# MAE 371: Final Project Report

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## I. Problem Description

Hail damage is a problem for aircraft that could lead to high expenses for repair and dangerous conditions during flight. Pilots and flight organizations need to know that they can rely on their equipment to deliver passengers from one point to another without worrying about hail. Thus, it is pertinent that a strong but lightweight protective solution is incorporated. For our testing purposes, we wanted to model the worst-case scenario, hail striking in between the stringers, where the webbers have the least support. By designing our structure to withstand the most possible damage, we can ensure that our design will be safe under most other impact conditions.

To simulate the worst-case impact, we are limited to a max layer thickness of ⅛ of an inch in the 4-by-4 inch impact section. We are allowed multiple layers but need an air gap between them in order to withhold the thickness parameter. Our only other constraints for this problem are weight and a light-passing test. We are competing to make the lightest structure that can pass the test. The light test will consist of assessing the damages of the structures by holding it up to a light, if light passes through then that indicates significant damage to the structure and it will fail the test.

## II. Design of Panel

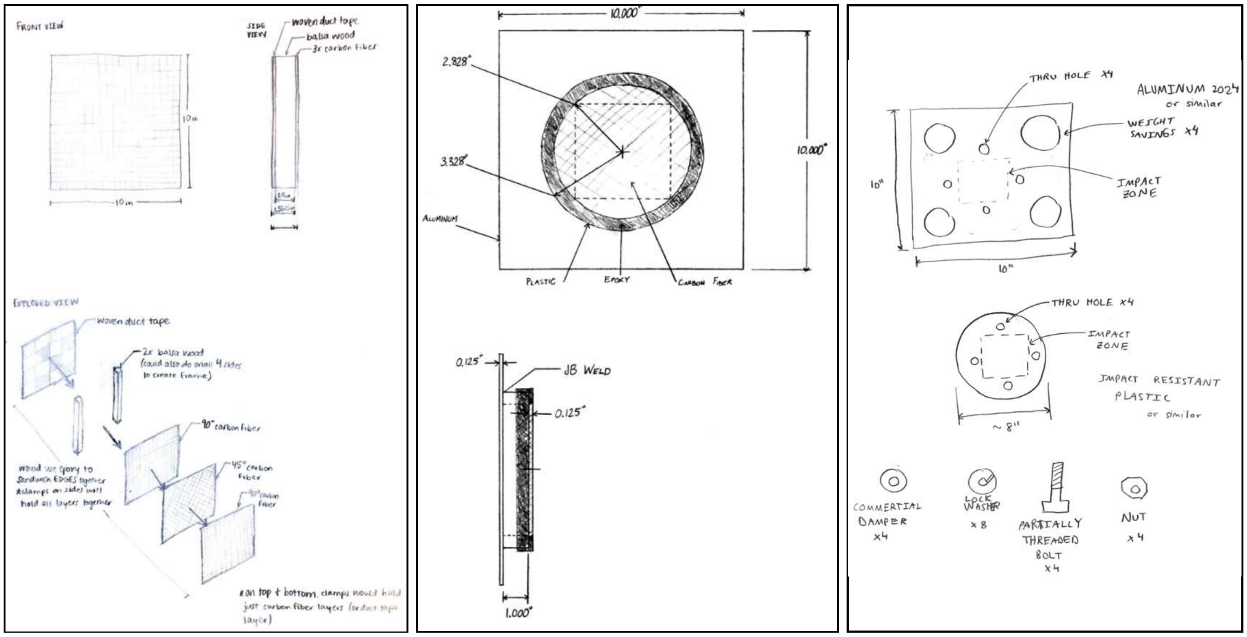


Figure 1: Three Initial Design Ideas

Prior to more in depth and specific analysis and design decisions, the three initial design ideas shown in Figure 1 were generated. This provided a basis for the following design considerations.

### A. Muti-layer Structure

The initial design decision revolved around how many layers of any given material would be required to stop the ice ball. Based on initial FEA analysis with a single aluminum plate and general intuition, it was determined that more than one layer would be required. It was determined that more than two layers would not be required for our structure. A backplate could provide stiffness and rigidity to the structure while a front layer absorbed the majority of the impact energy.

### B. Material Selection

Our front layer was designed with the purpose of absorbing and distributing most of the impact energy. In order to do this, we needed a flexible material that could deform without breaking. The obvious answer here would be to use some sort of composite fabric. Out of our available resources we could choose between carbon fiber or kevlar. After some material analysis, it was determined that kevlar would perform best in absorbing impacts, so it was the selected material for our front layer. We were able to use some spare kevlar from the BLAST lab, and put enough layers of kevlar to reach our maximum layer thickness of ⅛ inches,

The second layer of our structure was designed as both a means of rigidly holding together our first layer and acting as a last resort should our first layer of kevlar fail. This material would have to be rigid. After visiting our local metal shop, The Metal Supermarket, we made the decision to use 6061 Aluminum as our backing plate because it was a scrap metal that was available to us, it was rigid, and it was lightweight. For these reasons, it was our best option, it was light enough to keep us on the lighter side relative to steel, and it was strong enough to serve its purpose as a backing plate and safety.

Another material was needed to offset the kevlar from the backing plate. For the same reasons listed above, a 6” outer diameter 6063 aluminum pipe section was chosen.

### C. Spacer Design

In order to physically construct a structure comprised of two layers, a spacer design had to be selected. The final selection was a 6” outer diameter aluminum pipe with a ⅛” thickness. This met both the thickness and clear impact section requirements while avoiding stress concentrations in the corner that would occur with a square/rectangular design. The height of the spacer was calculated based on the failure elongation of the Kevlar. Making the height ½” made it so that the Kevlar would not fail before deforming enough to come into contact with the backplate. This contact region between the backplate and the Kevlar provided a significant increase in effective thickness.

### D. Part Connections

Numerous different connection and fastening methods such as rivets, bolts/nuts, and epoxy were considered. It was eventually determined that JB weld, a strong metal to metal bonder, would work well for securing the spacer to the backplate since significant bending moments or shear forces were not expected along the bonding area. Epoxy and a hose clamp were selected as retention for the Kevlar. The epoxy would bond the Kevlar together securely while the hose clamp would keep everything tight to the spacer.

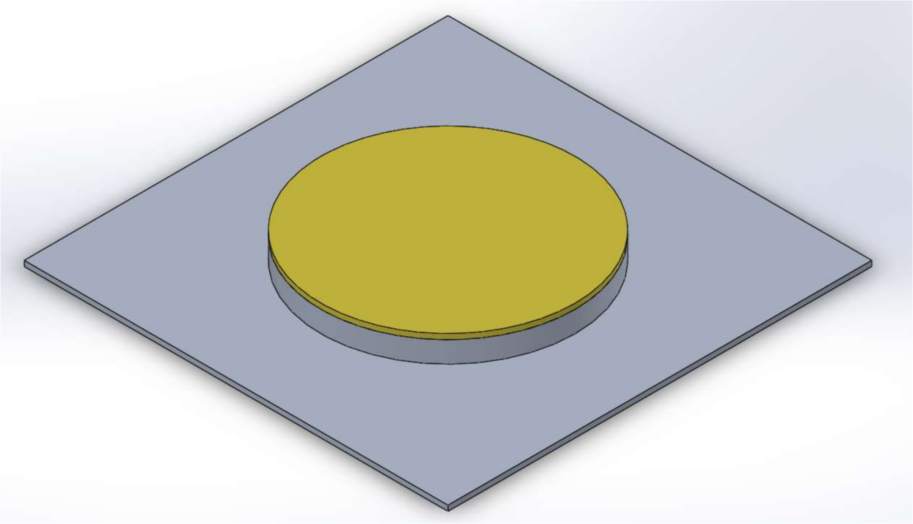


Figure 2: Solidworks model of simplified structure design

## III. Analysis

### A. Hand Calculations

Prior to choosing a final design and constructing a prototype of the structure, our team put together hand calculations to determine the kinetic energy of a golf ball-sized ice ball impacting a structure at ~300mph as well as the mass required to produce equivalent energy on the structure during preliminary testing. Given an ice ball of 1.68 inches, or 0.04267m, in diameter and assuming that the ice ball is perfectly spherical, the volume of the sphere was calculated as shown below.

$$V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left(\frac{0.04267m}{2}\right)^3 = 4.0679 * 10^{-5} m^3$$

Given the density of ice is 0.92 g/cm^3 and the volume of the ice ball, the mass of the ice ball can be calculated.

$$m_{ice} = \rho_{ice} * V = (4.0679 * 10^{-5} m^3) * 920(kg/m^3) = 0.0374243597\ kg$$

Assuming an impact velocity of 300 mph, or approximately 135 m/s, the kinetic energy of the ice ball upon impact was calculated as shown below.

$$KE_{ice} = \frac{1}{2} m_{ice} v^2 = \frac{1}{2}(0.0374243597 kg) * (135\ m/s)^2 = 341.021 J$$

While our group could not replicate an exact testing situation to test our prototype, we calculated the mass required of an object to create equivalent energy upon impact with the testing section of our prototype. As shown below, if an object were to be dropped straight down onto the testing section of the prototype from 1 meter high, the object would need to be 34.7625 kg.

$$KE_{ice} = 341.021 J = m_{object} g h = m_{object} * (9.81\ m/s^2) * 1m$$

$$m_{object} = 34.7625\ kg$$

To further characterize the damage a golf ball-sized ice ball would make to our prototype, the following method, detailed in a Plate Theory study [5], was used. These formulas, outlined below, provided a basis of which to calculate the stiffness of each "plate" within our structure, the max deflection of the plate, the applied force to the plate, and the stress at the center of the plate.

Step #1: Plate stiffness: where E = modulus of elasticity, h = thickness of the plate, and $\nu$ = Poisson's ratio.

$$D = \frac{Eh^3}{12(1-\nu)}$$

Step #2: Max Deflection: where a = plate radius, F = applied force, and D = plate stiffness

$$W_{max} = \frac{-F}{16\pi D} * (a^2)$$

To be able to easily calculate the applied force on the plate, the max deflection was viewed as the distance between the two sheets. For example, the layers of Kevlar, all treated as one collective plate, were assumed to reach max deflection when impacting the aluminum sheet on the opposite side of the spacer. As a result, the max deflection, $W_{max}$, was viewed as 0.5" for future calculations. While the speed, mass, and geometry of the ice ball vary the applied force on the structure, and in turn, the deflection of the Kevlar plate, assuming the worst case of maximum deflection built in a comfortable factor of safety for the design. With the $W_{max}$ assumption made, the applied force, F, could then be solved for by rearranging the $W_{max}$ formula (step #3). Using the calculated applied force, the uniform load, q, was solved for:

Step #4: Solve for uniform load: where F = applied load (point load), and a = radius of the plate

$$q = \frac{4F}{\pi a^2}$$

Finally, the stress at the center of the plate, $\sigma_{center}$, could be solved for using:

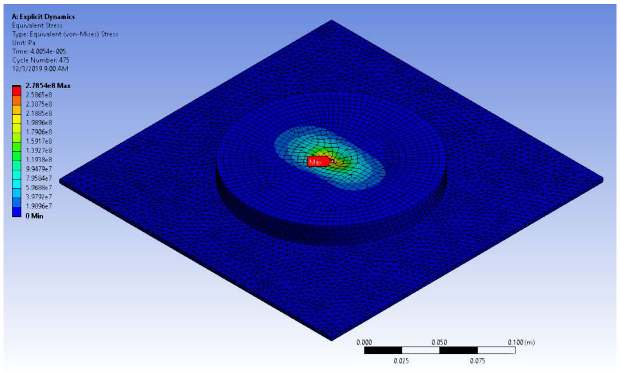
$$\sigma_{center} = \frac{3qWa^2(1+\nu)}{4h^3}$$

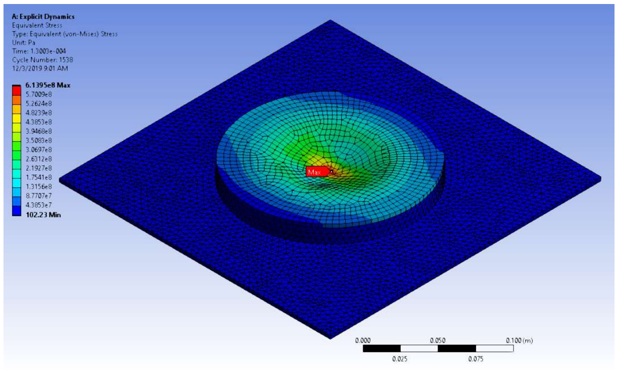
Completing this process for our Kevlar "plate" confirmed our design decision to utilize a back plate of aluminum as a safety measure for test day. Additionally, the calculation method showed an applied force of 22545N into the plate. If the Kevlar "plate" were to be treated as a plate with a spring beneath it, rearranging the F = ks formula in terms of deformation, the applied force F could be calculated by dividing the input energy ($KE_{ice}$) by the max deflection of the plate. This method produces an applied force of 26850N into the plate, ultimately validating the Plate Theory method for our testing purposes.

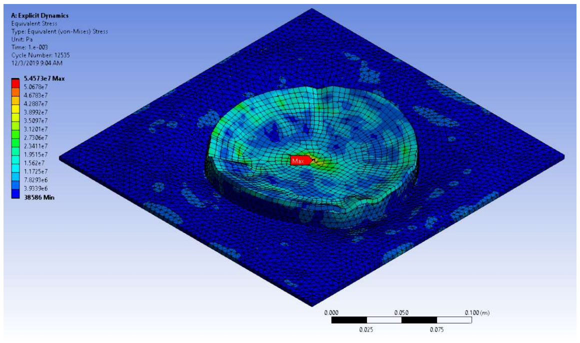
## B. FEA Explicit Dynamics Analysis

Explicit Dynamics FEA was completed in ANSYS in order to better understand the expected projectile impact and roughly evaluate the performance of various design decisions. The impact analysis was set up with the outside frame of the structure fixed and the iceball moving directly perpendicular towards the center of the structure at 135 m/s (~300 mph). The evaluated time period of 0.002 seconds was broken down into 150 steps, which included the iceball's full impact. Shoemaker *et al* [2] provided helpful material properties for kevlar and Nimmo [3] described the material properties of ice. The composite ballistic impact analysis completed by Soydan *et al* [4] was heavily referenced for the present analysis.

The FEA model included a simplified version of our true design. The kevlar was modeled without the mounting system and the spacer ring/backplate were treated as a single body. These simplifications reduce the complexity of the joints in the model, which reduces computation requirements, while maintaining relevance to the real life structure. Further simplifications in the model included treating the ice ball as a solid non-deformable body. This is not true to real life, where the iceball explodes and dissipates energy. Accordingly, the calculated stress and strain is a large overprediction of true interactions, which builds a comfortable factor of safety into the calculations and design.







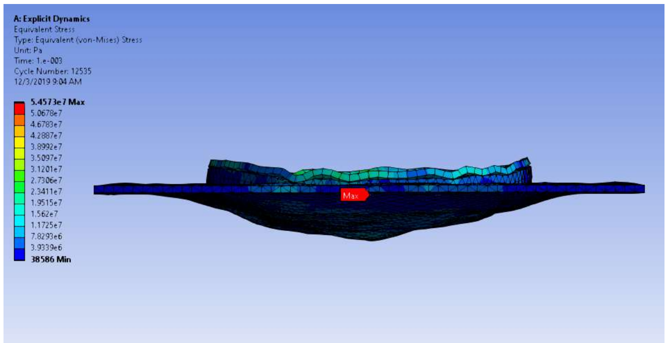


Figure 3. Von Mises Equivalent Stress of impact at 3 major timesteps

The graphical results of the FEA analysis are summarized by the various instantaneous Von Mises Equivalent Stress states shown in Figure 3. Key observations from the graphical results include the significant deformation of the kevlar which creates an effective increase in structure thickness where the kevlar and aluminum backplate interact. All of the stress and strain are evenly distributed which suggests that there are no concerning stress concentrations or design imbalances in the design. A relatively small amount of the stress and strain was seen to transfer from the Kevlar to the aluminum backplate.

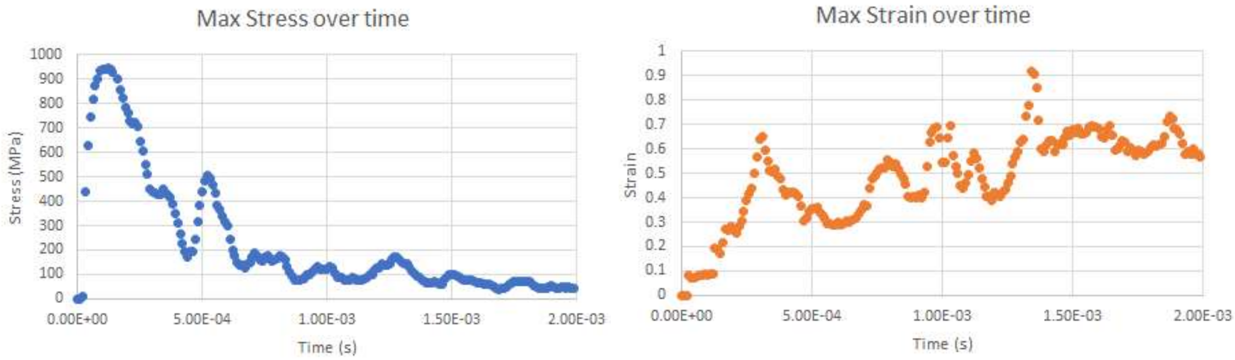


Figure 4. Max Von Mises Equivalent Stress and Strain over full analysis duration

The Max Von Mises Equivalent Stress and Strain throughout the entire FEA analysis time period is included in Figure 4. The maximum stresses and strains were observed to occur at the center of the kevlar, as expected. The max stress has two peaks, the first corresponding to the initial impact and the second to the kevlar coming into contact with the backplate. Following these two peaks, the stress drops significantly. The strain includes more than two peaks as the kevlar is seen to experience some oscillation following the redirection of the iceball.

## IV. Expected Outcomes

The final structure was expected to survive the impact of the ice ball. Based on the FEA and hand calculations discussed above, the kevlar section of the structure was expected to absorb much of the impact. The aluminum was projected to experience some deformation, but not fail.

The kevlar was expected to hit the backplate before it would tear away from the metal ring, so a failure in the mounting of the kevlar to the ring via epoxy and pipe clamp was not expected. The mounting of the ring and the kevlar to the backplate was not expected to fail because the force was only supposed to be perpendicular to the backplate since the ice ball's velocity was supposed to be traveling completely perpendicular to the structure. If gravity is the only force theoretically acting as a shear force, the epoxy and JB-weld should not fail. It was a potential concern that the normal stress between the ring and the backplate would cause failure by puncturing the backplate with the ring, but this was unlikely to happen before failure at the center because the stress should have been distributed around the entire ring's contact area with the backplate.

The design was expected to perform better than the FEA and hand calculations because neither took into account the shattering of the ice ball on impact which will be dissipating a significant portion of its kinetic energy. Furthermore, the design was anticipated to perform well relative to other structures because of its use of lightweight materials. Aluminum and kevlar are widely known and used for their strength to weight ratios. Considering these are the only materials used, and the simple nature of this design, its mass should have been quite low in comparison to the other structures. In summary, the structure was expected to meet the project requirements and weigh less than the competing, successful designs.

## V. Fabrication of Panel

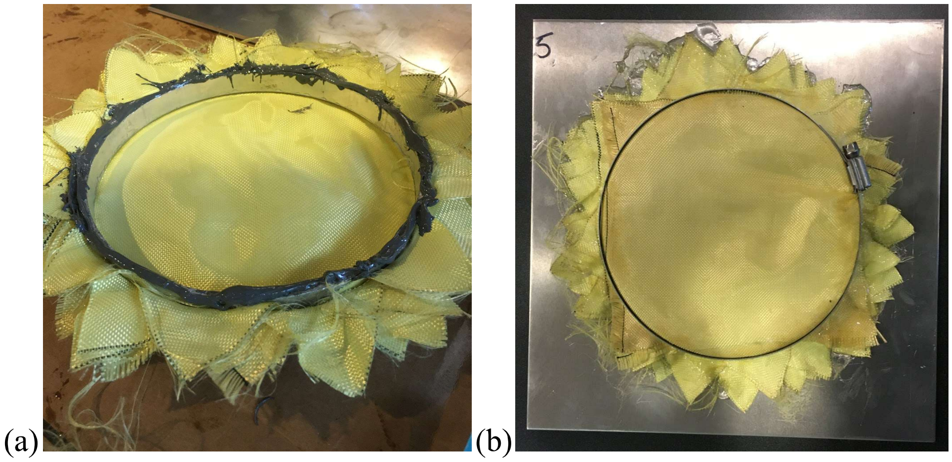


Figure 5: Images of structure throughout the fabrication process

The fabrication of the panel involved aluminum plates, a cut aluminum thick pipe, a hose clamp, kevlar sheets, and JB weld/epoxy. Alternatingly layers of epoxy and Kevlar were tightly spread across the aluminum pipe. Epoxy was kept from the center of the ring as best as possible. Kevlar/epoxy layers were added until a thickness of ⅛” was achieved. The hose clamp was then tightened around the pipe to ensure the Kevlar was pulled tight. The front layer and spacer were then dressed generously with JB weld and epoxy as seen in Figure 5a and pressed down onto the aluminum plate to cure. The fully fabricated structure can be seen in Figure 5b. The final mass of the structure was 0.732 kg (1 lb 9.8 oz).

## VI. Cost

Table 1, Cost Breakdown of Structure Materials

| **Item** | **Standard Price** | **Price Paid** |
|---|---|---|
| 6061 Al 10x10x⅛” plate | $26.00 | $18.89 |
| 6063 Al 6” OD, ⅛” thick pipe | $3.94 | $3.94 |
| 4-½”-6-½” hose clamp | $2.57 | $2.57 |
| Kevlar 29 Fabric | ~$50.00 | $0.00 |
| Epoxy | $21.66 | $21.66 |

| | | |
|---|---|---|
| **Total** | $104.17 | $47.06 |

Materials for the fabrication of the sample were purchased and collected by the various members of the group. All aluminum was purchased from a metal shop, The Metal Supermarket, in Raleigh while the Kevlar sheets were obtained from NC State's BLAST laboratory on campus. Finally, the JB weld epoxy was purchased from a local Lowe's Home Improvement.

## VII. Experimental Testing

Our structure was shot with an ice ball of a speed that was approximately 375 mph. Our structure received minimal damage, other than a slight deformation in the layers of kevlar spanning the circular offset. We expected our structure to easily withstand the impact but were shocked at how little damage it actually endured. This could be due to multiple reasons, the firing device had problems sealing the pressure off, so there was a pressure leak that increased the preparation time. This increase in preparation time could have allowed the ice ball to melt more than expected as the barrel chamber and the ice transferred heat. Upon reviewing the high-speed footage it became apparent that our structure was not impacted by a solid ball of ice, but that the ice shattered sometime between its launch and exit of the barrel. Our structure was hit with multiple smaller chunks of ice at slightly different times, which means less stress than it would have if it were hit with one solid chunk.

## VIII. Conclusion

This structure survived the impact of the ice ball, thus meeting the primary project objective. Its material hardly experienced any permanent deformation from the blast, other than the minor strain in the first layer of the kevlar. Seven of the fifteen competing structures built a successful product that weighed less than this design. Considering how well this structure performed, it is likely that significantly less material could have been used and still met the blast survival requirement. Overall, the structure performed very well with a large factor of safety and competitive weight.

## IX. References

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[2] Goode, T., Shoemaker, G., Schultz, S., Peters, K., & Pankow, M. (2019). Soft body armor time-dependent back face deformation (BFD) with ballistics gel backing. *Composite Structures*, *220*, 687–698. doi: 10.1016/j.compstruct.2019.04.025

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