WASP
Preliminary Design Review

October 21st, 2020

ASEN 4018-011 Team 9

Company Customer:
Sierra Nevada Corporation (SNC)

Faculty Advisor:
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Presenters:
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Additional Team Members:
Foster Greer, Aidan Kirby, Bailey Roker, Matthew Zola

Presentation Outline

1. Project Overview - Parker Simmons, Ansh Jerath
2. Feasibility: Structures - Adam Elsayed, Parker Simmons
3. Feasibility: Electronics and Software - Maddie Dube
4. Feasibility: Accuracy - Samuel Felice, Emma Markovich
5. Feasibility: Budget - Emma Markovich
6. Feasibility Conclusions - Ansh Jerath
7. Future Work - Adam Elsayed, Emma Markovich

Project Overview

Project Overview

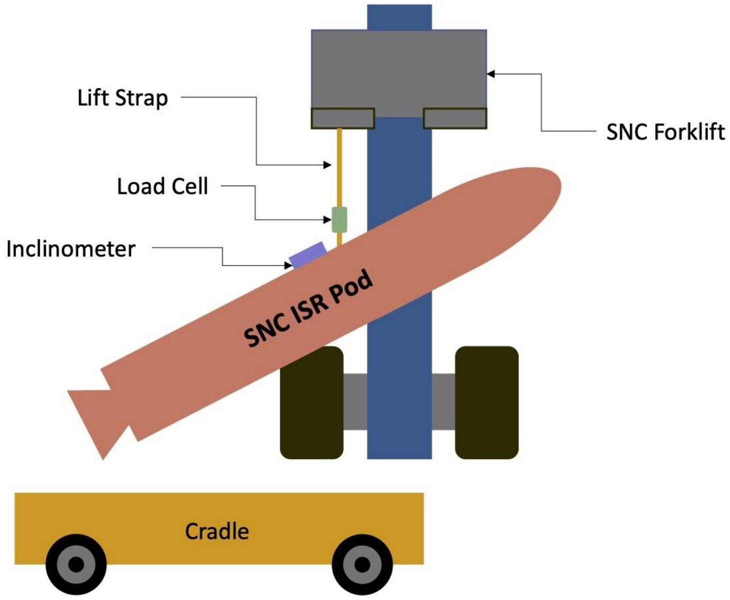
Background:

- **Sierra Nevada Corporation's ISR, Aviation, and Security (SNC IAS) division** needs a better way of **measuring the weight and CG** of their Intelligence, Surveillance, and Reconnaissance (ISR) pods.
- Currently, SNC utilizes a **forklift** to hang pods

Motivation:

- **Effective:** Current method of finding weight and CG is challenging.
- **Safety:** ISR Pods and Engineers are at risk with current method.

SNC's Current Method

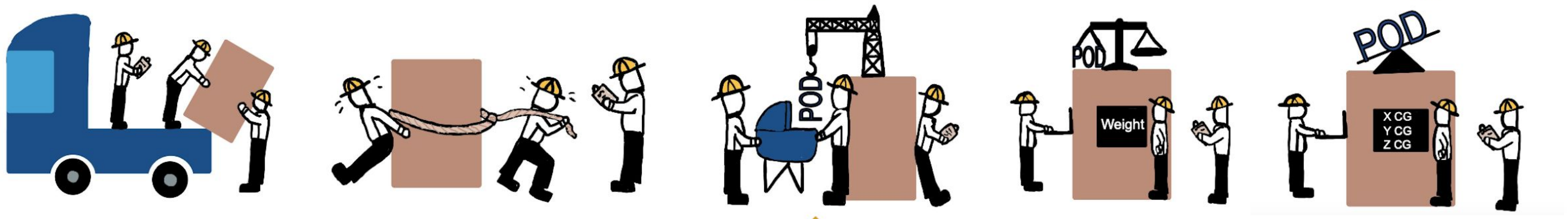


Mission Statement

Weight Analysis of Surveillance Pods **(WASP)** will provide SNC IAS mass properties engineers with an **upgraded apparatus and standardized method** for determining the **weight and center of gravity** of various ISR pods.

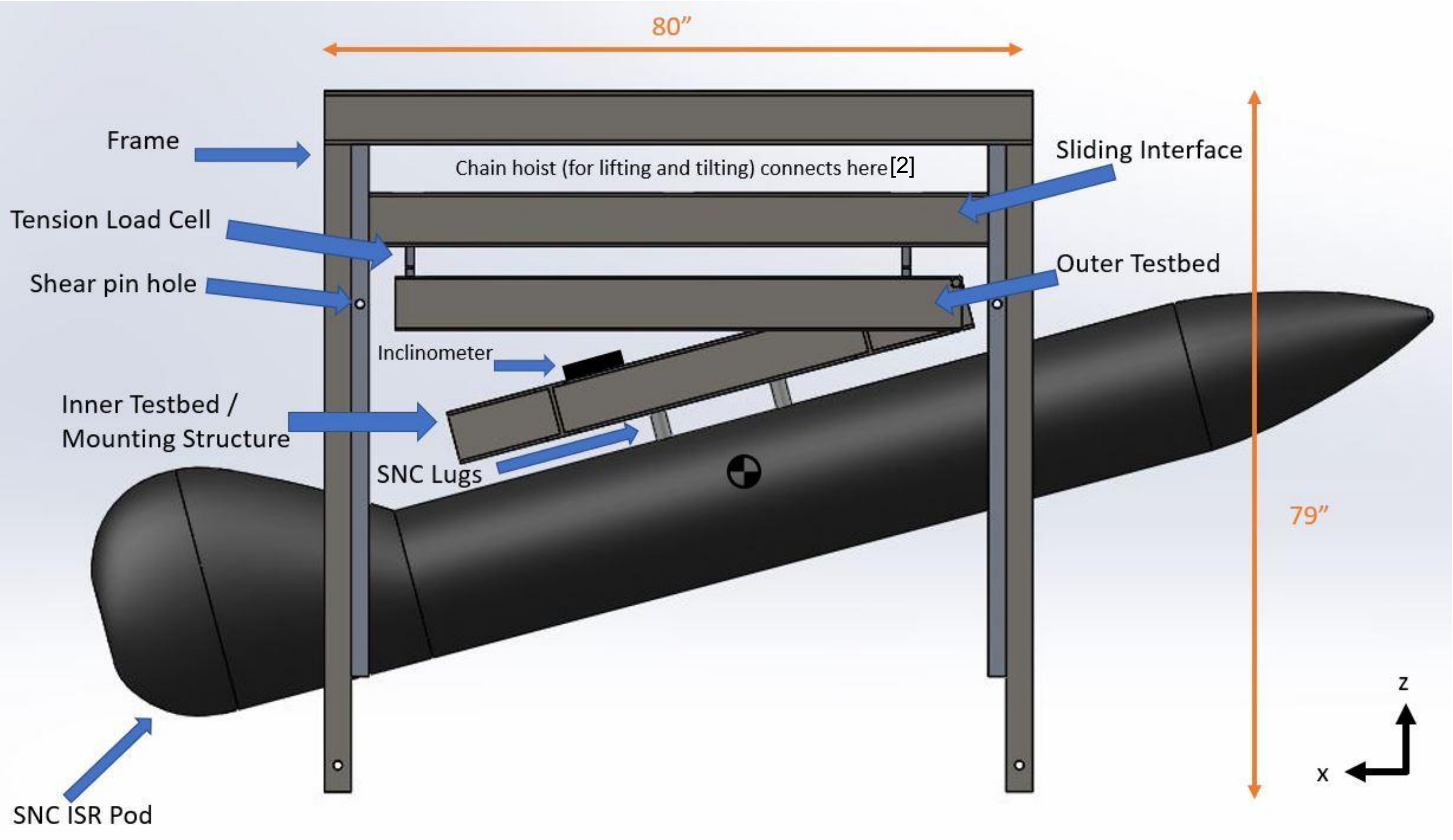
Concept of Operations

1) WASP unloaded from transport vehicle
2) WASP moved into hangar
3) Pod mounted to WASP and lifted from cradle
4) WASP weighs pod, records measurements
5) WASP tilts pod, records measurements



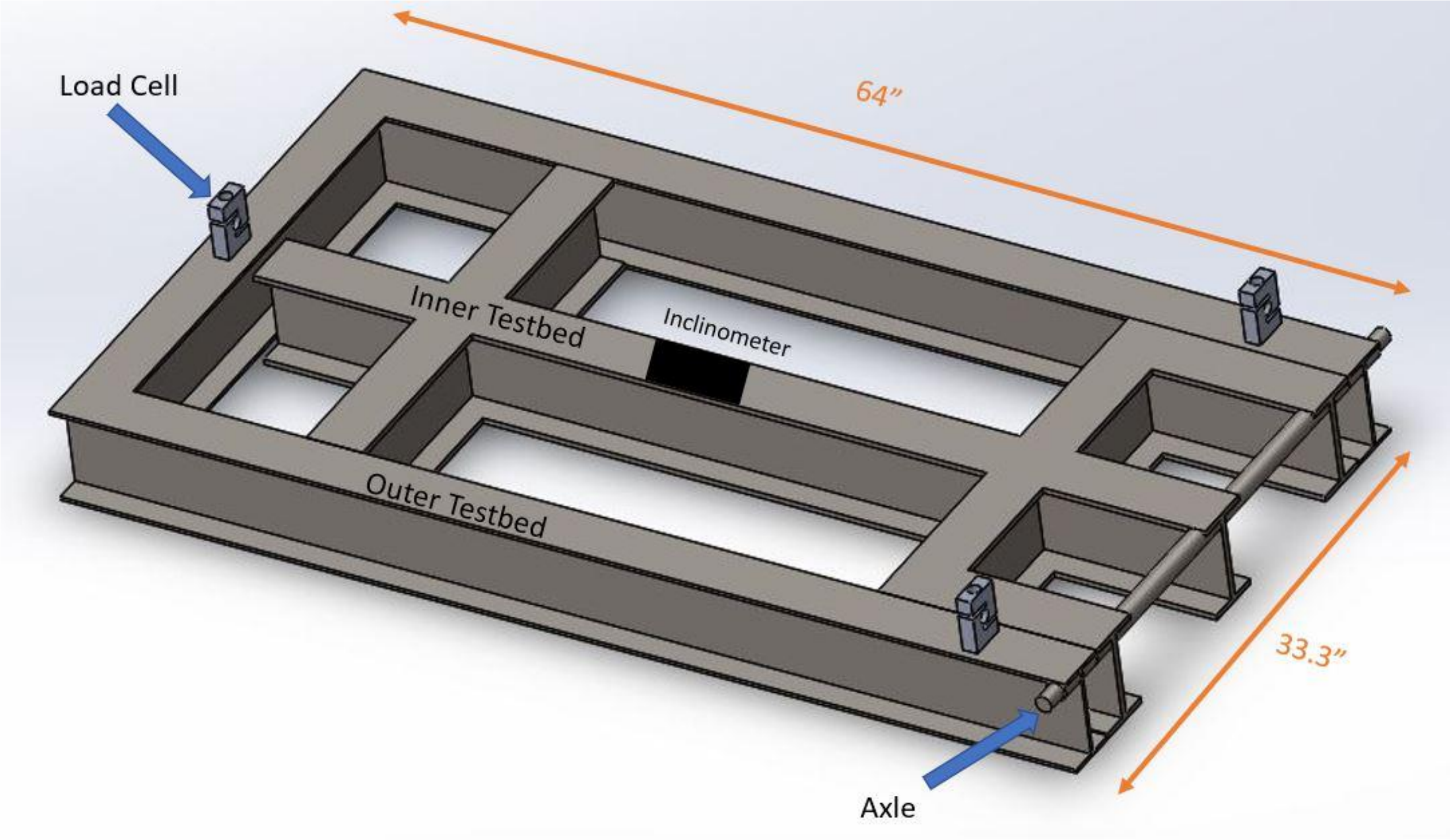
6) WASP returns pod to untilted configuration
7) GUI computes total weight, X CG, Y CG, and Z CG
8) Pod lowered into cradle, detached from WASP
9) WASP removed from hangar
10) WASP loaded into transport vehicle

Baseline Design



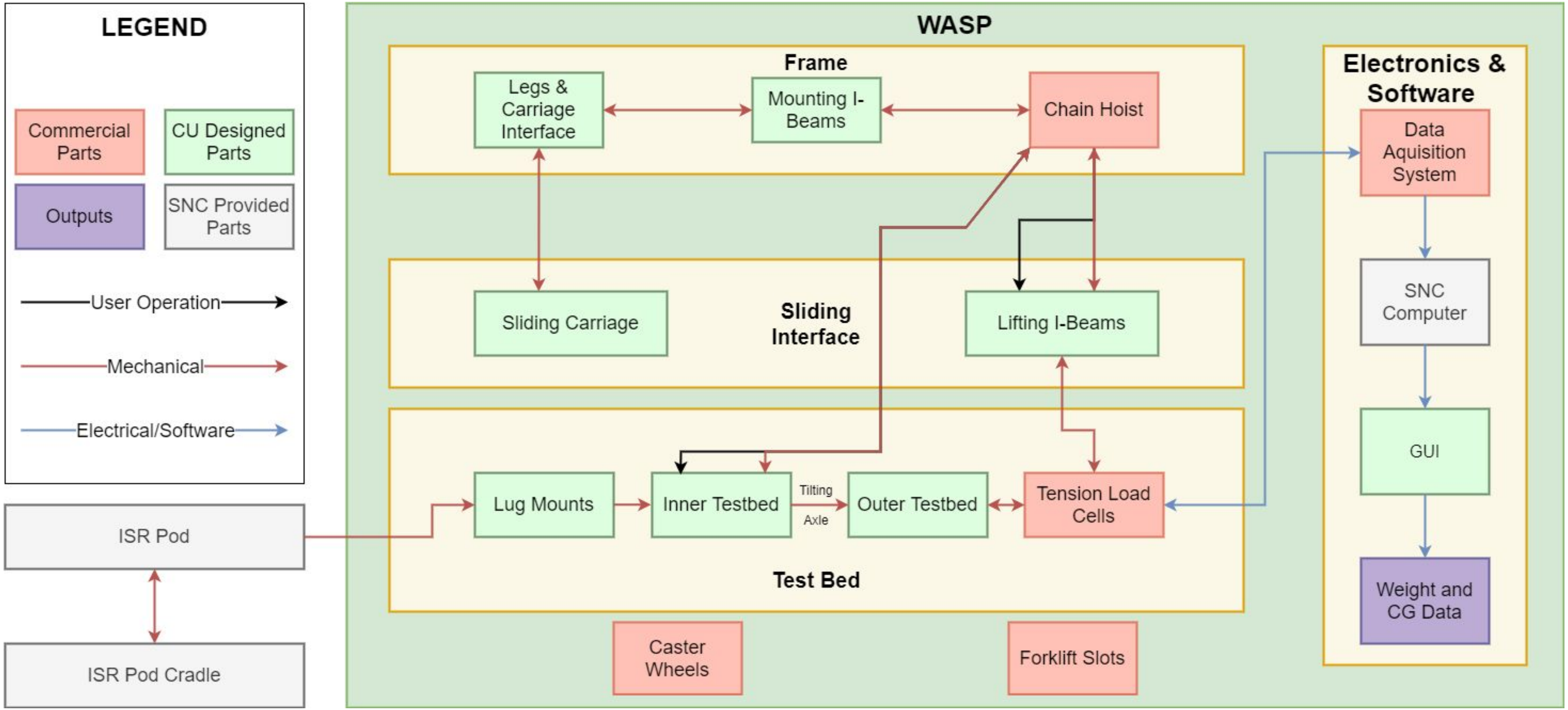
Current Structural Weight: **1179.22 lbs**

Baseline Design - Testbed



Testbed Weight:
322.88 lbs

Functional Block Diagram



Critical Project Elements (CPEs)

CPE	Description
E1	All static possible loading must be handled by the frame. It must be portable and support at least 2000 lbs.
E2	WASP should interface with lugs for all pod types.
E3	WASP must be capable of weight measurements with ±0.1% of true value; CG measurements within ±0.1" of true value.
E4	Testing procedures for weight and CG calculations must be well-developed.
E5	Since heavy loads are involved, both the pods and WASP operators should be safe from harm.

Design Feasibility

Critical Feasibility Statements

Label	Statement	CPE	Requirement	Feasible?
FOS	Frame members shall have a factor of safety greater than 2 against structural failure.	E1, E5	FR3	
COMPAT	The computer and DAQ must have compatible communication so data transfer is valid.	E3	FR8	
ACC/W	Sensors and Data Processing Unit shall perform such that the accuracy requirement for weight (0.1% pod weight) is met for 90% of tests.	E3	FR1	
ACC/CG	Sensors and Data Processing Unit shall perform such that the accuracy requirement for CG (0.1 in) is met 90% of tests.	E3	FR2	
COST	Cost of parts purchased by CU for WASP shall be less than $5,000.	E1	N/A	

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Structures

Preliminary Design Frame Analysis

Legs (Bars)

- Compressive strength
- Buckling [6]
- Deflection

Beams/Shafts

- Bending
- Shear
- Torsion (if applicable)
- Deflection (Bending and Torsion)
- Buckling of flange and web
    - Width/thickness ratio low enough to ignore this analysis (AISC LRFD Specification [13])

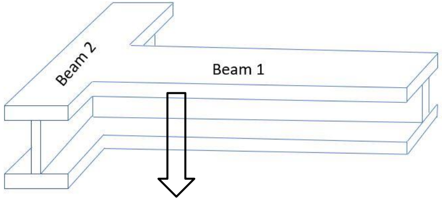
Material	A36 Carbon Steel [12]
σ_y	36300 psi
τ_y	~ 0.58 σ_y
E	29000 ksi
G	11500 ksi
ρ	0.284 lb/in^3

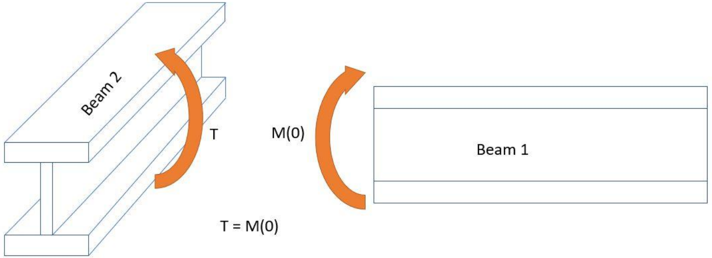
Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Beams - Analysis Outline

General Back of the Envelope (BOTE) Analysis

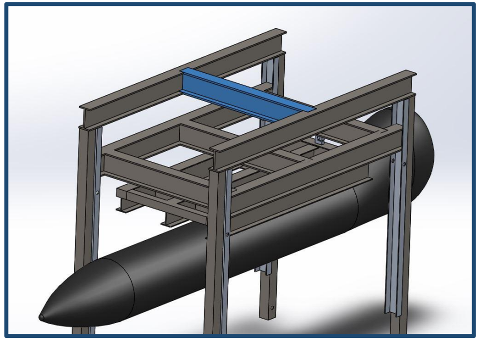
1. **Bending - Limiting factor**
   - Calculate M(x) using FBD [4]
   - Calculate v(x) using M(x) and BCs [5]
   - Solve for maximum deflection and maximum bending stress
   - Compute FOS using the flexure formula
2. **Torsion (If applicable)**
   - Use M(0) from connected beam (1) as T on beam of interest (2)
   - Calculate maximum twist angle and torsional stress
   - Compute FOS
3. **Shear**
   - Compute maximum shear, V(x) = M'(x)
   - Compute FOS
4. **Compare minimum safety factor for each beam to minimum safety factor for finite element analysis (FEA) grouped beams**

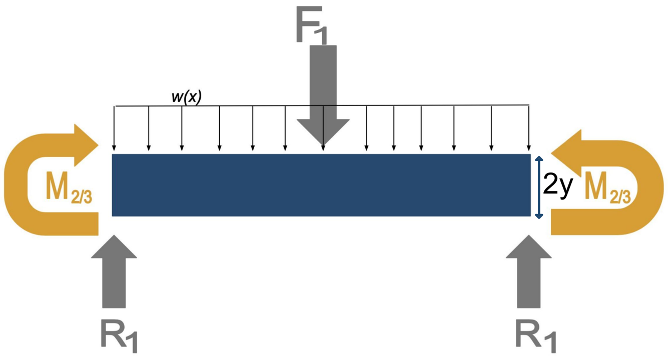




Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Hand Calculation Example - Bending of Beam 1





$y = 3"$

$L = 41.3"$

$y = 26.3in^4$

$R_1 = 1300lbs$

$M_{2/3} = -67.13lb - in$

For $0 \leq x \leq \frac{L}{2}$:

$$M(x) = R_1 x + M_{2/3} - \frac{wx^2}{2}$$

$$v(x) = \frac{R_1 x^3}{6EI} + \frac{M_{2/3} x^2}{2EI} - \frac{wx^4}{24EI} + \frac{c_1 x}{EI}$$

where

$$c_1 = \frac{wL^3}{48} - \frac{M_{2/3} L}{2} - \frac{R_1 L^2}{8}$$

$$\sigma_{bend} = \frac{yM_{max}}{I_x} = 3218psi$$

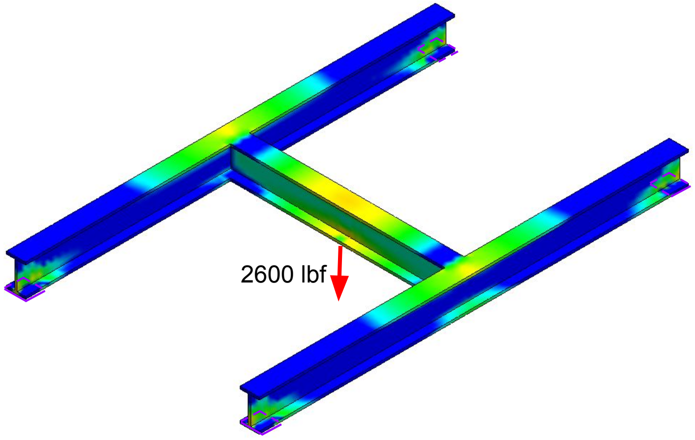
$$FOS_{bend} = \frac{\sigma_y}{\sigma_{bend}} = \boxed{11.28}$$

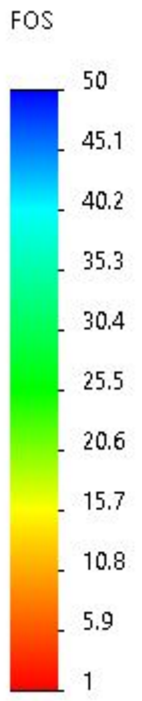
Feasible

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

FEA Example - Top of the Frame

■	Fixed Support
■	External Forces





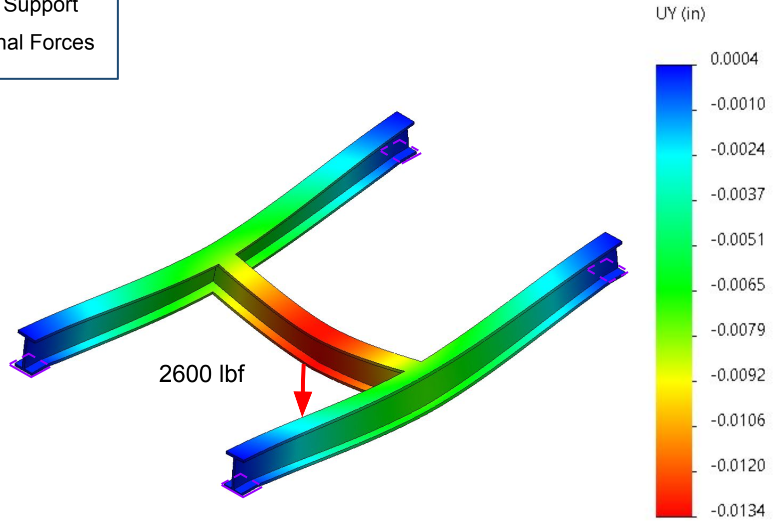
Chain Hoist Lifting Case

Minimum FOS: 8.96 Feasible

*Analysis done in SolidWorks Simulation

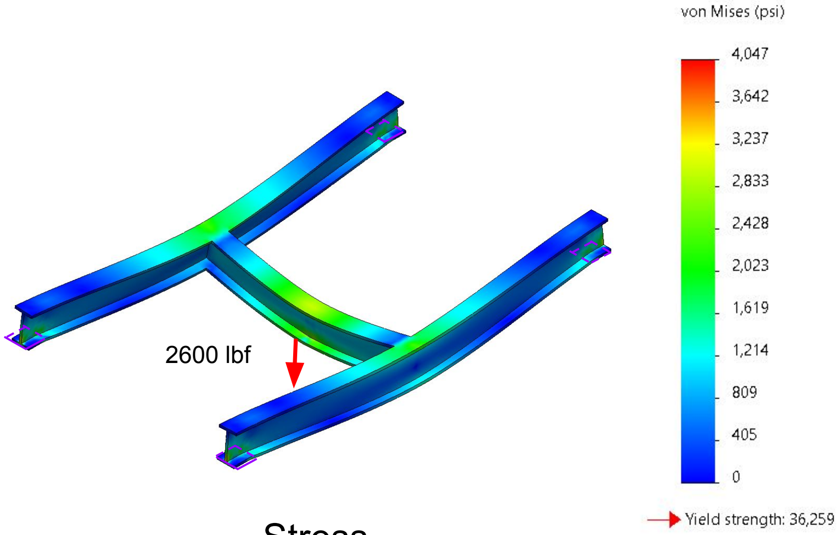
FEA Example - Top of the Frame

Fixed Support	External Forces



Displacement

Maximum: 0.0134 in



Stress

Maximum: 4,047 psi

*FOS Distribution in structures feasibility portion of PDR

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Structural Analysis Results

Part	BOTE Max Deflection (in)*	FEA Max Deflection (in)	BOTE Max Stress (psi)	FEA Max Stress (psi)	BOTE Min FOS	FEA Min FOS	Feasible? (FOS > 2)
Frame Legs	0.0017	0.0018	804	1827	43.20	19.8	Yes
Top of Frame	0.0064	0.0134	3218	4047	11.28	8.96	Yes
Sliding Interface	0.0047	0.0132	3215	4314	11.29	8.41	Yes
Testbed	0.0184	0.0080	2413.56	5011.2	15.04	7.24	Yes

* Maximum deflections are lower than current manufacturing tolerances (1/24")

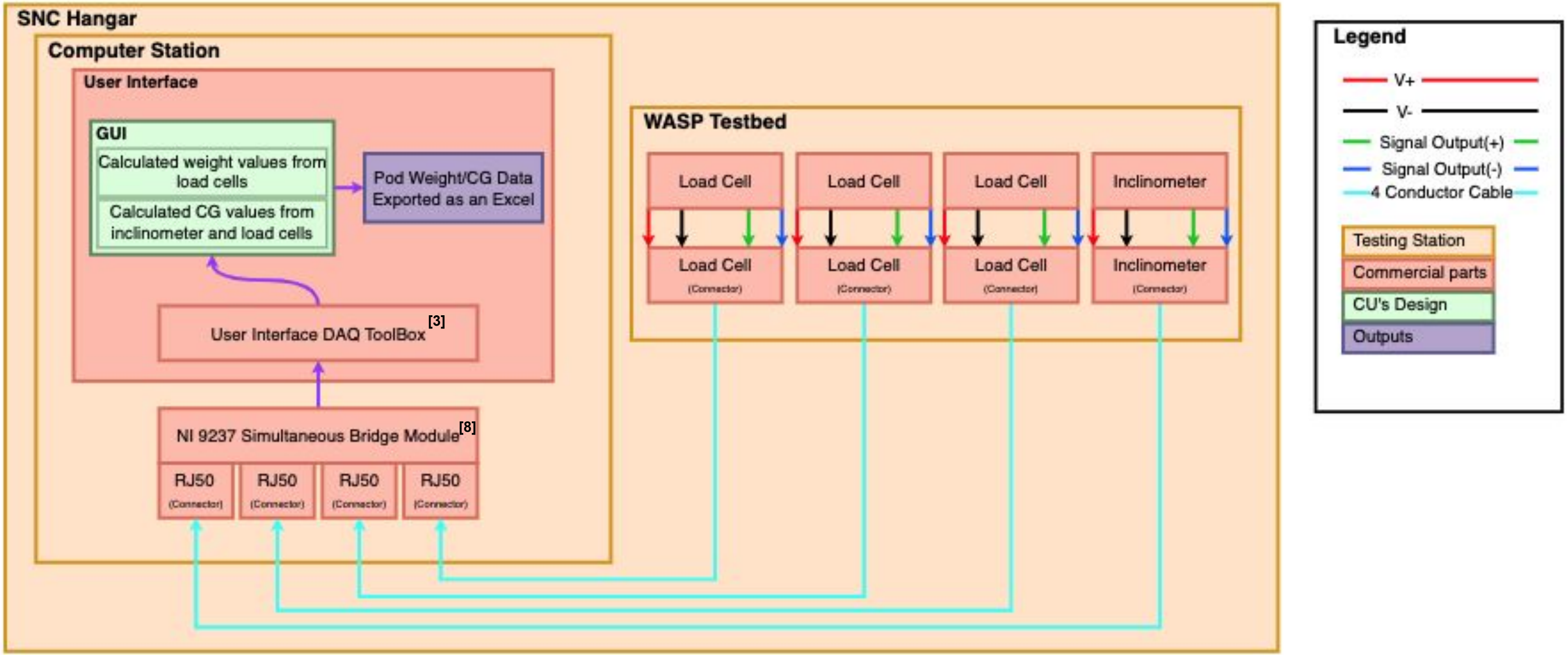
Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Electronics and Software

Relevant Feasibility Statements

Label	Statement	CPE	FR	DR
COMPAT	The computer and DAQ must have compatible communication so data transfer is valid	E3	FR8	8.1
ACC/W	Sensors and Data Processing Unit shall perform such that the accuracy requirement for weight (0.1% pod weight) is met for 90% of tests.	E3	FR1	1.1
ACC/CG	Sensors and Data Processing Unit shall perform such that the accuracy requirement for CG (0.1 in) is met 90% of tests.	E3	FR2	2.1

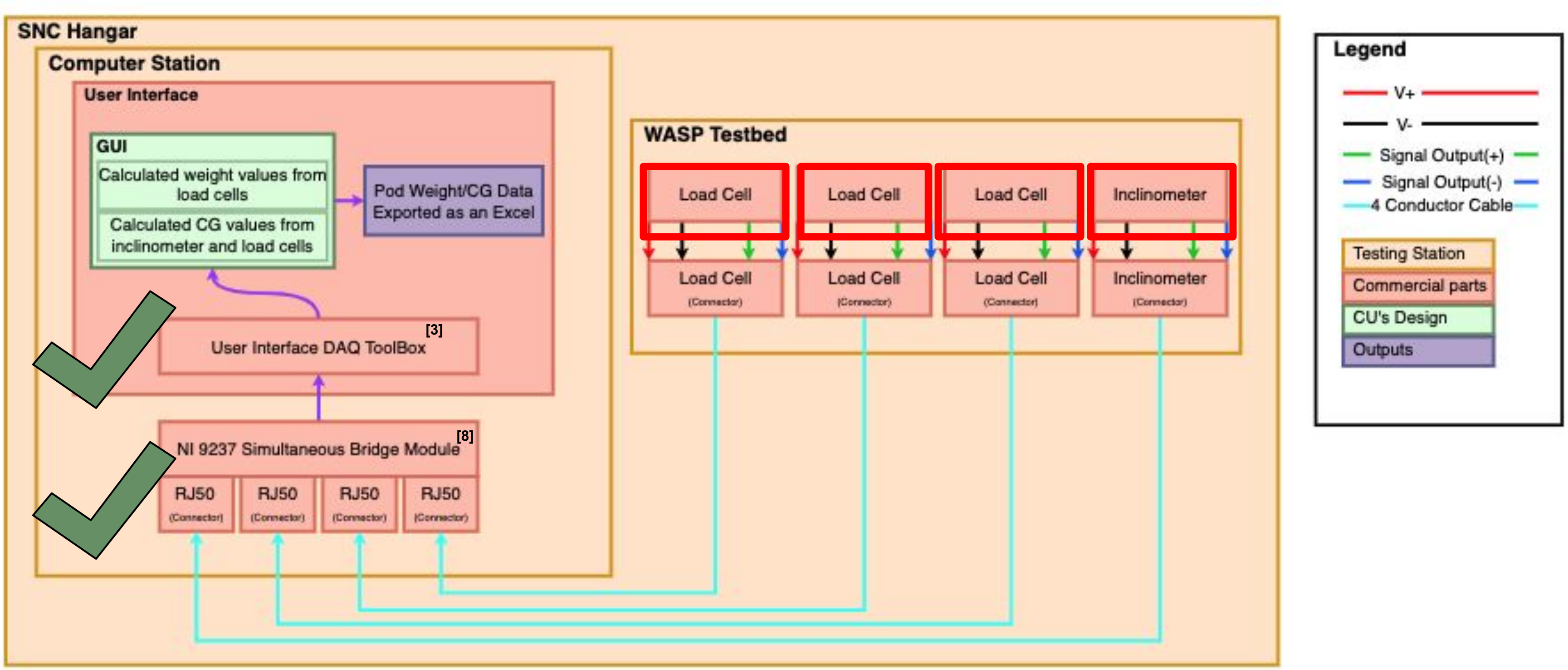
Functional Block Diagram



Feasibility Tracking

FOS	COMPAT	ACC/W	ACC/CG	COST

Compatibility Checks/ Sources of Error



Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Sensor Sensitivity

Sources of error in sensors:

- Internal error (Specs)
- Environmental

Governing Equations for Total Sensor Error:

$$\text{Error}_{\text{Sensor}} = \text{Error}_{\text{Internal}} + \text{Error}_{\text{Environmental}}$$

$$\text{Error}_{\text{Internal}} = \text{Accuracy} = \left((\text{Hysterisis})^2 + (\text{Non-linearity})^2 + (\text{Repeatability})^2 + (\text{Creep})^2\right)^{\frac{1}{2}}$$

$$\text{Error}_{\text{Environmental}} = \text{Error}_{\text{Temperature}} = \left((\text{Etemp}_{\text{ZeroBalance}} * dt)^2 + (\text{Etemp}_{\text{Output}} * dt)^2\right)^{\frac{1}{2}}$$

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Sensor Specs Used as Reference

Load Cell: Omega LC103B Series [11]

Specifications	Value
Accuracy Class	C3: ±0.023%
Combined Error	±0.02% (%FS)
Linearity	±0.02%

Inclinometer: Metrolog D-Series [7]

Specifications	Value
Range	Min: -5 (-15,-30) deg Max: +5 (+15,+30) deg
Accuracy	±0.04 deg (25°C) ±0.15 deg (-40°C - 80°C)
Temp Drift Error	0.06 deg (-40°C - 80°C)

Sensor References: https://www.omega.com/en-us/sensors-and-sensing-equipment/load-and-force/load-cells/lc103b/p/LC103B-1K [11]
https://www.metrolog.net/files/d_en_metrolog.pdf [7]

Weight and CG Accuracy

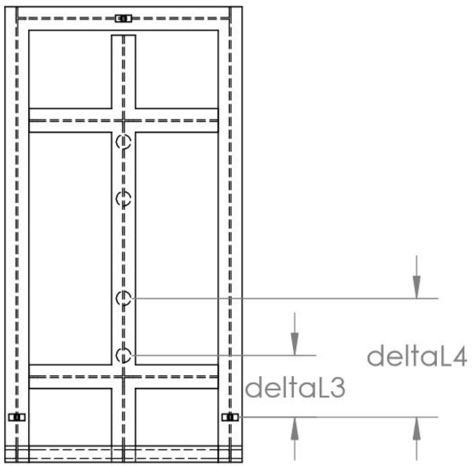
Relevant Feasibility Statements

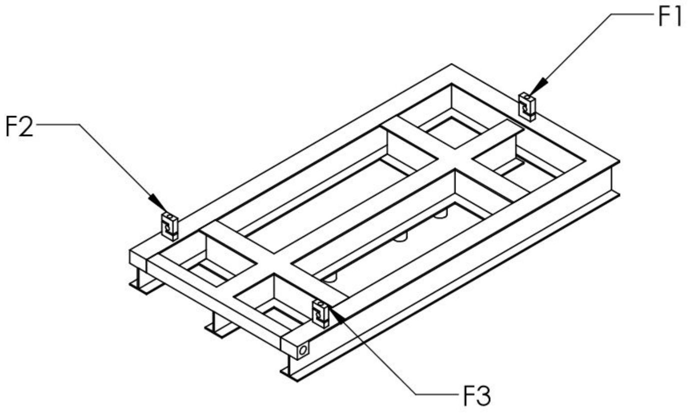
Label	Statement	CPE	FR	DR
ACC/W	Sensors and Data Processing Unit shall perform such that the accuracy requirement for weight (±0.1% pod weight) is met for 90% of tests.	E3	FR1	1.1
ACC/CG	Sensors and Data Processing Unit shall perform such that the accuracy requirement for CG (±0.1 in) is met 90% of tests.	E3	FR2	2.1

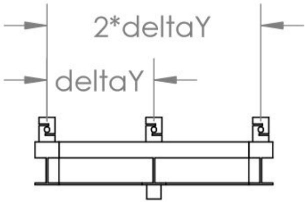
Feasibility Tracking

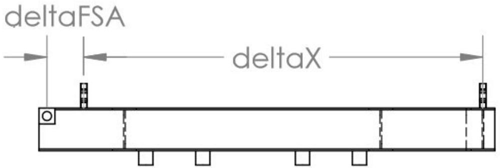
FOS	COMPAT	ACC/W	ACC/CG	COST

Weight and CG Equation Development

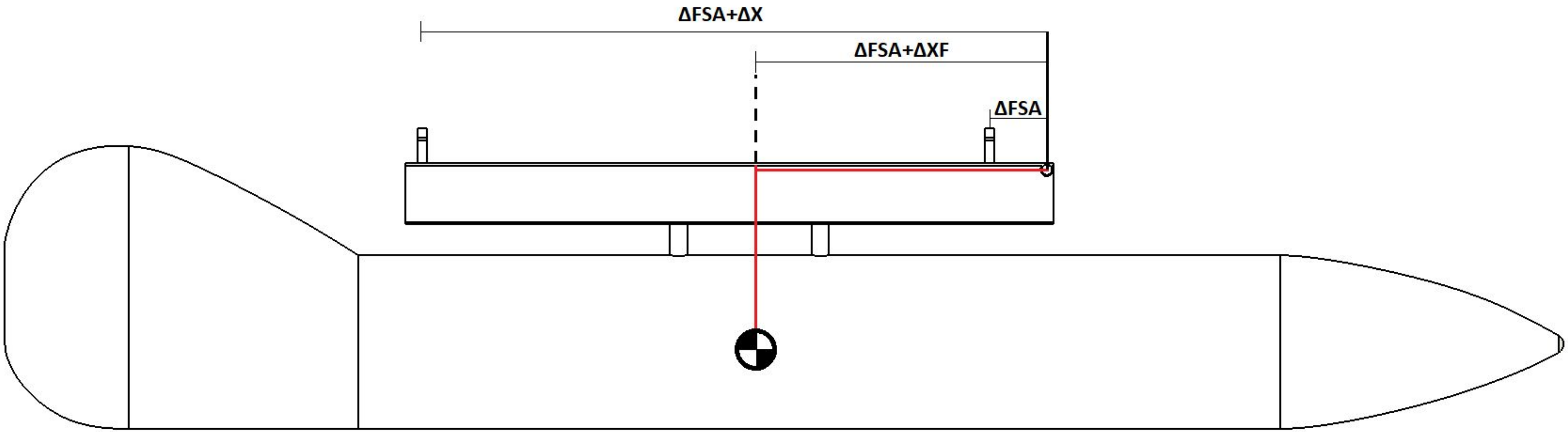








Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST



$$\sum_{i=1}^{3} F_i = W$$

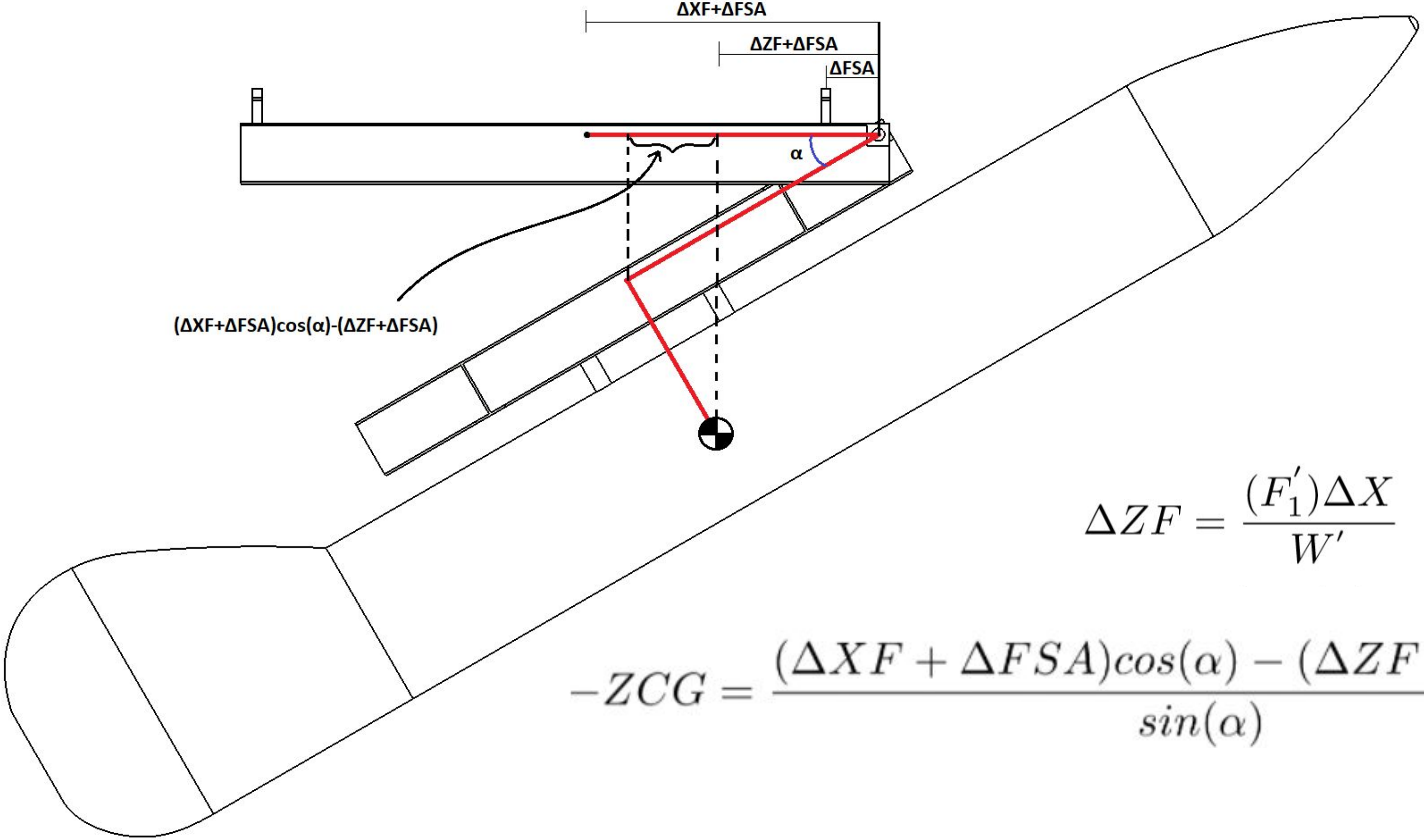
$$\Delta XF = \frac{(F_1)\Delta X}{W}$$

$$XCG = \Delta XF - \Delta L$$

$$YCG = \frac{(F_3 - F_2)\Delta Y}{W}$$

Reference: [1]

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST



$$\Delta ZF = \frac{(F_1')\Delta X}{W'}$$

$$-ZCG = \frac{(\Delta XF + \Delta FSA)cos(\alpha) - (\Delta ZF + \Delta FSA)}{sin(\alpha)}$$

Accuracy Feasibility - Approach

Motivation:

Range of pod weights (200-2000 lbs) causes challenge for weight accuracy of ±0.1%.

Load Cell accuracy is a function of **Full-Span of Operation (FSO)**, ex. ±0.1% FSO

- FSO = 2000 lbs, accuracy = ±0.1% FSO → error = ±2 lbs
- ±2 lbs error = **±0.1%** for 2000-lb pod
- ±2 lbs error = **±1%** for 200-lb pod

Approach:

Solution space characterized by load cells **allowable weight** and **accuracy capability**.

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Allowable Weight on Load Cells

W.A.S.P.

"Allowable" Criteria:

Expected maximum force on **single load cell** with specified factor of safety is **less than full-span for load cell**. (Not referencing manufacturer's specs for safe overload capacity.)

	Pod Weight Range Allowable		
Recommended Sensor Full-Span	**FOS = 1.0**	**FOS = 1.5**	**FOS = 2.0**
500 lbs	200-650 lbs	200-350 lbs	N/A
1000 lbs	200-1700 lbs	200-1000 lbs	200-650 lbs
2000 lbs	200-2000 lbs	200-2000 lbs	200-1700 lbs

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Defining Accuracy Solution Space - Monte Carlo

Error Sources - Weight:

- Load cells - internal and environmental
- DAQ - analog to digital conversion

Error Sources - CG:

- Load cells - internal and environmental
- Inclinometer - internal
- DAQ - analog to digital conversion
- Lengths of testbed - manufacturing tolerances

Error Source	Error Value
Load Cell	±0.021% FSO
Inclinometer	±0.04 deg
DAQ	±1 bin
Lengths	±1/24th inch

Extreme Case Considerations:

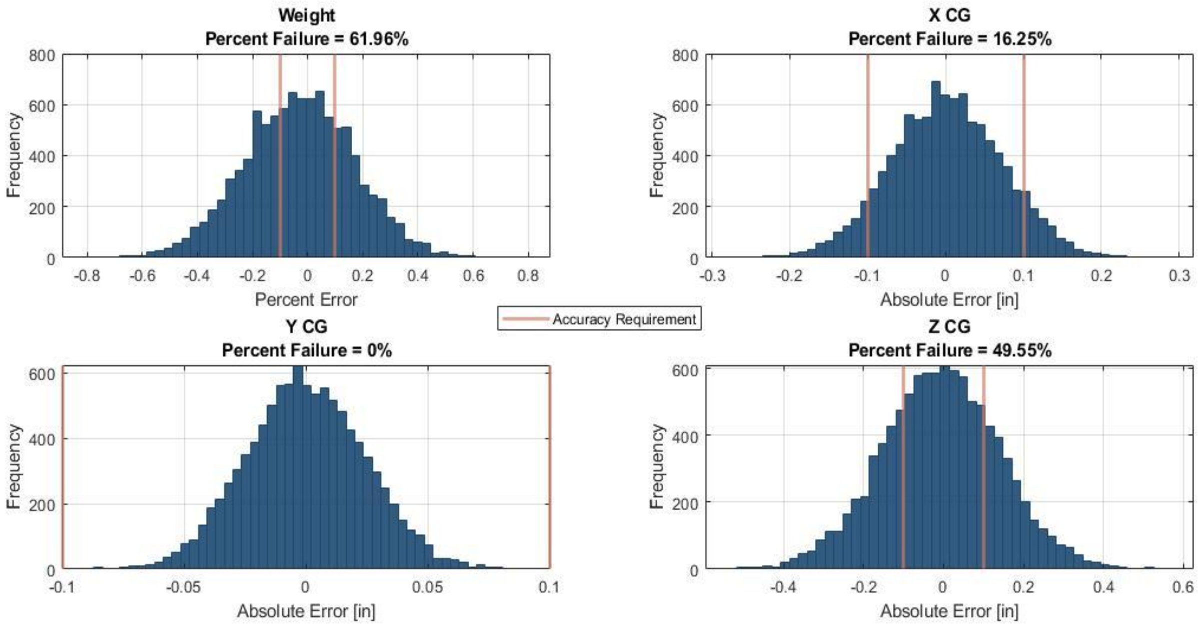
- Pod weight - min = 200lbs, max = 2000lbs
- Lug spacing - 14” or 30”
- X CG forward or aft of midpoint between lugs

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Monte Carlo Simulation - Example Failure Case

Parameters: 200lb pod, 14” lug spacing, CG forward of midpoint of lugs, N=10000

Load Cell: Omega LC103B-2K, Full-Span = 2000lbs

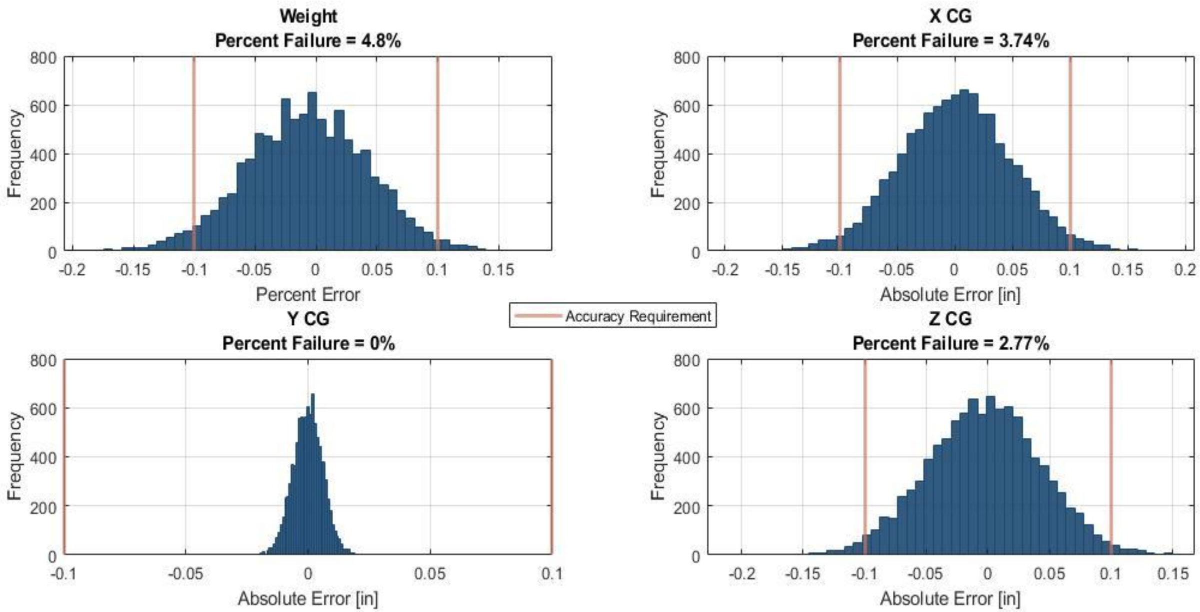


Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Monte Carlo Simulation - Example Success Case

Parameters: 200lb pod, 14” lug spacing, CG forward of midpoint of lugs, N=10000

Load Cell: Omega LC103B-500, Full-Span = 500lbs



Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Feasible Solution Space

Legend
X = Weight not allowable (FOS=1.5)
< 90% Predicted Success
> 90% Predicted Success
> 95% Predicted Success

Customer confirmed →

	Load Cell Sensor Full-Span		
Pod Weight [lbs]	**500 lbs**	**1000 lbs**	**2000 lbs**
200	> 95%		
300	> 95%		
350	> 95%	> 90%	
400	X	> 95%	
500	X	> 95%	
600	X	> 95%	
700	X	> 95%	> 90%
800	X	> 95%	> 90%
850	X	>95%	>95%
900	X	> 95%	> 95%
1000	X	> 95%	> 95%
1100	X	X	> 95%
1200	X	X	> 95%
1300	X	X	> 95%
1400	X	X	> 95%
1500	X	X	> 95%
1600	X	X	> 95%
1700	X	X	> 95%
1800	X	X	> 95%
1900	X	X	> 95%
2000	X	X	> 95%

Accuracy Requirements can be satisfied for full range of pods (200-2000 lbs) with use of 3 Load Cell types.

Financial Feasibility

Relevant Feasibility Statements

Label	Statement	CPE	FR	DR
COST	Cost of parts purchased by CU for WASP shall be less than $5,000.	E1	N/A	N/A

Finances

Subsystem-Level Budgets

Structural Components	Est. Cost
Raw Materials	$2500
Hardware	$500
Chain Hoist	$400
Contingency/Manufacturing (22%)	$750
Total	**$4150**

Electrical Components	Est. Cost
Load Cells (2 sets)	$1200
Inclinometer	$400
Cables	$100
DAQ system	$2000*
Contingency (30%)	$500
Total	**$2200**

*DAQ for development provided by CU, SNC will need to purchase for ongoing use

Overall Budget

Subsystem	Est. Cost
Structural Components	$4150
Electrical Components	$2200
Total	**$6350**

Takeaway: WASP Project Budget is only $5000. We will need support from SNC to purchase the sensors to make this project monetarily feasible.

Overall Budget - SNC Provides Sensors

Subsystem	Est. Cost
Structural Components	$4150
Electrical Components	$2200
Sensors	($1600)
Total	**$4750**

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Feasibility Conclusions

Conclusions

Label	Statement	CPE	Requirement	Feasible?
FOS	Frame members shall have a factor of safety greater than 2 against failure in compression, shear, bending, torsion, and buckling.	E1, E5	FR3	YES
COMPAT	The computer and DAQ must have compatible communication so data transfer is valid	E3	FR8	YES
ACC/W	Sensors and Data Processing Unit shall perform such that the accuracy requirement for weight (0.1% pod weight) is met for 90% of tests.	E3	FR1	YES*
ACC/CG	Sensors and Data Processing Unit shall perform such that the accuracy requirement for CG (0.1 in) is met 90% of tests.	E3	FR2	YES
COST	Cost of parts purchased by CU for WASP shall be less than $5,000	E1	N/A	YES**

* Customer expressed satisfaction with 0.1% accuracy in load cells

** Budget is still close to $5000 with SNC help

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Future Work

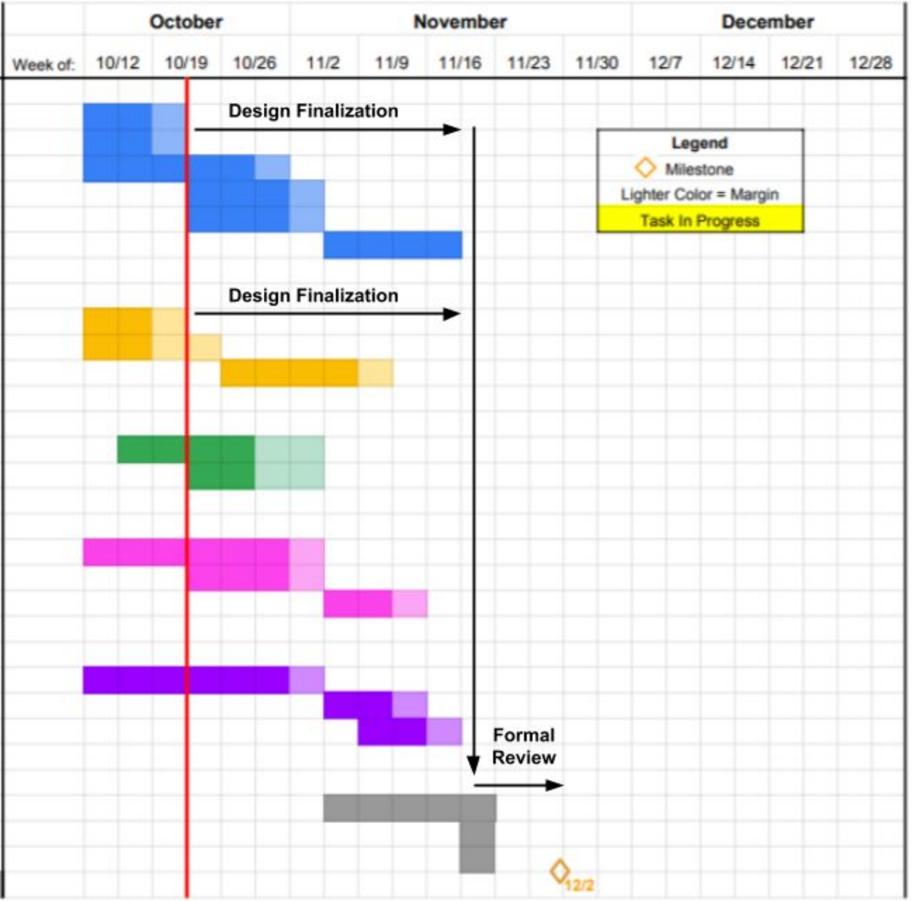
Further Design/Analysis Required

- Meet 30 degree tilt goal (frame height increase)
  - Structural and financial issues
- Attachment Points
  - Connections between members (cleats [10], welding)
  - Lug mounting
  - Chain hoist attachment points
  - Tilting mechanism cables
  - Wheels
  - Forklift slots
- Manufacturing concern regarding resources
- DAQ interfacing with Matlab [3]
- Sensitivity of CG calculation to deflection of members
- Transient load cases for allowable weight ranges

Feasibility Tracking				
FOS	COMPAT	ACC/W	ACC/CG	COST

Path Moving Forward

Plan for CDR						
Task	Duration (weeks)	Planned Start Date	Actual Start Date	Planned End Date	Deadline Date	Actual End Date
Structures						
Redesign of PDR Baseline	1	10/12	10/12	10/19	10/23	
Component Selection (Structures)	1	10/12	10/12	10/19	10/23	
Manufacturing Plan	2.5	10/12	10/12	10/29	11/2	
Detailed Design Components	1.5	10/23		11/2	11/6	
Detailed Static Analysis	1.5	10/23		11/2	11/6	
Manufacturing Drawings	1.5	11/6		11/17	11/17	
Electronics and Software						
Software Flow Chart	1	10/12	10/12	10/19	10/23	
Component Selection (E&S)	1	10/12	10/12	10/19	10/26	
Compatibility Verification	2	10/26		11/9	11/13	
Test						
Test Procedures	2	10/14		10/28	11/4	
Facility/Equipment Scheduling	2	10/14		10/28	11/4	
Systems						
Requirements Updating	3	10/12	10/12	11/2	11/6	
Verification & Validation Plans	1.5	10/23		11/2	11/6	
Risk Analysis	1	11/6		11/13	11/17	
Project Management						
Work Breakdown Structure	3	10/12	10/12	11/2	11/6	
Finalized Budget	1	11/4		11/11	11/15	
Gantt Chart for Spring Semester	0.5	11/12		11/15	11/18	
Deliverables						
CDR PowerPoint slides	2	11/4		11/18	11/18	
CDR Peer Reviews		11/18		11/23	11/23	
Final CDR slides for submission		11/18		11/23	11/23	
CDR Presenation				12/2	12/2	



Acknowledgements

SNC Team:

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Advisory Board Members:

Professor Bobby Hodgkinson, Dr. Jelliffe Jackson, Dr. Francisco Lopez Jimenez, Professor Matt Rhode, Professor Trudy Schwartz

PDR Reviewers:

Lara Buri, Dr. Francisco Lopez Jimenez, Team VORTEX, Addison Woodard

Thank you to everyone who supported the WASP Team!

Questions?

References

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Supporting Materials

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Systems

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Electronics and Software

Weight and CG Accuracy

Budget

Administrative

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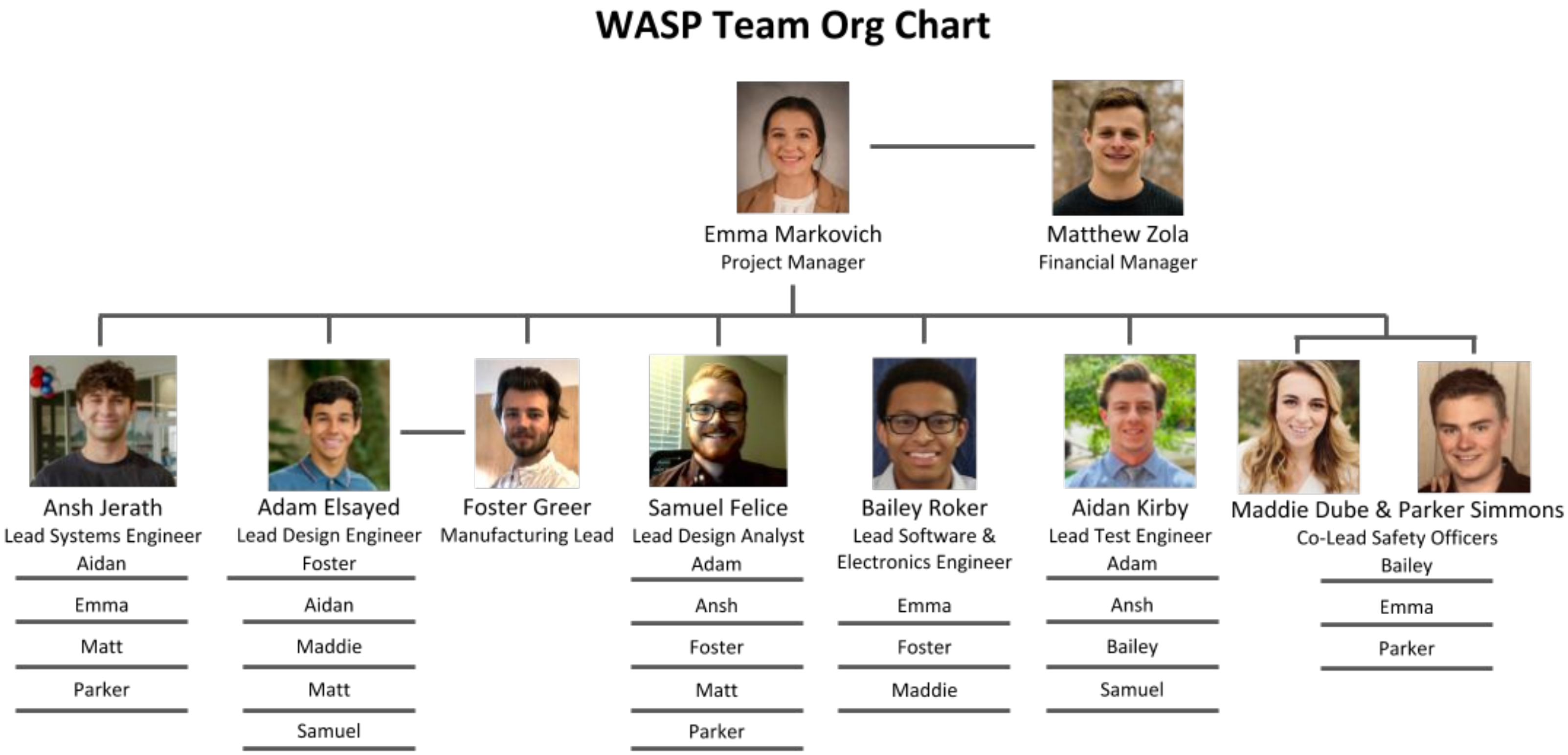
Organization Chart



Acronym List

Acronym	Definition
ACC	Accuracy
BC	Boundary Conditions
BOTE	Back of the Envelope (Hand-derived)
CAD	Computer-Aided Design
CG	Center of Gravity
COMPAT	Compatibility
CONOPS	Concept of Operations
COTS	Consumer Off-The-Shelf

Acronym	Definition
CPE	Critical Project Elements
DAQ	Data Acquisition System
DR	Design Requirement
FEA	Finite Element Analysis
FOS	Factor of Safety
FSO	Full Span of Operation
FR	Functional Requirement
GUI	Graphical User Interface

Acronym List

Acronym	Definition
IAS	ISR, Aviation & Security
ISR	Intelligence, Surveillance, & Reconnaissance
NIST	National Institute of Standards and Technology
PDR	Product Design Review
SNC	Sierra Nevada Corporation
UI	User Interface
VBA	Visual Basic for Applications
WASP	Weight Analysis of Surveillance Pods

Key Term Definitions

Term	Definition
Frame	The physical truss structure of WASP
ISR Pod/Pod	The physical object being measured by WASP, given by SNC.
Measurement Set	One recorded value for each sensor (load and inclination) in the flat and tilted configurations.
Test	The execution of a full procedure which starts after set-up and concludes when weight and CG values are output.
Tool	Equivalent to WASP.
User Procedure	Instructions document that describes transportation, maneuvering, and testing process for test engineers.
WASP	All elements of the final product/deliverable.

Systems

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What constitutes a “measurement repetition”?

The process for one **“measurement repetition”** is…

1. Calibrate the sensors in zero-load condition
2. Mount the pod to lugs
3. Lift and lock into flat configuration
4. Record measurements from sensors at flat configuration
5. Tilt and lock into tilted configuration
6. Record measurements sensors at tilted configuration
7. Untilt and lock into flat configuration
8. Lower the pod to cradle
9. Demount pod

If it is determined through experimental testing that the **mounting error** is small enough to be **considered negligible** (smaller than expected electronics system error), the measurement repetition will be altered to **exclude mounting and demounting**.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
1			WASP shall measure the weight of the ISR pod.	Customer specified functional requirement.	Demonstration - WASP outputs weight value when a full test is performed.
	1.1		WASP shall measure the weight of the pod within a tolerance of ± 0.1% of the total pod weight.	Customer specified accuracy requirement.	Testing - Perform several tests and confirm that reported weight meets the accuracy requirement for at least two tests on a test article of known weight.
		1.1.1	Sensors shall be of high enough resolution (≤ 0.2 lbs) to meet weight tolerance requirement for lightest pod.	Derived accuracy requirement.	Inspection/Demonstration - Inspection of sensor specifications and demonstration of sensor output resolution.
		1.1.2	Sensor shall be precise enough (repeatability ≤ 0.11 lb) to meet the weight accuracy requirements.	Derived accuracy requirement.	Inspection/Testing - Inspection of sensor specifications. Repeatability test: load device, record multiple measurements, statistically evaluate variance.
		1.1.3	Sensor calibration shall be National Institute of Standards and Technology (NIST) traceable such that measured values are accurate to within ± 0.1% of the pod's true total weight.	Customer specified accuracy requirement.	Inspection/Testing - Inspection of sensor specifications, NIST-traceable certified, and testing to verify measurement accuracy.
		1.1.4	Sensors shall be removable from the frame to minimize harmful vibrations due to transporting the device.	Derived design requirement.	Demonstration - Show that sensors can be disconnected and reconnected.
	1.2		Sensors will be recalibrated per sensor supplier-recommended method prior to each measurement set to minimize errors due to drift, bias, hysteresis, etc.	Derived accuracy requirement.	Inspection - Operational guidelines and user manual will require sensor recalibration prior to each measurement set.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
2			WASP shall measure the X, Y, and Z CG of the ISR pod.	Customer specified functional requirement.	Demonstration - WASP outputs CG location when a full test is performed.
	2.1		WASP shall measure the X, Y, and Z CG of each pod with an accuracy of ± 0.1 in.	Customer specified accuracy requirement.	Testing - Perform several tests and confirm that reported CG location meets the accuracy requirement for at least five tests.
		2.1.1	Sensors shall have high enough resolution (≤ 0.2 lbs) to meet the CG accuracy requirements.	Derived accuracy requirement.	Inspection - Confirm the resolution of the sensors.
		2.1.2	Sensor shall be precise enough (repeatability ≤ 0.11 lb) to meet the CG accuracy requirements.	Derived accuracy requirement.	Inspection/Testing - Confirm repeatability tolerance on sensor data sheet. Perform test on a load of known value several times and evaluate variance.
		2.1.3	Sensor calibration shall be NIST-traceable such that measured values are accurate to within ± 0.1 in. of the pod's true CG.	Customer specified accuracy requirement.	Inspection/Testing - Inspection of sensor specifications, NIST-traceable certified, and testing to verify measurement accuracy.
		2.1.4	Sensors shall be removable from the frame to minimize harmful vibrations due to transporting the device.	Derived design requirement.	Demonstration - Show that sensors can be disconnected and reconnected.
	2.2		Sensors shall be recalibrated per sensor supplier-recommended method prior to each measurement set to minimize errors due to drift, bias, hysteresis, etc.	Derived accuracy requirement.	Inspection - Operational guidelines and user manual will require sensor recalibration prior to each measurement set.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
	2.3		WASP shall use at minimum three sensors to measure CG in three-dimensions.	Derived design requirement.	Inspection - Verify that at least three sensors are used to measure CG.
3			WASP shall interface with all existing ISR pods.	Customer specified design requirement.	Demonstration - Mount and lift all five existing pod type.
	3.1		WASP shall support pods of 2000 lbs without yielding with a safety factor of 2.0 to make safe and accurate measurements.	Derived design requirement.	Testing - Structural analysis on each component and test with 2000 lb test article.
	3.2		The WASP mounting interface shall support all current SNC pod mounting types.	Customer specified design requirement.	Testing - Attach each pod type to WASP.
		3.2.1	WASP shall interface with 14in. And 30 in. lug spacing per MIL-STD 8591.	Derived design requirement.	Inspection - WASP will have lugs 14 in. and 30 in. apart.
		3.2.2	WASP shall interface with additional lug designs currently used by SNC IAS.	Derived design requirement.	Demonstration - Pods with abnormal lug mounts will be connected to WASP.
	3.3		WASP shall lift pods out of their cradles.	Derived design requirement.	Testing - WASP will lift a pod of 2000 lbs out of its cradle.
	3.4		WASP shall support pods with X CG of ± 3 in. from the center of the lug mounts.	Derived design requirement - Stability.	Analysis - Ensure the range of possible CG locations is always between WASP’s legs.
4			WASP shall be free-standing, and it shall be maneuvered around a hangar by engineers or technicians.	Customer specified functional requirement.	Demonstration - Maneuver WASP around an open space.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
	4.1		WASP shall have a transport mechanism.	Derived design requirement.	Inspection - verify that WASP has a transportation mechanism.
		4.1.1	WASP shall be locked in place during testing.	Derived accuracy requirement.	Inspection/Testing - Locking device will be used while measuring a 2000 lb test article.
	4.2		WASP shall be moved by no more than 2 engineers/technicians.	Customer specified design requirement.	Demonstration - 2 WASP team members will maneuver WASP around an open space.
		4.2.1	WASP shall be maneuverable with less than 45 lbs of push/pull force per person.	Derived design requirement - MIL-STD 1472 Table XVIII.	Analysis - Dynamics-rooted derivation will reveal limits on allowable motion (speed, acceleration, distance, etc.).
5			WASP shall fit into the SNC IAS box truck.	Customer specified functional requirement.	Demonstration - The final device will be loaded and unloaded from the SNC IAS box truck.
	5.1		WASP shall occupy less than 44 in. by 88 in. by 79 in. (LxWxH) cubic volume when being transported.	Derived design requirement.	Inspection - CAD models will provide these dimensions.
	5.2		WASP shall weigh less than 2000 lbs.	Derived design requirement.	Inspection - CAD will provide a weight estimate. Verified by weighing WASP.
6			WASP shall have a test procedure to make consistent weight and CG measurements.	Derived functional requirement.	Demonstration - Engineers who did not design WASP will conduct supervised tests using the test procedure.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
	6.1		WASP shall complete a single test in no more than 30 minutes.	Customer specified design requirement.	Demonstration - WASP team members will complete a test within the time constraint.
		6.1.1	WASP shall make one set of measurements and calculations in no more than 6 minutes.	Derived design requirement.	Demonstration - WASP team members will complete a set within the time constraint.
	6.2		WASP shall require no more than 2 engineers/technicians to complete a test.	Customer specified design requirement.	Demonstration - 2 WASP team members will safely and accurately complete a test.
	6.3		WASP shall have a physical user manual or procedure.	Derived design requirement.	Inspection - The final device will include a user manual.
7			WASP shall not maneuver the ISR pods in any way that could damage them.	Customer specified functional requirement.	Demonstration - An engineer will verify all the ways a pod is maneuvered during a test.
	7.1		WASP shall not rotate the pod more than 30 degrees about the Y-axis.	Customer specified design requirement.	Inspection - Maximum allowable rotation will not be exceeded (measured using an inclinometer).
	7.2		WASP shall not rotate the pod about the X-axis.	Customer specified design requirement.	Demonstration - During a test, WASP will not rotate a pod about the X-axis.
	7.3		WASP's lifting/tilting device(s) shall remain static when not lifting/rotating the pod.	Derived design requirement.	Demonstration - Engineers will visually confirm that these devices remain static during a test.

Requirements

FR	DR1	DR2	Requirement	Motivation	Validation
8			WASP shall include a computer-based tool to aid in calculations.	Customer specified functional requirement.	Inspection - WASP will include a computer-based tool.
	8.1		WASP shall have a computer-based tool that interfaces with the sensors.	Derived design requirement.	Demonstration - WASP will interface with a computer through the computer-based tool.
		8.1.1	Connections to sensors shall be detachable.	Derived design requirement.	Demonstration - The sensors will be detached and reattached.
		8.1.2	The computer-based tool shall reboot connection with sensors after each measurement.	Derived accuracy requirement.	Demonstration - WASP will reset connection to sensors between measurements.
	8.2		WASP shall have a supporting user interface (UI) that processes and analyzes sensor data.	Customer specified design requirement.	Demonstration - WASP will read sensor data and run calculations on the UI.
		8.2.1	The UI shall function autonomously.	Derived design requirement.	Demonstration - WASP will perform measurements and interfacing to users autonomously during a test.
		8.2.2	The UI shall have alternative functioning methods to backup the autonomous system.	Derived design requirement.	Demonstration - WASP will provide options for types of measurements and interfacing to users during a test.
	8.3		WASP shall save weight and CG location results in an Excel-compatible file type.	Customer specified design requirement.	Demonstration - Verify that final saved results are stored in a file that can be viewed as an Excel Workbook.

Structures

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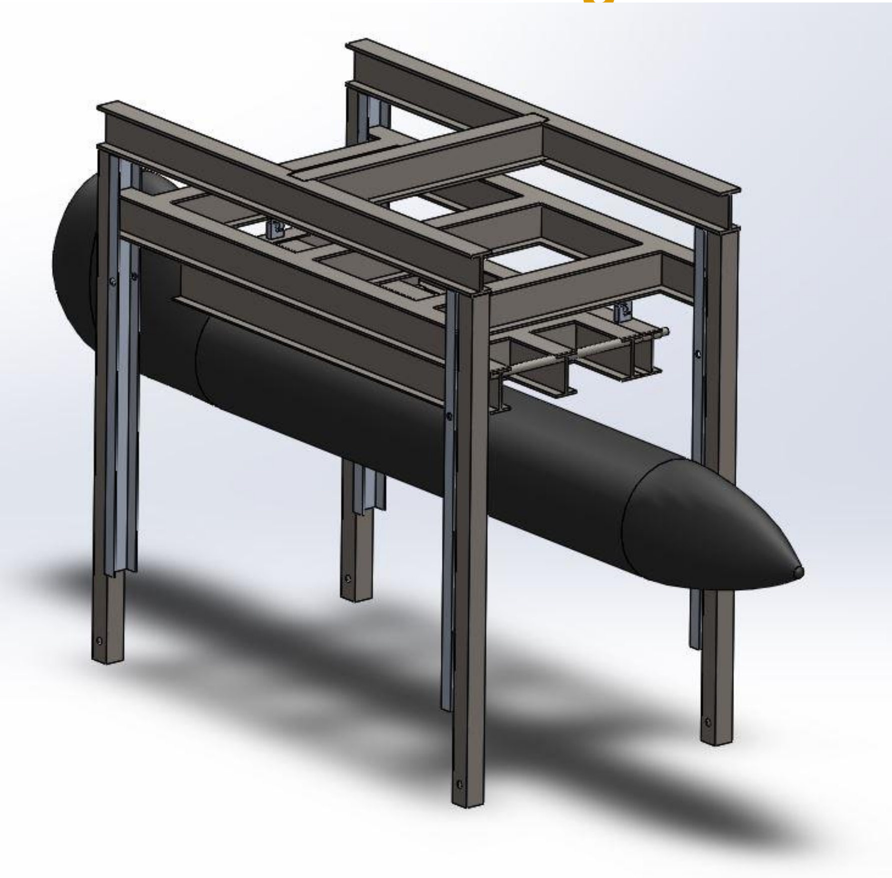
Isometric View of Design

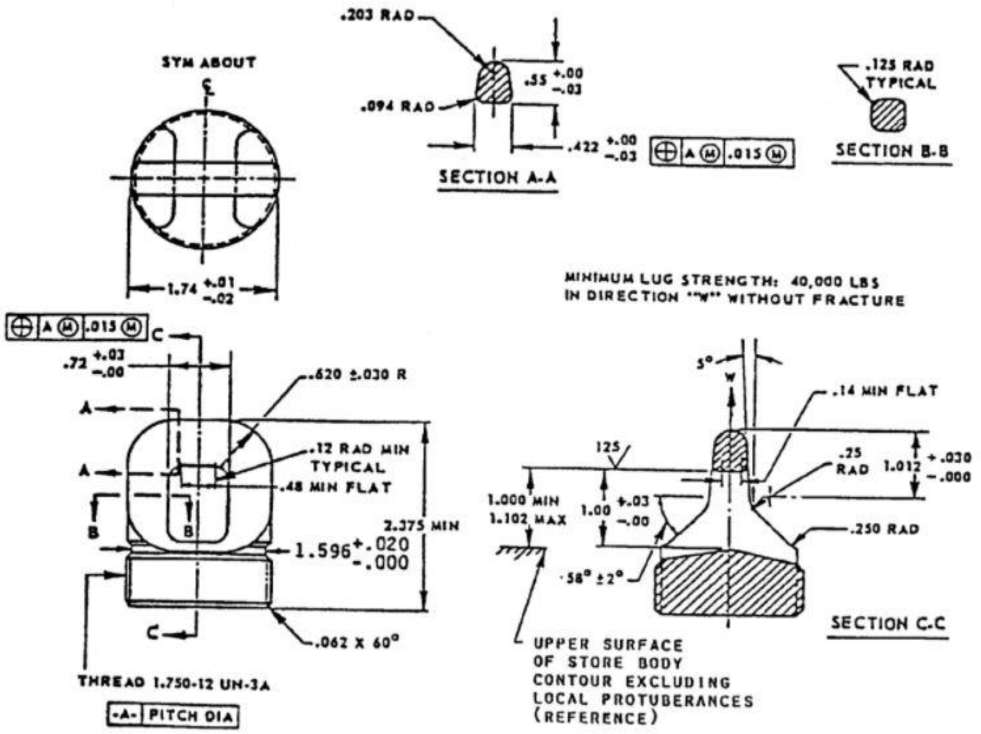


Lugs

Generic Lug

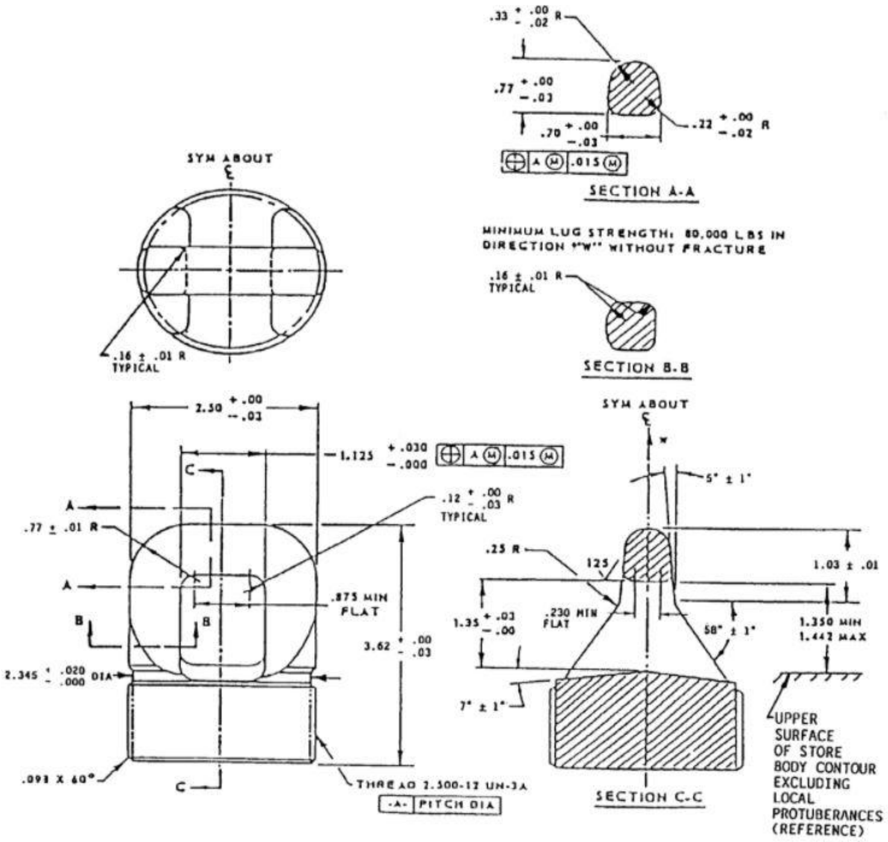
Lugs

14” Lugs for the 1000 lb weight class (MIL-STD 8591)



Lugs

30” Lugs for the 2000 lb weight class (MIL-STD 8591)



Current Chain Hoist Being Considered

- Hurricane 360 Hand Chain Hoist
  - 2 ton capacity
  - 10’ - 30’ lifting
  - $391 - $534 depending on lift distance
  - Can rotate pull chain so it doesn’t interfere with the structure

Frame Analysis - Hand Derivations

- <u>Common Assumptions (Beams/Shafts, Bars, Axle)</u>
  - Isotropic material with constant cross section
  - Torsional twisting is the same throughout the cross section
    - e.g. the entire "I" of the I-beam twists the same amount at any given distance along the length of the beam
  - Every force other than beam weight is modeled as a point load
  - Elastic behavior
  - L is the beam/bar length

Bar Analysis (Legs)

- Isotropic
- Constant cross section
- Euler Column (buckling)
  - Limitation: Assumes solid beam cross section

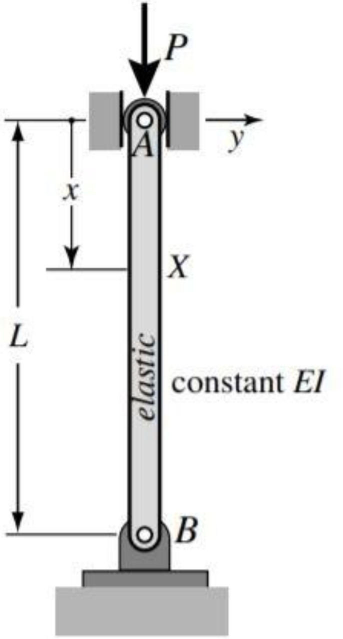
$$P_{cr} = \frac{\pi^2 EI}{L^2} = \frac{pi^2(29000000\,psi)(1.98\,in^4)}{(73\,in^2)} = 106000\,lbf$$

$$FOS = \frac{P_{cr}}{P} = \frac{106000\,lbf}{1000\,lbf} = 106$$

- Compression
  - Min. compressive strength at center of shear pin hole

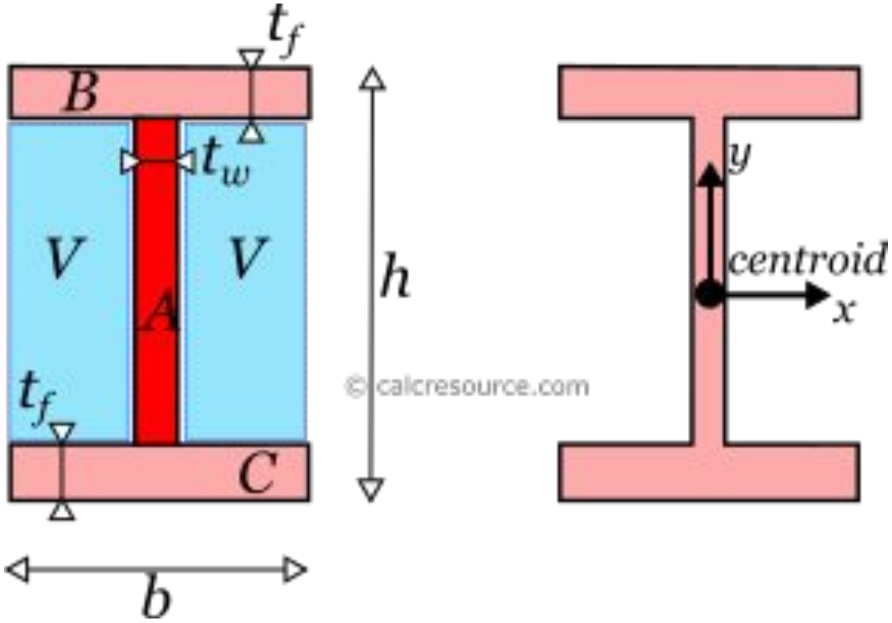
$$\sigma_{min} = \frac{P_{max}}{A_{min}} = \frac{1000\,lbf}{1.19\,in^4} = 840\,psi$$

$$FOS = \frac{sigma_{yield}}{sigma_{min}} = \frac{36300\,psi}{840\,psi} = 43.2$$



Beam Analysis Equations

- Geometry for Beam:



$$I_x = \frac{bh^3}{12} - \frac{(b - t_w)(h - 2t_f)^3}{12}$$

$$J_\alpha \approx J_\beta \approx \frac{bt^3}{3} = J$$

$$J_f = \frac{bt_f^3}{3}$$

$$J_w = \frac{(h - 2t_f)t_w^3}{3}$$

Beam Analysis Equations

$$\sigma_{bend} = \frac{-y_{max} M_{max}}{I_{xx}}$$

$$FOS_{bend} = \frac{\sigma_y}{\sigma_{bend}}$$

$$\tau_{shear} = \frac{V_{max}}{A_c}$$

$$FOS_{shear} = \frac{\tau_y}{\tau_{shear}}$$

$$where$$

$$V(x) = M'(x)$$

$$and$$

$$\tau_y \approx \frac{\sigma_y}{2}$$

$$\tau_{torsion} = \frac{Tt}{J}$$

$$FOS_{torsion} = \frac{\tau_y}{\tau_{torsion}}$$

Reasoning for Iterative Process for Beam Modeling

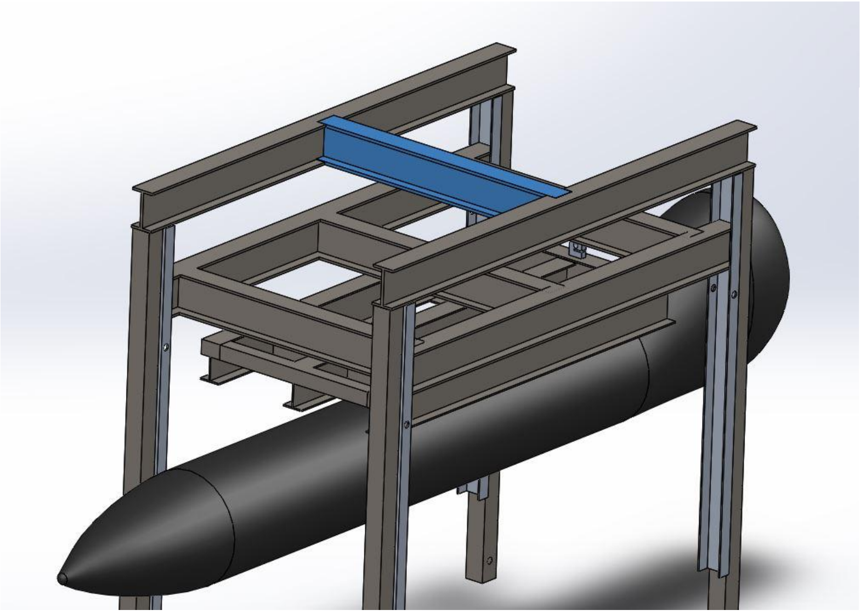
- Fixed-fixed assumption is <u>bad</u> for beams connected to other beams (i.e. beam 1 and beam 2)
- If fixed, the connection between beam 1 and 2 must be level ($v'(0) = 0$)
- This suggests that a large moment must act on the end of beam 1. Because it is connected to beam 2, an equal and opposite torque must act on beam 2. This leads to a nonzero twist angle: cannot assume fixed.

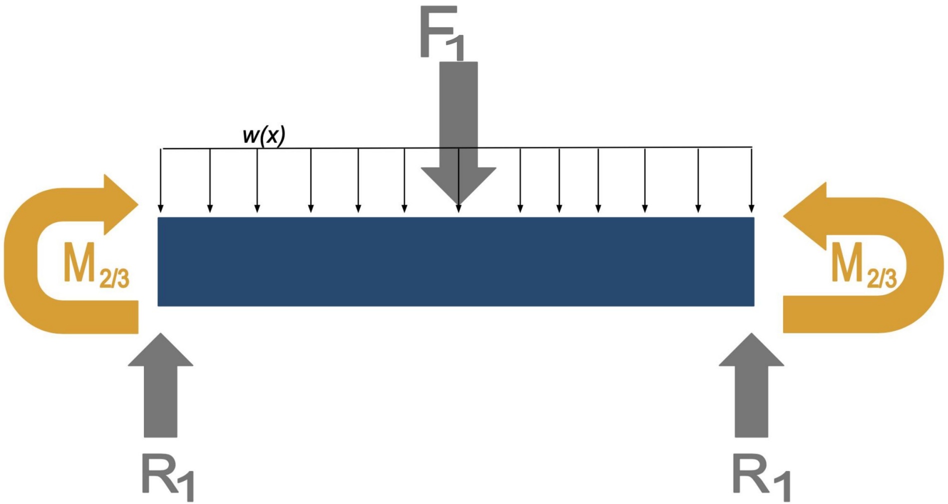
Steps for Iterative Moment Calculation

- Bending of beam 1 leads to torsion of beam 2
    - Arbitrarily choose an end moment for beam 1. Use this to calculate v'(0) for beam 1. Assuming a perfect connection, this is the twist angle for beam 2. Use this twist angle to solve for the torque in beam 2. Plug that torque in as the end moment of beam 1 and resolve v'(0). Continue this until the result converges.
    - At this point, T_2 = M_1 and v'(0) for beam 1 equals the twist angle of beam 2
    - <u>Higher fidelity model than simply assuming beam 1 is fixed or pinned</u>

- Similar process used for sliding interface and testbed
    - More complex because multiple beams impart moments on twisting beam

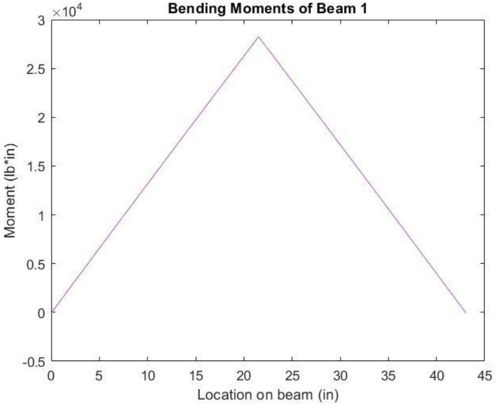
Beam 1

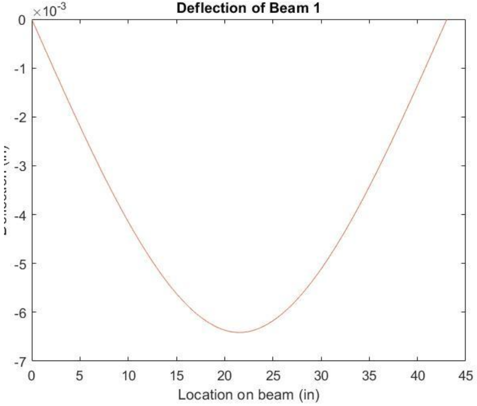




Beam 1

- Neither fixed nor pinned
- Symmetric





For $0 \leq x \leq \frac{L}{2}$:

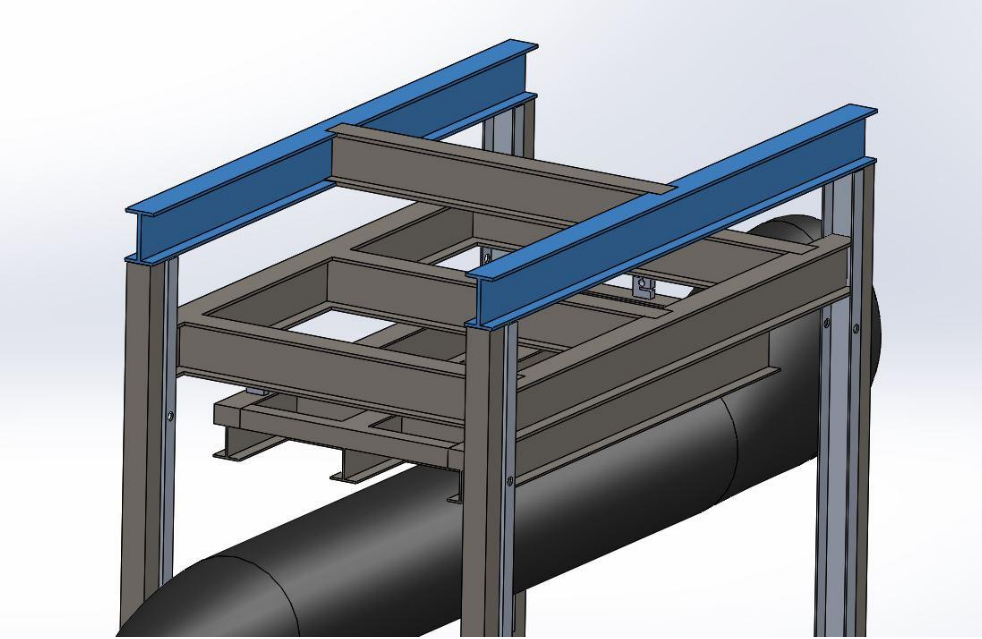
$$M(x) = R_1 x + M_{2/3} - \frac{wx^2}{2}$$

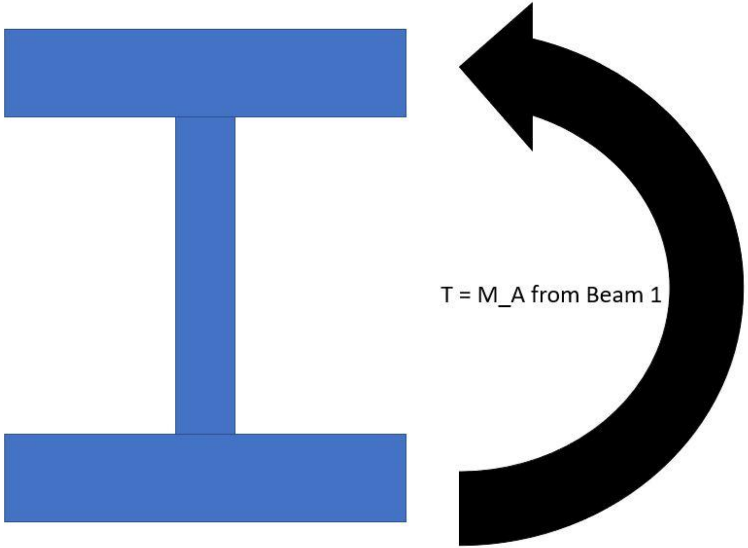
$$v(x) = \frac{R_1 x^3}{6EI} + \frac{M_{2/3} x^2}{2EI} - \frac{wx^4}{24EI} + \frac{c_1 x}{EI}$$

where

$$c_1 = \frac{wL^3}{48} - \frac{M_{2/3} L}{2} - \frac{R_1 L^2}{8}$$

Beams 2/3



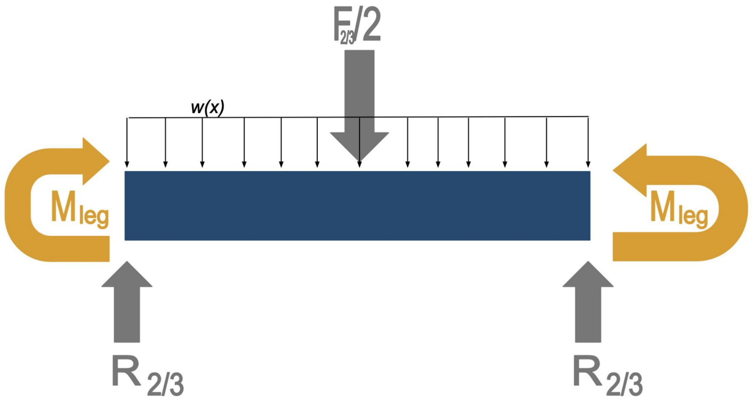


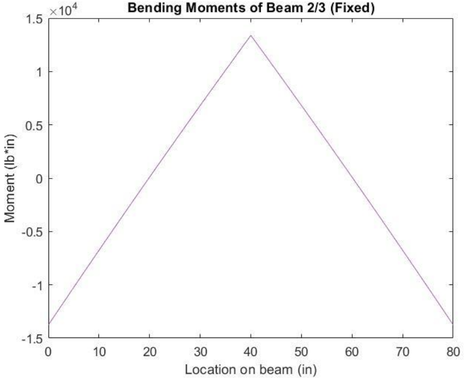
$$T_{internal} = T = \frac{M_{2/3}}{2}$$

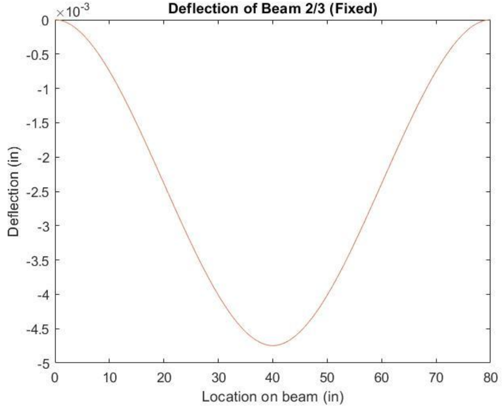
$$\phi_{max} = \frac{\frac{T}{2}\frac{L}{2}}{GJ} = \frac{TL}{4GJ}$$

Beam 2 - Fixed

- Fixed
- Symmetric







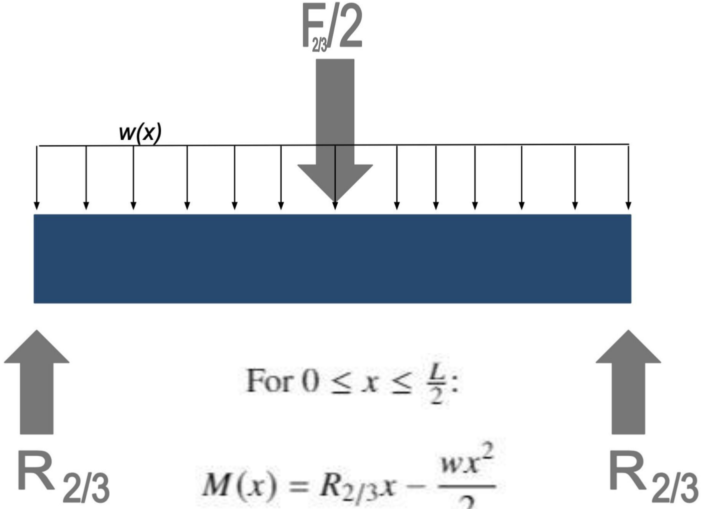
For $0 \le x \le \frac{L}{2}$:

$$M(x) = R_{2/3}x + M_{leg} - \frac{wx^2}{2}$$

$$v(x) = \frac{R_{2/3}x^3}{6EI} + \frac{M_{leg}x^2}{2EI} - \frac{wx^4}{24EI}$$

Beam 2 - Pinned

- Fixed - No moments at ends
- Symmetric



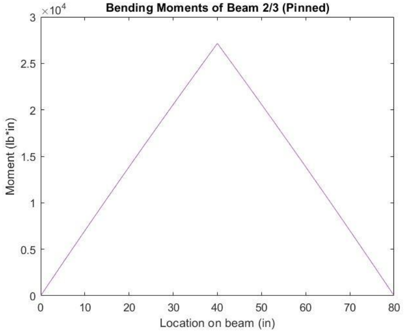
For $0 \le x \le \frac{L}{2}$:

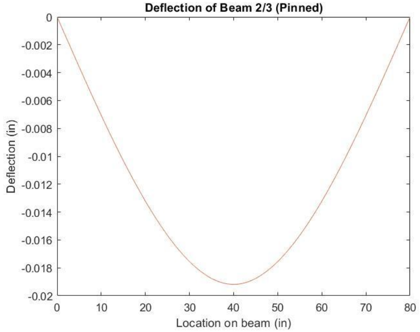
$$M(x) = R_{2/3}x - \frac{wx^2}{2}$$

$$v(x) = \frac{R_{2/3}x^3}{6EI} - \frac{wx^4}{24EI} + c_1 x$$

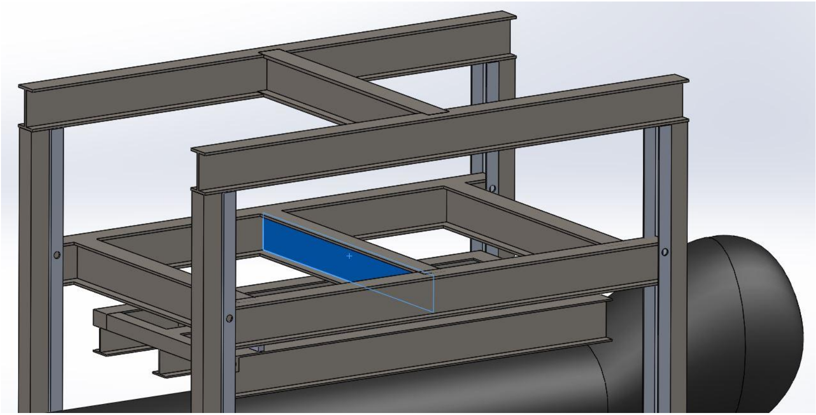
where:

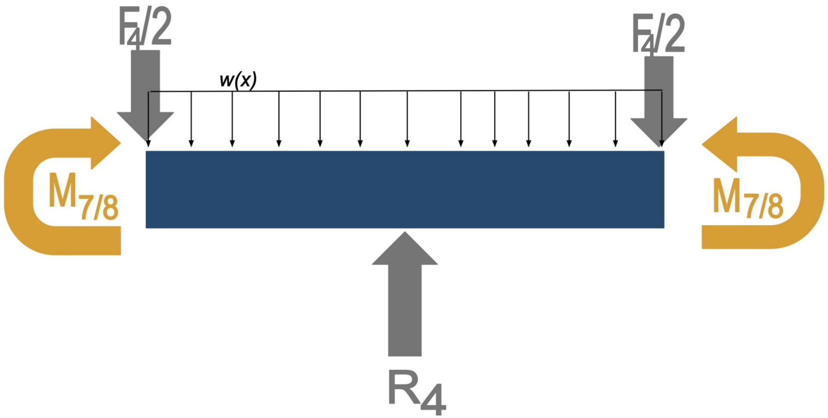
$$c1 = \frac{wL^3}{48} - \frac{R_{2/3}L^2}{8}$$

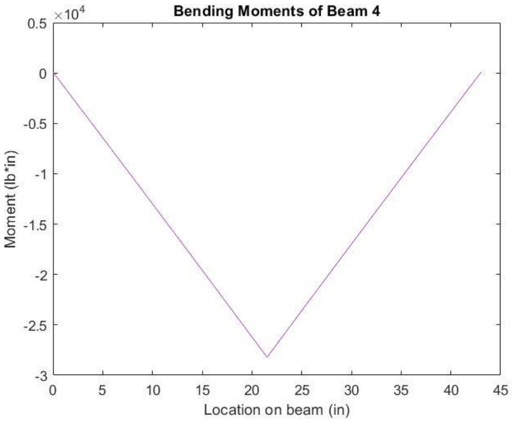


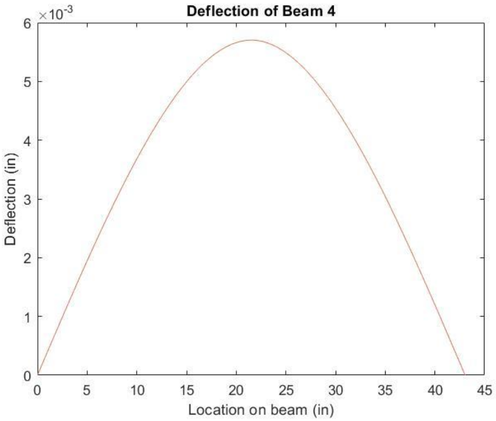


Beam 4







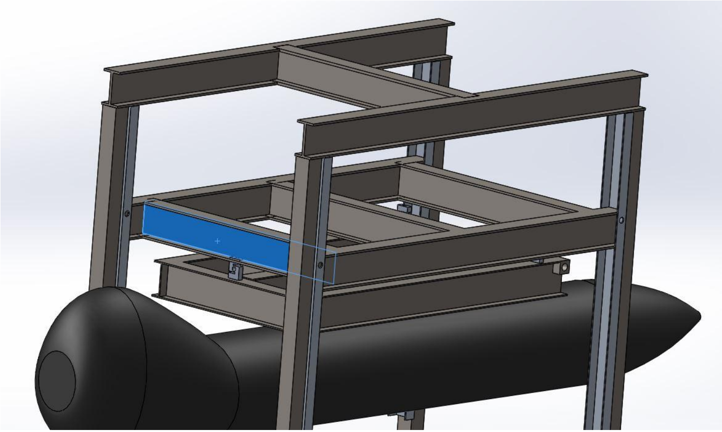


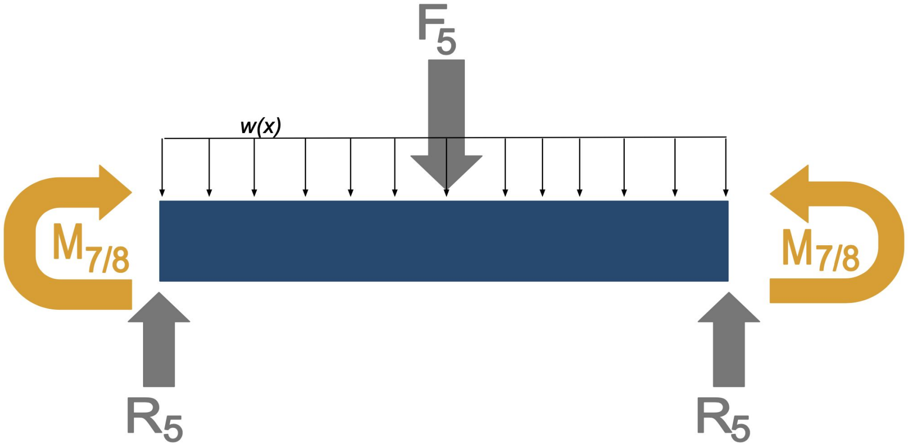
$$M(x) = M_{7/8} - \frac{F_4 x}{2} - \frac{w x^2}{2}$$

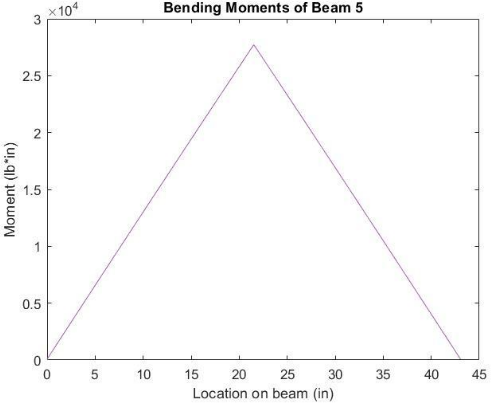
$$v(x) = \frac{1}{EI}\left(\frac{M_{7/8} x^4}{2} - \frac{F_4 x^3}{12} - \frac{w x^4}{24} + C_1 x\right)$$

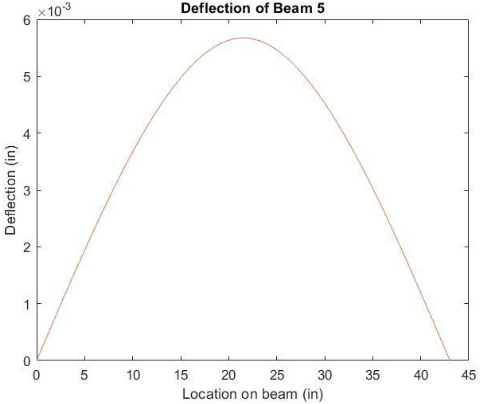
$$C_1 = \frac{-M_{7/8} L}{2} + \frac{F_4 L^2}{16} + \frac{w L^3}{48}$$

Beam 5







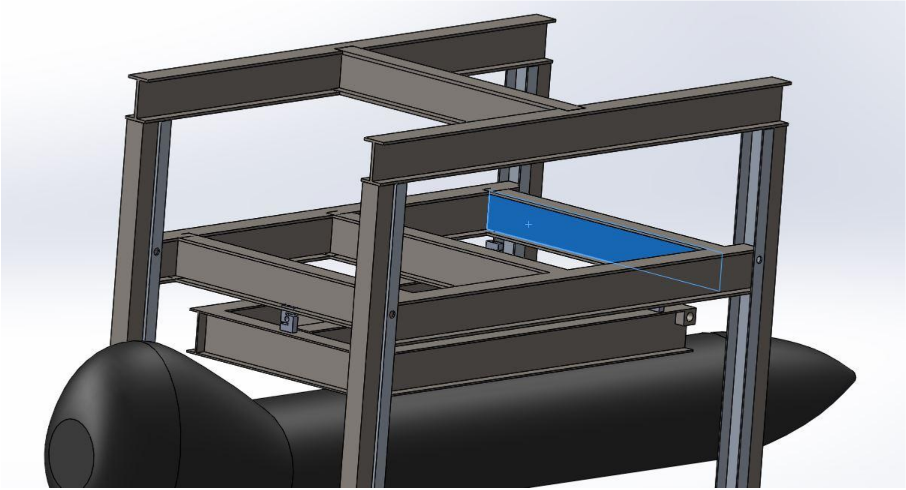


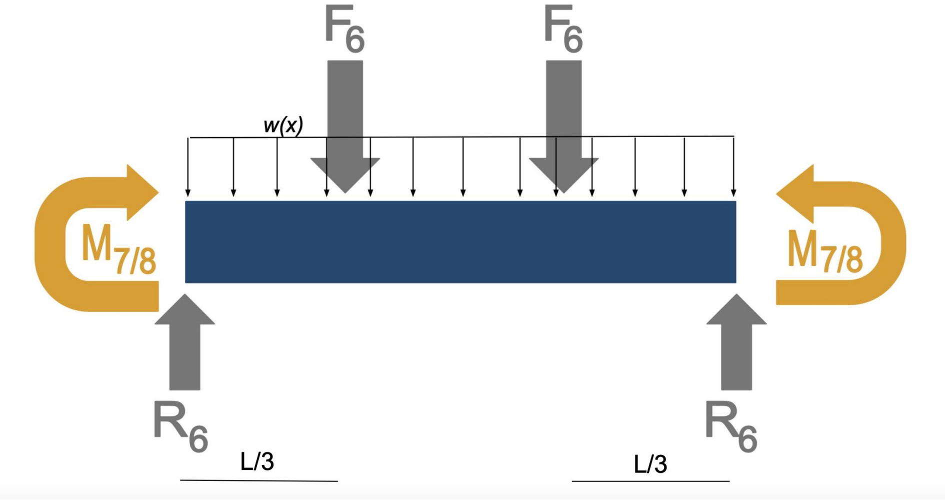
$$M(x) = M_{7/8} + R_5 x - \frac{wx^2}{2}$$

$$v(x) = \frac{1}{EI}\left(\frac{M_{7/8}x^2}{2} + \frac{R_5 x^3}{6} - \frac{wx^4}{24} + C_1 x\right)$$

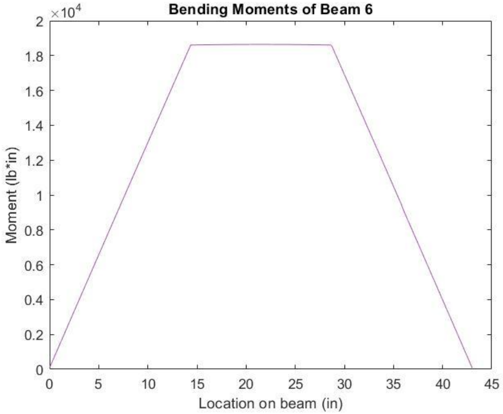
$$C_1 = \frac{M_{7/8}L}{2} + \frac{R_5 L^2}{8} - \frac{wL^3}{48}$$

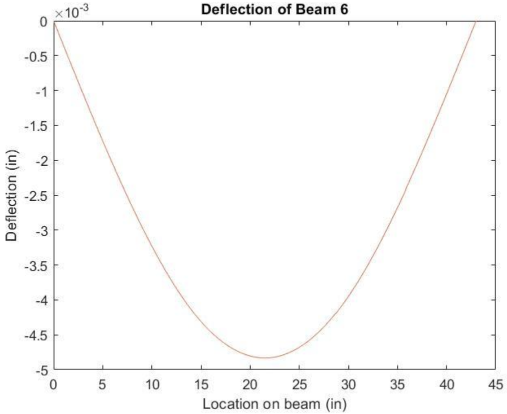
Beam 6





Beam 6 cont





for 0<x<a:

$$M(x) = M_{7/8} + R_6 x - \frac{wx^2}{2}$$

$$v(x) = \frac{1}{EI}\left(\frac{M_{7/8}x^2}{2} + \frac{R_6 x^3}{6} - \frac{wx^4}{24} + C_1 x\right)$$

for a<x<b:

$$M(x) = M_{7/8} + R_6 x - F(x-a) - \frac{wx^2}{2}$$

$$v(x) = \frac{1}{EI}\left(\frac{M_{7/8}x^2}{2} + \frac{R_6 x^3}{6} - \frac{Fx^3}{6} + \frac{Fax^2}{2} - \frac{wx^4}{24} + C_3 x + C_4\right)$$

where:

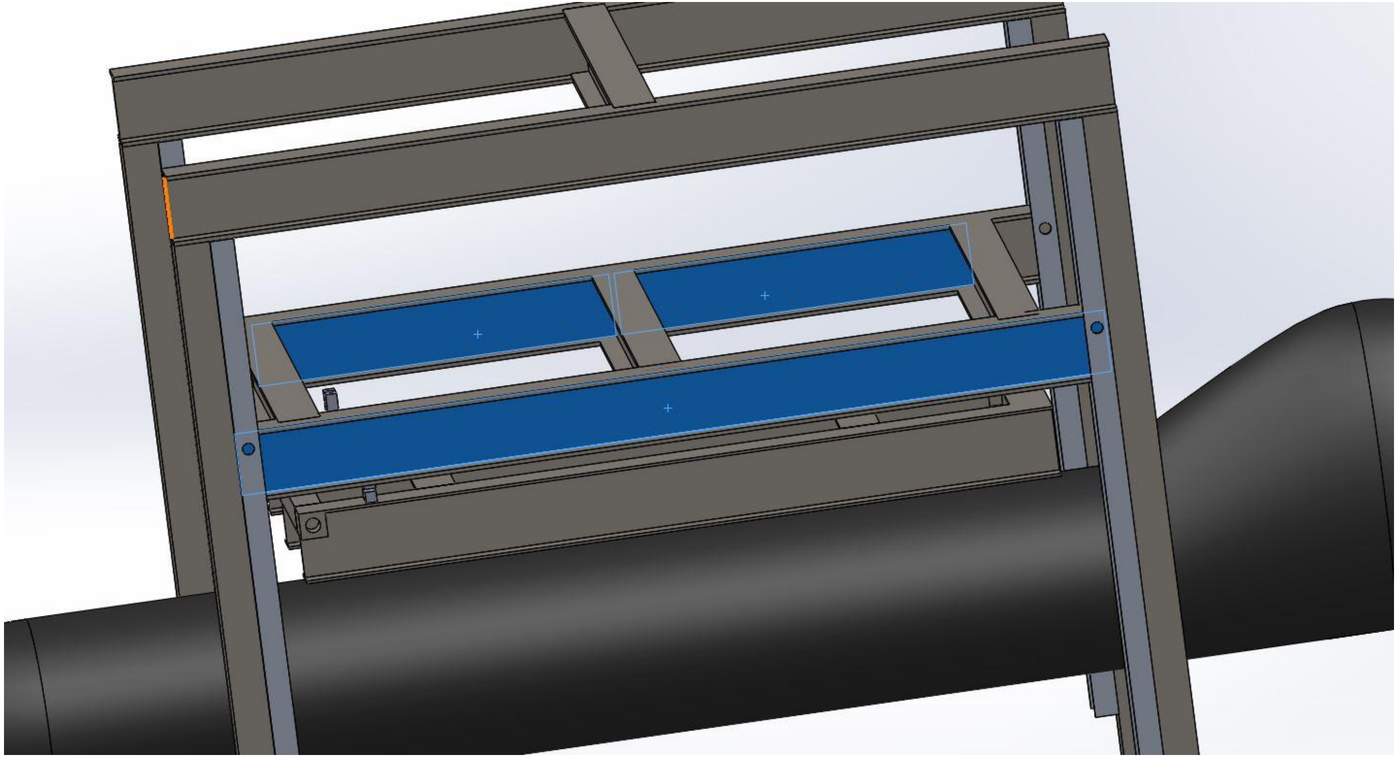
$$a = \frac{L}{3} \qquad b = \frac{L}{2}$$

$$C_3 = -M_{7/8}b - \frac{R_6 b^2}{2} + \frac{Fb^2}{2} - Fab + \frac{wb^3}{6}$$

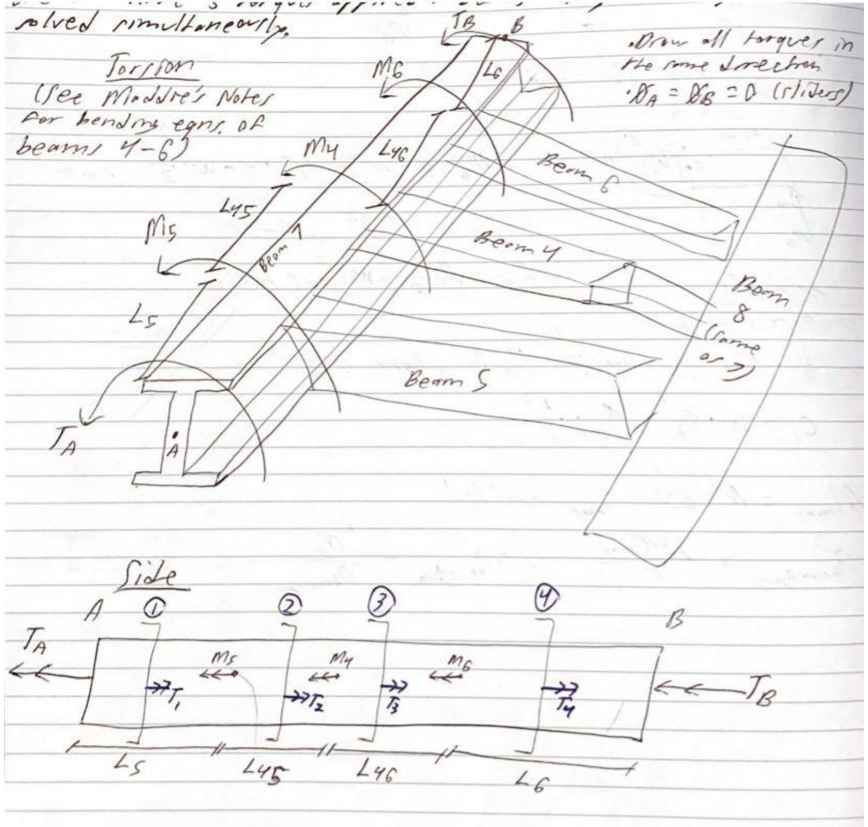
$$C_1 = \frac{Fa^2}{2} + C_3$$

$$C_4 = C_1 a - C_3 a - \frac{Fa^3}{3}$$

Beams 7 / 8



Beams 7/8 - Torsion



$$\phi_A = 0;$$

$$\phi_{A-5} = \frac{T_1 L_5}{GJ} = v_5'(0)$$

$$\phi_{A-4} = \frac{T_1 L_5}{GJ} + \frac{T_2 L_{45}}{GJ} = v_5'(0) + \frac{T_2 L_{45}}{GJ} = v_4'(0)$$

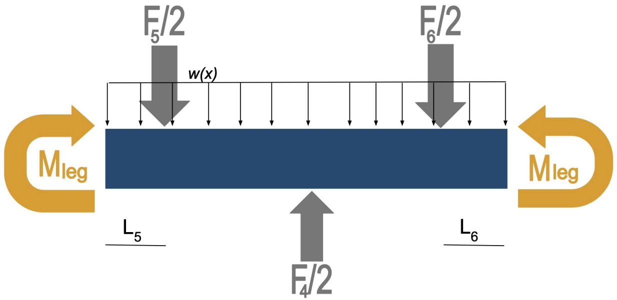
$$\phi_{A-6} = \frac{T_1 L_5}{GJ} + \frac{T_2 L_{45}}{GJ} + \frac{T_3 L_{46}}{GJ} = v_4'(0) + \frac{T_3 L_{46}}{GJ} = v_6'(0) \frac{T_2 L_{45}}{GJ} = v_4'(0)$$

$$\phi_{A-B} = \frac{T_1 L_5}{GJ} + \frac{T_2 L_{45}}{GJ} + \frac{T_3 L_{46}}{GJ} + \frac{T_4 L_6}{GJ} = v_6'(0) + \frac{T_4 L_6}{GJ} = 0$$

More complex iterative solver for beams 4-8 created based off these equations

Beams 7/8 - Lifting

- Symmetric (L5 = L6, F5 = F6)
- Modeled with rollers



For $0 \leq x \leq L_5$:

$$M(x) = M_{leg} - \frac{wx^2}{2}$$

$$v(x) = \frac{M_{leg}x^2}{2EI} - \frac{wx^4}{24EI}$$

For $L_5 \leq x \leq \frac{L}{2}$:

$$M(x) = M_{leg} - \frac{wx^2}{2} - \frac{F_5(x - L_5)}{2}$$

$$v(x) = \frac{M_{leg}x^2}{2EI} - \frac{wx^4}{24EI} + \frac{F_5L_5x^2}{4EI} - \frac{F_5x^3}{12EI} + \frac{c_3x + c_4}{EI}$$

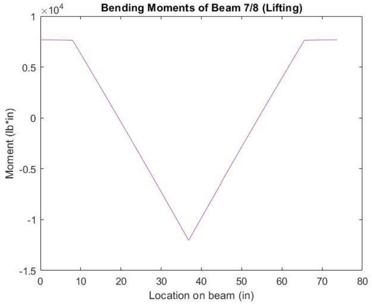
where

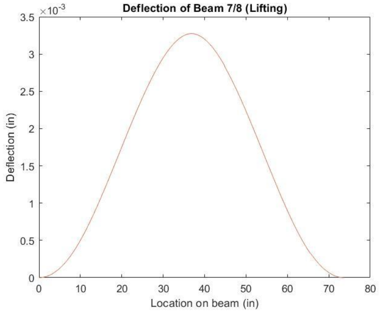
$$c_3 = \frac{-F_5L_5^2}{4}$$

$$c_4 = \frac{F_5L_5^3}{12}$$

and

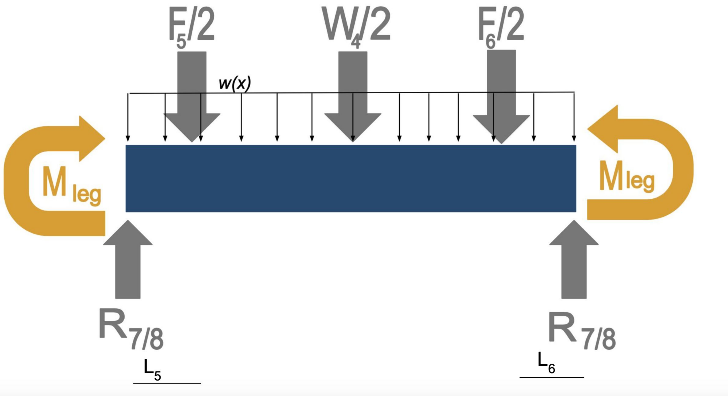
$$M_{leg} = \frac{2}{L}\left(\frac{F_5 * L^2}{16} - \frac{F_5L_5L}{4} + \frac{wL^3}{48} + \frac{F_5L_5^2}{4}\right)$$

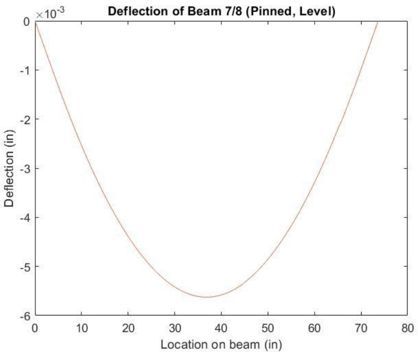


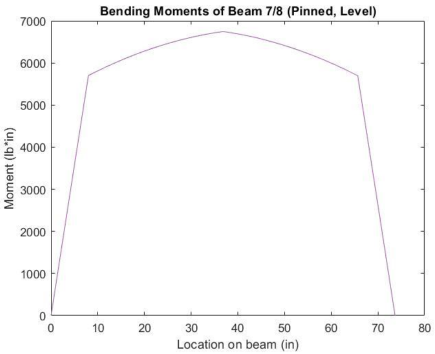


Beams 7/8 - Pinned, Level

- Symmetric







For $0 \le x \le L_5$:

$$M(x) = R_{7/8}x - \frac{wx^2}{2}$$

$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{c_1 x}{EI}$$

For $L_5 \le x \le \frac{L}{2}$:

$$M(x) = R_{7/8}x - \frac{wx^2}{2} - \frac{F_5(x - L_5)}{2}$$

$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{F_5 L_5 x^2}{4EI} - \frac{F_5 x^3}{12EI} + \frac{c_3 x + c_4}{EI}$$

$$c_1 = c_3 + \frac{F_5 L_5^2}{4}$$

$$c_3 = \frac{F_5 L^2}{16} + \frac{wL^3}{48} - \frac{F_5 L_5 L}{4} - \frac{R_{7/8} L^2}{8}$$

$$c_4 = \frac{F_5 L_5^2}{12}$$

Beams 7/8 - Pinned, Tilted

- F6 is no longer equal to F5

For $0 \le x \le L_5$:

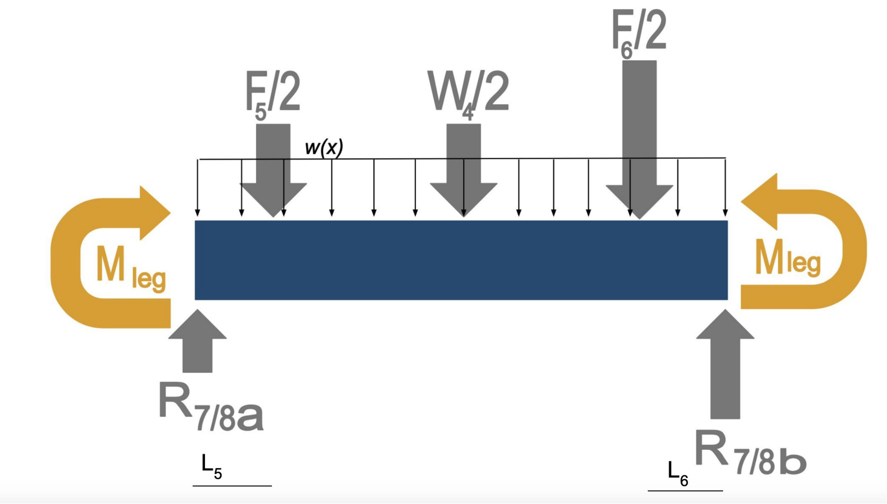
$$M(x) = R_{7/8}x - \frac{wx^2}{2}$$

$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{c_1x + c_2}{EI}$$

For $L_5 \le x \le \frac{L}{2}$:

$$M(x) = R_{7/8}x - \frac{wx^2}{2} - \frac{F_5(x - L_5)}{2}$$

$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{F_5L_5x^2}{4EI} - \frac{F_5x^3}{12EI} + \frac{c_3x + c_4}{EI}$$



Beams 7/8 - Pinned, Tilted (Continued)

For $\frac{L}{2} \leq x \leq L - L_5$:

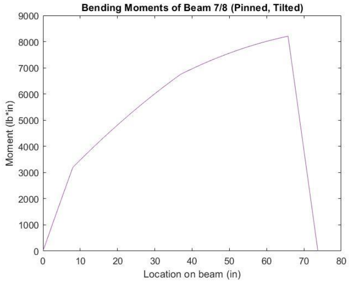
$$M(x) = R_{7/8} - \frac{wx^2}{2} - \frac{F_5(x - L_5)}{2} - \frac{W_4(x - \frac{L}{2})}{2}$$

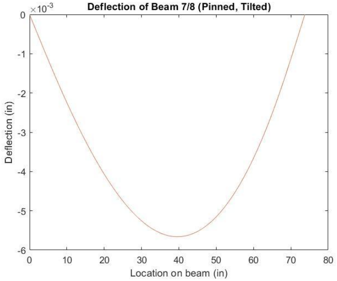
$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{F_5L_5x^2}{4EI} - \frac{F_5x^3}{12EI} + \frac{W_4Lx^2}{8EI} - \frac{W_4x^3}{12EI} + \frac{c_5x + c_6}{EI}$$

For $L - L_5 \leq x \leq L$:

$$M(x) = R_{7/8} - \frac{wx^2}{2} - \frac{F_5(x - L_5)}{2} - \frac{W_4(x - \frac{L}{2})}{2} - \frac{F_6(x - [L - L_5])}{2}$$

$$v(x) = \frac{R_{7/8}x^3}{6EI} - \frac{wx^4}{24EI} + \frac{F_5L_5x^2}{4EI} - \frac{F_5x^3}{12EI} + \frac{W_4Lx^2}{8EI} - \frac{W_4x^3}{12EI} + \frac{F_6(L - L_5)x^2}{4EI} + \frac{F_6x^3}{12EI} + \frac{c_7x + c_8}{EI}$$





Beams 7/8 - Pinned, Tilted (Continued)

$$c_2 = 0$$

$$c_4 = \frac{F_5 L_5^2}{12}$$

$$c_6 = c_4 + \frac{W_4 L^3}{96}$$

$$c_8 = c_6 + \frac{F_6 (L - L_5)^3}{12}$$

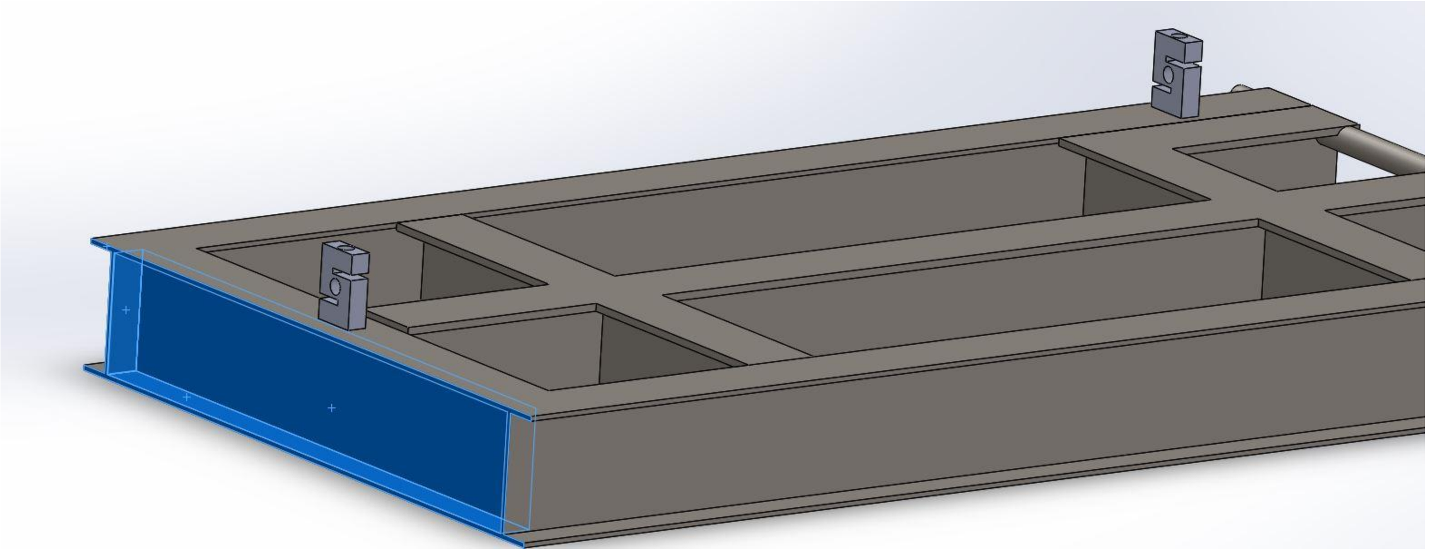
$$c_7 = \frac{1}{L}[\frac{-R_{7/8} L^3}{6} + \frac{w L^4}{24} - \frac{F_5 L_5 L^2}{4} + \frac{F_5 L^3}{12} - \frac{W_4 L^3}{8} + \frac{W_4 L^3}{12} - \frac{F_6 (L - L_5) L^2)}{4} + \frac{F_6 L^3}{12} - c_8]$$

$$c_5 = \frac{F_6 (L - L_5)^2}{4} + c_7$$

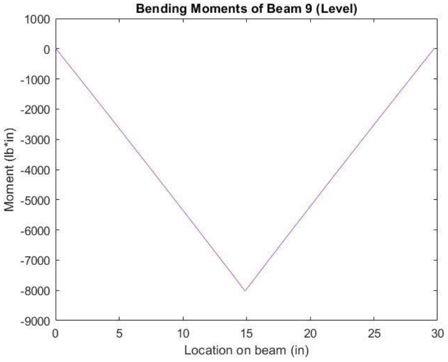
$$c_3 = \frac{W_4 L^2}{16} + c_5$$

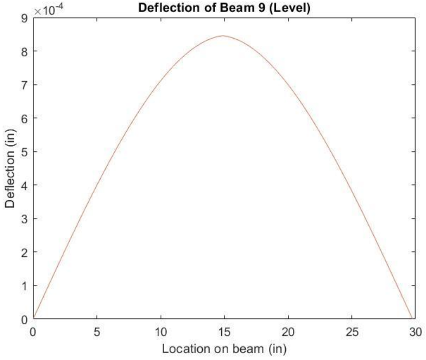
$$c_1 = \frac{F_5 L_5^2}{4} + c_3$$

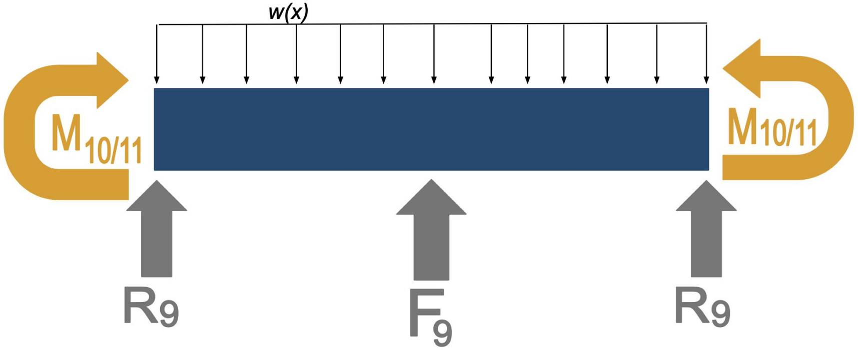
Beam 9



Beam 9 - Level







For $0 \le x \le \frac{L}{2}$:

$$M(x) = M_9 - R_9 x - \frac{wx^2}{2}$$

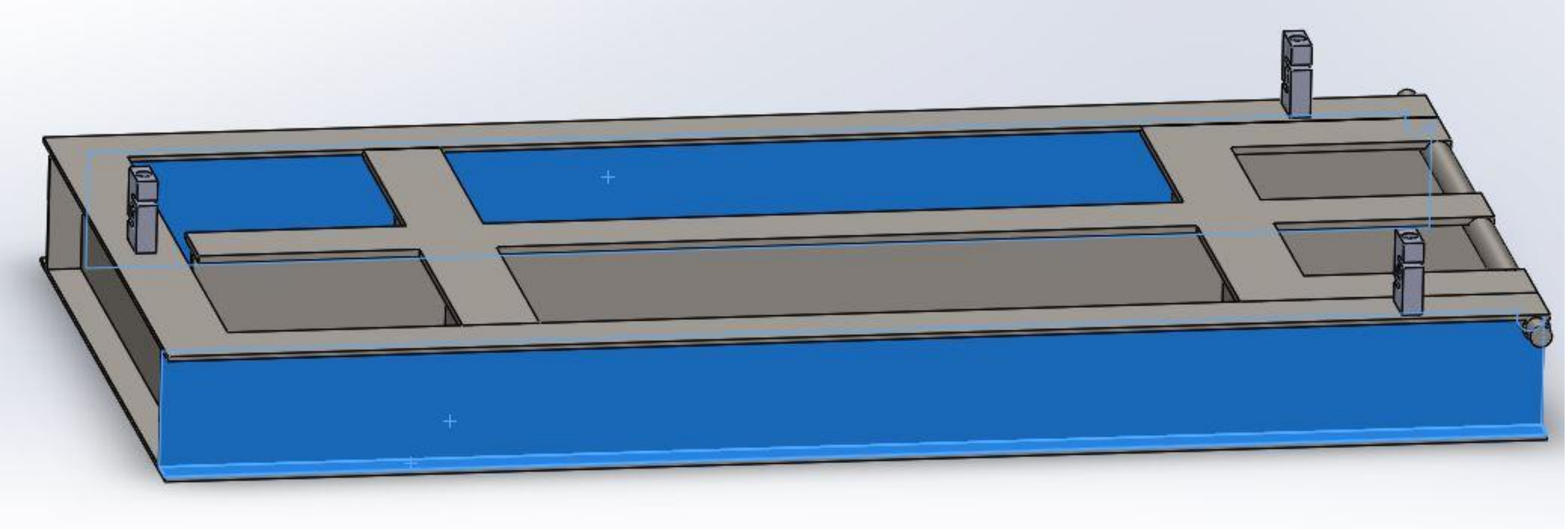
$$V(x) = R_9 + wx$$

$$v(x) = \frac{1}{EI}\left(\frac{M_9 x^2}{2} - \frac{R_9 x^3}{6} - \frac{wx^4}{24} + C_1 x\right)$$

where

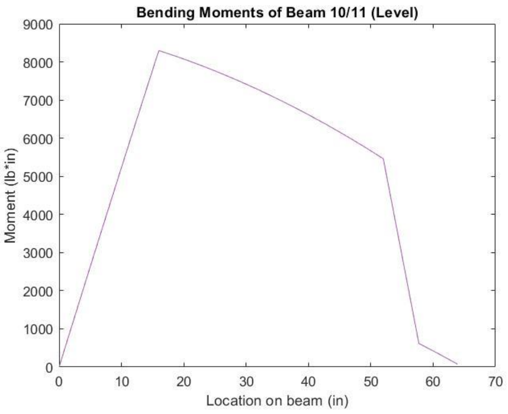
$$C1 = \frac{R_9 L^2}{8} + \frac{wL^3}{8} - \frac{M_9 L}{2}$$

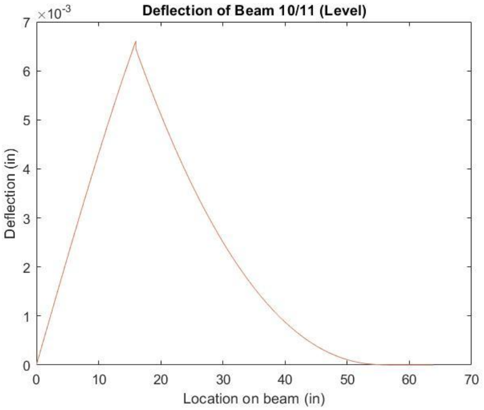
Beam 10/11

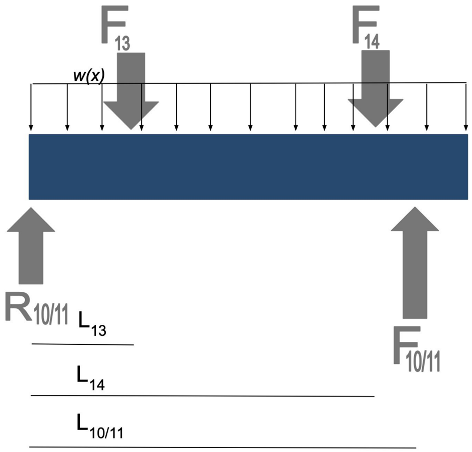


Beams 10 / 11 - Level

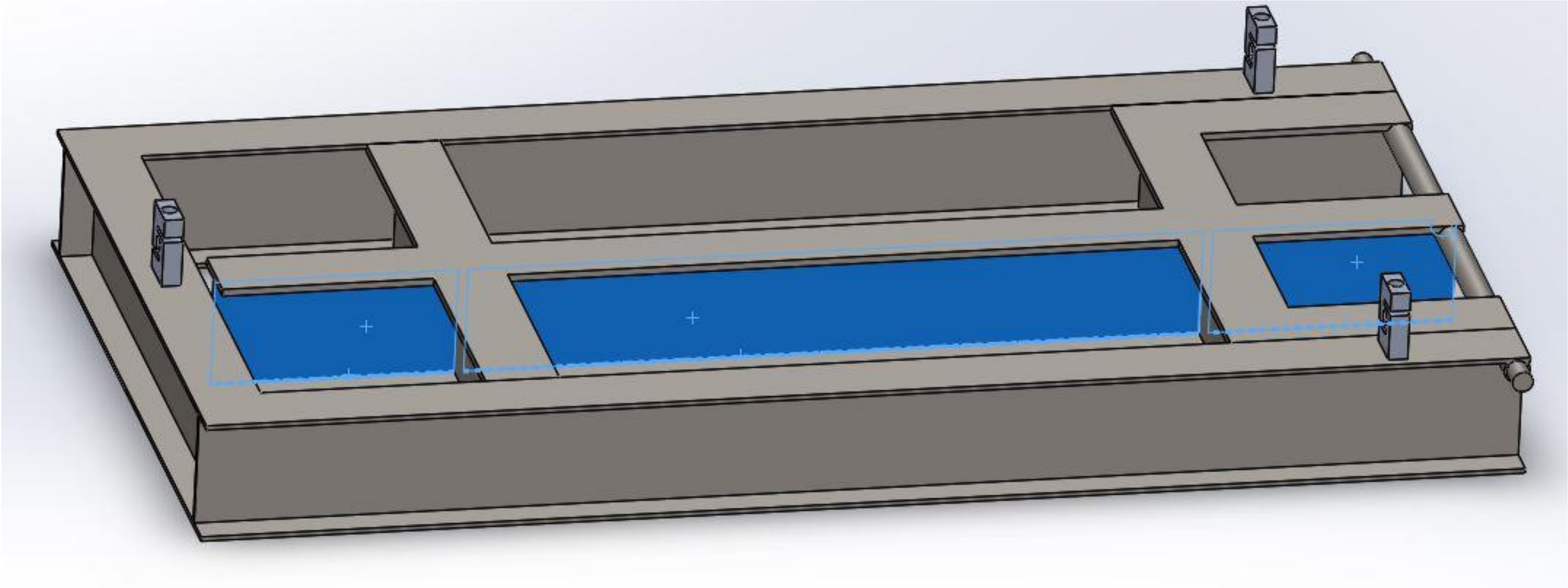
- Assume no force on axle
- Beam 9 behaves like an axle as well - no end moment
- Thus, this is a pinned-free situation
- This calculation is lower fidelity than the rest (more assumptions)



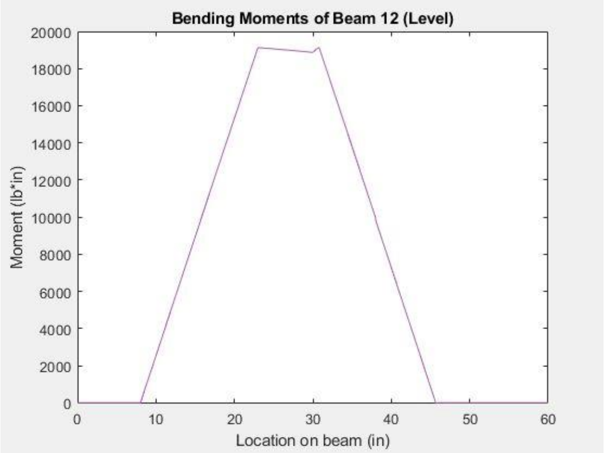


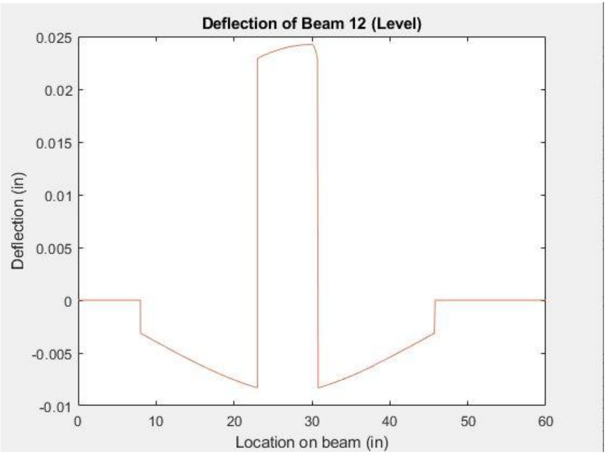


Beam 12



Beam 12 - Level





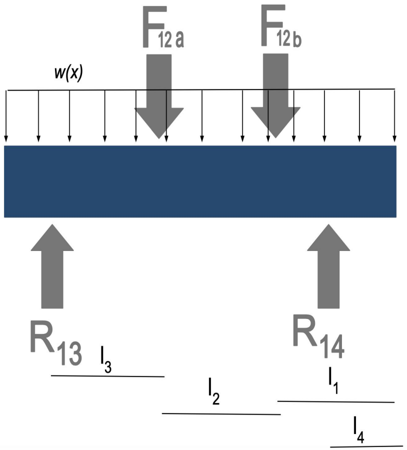
Between Beam 13 reaction force and beam 12 a force

$$M(x) = R_{13}(x - L_1) - \frac{wx^2}{2}$$

$$V(x) = R_{13} - wx$$

$$v(x) = \frac{1}{EI}\left[\frac{R_{13}x^3}{6} - \frac{R_{13}L_1x^2}{2} - \frac{wx^4}{24} + C_1x\right]$$

$$C_1 = \frac{R_{13}L_1L}{2} + \frac{w\frac{L}{2}^2}{6} - \frac{R_{13}\frac{L}{2}^2}{2}$$



Between beam 12 a force and center-beam point

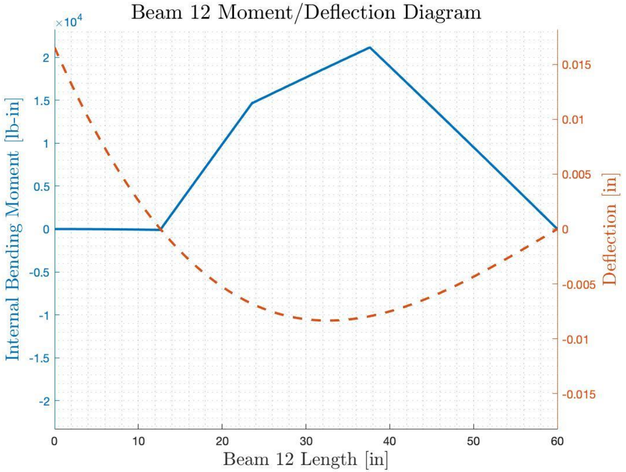
$$M(x) = R_{13}(x - L_1) - \frac{wx^2}{2} - F_{12,a}(x - L_1 - L_3)$$

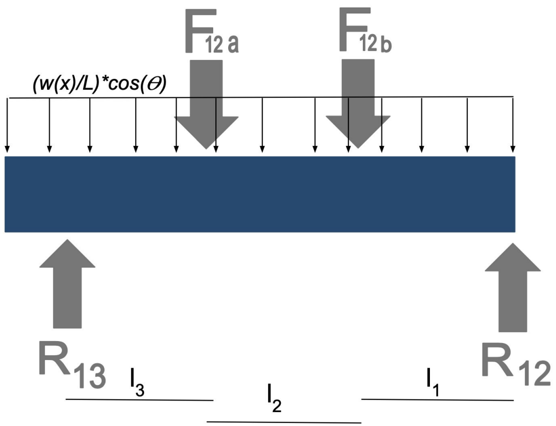
$$V(x) = R_{13} - wx - F_{12,a}$$

$$v(x) = \frac{1}{EI}\left[\frac{R_{13}x^3}{6} - \frac{R_{13}Lx^2}{2} - \frac{wx^4}{24} - \frac{F_{12,a}x^3}{6} - \frac{F_{12,a}L_1x^2}{2} - \frac{F_{12,a}L_3x^2}{2} + C_3x\right]$$

$$C_3 = -\frac{R_{13}\frac{L}{2}^2}{2} + \frac{R_{13}L_1L}{2} + \frac{w\frac{L}{2}^3}{6} + \frac{F_{12,a}\frac{L}{2}^2}{2} + \frac{F_{12,a}L_1L}{2} + \frac{F_{12,a}L_3L}{2}$$

Beam 12 Tilted





$for\ 0 < x < L - (l_1 + l_2 + l_3))$

$V_1(x) = -\frac{wx}{Lcos(\theta)}$

$M_1(x) = \frac{wx^2}{2Lcos(\theta)} + xV_1(x)$

$for\ 0 < x < L - (l_1 + l_2))$

$V_2(x) = -\frac{wx}{Lcos(\theta)} + R_{13}cos(\theta)$

$M_2(x) = \frac{wx^2}{2Lcos(\theta)} - R_{13}cos(\theta)(L - (l_1 + l_2 + l_3)) + xV_2(x)$

$for\ 0 < x < L - l_1$

$V_3(x) = -\frac{wx}{Lcos(\theta)} + R_{13}cos(\theta) - F_{12a}cos(\theta)$

$M_3(x) = \frac{wx^2}{2Lcos(\theta)} - R_{13}cos(\theta)(L - (l_1 + l_2 + l_3)) + F_{12a}cos(\theta)(L - (l_1 + l_2)) + xV_3(x)$

$for\ 0 < x < L$

$V_4(x) = -\frac{wx}{Lcos(\theta)} + R_{13}cos(\theta) - F_{12a}cos(\theta) - F_{12b}cos(\theta)$

$M_4(x) = \frac{wx^2}{2Lcos(\theta)} - R_{13}cos(\theta)(L - (l_1 + l_2 + l_3)) + F_{12a}cos(\theta)(L - (l_1 + l_2)) + F_{12b}cos(\theta)(L - l_1) + xV_4(x)$

Beams 13/14 - Level

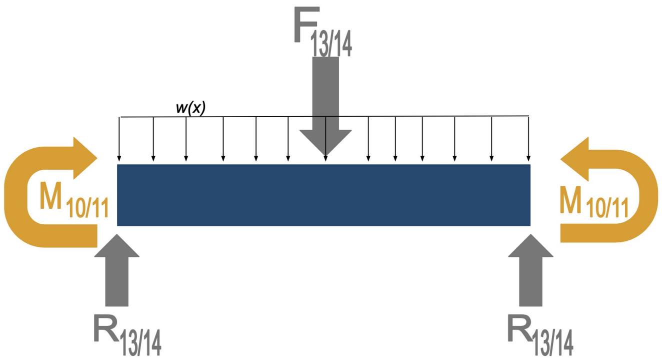
$$M(x) = M_{10/11} + R_{13/14}x - \frac{wx^2}{2}$$

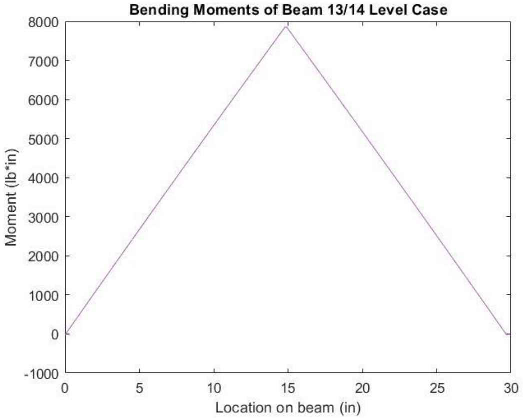
$$v(x) = \frac{1}{EI}\left(\frac{M_{10/11}x^2}{2} + \frac{R_{13/14}x^3}{6} - \frac{wx^4}{24} + C_1x\right)$$

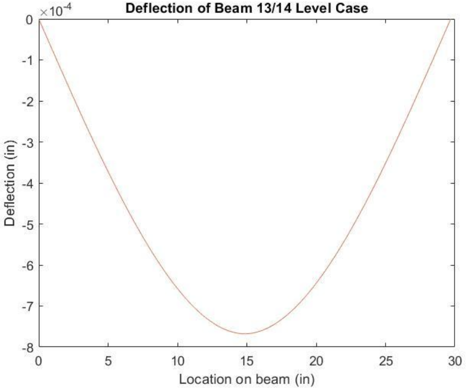
where:

$$a = \frac{L}{2}$$

$$C_1 = -M_{13/14}a - \frac{R_{13/14}a^2}{2} + \frac{wa^3}{6}$$

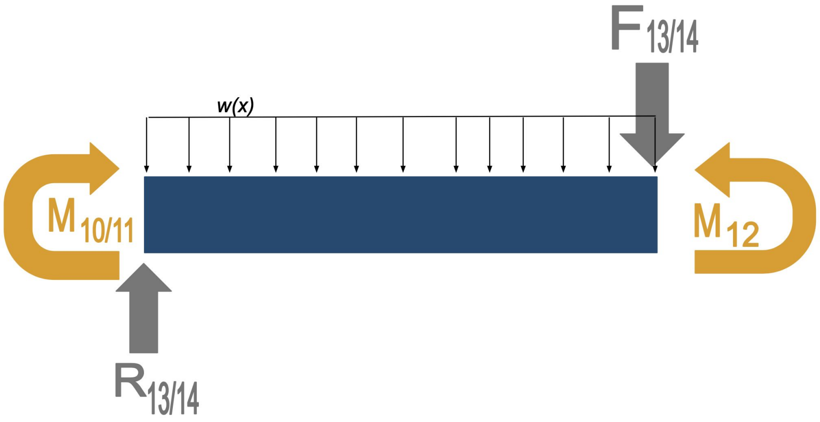






Beams 13/14 - Level Alternative Model

- Analyze from connection to beam 10/11 to connection to beam 12



*A value for M12 cannot be found yet as beam 12 has not been incorporated into an iterative bending-torsion solver.

for 0<x<a:

$$M(x) = M_{10/11} + R_{13/14}x - \frac{wx^2}{2}$$

$$v(x) = \frac{1}{EI}\left(\frac{M_{10/11}x^2}{2} + \frac{R_{13/14}x^3}{6} - \frac{wx^4}{24} + C_1 x\right)$$

for a<x<L:

$$M(x) = M_{12} - F(x-a) - \frac{w(x-a)^2}{2}$$

$$v(x) = \frac{1}{EI}\left(\frac{M_{12}x^2}{2} - \frac{Fx^3}{6} + \frac{Fax^2}{2} - \frac{wx^4}{24} + \frac{wx^3a}{6} - \frac{wa^2x}{4} + C_3 x + C_4\right)$$

where:

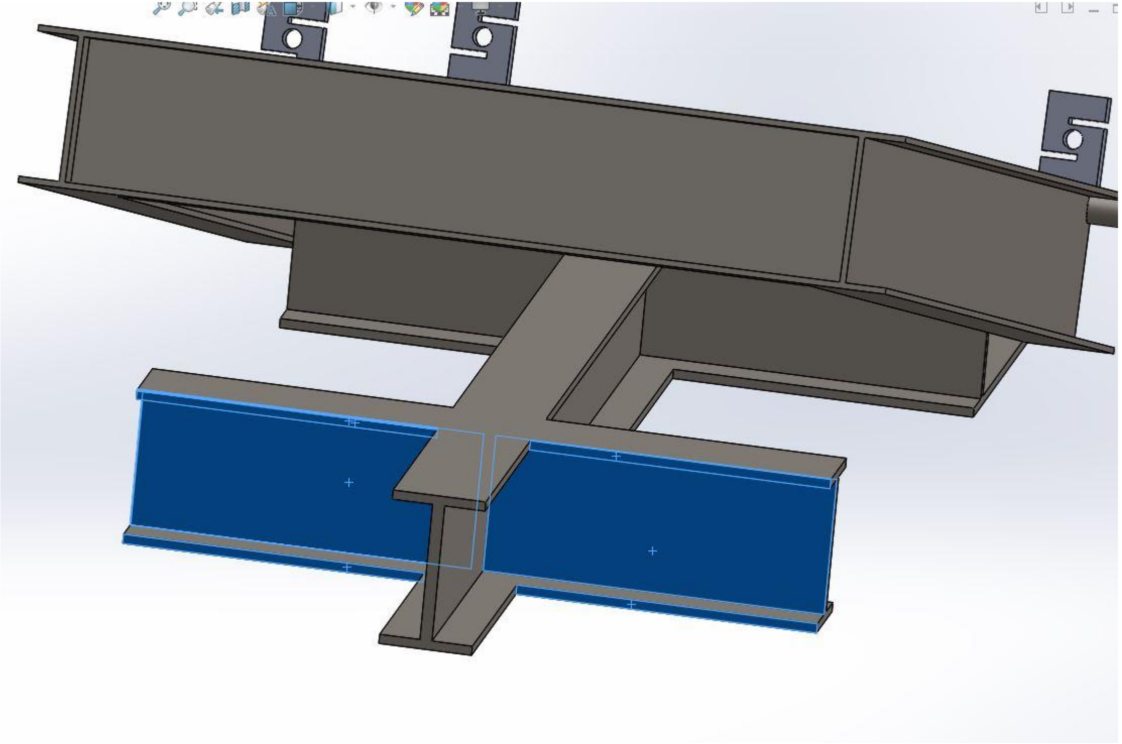
$$a = \frac{L}{2}$$

$$C_3 = -M_{12}L + \frac{FL^2}{2} - FaL + \frac{wL^3}{6} - \frac{wL^2a}{2} + \frac{wL^3}{2}$$

$$C_1 = M_{12}a - M_{10/11}a - \frac{R_{13/14}a^2}{2} + \frac{Fa^2}{2} + C_3$$

$$C_4 = \frac{M_{10/11}a^2}{2} - \frac{M_{12}a^2}{2} + \frac{R_{13/14}a^3}{6} - \frac{Fa^3}{3} + C_1 a - C_3 a$$

Beam 13 - Tilted



Beams 13 - Tilted

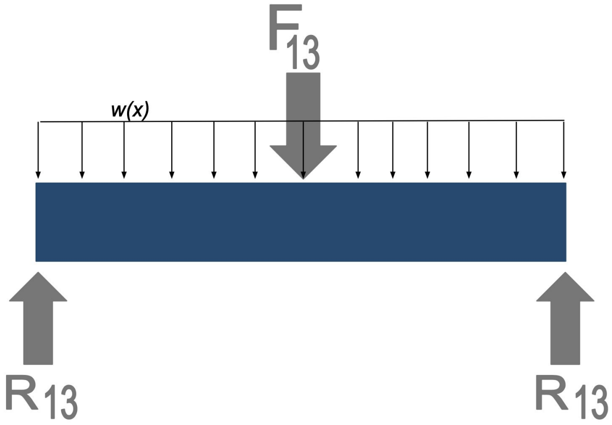
- Suspended by cables (R13)

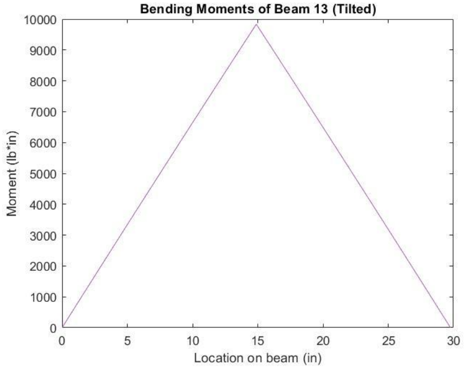
For $0 \le x \le \frac{L}{2}$:

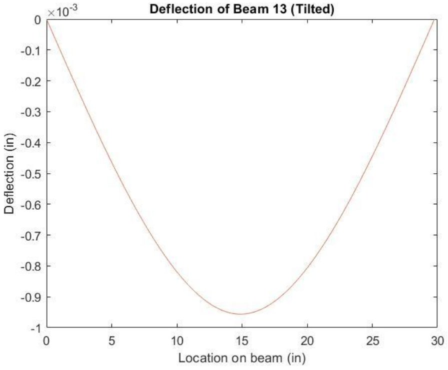
$$M(x) = R_{13}x - \frac{wx^2}{2}$$

$$V(x) = wx - R_{13}$$

$$v(x) = \frac{1}{EI}\left[\frac{R_{13}x^3}{6} - \frac{wx^4}{24} + \left(\frac{wL^3}{48} - \frac{R_{13}L^2}{8}\right)x\right]$$







Axle

$$V = W/2$$

$$\tau_{use} = \frac{\tau_{yield}}{FOS}$$

$$diameter = 2\sqrt{\frac{V}{\pi * \tau_{use}}}$$

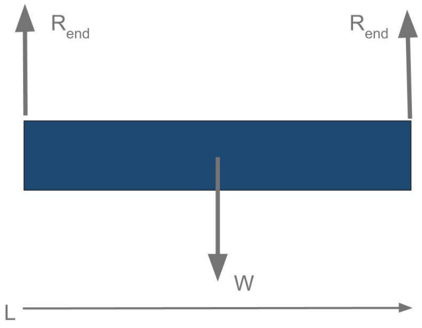
$$M(x) = M_{end} - R_{end}x + \frac{wx^2}{2}$$

$$\sigma_{use} = \frac{\sigma_{yield}}{FOS}$$

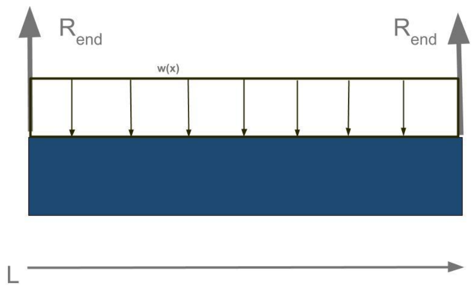
$$diameter = 2 * \sqrt[3]{\frac{4M_{max}}{\sigma_{use}\pi}}$$

The diameter of the axle is chosen to be the larger value

Shear Model

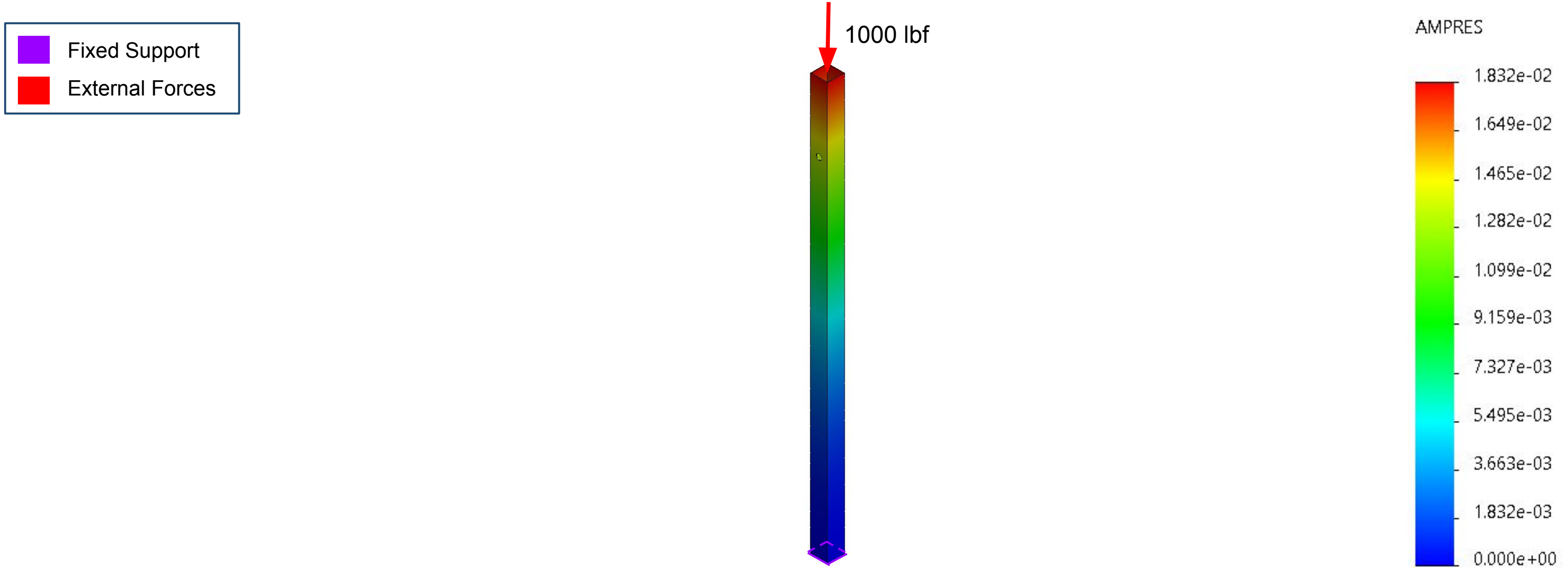


Bending Model



Note: We are looking at an extreme case where the test bed is vertical (will never happen) and the load for shear is a point load (not distributed). Bending Moment is looked at as a distributed load since it is the most likely failure mode.

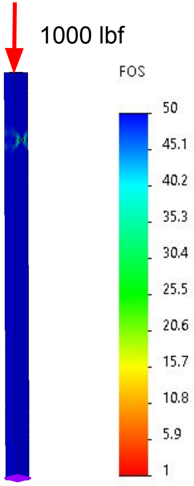
Frame Legs (Buckling FEA)



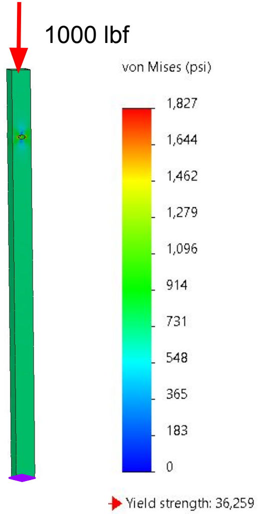
Frame Leg Buckling Analysis
Beam FOS: 26.3

Frame Legs (Compression FEA)

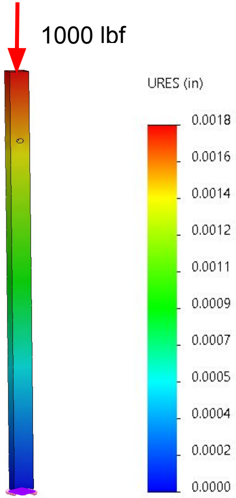
Fixed Support
External Forces



FOS
Minimum:19.8
*Near shear pin hole



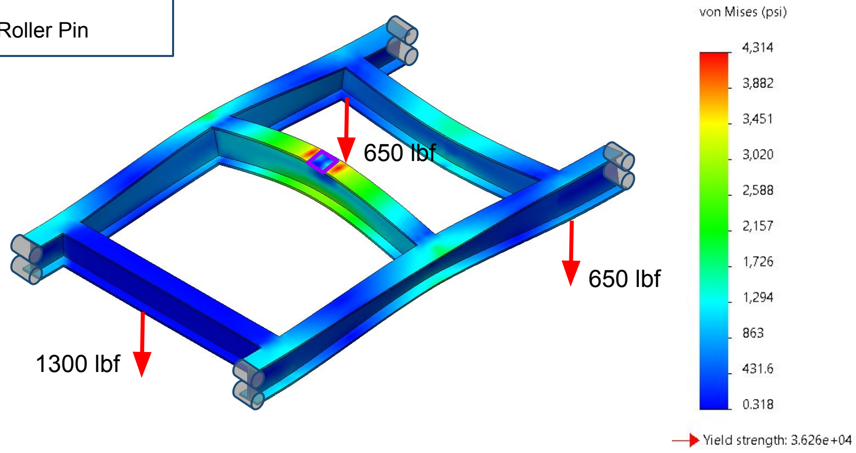
Stress
Maximum: 1827 psi



Displacement
Maximum: 0.0018 in

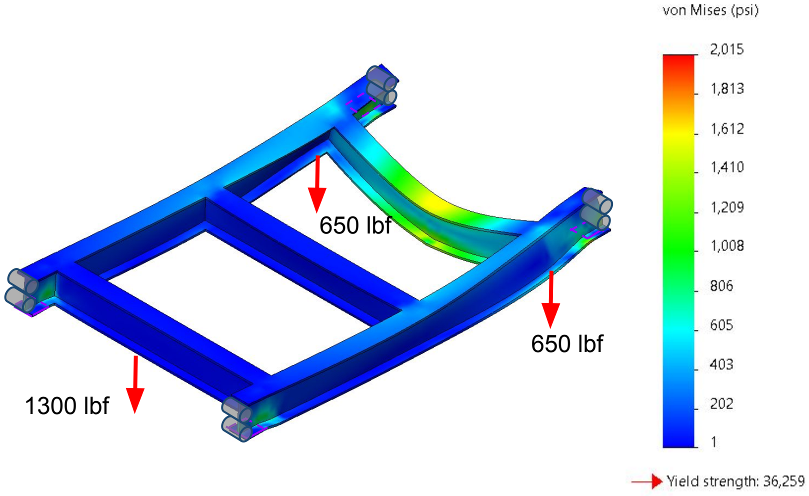
Sliding Interface (Stress FEA)

Fixed Support
External Forces
Roller Pin



Stress

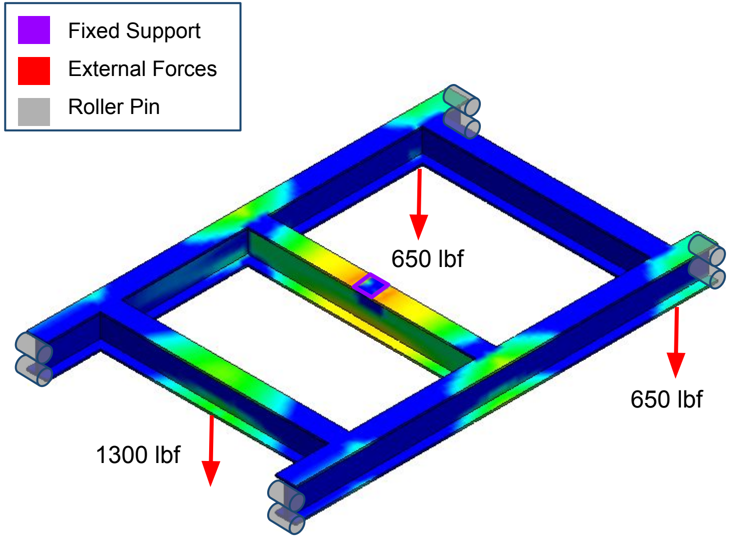
Maximum: 4,314 psi



Stress

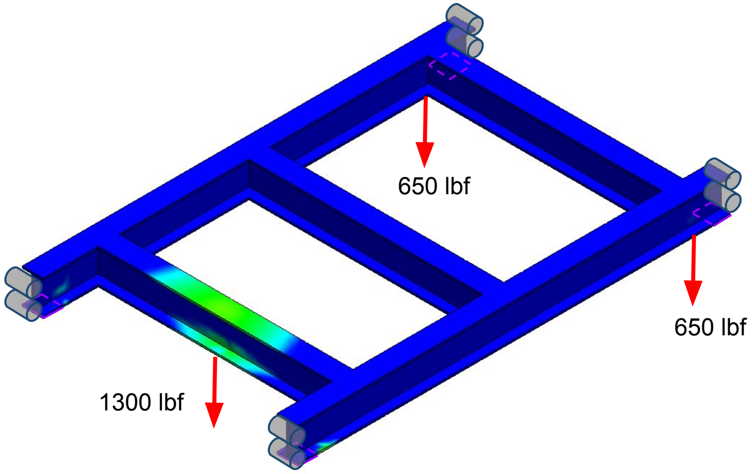
Maximum: 2,015 psi

Sliding Interface (FOS FEA)



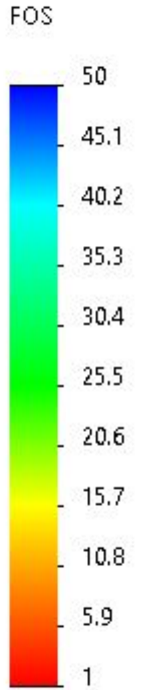
Chain Hoist Lifting Case

Minimum FOS: 8.41

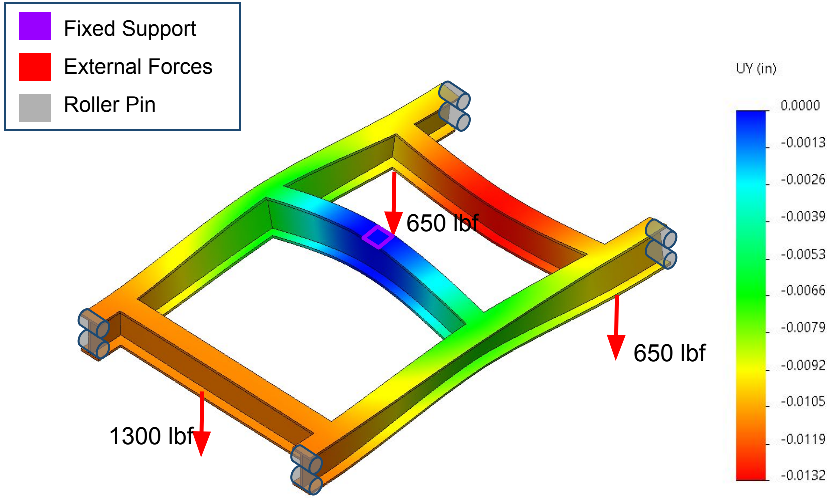


Pinned Case

Minimum FOS: 18.00

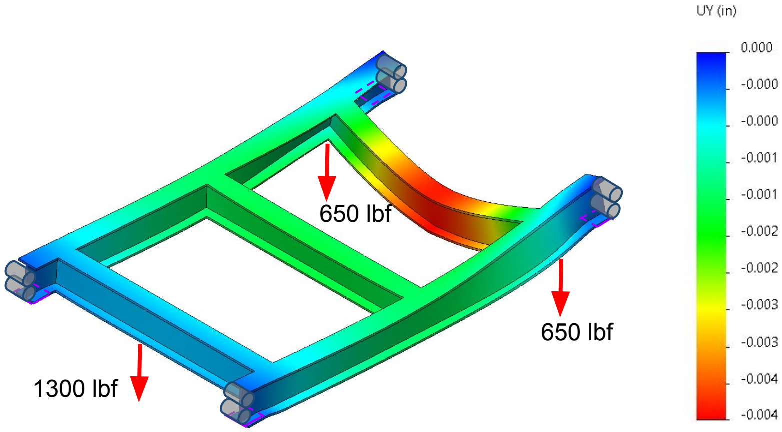


Sliding Interface (Displacement FEA)



Displacement

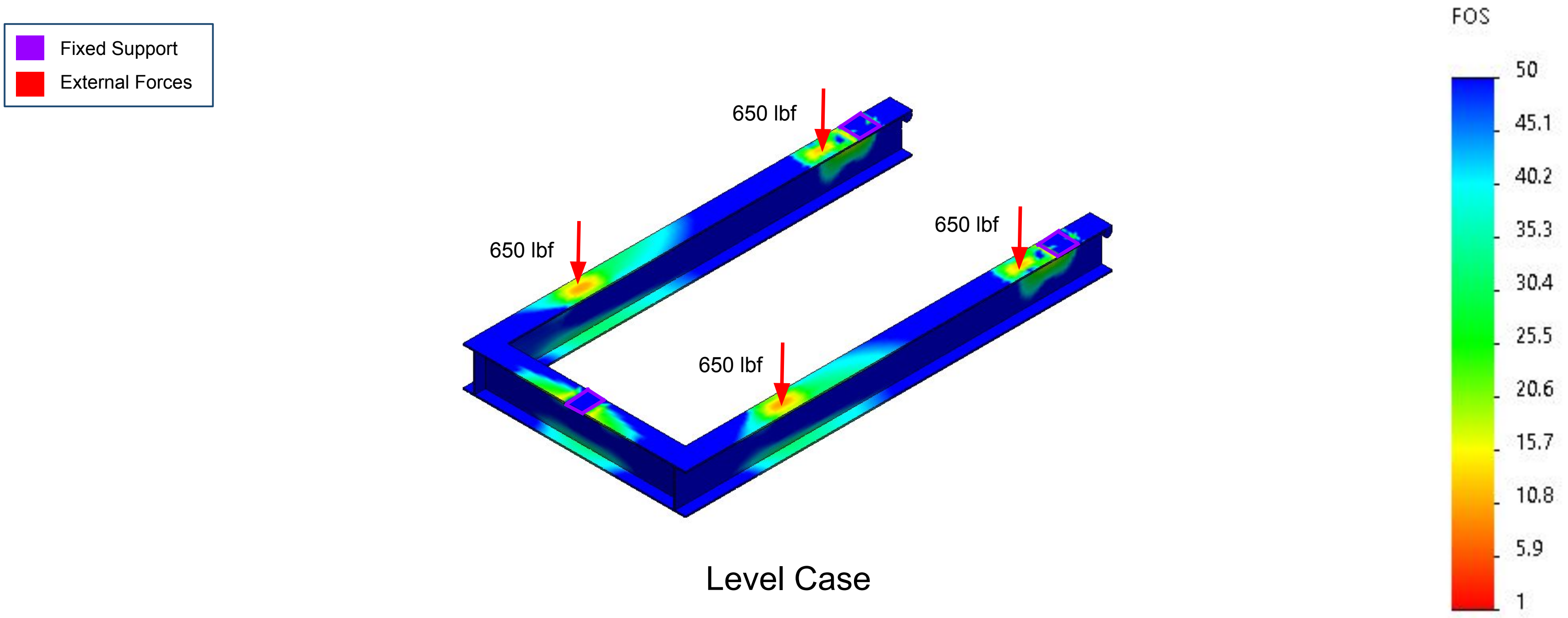
Maximum: 0.0132 in



Displacement

Maximum: 0.004 in

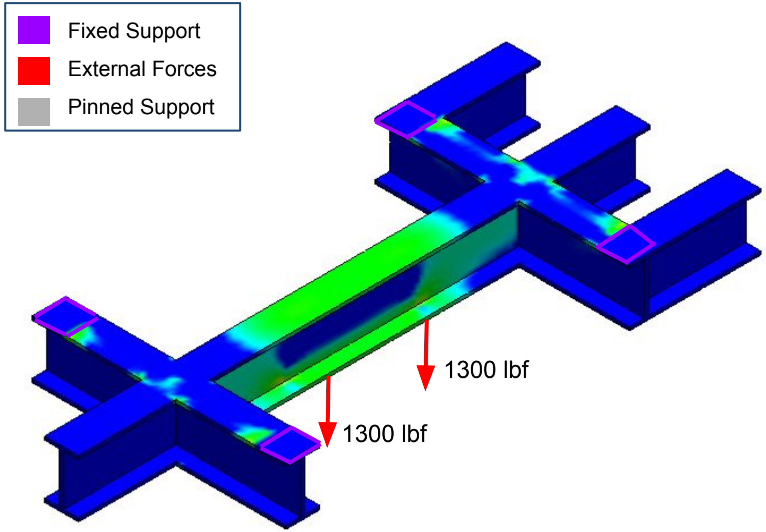
Testbed FEA (FOS)



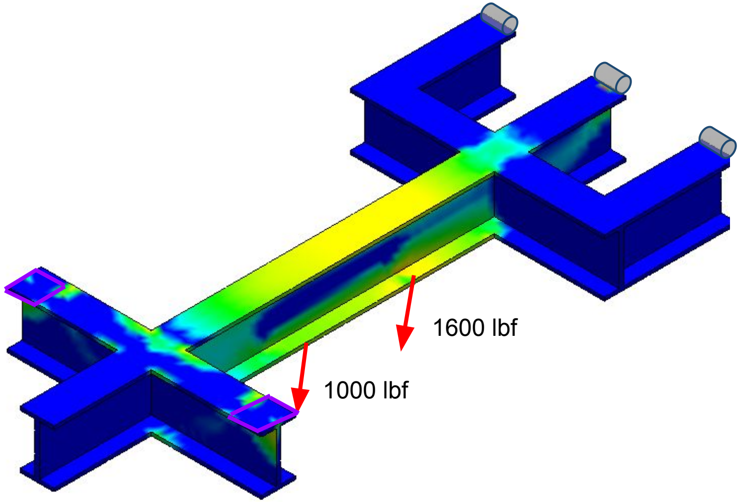
Level Case

Minimum FOS: 7.69

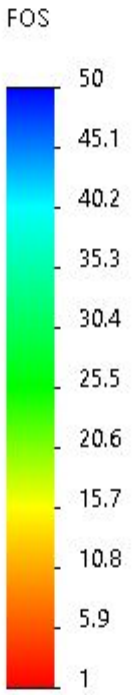
Testbed (FOS FEA)



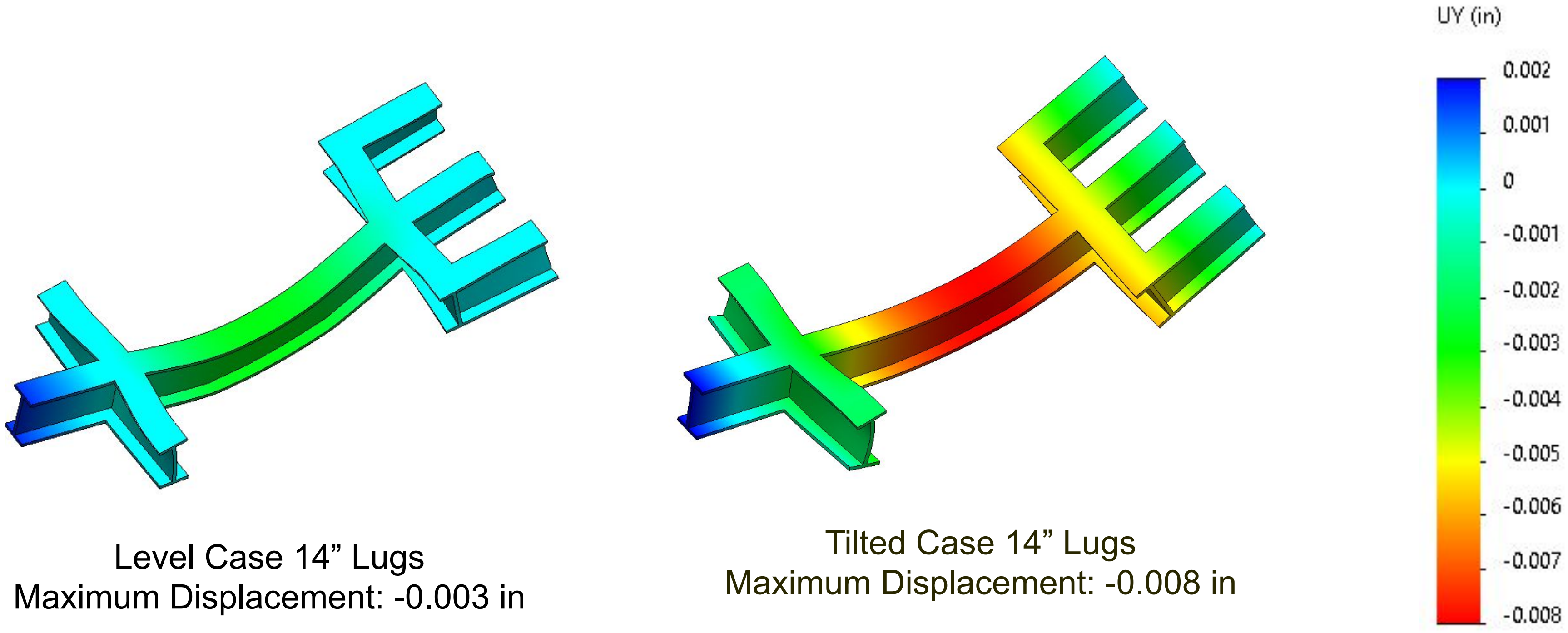
Level Case 14” Lugs
Minimum FOS: 11.32



Tilted Case 14” Lugs
Minimum FOS: 7.24



Testbed FEA (Deflection)



Level Case 14” Lugs
Maximum Displacement: -0.003 in

Tilted Case 14” Lugs
Maximum Displacement: -0.008 in

All Beam Load Cases - BOTE

Beam(s)	FoS (Bending)	Bending Deflection (in)	FoS (Shear)	FoS (Torsion)	Max Twist Angle (Degrees)
1	11.28	0.0064	69.14	N/A	0
2/3 - Fixed Ends	23.12	0.0047	130.06	192.71	0.0234
2/3 - Pinned Ends	11.70	0.0192	130.06	192.71	0.0234

*Hand analyses look at each beam and load case individually - there will not be a perfect match between these safety factors and those calculated using FEA

All Beam Load Cases - BOTE

Beam(s) and Load Case	FoS (Bending)	Bending Deflection (in)	FoS (Shear)	FoS (Torsion)	Max Twist Angle (Degrees)*
4 - Lifting	11.29	0.0057	69.14	N/A	0.0332
5 - Level	23.71	0.0026	141.57	N/A	0.0174
6 - Tilted	17.38	0.0047	70.79	N/A	0.0174
7/8 - Lifting	11.91	0.0033	130.92	64.97	0.0640
7/8 - Pinned (testbed level)	47.17	0.0056	148.57	Not completed	Not completed
7/8 - Pinned (Testbed tilted)	38.77	0.0057	103.47	Not completed	Not completed

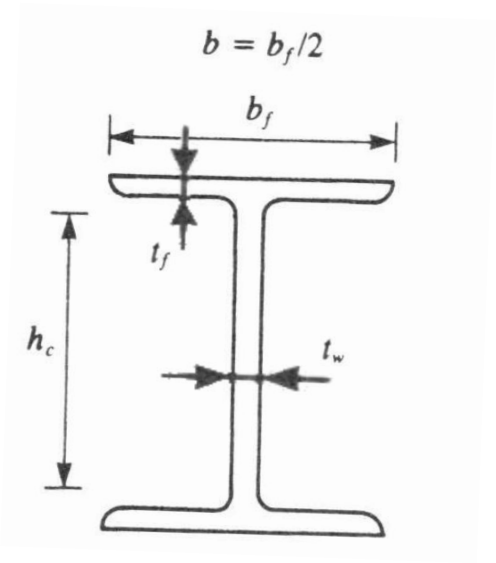
*Max twist angle for beams 4-6 is really the rotation angle caused by beams 7/8 - found with lifting case (highest values)

All Beam Load Cases - BOTE

Beam(s) and Load Case	FoS (Bending)	Bending Deflection (in)	FoS (Shear)	FoS (Torsion)	Max Twist Angle (Degrees)**
9 - Level	39.67	0.00084	166.97	N/A	0.0218
10/11* - Level	38.35	0.00660	107.90	581.39	0.0062
12 - Level	22.86	0.00530	71.74	N/A	N/A
12 - Tilted	15.04	0.01840	68.12	N/A	N/A
13 - Tilted	32.36	0.00096	137.06	N/A	0.0177
13/14 - Level	40.51	0.00077	169.48	N/A	0.0009

*Beam 10 analysis is low fidelity - this was difficult to model by hand.
**Beams 9, 13, and 14 rotation angles from from level beam 10 analysis

I-Beam Compactness Analysis (Buckling)



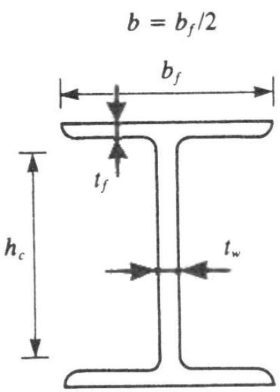
Beam Element	Width-Thickness Ratio	Limiting Width-Thickness Ratio, λ_p	
		General	A36 Steel
Flanges of W and other I shapes and channels	b/t	$65/\sqrt{F_y}$	10.8
Flanges of square and rectangular box sections; flange cover plates and diaphragm plates between lines of fasteners or welds	b/t	$190/\sqrt{F_y}$	31.7
Webs in flexural compression	h_c/t_w	$640/\sqrt{F_y}$	106.7

*Schaum's Outline of Structural Steel Design - Rokach, 1991, Based upon American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) Specification

Rule of thumb: If $\lambda \leq \lambda_p$, "local buckling need not be considered"

I-Beam Compactness Analysis (Buckling)

Beam	b	t	h_c	t_w	λ_f	λ_w
S6x17.25	1.783”	0.359”	5.282”	0.465”	**4.965**	**11.359**
S6x12.5	1.666”	0.359	5.282”	0.232	**4.641**	**22.767**
					≤ 10.8	**≤ 106.7**



Result: All I-beams used are considered compact, thus local buckling of the web and flange need not be considered.

Electronics and Software

Return to Supporting Material Quick Links

LC103B S-Beam Load Cell Specs

Specifications:

Accuracy (>25lb): class C3

Approvals(>25lb): OIML R60

Output sensitivity (mV/V): 3.0±0.008 *(≤25lb 2.0±0.006)*

Maximum number of load cell intervals (nLC): 3000

Ratio of minimum LC verification interval (Y=Emax/vmin): 10000

Combined error (%FS): ±0.020

Minimum dead load: 0

Safe overload (%FS): 150%

Ultimate overload (%FS): 300%

Zero balance (%FS): ±1.0%

Excitation, recommended voltage (V): 5 to 12(DC)

Excitation maximum (V): 18(DC)

Input resistance (Ω): 430 ± 50

Output resistance (Ω): 351 ± 2

Insulation resistance (MΩ): ≥ 5000 (50VDC)

Compensated temperature (°C): -10 to 40

Operating temperature (°C): -35 to 65

Storage temperature (°C): -40 to 70

Element material: Stainless steel

Ingress protection (according to EN 60529): IP67

Recommended torque on fixation (Thread:lbf.ft):1/4"UNF:18 1/2"UNF:55 3/4"UNF:330 1"UNF:550 1 1/8"UNF:1070

Recommended torque on fixation (Thread:Nm):M8:25 M12:75 M20:450 M24:750 M30:1450

https://www.omega.com/en-us/sensors-and-sensing-equipment/load-and-force/load-cells/p/LC103B

TE Connectivity D-Series Inclinometer

PERFORMANCE SPECIFICATIONS

	Conditions	Min	Type	Max	Unit
Measurement range		-5 (-15,-30)		+5(+15,+30)	°
Resolution		0.001		0.005	°
Accuracy,digital,analogue (absolute)	Ta = +25°C		0.04		°
Accuracy,digital,analogue (absolute)	Ta = - 40°C to 85°C		0.15	(0.3,0.8)	°
Offset temperature drift error	Ta = - 40°C to 85°C		0.06		°
Noise RMS			0.001		°
Frequence responce			2	3	Hz
Power supply		10		30	VDC
Operation temperature range		-40		+85	°C
Storage temperature range		-40		+85	°C
Weight			290		g
Dimensions	W x D x H		84 x 70 x 46		mm
Unit with RS 232 interface and analogue output signal					
Transmission rate, programmable		0.1	10	16	Hz
Baud rate, programmable		2.4	9.6	57.6	kB
Current output		20		4	mA
Voltage output		0.5		4.5	V
PWM output	1 KHz	20		80	%
Switch output,programmable	Step		0.1		°
Current consumption			30	40	mA
Unit with CANopen interface					
Baud rate, programmable		0.02	0.25	1	MBaud
Code	Binary				-
Interface	CAN according to CAL				-
Current consumption			50	90	mA

https://www.metrolog.net/files/d_en_metrolog.pdf

MATLAB Data Acquisition Toolbox

Data Acquisition Hardware Vendors

Use data acquisition hardware from National Instruments and other vendors. Access subsystems common to different devices as well as device-specific features.

National Instruments

Acquire and analyze data from NI-DAQmx devices, including CompactDAQ, X-Series, M-Series, E-Series, USB, myDAQ, ELVIS II, and more.

- National Instruments Support
- Getting Started with NI Devices
- Discover NI Devices
- Acquire Data Using NI Devices

National Instruments support.

https://www.mathworks.com/products/data-acquisition.html

NI 9237 Bridge Module

DATASHEET

NI 9237

4 AI, ±25 mV/V, 24 Bit, 50 kS/s/ch Simultaneous, Bridge Completion

- 4 channels, 50 kS/s per channel simultaneous AI
- ±25 mV/V input range, 24-bit resolution
- Programmable half- and full-bridge completion with up to 10 V internal excitation
- 60 VDC, Category I bank isolation
- RJ50 or D-SUB connectivity options
- -40 °C to 70 °C operating range, 5 g vibration, 50 g shock

http://www.ni.com/pdf/manuals/374186a_02.pdf

NI cDAQ-9171 Compact DAQ

DEVICE SPECIFICATIONS

NI cDAQ™-9171

NI CompactDAQ One-Slot Bus-Powered USB Chassis

These specifications are for the NI cDAQ-9171 chassis only. These specifications are typical at 25 °C unless otherwise noted. For the C Series module specifications, refer to the documentation for the C Series module you are using.

Analog Input

Input FIFO size	127 samples
Maximum sample rate[1]	Determined by the C Series module
Timing accuracy[2]	50 ppm of sample rate
Timing resolution[2]	12.5 ns
Number of channels supported	Determined by the C Series module

https://www.ni.com/pdf/manuals/374037b.pdf

Analog Output

Number of channels supported	
Hardware-timed task	
Onboard regeneration	16
Non-regeneration	Determined by the C Series module
Non-hardware-timed task	Determined by the C Series module
Maximum update rate	
Onboard regeneration	1.6 MS/s (multi-channel, aggregate)
Non-regeneration	Determined by the C Series module
Timing accuracy	50 ppm of sample rate
Timing resolution	12.5 ns
Output FIFO size	
Onboard regeneration	8,191 samples shared among channels used
Non-regeneration	127 samples
AO waveform modes	Non-periodic waveform, periodic waveform regeneration mode from onboard memory, periodic waveform regeneration from host buffer including dynamic update

Weight and CG Accuracy

[Return to Supporting Material Quick Links]

MCS: Geometry Parameters

Angle = 30 deg

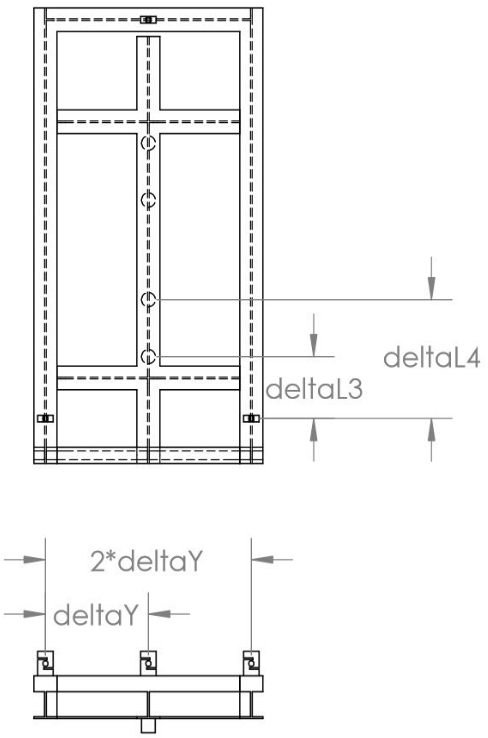
deltaX = 56.04"

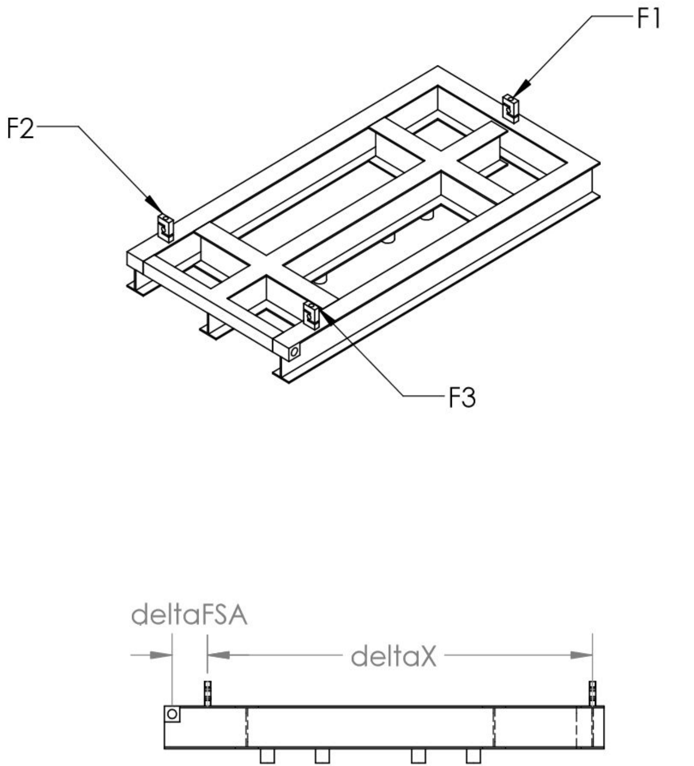
deltaY = 15"

deltaFSA = 5.17"

deltaL3 = 8.71"

deltaL4 = 16.71"





High-Level MCS Trends

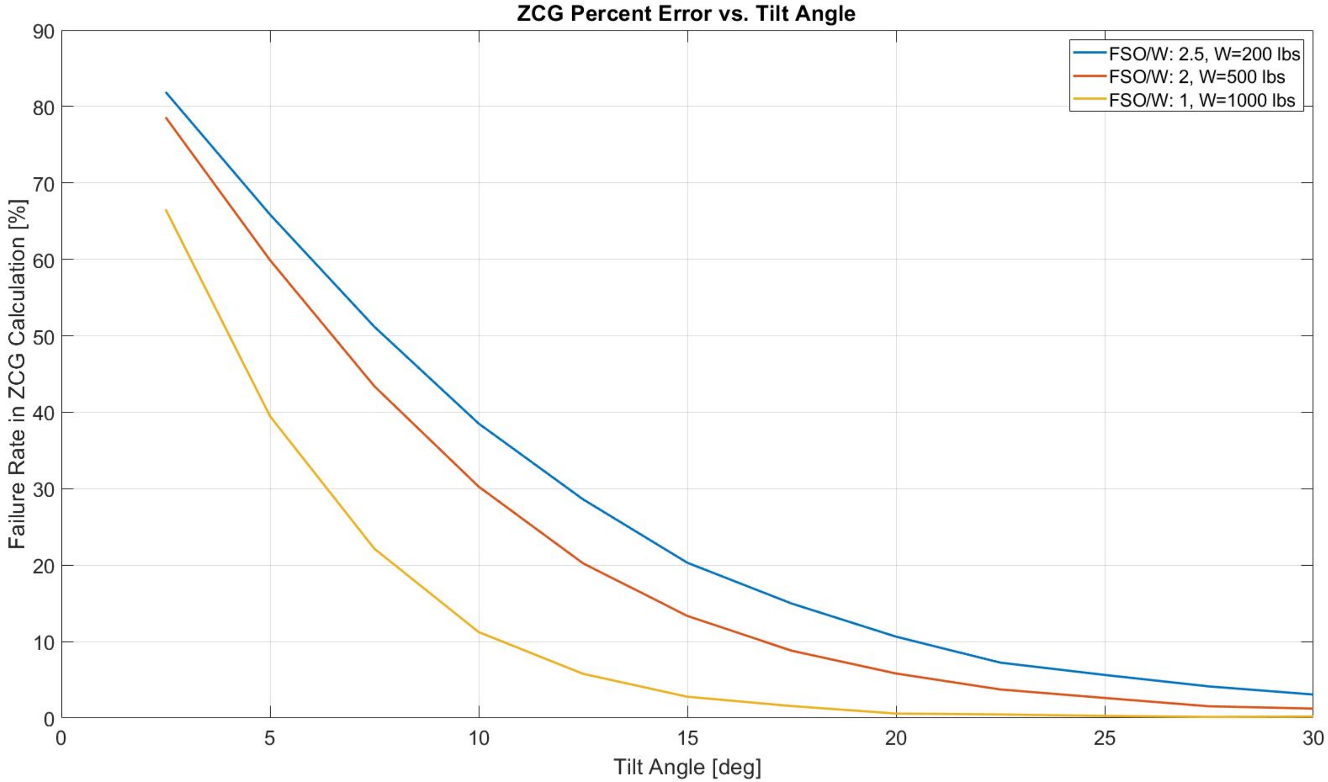
Worst-Case Extremes:

- Weight = 200 lbs (lightest pod)
- Lug Spacing = 14”
- CG aft of midpoint between lugs

Limiting Factors:

- Lighter pods are weight accuracy limited (exponential decay)
- Becomes X CG accuracy limited with increasing pod weight
  - Approximately 3.5% failure rate
- X CG accuracy converges, bounded by 2.8% < fail % < 3.1%

Accuracy Sensitivity to Angle



Max Load on Single Sensor

				Max Load Single Cell		
Pod Weight	Testbed Weight	Max Load Pod Only	Testbed Contribution	FoS = 1.0	FoS = 1.5	FoS = 2.0
200	323	97.121	161.50	258.62	387.9	517.24
300	323	145.68	161.50	307.18	460.8	614.36
350	323	169.96	161.50	331.46	497.2	662.92
375	323	182.1	161.50	343.60	515.4	687.20
400	323	197.57	161.50	359.07	538.6	718.14
500	323	246.97	161.50	408.47	612.7	816.94
600	323	291.36	161.50	452.86	679.3	905.72
650	323	315.64	161.50	477.14	715.7	954.28
700	323	339.92	161.50	501.42	752.1	1002.84
750	323	364.2	161.50	525.70	788.6	1051.40
800	323	395.15	161.50	556.65	835.0	1113.30
850	323	412.76	161.50	574.26	861.4	1148.52
900	323	437.04	161.50	598.54	897.8	1197.08
1000	323	493.94	161.50	655.44	983.2	1310.88

Max Load on Single Sensor (cont.)

				Max Load Single Cell		
Pod Weight	Testbed Weight	Max Load Pod Only	Testbed Contribution	FoS = 1.0	FoS = 1.5	FoS = 2.0
1100	323	534.16	161.50	695.66	1043.5	1391.32
1200	323	602.72	161.50	764.22	1146.3	1528.44
1300	323	642.12	161.50	803.62	1205.4	1607.24
1400	323	679.84	161.50	841.34	1262.0	1682.68
1500	323	740.91	161.50	902.41	1353.6	1804.82
1600	323	776.97	161.50	938.47	1407.7	1876.94
1700	323	825.53	161.50	987.03	1480.5	1974.06
1800	323	874.09	161.50	1035.59	1553.4	2071.18
1900	323	922.65	161.50	1084.15	1626.2	2168.30
2000	323	987.87	161.50	1149.37	1724.1	2298.74

Max Failure Percentage

	Maximum % Failure in Weight or CG		
Pod Weight	FSO = 500 lbs	FSO = 1000 lbs	FSO = 2000 lbs
200	4.93	33.33	61.90
300	3.08	13.99	45.89
325	3.28	11.33	42.35
350	3.46	8.59	39.30
375	2.87	6.25	34.79
400	2.73	5.06	32.82
425	3.21	3.58	29.59
500	2.97	3.15	22.17
600	3.10	3.18	13.94
650	2.94	3.46	10.76
700	X	3.07	8.58
750	X	2.87	6.72
800	X	3.36	5.25
850	X	2.89	3.45
900	X	2.95	3.18
1000	X	3.03	3.21

Max Failure Percentage (cont.)

	Maximum % Failure in Weight or CG		
Pod Weight	FSO = 500 lbs	FSO = 1000 lbs	FSO = 2000 lbs
1100	X	2.82	3.34
1200	X	3.01	3.27
1300	X	2.94	3.13
1400	X	2.80	2.84
1500	X	2.81	3.08
1600	X	2.80	3.17
1700	X	3.01	2.96
1800	X	X	2.88
1900	X	X	3.04
2000	X	X	2.85

Budget

Return to Supporting Material Quick Links

Financial Budget

WASP Financial Budget								
Summary								
Budget	Expenses	Future Expenses	Remaining	Margin				
$5,000.00	$0.00	$7,924.93	-$2,924.93	-58.50%				
	Unit Cost	QTY	Project Cost	Lead Time	Order by	Purchased?	Cost Estimate Justification	Accumulated Cost
Frame			$ 3,332.78					$ -
S6x17.25 A36 I-Beam (20' length)	$ 403.60	3	$ 1,210.80			☐	https://www.metalsdepot.com/steel-products/steel-bear	
S6x17.25 A36 I-Beam (10' length)	$ 252.20	0	$ -			☐	https://www.metalsdepot.com/steel-products/steel-bear	
S6x17.25 A36 I-Beam (5' length)	$ 150.15	2	$ 300.30			☐	https://www.metalsdepot.com/steel-products/steel-bear	
3"x.120" A36 Square Tube (96" length)	$ 56.12	4	$ 224.48			☐	https://www.metalsdepot.com/steel-products/steel-squa	
4x5.4 A36 Channel (20' length)	$ 97.20	1	$ 97.20			☐	https://www.metalsdepot.com/steel-products/steel-char	
Axle Shaft			$ -			☐		
Cleats			$ -			☐		
Steel Cable			$ -			☐		
Fasteners			$ -			☐		
Axle Metal			$ -			☐		
Sliding interface						☐		
Misc Structures	$ 1,000.00	1	$ 1,000.00			☐		
Shipping	$ 500.00	1	$ 500.00			☐		
Welding Supplies			$ -					
Shear Pins								
Hardware			$ 391.00					$ -
Chain Hoist	$ 391.00	1	$ 391.00			☐	https://hoistzone.com/shop/cm-hurricane-360-hand-cha	
			$ -			☐		
Electronics			$ 4,126.70					$ -
Load Cell - 500 lbf	$ 208.00	3	$ 624.00	10 weeks		☐	https://www.omega.com/en-us/sensors-and-sensing-ec	
Load Cell - 1000 lbf	$ 208.00	3	$ 624.00	10 weeks		☐	https://www.omega.com/en-us/sensors-and-sensing-ec	
HPS-45-2-485 Inclinometer	$ 340.70	1	$ 340.70	1 week		☐	https://www.leveldevelopments.com/products/inclinome	
NI-9237 Bridge Input Module	$ 1,655.00	1	$ 1,655.00			☐	https://www.ni.com/en-us/shop/hardware/products/c-se	
NI cDAQ-9171	$ 333.00	1	$ 333.00			☐	https://www.ni.com/en-us/support/model.cdaq-9171.htm	
NI 9949 RJ-50 to Screw Terminal Adapter	$ 228.00	1	$ 228.00			☐	https://www.ni.com/pdf/manuals/372278b.pdf	
RJ50 Cables	$ 37.00	1	$ 37.00			☐		
Unknown Expenses	$ 200.00	1	$ 200.00			☐		
Cables	$ 85.00	1	$ 85.00			☐	https://www.digikey.com/en/products/detail/belden-inc/	
						☐		
Scaled-Down Model			$ 74.45					$ -
SEN-13329(Load Cell 3x): ~$25	$ 8.50	3	$ 25.50			☐	https://www.digikey.com/product-detail/en/sparkfun-ele	
Inclinometer/Accelerometer: ~$20	$ 18.95	1	$ 18.95			☐	https://www.digikey.com/product-detail/en/sparkfun-ele	
Cables	$ 5.00	1	$ 5.00			☐	https://www.wireandcableyourway.com/belden-9418-1	
3D printing	$ 25.00	1	$ 25.00			☐		