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Avoiding Bridge Failure: The Effect of Material and Bridge Structure type on Ultimate Bridge Strength

Daniel A. Amoshie [1], **Munashe D. Nyazenga** [2]
Engineering Department, Ashesi University

[1] Electrical Engineering; daniel.amoshie@ashesi.edu.gh
[2] Computer Engineering; munashe.nyazenga@ashesi.edu.gh

Abstract - Bridge failure can be catastrophic, hence the need to continuously improve bridge designs. But what material type or bridge structure type can be used to make the strongest bridge? The purpose of this research paper is to investigate how material type (wood, concrete, steel, etc.) and bridge structure type (beam, arch, and truss), in combination, affect bridge strength. In this research paper, a recommendation of the best material type and bridge structure type suitable for bridge construction will be made. A Static Stress Analysis Simulation was performed on several bridge designs of different materials and structures to determine the maximum von Mises stress for each, under normal bridge loading conditions. These bridges were first designed then simulated using Autodesk Inventor Software 2019 and based on the statistical results obtained from a Two-way Analysis of Variance ANOVA test at 95% significance level, the highest average maximum von Mises stress for bridges of structure type truss and bridges of material type steel suggest that under static stress analysis simulation conditions similar to ours, truss bridges and steel bridges are the strongest, hence are ideal for bridge construction. In this research study, we are interested in how the two factors – material type and bridge structure, in interaction, affect bridge strength.

Keywords- *Bridge strength, Bridge failure, von Mises stress, Static Stress Simulation analysis, Finite Element Analysis (FEA), Two-way Analysis of Variance (ANOVA), Tukey HSD (Honestly Significant Difference).*

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1. Introduction

A bridge collapse, like that of the I-35W Mississippi River Bridge shown in Figure 1 below, can be a major disaster. Bridges that cannot hold enough weight to fulfill their intended purpose can be a serious threat to the public [2].

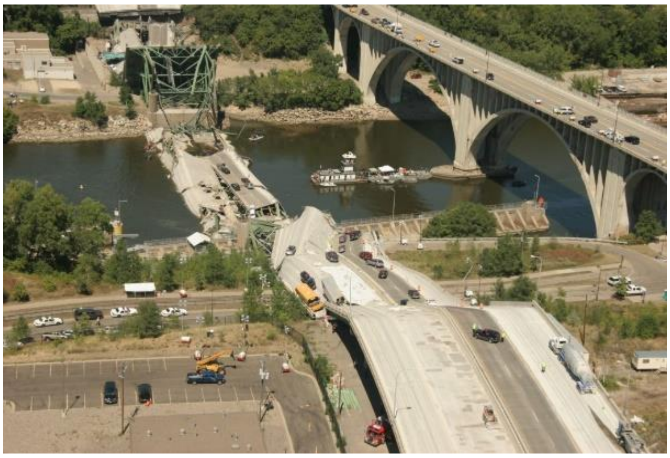

Figure 1: The I-35W Mississippi River Bridge, which catastrophically failed during the evening rush hour on August 1, 2007

The bridge catastrophically failed during the evening rush hour on August 1, 2007, collapsing into the river and riverbanks below. As a result, thirteen people were killed and over a hundred were injured [3]. The National Science Teaching Association (NSTA) later determined that a design flaw was the primary cause of the bridge's collapse [2].

Therefore, with the discussed problem in mind, this paper seeks to investigate how material type and bridge structure type, in combination, affect bridge strength with the aim of recommending to engineers the strongest material type or bridge structure type suitable for bridge construction under normal bridge loading conditions. Three main bridge structure types (beam, arch, and truss) were simulated using Autodesk Inventor software, while varying the material (wood, concrete, aluminum, steel, iron, and copper). The software uses pre-loaded scientific material information i.e., Yield Strength, ultimate Tensile Strength, Young's Modulus and Poisson's ratio to produce simulation results. All bridges will be put under fixed constraints, fixed moments, and a constant force of magnitude 5000N in the z-direction to determine the von Mises stress. The von Mises stress is a value used to determine if a given material will yield or fracture and would help us understand the ultimate bridge strength based on the two factors under study [4]. The higher the von Mises stress, the greater the bridge strength.

2. Materials and Methods

From the main research question, the purpose of the experiment was to determine how two independent variables (material type and bridge structure type), in combination, affect a dependent variable (maximum von Mises stress); hence in the experimental design it was foreseen that a factorial test would be undertaken. Checking and testing of certain assumptions determined at a later stage whether a non-parametric or parametric factorial test was ideal for the experimental data collected.

2.1 Materials

In this study, two similar laptops (Lenovo ThinkPad) with the same processor (Intel Core-i5), RAM

(7.77 GB usable) and operating system (Windows 10, 64-bit) were used. A software tool, Autodesk Inventor Software 2019, was used to design and perform a *Static Stress Simulation Analysis* on three main bridge structure designs while varying material. RStudio was used for data analysis and the plotting of graphs, while Microsoft Excel was used to record, tabulate, and plot graphs from data collected before and after analysis.

2.2 Methods

A. *Static Stress Simulation Analysis*

Experimental Protocol - To determine which material or bridge structure type would make the strongest bridge, three bridges with different structure type were designed as shown in Figure 2(a-c) and simulated (simulation results are as shown in Figure 2(d-f)), while varying the material, using Autodesk Inventor Software to determine the maximum von Mises stress.

These materials are wood, concrete, aluminum, steel, iron, and copper. The type of simulation study performed on the bridges is *Single Point Static Stress Analysis/Finite Element Analysis* which evaluates structural loading conditions using pre-loaded scientific material information i.e., Yield Strength, ultimate tensile strength, Young’s Modulus and Poisson’s ratio to help determine the best bridge design through the stress values [3]. All bridges will be put under fixed constraints, fixed moments, and constant force of magnitude 5000N in the z-direction to determine the von Mises stress.

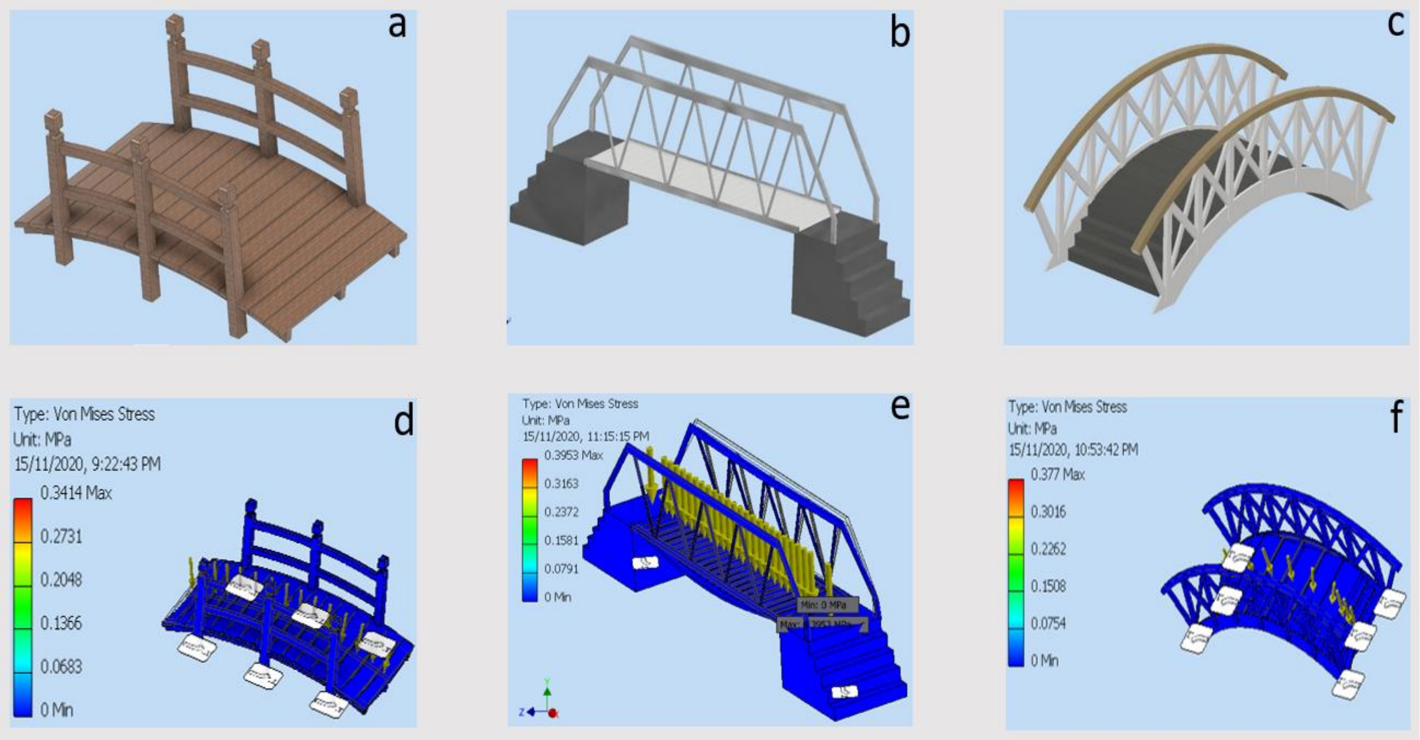

Figure 2: (a, b, c) show the three designed bridges (beam, truss, arch) before simulation, (d, e, f) shows the three bridge designs (beam, truss, arch) with results after simulation

Varying bridge material- The same simulation on each bridge structure type was performed on two similar laptops (Machine A & Machine B) as discussed previously, with three repetitions on each machine under the same conditions while varying material type.

Afterwards, statistical analysis had to be performed based on the results obtained from this simulation to investigate whether the type of material used and/or bridge structure type had an effect on maximum stress of the bridge. To answer the main research question from the results of the statistical analysis, a comparison of the maximum von Mises stress of each bridge structure type under different types of materials helped in determining the material type and/or bridge structure type that would make the strongest bridge.

B. *Statistical Analysis*

After collection of experimental data from the *Static Stress Simulation Analysis*, the next step was to determine the most ideal statistical analysis based on the data collected, hence, a normality test was performed to determine whether a non-parametric statistical analysis or parametric statistical analysis was to be performed.

Test for normality- To check whether maximum stress, as the dependent variable, fitted a normal distribution (bull curve), we used Shapiro-Wilk normality test, a significance level of 0.05, to test if the maximum von Mises stress values are a simple random sample from a normal distribution. In other words, we formulated a null hypothesis (H_o) that the maximum von mises stress of all bridge samples are normally distributed. The Shapiro-Wilk normality test results are shown in Table 1 below.

Table 1: Shapiro-wilk normality test

Data	*W-value*	*p-value*	*Norm. Distributed*
von Misses Stress	0.96062	0.2247	yes

With the W-value very high (W-value = 0.96062) and the p-value > 0.05 (p-value = 0.2247) we failed to reject the null hypothesis implying that the data is normally distributed. To further verify normality, a histogram was made out of this dependent variable to visualize the normality assumption of the distribution.

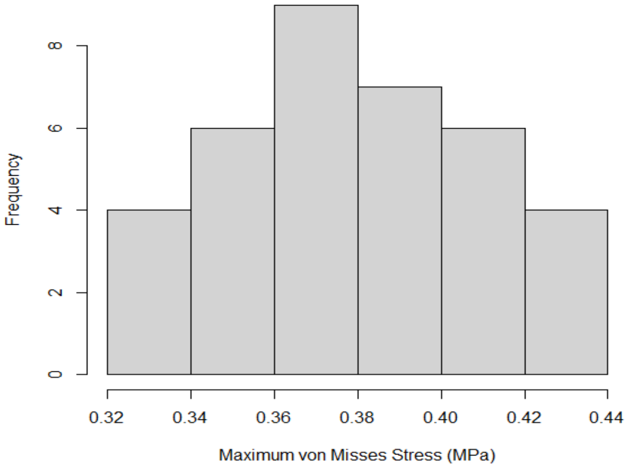

Figure 3: Histogram for maximum von Mises stress

The independent variable, '*Maximum von Mises stress*', followed a bell curve with most observations grouped towards the middle of the distribution and few on the tails, so a parametric statistical analysis was to be conducted.

***Two-way ANOVA test (with replication)*-** To investigate whether material and bridge structure type, in combination, affected maximum von Mises stress of the bridge a parametric test had to be performed as proven earlier. In our case, a statistical test that would help us analyze difference between the means of more than two groups was ideal. Since data had been collected on a quantitative dependent variable, maximum von Mises stress, at multiple levels of two categorical independent variables i.e., material type and bridge structure type, a two-way ANOVA could be used as the statistical test. This led to the formulation of two hypotheses (H_0 & H_1) that there is no difference in the average maximum von Mises stress for any bridge structure type and that there is no difference in the average maximum von Mises stress for any material type, respectively. Take note that, for the purpose of this research we are not interested in how the two factors in interaction have an effect on maximum stress hence bridge strength. As a result of that we said, $\mu_1 = \mu_2 = \mu_3$ for material type and $\mu_1 = \mu_2 = \mu_3$ for bridge structure type. The alternative hypotheses (H_a & H_b) were that there is a difference in the average maximum von Mises stress for any bridge structure type and that there is a difference in the average maximum von Mises stress for any material type, respectively, implying that $\mu_1 \neq \mu_2 \neq \mu_3$ for bridge structure type and $\mu_1 \neq \mu_2 \neq \mu_3$ for material type. In case differences existed, and further analysis of the data obtained was required, a Tukey HSD post-hoc test would be performed to compare the various groups and determine whether statistical significance exist between the individual groups.

3. Results and Discussion

A. *Static Stress Simulation Analysis*

***Data Collection*-** The raw data obtained from the Static Stress Simulation Analysis performed using Autodesk Invertor Software 2019 are shown in Table 2 with each value in each cell representing the average of three repetitions of each simulation on a single machine for a corresponding bridge structure type and material type.

Table 2: Table showing raw data obtained from Static Stress Simulation Analysis

			Materials					
			Aluminium	**Wood**	**Copper**	**Concrete**	**Iron**	**Steel**
Bridge Type	**Beam**	**Machine A**	0.322500	0.32394	0.34142	0.34890	0.35669	0.36315
		Machine B	0.320500	0.32383	0.34168	0.34856	0.35673	0.36312
	Arch	**Machine A**	0.367323	0.37206	0.37411	0.37905	0.38524	0.38696
		Machine B	0.367143	0.37239	0.37300	0.38008	0.38535	0.38696
	Truss	**Machine A**	0.395299	0.41560	0.41621	0.41682	0.42669	0.43961
		Machine B	0.395341	0.41579	0.41620	0.41685	0.42673	0.43977

Though further analysis through graphs had to be done to verify if differences actually exist in the maximum von Mises stress of the simulations replicated on the two different laptops (Machine A & Machine B) – to ensure that data obtained is consistent, from the table it is quite clear that the results obtained from the two computers is consistent. This is most probably because the simulations were replicated under the same conditions on each machine. But to obtain more meaningful explanations on the two main factors (material type and bridge structure type) under investigation, further statistical analysis had to be performed since conclusions cannot be drawn from this table alone. This prompted the use of the Two-way ANOVA, discussed in detail in the next section, to further observe whether significant statistical differences exist in the two factors.

B. *Statistical Analysis*

***Two-way ANOVA test (with replication)*-** The Two-way ANOVA summary is shown in Table 3. It can be observed that both material type and bridge structure type explain a significant amount of variance in average maximum von Mises stress (p-values < 0.05).

Table 3: Two-way ANOVA summary - A *statistically significant difference in average maximum von-misses stress by both bridge structure type (F=92706, p < 0.05), by*

material type (F=5231.8, p<0.05) and by interaction (F=417.5)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Bridge Type	0.03457	2	0.01728	92706.3	7.65277E-37	3.55456
Material Type	0.00488	5	0.00098	5231.82	8.47E-28	2.77285
Interaction	0.00078	10	7.8E-05	417.5	3.48587E-19	2.4117
Within	3.4E-06	18	1.9E-07			
Total	0.04023	35				

We found a statistically significant difference in average maximum von-misses stress by both bridge structure type (F=92706, p < 0.05), by material type (F=5231.8, p<0.05) and by interaction (F=417.5), though the interaction is not further analyzed in this study. Hence, we reject the null hypotheses, H_0 & H_1, discussed in the *Materials and Methods* section and accept the alternative hypotheses, H_a & H_b, which state that there is a difference in the average maximum von Mises stress for any bridge structure type and that there is a difference in the average maximum von Mises stress for any material type, respectively. This shows that there were noticeable differences in both factors. But we had no idea where these differences came from i.e., the specific groups in the factors. Therefore, to further identify where the differences came from, a Tukey's HSD post-hoc test had to be performed to find out which individual groups differed from each other.

Tukey's HSD post-hoc test- Since the two-way ANOVA tests showed that differences exist between the means of both the bridge structure type and material type, a post-hoc test was required to further identify these differences. Hence, we carried out a Tukey HSD test shown in Table 4 & 5 below.

Table 4: Tukey's Multiple comparisons of means - *A significance level of 0.05 showed that significant differences exist between all bridge structure type groups.*

Group 1	*Group 2*	*diff*	*lower*	*upper*	*p adj*	*sig*
Beam	Arch	-0.03489	0.034436	0.035336	1.4E-14	yes
Truss	Arch	0.040938	0.040488	0.041388	1.35E-14	yes
Truss	Beam	0.075823	0.075373	0.076273	1.2E-14	yes

Table 5: Tukey's multiple comparisons of means - *A significance level of 0.05 showed that significant differences exist between all material type groups.*

Group 1	*Group 2*	*diff*	*lower*	*upper*	*p adj*	*sig*
Concrete	Aluminium	0.020359	0.019567	0.021151	1.87E-14	yes
Copper	Aluminium	0.015751	0.014958	0.016543	1.87E-14	yes
Iron	Aluminium	0.028221	0.027429	0.029014	1.83E-14	yes
Steel	Aluminium	0.035242	0.03445	0.036035	1.8E-14	yes
Wood	Aluminium	0.009253	0.00846	0.010045	1.87E-14	yes
Copper	Concrete	-0.00461	0.003816	0.005401	5.3E-12	yes
Iron	Concrete	0.007862	0.00707	0.008655	1.93E-14	yes
Steel	Concrete	0.014883	0.014091	0.015676	1.87E-14	yes
Wood	Concrete	-0.01111	0.010314	0.011899	1.87E-14	yes
Iron	Copper	0.012471	0.011678	0.013263	1.87E-14	yes
Steel	Copper	0.019492	0.018699	0.020284	1.87E-14	yes
Wood	Copper	-0.0065	0.005706	0.007291	3.22E-14	yes
Steel	Iron	0.007021	0.006229	0.007813	2.28E-14	yes
Wood	Iron	-0.01897	0.018176	0.019761	1.87E-14	yes
Wood	Steel	-0.02599	0.025197	0.026782	1.85E-14	yes

In Table 4, a Tukey's HSD test at a significance level of 0.05 showed that significant differences exist between all bridge structure type groups. Also, in Table 5, a Tukey's HSD test at a significance level of 0.05 showed that significant differences exist between material type groups. The post-hoc test revealed from the significant pairwise differences in bridge structure type that truss bridge had the highest mean maximum von Mises stress than all the other bridge structure type i.e., beam and arch. Additionally, the post-hoc test revealed from the significant pairwise differences in material type that steel bridge had the higher mean maximum von Mises stress than all the other bridge material types i.e., wood, concrete, aluminum, iron, and copper.

Group-wise comparison- From the two-way ANOVA test, we know that both bridge structure type and material type are significant variables, hence, we need to show which of the combinations of bridge structure type and material type that are statistically different from one another. A groupwise comparison bar graph, shown in Figure 4, to find out which group means are statistically different, showed the highest maximum von Mises stress for truss bridges and steel bridges. This suggests that bridges of structure type truss and bridges of material type steel would make the strongest bridge under experimental conditions similar to ours. The small standard error bars further confirm that that data obtained from the replication performed on both laptop computers is consistent.

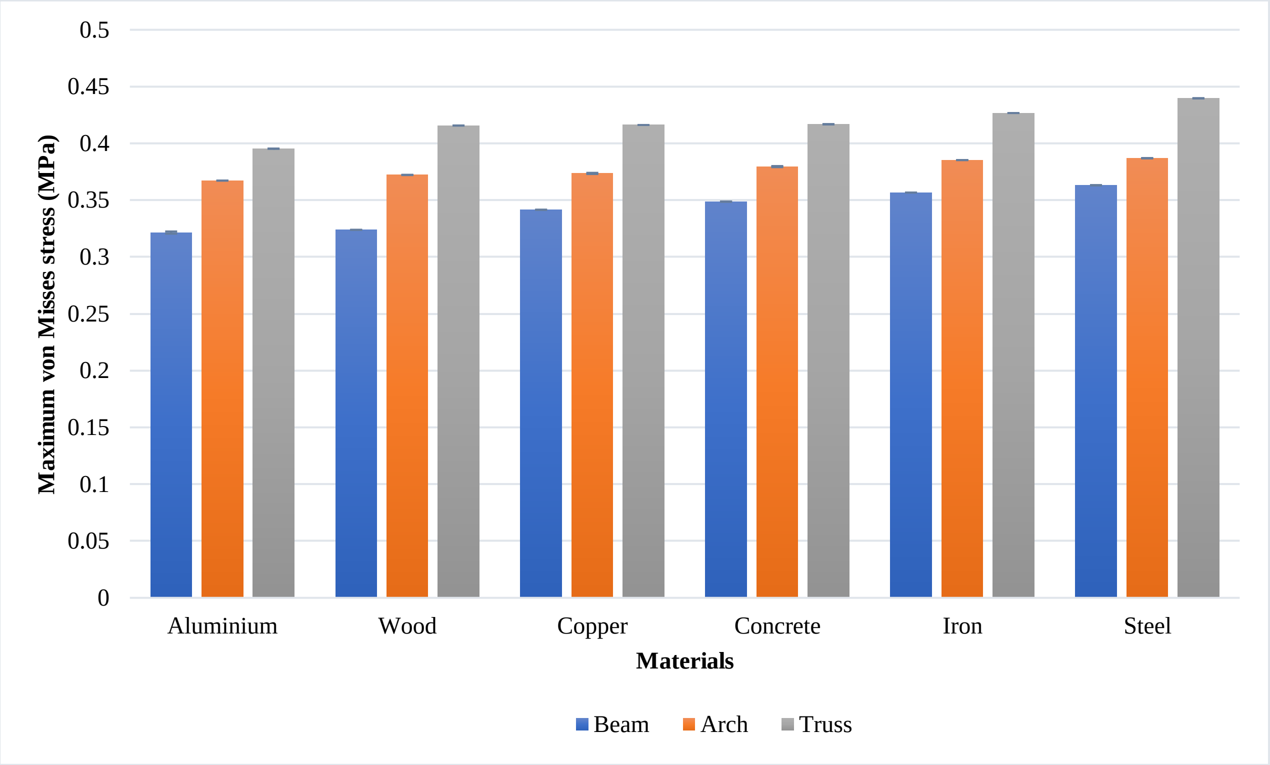

Figure 4: A group-wise comparison bar-chart. Each bar shows the average maximum von Mises stress on a bridge made of the corresponding material. Error bars indicate standard error.

4. Conclusion

Both material type and bridge structure type simulated in combination affect the maximum von-misses stress hence the strength of the bridge. The highest von mises stress of a truss bridge and steel bridge suggests that under static stress simulation conditions like ours, this bridge structure and material types, respectively, would make the strongest bridges. Truss outperformed other bridge structures as shown by its greater and higher mean difference in the Tukey's HSD post-hoc test. Steel outperformed other materials, as shown by its high mean in the group-wise comparison. Also, arch bridges are stronger than beam bridges. Iron and concrete are also preferable material choices for bridge design. Though it was beyond the scope of our study, the existence of an interaction effect between bridge structure type and material type shows that material type affects the strength of a specific bridge structure type, though at a force of magnitude greater than the one we used in our simulation, this might not necessarily be the case. A more concrete recommendation can be drawn if the interaction between the two factors is considered. That is an improvement that can be made in a future research study.

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