Boston University

EK301-A1

Professor Farny

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Final Design Lab Report

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I. Introduction

For our final design of the optimized acrylic truss structure, we prioritized maximizing the load capacity over the load-to-cost ratio. This approach was taken to ensure that the truss structure could handle significantly more than the required 32 oz nominal load, providing a substantial safety factor, much like real-world engineering designs where reliability and durability are critical considerations. By aiming for a load capacity that is higher than the minimum requirement, we aimed to ensure that the truss would not only meet the specifications but also offer enhanced performance and robustness. Building off the preliminary design, we revised our truss design to improve the load bearing capacity as well as fixing the roller supports to be 1 inch above the pin support.

Although our primary focus was on maximizing load capacity, we carefully managed uncertainty to remain within acceptable limits. While some compromises were inevitable, we ensured that each truss member's dimensions were as precise as possible based on our model. To facilitate accurate assembly, we rounded member lengths to the nearest hundredth of an inch, paying close attention to detail. This precision helped minimize discrepancies between the model and the physical structure, allowing our final truss to meet its load-bearing objectives while staying true to the design.

While we accounted for uncertainties related to the construction process, we did not factor in potential variations in material properties, focusing instead on theoretical performance. This decision allowed us to test our ability to build a strong, reliable structure using the skills and knowledge we gained throughout the project.

II. Procedure

Since submitting the Preliminary Design Report, we made a series of refinements to improve the strength and accuracy of our truss model. The most critical modification was adjusting the roller support to be 1 inch higher than the pin support, aligning with the updated project specifications. This change altered the geometry of the truss and affected force distribution, so we recalculated all member lengths and internal angles to ensure accurate load analysis. Additionally, we slightly adjusted the joint locations to maintain symmetry and ensure efficient load paths throughout the truss.

Our analysis was conducted using a MATLAB-based program developed earlier in the project. The program calculates member forces for a given load, identifies members in compression, and evaluates their buckling strength using the fit equation:

$$P_{crit} = 2390 \cdot L^{-1.811} \tag{1}$$

Using this tool, we increased the applied load until the first compression member reached its buckling threshold. This updated analysis resulted in a revised maximum predicted load of 65 oz, up from the previous 50 oz, reflecting the improved design. To account for variability in member strength, we included a ±1.35 oz uncertainty derived from the class-wide buckling fit. While we did not include material inconsistencies beyond this, we used this uncertainty range to predict failure bounds and evaluate the reliability of our design.

For construction, we gathered materials including large acrylic strips, a scoring knife, and duct tape. We measured and cut each member, then assembled the truss according to the updated design. It was crucial to ensure that no joint was stressed before the load was applied to prevent internal deformation.

Each joint was assembled using fiber-reinforced binding tape, following the recommended taping method. We first applied tape to the inside faces of each joint with fibers oriented across the gap. After assembling the entire truss, we applied additional tape to the outer faces of each joint. Finally, we wrapped the ends of the tape around the joint, creating a strong, compression-resistant connection.

III. Analysis

The most notable change was incorporating the vertical offset of the roller support, which was updated to be 1 inch higher than the pin support in accordance with the final project specifications. This altered the truss geometry and affected internal force distributions, particularly in members connected to the support joints. As a result, we recalculated all member lengths, directions, and corresponding force contributions using updated joint coordinates.

We retained the same two-dimensional, pin-jointed truss assumptions from our preliminary analysis and continued to use the governing buckling formula (Eqn. 1). This equation allowed us to predict the critical buckling strength of each member and identify the one most likely to fail first under an increasing load. Our MATLAB-based solver calculated axial forces for all members under a gradually increasing applied load. We iterated until the compressive force in one member exceeded its critical buckling strength, which defined our predicted failure load of 65 oz.

To account for uncertainty, we used the class-wide fit uncertainty of ±1.35 oz provided for the buckling strength model. While we did not re-fit the buckling curve ourselves, we incorporated this uncertainty into a three-scenario analysis:

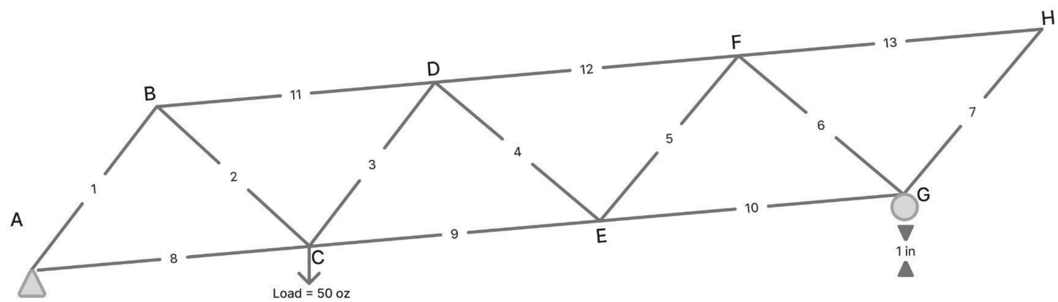
- Nominal Case: Members fail at exactly their predicted buckling loads.
- Strong Case: Members are 1.35 oz stronger than predicted.
- Weak Case: Members are 1.35 oz weaker than predicted.

This approach provided a range of possible failure loads and allowed us to estimate a confidence interval for our maximum load prediction. This will be especially useful when comparing our predicted failure load to our actual test result and understanding whether the design performed within acceptable bounds. The structure of our analysis remained consistent with the preliminary design, but through refined geometry and updated constraints, we achieved improved accuracy and load capacity. These changes directly contributed to the decision to raise our predicted maximum load from 50 oz to 65 oz.

In addition to theoretical variability, we recognized practical sources of uncertainty from construction. The use of tape for joints and the limitations of hand-cutting acrylic introduced discrepancies between our model and physical truss. Despite careful measurement (rounding lengths to the nearest hundredth of an inch), we acknowledged that imperfections in cutting and joint assembly reduced the precision of our build. These factors contributed to real-world variability not fully captured by our theoretical model.

Furthermore, we did not explicitly account for cost uncertainty in our analysis. However, to mitigate this, we aimed to achieve a low load-to-cost ratio and a predicted load significantly above the 32 oz requirement, ensuring our design was robust even under less-than-ideal conditions. We used the lower-bound failure load from our uncertainty analysis as a conservative design benchmark, helping to reduce the risk of underbuilding.

IV. Results



From the Acrylic Data Fit provided, the fit error bar is a constant that results in U_fit = ± 1.35 oz (95%). Uncertainty was calculated based on this value, as a 5% of the buckling strength for each member. Using the code in Appendix A.1, we get the result in Table 1.

Table 1: Internal member forces, lengths, and buckling strengths for final design under the max 65 oz load.

Member Number	**Member Length (inches)**	**Tension/ Compression**	**Buckling Strength and Uncertainty (± oz)**	**Magnitude of the Force at Max Truss load (oz)**
1	8.771	Compression	46,83 ± 1.35	47.320
2	10.191	Compression	35.69 ± 1.35	27.356
3	9.882	Tension	–	0
4	9.559	Compression	40.07 ± 1.35	0
5	9.559	Tension	–	0
6	9.559	Compression	40.07 ± 1.35	0
7	9.261	Tension	–	0

8	9.764	Tension	–	17.502
9	10.913	Tension	–	0
10	10.339	Tension	–	0
11	12.004	Compression	26.53 ± 1.35	0
12	10.339	Tension	–	0
13	9.764	Tension	–	0

Maximum load: 65 oz ± 1.35 oz
Member to buckle first: Member 1
Reaction forces in Oz:

- Sx1 (Pin at A): 0.000 oz
- Sy1 (Pin at A): 43.403 oz
- Sy2 (Roller at G): 21.597 oz

Cost of the truss: $209.91
Theoretical Max Load/ Cost Ratio in Oz/$: 0.310 oz/$

```
EK301, Section A1, Group6: Jessica Q. Jinyu F. Riasat A., 4/22/2025
-----------------------------------------------------------
Load: 32 oz
Member forces in oz:
m1: -47.320 (C)
m2: -27.356 (C)
m3: 0.000 (T)
m4: -0.000 (C)
m5: 0.000 (T)
m6: -0.000 (C)
m7: 0.000 (T)
m8: 17.502 (T)
m9: 0.000 (T)
m10: 0.000 (T)
m11: -0.000 (C)
m12: 0.000 (T)
m13: 0.000 (T)

Reaction forces in oz:
Sx1: 0.000
Sy1: 43.403
Sy2: 21.597

-----------------------------------------------------------
The member to buckle first is member 1
Length of that member: 8.77 in
Predicted buckling strength: 46.83 oz ± 1.35 oz
The maximum load that the physical truss could support is 65 oz ± 1.35 oz

-----------------------------------------------------------
Cost of the truss: $209.91
Theoretical max load/cost ratio in oz/$: 0.310
-----------------------------------------------------------
```

```
Member Lengths (in inches):
Member  1: 8.771 in
Member  2: 10.191 in
Member  3: 9.882 in
Member  4: 9.559 in
Member  5: 9.559 in
Member  6: 9.559 in
Member  7: 9.261 in
Member  8: 9.764 in
Member  9: 10.913 in
Member 10: 10.339 in
Member 11: 12.004 in
Member 12: 10.339 in
Member 13: 9.764 in

Buckling Strengths for Compression Members:
-------------------------------------------------------------
| Member | Length (in) | Force (oz) | Buckling Strength ± Unc. |
-------------------------------------------------------------
|   m1   |     8.771   |   -47.320  |      46.83 ± 1.35    |
|   m2   |    10.191   |   -27.356  |      35.69 ± 1.35    |
|   m4   |     9.559   |    -0.000  |      40.07 ± 1.35    |
|   m6   |     9.559   |    -0.000  |      40.07 ± 1.35    |
|   m11  |    12.004   |    -0.000  |      26.53 ± 1.35    |
-------------------------------------------------------------
```

Figure 2: Final Design MATLAB Program Output

V. Discussion and Conclusion

Our decisions in design were constrained and informed mostly by the project's metrics. The cost was something we really had to take into account as it took a couple iterations to optimize, and reducing the weight while still supporting the load informed our idea to adjust the angles of members in the truss rather than add more members. We prioritized structural robustness over efficiency, aiming to exceed the minimum required 32 oz load by a substantial margin. This decision reflects real-world engineering practices, where overbuilding is often preferred to ensure safety and performance under unpredictable conditions.

Our final design was informed by the performance and limitations of our previous 7-joint Warren truss, which successfully supported a maximum theoretical load of 50 oz ± 1.35 oz at a cost of $177.53. This initial design performed well, with a load-to-cost ratio of 0.282 oz/$, and it helped us identify areas for improvement in both structure and modeling. One key takeaway from that design was the importance of buckling in shorter, central members. In particular, Member 8 was the first to reach its critical buckling strength at 41.18 oz under a force of 40.53 oz. While the overall structure was strong and cost-efficient, we realized that the buckling risk was concentrated in a single member and that small geometric changes could lead to early failure.

In response, we transitioned to an 8-joint Warren truss, which gave us greater control over joint spacing and allowed us to meet all project specifications, including placing the roller support 1 inch above the pin support. This change also enabled a more even force distribution across the structure and reduced the likelihood of a single member dictating failure. As a result, our final design supports a predicted 65 oz ± 1.35 oz and has a cost of $209.91, yielding a load-to-cost ratio of 0.310 oz/$. Though slightly less efficient in terms of material use, the design is more robust and safer under realistic conditions.

We also observed that our final design contains a greater number of zero-force members. While these members don't carry load at the nominal load case, they serve an important role in adding structural redundancy and improving stability. The zero-force members presence reflects our shift in strategy, from a purely cost-efficient structure to one that prioritizes strength and fault tolerance. In real-world applications, this kind of conservative design is valuable for maintaining integrity under unforeseen conditions or uneven loading.

From a learning standpoint, the most insightful aspect of the project was seeing how theoretical assumptions play out in real-world construction. Factors like tape joint strength, imperfect acrylic cuts, and the inability to make perfectly aligned connections all introduced uncertainty that wasn't reflected in the model. We accounted for this by building in extra strength and relying on lower-bound estimates of failure loads. Additionally, coding the analysis ourselves provided a deeper understanding of how forces are distributed and how sensitive buckling is to length and load.

If we were to redesign the truss, we would prioritize optimizing the load-to-cost ratio rather than solely maximizing load capacity. Additionally, we believe the tape is the biggest source of uncertainty in this project. To improve stability, we would replace the tape with a more reliable method, such as using rigid joints to slot the members together or a plastic cement to bond the acrylic components.

VI. Appendix

A.1 — MATLAB Code Developed to Analyze Final Design Truss

Connection matrix C for joint

```
jointq = "How many joints? ";
numj = input(jointq);
numm = (2*numj) - 3;

C = zeros(numj, numm);

% Loop through each join and each member
for j = 1:numj;
    for m = 1:numm
        prompt = sprintf("Is member %d connected to joint %d? (1 for yes, 0 for no): ", m, j);
        C(j,m) = input(prompt);
    end
end
```

Connection matrix for support force Sx Sy

```
Sx1 = zeros(numj, 1);
Sy1 = zeros(numj, 1);
Sy2 = zeros(numj, 1);

Sx = zeros(numj, 3);
Sy = zeros(numj,3);

connection_matrixS_joint = zeros(numj,3);

% Loop through each joint and each force


for j = 1:numj
    support = sprintf("Is the x reaction force on joint %d? (1 for yes, 0 for no): ", j);
    Sx1 (j,1) = input(support);
end

for j = 1:numj
    support = sprintf("Is the first Y reaction force on joint %d? (1 for yes, 0 for no): ", j);
    Sy1 (j,1) = input(support);
end

for j = 1:numj
    support = sprintf("Is the second Y reaction force on joint %d? (1 for yes, 0 for no): ", j);
    Sy2 (j,1) = input(support);
end


Sx = [Sx1, zeros(numj,1), zeros(numj,1)];
Sy = [zeros(numj,1), Sy1, Sy2];
```

Joint Location

```
X_flat = zeros(numj,1);
Y_flat = zeros(numj,1);

for j = 1:numj
    x = input(sprintf("Flat X location (x-axis) of joint %d from Origin: ", j));
    X_flat(j) = x;
    y = input(sprintf("Flat Y location (y-axis) of joint %d from Origin: ", j));
    Y_flat(j) = y;
end

% Rotate points counter-clockwise by theta
theta = atan(1 / 31);  % Tilt angle in radians

% Temporary rotated coordinates
X_rot = X_flat * cos(theta) - Y_flat * sin(theta);
Y_rot = X_flat * sin(theta) + Y_flat * cos(theta);

% Get current elevation of Joint 7 (index 7)
dy = Y_rot(7) - Y_rot(1);  % should be around 0.8705
scale_factor = 1 / dy;     % scale so elevation becomes exactly 1 inch

% Apply scaling to rotated coordinates
X = X_rot * scale_factor;
Y = Y_rot * scale_factor;
```

Load

```
L = zeros(2*numj,1);

for j = 1:numj
    loadh = input(sprintf("horizontal load at joint %d",j));
    loadv = input(sprintf("vertical load at joint %d",j));
    L(j,1) = loadh;
    L(numj+j,1) = loadv;

end
```

Member Lengths

```
R = zeros(numm, 1);
for i = 1:numm
    joints = zeros(1,2);
    for j = 1:numj
        if C(j,i) == 1
            if joints(1) == 0
                joints(1) = j;
            else
                joints(2) = j;
            end
        end
    end
    if joints(2) == 0
        error("Member %d only connected to one joint — check connection matrix C!", i);
    end
    X_joint1 = X(joints(1));
    Y_joint1 = Y(joints(1));
    X_joint2 = X(joints(2));
    Y_joint2 = Y(joints(2));
    R(i) = sqrt((X_joint2 - X_joint1)^2 + (Y_joint2 - Y_joint1)^2);
end
```

Initialize matrix A

```
A = zeros(2 * numj, numm);
for m = 1:numm
    connected_joints = find(C(:, m) == 1);
    joint1 = connected_joints(1);
    joint2 = connected_joints(2);
    dx = X(joint2) - X(joint1);
    dy = Y(joint2) - Y(joint1);
    length = sqrt(dx^2 + dy^2);
    R(m) = length;
    A(joint1, m) = dx / length;
    A(joint2, m) = -dx / length;
    A(joint1 + numj, m) = dy / length;
    A(joint2 + numj, m) = -dy / length;
end

A = [A,S];

% Display matrix A
disp('Matrix A:');
disp(A);
```

Solve for Forces

```
T = A \ L;
```

Buckling calculations

```
max_buckling = zeros(numm, 1);
for i = 1:numm
    max_buckling(i) = 2390 * R(i)^(-1.811);
end

% Theoretical max load calculation
[maxload, ind] = max(L);
Q = 1;
mass = 0;
breakload = 0;

while Q == 1
    mass = mass + 1;
    L(ind) = mass;
    T_crit = A \ L;
    for mm = 1:numm
        if abs(T_crit(mm)) > max_buckling(mm)
            Q = 0;
            breakload = mm;
        else
            max_th_load = max(L);
        end
    end
end
```

Uncertainty (based on class average)

```
U_fit = 1.35;  % oz
buckling_strength = max_buckling(breakload);
buckling_length = R(breakload);
uncertainty_max_load = U_fit;
```

Failure analysis

```
load = max(L);
for i = 1:numm
    rr(i) = load / T_crit(i);
    P_load(i) = (2390) * R(i)^(-1.811);
    W_fail(i) = -P_load(i) / rr(i);
end
Wfail = min(W_fail);
```

Cost and efficiency

```
totallength = sum(R);
C1 = numj * 10;
C2 = totallength * 1;
Cost = C1 + C2;
```

Print Results

```
fprintf("\nEK301, Section A1, Group6: Jessica Q. Jinyu F. Riasat A., 3/22/2025 \n");
fprintf("------------------------------------------------------------\n");
fprintf("Load: %d oz\n", load);
fprintf("Member forces in oz:\n");
for i = 1:numm
    if T_crit(i) > 0
        tc = 'T';
    else
        tc = 'C';
    end
    fprintf("m%d: %.3f (%c)\n", i, T_crit(i), tc);
end

fprintf("\nReaction forces in oz:\n");
fprintf("Sx1: %.3f\n", T_crit(numm+1));
fprintf("Sy1: %.3f\n", T_crit(numm+2));
fprintf("Sy2: %.3f\n", T_crit(numm+3));

fprintf("\n------------------------------------------------------------\n");
fprintf("The member to buckle first is member %d\n", breakload);
fprintf("Length of that member: %.2f in\n", buckling_length);
fprintf("Predicted buckling strength: %.2f oz ± %.2f oz\n", buckling_strength, U_fit);
fprintf("The maximum load that the physical truss could support is %d oz ± %.2f oz\n", max_th_load, uncertainty_max_load);

fprintf("\n------------------------------------------------------------\n");
fprintf("Cost of the truss: $%.2f\n", Cost);
fprintf("Theoretical max load/cost ratio in oz/$: %.3f\n", abs(max_th_load / Cost));
fprintf("------------------------------------------------------------\n");
```

```
% Member lengths in inches

fprintf('\nMember Lengths (in inches):\n');
for i = 1:numm
    fprintf("Member %2d: %.3f in\n", i, R(i));
end


% Buckling Strengths for Compression Members

U_fit = 1.35; % from acrylic fit data
fprintf('\nBuckling Strengths for Compression Members:\n');
fprintf('-------------------------------------------------------------\n');
fprintf('| Member | Length (in) | Force (oz) | Buckling Strength ± Unc. |\n');
fprintf('-------------------------------------------------------------\n');

for i = 1:numm
    force = T_crit(i);
    if force < 0  % Only for compression members
        length = R(i);
        buckling = 2390 * length^(-1.811);
        fprintf('|   m%-2d  |   %7.3f  |  %8.3f  |   %8.2f ± %.2f    |\n', ...
            i, length, force, buckling, U_fit);
    end
end
fprintf('-------------------------------------------------------------\n');
```

A.2 — Minutes of Case Study Discussion

Minutes of Case Study Discussion

Participants: Jessica (chair), Riasat (recorder), Jinyu

Date: February 28, 2025

Time: 6:00 pm

Location: Photonics 1st Floor

Planned Agenda:

1. Review the Hartford Civic Center Collapse Case
2. Discuss implications for engineering practice and computer modeling
3. Discuss appropriate safety factors for our truss
4. Determine takeaways relevant to our EK301 project

Discussion:

1. Case study overview
    - The Hartford Civic Center Arena Collapse occurred on January 18, 1978, when the roof of the Hartford Coliseum in Connecticut completely collapsed just hours after hosting a hockey game. The collapse happened due to a combination of poor design choices, underestimated loads, and a lack of accountability throughout the design and construction process.
    - Engineers used an innovative space frame roof design to save costs, but it lacked sufficient bracing and structural redundancy. Deflections in the frame were observed even during construction, but no corrective action was taken. Computer models used to verify the design failed to consider key failure modes such as buckling and torsional instability, and the structure ultimately could not support the combined dead load and a relatively small live load of snow.
    - Though there were no fatalities, the event is considered a landmark case in structural engineering failure, highlighting the dangers of overreliance on technology, poor communication, fragmented responsibility, and the absence of independent peer review.
2. Key engineering & ethical issues discussed
    - Design & structural failures:

- Jessica**:** The design incorporated a space frame structure with unconventional details that reduced buckling resistance. Specifically, diagonal and horizontal members did not intersect at common nodes, and some braces were omitted entirely.
- Riasat**:** The top compression members were significantly overstressed by over 800% in some areas, which led to immediate long-term instability.
- Jinyu**:** Structural code violations were prevalent, including improper slenderness ratios and bolt hole dimensions. The misplacement of braces and use of substandard steel in some areas further compromised structural integrity.

- Over reliance on computer modeling:
  - Jessica**:** The design team depended heavily on early computer simulations and ignored physical warning signs when actual deflection exceeded predictions. There was a disconnect between theory and observed behavior.
  - Riasat**:** The program used did not factor in torsional buckling, which Loomis and Loomis later determined was the likely failure mode. This shows how critical it is to know the limitations of your software tools.
  - Jinyu**:** The engineers took computer results at face value instead of validating them with conservative design or physical checks. This "black box" trust in simulations without questioning their boundaries is deeply problematic.
- Accountability & inspection oversight:
  - Jessica**:** Responsibility was fragmented. The construction manager refused to hire a structural inspector, despite the architect's recommendation, leaving no qualified professional to evaluate design or site conditions during construction. Multiple warnings during construction were ignored. An ethical engineer should investigate unexpected results, not dismiss them.
  - Riasat**:** The refusal to hire a structural inspector left the project with no qualified oversight, a dangerous procedural failure. Excessive deflections were noted multiple times and even reported by a concerned citizen, yet

the engineers dismissed the issues. This shows a clear ethical lapse and a failure to respond to real-world feedback.

- Jinyu**:** The fragmentation of responsibility led to no single person being accountable for the structural integrity. The lack of a peer review, which was typically required for large structures in Hartford, also allowed critical flaws to go unnoticed. Peer review could have flagged the severe design weaknesses early on.

3. Safety Factors in Engineering Design
   - Jessica**:** Buildings with high occupancy should always include a higher safety factor due to risk to human life. This case shows the need to design for worst-case scenarios, especially in public spaces. Safety factors must not be minimized for cost-cutting reasons.
   - Riasat**:** Our group agreed that a safety factor of at least 3.0 would be appropriate if our truss were used in a real-world scenario.
   - Jinyu**:** Variability in materials and construction requires conservative design practices, especially when new techniques are involved. Buckling, fatigue, and material imperfections are hard to model perfectly. The safest designs use redundancy and overdesign to ensure no single point of failure brings down the structure.
4. Conclusion
   - The Hartford Civic Center collapse teaches that engineering decisions must be validated beyond computer models, especially when public safety is at stake.
   - Unexpected behavior in construction (e.g., excessive deflections) should be treated as critical feedback, not dismissed.
   - Our group propose a safety factor of 3.0 for our truss if it were to be used in a real-world setting with potential human occupancy or risk. Even in controlled environments, materials like acrylic can have unpredictable properties due to manufacturing inconsistencies, micro-cracks, or flaws introduced during hand-cutting and taping. A safety factor of 3.0 helps ensure the structure remains safe even if some components underperform or deviate from theoretical values.
   - Future engineers are ethically bound to prioritize human life. The Hartford Civic Center collapse showed the catastrophic consequences of underestimating loads and neglecting real-world feedback. Overbuilding with a safety factor of 3.0

creates redundancy and ensures that no single point of failure will compromise the entire structure, especially in public or load-critical scenarios.

- Ethical engineering includes planning for uncertainty, prioritizing public welfare, and maintaining accountability across all project phases.
- Clear roles, independent reviews, and conservative assumptions must be embedded into every high-risk structural project.