Final Design Report

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Section A6

Engineering Mechanics

ENG EK 301

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Introduction

During this project, our group's goal was to design and create a single, planar, simple truss. Even though the truss model had to comply with several restrictions, such as not extending below the line connecting the two end joints, and cost less than $305, we were able to implement what we believe is a successful, final design. We are confident that our final truss model will support a live load of 32oz (2lb).

For this design, we used our knowledge of mechanics along with our programming abilities to efficiently analyze several truss designs. Our approach for this final model was mainly focused on a load-to-cost ratio. This means that our current truss is a model that can resist the greatest load while maintaining a coherent cost. However, in order for our group to successfully create the modeled truss, we needed to be very precise with our measurements of the acrylic members, as the tolerances for these were very narrow. This is why we were very meticulous during our truss manufacturing session when executing the cuts of the acrylic strips; despite the one-hour time limit allotted, our group met outside the designated time in order to properly attach the strips at the joints.

Finally, we performed a mock trial ourselves before the testing session to analyze the parts of our truss that could potentially fail. Based on this, we reinforced some joints with more tape, as these showed a potential failure of the truss.

Procedure

We applied several theories to the same preliminary design: the joint and section methods, zero force members by using two-force and three-force member theory, and each member's buckling strength by applying the findings from our class's buckling lab.

The initial condition that we used for the truss still follows the requirements of the triangular inner part, simple truss and the relationship between number of joints and members ($M = 2J-3$). Also, the location of the hanging weight is between 8-12 inches from the pin support.

For the design process, the adjustment has been made. From the preliminary design, we found that the number of the joint doesn't determine the strength of the design but the distance of between the hanging joint and the support does; therefore, we change strategy from 4 joints at base to 3 joints at base to move the hanging joint as far from the support as possible to balance the weight. We will also switch the 2 joints that hold one member to compare the difference. Then, we randomize the parameter by starting from 7 joints, find the critical member and add 1 more joint to support that member.

After we found the most efficient in term of load-to-cost ratio, while still able to hold the significant weight, we randomized the coordinate of each joint in the matrix, check if the length of each member eligible and find the relationship between the change of each joint position to discover the design that can hang the heaviest weight with most significant cost.

Lastly, we will take the uncertainty of the critical member in an account for calculating the uncertainty of the design by this equation: $\frac{U_F}{F} = \frac{U_{Wmax}}{W\,max}$, F represents force in critical member. This equation is formed by the fact that internal forces for each member directly depend on the applied weight load; hence, the percentage of uncertainty of critical member will affect the max load in the same percentage.

Analysis

For the analysis, our group still conducted the observation with the same concept. Each member will have the internal force as the following above respectively including whether the member is in tension or compression by assuming that all members are in tension; then, generating force equilibrium equations both x-axis and y-axis by joint-method of the truss. If the member is in tension, that member doesn't need to be analyzed in buckling analysis since the critical point for tension is significantly more than that for compression.

Based on Buckling Lab fit, the critical point of each length corresponds to this equation F = 3654.533*L^(-2.119) with 1.685 ox as uncertainty. We will calculate the uncertainty after we find the design that can afford the heaviest weight.

As we conducted our analysis on the number of joint and overall draft design, we found that the 8-joint design is the most sustainable design in both efficiency and fabrication as the following figure 1. The internal member between each diagonal can't be all in parallel because it will not support the weight load at the second joint.

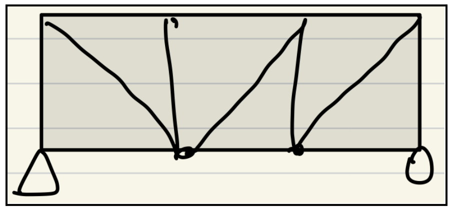

Figure 1: original design before parameter randomization

Next step, we randomized parameter for each joint's coordinate and we run it through algorithm that will check both max load and all the member lengths. We started by randomized the length between 4 joints on bases and we found that the most effective one are consisted of 11.2 inches, 8.8 inches and 13 inches. Then, we randomized each joint coordinate to see the relationship between change of each joint position and the weight it can afford until we found the maximum point as our final design in figure 2 in the result section of this report.

For an uncertainty, as $\frac{U_F}{F} = \frac{U_{Wmax}}{W\,max}$, we calculated the uncertainty of the weight maximum and considered if the lowest max load, caused by uncertainty, still meets the requirement (in the range of practical usage) and if it affects the effectiveness of the design based on the percentage of error.

Results

Diagram for final design

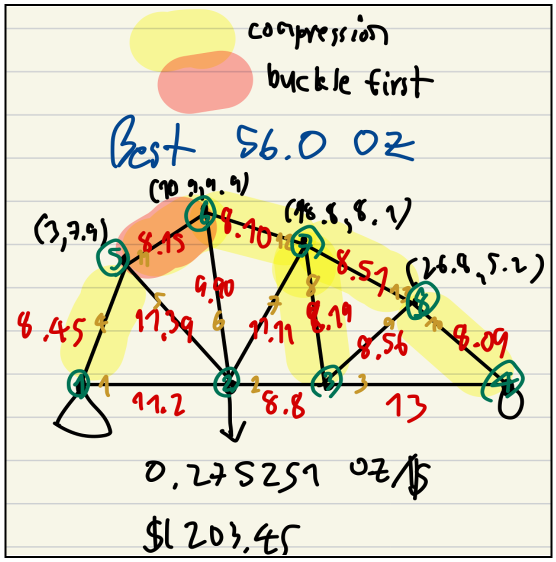

Figure 2: Diagram for final design with compression and critical member highlighted

Model Verification for final design (code MATLAB in appendix)

```
EK301, Section A6, Group 10, Final Design: Pree S., Santiago H., 12/05/2023.
Load: 56.00 oz
 Member forces in oz
m1: 14.048 (T)
m2: 33.319 (T)
m3: 22.661 (T)
m4: 39.572 (C)
m5: 38.165 (T)
m6: 20.126 (T)
m7: 12.895 (T)
m8: 7.401 (C)
m9: 12.052 (T)
m10: 29.576 (C)
m11: 42.843 (C)
m12: 43.223 (C)
m13: 34.287 (C)
Reaction forces in oz:
Sx1: 0.000
Sy1: 36.994
Sy2: 19.006
Uncertainty in oz: 2.202
The critical member: 11
Cost of truss: $203.45
Theoretical max load/cost ratio in oz/$: 0.275251
```

Figure 3: MATLAB algorithm's result for final design analysis

Result

Member Number	Member Length (inches)	Tension/Compression	Buckling Strength (oz) [for compression]	Force Magnitude in design (oz)
1	11.2	T	21.854	14.048

2	8.8	T	36.431	33.319
3	13	T	15.936	22.661
4	8.45	C	39.699 $\pm$1.685	39.572
5	11.39	T	21.103	38.165
6	9.90	T	28.357	20.126
7	11.11	T	22.243	12.895
8	8.19	C	42.439 $\pm$1.685	7.401
9	8.56	T	38.626	12.052
10	8.09	C	43.518 $\pm$1.685	29.576
11	8.15	C	42.872 $\pm$1.685	42.843
12	8.10	C	43.398 $\pm$1.685	43.223
13	8.51	C	39.118 $\pm$1.685	34.287

Table 1: shows length, buckling strength and the internal force for each member when hanging the max load (56.00 oz) at the second joint

Summary

From the analysis and MATLAB algorithm we designed, we got the calculation that the critical Member for this design is member 11 due to the fact that at 56.1 oz it will exceed its limitation although member 12 almost reaches the critical point as well. From an uncertainty equation, $\frac{U_F}{F} = \frac{U_{Wmax}}{W\,max}$, we will get $U_{Wmax} = \frac{U_F}{F} * W\,max = \frac{1.685}{42.872} * 56$ = 2.20 oz

Therefore, we can conclude that our design can afford the max load at 56.0 oz with uncertainty of 2.20 oz with the truss cost of 10*(8 joints) + 1*(123.45 inches) = $203.45 which makes the load-to-cost ratio equals to 0.275 oz/$. Our truss meets the requirements in every aspect even when the uncertainty is taken into account.

Discussion & Conclusion

Our design rationale and optimization strategies were the base for our final truss design. Initially, we applied various theories such as joint and section methods, zero-force members, and buckling strength principles; the truss's preliminary design complied with initial requirements like the truss’s triangular inner part, simplicity, and joint/member relationship.

As we designed more potential models and tested more variables, we figured that the structure’s strength was not solely determined by the number of joints, but also by the distance between the support and the joint where the load will be applied. Consequently, we made some adjustments, and transitioned from four joints at the base to three joints, strategically placing the joint where the load will be applied farther from the support. We also experimented with the arrangement of the joints, randomizing several parameters to find the most efficient load-to-cost ratio while ensuring that the structure could support the weight that will be applied (32 oz). Our analysis highlighted that an eight-joint design was the most sustainable in terms of both efficiency and strength. Parameter randomization further refined the design, and we meticulously considered uncertainties in the critical member's force for a proper evaluation.

Lastly, we are aware that the knowledge acquired from this project is very valuable and will definitely be of use for upcoming engineering challenges, and despite the fact that our approach was effective, we acknowledge the fact that there is always room for improvement. Alternative design methods may enhance both efficiency and precision and should always be taken into consideration.

Appendix (Hartford Civic Center Arena Roof Collapse Case Study & MATLAB code reference)

<u>Agenda:</u>

Date | Time	Location/Medium	Topic/Plan
12/06/23 | 16:00	Photonics Building	Studying Case
12/07/23 | 18:00	Photonics Building	Discussion and Minutes
12/08/23 | 13:30	Video Call (Zoom)	Conclusion and Report

Discussion:

In addition to truss design, we performed some literature review on case study discussion from Hartford Civic Center Arena Roof Collapse by Rachel Martin on December, 6th - 8th 2023 during afternoon time (1 pm - 6 pm) at common area on the first floor of Photonics Center or on Zoom. We, Pree Simphliphan and Santiago Henao, are the participants of this meeting. During this two-person discussion, Santiago was the discussion leader, Pree was the minutes taker, and both contributed the critical points to our discussion which were helpful for our truss design process. The following are the details of our discussion.

Important Points:

- (Pree) The discrepancies between the calculation design and the actual design: from the case, the engineer chooses to ignore the significant increase in weight load when attaching the roof to the arena. It’s the undeniable fact that there is always a discrepancies between theoretical and pragmatic conditions but as an engineer, we should take a worst case scenario caused by those discrepancies as a minimum requirement to achieve while considering cost and efficiency as well.
- (Santiago) Another important point is what they mention in the part of technical concerns. The article says that the engineers for this project depended on computer analysis to assess the safety of their design. However, they did not account for the fact that the computers did not consider the susceptibility to buckling of the roof. This is completely unacceptable for a design. If the project depends on computer analysis, one needs to make sure that the computer program accounts for all of the potential failures in the project.

- (Pree) The unexpected factors from practical usage such as snowfall: in this case study, the arena was located in Hartford, Connecticut, the New England area where there is occasionally heavy snowfall during the winter. Therefore, the snow can accumulate on the roof and cause more weight. Moreover, it can experience windshields providing more risk in damage. In my opinion, in case that happens, the infrastructure should also include the evacuation plan for the public safety to prevent life loss.
- (Santiago) The final point that I want to highlight is the fact that even though “deflections apparent during construction were brought to the engineer's attention multiple times. The engineer, confident in his design and the computer analysis which confirmed it, ignored these warnings and did not take the time to recheck its work” (Martin). I think an ethical, well prepared engineer would pay attention to these concerns. Even if some tests and analysis are successful, if there is even the smallest doubt or failure, one should recheck and make sure everything runs properly (assuring people’s health and wellbeing). As mentioned in the Code of Ethics for Engineers, “Engineers shall acknowledge their errors and shall not distort or alter the facts” (NSPE).

<u>Appropriate safety factors to be used on our truss:</u>

Taking into account the ethical standards in the Code of Ethics for Engineers, some appropriate safety factors for our truss project are the following:

1. Factor for Public Welfare:

We believe that maintaining a safety factor in which our load can resist 1.5 times the mentioned weight is appropriate for the safety and health of our public. So, in our case, if our truss can resist 2 lbs, we should advise the public that is resists 1.33 lbs, as 1.33 * 1.5 = 2. This way, we are compliant with the requirement of holding paramount the “safety, health, and welfare of the public” (NSPE), since a safety factor of 1.5 ensures an additional margin of safety in case unforeseen external factors impact the truss's stability.

2. Factor for Material Variability:

We also consider material tolerance and variability should be taken into account. For this aspect of engineering manufacturing we believe that checking every piece of acrylic and tape used in our truss should undergo some tests, confirming that the material being used is not defective. This safety factor addresses the variability in materials; by carefully considering potential variations in material, the truss can be designed to resist material strength deviations or defects, providing reliability to our model.

3. Factor for Constructability and Implementation:

Finally we think that another safety factor to implement for our truss is one that accounts for the facility of construction and implementation of the project. Constructability and implementation considerations are essential for our truss as engineers should design having practicality and potential challenges in construction in mind. Besides those factors, “Engineers shall acknowledge their errors and shall not distort or alter the facts” (NSPE). By adding a factor for constructability and implementation, the design process becomes practical and reduces the occurrence of errors during construction. Moreover, this factor aligns with the commitment to honesty and integrity in engineering practices, mentioned in the Code of Ethics for Engineers.

Conclusions:

This case study provided us with useful information in different truss designs and concepts that would be helpful in our pioneer truss design. There are several factors to be taken in an account of while designing truss: the type of the joints and connections, the discrepancies between our MATLAB algorithm prediction and the actual design, the safety factor that we need to include to ensure the public safety such as the extra weight load afforded from the minimum requirement by 1.5 times, or even the defense of unexpected situation that could happen during the usage such as mechanism against snowfall or thunderstorm, the evacuation plan during those scenario ,etc.

Our final design of the truss will take all of these factors into consideration between our design process; we will ensure to follow the ethics of engineers to fabricate the useful product and ensure the safety of all users.

MATLAB Code reference:

```
C = [1 0 0 1 0 0 0 0 0 0 0 0 0;
     1 1 0 0 1 1 1 0 0 0 0 0 0;
     0 1 1 0 0 0 0 1 1 0 0 0 0;
     0 0 1 0 0 0 0 0 0 1 0 0 0;
     0 0 0 1 1 0 0 0 0 0 1 0 0;
     0 0 0 0 0 1 0 0 0 0 1 1 0;
     0 0 0 0 0 0 1 1 0 0 0 1 1;
     0 0 0 0 0 0 0 0 1 1 0 0 1;];
Sx =[1 0 0;
     0 0 0;
     0 0 0;
     0 0 0;
     0 0 0;
     0 0 0;
     0 0 0;
     0 0 0;];
Sy =[0 1 0;
     0 0 0;
     0 0 0;
     0 0 1;
     0 0 0;
     0 0 0;
     0 0 0;
     0 0 0;];
X = [0,11.2,20,33,3,10.9,18.8,26.8];
Y = [0,0,0,0,7.9,9.9,8.1,5.2];
L = [0;0;0;0;0;0;0;0;0;1;0;0;0;0;0;0;];
```

Figure 4: .mat file for final design's MATLAB input

```
%receive input

our_struct = open('TrussDesign3_PreeSantiagoH_A6.mat');
C = our_struct.C;
L = our_struct.L;
Sx = our_struct.Sx;
Sy = our_struct.Sy;
X = our_struct.X;
Y = our_struct.Y;

[num_joint,num_member] = size(C);

%identify the max buckling for esch member
uncertainty = 1.685; %in oz
max_load_each = [];
length_member = [];
for i = 1:num_member
    % (a,i)
    x=[];
    y=[];
    for j = 1:num_joint
        if C(j,i) == 1
            x=[x;X(j)];
            y=[y;Y(j)];
        end
    end
    lengthofmem =((x(1)-x(2))^2+(y(1)-y(2))^2)^0.5;

    length_member = [length_member,lengthofmem];
    max_load_each = [max_load_each;3654.533*(lengthofmem)^(-2.119)];%based on class buckling lab data
end

%find the joint that weight applied
for i = 1:length(L)
    if L(i) ~= 0
        weight_joint = i;
        break
    end
end

%Creating Matrix A
A = zeros(2*num_joint,num_member+3);
A(1:num_joint,num_member+1:num_member+3) = Sx;
A(num_joint+1:2*num_joint,num_member+1:num_member+3) = Sy;
```

```
%substitue force equilibrium component in the matrix
for i = 1:num_joint
    for j = 1:num_member
        if C(i,j) == 1
            for m = 1:num_joint
                if (C(m,j)==1) && (m ~= i)
                    A(i,j)=(X(m)-X(i))/length_member(j);
                    A(num_joint+i,j)=(Y(m)-Y(i))/length_member(j);
                end
            end
        end
    end
end

%analysis to find the max weight by starting with 32 oz
%keep it in the while loop to increase weight by 0.1 oz until it buckles
%in while loop include for loop to check member1-21 to see if it would buckle
%by check if it's compression and exceed the maximum force the member can
%handle or not if it's break, at the end, we have to go down 1 step to get
%the actual max load
T = A^(-1)*L;
state = true;
while state
    L(weight_joint)=L(weight_joint)+0.1;
    T = A^(-1)*L;
    for i = 1:num_member
        if (max_load_each(i)<abs(T(i))) && (T(i)<0)
            state = false;
            critical_member = i;
            break
        end
    end
end
L(weight_joint) = L(weight_joint)-0.1;
T = A^(-1)*L;

%calculate uncertainty of final weight
uncertainty_weight = uncertainty*L(weight_joint)/abs(T(critical_member));
```

```
%display output and identify the critical member
fprintf('EK301, Section A6, Group 10, Final Design: Pree S., Santiago H., 12/05/2023.\n');
fprintf('Load: %.2f oz\n Member forces in oz\n',L(weight_joint));
for i = 1:num_member
    if T(i)>=0
        fprintf('m%d: %.3f (T)\n',i,T(i));
    else
        fprintf('m%d: %.3f (C)\n',i,-T(i));
    end
end
fprintf('Reaction forces in oz:\n');
fprintf('Sx1: %.3f\n',T(num_member+1));
fprintf('Sy1: %.3f\n',T(num_member+2));
fprintf('Sy2: %.3f\n',T(num_member+3));
cost = 10*num_joint+sum(length_member);
fprintf('Uncertainty in oz: %.3f\n',uncertainty_weight);
fprintf('The critical member: %d\n',critical_member);
if max_load_each(critical_member)<abs(T(critical_member))
    fprintf('The model can handle less than 32 oz\n');
end
fprintf('Cost of truss: $%.2f\n',cost);
fprintf('Theoretical max load/cost ratio in oz/$: %.6f\n',L(weight_joint)/cost);
```

Figure 5-7: MATLAB algorithm for analysis the max load and internal force for the final design