Optimized Design of Crumple Zone on Vehicles

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Crumple Zone and Its Components

1. A crumple zone is a structural safety features with goals of absorption of kinetic energy during a collision.
2. Typical location: Front of vehicle
3. Should be reasonably deformable but also stiff to absorb significant energy
4. Main components:
   a. Bumper
   b. Crash box
   c. Longitudinal Beams
5. Longitudinal beams are primary absorber of energy.

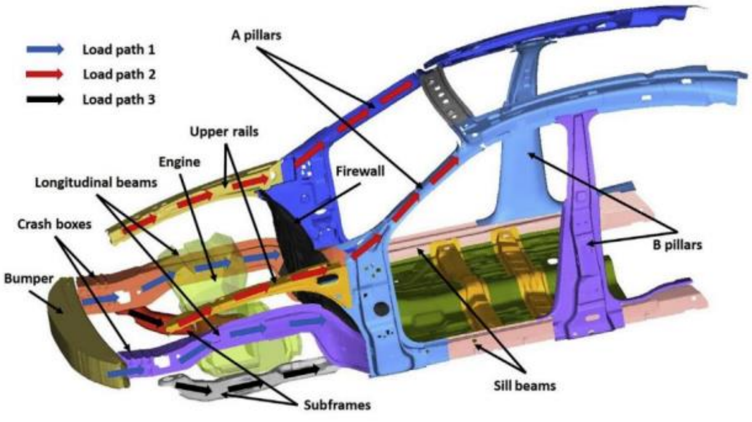

Figure 1. Crumple Zone Load Paths (Load path 1 is most significant)

Our Capstone: Optimization of Crumple Zone

1. Centered around the optimization of crumple zone in terms of:
    a. Weight
    b. Cost
    c. Energy Absorption
2. Method: Compression of different tube designs
    a. Primarily simulation-based (ANSYS Explicit Dynamics) but will also have prototypes for experimental testing
3. Focused on longitudinal beam component
4. Process:
    a. Will verify our simulation method against literature
    b. Will optimize the longitudinal beam design and compare to baseline results.

Motivation

1. In light of climate change, it is important to manufacture lighter crumple zones as these will produce less CO_2 emissions
   a. European commission has set targets for 15% reduction in CO_2 emissions from cars for 2025 onward and 37.5% reduction from 2030 onward.
2. Passenger collision safety is a highly prioritized and pending issue
   a. 8th leading cause of death for all age groups globally (2018)

Longitudinal Beam Components and Literature

- Drawing from this paper's work, we worked on creating our baseline designs which are listed below:
  - Individual Aluminum Square Tube (AST), Individual Foam, and Individual Honeycomb Filling
  - AST Filled with Foam.
  - AST with Honeycomb Filling
  - AST with Honeycomb Filling and Foam.
  - According to the literature, the final combination of tube, honeycomb, and foam should absorb the most energy.

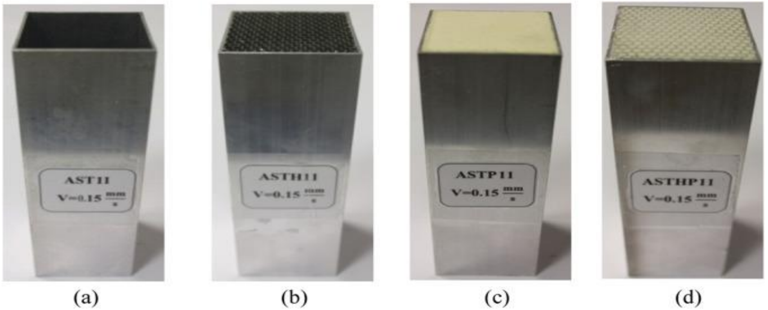

Figure 2:

Elastic Perfectly Plastic Material Model

- Elastic-perfectly plastic assumes that the ultimate tensile strength of the material is on the same line as the yield strength.
- It is a conservative model that underestimates the peak force and energy absorbed.
- Our simulations should underestimate the peak force compared with the experimental results in Hussein et al.

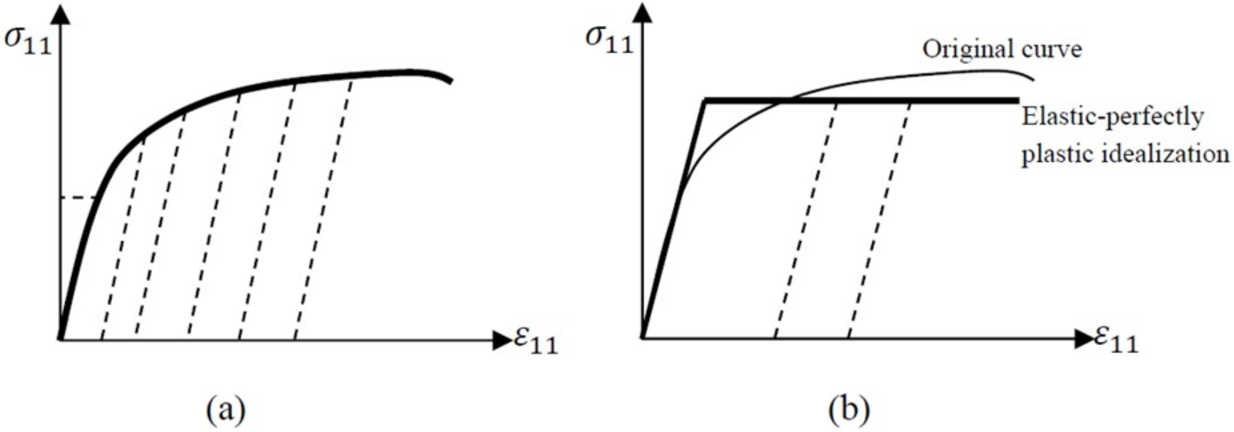

Figure 3. Stress-strain curve of Original Curve Versus Elastic-Perfectly Plastic Model [X]

Material Properties

	Density	Young's Modulus	Poisson Ratio	Yield Strength	Tangent Modulus
Foam (Polyurethane Foam)	180 kg/m^3	67.74 MPa	0.3	2.41909 MPa	0
Tube (Aluminum Alloy AA 6060-T5)	2.70 g/cc	68.9 GPa	0.33	145 MPa	0
Honeycomb (Aluminum 5052-H39)	2.7g/cm^3	68 GPa	0.33	255 MPa 292 MPa	0

- Yield strength used for the honeycomb individual simulation was 255 MPa, but in the tube-honeycomb and tube-honeycomb-foam models it is 292 MPa.

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Model Verification

- Model results using the elastic perfectly plastic model in ANSYS were compared with experimental data from the literature. In the elastic region, the analytical and numerical stiffness were calculated:

$$k_{theory} = \frac{EA}{L}, \qquad k_{FEA} = \frac{F}{x}$$

$k = stiffness$	$E = Young's\ Modulus$	$L = Length$
$x = deformation$	$F = Reaction\ Force$	

- Tube model had 1.1% error between k_{theory} and k_{FEA}, honeycomb model had 2.0% error, and Foam had 6.5% error. Slight error is due to assumptions in the theoretical calculation where the effect of Poisson's ratio is negligible, and the material deforming has infinite length.

Shell vs Solid Elements

- Mesh elements for the tube and honeycomb are shell. For foam, we used solid elements.
- If we had used solid elements, we would need 4 elements throughout the thickness of honeycomb walls and tube walls to capture bending.
    - Thus, opting for shell elements in these cases is less computationally expensive

Example of Boundary Conditions: Tube

- Fixed support on the edges of one end
- Displacement condition on the edges of the opposite end
    - Uniaxial compression
    - Displacement loading is linear against time

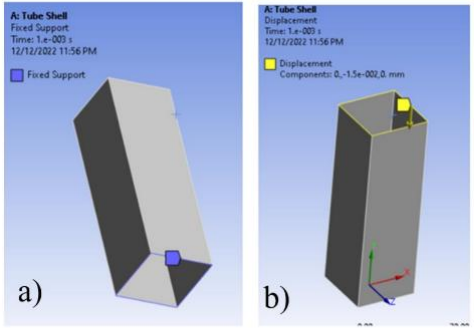


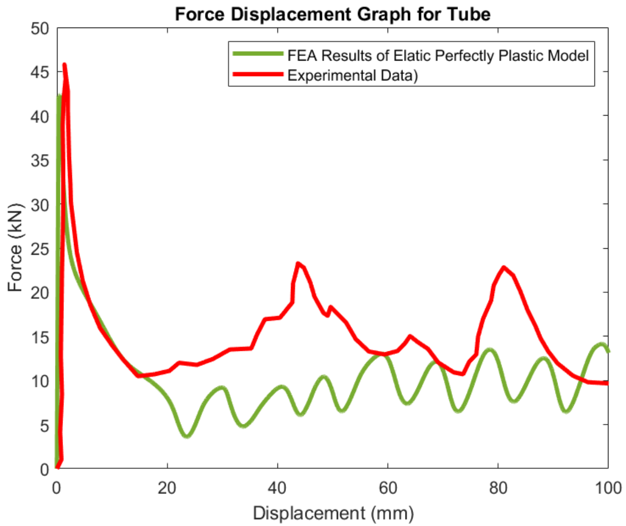
Figure 4. Hollow Tube 100 mm Compression Simulation, Boundary Conditions

	Steps	Time [s]	X [mm]	Y [mm]	Z [mm]
1	1	0.	0.	0.	0.
2	1	1.e-003	0.	-1.5e-002	0.
3	2	2.e-003	= 0.	= -3.e-002	= 0.
4	3	3.e-003	= 0.	= -4.5e-002	= 0.
5	4	4.e-003	= 0.	= -6.e-002	= 0.
6	5	5.e-003	= 0.	= -7.5e-002	= 0.
7	6	6.e-003	= 0.	= -9.e-002	= 0.
8	7	7.e-003	= 0.	= -0.105	= 0.
9	8	8.e-003	= 0.	= -0.12	= 0.
10	9	9.e-003	= 0.	= -0.135	= 0.
11	10	1.e-002	= 0.	-0.15	= 0.
*					

Figure 5. Displacement Tabular Data to show Uniaxial Compression and Linear Loading

Tube Simulation

1. Simulation peak difference is expected due to conservative elastic perfectly plastic model assumption
2. Shell element used for the tube with 10 elements for each side
3. 6.33% peak force error compared to experimental data



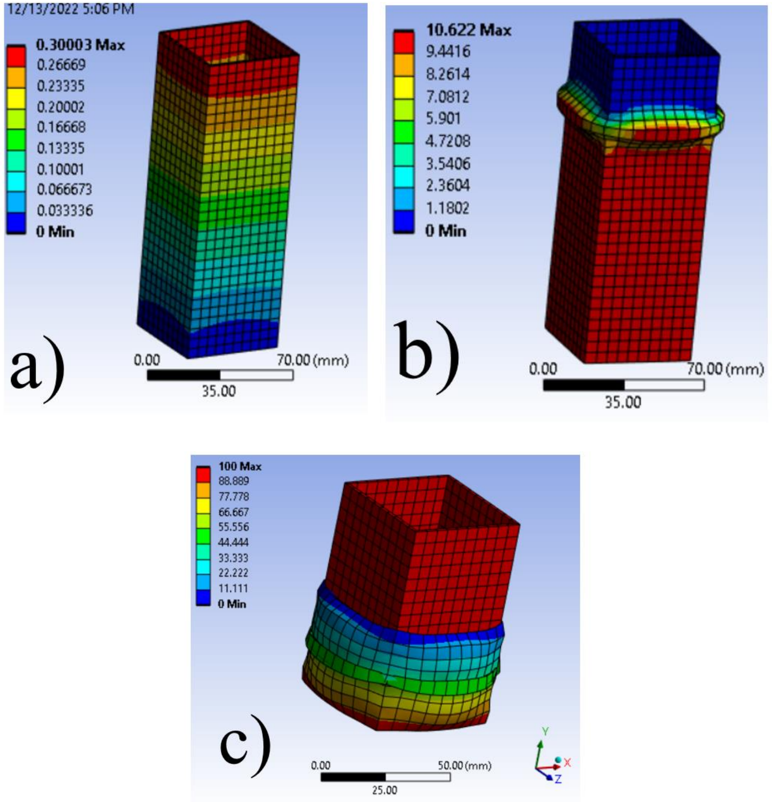
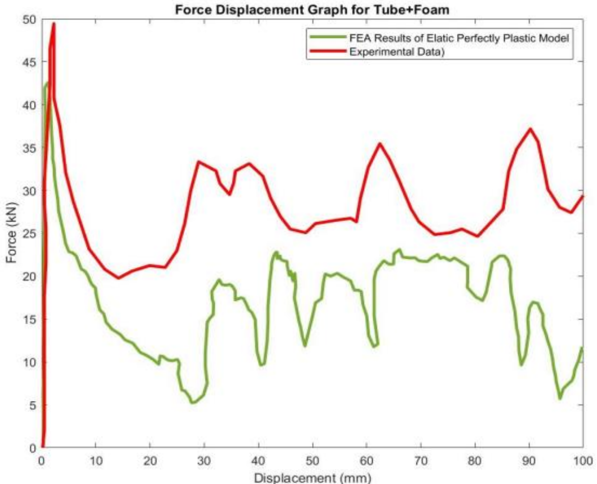


Figure 4. Hollow Tube 100 mm Compression Simulation, Total Deformation. (a) Stress Contours Before Yielding (b) Stress Contours After Yielding (c) Stress Contours After 100 mm Compression

Tube + Foam Simulation

1. Simulation peak difference is expected due to conservative elastic perfectly plastic model assumption
2. Shell element used for the tube and solid element used for th foam
3. Bonded contacts between shell and solid
4. 15% peak force error in comparison to experimental data



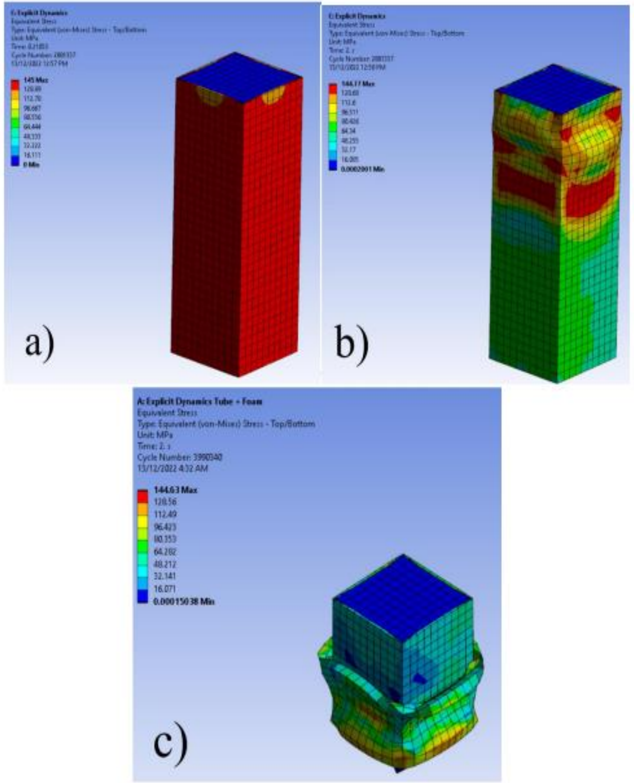


Figure 5. Stress contours of Tube + Foam: (a) Before yielding (b) After yielding (c) After 100 mm compression

Tube + Honeycomb Simulation [In Progress]

Issue 1: Computational Expense

a. 600+ hours for full 150 mm tube simulation to run
   i. Solutions:
      1. Used symmetry and modeled only a quarter of the tube
         a. Applied appropriate constraints on relevant surfaces (rollers)
      2. Mass scaling by 100 or 1000

Issue 2: Overestimation of Peak Force

a. Simulation peak force was inaccurate compared to literature. Concluded that buckling was occurring experimentally that the simulation was not capturing
   i. Solutions:
      1. Increase mesh density to at least four elements per side in order to capture buckling

Next Steps

1. Finish the simulations last baseline models:
    a. Tube + Honeycomb
    b. Tube + Honeycomb + Foam
2. Begin optimizing the longitudinal beam design
    a. Ideas:
        i. Functionally graded honeycomb
        ii. Enneagonal tube
3. Printing out prototypes for experimental testing

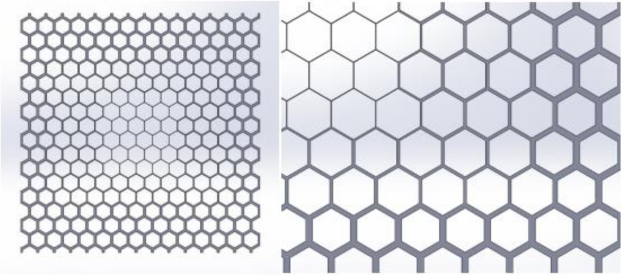


Figure 6. Functionally graded honeycomb

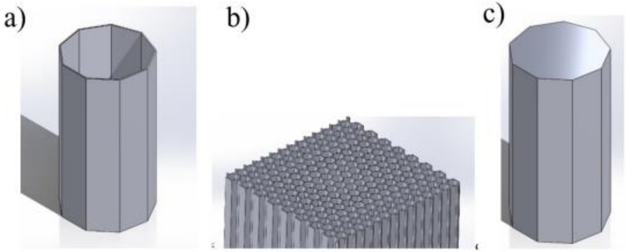


Figure 7. (a) Enneagonal tube (b) Functionally graded honeycomb (c) Enneagonal foam

References

[X] “Engineering at Alberta Courses» Plasticity in Uniaxial Stress State,” Engcourses-uofa.ca, 2022. https://engcourses-uofa.ca/books/introduction-to-solid-mechanics/constitutive-laws/plasticity/mathematical-modelling-of-plasticity/plasticity-in-uniaxial-stress-state/.