Title
Optimization of a Portable Automotive Vehicle Ramp using Finite Element Analysis

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OPTIMIZATION OF A PORTABLE AUTOMOTIVE VEHICLE RAMP USING FINITE ELEMENT ANALYSIS

By

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A capstone project submitted for
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University Honors
University of California, Riverside

APPROVED

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Abstract

A three-dimensional static analysis was used to model a portable vehicle ramp used to raise passenger vehicles. The objective is to examine various ramp materials and alternative designs of the supporting sections below the ramp, to optimize this product in load-bearing capabilities, safety factors, and cost-effectiveness in minimizing material use. Finite element analysis (FEA) is a computational method using a discretization of structural displacement fields to predict how a product reacts to real-world forces, vibrations, and other physical phenomena. The commercial software that is used is Abaqus Student Edition, an FEA solver capable of structural models with a limit of 1000 analysis points on the system.

The ramp is at an angle of 17 degrees and has dimensions of 35.5 in L x 12 in W x 8.5 in H. A pair of ramps is designed to elevate an average midsize sedan weighing approximately 3,350 lbs and the design will assume 70% of the weight of the vehicle is concentrated at the front half of the vehicle, due to the engine, transmission, battery, and other components below the hood. The simulation was designed to assume the ramp as fixed to the ground. Manufacturers, such as Pittsburgh Automotive, use a plastic 'poly material', which was assumed to be Polymethylmethacrylate (PMMA) or acrylic. This is compared to other materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high-density polyethylene (HDPE), polystyrene (PS), and polyvinyl chloride (PVC). Five different ramp support designs were also evaluated. Using weighted decision matrices, it was found that using PVC instead of PMMA, and a section design similar to the Pittsburgh Automotive ramp sections, was the best material and design selections to optimize safety, load-bearing capabilities, and cost.

Acknowledgments

In addition to fulfilling the UC Riverside University Honors Capstone Project requirement, this project was conducted for a mechanical engineering graduate course, ME 267 Finite Element Methods in Solid Mechanics, taught by Dr. Mona Eskandari. Having taken this as an undergraduate student, I acknowledge the experience of taking the graduate course and the personal growth and invaluable skills gained as a result of it.

Although this was an independent project, I could not have successfully completed this without the support of my community. I appreciate the mentorship provided by both of my faculty mentors: Dr. David Cocker and Dr. Mona Eskandari. Both Dr. Cocker and Dr. Eskandari are incredibly ambitious, dedicated, and inspiring in their own unique ways, and I am honored to have had this opportunity to work with them. I am also grateful to my classmates and peers who assisted in troubleshooting minor issues as well as providing moral support. Therefore, I would like to thank my faculty mentors for their guidance, The UCR University Honors Program for their resources provided, as well as my peers for the support they had provided.

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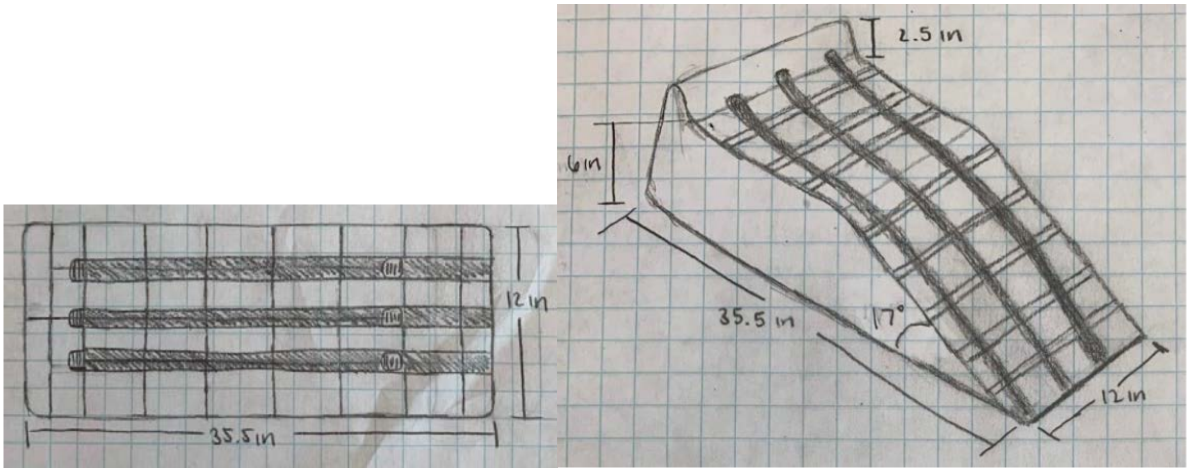
Introduction

In modern society, having one's own passenger vehicle is essential to provide a practical means of transportation. However, owning a vehicle comes with many expenses including purchasing, insuring, and maintaining the vehicle. Because of this, many automotive owners prefer to perform maintenance on their vehicles, which requires lifting the vehicle to work beneath it. Common automotive lifting tools include jacks, stands, and ramps shown in Figure 1. The most inexpensive option is the portable vehicle ramp to raise the front half of the car by driving onto it. The ramps currently on the market are commonly made of a durable plastic material with hollowed-out sections below the ramp, allowing the ramps to support up to 350 times their weight. This project models a pair of vehicle ramps to determine how to ensure the best ramp design in terms of optimizing cost and factor of safety. The ramps follow a design similar to Pittsburgh Automotive's Portable Vehicle Ramps, shown in Figure 1b, which elevates the front wheels of a passenger car by 6 in. The dimensions of this ramp are shown in Figure 2. The analysis was conducted assuming a uniform distribution pressure-load from an average midsize sedan weighing 3,350 lbs, with a tire width of 8.5 in contacting the ramp platform.

a) Hydraulic Floor Jack and Jack Stands [1]

b) Pittsburgh Automotive 13,000 lbs Portable Vehicle Ramp Set [2]

Figure 1: Common Automotive Lifting Tools



a) Bottom view sketch of sections supporting ramp with dimensions

b) 3⁄4 view sketch of a single portable vehicle ramp with dimensions

Figure 2: Sketches of Portable Vehicle Ramp with dimensions

Finite element models were created to analyze the various materials and ramp designs. FEA refers to computational simulations that predict how a model of an object will react to physical phenomena by dividing the subject into a mesh of discrete elements, “building blocks,” to analyze the system as a whole [3]. Meshes with large elements are referred to as coarse and meshes with many small elements are referred to as fine, providing more accurate results. These elements are comprised of nodes, points on the elements where the degrees of freedom are defined. Degrees of freedom represent the possible movement of the point due to loads exerted on the structure, such as translating or rotating about X, Y, Z [4]. The FEA commercial software that was used to conduct these analyses was Abaqus Student Edition, which limits all analyses to 1000 nodes. All models created were as refined as possible, approaching the 1000 node limit, and for consistency purposes - used the same element type.

Computational Methods

It was first determined that English units will be used consistently. A dimensioned standard solid ramp (dimensioned in inches) with no cutout sections, Model 1, was first created in Abaqus, extruded to a 12 in thickness, with dimensions shown in Figure 3. The five materials of Impact-Grade Molded Acrylonitrile Butadiene Styrene (ABS), Impact-Grade High-Density Polyethylene (HDPE), Polylactic Acid Biopolymer (PLA), Impact-Modified Polystyrene (PS), Rigid-Grade Polyvinyl Chloride (PVC), and Polymethyl-methacrylate (PMMA or acrylic) and their material properties of density $\rho\ [\frac{\square\square\square}{\square\square^{3}}]$, Poisson's Ratio, and Young's Elastic Modulus □ [□□□]were added to the model.

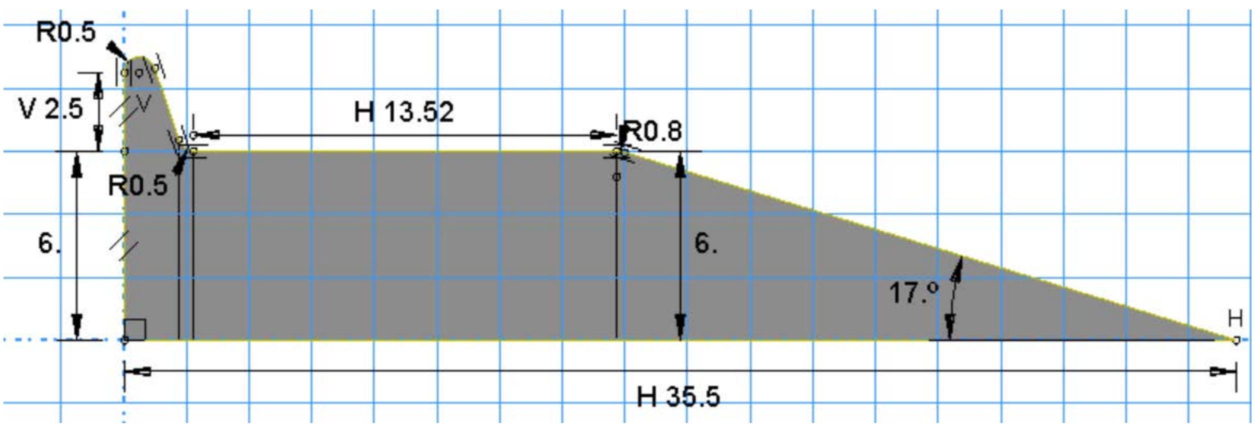
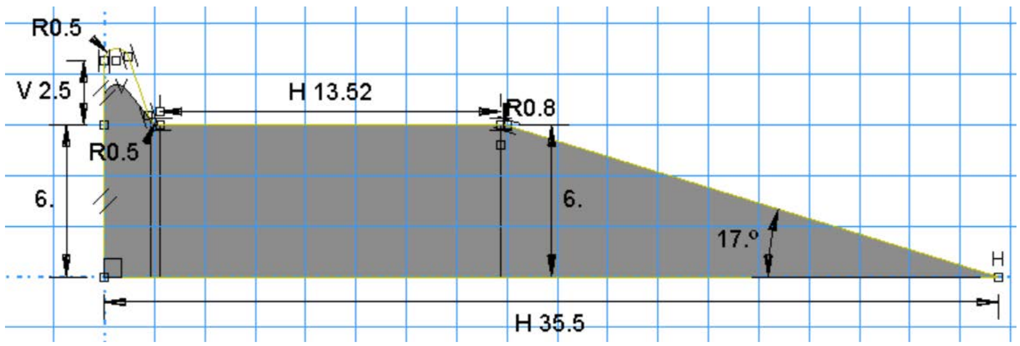
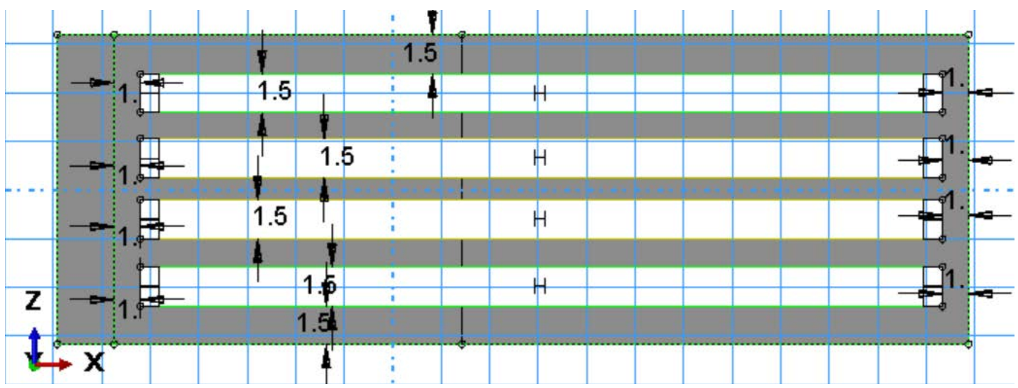
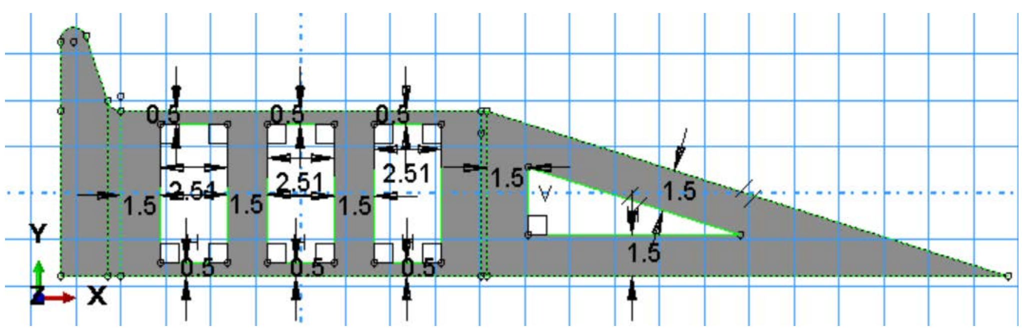


Figure 3: Dimensions of Standard Ramp Side View in inches

The material properties, including ultimate tensile strength $\sigma_{\square\square\square}$ [□□□] were extracted from Ref. [5] and this data table can be found in Appendix 1. Because ranges were often provided for the material properties, the maximum density was selected to ensure maximum strength, minimum ultimate tensile strength to expect the lowest possible stress that could cause failure, and the lowest Young's modulus to minimize deflection of the ramp platform. The cost per pound of the materials were identified from Ref. [6] - [11] to use in the calculation for cost-optimization. Solid, homogeneous sections of each material were then created for each material.

This model was copied four times to make four other ramp design models. The other four models were all modified using Abaqus's Cut Extrude tool. The dimensions of these cut-extrusions are shown in Table 1. The isometric view of these models are shown in Table 2.

Ramp Design Model # - Name (View Angle)	**Abaqus Model**
Model 1 - Standard Ramp (Side View)	
Model 2 - Vertical Sections (Bottom View)	
Model 3 - Horizontal Sections (Side View)	

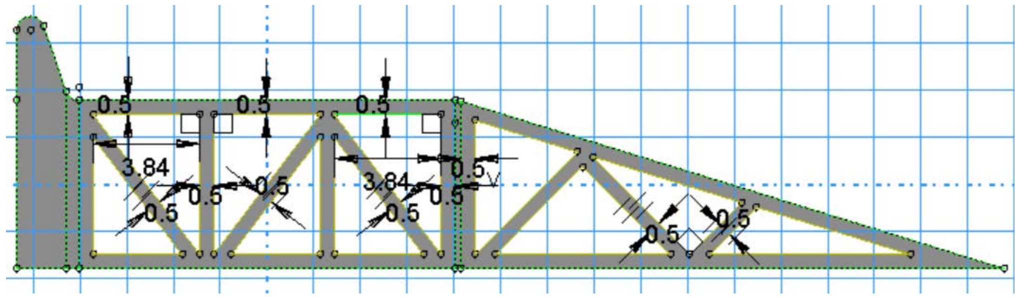
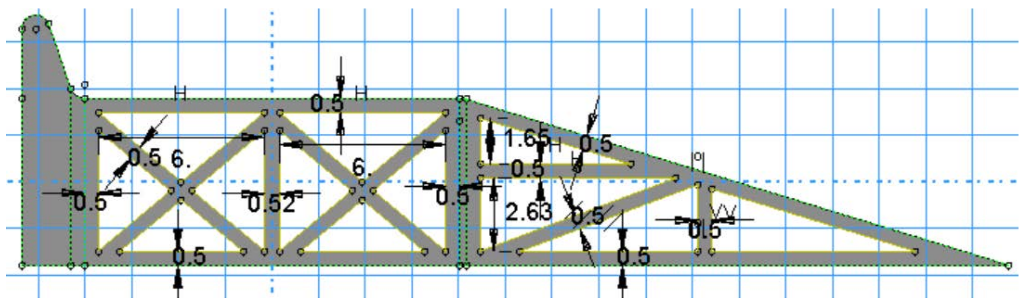
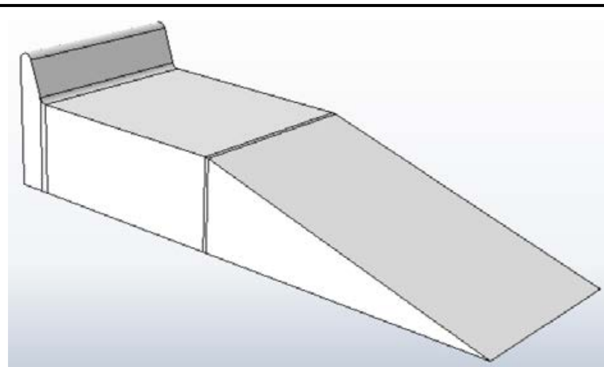
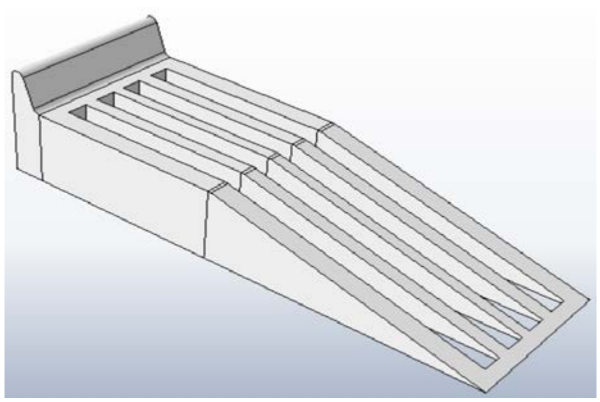
Model 4 - Triangular-Truss Supports (Side View)	
Model 5 - X-Truss Supports (Side View)	

Table 1: Dimensioned Abaqus Sketches of each Ramp Design Model in inches

Ramp Design Model # - Name	Abaqus Model
Model 1 - Standard Ramp	
Model 2 - Vertical Sections	

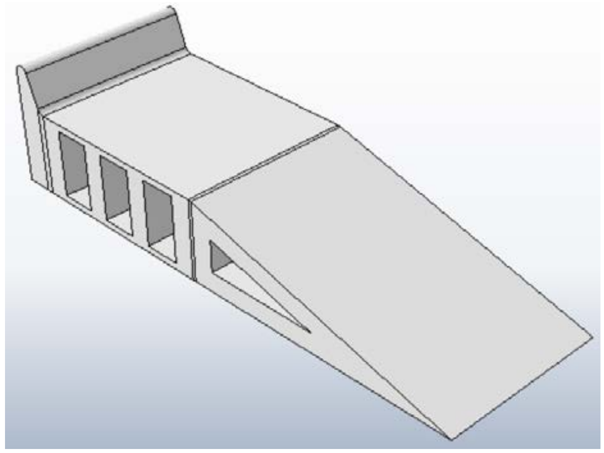
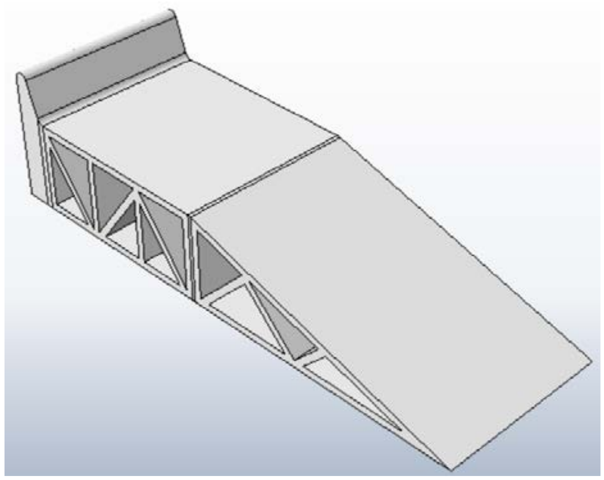
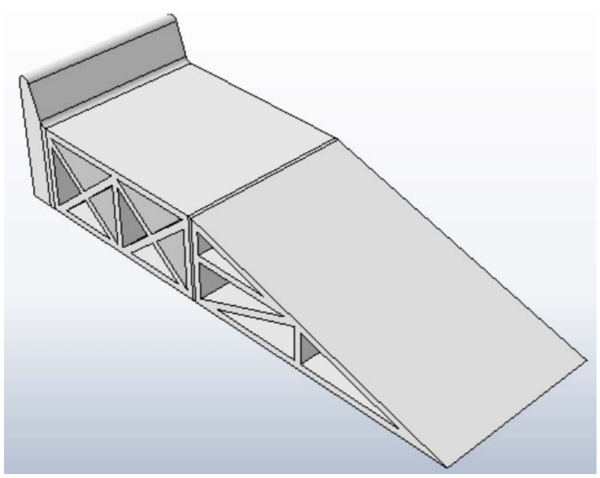
Model 3 - Horizontal Sections	
Model 4 - Triangular-Truss Supports	
Model 5 - X-Truss Supports	

Table 2: Abaqus Models of Ramp Designs

The loads were next calculated as shown below to be a pressure of 328.529 □□□ for a tire width of 8.5 in, assuming that it contacts the entire length of the flat surface of the ramp. The calculations take into consideration that only a single ramp will be used in the analysis due to symmetry, assuming uniform weight distribution of the car. This same pressure is applied for all the ramp models.

Calculation of Load Applied from Vehicle Weight:

[illegible] = [illegible] → [illegible] = [illegible].[illegible]([illegible]) = [illegible] →
[illegible] = [illegible]/[illegible] = [illegible].[illegible] → [illegible] = [illegible].[illegible] × [illegible].[illegible] [illegible] =
[illegible].[illegible]

Tire width = 8.5” [illegible] = [illegible] × [illegible] = $(13.52'')(8.5'') = 114.92$ [illegible]^2

[illegible] = [illegible]/[illegible] = [illegible].[illegible] / [illegible].[illegible] → [illegible] = [illegible].[illegible] ← Assume same pressure for all ramp models

An Encastre boundary condition, fixing the ramp translationally and rotationally in the x-, y-, and z-directions, was applied at the base of all models, as shown in Figure 4. It is assumed that the ramp will be fully fixed to the ground by the weight of the vehicle. The meshes of all models consistently used C3D4 Linear Tetrahedral elements, as shown in Figure 5, which were best suited for the geometry of the triangular portion of the ramp. The meshes were refined to approach as close to 1000 nodes as possible, all ranging from 805 - 988 nodes to ensure accurate results (reference Appendix 2 for the table of mesh properties).

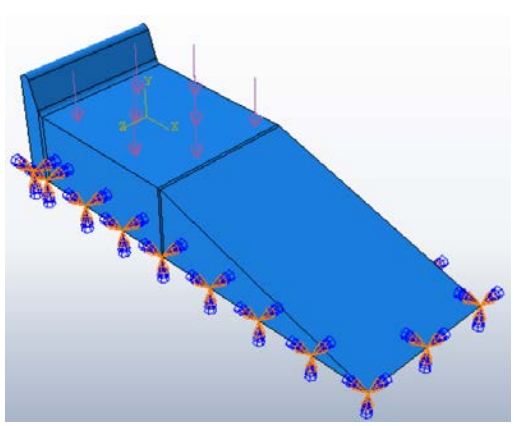


Figure 4: Abaqus Simulation of Applied Pressure Load and Boundary Conditions

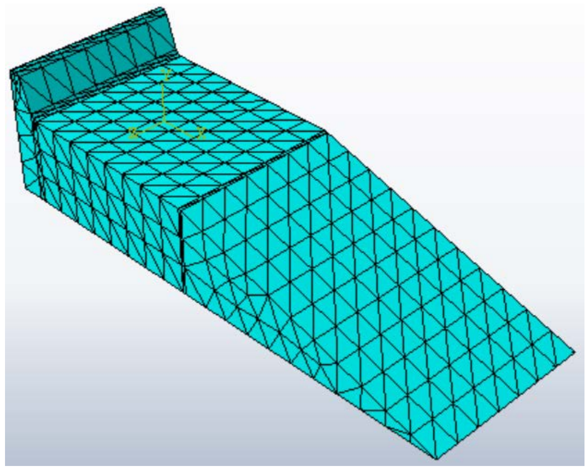


Figure 5: FEA Simulation Mesh of C3D4 Linear Tetrahedral elements

The approach is that five ramp models were first created with PMMA as the material. PMMA was selected because it had the highest ultimate stress value of the six materials. A decision matrix was then used in ranking safety, deflection, and cost for the order of their importance from 1-3, and assigned a ranking of where each ramp model design ranked from 1-5 for these requirements, scoring 0 if the safety factor is below 1, being deemed unsafe. Using the decision matrix to determine the best ramp design, this model was then duplicated, and each assigned one of the five other materials to run new FEA analysis.

After running the analysis, the mass [□□□],displacement [□□],and maximum stress [□□□] were recorded. For displacement, the U2 values, displacement in the vertical y-direction were used. This is to observe whether the ramp will be compressed significantly. Although a minor deflection is inevitable, it is important that it is minuscule so that the ramp will serve its purpose of raising the vehicle approximately 6 in. For the stress, counterintuitively, the minimum blue values were used due to the fact that it is the negative displacement (compression) that is the focus for this application. The von Mises stress was used since it is a stress used as a failure criterion, to determine whether a material will yield or fracture under stress [12].

Results

In the initial analyses for the different ramp section designs, maintaining the material, PMMA, consistent for the five models, the mass of each model was obtained in pound-mass [□□□] from using the Abaqus Query Tool for Mass Properties. The mass was used to calculate the total cost by multiplying the mass in □□□ by the PMMA cost of $6.74/lbs. The safety factor was next calculated using the ratio of the ultimate stress and the maximum stress, shown in Equation (1). The ultimate stress was obtained from Ref. [5] and the maximum stress was the maximum von Mises stress obtained from the Abaqus FEA simulation results. The displacement was the negative U2 displacement, the downwards deflection in the vertical axis, also obtained from the FEA simulation results. These results are summarized in Table 3. These simulation results can be referenced in Appendix 3, but it is important to note that the Abaqus software graphics show exaggerated deformations when the vertical deflection values are truly on average 0.015 in, equivalent to 0.038 cm.

$$\text{□□□□□□ □□□□□□} = \frac{\text{□}_{\text{□□□}}}{\text{□}_{\text{□□□□□□□}}} \qquad (1)$$

Section Design	Mass [lbm]	Total Cost [$]	Displacement [in]	Max Stress [psi]	Ultimate Stress [psi]	Safety Factor
1	81.61	550.06	0.00449	435.40	2,030.00	4.66
2	46.90	316.12	0.00429	427.20	2,030.00	4.75
3	57.17	385.31	0.01157	892.30	2,030.00	2.28
4	40.19	270.91	0.02710	2,102.00	2,030.00	0.97
5	42.63	287.30	0.05022	2,989.00	2,030.00	0.68

Table 3: Analysis Results from Varying Model, Constant Material (PMMA)

Table 4 shows the Decision Matrix used to determine the best design. It was initially expected for Model 4 or 5 to be the best design since trusses are greatly used in engineering and architecture, however, the bars used may have been too thin, resulting in an unsafe design with a factor of safety below 1. However, Model 2 with the vertical sections design, similar to the Pittsburgh Automotive ramp currently in the market, was the best ramp design selection in terms of optimizing safety, cost, and load-bearing capabilities.

Section Design Selection											
Requirements	Requirement Importance Factor	Model Type									
		Mod 1 Score	Mod 1 Total	Mod 2 Score	Mod 2 Total	Mod 3 Score	Mod 3 Total	Mod 4 Score	Mod 4 Total	Mod 5 Score	Mod 5 Total
Platform Deflection	2	4	8	5	10	3	6	2	4	1	2
Safety	3	4	12	5	15	3	9	0	0	0	0
Cost	1	1	1	3	3	2	2	5	5	4	4
Total		21		28		17		9		6	

Table 4: Section Design Decision Matrix

Having determined the ramp design, analyses were then conducted of this selected design for six different plastic materials. The cost and safety factors were calculated in the same way as in the prior analysis. The results yielded are shown in Table 5. These results were then used to determine decision matrix scores, shown in Table 6. Table 6 shows that PVC was the material that was best at minimizing deflection, maximizing the safety factor while minimizing costs.

	Cost [$/lbs]	Mass [lbm]	Total Cost [$]	Max Displacement [in]	Max Stress [psi]	Ultimate Stress [psi]	Safety Factor
ABS	1.50	11.56	17.34	0.00490	428.40	3,480.00	8.12
HDPE	0.39	37.41	14.59	0.01329	431.30	1,450.00	3.36
PLA	0.91	68.39	62.24	0.00176	429.80	2,030.00	4.72
PS	1.39	59.23	82.33	5.69900	428.40	1,800.00	4.20
PVC	0.59	55.41	32.69	0.00278	430.60	4,350.00	10.10
PMMA	6.74	46.90	316.12	0.00429	427.20	8,990.00	21.04

Table 5: Analysis Results from Varying Material, Constant Model (Model 2)

Material Selection													
Requirements	Requirement Importance Factor	Material Type											
		ABS Score	ABS Total	HDPE Score	HDPE Total	PLA Score	PLA Total	PS Score	PS Tot	PVC Scor	PVC Total	PMMA Score	PMMA Total
Platform Deflection	2	3	6	2	4	6	12	1	2	5	10	4	8
Safety	3	4	12	1	3	3	9	2	6	5	15	6	18
Cost	1	5	5	6	6	3	3	2	2	4	4	1	1
Total		23		13		24		10		**29**		27	

Table 6: Material Selection Decision Matrix

Figures 6 and 7 show the deflection and von Mises stress color contour plots, respectively, obtained from the Abaqus FEA simulation results. In Figure 6, it is important to note that the color scale is reversed due to the way that Abaqus was programmed. Abaqus was designed to show positive deflections due to expansion as red and negative deflections resulting from compression as blue. The focus for this application is in determining how much the weight of the vehicle compresses the ramp downwards, therefore the blue values are the focus for this application. It is also important to note that Abaqus simulation graphics exaggerated the deformations, which are not to scale with the results. This emphasizes the importance of observing the magnitude of the values, rather than focusing only on the graphic representations. For Figures 6 and 7, although the platform appears significantly compressed, the blue values do indicate that the maximum deflection there is -2.775e-3 in or 0.002775 in, equivalent to 0.007055 cm. Because the initial height of that platform was intended to raise the vehicle by 6 in, the vehicle would still be raised by 5.997225 in ~ 6 in, a negligible deflection.

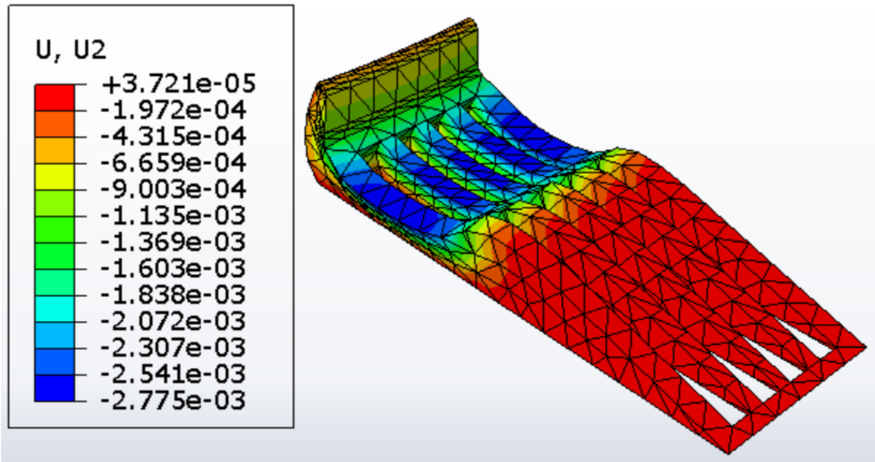


Figure 6: Color Contour Deflection Plot of PVC Model 2

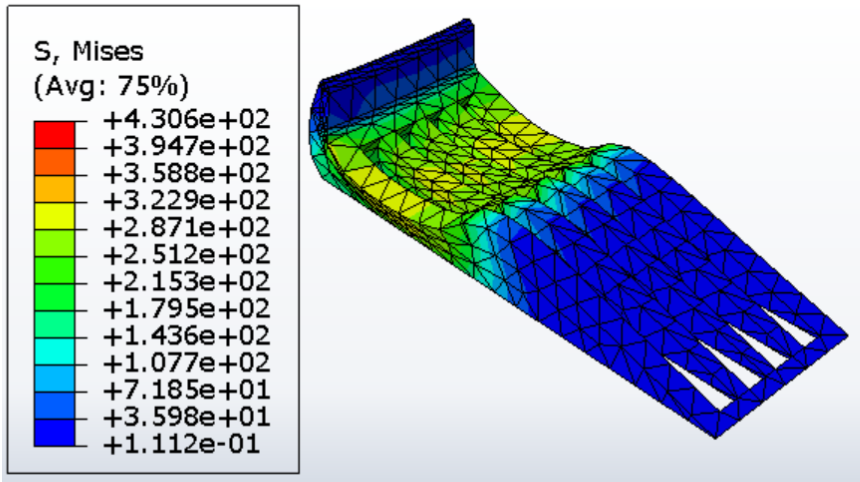


Figure 7: Color Contour von Mises Stress Plot of PVC Model 2

Conclusion

Five different ramp models: Standard Ramp, Vertical Sections, Horizontal Sections, Triangular-Truss supports, and X-Truss Supports were modelled and analyzed in Abaqus. These models were analyzed by placing a load of an average midsize sedan weighing 3,350 lbs with 70% of its weight in the front half of the vehicle (the portion of the car on top of the two ramps). Only a single ramp was modelled due to symmetry, and assuming uniform weight distribution of the vehicle. The meshing was kept as consistent as possible, in using Linear Tetrahedral elements, and were all fine meshes close to 1000 nodes. Abaqus was used to identify the mass, maximum stress, and maximum displacement (vertical deflection) values for each model. These values were ranked in order for each model design to utilize a decision matrix for determining the best ramp support sections design. Model 2 - Vertical Sections, similar to the Pittsburgh Automotive ramp design was selected as the best design option of the five models. Conducting analyses in varying the material (ABS, HDPE, PLA, PS, PVC, PMMA) for this model and utilizing a decision matrix, showed that PVC was the best material for optimizing the design.

In examining various ramp materials and alternative designs of the supporting sections below the ramp, it is concluded that the ramp design of Model 2 - Vertical Sections and using PVC as the material optimizes this vehicle ramp most in terms of safety, cost, and reliability. The American Society of Mechanical Engineers (ASME) typically requires safety factors of 3.5, but may vary for different applications [13]. This design had a safety factor of 10.10, which is 188.57% greater than required. The deflection was also only 0.002775 in ~ 0.003 in, meaning the ramp will still raise the vehicle 5.997 in instead of 6.000 in. In terms of cost, although it was not the cheapest material, it fell in the mid-range pricing, which was reasonable since the safety and reliability would not be compromised.

Future work recommended for this project is to further research other FEA software such as ANSYS, Autodesk Simulation, COMSOL Multiphysics, and SolidWorks Simulation. Abaqus Student Edition was selected for this project because this project was conducted for a graduate-level FEA course which centered upon using Abaqus to conduct analyses. If alternative FEA software has certain advantages that Abaqus does not, then future work can pertain to creating more simulations using the other software to compare the results. Following this, experiments can be created in constructing physical prototypes and testing them with various loads from different compact to mid-sized vehicles. Although physical experiments are significantly more expensive than computational simulations, this would yield the most accurate and dependable results. These experiments would be necessary if the ramp were intended for actual use and especially for mass-manufacturing and production as a consumer product. In the case that the ramp is intended for actual use, more variations of ramp designs would be created and tested with FEA prior to building prototypes. Design modifications could include adding more trusses to support Models 4 & 5 or increasing the thickness of the trusses used. Further examination into other types of plastic materials would be considered for optimizing the ramps.

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Appendix

Appendix 1: Material Properties Table

	ABS	HDPE	PLA	PS	PVC	PMMA
Density ρ $[\frac{□□□}{□□^{3}}]$	0.0106	0.0343	0.0627	0.0543	0.0508	0.0430
Poisson's Ratio	0.35	0.46	0.33	0.35	0.32	0.37
Young's Modulus □ [ksi]	356	117	1006	306	642	400
$\sigma_{□□□}$ [psi]	3480	1450	2030	1800	4350	8990

ABS - Acrylonitrile Butadiene Styrene, Impact Grade, Molded
HDPE - High-Density Polyethylene, Impact Grade
PLA - Polylactic Acid Biopolymer
PS -Polystyrene, Impact Modified
PVC - Polyvinyl Chloride, Rigid Grade
PMMA - Polymethyl-methacrylate (acrylic)

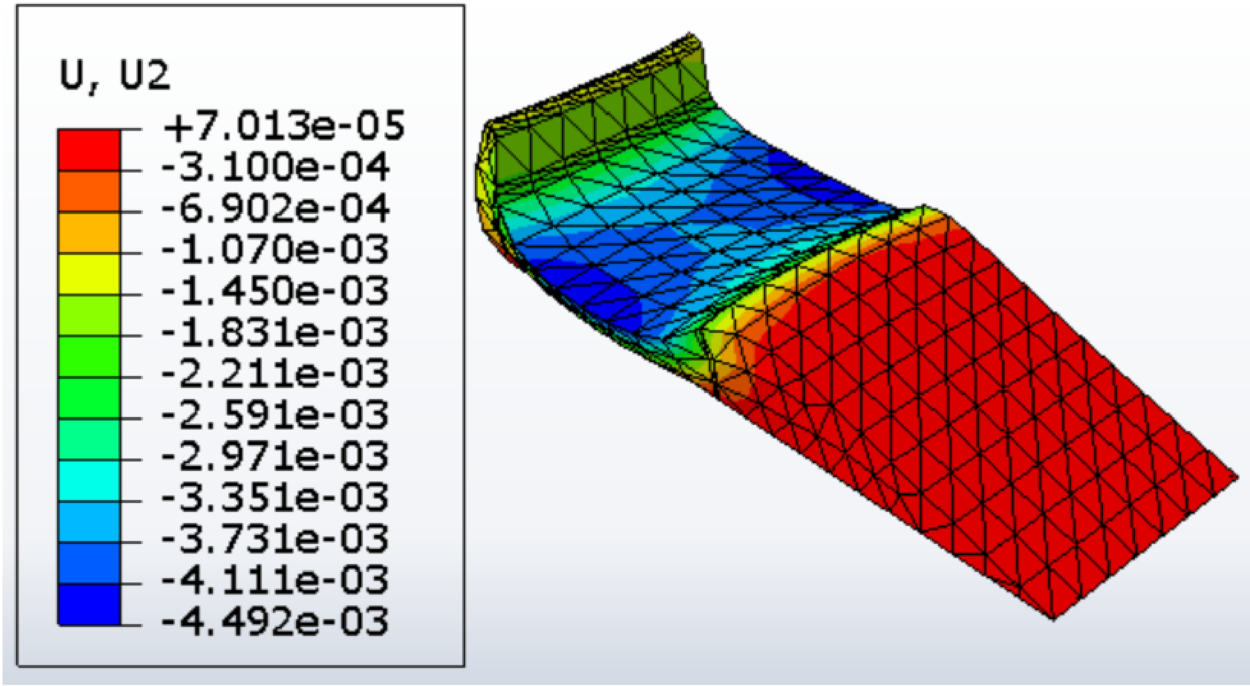
Appendix 2: Mesh Properties of each Model Variation, Constant material (PMMA)

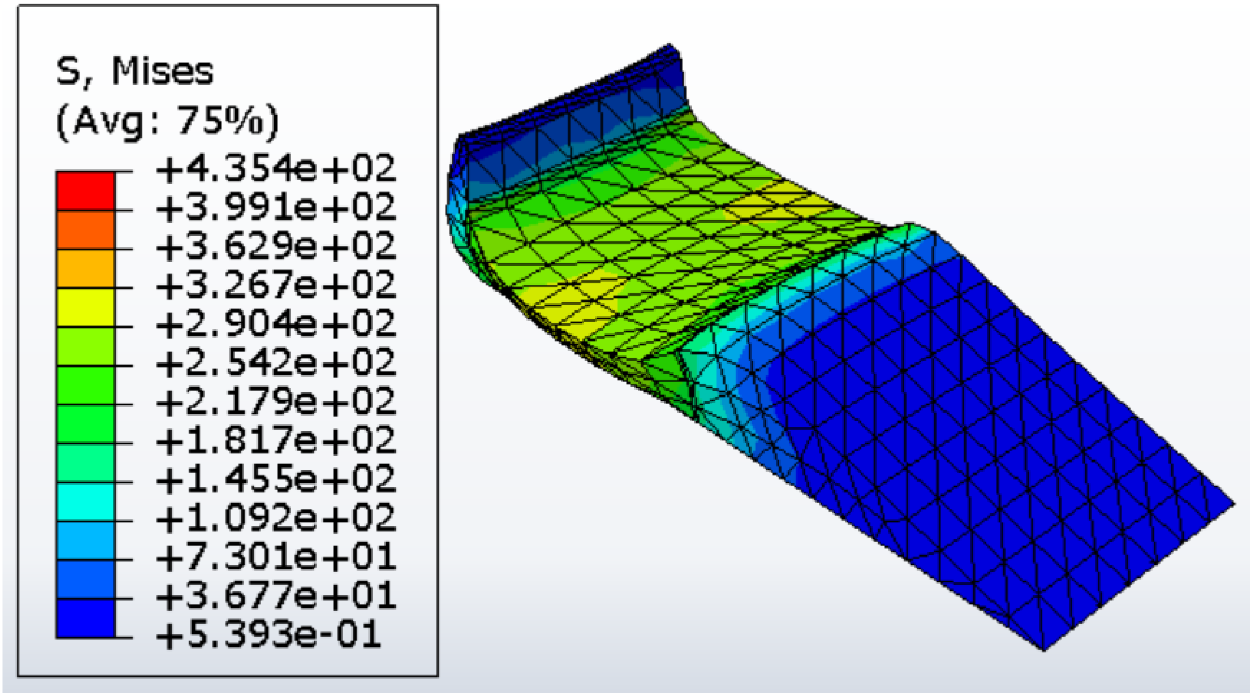
Section Design	Nodes	Elements	Element Type(s)
1	805	3,160	C3D4 Linear Tetrahedral
2	838	2,228	C3D4 Linear Tetrahedral
3	917	3,121	C3D4 Linear Tetrahedral
4	988	3,179	C3D4 Linear Tetrahedral
5	972	3,215	C3D4 Linear Tetrahedral

Appendix 3: Color Contour Plots of Various Models, Constant Material (PMMA)

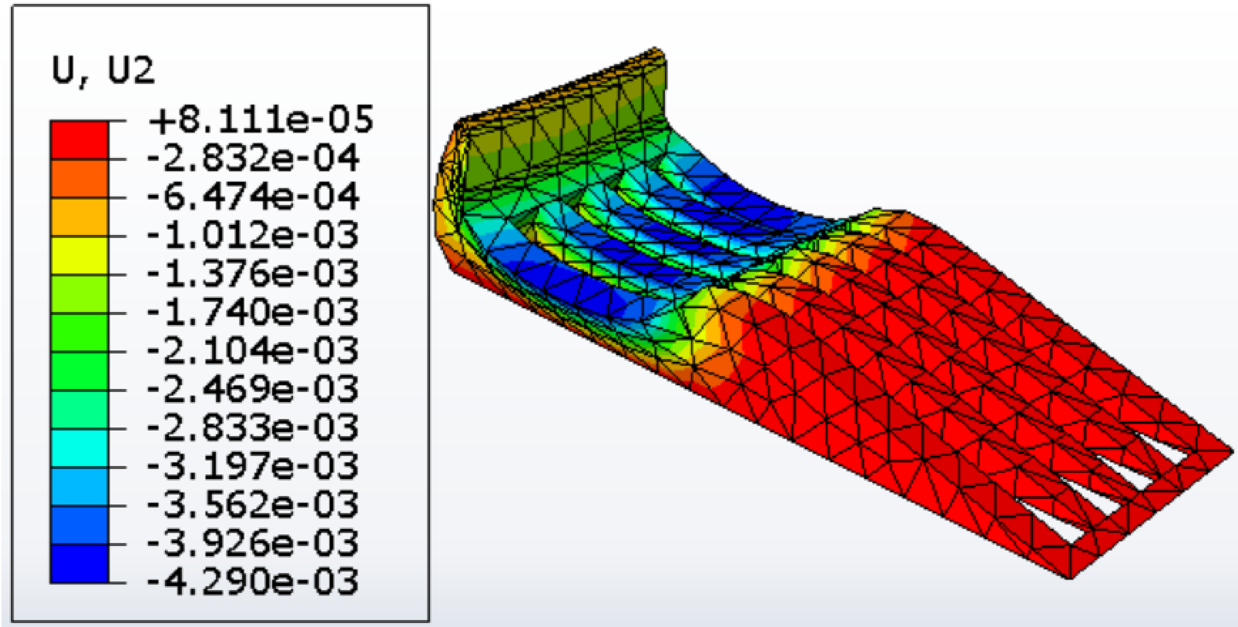
*Note: the units of U and S are both psi

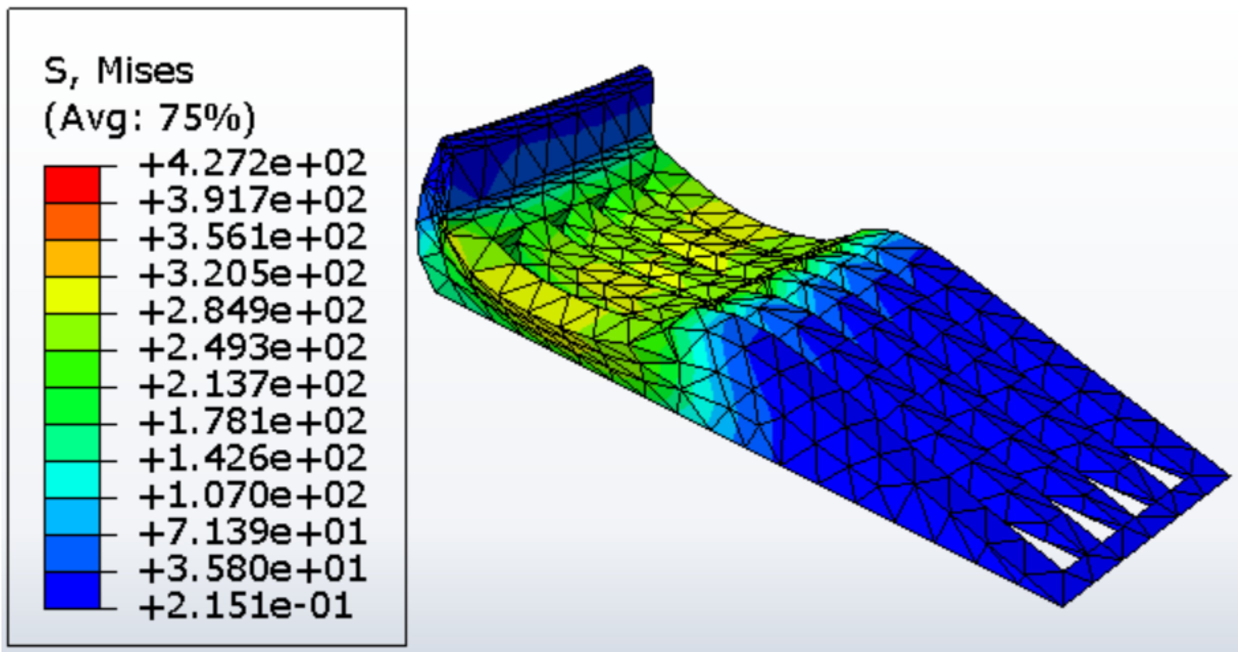
PMMA Model 1 Ramp - Standard Ramp



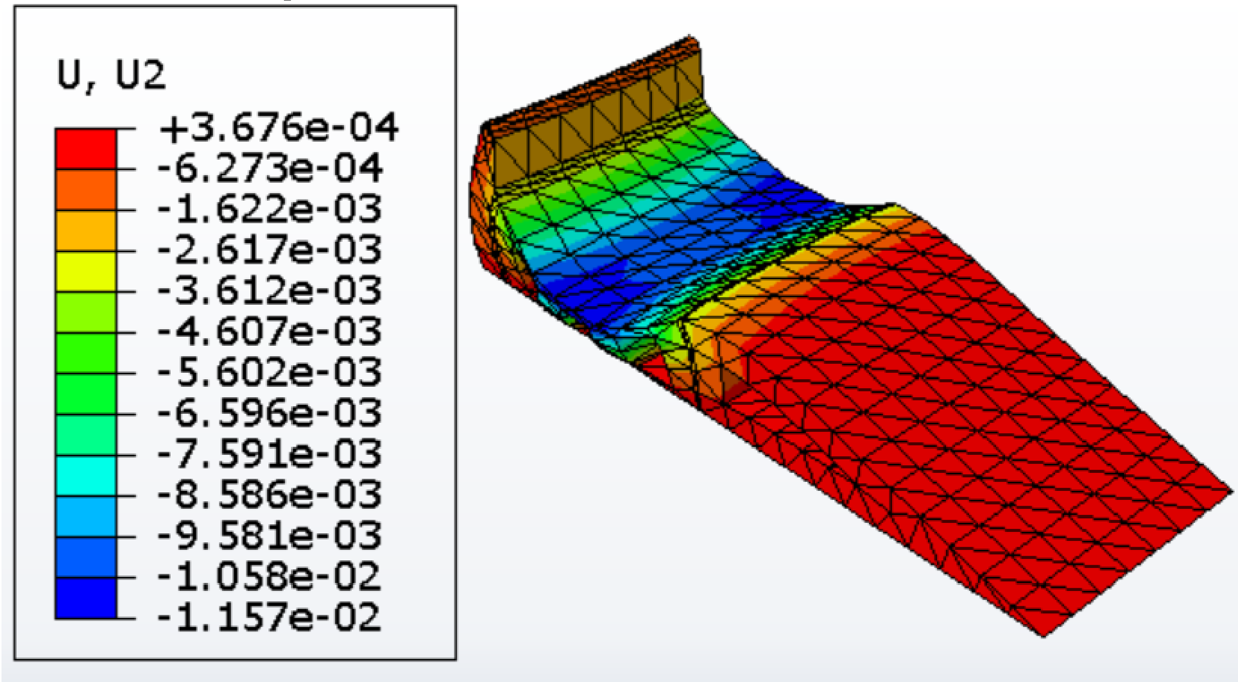


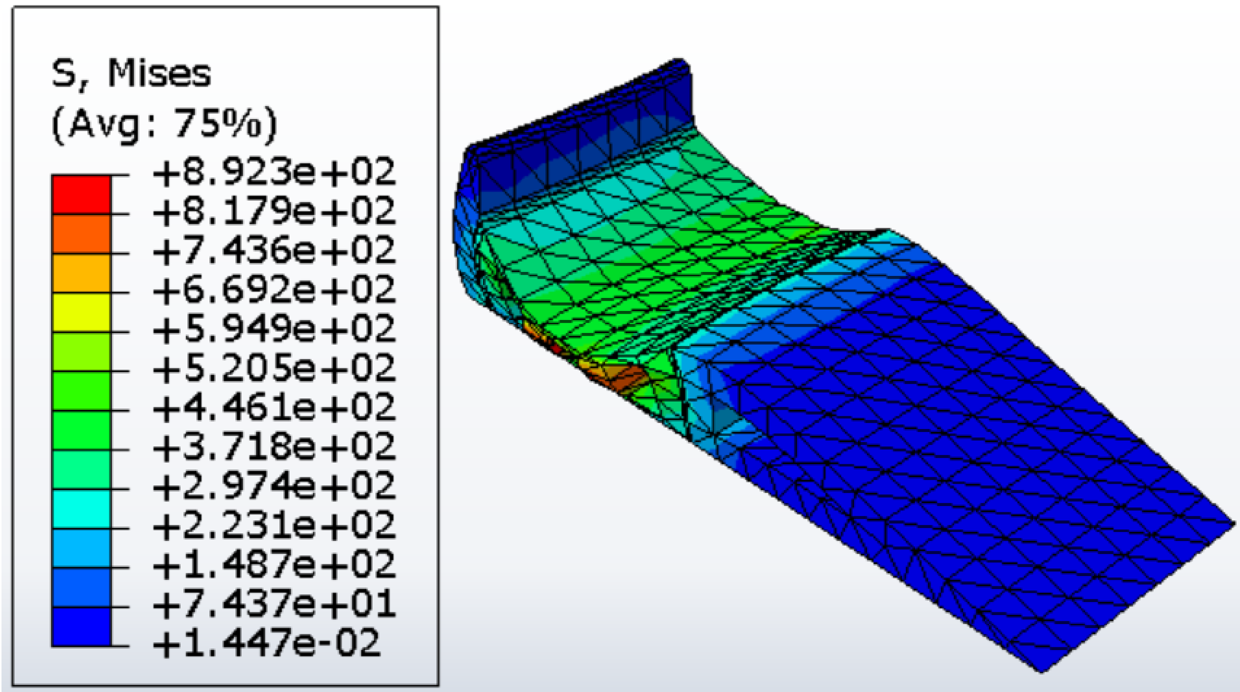
PMMA Model 2 Ramp - Vertical Sections



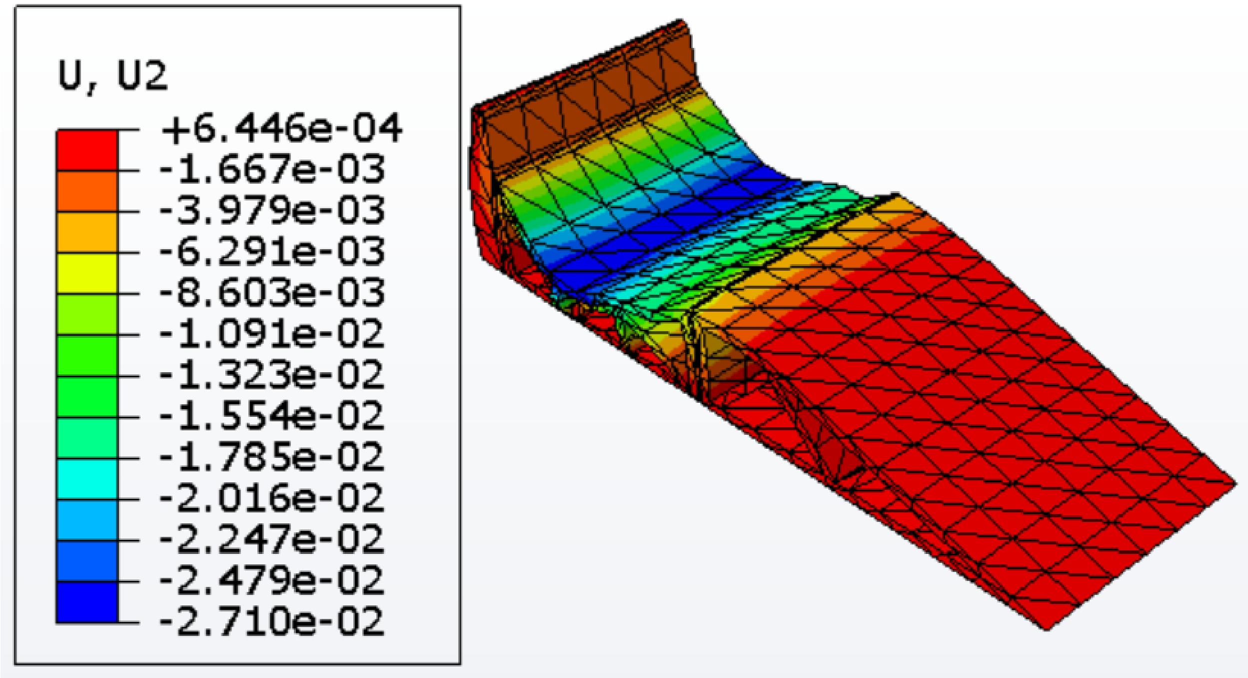


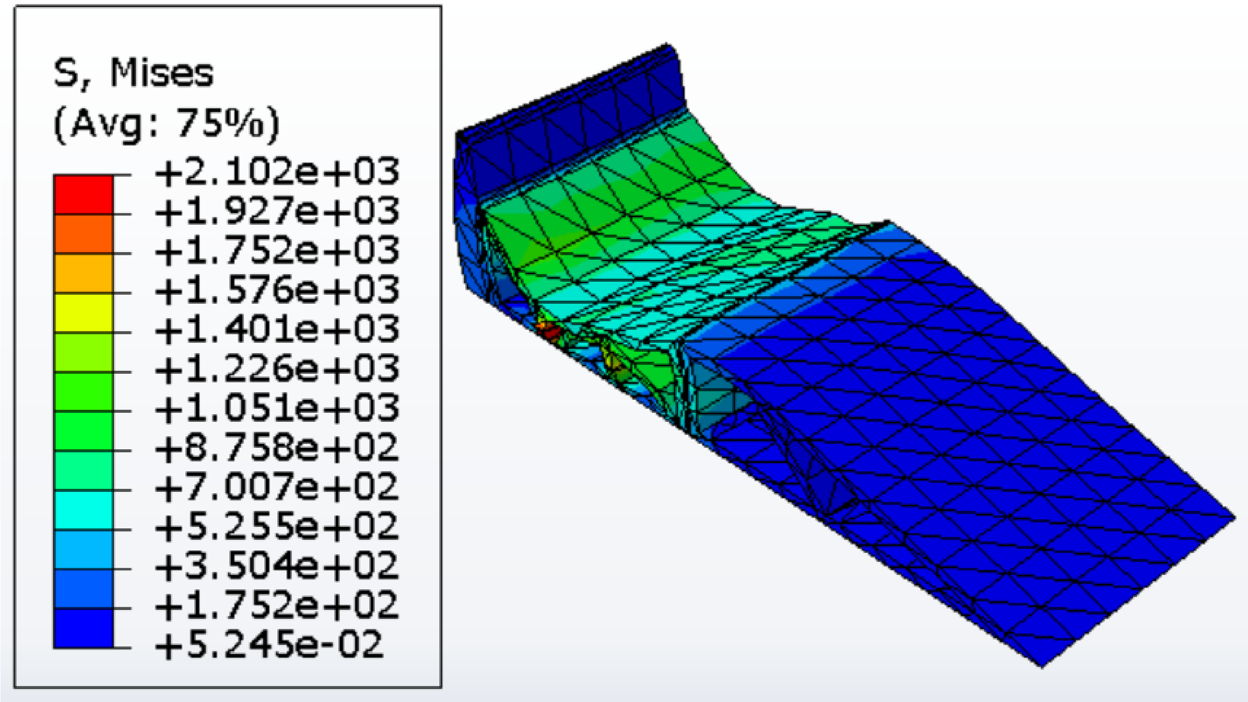
PMMA Model 3 Ramp - Horizontal Sections



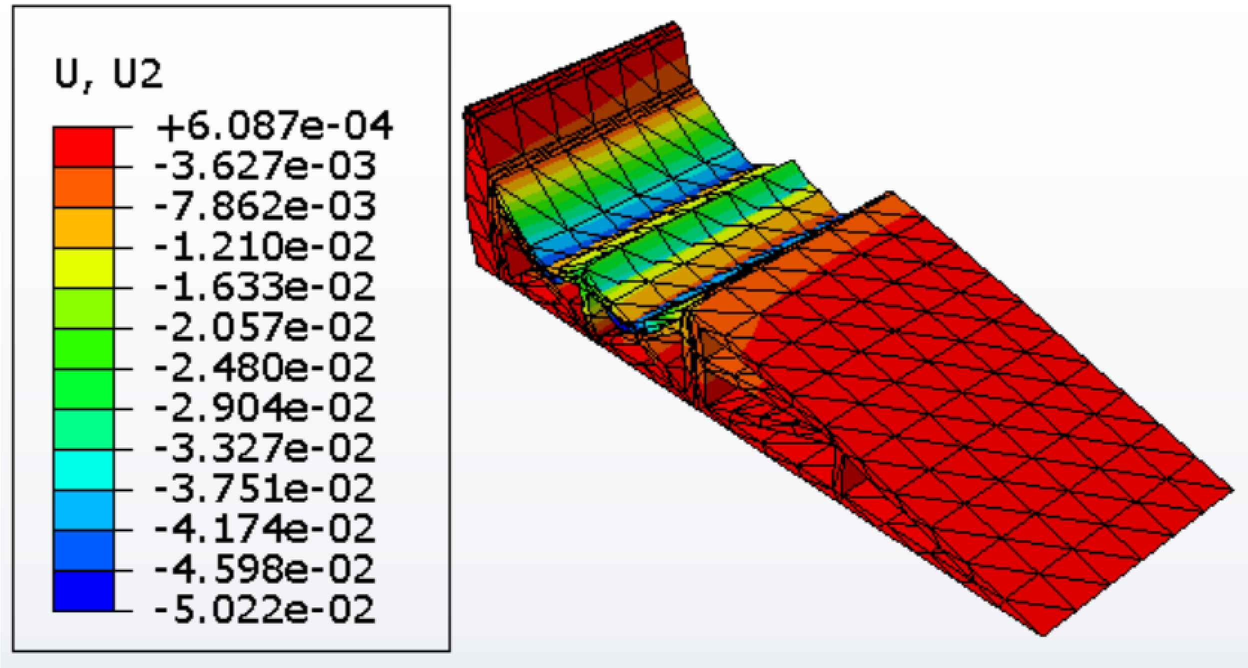


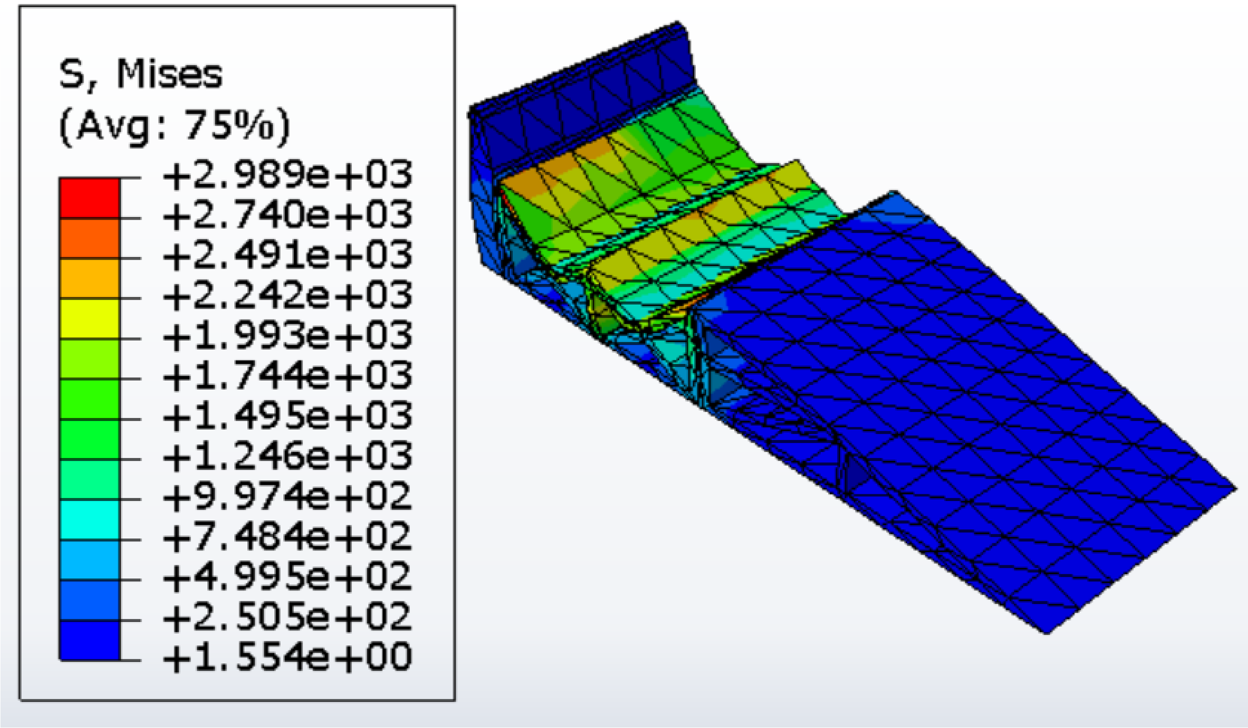
PMMA Model 4 Ramp - Triangle-Truss Supports





PMMA Model 5 Ramp - X-Truss Supports

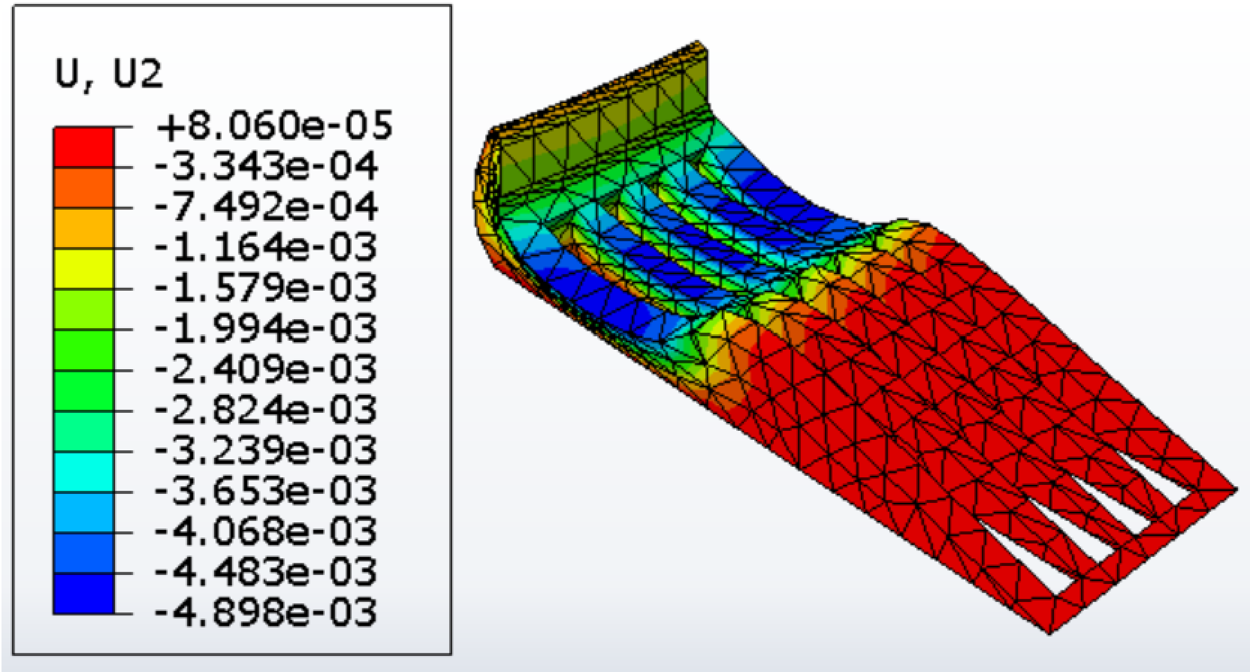


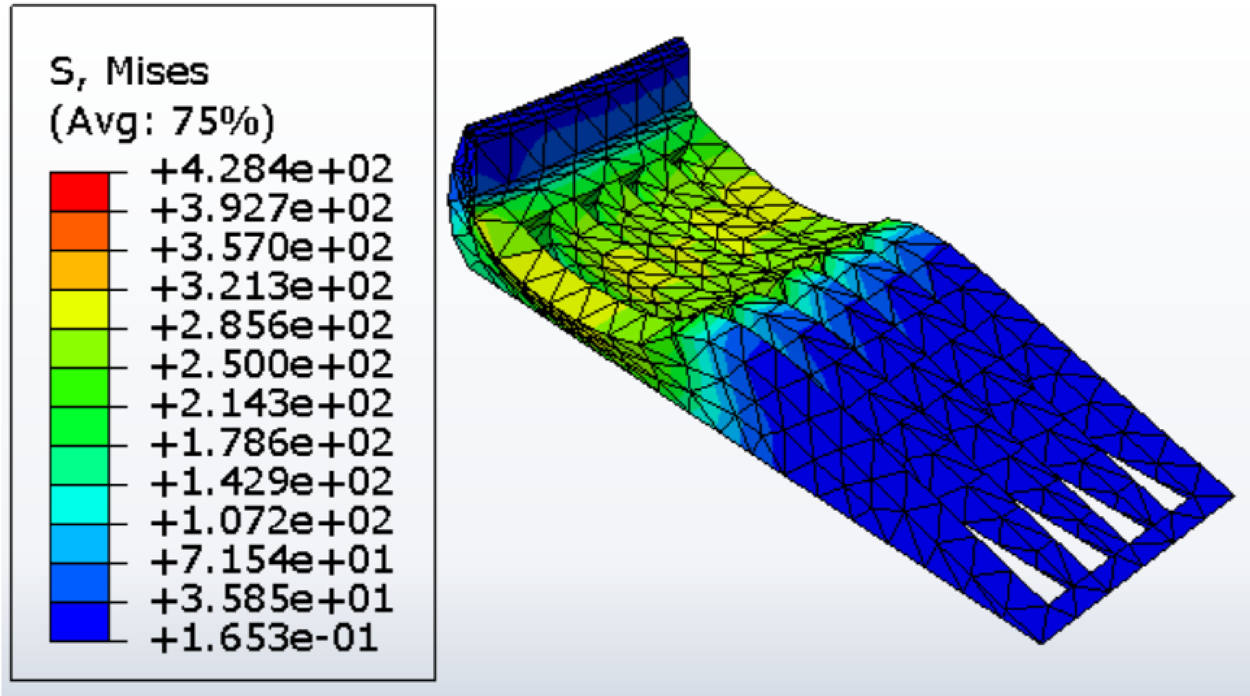


Appendix 4: Color Contour Plots of Various Materials, Constant Model (Model 2)

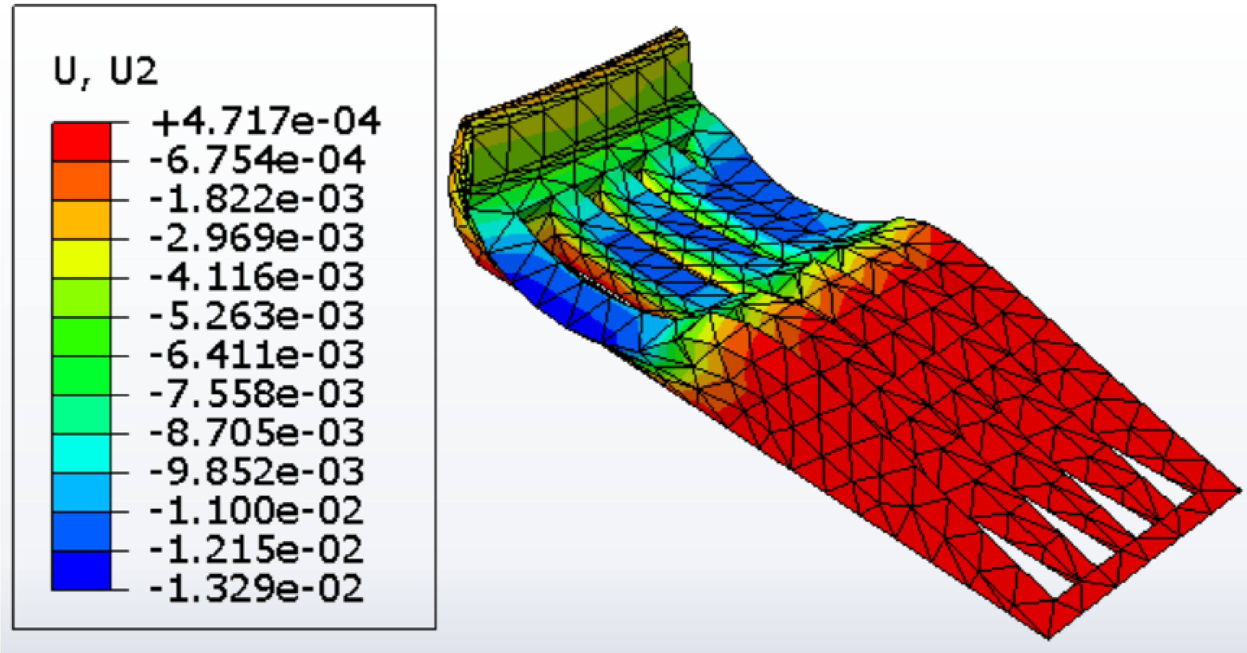
*Note: the units of U and S are both psi

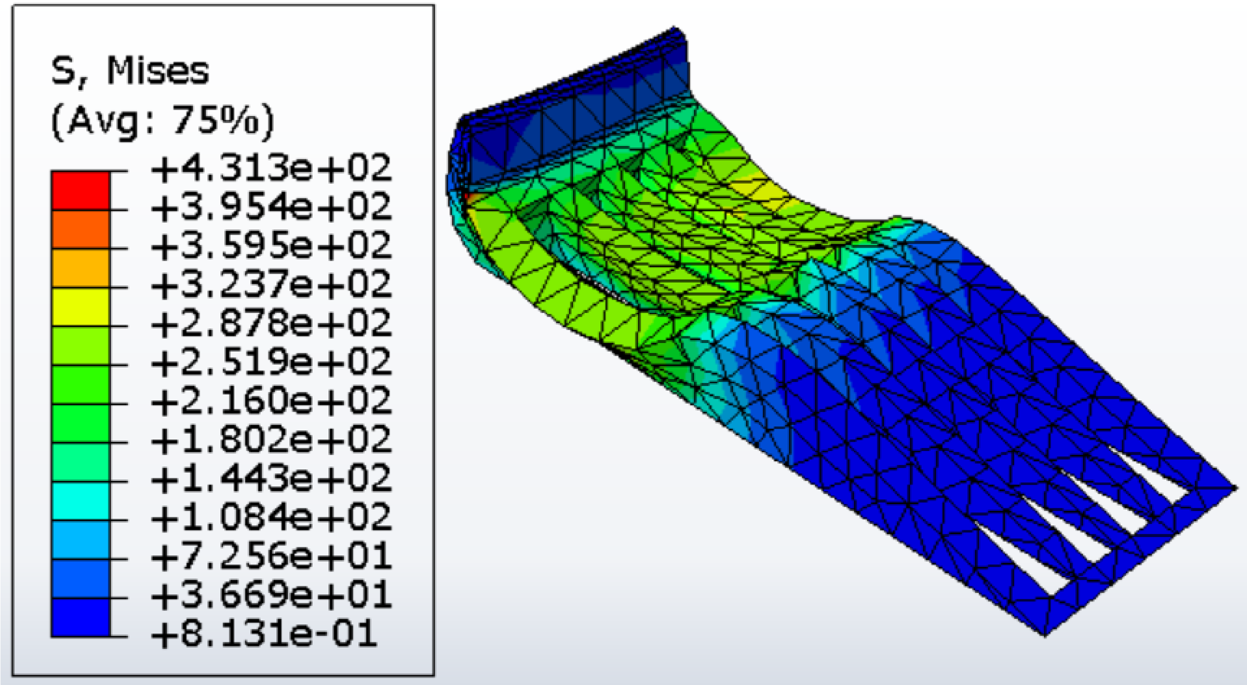
Impact Grade, Molded ABS Model 2 Ramp - Vertical Sections



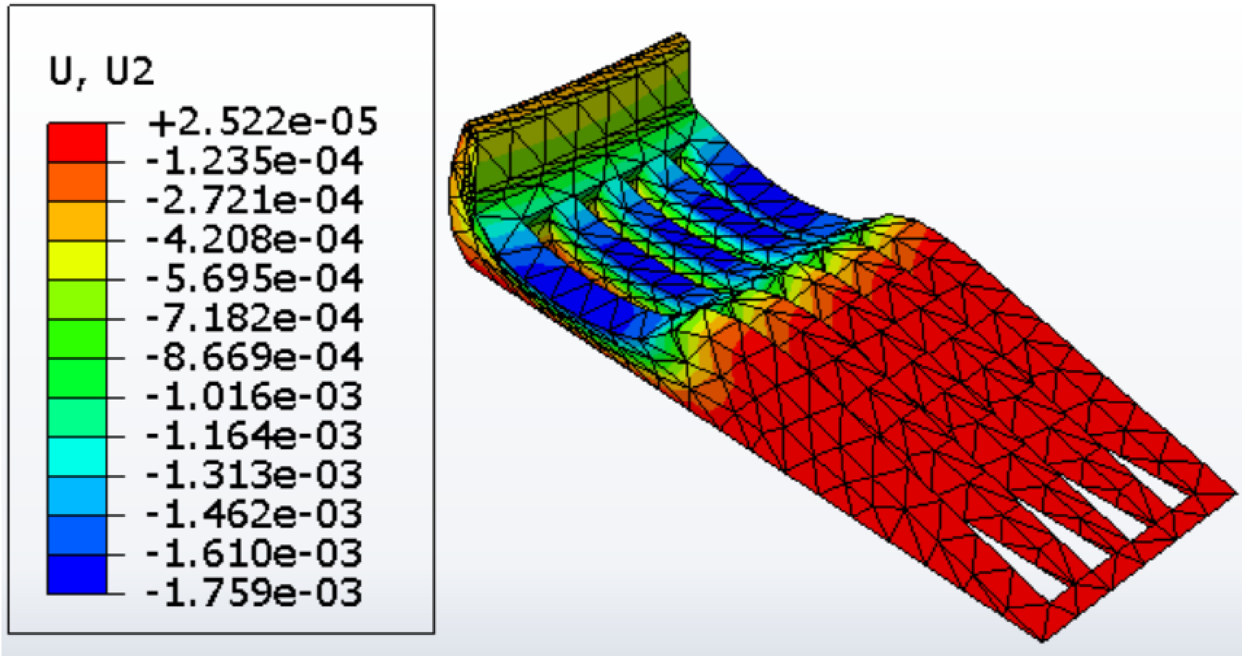


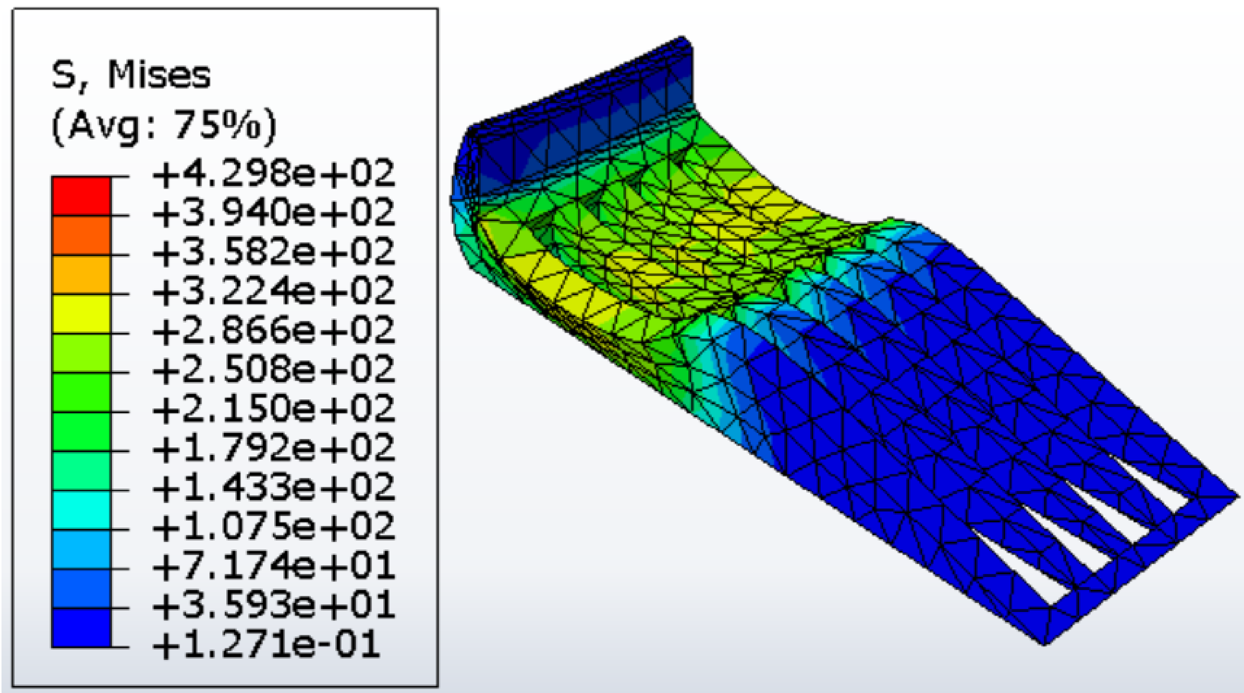
Impact Grade HDPE Model 2 Ramp - Vertical Sections



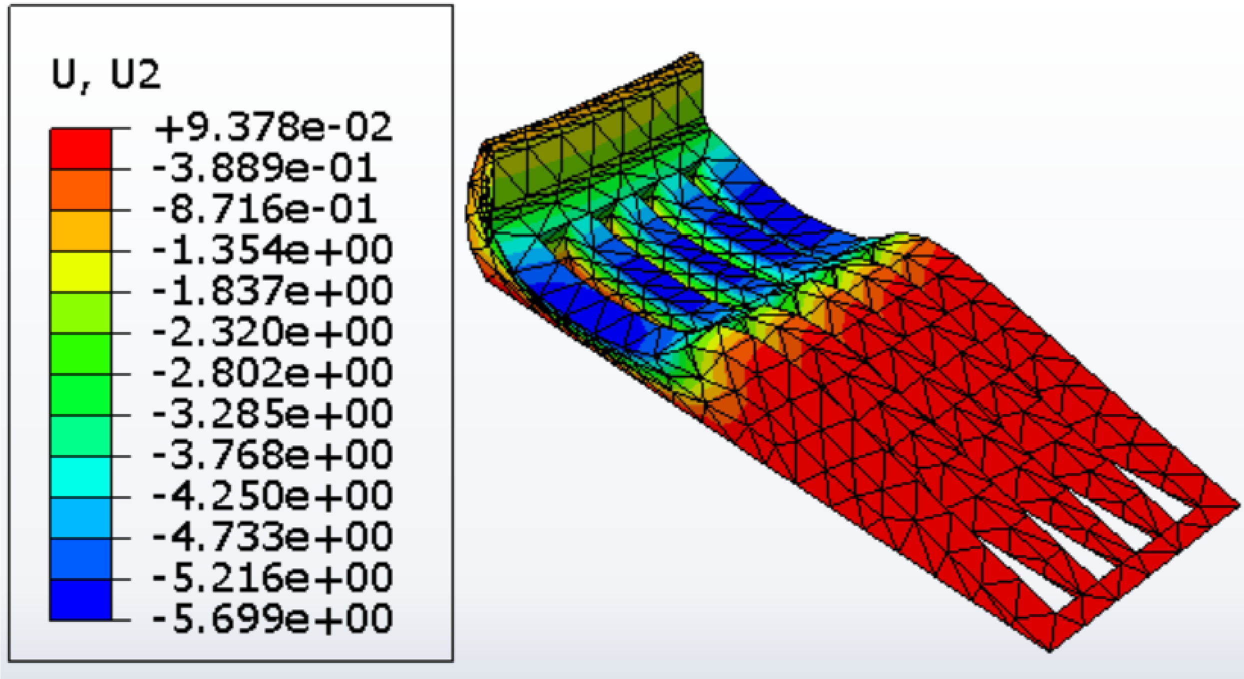


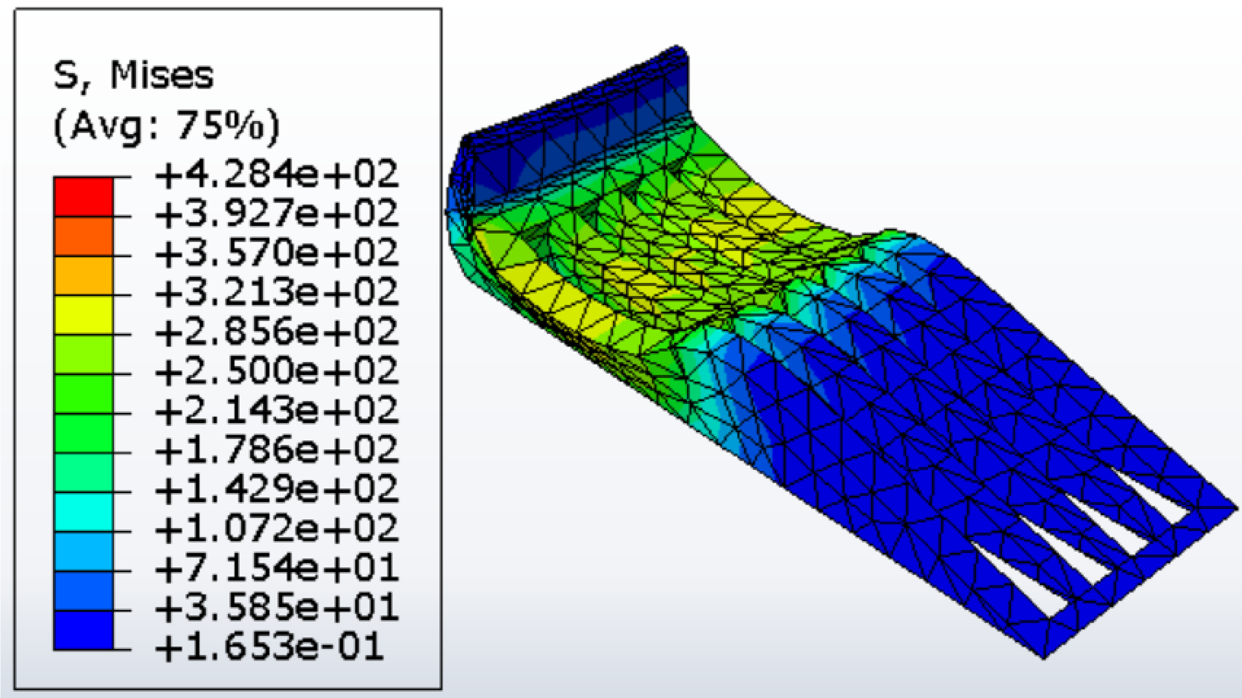
PLA Biopolymer Model 2 Ramp - Vertical Sections



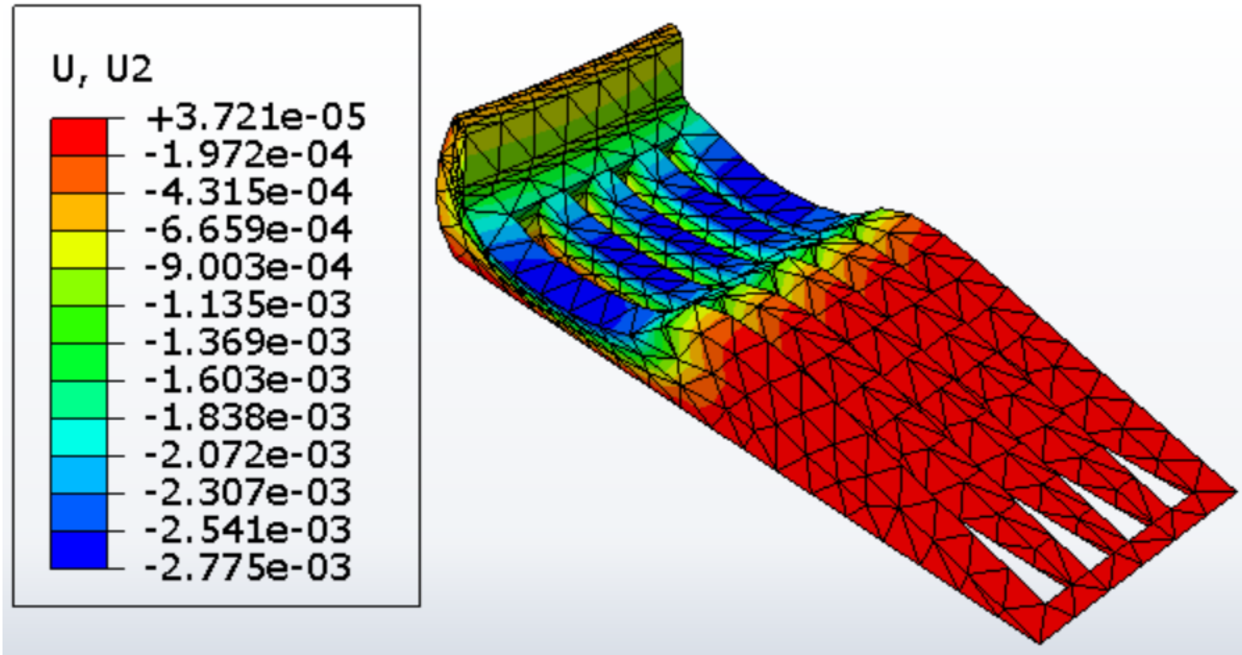


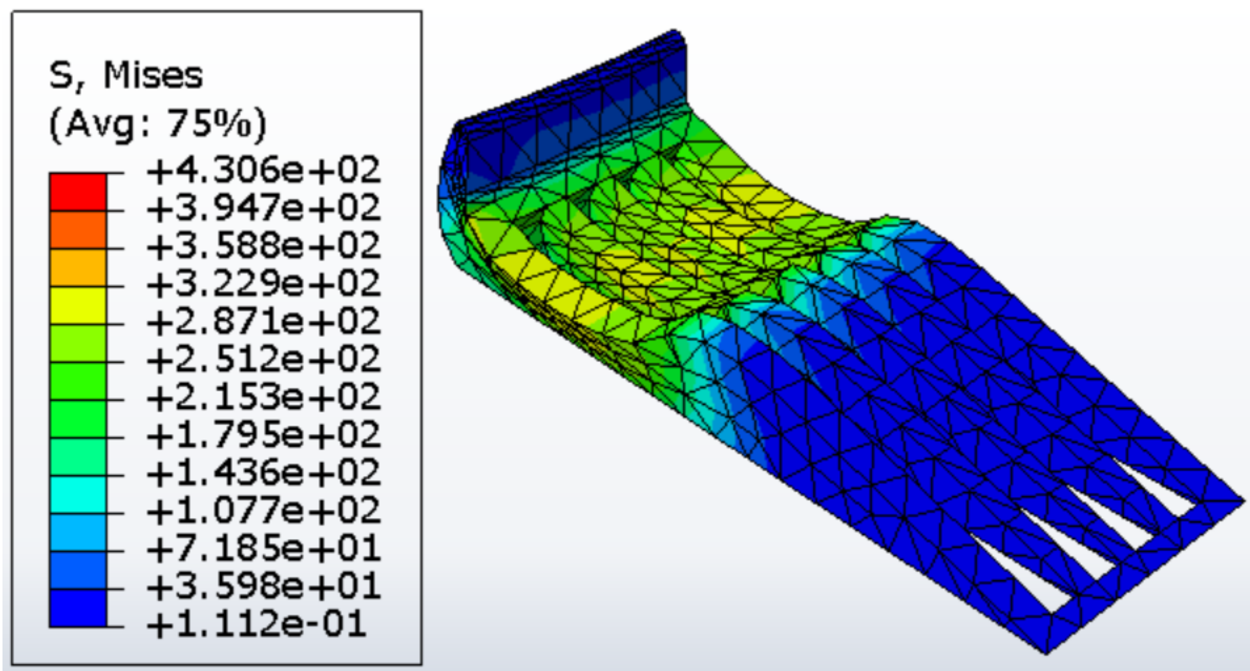
Impact Modified PS Model 2 Ramp - Vertical Sections





Rigid Grade PVC Model 2 Ramp - Vertical Sections





PMMA (Acrylic) Model 2 Ramp - Vertical Sections