Innovative Cargo Rack Solutions

A Senior Project

presented to

the Faculty of the Mechanical Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

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June, 2012

Innovative Cargo Rack Solutions Final Design Report

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California Polytechnic State University

San Luis Obispo 2011

Statement of Confidentiality

The complete senior project report was submitted to the project advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

Statement of Disclaimer

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Executive Summary

This report describes the process of designing, building, and testing a lowering mechanism for a roof-mounted SUV cargo box. It provides a detailed problem description and a specific list of requirements that our design must comply with. Existing products and concepts are presented which meet one or more of our design requirements. Six design concepts are discussed and down-selected to three for further development. A final design has been chosen and described in detail. A team management plan is included to specify member responsibilities and a schedule details major deadlines and goals. Manufacturing processes and testing procedures are described in detail. The resulting prototype is discussed, evaluated, and future improvements are presented. Further development of the design is described and conclusions based on the prototype's performance have been provided.

FIGURE 1: PHOTOGRAPH OF FINISHED PROTOTYPE

Chapter 1: Introduction

Problem Statement

[redacted]

List of Requirements

[redacted]

[redacted]

Design Specifications

[redacted]

Chapter 2: Background

Existing Products

[redacted]

[redacted]

FIGURE 2.YAKIMA EZ LOADER

[redacted]

FIGURE 3. THULE HULLAVATOR

[redacted]

Figure 4. Safari Condo

Off-the-Shelf Product Implementation

[redacted]

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Figure 5. Examples of Thule Feet

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FIGURE 6. EXAMPLES OF SPRING AND DAMPERS

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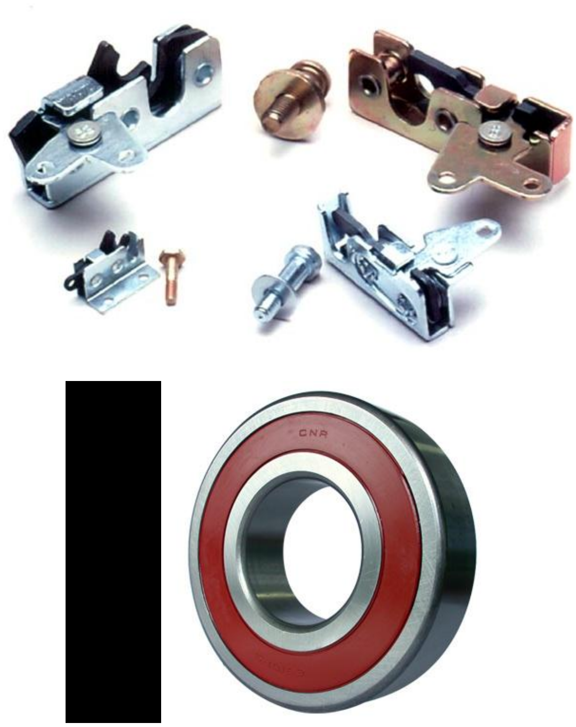

FIGURE 7. BEARINGS AND LATCHES

Chapter 3: Design Development

Method of Approach

[redacted]

Ideation

[redacted]

[redacted]

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[redacted]

[redacted]

[redacted]

[redacted]

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Down-Selecting and Final Design Concept

[redacted]

[redacted]

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Design Variations

[redacted]

[redacted]

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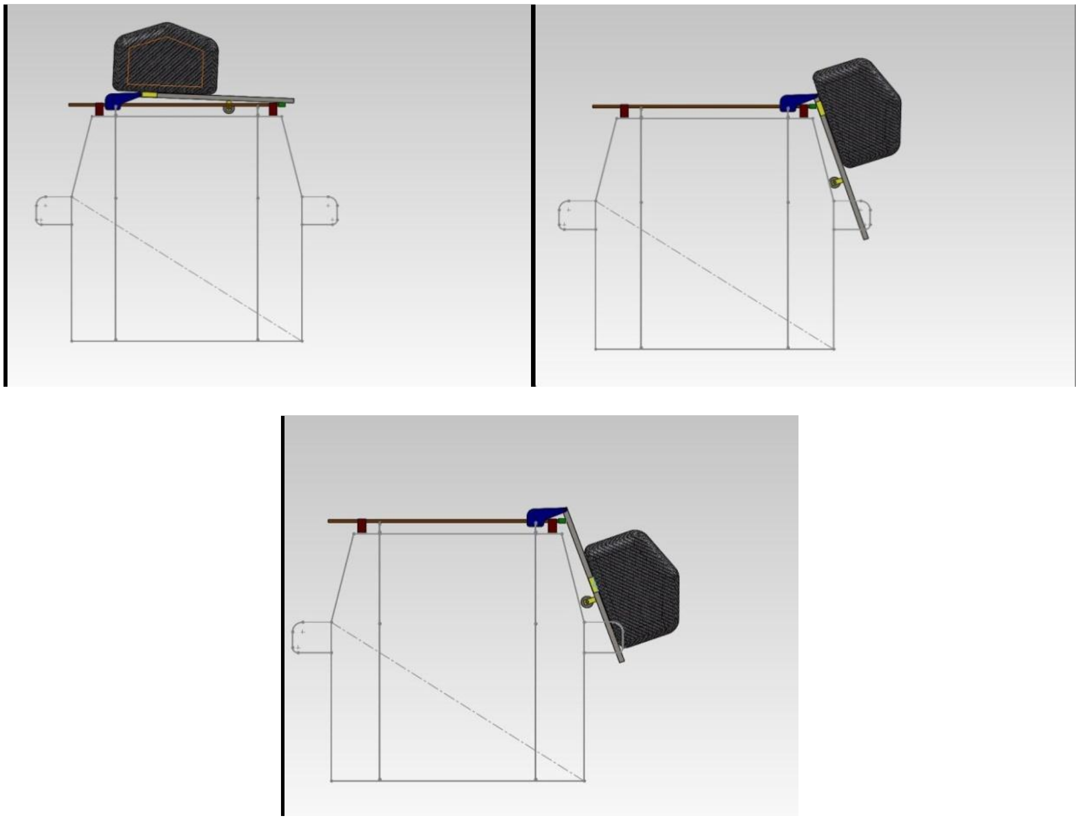

FIGURE 8. DESIGN VARIATION #1 MOTION IN SOLIDWORKS

[redacted]

[redacted]

[redacted]

[redacted]

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Chapter 4: Description of Final Design

Final Design Layout

FIGURE 9. CARGO BOX MECHANISM IN POSITION FOR CARGO LOADING.

[redacted]

[redacted]

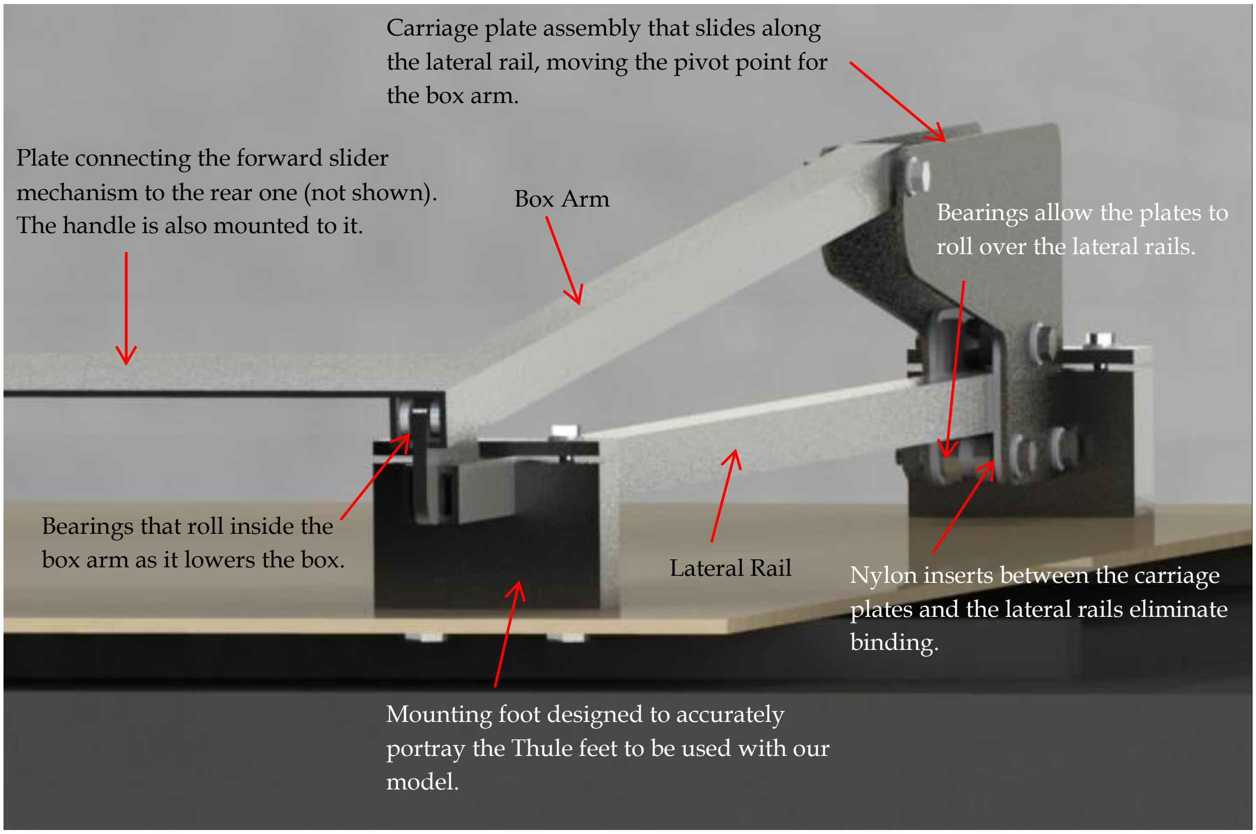

FIGURE 10. LAYOUT OF THE SLIDER MECHANISM THAT LOWERS THE CARGO BOX FOR LOADING. THE LATERAL RAIL RUNS LEFT TO RIGHT ON THE TOP OF THE VEHICLE, WITH THE FRONT BEING TO THE RIGHT.

Final Design Decision Process

[redacted]

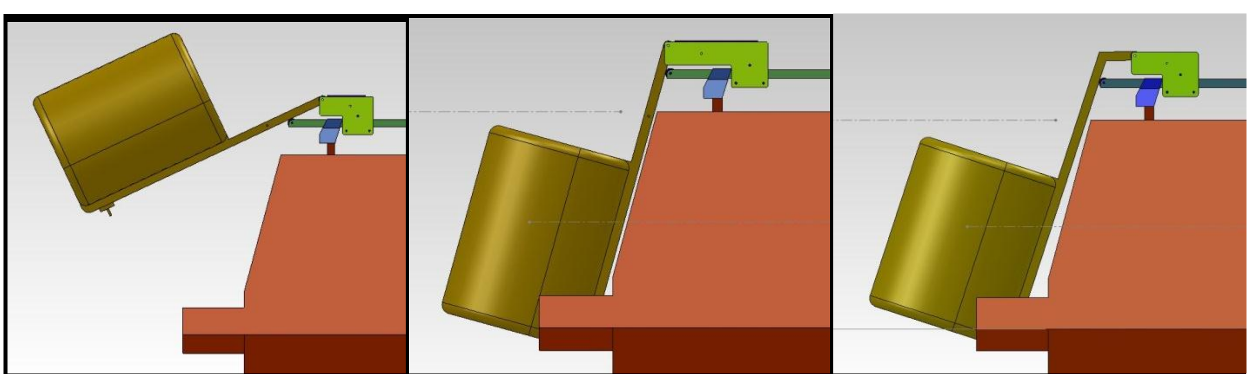

FIGURE 11. SCREEN SHOTS OF THE DIFFERENT SLIDER CONFIGURATIONS WITH THE SHORTER SLIDER (LEFT), THE LONG SLIDER (MIDDLE), AND THE SHORT SLIDER WITH A BENT CANTILEVER ARM (RIGHT).

[redacted]

[redacted]

[redacted]

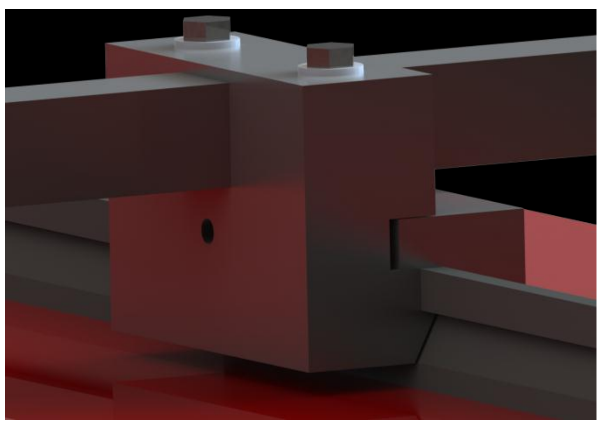

FIGURE 12. PROTOTYPED FOOT ASSEMBLY

[redacted]

FIGURE 13. QUICK RELEASE PINS LOCK CARGO BOX IN STOWED POSITION

Project Scheduling

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Cargo Box Design

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FIGURE 14. SOLIDWORKS MODEL OF PLUG.

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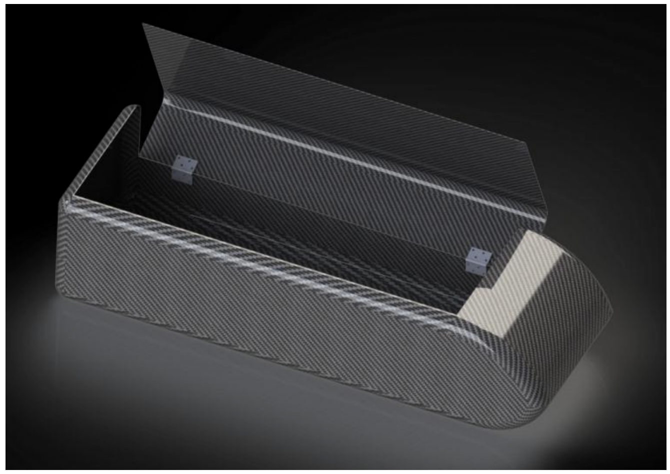

FIGURE 15. SOLIDWORKS MODEL OF BOX AND LID ASSEMBLY.

[redacted]

Cargo Box Manufacturing

[redacted]

[redacted]

Figure 16. Shopbot Cutting Plug out of Foam.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

A change in direction for the cargo box

[redacted]

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[redacted]

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FIGURE 17. MODIFIED CARGO BOX

Design Analysis

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[redacted]

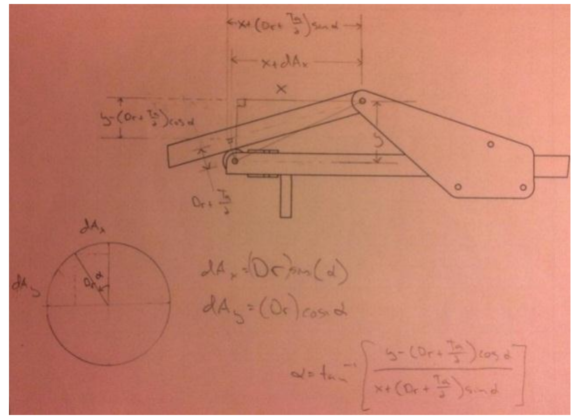

FIGURE 18. CARGO BOX SLOPE ALPHA, AS A FUNCTION OF CONTROL DIMENSION X.

[redacted]

[redacted]

[redacted]

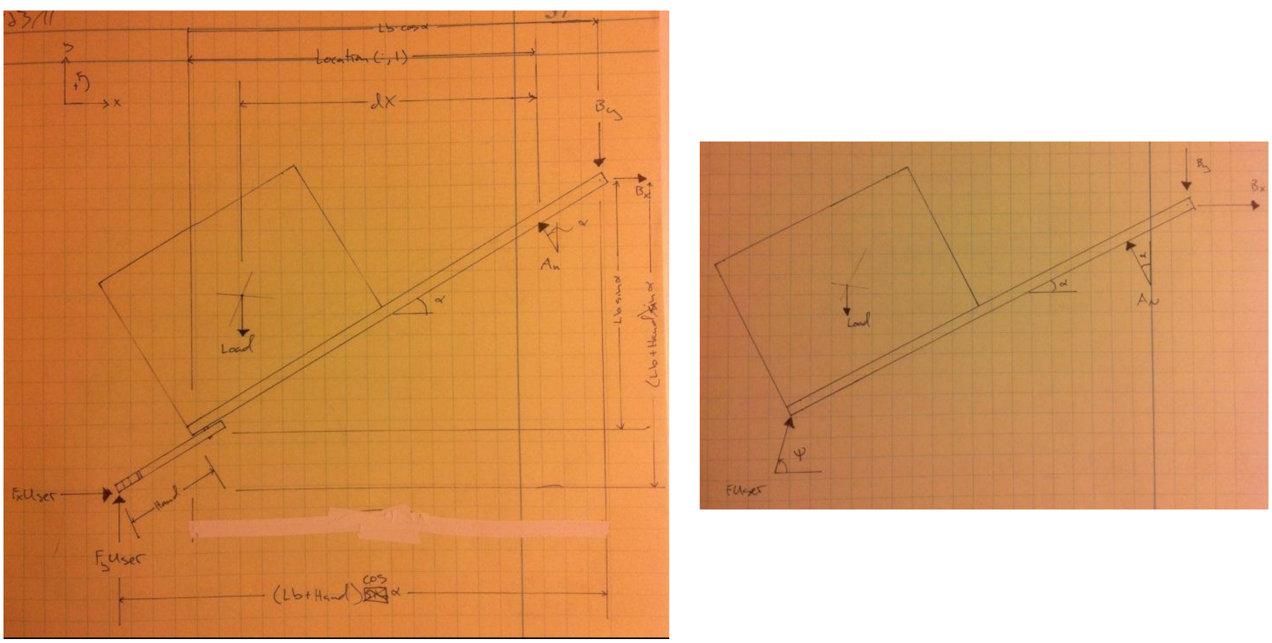

FIGURE 19. DIMENSIONED FREE BODY DIAGRAM OF CARGO BOX.

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[redacted]

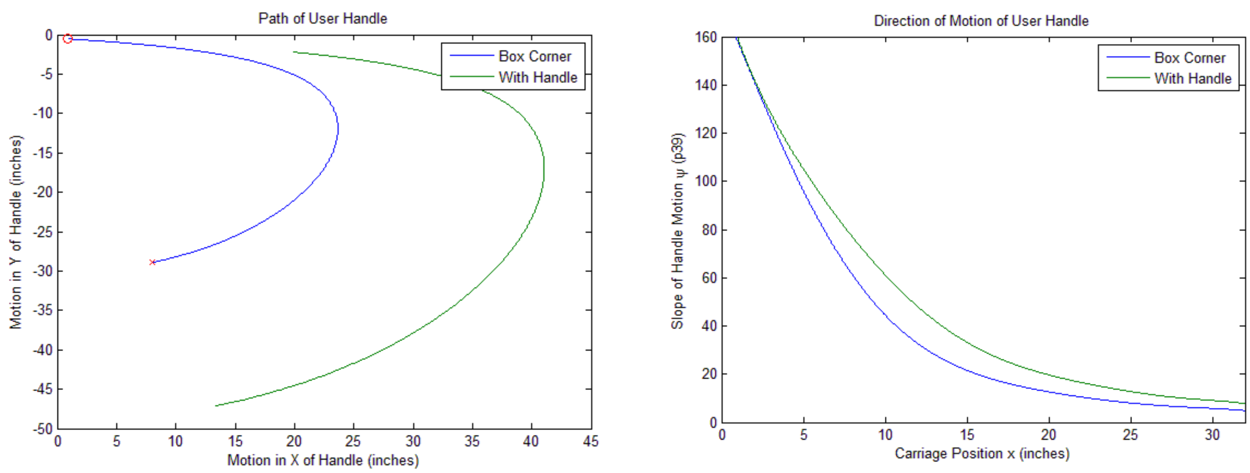

FIGURE 20. USER HANDLE PATH AND USER FORCE DIRECTION

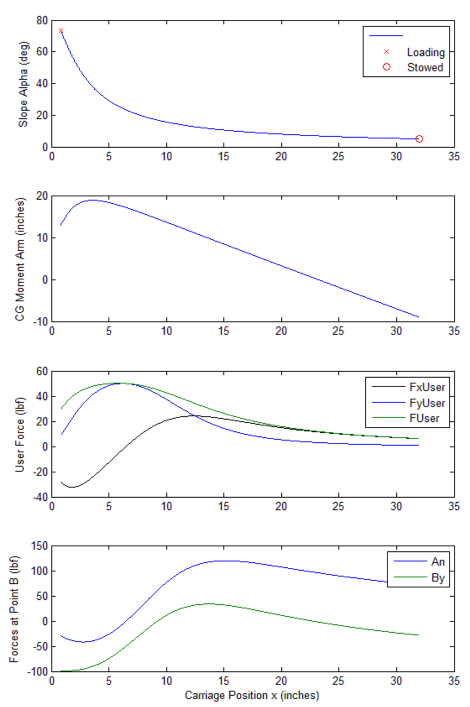

FIGURE 21. GEOMETRIC RELATIONS AND RELEVANT FORCES.

[redacted]

[redacted]

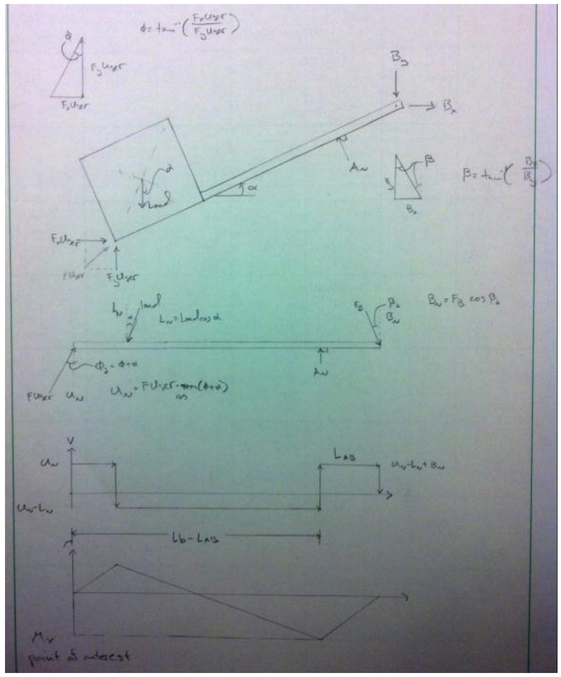

FIGURE 22. SHEAR AND BENDING MOMENT DIAGRAMS FOR BOX-MOUNTED RAILS.

[redacted]

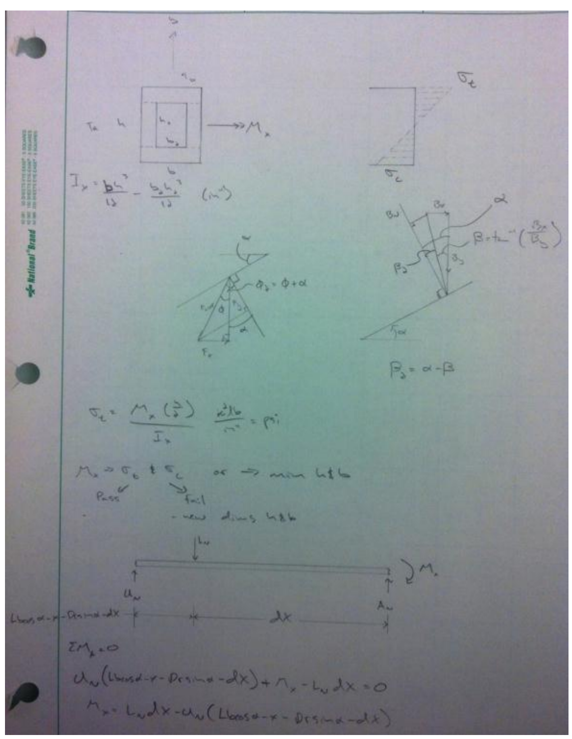

FIGURE 23. FAILURE ANALYSIS IN BOX-MOUNTED RAILS DUE TO BENDING.

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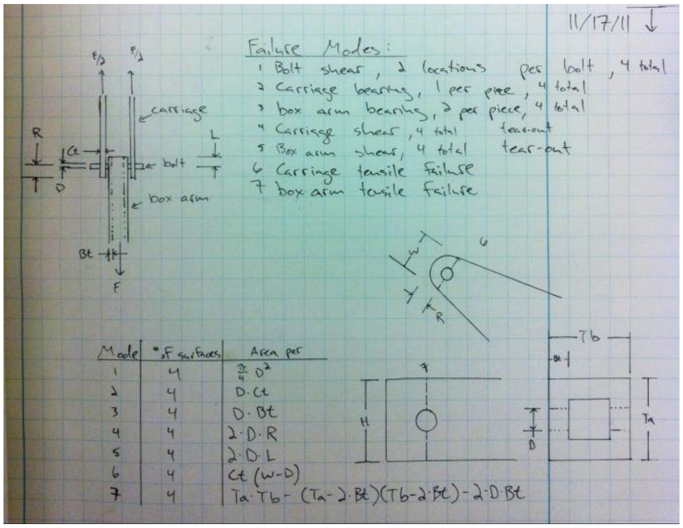

FIGURE 24. FAILURE MODES AT POINT B.

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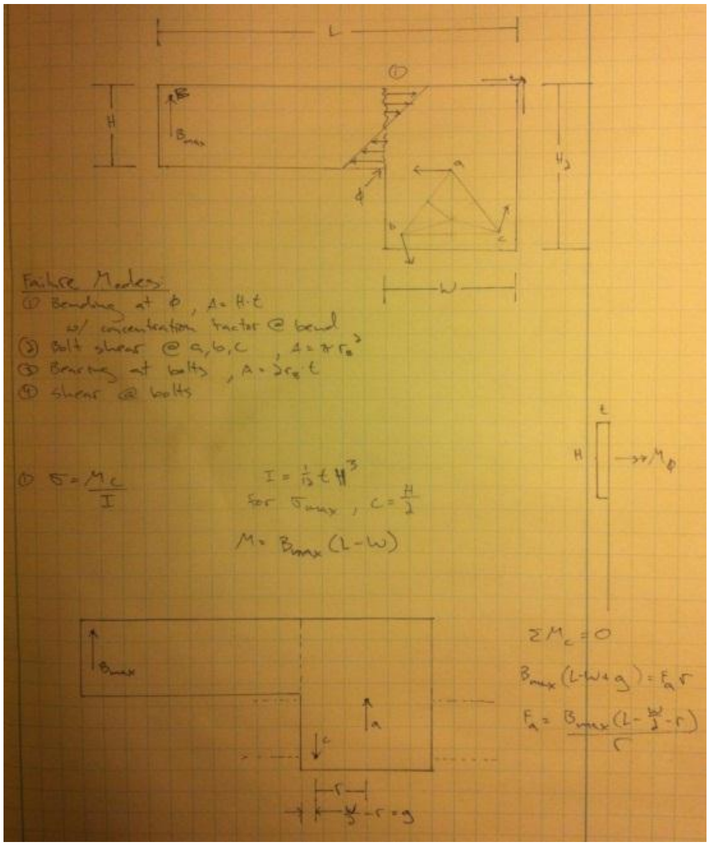


FIGURE 25. FAILURE MODES FOR THE CARRIAGE PLATES.

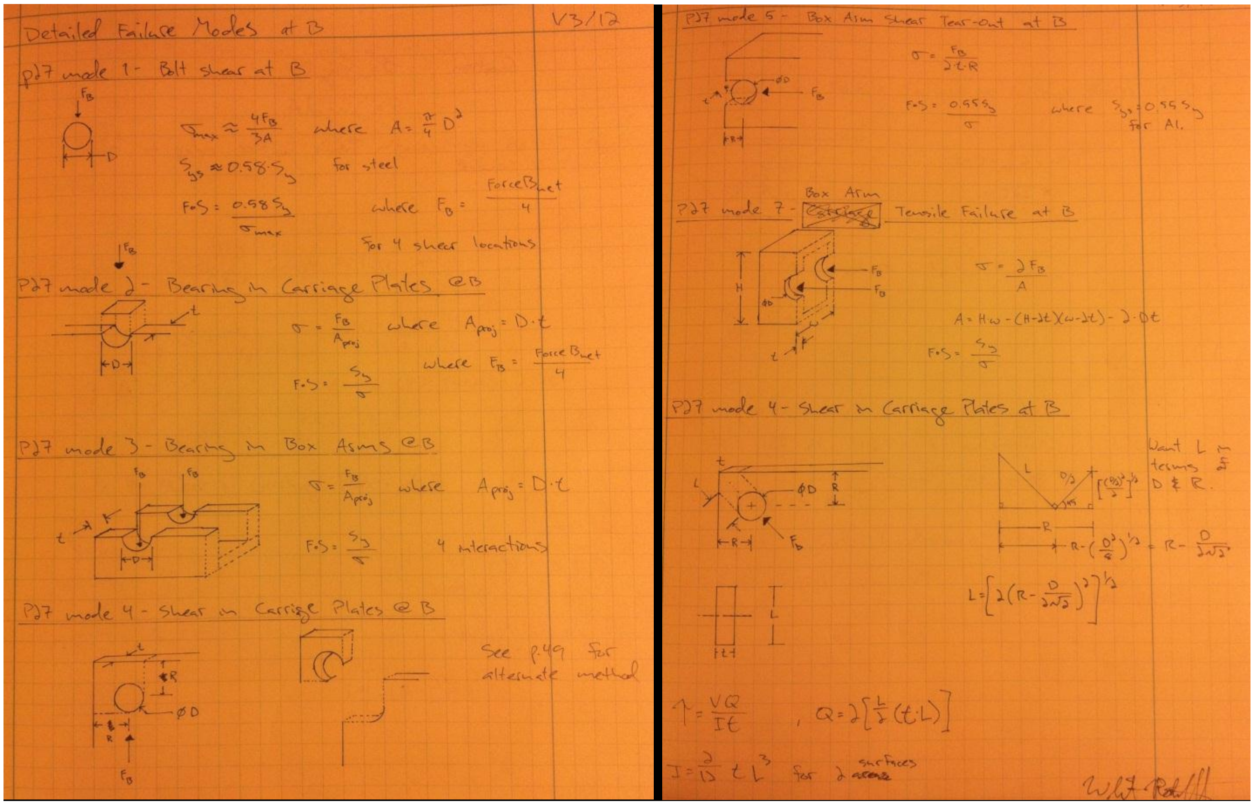


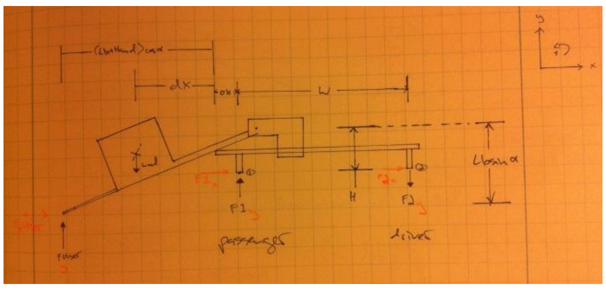
FIGURE 26. DETAILED FAILURE MODES AT POINT B.

[redacted]

TABLE 1. MECHANICAL FAILURE MODES & THE RESULTING SAFETY FACTOR FOR EACH.

[redacted]

[redacted]



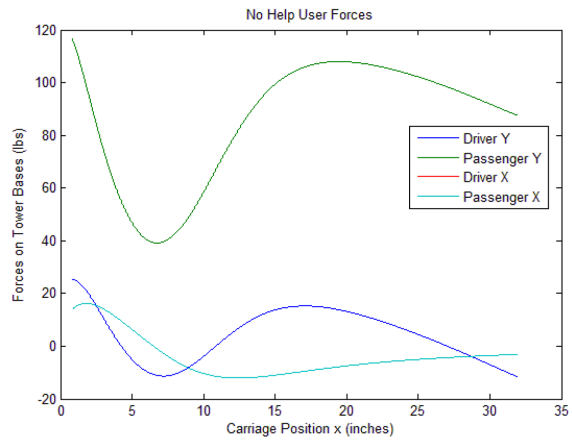


FIGURE 27. SYSTEM FREE BODY DIAGRAM AND ROOF FORCES.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

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Cost Analysis

[redacted]

Safety Considerations

[redacted]

[redacted]

Maintenance and Repairs

[redacted]

[redacted]

[redacted]

[redacted]

Chapter 5: Design Verification Plan

User Force Verification

[redacted]

[redacted]

Carriage Plate Failure

FIGURE 28. PHOTO OF THE EXPERIMENTAL APPARATUS TO BE USED IN CARRIAGE PLATE TESTING.

[redacted]

[redacted]

Box Arm Bending Failure

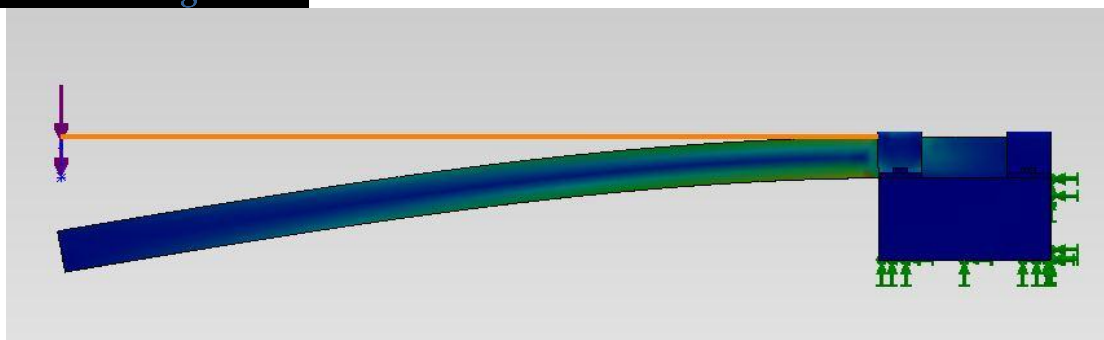

FIGURE 29. FAILURE MODE OF BOX ARM UNDER A BENDING LOAD (DEFLECTION SHOWN IS MAGNIFIED).

[redacted]

Chapter 6: Project Management Plan

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Chapter 7: Conclusions and Recommendations

[redacted]

Future Development

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Box Optimization

[redacted]

User-assist mechanism

[redacted]

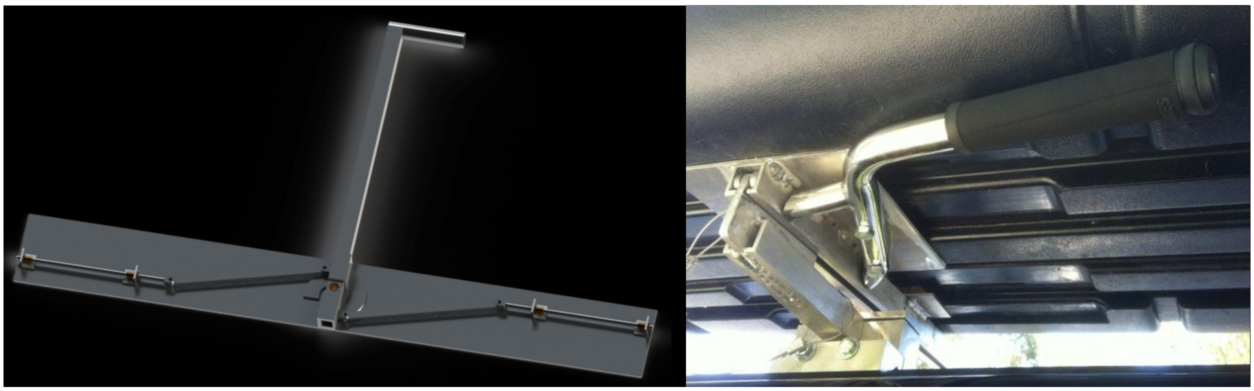

FIGURE 30. USER HANDLE

[redacted]

FIGURE 31. PULLEY SYSTEM TO SIMULATE USER ASSIST MECHANISM

[redacted]

Appendix A: References

[redacted]

Existing Products:

http://www.eazydrivemobility.com.au/wheelchair_hoist_roof.html

http://www.safaricondo.com/kayak/indexeng.html

http://www.fiberglassrv.com/forums/f55/kayak-rack-30449-2.html

http://www.orsracksdirect.com/yakima-ez-loader-roof-rack.html

http://thule.com/en/Global

http://yakima.com/

http://www.dailymotion.com/video/xdy3uh_the-ultimate-roof-rack-system_auto

http://www.karitek.co.uk/ELRRIntroMulti.html

Specifications, standards and other information:

http://papers.sae.org/2011-01-0491

http://papers.sae.org/2006-01-0729/

http://www.toyota.com/

http://www.ford.com/

Contacts:

[redacted] mikeallwein@sbcglobal.net

[redacted] mlmcfarl@calpoly.edu

Appendix B: Schedule

[redacted]

[redacted]

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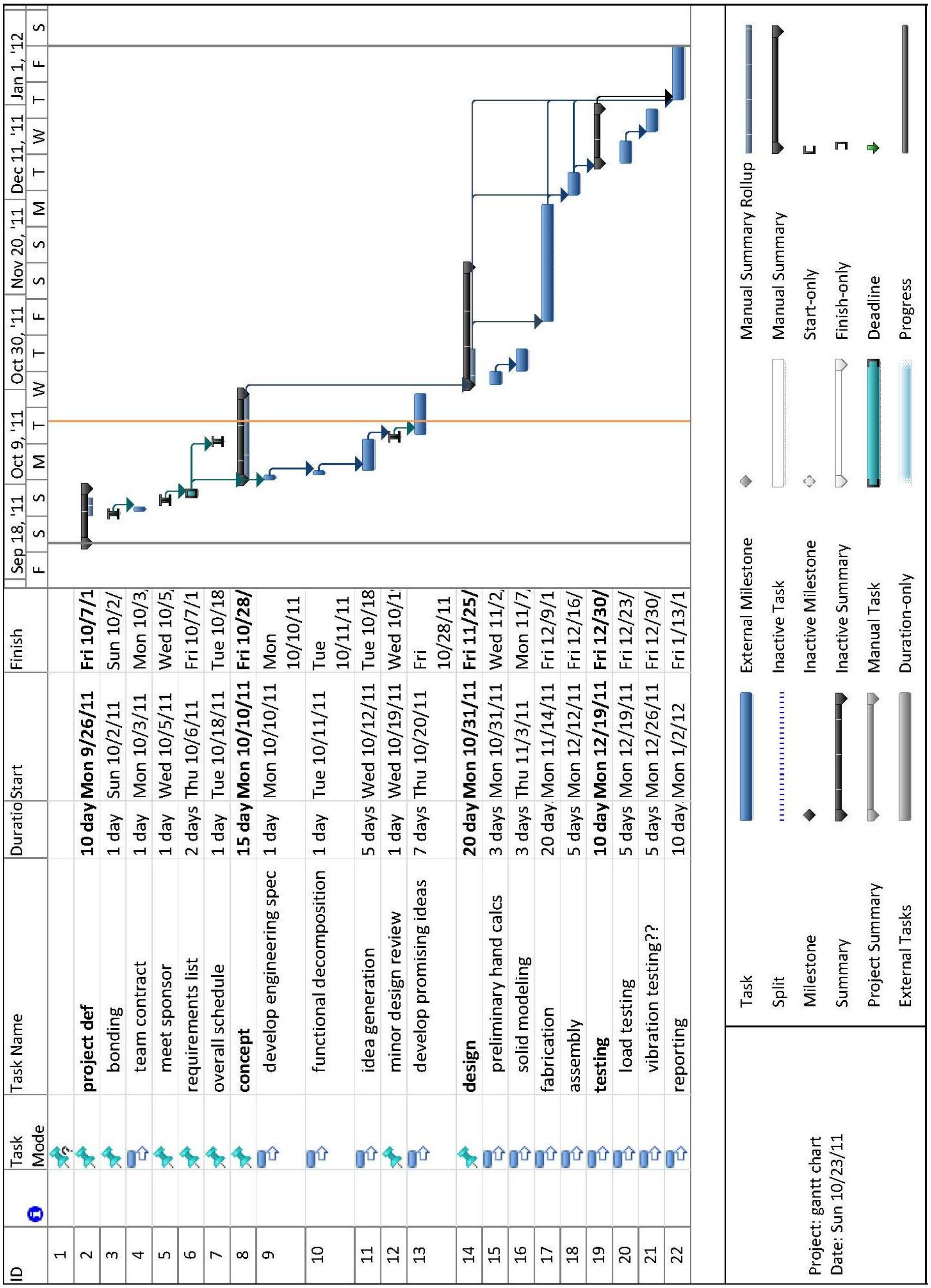
Appendix C: Gantt Chart



Appendix D: Concept Drawings

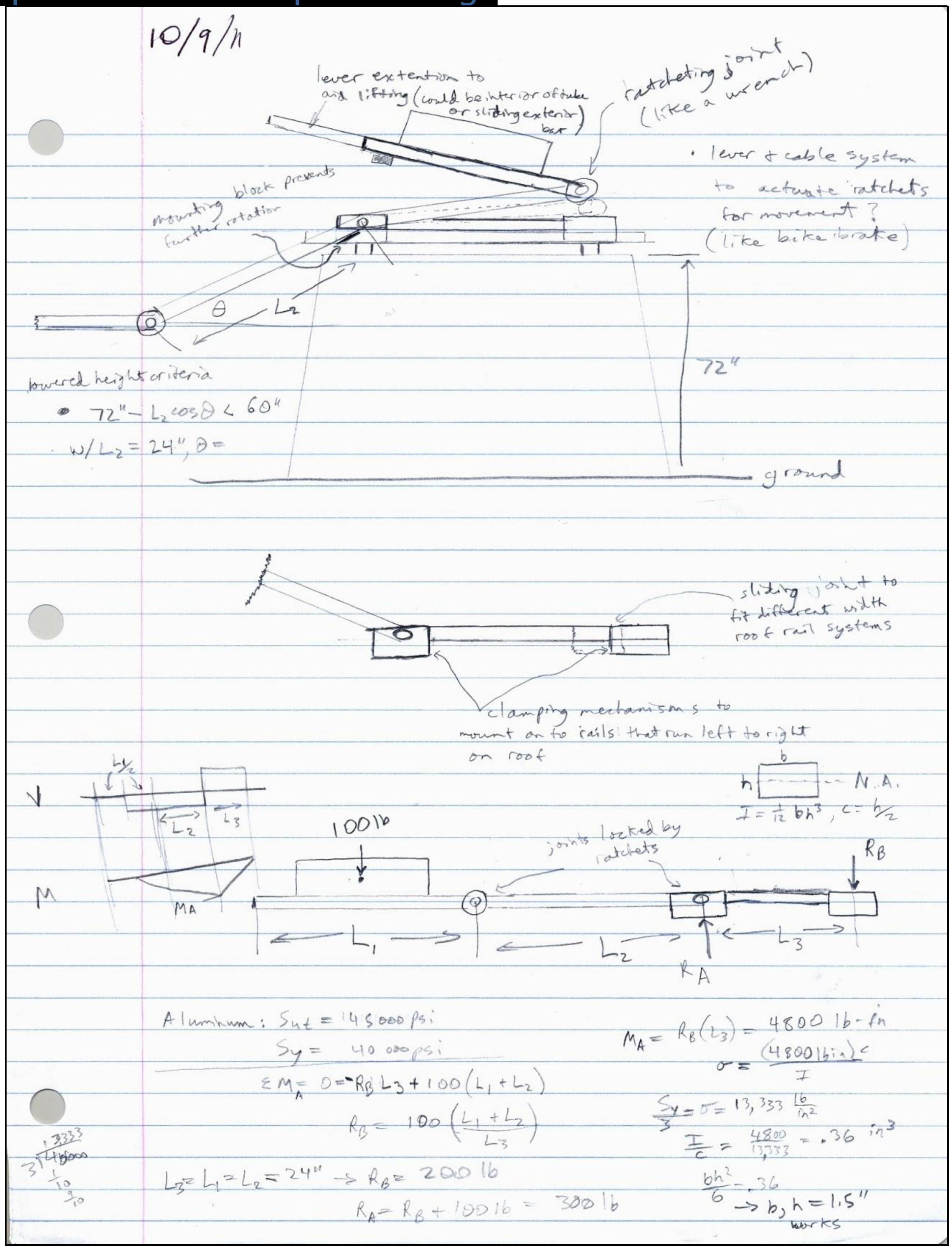


FIGURE 32. CONCEPT DRAWING OF THE FOLDING LINKAGE WITH LOCKING JOINTS AND ACCOMPANYING BASIC CALCULATIONS.

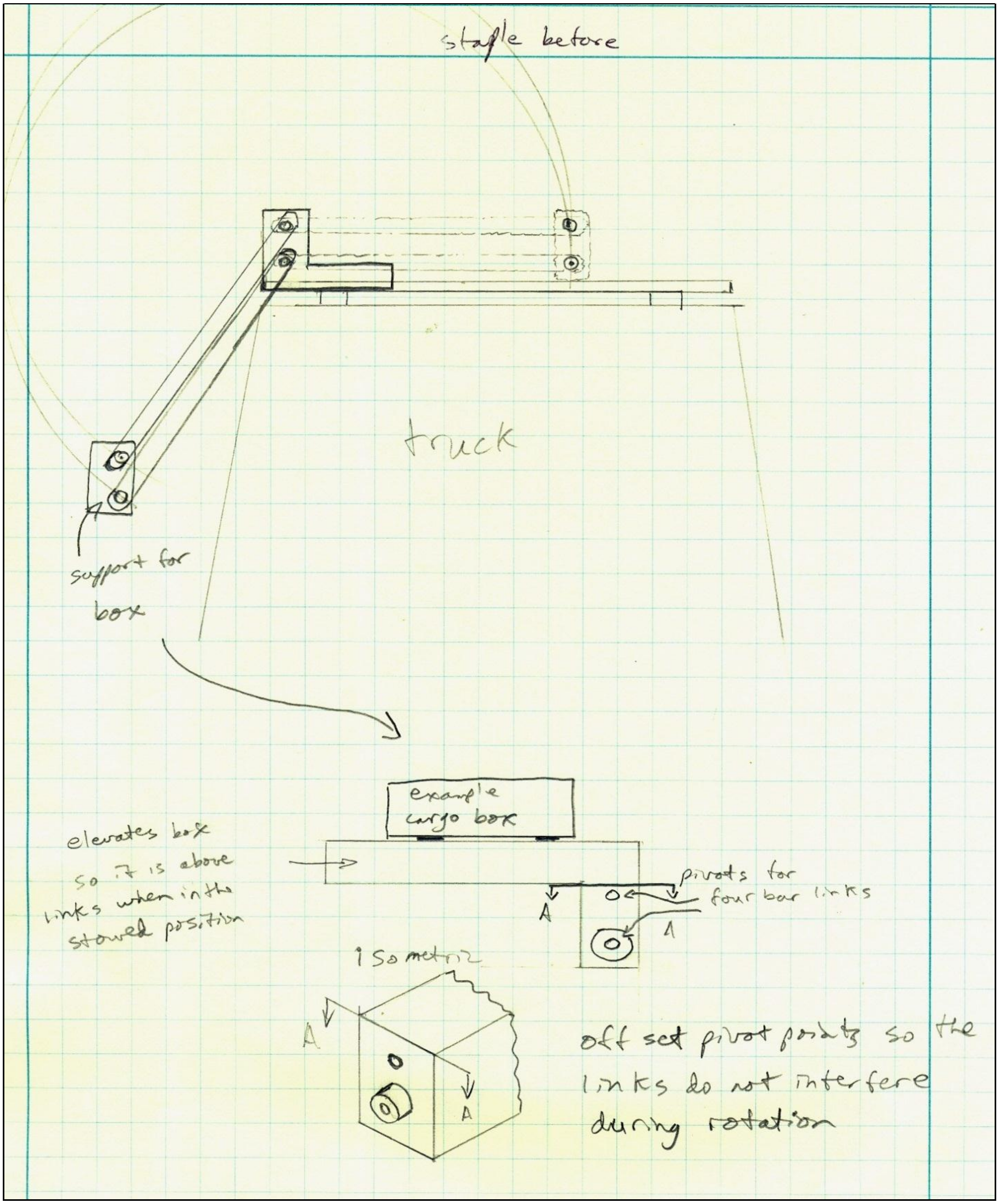
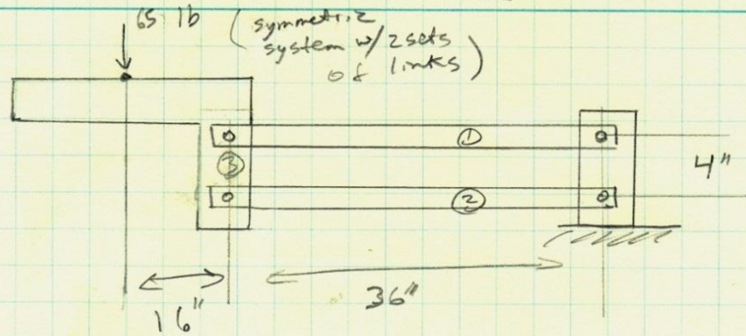
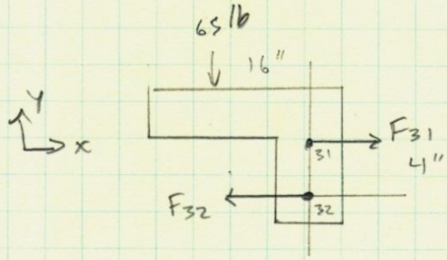


FIGURE 33. SKETCH OF THE OFFSET PARALLEL FOUR-BAR LINKAGE.

(100 lb) load in (30 lb) box



for a hypothetical 32" wide box on top



$$+\circlearrowleft \sum M_{31} = (65\text{ lb})(16") - F_{32}(4") = 0$$

$$F_{32} = 260\text{ lbs.} \quad (\text{left})$$

$$\begin{array}{r} 65 \\ 4 \\ \hline 260 \end{array}$$

$$\sum F_x = 0$$

$$F_{32} = F_{31}$$

$$F_{31} = 260\text{ lbs.} \quad (\text{right})$$

main failure mode would be buckling;

~~Eul~~ Euler beam equation in Shigley's (4-43)

$$P_{cr} = \frac{C\pi^2 E I}{L^2} \quad ; \; C = 1 \text{ for both ends pivoting}$$

try Aluminum material

$E = 10.4$ Mpsi

(Shigley's inside cover)

$$I_{cr} = \frac{P_{cr} L^2}{\pi^2 E} = \frac{(260\text{ lb})(36\text{ in})^2}{\pi^2 (10.4 \times 10^6 \text{ lb/in}^2)}$$

$$I_{cr} = .0324\text{ in}^4$$

if links are solid square cross-section!

b, h, N.A.

$$I = \frac{1}{12} b h^3$$

$$I = \frac{1}{12} h^4$$

$$h = \sqrt[4]{12(.0324\text{ in}^4)}$$

$$h = .7896\text{ in} \quad (\text{no safety factor yet})$$

FIGURE 34. SIMPLE CALCULATIONS FOR THE OFFSET FOUR-BAR IDEA.

FIGURE 35. CONCEPT DRAWING OF THE SLIDE AND TILT.

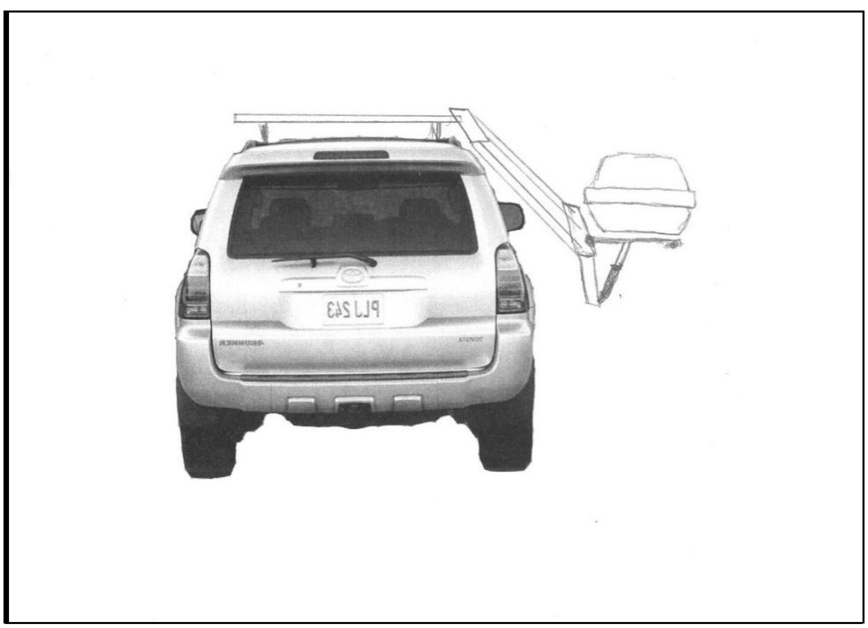


FIGURE 36. CONCEPT DRAWING OF THE FOLD-UP.

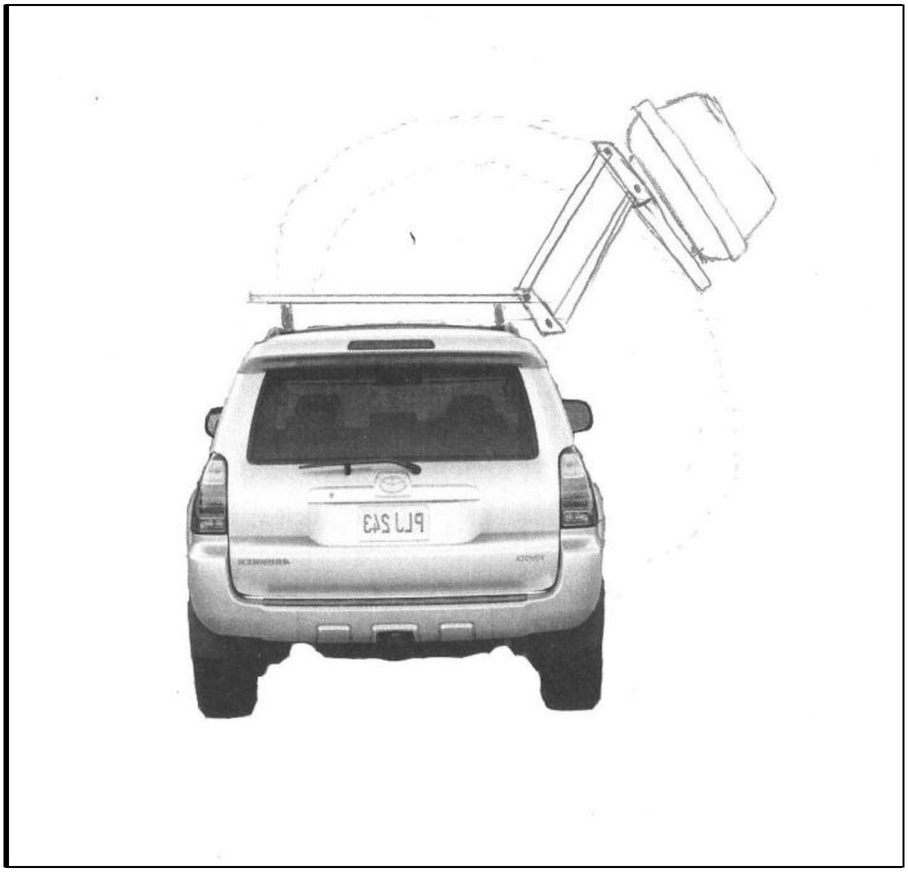


FIGURE 37. CONCEPT DRAWING OF THE FOLD-UP MIDWAY THROUGH ITS LOWERING MOTION.

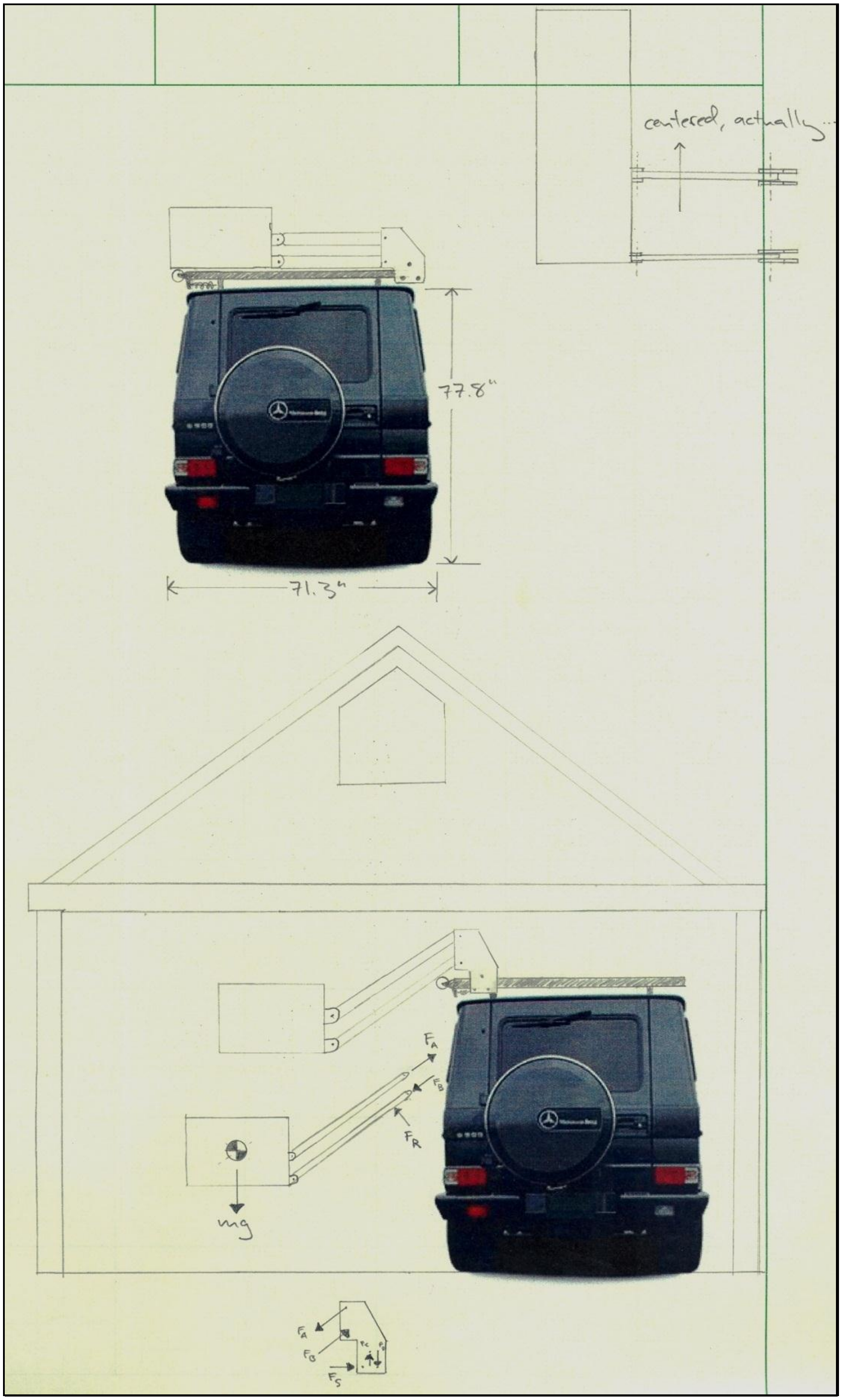


FIGURE 38. CONCEPT DRAWING OF THE SLIDING PARALLEL FOUR-BAR.

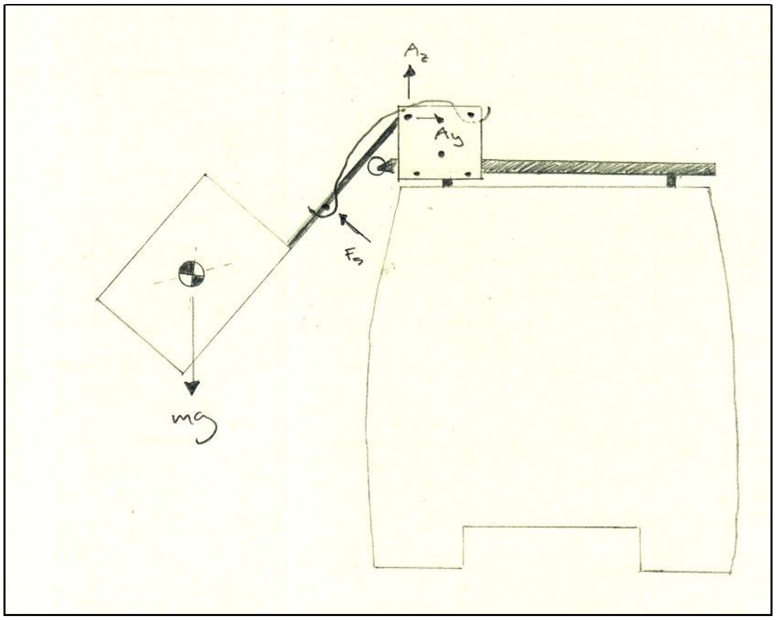


FIGURE 39. CONCEPT DRAWING OF THE SLIDING CANTILEVER.

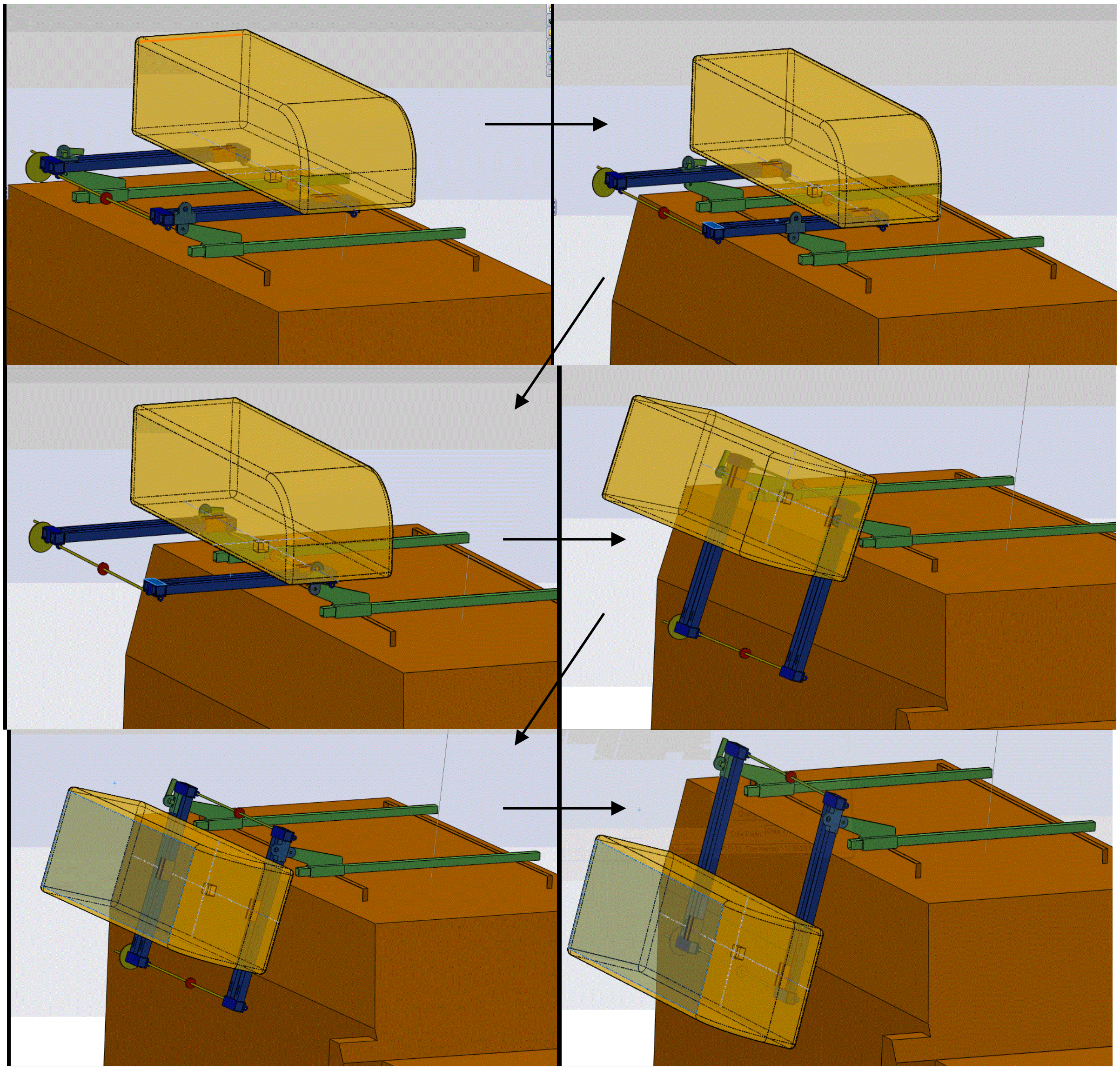


FIGURE 40. SKETCHES OF THE UNLOADING PROCEDURE FOR THE CRANK AND SLIDER CONCEPT.

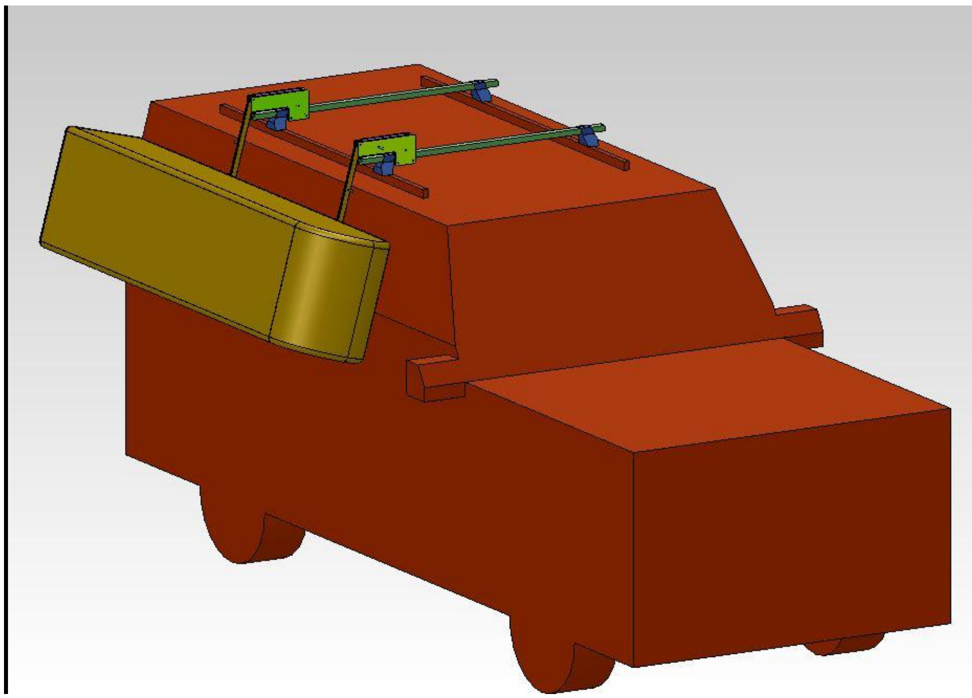


FIGURE 41. SOLID MODEL OF THE SLIDING CANTILEVER DESIGN IN THE LOADING POSITION.

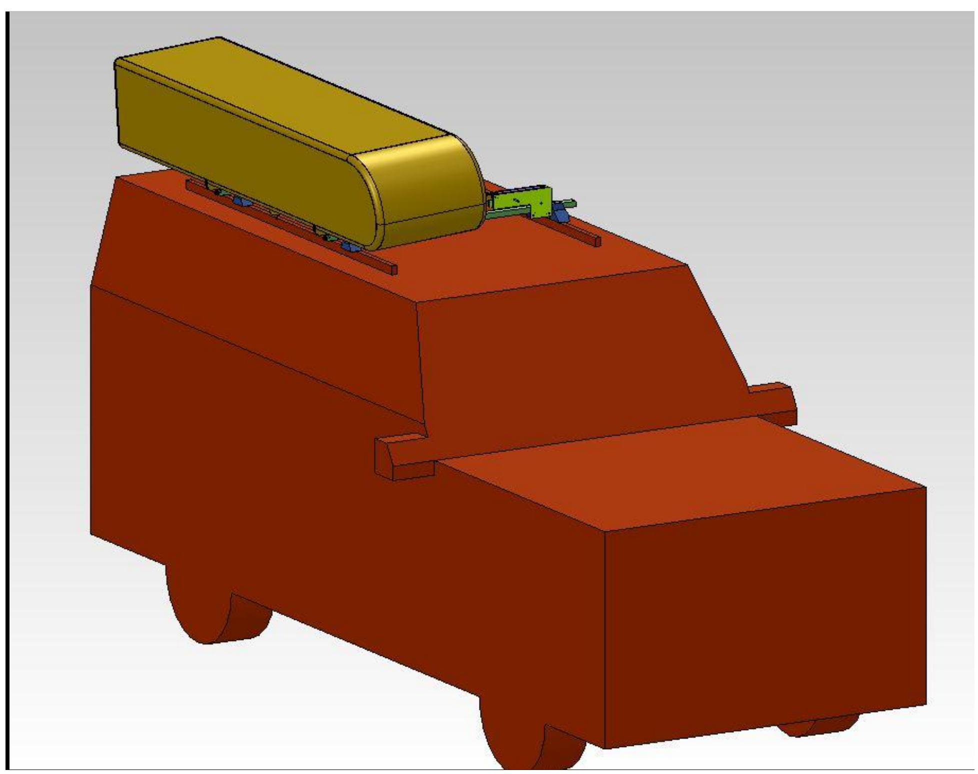


FIGURE 42. SOLID MODEL OF THE SLIDING CANTILEVER DESIGN IN THE STOWED POSITION.

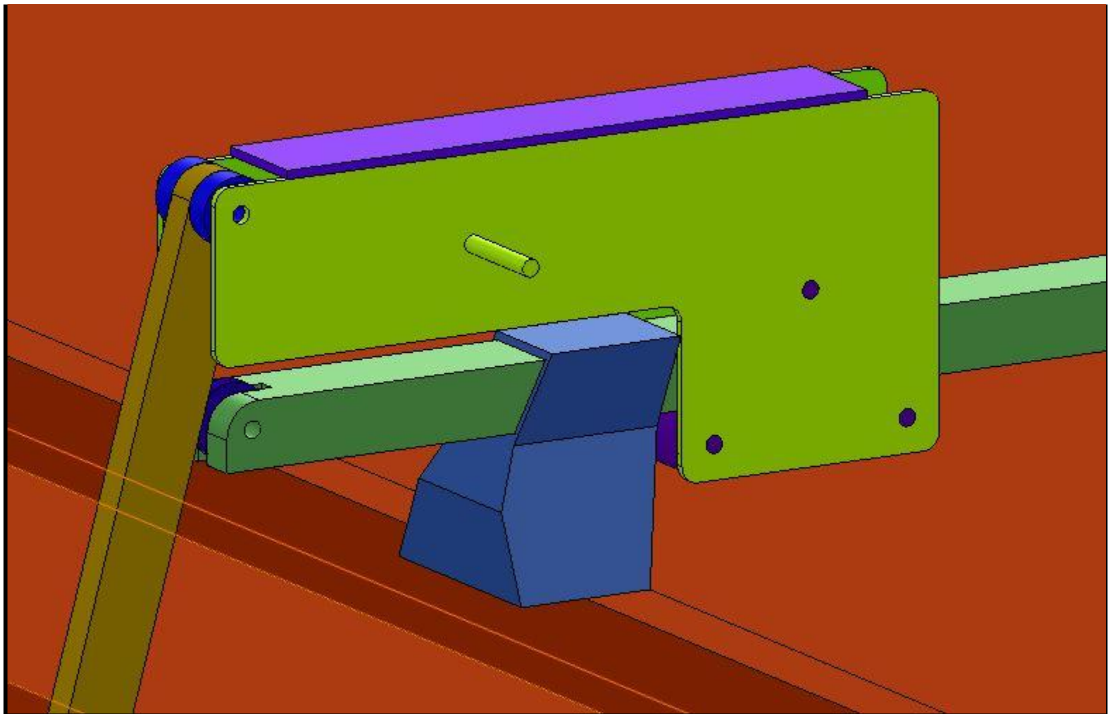


FIGURE 43. CLOSE UP OF THE SLIDING PIVOT POINT IN THE SLIDING CANTILEVER DESIGN.

Appendix E: K'NEX Models

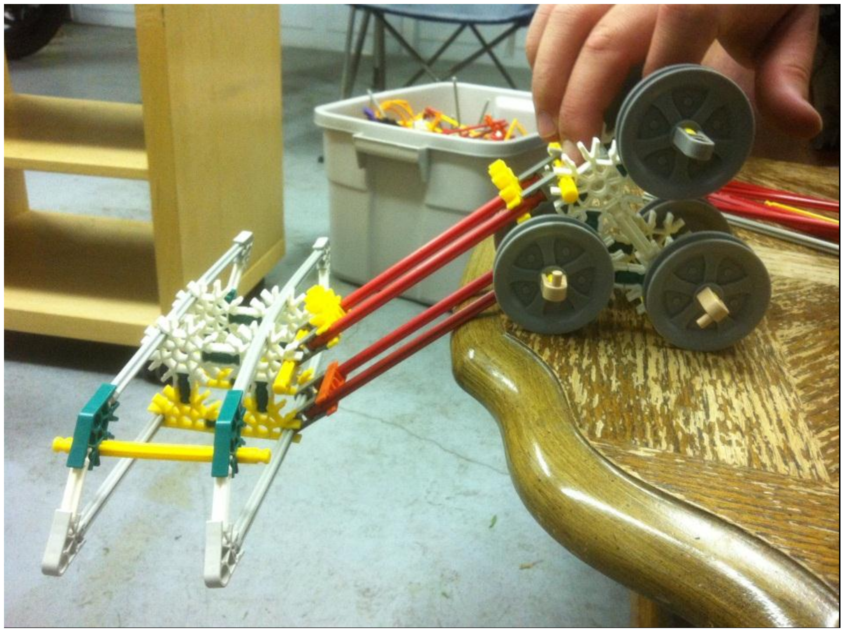


FIGURE 44. K'NEX MODEL OF THE SLIDING PARALLEL FOUR-BAR CONCEPT.

FIGURE 45. A K'NEX MODEL OF THE FOLD-UP IN ITS CARGO LOADING POSITION.

FIGURE 46. THE FOLD-UP CONCEPT HALF-WAY THROUGH BEING FOLDED UP.

FIGURE 47. THE FOLD-UP IN ITS STOWED POSITION.

Appendix F: Design Requirements

TABLE 2. DESIGN REQUIREMENTS

[redacted]

http://papers.sae.org/2006-01-0729/
(I will clarify)

[redacted]

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Appendix G: QFD

TABLE 3. QFD

Innovative Cargo Rack Solutions — Customer Requirements	Weighting	Cargo Weight (lbs)	Cargo Volume (ft^3)	Loading Height Increase (in)	Loading Width Increase (in)	Loading Length Increase (in)	Distributed Load (psf)	Aero Load Speed (mph)	Installation Effort (%)	Force to Lift (lbs)	Cargo Box Loading Height (ft)	Max Cargo Rotation (deg)	Number of Main Systems (#)	System Weight (lbs)	Car Door Interference (0/1)	SUV's that it fits (%)	Scratch Likelyhood (%)	Moment on Interface (0/1)	Fits in Garage (0/1)	Benchmarks (1-4 scale): Thule 668ES Frontier	Thule Hullavator	Safari Condo
Functional Performance																						
Weight Capacity	7	100																		4	2	3
Volume Capacity	7		11.25																	4	1	4
Fits in Garage	10			6	30	0													1	1	4	1
Withstands Snow Loads	5						20													4	4	4
Withstands Aero Loads	5							60												4	3	3
Mechanical Simplicity													3	45						4	1	2
Human Factors																						
Easy to Install	6								30					45						4	2	2
Easy to Load	15									50	5	90								1	4	3
Looks Fast	2																			3	3	3
No Annoying Noises	4																			2	2	2
Doesn't Hinder Door Opening	7														0					4	1	2
Interface with SUV																						
No Additional SUV Rails	8															85				4	4	1
Doesn't Scratch Vehicle	9																10			3	3	3
Interface Loads w/in MFG Tolerance	15																	0		4	3	3
Units		lbs	ft^3	in	in	in	psf	mph	%	lbs	ft	deg	#	lbs	0/1	%	%	0/1	0/1			
Targets		100	11.25	6	30	0	20	60	30	50	5	0	3	45	0	85	0	0	1			
Thule 668ES Frontier		110	11	16	0	0			20		7	0	1	33	0	90	10	0	1			
Thule Hullavator		75	0	2	25	0		60	30	10	4	90	2	35	1	70	5	0	1			
Safari Condo		100		4		72		60	45	60	5	35	2	45	1	50	10	0	0			

Appendix H: Expenses

TABLE 4. EXPENSES

Date	Item	Cost	Notes	Part Ref. #	Supplier	Order #	Paid?
12/20/2011	steel and Al square tube	$52.00					yes
1/3/2012	(4) 608	$32.67			Central Coast Bearing		yes
1/16/2012	hardware	$2.69			Ace		yes
1/16/2012	(2) 608, 6000, 6200 bearings	$42.35		608, 6000, 6200	Central Coast Bearing		yes
1/18/2012	hardware	$2.31			Ace		yes
1/19/2012	3ft of Nylon 6/6 Strip, .050" Thick, 4" Wide	$10.93		8730K39	McMaster-Carr	15763988	yes
1/31/2012	carriage plates and Al tube	$47.41			B&B steel		yes
2/7/2012	hardware	$12.47			Ace		yes
2/7/2012	hardware	$2.56			Ace		yes
2/14/2012	Berkeley Digital Fish Scale	$35.10			Amazon	104-8501169-5409027	yes
2/14/2012	.25"x5"x12" 6061 plate	$14.05	plus shipping	8975K434	McMaster-Carr	1288903	yes
2/14/2012	5/15"x12" Anodized 6061 rod	$5.35	plus shipping	6750K141	McMaster-Carr	1288903	yes
2/14/2012	Chrome-Plated Steel Unthreaded Spacer 5/8" OD, 1" Length, .344" ID	$28.91	plus shipping	93320A225	McMaster-Carr	1288903	yes
2/14/2012	(4) SR4ZZ ball bearings for contact Point A	$52.00	estimate	SR4ZZ	Central Coast Bearing		
	(6) 608	$49.01	future expense	608	Central Coast Bearing		
	1" 6061 square tube, 8ft and 1/8" wall thickness	$25.00	future expense				
	(2) 1.4"x4"x2.5" 6061 block [bought as (1) 1.5x3x12"]	$39.29	future expense	8975K315	McMaster-Carr		
	foam, carbon cloth, fiber glass	free					
	hardware for 2nd carriage assembly and other two feet		future expense				
		$454.10	projected total				
		$288.80	total to date				

Appendix I: Testing Procedures

User Input Force Verification

[redacted]

[redacted]

[redacted]

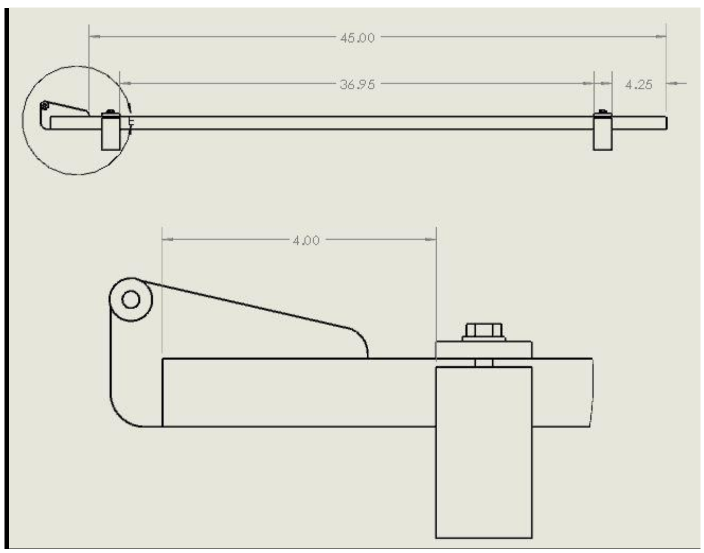

FIGURE 48. DIMENSIONS FOR PROPERLY SETTING UP THE EXPERIMENTAL APPARATUS.

[redacted]

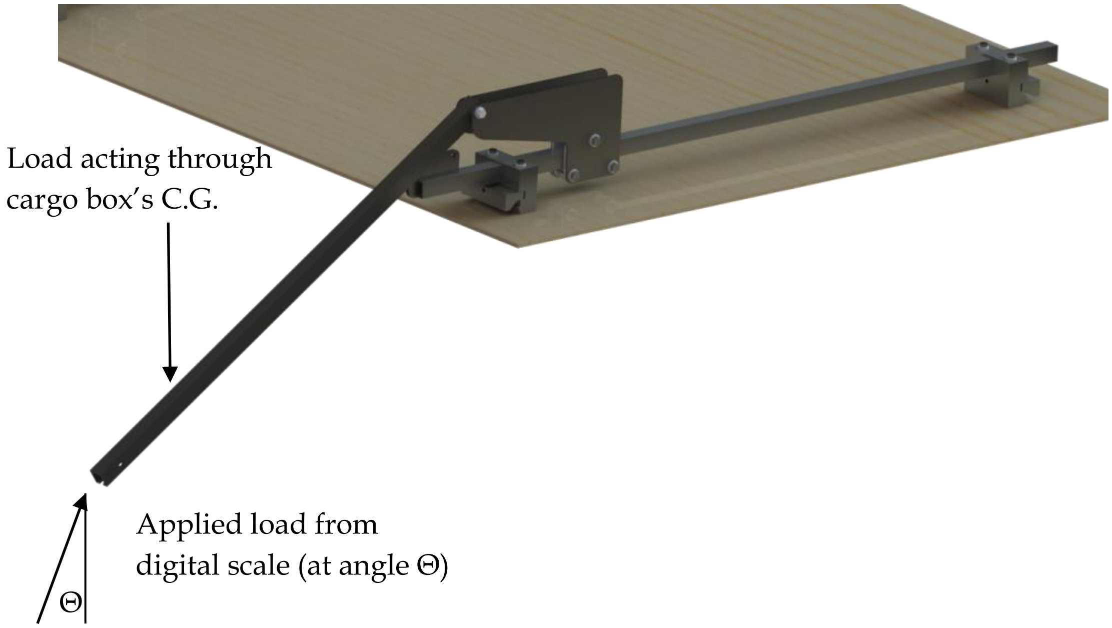

FIGURE 49. EXPERIMENTAL APPARATUS SHOWING WHERE LOADS ARE ACTING ON THE BOX ARM.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Carriage Plate Failure Testing

[redacted]

[redacted]

[redacted]

[redacted]

FIGURE 50. APPARATUS FOR PART A. OF THE PROCEDURE SHOWING WHERE THE PLATES WILL BE LOADED.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

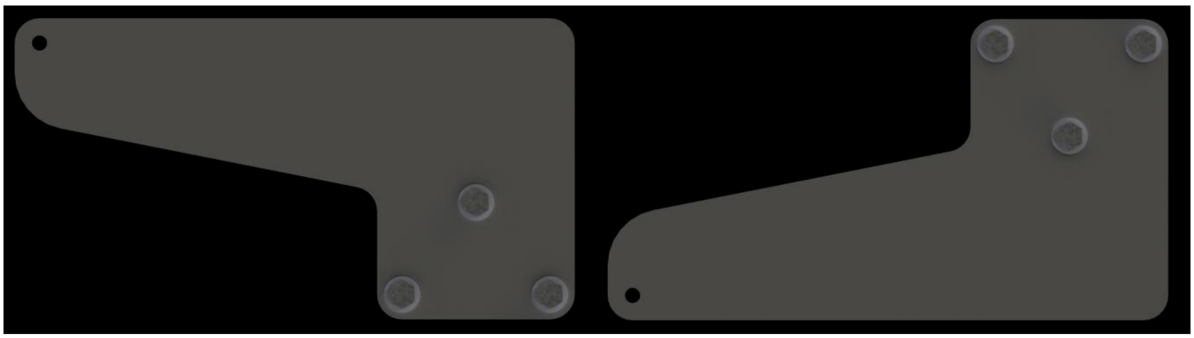

FIGURE 51. SIDE VIEW OF THE LOADING CONFIGURATIONS USED IN TESTING. PART A. IS ON THE LEFT AND PART B. IS ON THE RIGHT.

[redacted]

[redacted]

Box Arm Bending Failure

[redacted]

[redacted]

[redacted]

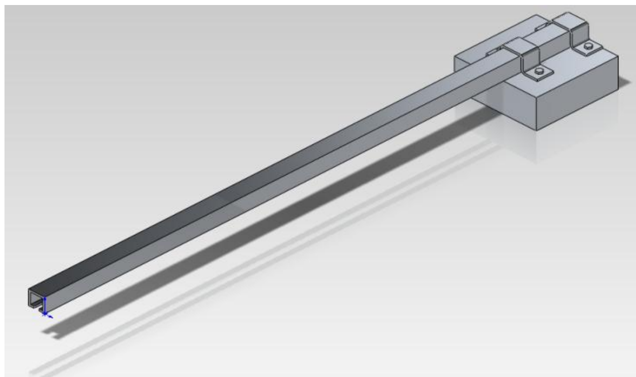

FIGURE 52. CARGO BOX ARM STRAPPED TO A SOLID SURFACE SO IT CAN BE LOADED AND TESTED FOR BENDING FAILURE.

[redacted]

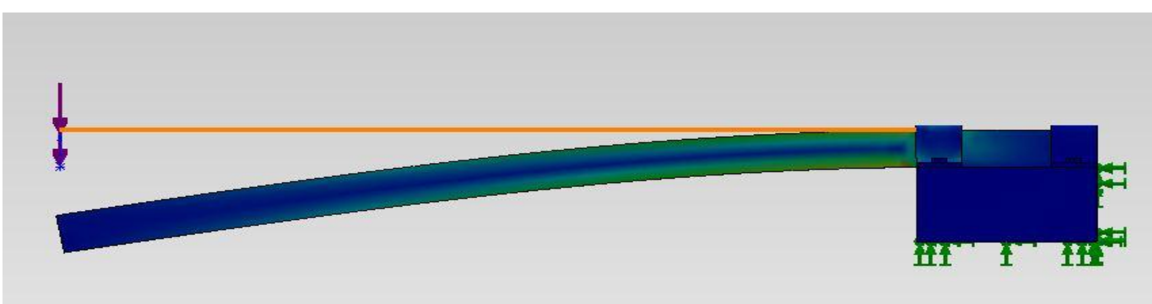

FIGURE 53. EXAMPLE OF THE DEFORMATION THAT OCCURS DURING BENDING (TAKEN FROM A SOLIDWORKS SIMULATION). THE COLOR SPECTRUM SHOWS THE VON MISES EQUIVALENT STRESS LEVELS ALONG THE ARM, WITH RED FOR HIGHER STRESSES, GREEN FOR MEDIUM LEVELS AND BLUE FOR LOW STRESS LEVELS.

[redacted]

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