords is similar to the second case. The load-bearing capacity per beam increases to 51100 N with a total load on the system of 868700 N. The value of the permissible load on the structure is 1.93 times more than that of case-II. The maximum yield strength is 19.69 MPa, observed near the floor beam's joint region and the chords, as depicted in Fig. 8 (a). The vertical and diagonal members of the structure have moderate stress. The failure may occur from the joint section of the floor beam and the chords. The system's weight increases to a value of 12032.74 N, and the efficiency score of this structure is 72.20. The efficiency score increases drastically in this case. However, the optimization is crucial because there is a maximum displacement on the floor beam. The next optimization technique will be adding the members in the lower section of the floor beam to reduce the beam displacement.

3.4. Case-IV

The seven pairs of lower lateral bracing were added to the third configuration, as depicted in Fig. 5. The load-bearing capacity per beam increases to 65000 N, making the total load of 1105 kN on the structure. This capacity is about 1.27 times greater than the load of case-III. The mesh elements in the system are 979, having 1026 nodes. The maximum stress of 18.89 MPa is on the structure's vertical and diagonal members, as shown in Fig. 9(a). The stress is somehow uniformly distributed all over the members. The system load and the bridge efficiency score are 13203.31 N and 83.69, respectively, as shown in Table 4. The system can bear more load than other cases and is the safest structural design of all. The maximum displacement of 63.08 mm is on the lateral bracing. The displacement was not only on the beams, but the overall structure was slightly dragged down due to the effect of lateral bracing, as shown in Fig. 9 (c).

3.5. Discussion

The stepwise optimization technique increases the safe load per beam, which considerably reduces the bridge deflection. The other studies on the static linear analysis of different structures show similar results. M Urdea et al. [7] studied the significance of adding truss structures on the bridge. The hollow round pipes are assembled to form the layout. The added Howe truss reduces the displacement to 8.72 mm for the maximum stress of 102.036 N/mm^2.

Our study's significant differences with others are the bridge span, the cross-section, beam number, and the initial load. The initial load of 5000 N was applied based on optimization to main-

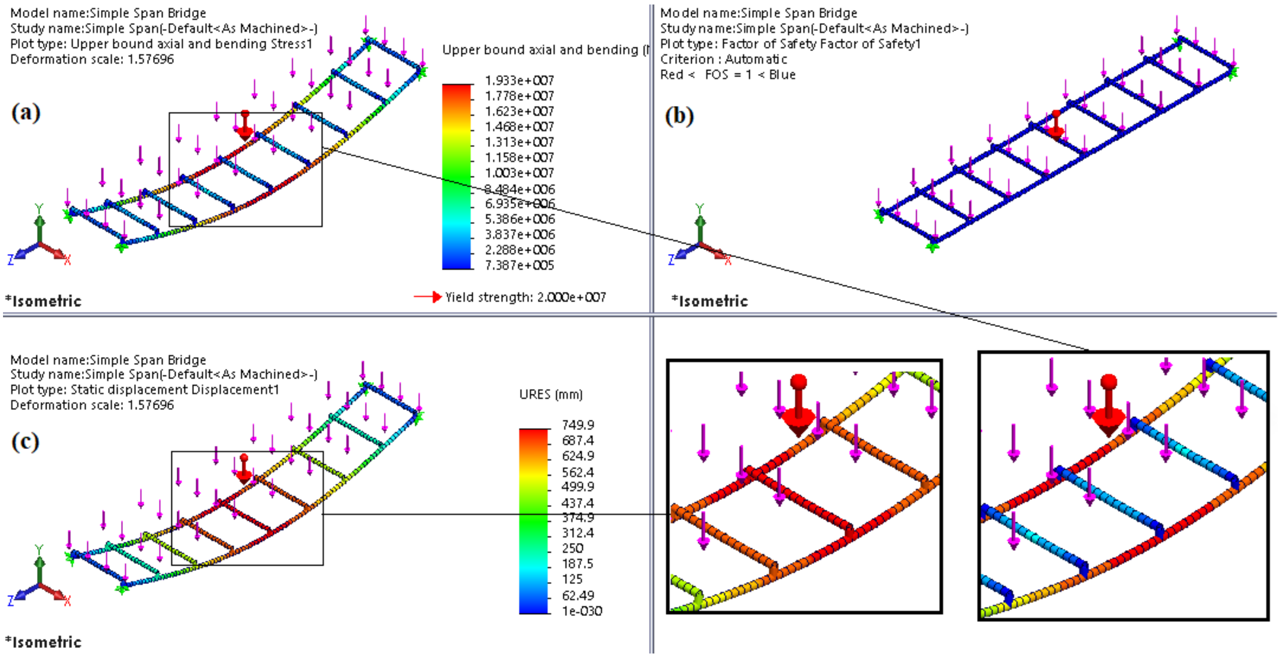


Figure 6: (a) Results of stress, (b) factor of safety, (c) displacement of simple span bridge under maximum loading (Case-I).

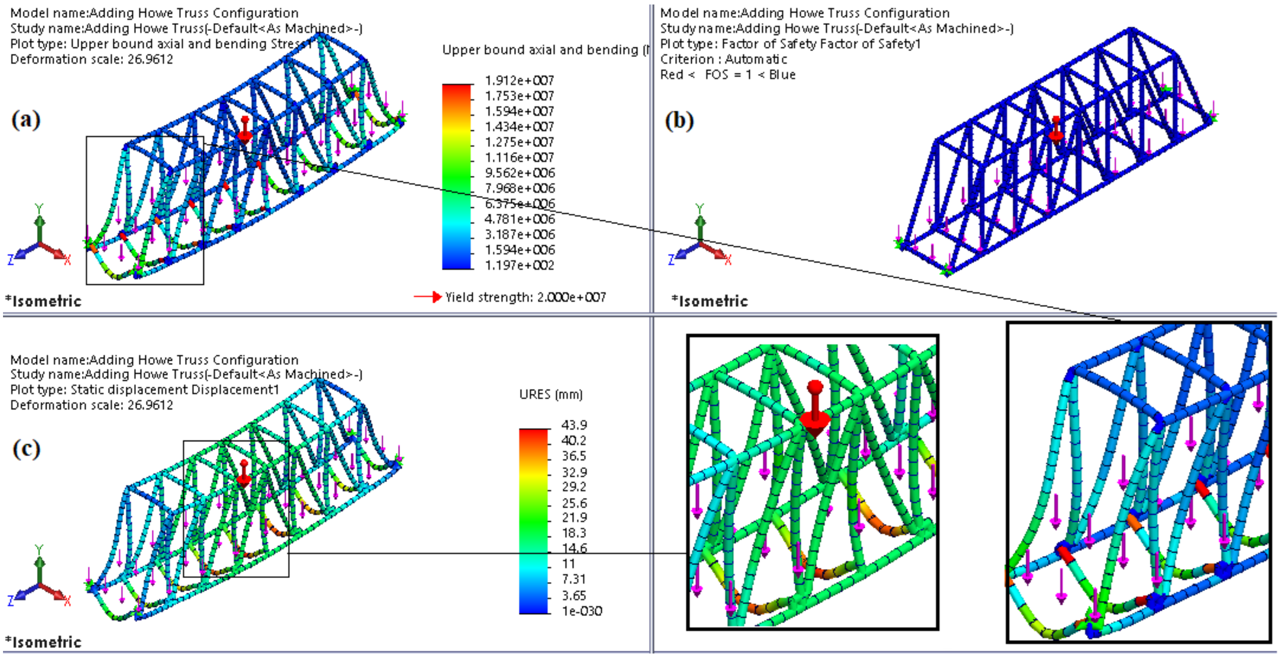
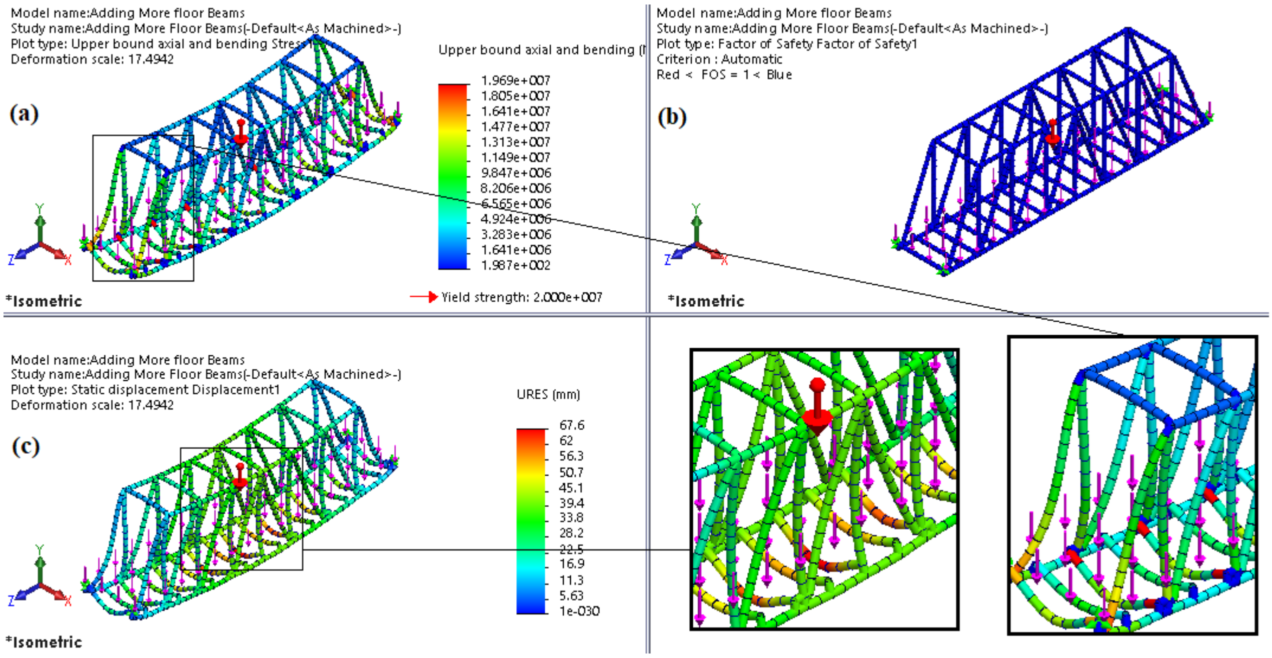


Figure 7: (a) Result of stress, (b) factor of safety, (c) displacement after adding the Howe truss Structure (Case-II).

Table 2: Summary of results.

Configuration	Initial Applied Force (N)	FOS	Safe Force Per Beam (N)	Force Item	Total force Applied (N)	Structure Weight (N)	Efficiency Score	Maximum Deflection (mm)
Simple Span	5000	1.69	8450	9	76050	3145.60	24.18	749.9
Adding Howe Truss	5000	10	50000	9	450000	10973.87	41.01	43.9
Adding more floor Beams	5000	10.22	51100	17	868700	12032.20	72.20	67.6
Adding Lateral Bracing	5000	13	65000	17	1105000	13203.31	83.69	63.08

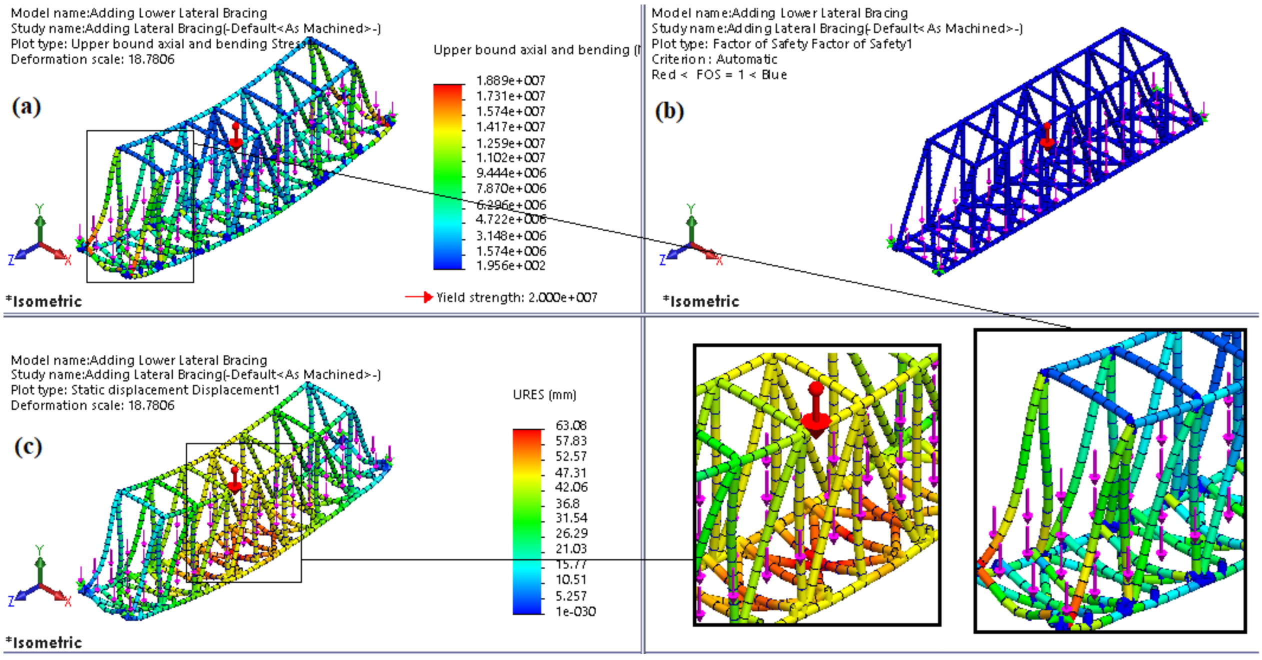


Model name:Adding More floor Beams
Study name:Adding More Floor Beams(-Default<As Machined>-)
Plot type: Upper bound axial and bending Stress
Deformation scale: 17.4942

Model name:Adding More floor Beams
Study name:Adding More Floor Beams(-Default<As Machined>-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Red < FOS = 1 < Blue

Model name:Adding More floor Beams
Study name:Adding More Floor Beams(-Default<As Machined>-)
Plot type: Static displacement Displacement1
Deformation scale: 17.4942

Figure 8: (a) Result of stress (b) factor of safety, (c) displacement after adding more floor beams (case-III).



Model name:Adding Lower Lateral Bracing
Study name:Adding Lateral Bracing(-Default<As Machined>-)
Plot type: Upper bound axial and bending Stress
Deformation scale: 18.7806

Model name:Adding Lower Lateral Bracing
Study name:Adding Lateral Bracing(-Default<As Machined>-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Red < FOS = 1 < Blue

Model name:Adding Lower Lateral Bracing
Study name:Adding Lateral Bracing(-Default<As Machined>-)
Plot type: Static displacement Displacement1
Deformation scale: 18.7806

Figure 9: (a) Result of stress, (b) factor of safety, (c) displacement after adding lower lateral bracing (case-IV).

tain the maximum stress below the wood's yield stress, which is $1.99 \times 10^7 \mathrm{N/m^2}$. The stepwise modification helps to enhance the efficiency score of the bridge. Modifying the simple bridge to the Howe bridge with added lateral bracing drastically increases the efficiency score to 83.69. It reduces the maximum deflection to 63.08 mm at the center of the structure. The results for all the cases are summarized in Table 2.

4. Conclusion

This paper studied the structural deformation of a bridge under maximum loading. The purpose was to find the optimized bridge that can withstand the maximum load bestowing to its capacity. Increasing the structures escalates the load-bearing capacity and improves efficiency. The overall cost of the system also increases due to the addition of new members. A simple span bridge made up of Balsa wood was modeled, and the basis for optimization is adding three different structural components to it. Linear static analysis was the primary approach for finding the FOS, maximum stress, efficiency score, and maximum displacement. The main findings are:

- The simple span bridge could withstand an 8450 N load per beam. It has a maximum displacement of 749.9 mm and an efficiency score of 24.18.
- The most optimized system among all was case-IV, which could withstand 65000 N per beam. The displacement of the system under maximum allowable loading was about 63.08 mm. The whole structure has a uniformly distributed stress and displacement. The efficiency score increased drastically to 83.69.

This study infers the stepwise iteration process helps to optimize the bridge performance. Under simple modification by adding the appropriate truss structure in the required position can improve the system recital. The added Howe truss structure and later bracing increased the efficiency score and reduced the displacement drastically. The iterative optimization technique is essential for making the structure more efficient and effective.

References

[1] Beer F P, Johnston E, Eisenberg E R, & Clausen W E, *Vector Mechanics for Engineers: Statics and Dynamics,* McGraw-Hill, New York, (2010), ISBN 978–0–07–352940–0.

[2] Bridge Design Project- Dassault Systèmes SolidWorks Corporation, https://www.solidworks.com/sites/default/files/2017-12/Bridge-Design-Project.pdf, December 2020

[3] Reddy P K & Nagaraju C, Structural optimization of different truss members using finite element analysis for minimum weight, *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), (*2019), 99-110.

[4] Petrova R V, *Introduction to Static Analysis Using SolidWorks Simulation*, CRC Press, Boca Raton, (2014), ISBN 978-1-4822-3619-4.

[5] Kurowski P M, *Engineering Analysis with SOLIDWORKS Simulation 2018, SDC Publication, Mission KS, (2018), ISBN 978-1-63057-153-5.*

[6] Beams- Dassault Systèmes SolidWorks Corporation, `http://help.solidworks.com/2017/english/solidworks/cworks/c_Beams.htm`, December 2020

[7] Urdea M, Static linear analysis for trusses structure for supporting pipes, in *IOP Conf. Ser. Material Science and Engineering*, 1, 399, China, 2018.