Drivetrain Education: Lecture 1

02/17/2025

Introductions

Who am I?

- My name is Sidh
- Senior in Mechanical Engineering
- FSAE Involvement:
  - Sophomore Year → General Member (Powertrain/Drivetrain)
  - Junior Year → PF24 Rear Sprocket
  - Senior Year → PF25 Drivetrain System
- Other Involvement
  - The Data Mine Corporate Partners Program → Kautex
  - Passion Project → Machine Learning Object Sorter
  - Purdue Bands and Orchestras → Wind Ensemble, Boiler Brass

Your Turn!

- Name
- Major + Year in School
- Briefly explain experience in FSAE
- Fun Fact about yourself

Drivetrain Education Rundown

Goals of Education

- To become better engineers (not just educated in drivetrain itself)

- While you will walk out of here with knowledge about the system, I want you to understand that what you learn in your classes does apply to FSAE and beyond

Structure/Logistics

- FRNY 1043, 6-8PM (room reservation)
- We will alternate between “lectures” and “office hours”
  - Lectures – I will be presenting you with information (like today)
    - Will not take place every week
    - I will most likely not use the entire time, but it is there if we need it
  - Office Hours – If you have questions about projects, or anything I have talked about here, feel free to stop by
    - Will take place when lecture is not taking place
- Note: There is no published schedule. Lectures will take place kind of on an as needed basis. I will be using group chat to communicate that out

General Lecture Progression

- Intro to Drivetrain Education + Intro to Drivetrain System
- CAD Design
- Loads/Analysis (hand calcs)
- Analysis (FEA)

- Additional Topics
  - FEA
  - Let me know if there is something that you would like me to talk about…

Projects

- Expectations
  - Depth (put in as much work as you can)
  - Written Deliverables (Reports and/or Presentations)
    - Feel free to use this in a portfolio of projects
  - Presentations
    - Dependent on project; I might have a “presentation day”
- Examples of Projects
  - Titanium Halfshafts
  - Diff Carrier FEA Study
  - Sprocket Design
  - If you have worked with me in the past, feel free to pitch ideas to me

Projects (cont'd)

- What you put in is what you get out
  - No grades
  - Quality of work will help you learn more

Model Based Systems Engineering

Systems Engineering

- A disciplinary approach to enable successful realization, use, and retirement of engineered systems
- Brings together several techniques to ensure that requirements are satisfied by the designed system

- Concentrates on the following during system lifecycle
  - Architecture
  - Implementation
  - Analysis
  - Management

Systems Thinking

- A method and approach of looking at a system as something that is part of a larger system and not a self-sufficient entity

- Larger System → System → Subsystem → Part

- Parts are connected to other parts AND depend on each other to work properly

Model

- Simplified version of something:
  - Graphical
  - Mathematical
  - Physical

- Goal is to <u>eliminate complexity</u> by making <u>reasonable</u> simplifying assumptions

Why?

- If everyone took liberties with design, car would not be well integrated (lot of guess and check)
- We do not have resources (time) to develop an initial car, then perform analysis, then remanufacture car
- Able to fully model the car using simplifying assumptions, make sure that integration is done well, then the car can be made

MBSE in Drivetrain

- Drivetrain uses assumptions and models to be able to design components
  - Only one minor failure in the last 4 years (PF23 tab issue) related to drivetrain

Before moving to the next section…

- Pretend you never saw the drivetrain on this car

Before moving to the next section…

- Pretend you never saw the drivetrain on this car

- The way we do things is the way we do things, not the only solution!!

Introduction to Drivetrain System

Integrating Systems

Integrating Systems

- POW > Engine
  - Function:
    - Provides the necessary power required to drive the car forward
    - Engine drives the front sprocket, which interfaces with drivetrain
    - Four stroke (Intake, Compression, Power, Exhaust)
  - Drivetrain system has to efficiently, reliably, and safely transmit the power coming from the engine and convert it to usable wheel speed

- AERO > Rear Wing
  - Function:
    - Redirect airflow headed towards the back of the car upwards to create a reactionary downward force at the rear (downforce)
  - Pushbar design must not interfere with the rear wing

Integrating Systems

- AERO > Undertray
  - Function:
    - Generate downforce for the overall vehicle by using Venturi tunnels (ground effect)
  - Undertray, to an extent, dictates the sizing of the overall drivetrain subsystem
  - Drivetrain system must have clearance to the undertray
  - If towbar comes back to drivetrain, then have to ensure that towbar placement does not negatively affect AERO while being rules compliant

Integrating Systems

- CHA > Frame
  - Function:
    - Acts as mounting point for all components on the car
    - Frame stiffness and component placement on the frame, affects vehicle handling
  - Frame design dictates placement of the differential axis, which affects drivetrain component placement and respective mounting points

- SUS > Hubs
  - Function:
    - Connection between the wheels and the CV's
    - Allows the wheels to spin and turn freely
  - CV Insert design will drive hub design, and can have affect on CV-Halfshaft and Hubs architecture

Integrating Systems

- How does drivetrain make it back to tires?
  - Start with front sprocket

Integrating Systems

Front sprocket → ? → ? → ? → ?

? → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → ? → ? → ?

? → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → ? → ?

? → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → Differential → ?

? → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → Differential → Bearings

? → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → Differential → Bearings

Inboard CV's → ? → ? → ? → Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → Differential → Bearings

Inboard CV's → Halfshafts → ? → ? → Tires

Integrating Systems

- Front sprocket
- Chain
- Rear Sprocket
- Differential
- Bearings

- Inboard CV’s
- Halfshafts
- Outboard CV’s
- ?
- Tires

Integrating Systems

Front sprocket → Chain → Rear Sprocket → Differential → Bearings

Inboard CV's → Halfshafts → Outboard CV's → Hubs → Tires

Boundaries

Boundaries

Green text indicates responsibility of drivetrain

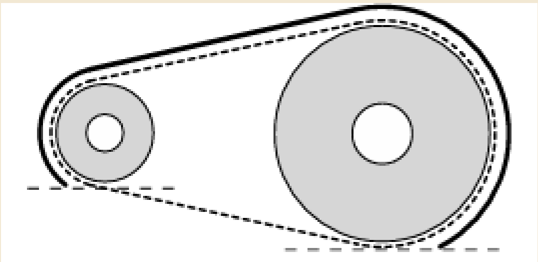
- Suspension
  - Two sets because final architectural decisions have to be made:
    - Wheel Hubs/**CV Inserts**
    - Wheel Hubs + CV Insert Solution/**CV’s (Tripods)**
- Aero
  - Rear Wing/**Pushbar**
  - **Aero responsible for Towbar on PF25 (as of June 2024)**
- Chassis
  - Mounting of Driveline(Frame)/**Tabs (i.e. for Uprights, Chain Guard, etc)**
- Powertrain
  - Engine/**Front Sprocket (Mounting, Selection, etc)**

Requirements

Requirements

Rule	Exact Text	Requirements From Rule
T.5.1	Any transmission and drivetrain may be used.	Any configuration can be used as team sees fit. Must comply with rest of rules below.
T.5.2.1	Exposed high speed final drivetrain equipment such as Continuously Variable Transmissions (CVTs), sprockets, gears, pulleys, torque converters, clutches, belt drives, clutch drives and electric motors, must be fitted with scatter shields intended to contain drivetrain parts in case of radial failure.	Drivetrain system must contain "shield" (i.e. Chain Guard) to prevent exposed parts from scattering (i.e. Sprocket, Chain).

Requirements

Rule	Exact Text	Requirements From Rule
T.5.2.2	The final drivetrain shield must: a. Be made with solid material (not perforated) b. Cover the chain or belt from the drive sprocket to the driven sprocket/chain wheel/belt or pulley c. Start and end no higher than parallel to the lowest point of the chain wheel/belt/pulley d. Cover the bottom of the chain or belt or rotating component when fuel, brake lines T.3.1.8, control, pressurized, electrical components are located below	Final guard must be made of a solid material and cover the sprocket-chain system as shown in the image. 
T.5.2.3	Body panels or other existing covers are acceptable when constructed per T.5.2.7 / T.5.2.8.	Body panels can be used as part of the guard system if constructed to rules specification.
T.5.2.4	Frame Members or existing components that exceed the scatter shield material requirements may be used as part of the shield.	Existing frame members and/or components can be used as long as they EXCEED material requirements

Requirements

Rule	Exact Text	Requirements From Rule
T.5.2.5	Scatter shields may be composed of multiple pieces. Any gaps must be small (< 3 mm).	Guard system can be made of multiple components if gaps are small (i.e. less than 3 mm).
T.5.2.6	If equipped, the engine drive sprocket cover may be used as part of the scatter shield system.	OEM guards can be used.
T.5.2.7	Chain Drive - Scatter shields for chains must: a. Be made of 2.66 mm (0.105 inch) minimum thickness steel (no alternatives are allowed) b. Have a minimum width equal to three times the width of the chain c. Be centered on the center line of the chain d. Stay aligned with the chain under all conditions	For chain driven systems (what we historically run), the following must be met: a. Made of 0.105 inch minimum thick steel b. Overall width equal to 3 times width of chain c. Centered along center line of chain at all times d. Stay aligned with chain under all conditions
T.5.2.9	Attachment Fasteners - All fasteners attaching scatter shields and guards must be 6 mm or 1/4” minimum diameter Critical Fasteners, see T.8.2	All fasteners used in guard system must be in accordance to T.8.2

Requirements

Rule	Exact Text	Requirements From Rule
VE.2.2	Each vehicle must have a removable device which attaches to the rear of the vehicle that: a. Allows two people, standing erect behind the vehicle, to push the vehicle around the competition site b. Is capable of slowing and stopping the forward motion of the vehicle and pulling it rearwards	Car must have a push bar that attaches to rear and: a. Allows two people to push car around at comp b. Capable of slowing and stopping forward vehicle motion and pulling it backwards
VE.2.3.1.b	One extinguisher must accompany the vehicle when moved using the push bar	A fire extinguisher must accompany vehicle when moved using push bar
D.2.1.1	Outside of the Dynamic Area(s), vehicles must be pushed at a normal walking pace using the Push Bar (VE.2.2), with a driver in the cockpit and with another team member walking beside	Vehicle to be pushed around outside of dynamic areas

Requirements

Rule	Exact Text	Requirements From Rule
D.2.1.2.b	The team may move the vehicle with: b. The rear wheels supported on dollies, by push bar mounted wheels	Team may move vehicle with dollies that support the rear wheels
D.2.1.3	When the Push Bar is attached, the engine must stay off, unless authorized by the officials	Push bar on car = engine off

Problem Statement/Design Req.

Create a structural system to transmit mechanical power from the engine to suspension components via a chain drive system. System should:

- Allow for chain tensioning
- Sustain repeated launch loads
- Allow for a desirable Final Drive Ratio given Torque Curves and desired shift points
- House a Differential to allow for different wheel speeds

Requirements

- Withstand extreme load cases with an adequate factor of safety, as dictated by team standards with regards to safety
- Contain a chain tensioning system to account for approximately 3% of chain stretch due to fatigue throughout the season
- Integrate desired final drive that will break traction
- Hardware within system will be torque spec'd or safety wired to prevent failure on track (with exact torque spec determined by what hardware is used, mostly NAS 3)

- Design to the following boundary conditions while maintaining the aforementioned margins to safety:
  - Peak engine torque
  - Tire size
  - Longtudinal Acceleration (historically done about 1.65G)
  - Approximate Vehicle Weight
  - Final Drive Ratio

Architecture

Differential

	Drexler LSD	Custom Spool	Another Purchased Diff
Team History	Ran by team for several seaons now, and has proven to be a dependable option	Completely new, but team has documented experimentation with designing one	None; this would be a complete experiment to see how it works with our setup
Mass compared to benchmark	~ 6.8 lbs (benchmark) Assuming V3; dry weight	Significantly lower	Comparitively similar to the benchmark
Tuning	Possible	Not possible	Possible
Implementation	Historical knowledge, can tune as needed to improve handling	Architecture on several systems would have to pivot drastically; negative to driveability	No knowledge, would have to rework a lot of components that have been used in the past

Drexler Limited Slip Differential

	Nonadjustable (PF24)	Adjustable (PER)
Team History	Ran for several seasons with no major issues	To my knowledge, never ran

Perks	Decent past knowledge	• Time saving on adjustments made during initial set up and testing
		• Customizable preload adjustment range
		    • Can account for variable race and track condition (more knowledge to do successfully)
		• Relatively compatible to what team has ran historically
		    • Allows us to run both an adjustable and non adjustable and swap as needed or wanted

Another Purchased Diff

- Types of diffs available for use:
  - Open Differential/Spool
  - Detroit Locker Differential
  - Cam and Pawl Differential
  - Salisbury or Clutch Pack Differential
  - Automatic Torque Biasing Differential
- The preferred differential among many FSAE teams remains a clutch pack differential
  - Open diff and spool is a negative to driveability
  - Other differentials are more complex and not well supported for FSAE teams

Rear Sprocket

	Custom	Purchased
Team History	Ran successfully in the past with no major issues	To my knowledge, never ran
Flexibility	Ability to control design to exactly how it is required (FDR, mass optimization, etc); can also work in a variety of conditions	Extremely restricted selection and application; would have to design around rear sprocket, which is not a good idea
	Titanium	**Aluminum**
Mass (benchmark = Al)	Slight weight loss (~0.1 lbm loss)	Benchmark (~0.5 lbm)
Machining Time	Much longer machining time compared to Aluminum + Wire EDM	Took me around 5-7 hrs with about 1-3 hrs of stock prep put in beforehand + Wire EDM
Cost	Significantly Higher	Benchmark

Differential Carriers

	Titanium	Aluminum
Team History	To my knowledge, not run at least in recent history	Traditionally ran for the last couple of seasons
Mass (benchmark = Al)	Slight weight loss (potentially a bit more than sprocket)	Benchmark
Machining Time	Much longer machining time compared to Aluminum	Benchmark
Cost	Significantly Higher	Benchmark

Chain Tensioning Mechanism

	Linear Translation (aka Turnbuckles)	Idler Sprocket	Eccentric Differential Carriers
Team History	Ran in recent history since PF20	Ran once in recent history (PF19)	To my knowledge, never ran by team, but at least not in recent seasons
Mounting	Refer to PF24 CAD	Along length of chain; placement is key since chain guard has to cover idler sprocket	Same location as differential carries along diff axis, except would connect directly to two points on chassis
Manufacturability	Rod ends purchased; Custom body (relatively simple)	Would probably purchase sprocket, but manufacture adjustable mounting mechanism	Most difficult of the bunch to manufacture due to complexity of components
Approx Mass	Benchmark	Very similar, potential to be slightly higher or lower	Heavier

Chain Tensioning Mechanism

	Linear Translation (aka Turnbuckles)	Idler Sprocket	Eccentric Differential Carriers
Serviceability	Easy to adjust chain tension with excellent tool access	Relatively simple to adjust chain tension with extra measures needed for easy tool access	Similar to turnbuckles, but adjustment takes place on diff carriers (maybe slight issues with tool access)
Simplicity of Design	Benchmark (simple design and manufacturing)	Adjustable mount has potential to be complicated pending mounting location	Adds complexity to the differential carrier system
Aligns with measures to reduce halfshaft angle	Not really	Yes	Yes
Additional Considerations	One turnbuckle takes about 45 mins to make	Analysis for idler sprocket; to my knowledge, no effect on FDR; have to understand why we stopped running; adds chain length; mounting	If running, have to figure out how to simplify this system as best as possible.

Halfshafts

	Custom (Ti)	Purchased (4130 Steel)
Team History	Idea has been talked about before but would have to do a significant amount of work (obtaining high fidelity laser scan, sourcing manufacturing, analysis, etc)	Used for the last several seasons, serves as a dependable option that is structurally sound; Variety of sizes available for purchase and can be machined to final size
Mass (benchmark = purchased)	Can't get an exact amount in terms of mass saved, but increases as the length of halfshaft increases	Benchmark
Machining Time	MUCH longer (and will most likely have to send this out)	Benchmark; comes with spline
Cost	Significantly higher	Benchmark

CV Inserts

	Reiteration / Revalidation on PF24's Design	New Design / Purchased
Team History	Ran in the last couple of seasons since PF20; No notable issues to my knowledge	Not run in recent history
Change to recent hubs design philosophy	Zero change	Would be a change depending on design
	17-4 Prehard Stainless w H900 Heat Treatment	**Another Material with Appropriate Hardness**
Team History	Ran on PF24	Not ran on PF24
Manufacturing	Cut to length, HT in ME, Wire EDM	Would look similar to 17-4, might have to HT to a different specification

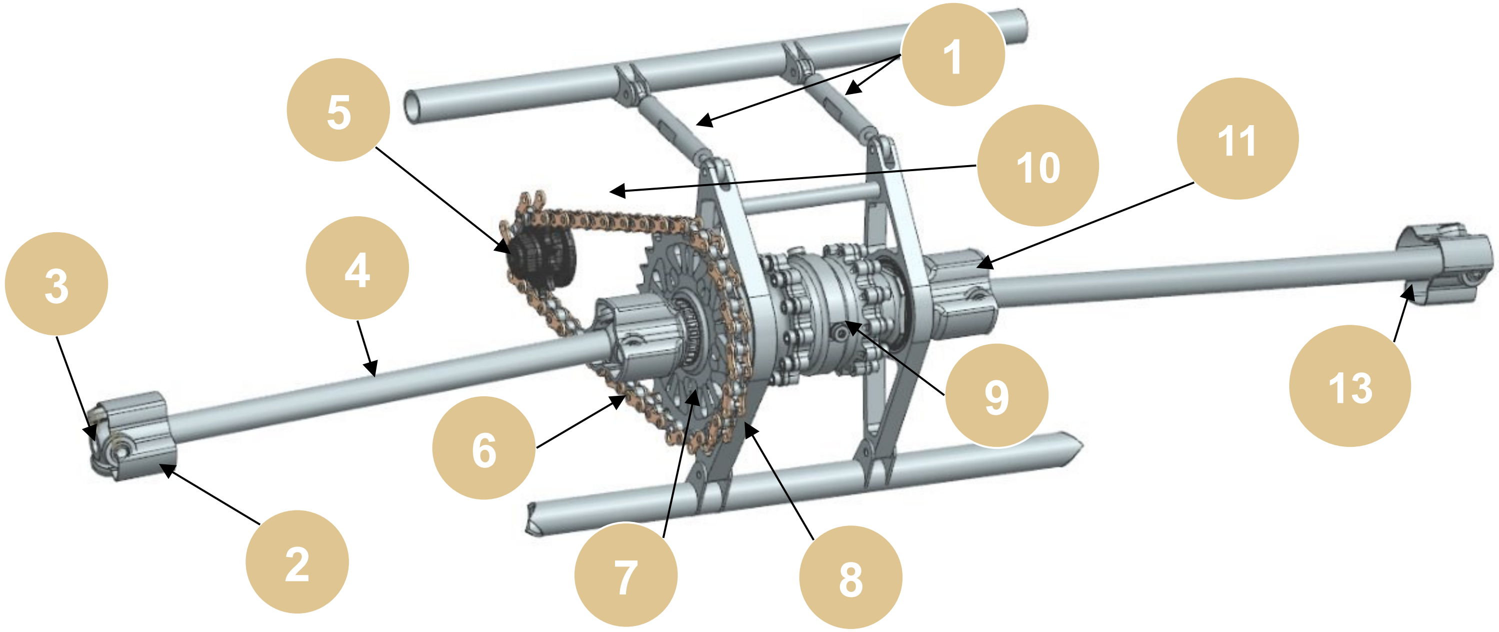
Boots

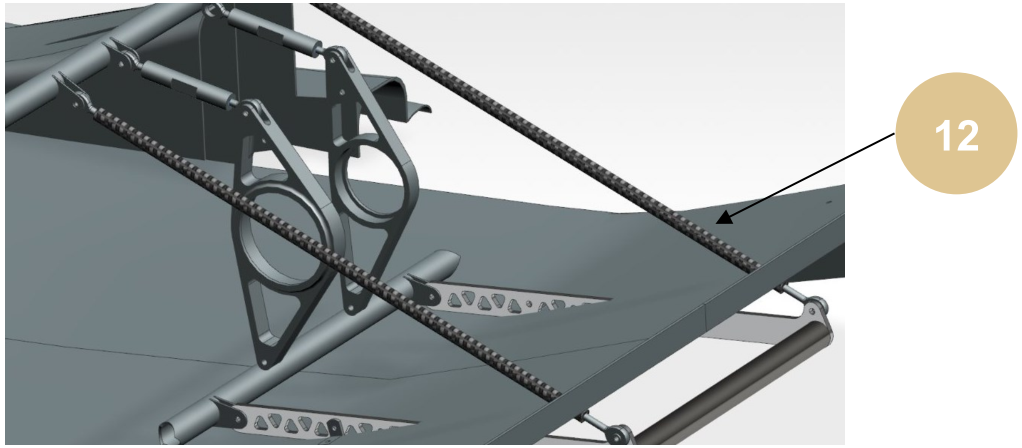
	Purchased	Custom (Nitrile Glove Special)	Custom (3D Printed)
Team History	Typically ran in recent seasons	Ran on PF24 after purchased boots failed	Ran at least once in recent history (PF19)
Cost	~$12 for 1	~$5 for 2	Filament dependent
Other considerations	Have to fully understand why it failed last year to be able to conclusively say if this was a failure or not	Doesn't take long to make, but definitely has the appearance of a lower fidelity prototype	Can be made to exact specifications based on the design; Is also something else that has to be designed and manufactured

Other Components

Component	Notes
Chain Guard	Custom Steel by rules and manufactured in house
Chain	Purchased DID 520 Roller Chain
Inboard CV Housing (Tulips)	Purchased – Diff Custom – Spool
CV's (Tripods)	Purchased (RCV)

PF24 Drivetrain





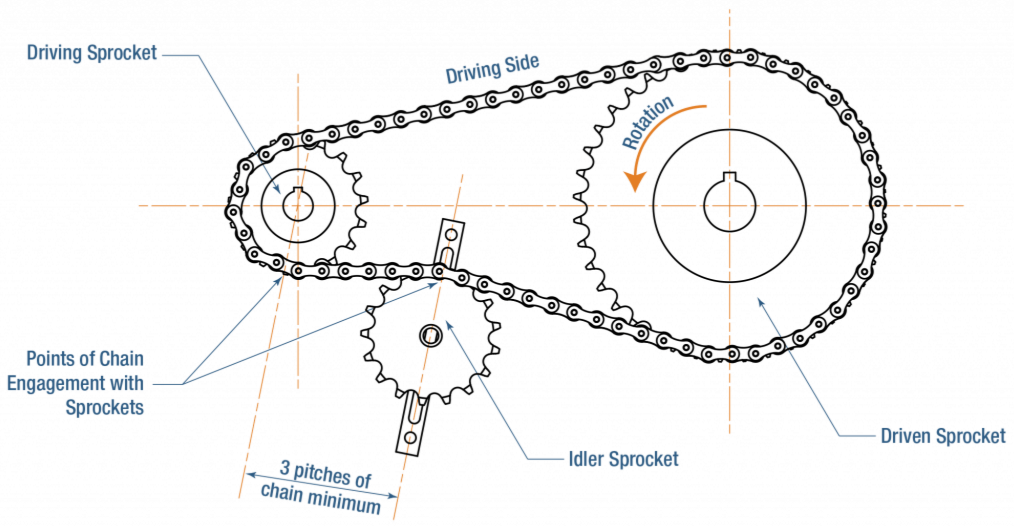
1. Turnbuckles
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard (not pictured)
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots (not pictured)

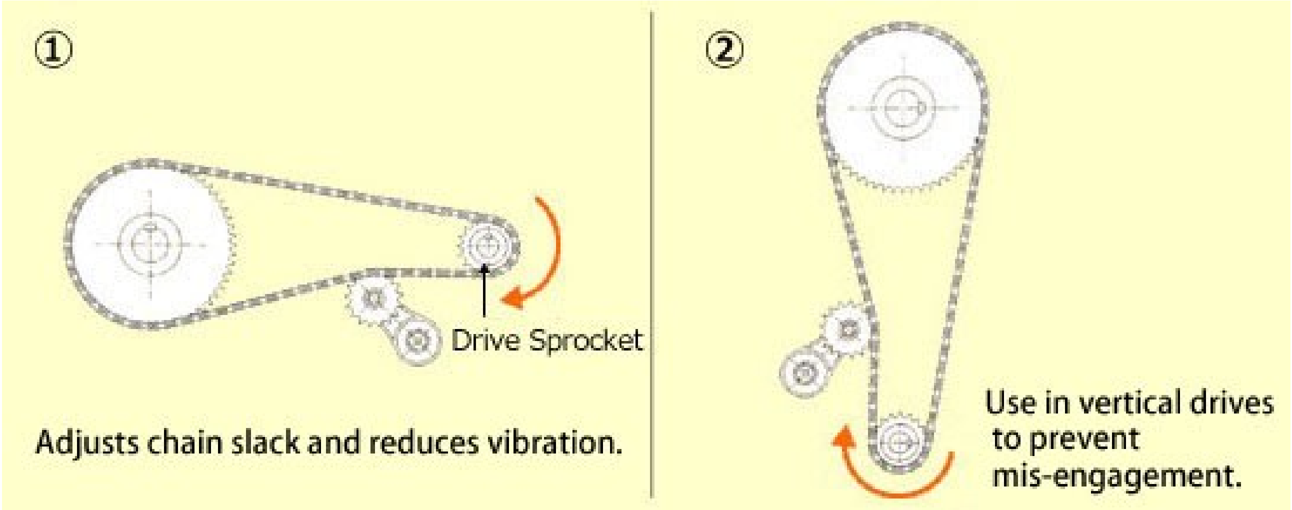
Appendix A:
Basics of an Idler Sprocket

Idler Sprocket Basics

- An idler sprocket is a smaller sprocket that is placed along the length of the chain to allow the chain to maintain constant tension.
  - Chain too loose → risk chain falling out of place and could cause injury
  - Chain too tight → excessive wear on sprockets and chains, which requires replacement more often
- Should be installed on the slack side of the chain
  - Usually the length of the chain that runs closer to the bottom for our purposes
- Loading, chain wrap, and chain speed are important to consider
- A chain rider is an alternative that functions similarly to an idler sprocket (no teeth to worry about, but radial loading still a factor)

Reference Images





Drivetrain Education: Lecture 2

02/24/2025

Quick Notes

Notes

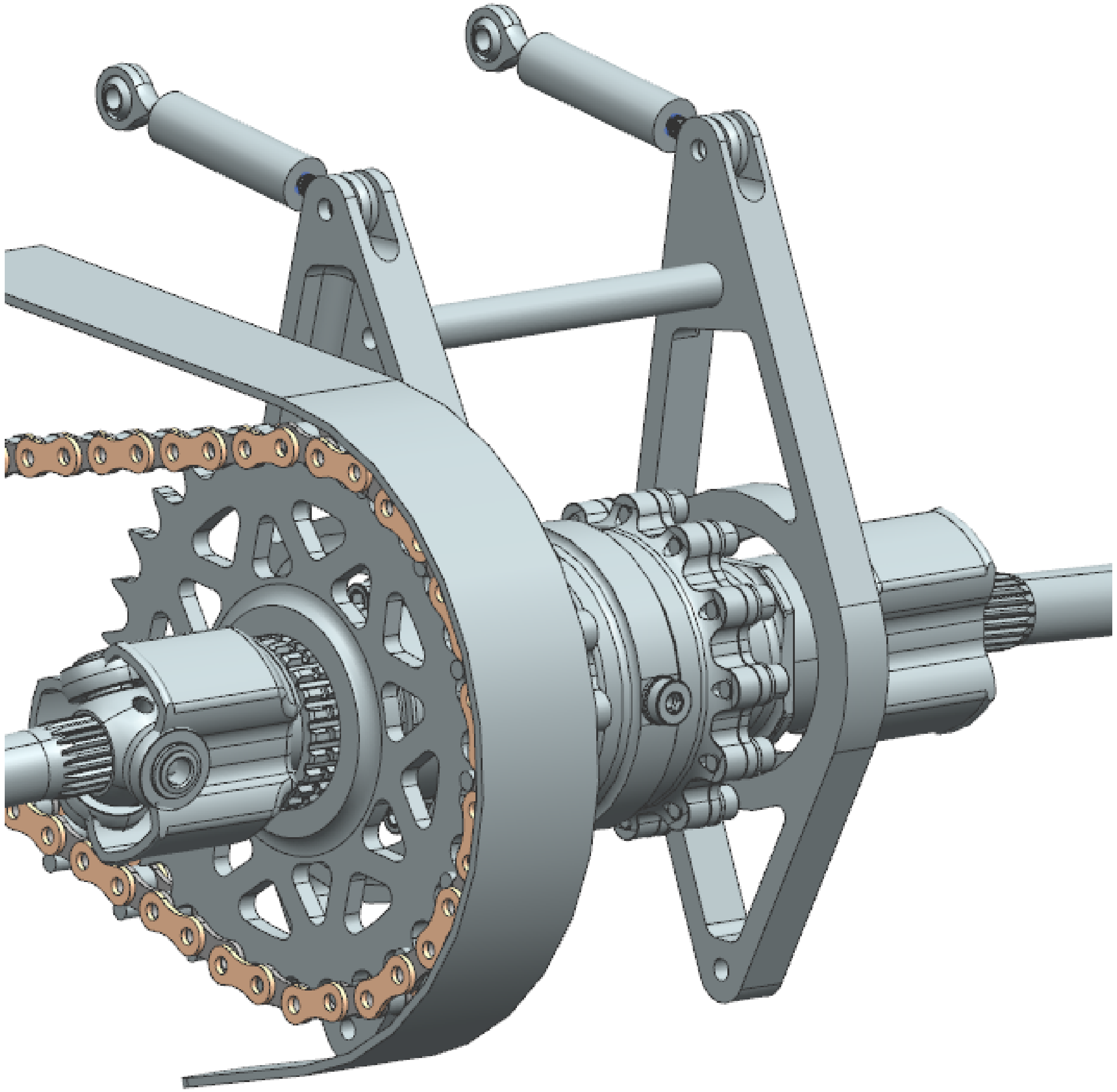
- Final list of projects will be out in 1 week
  - Aiming to get assignments out before spring break
  - Gives you time to get exposed to the material
- There will be another form to fill out once I have this list ready
- Send me any topics you would like to learn about
  - I have maybe 2-3 lectures of content left in drivetrain before I start running out of topics
- If you have any questions, feel free to stop me at any point

Recap

Recap

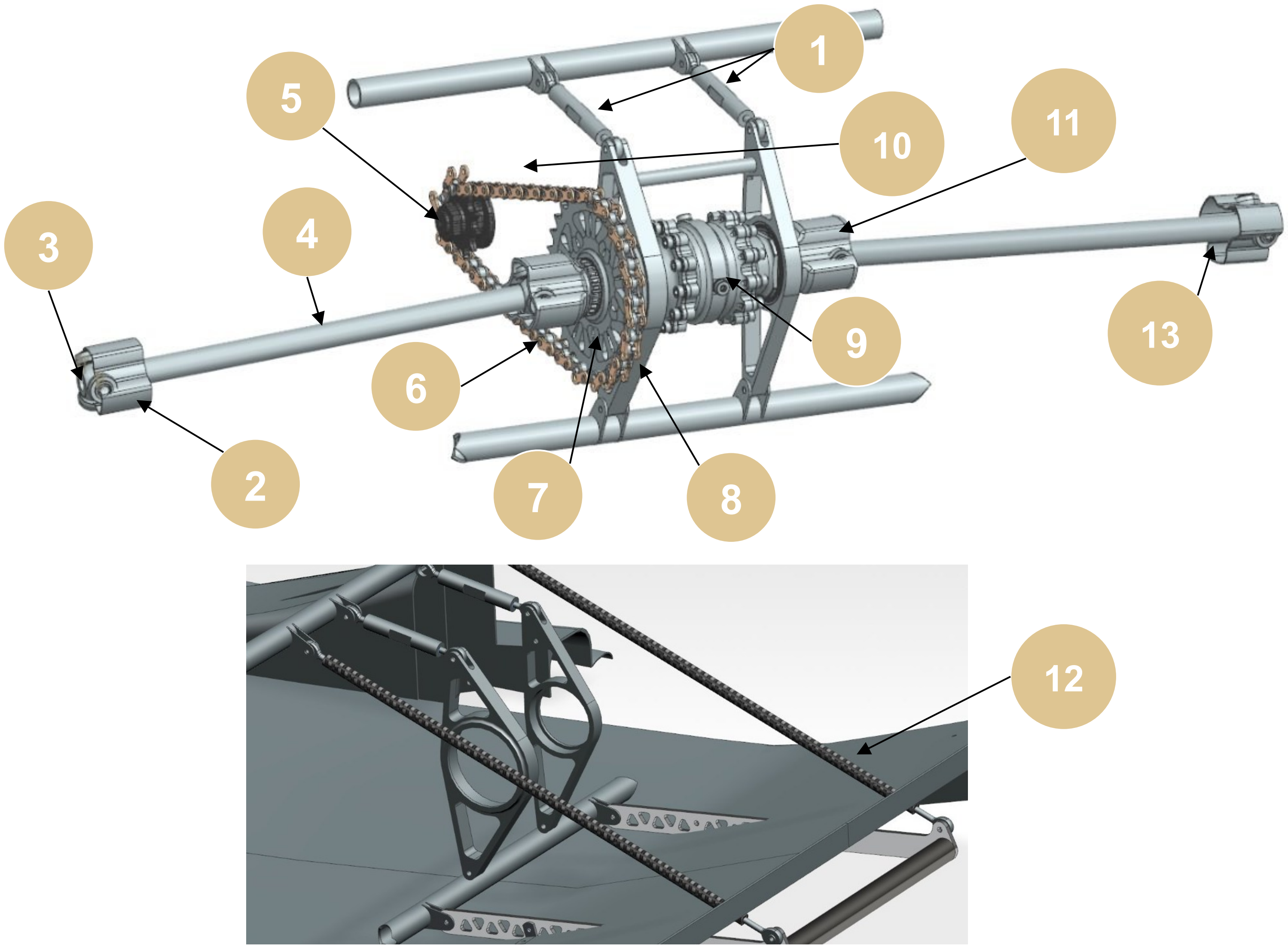
- What is the function of the drivetrain system on an FSAE car?
- What are some components you could use to design a drivetrain, and how would you use those to achieve your overall function?
- What are the systems that we integrate with?
- How does the engine power make it to the wheels?

Drexler Limited Slip Differential



There are many ways to design any system!

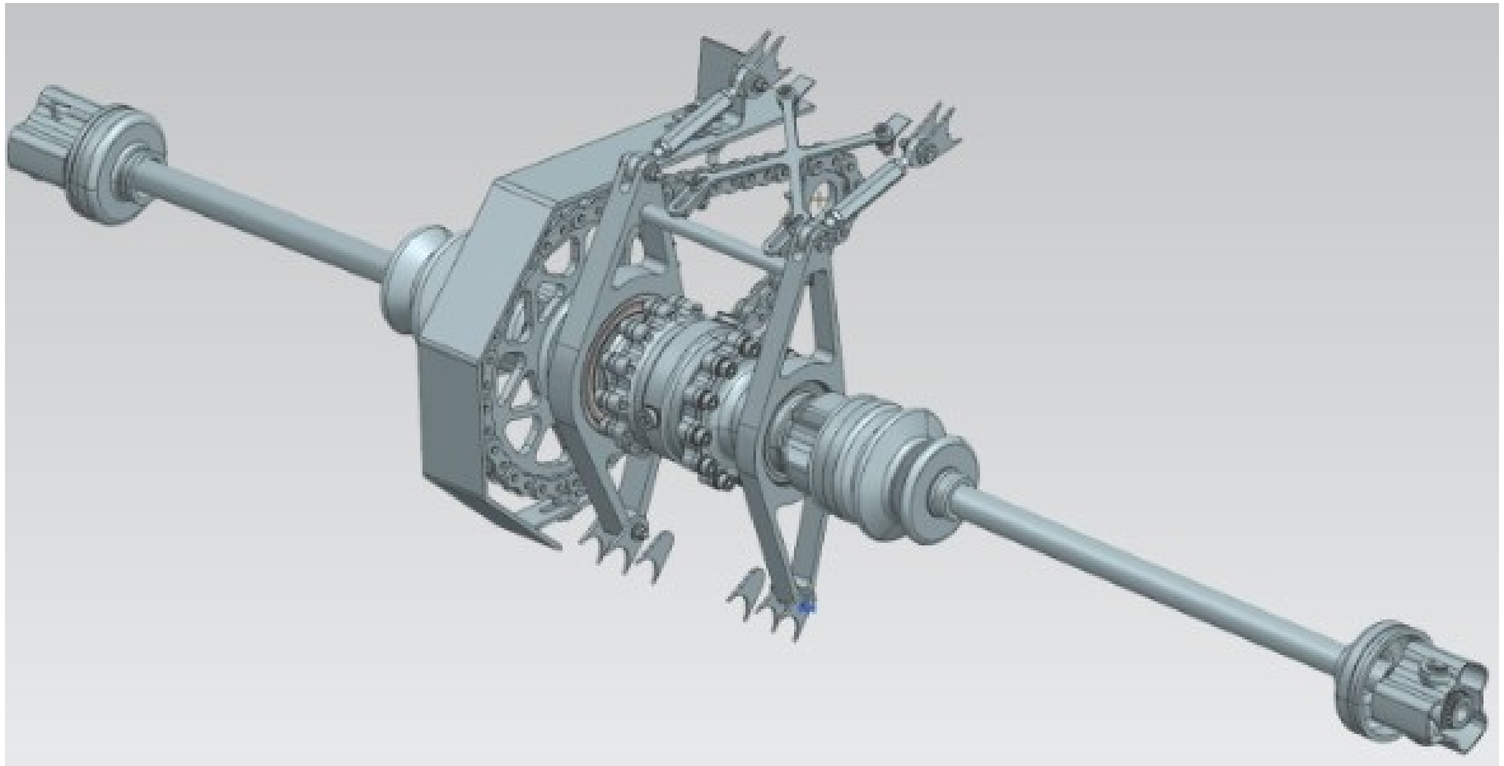
PF24 Drivetrain



1. Turnbuckles
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard (not pictured)
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots (not pictured)

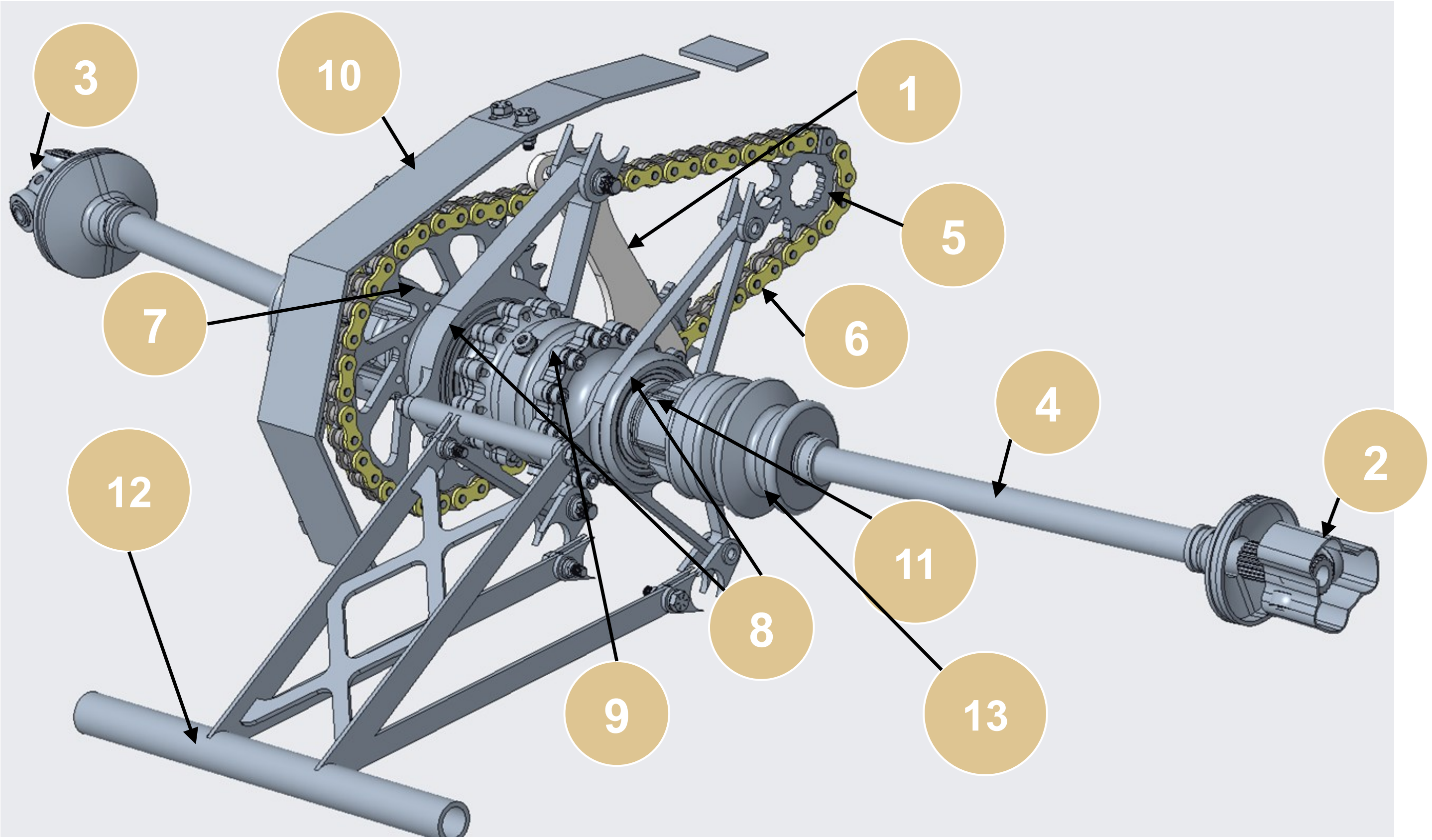
PF20 Drivetrain

- Final Drive = 34/11 = 3.09
- Architecture and philosophy between PF24 and PF20 very similar
  - Similar architecture ran for 5 seasons (PF20-24)
- Differences:
  - Higher FDR compared to PF24
  - Slight design differences



PF19 Drivetrain

- Final Drive = 34/11 = 3.09



1. Chain Tensioning System
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots

Any questions from last week?

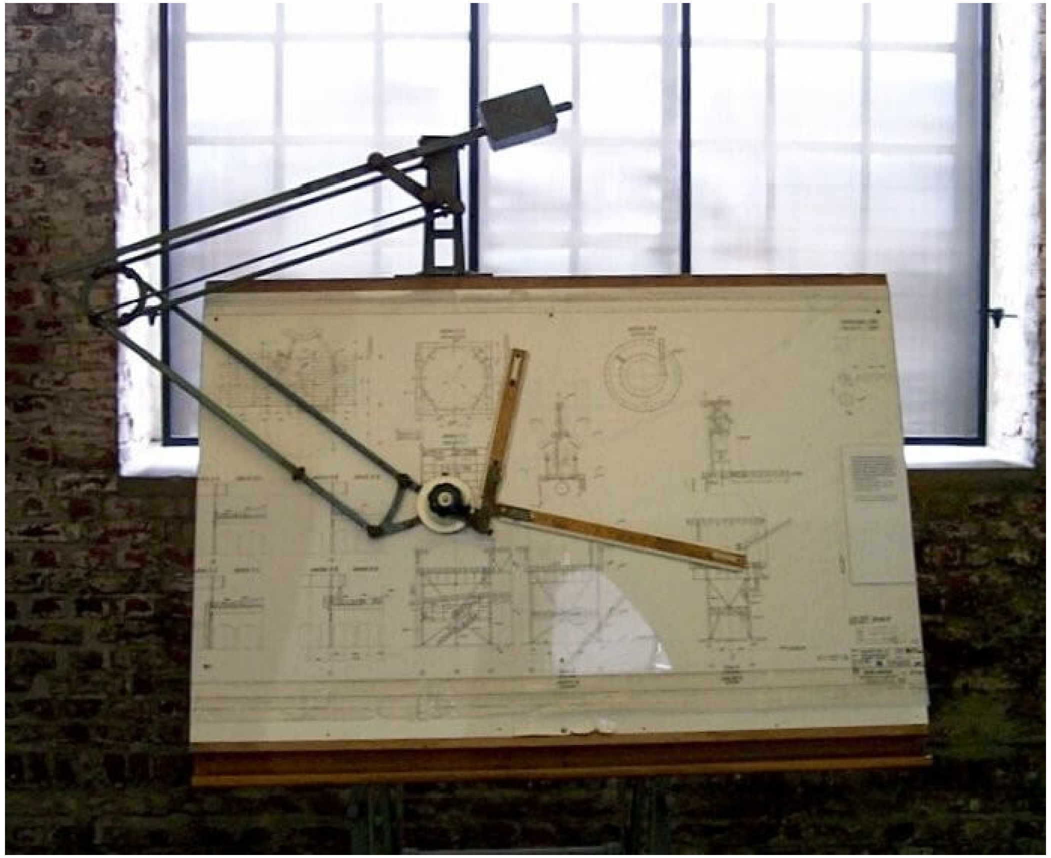
CAD

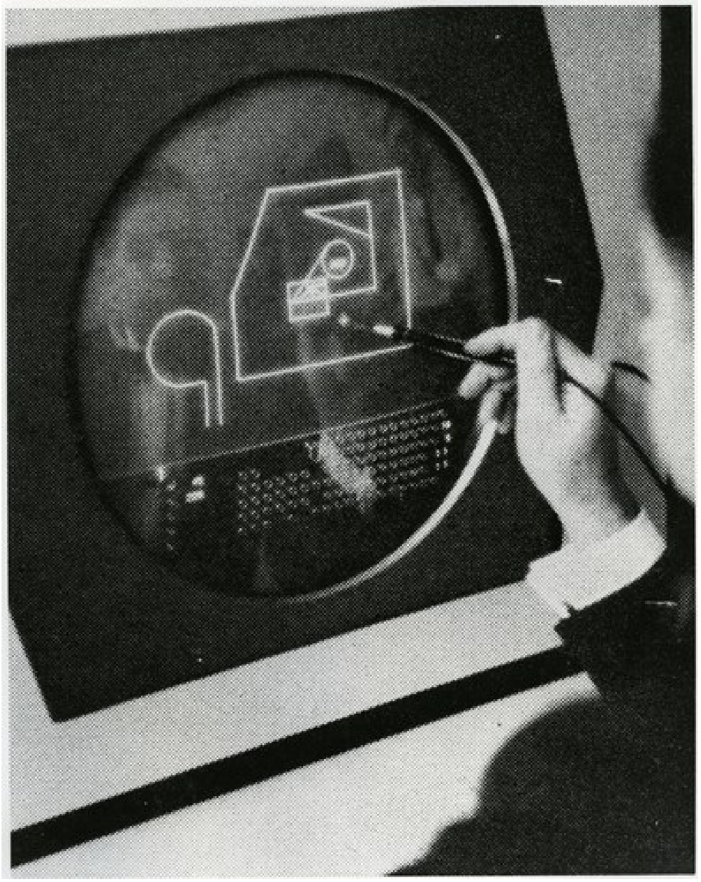
Introduction

- CAD = “Computer Aided Design”
- What is it?
  - Helps you design components
  - Helps you visualize your designed components
  - Allows you to export in a variety of methods to help with manufacturing and/or analysis
    - .stl → 3D Printing
    - .step → Analysis Packages (FEA)
    - .dxf → Laser Cutting
    - .jt, .iges, etc…

History

- Father of CAD = “Dr. Patrick Hanratty”
  - Created Pronto in 1957, allowing designers to sketch on computer as opposed to on paper

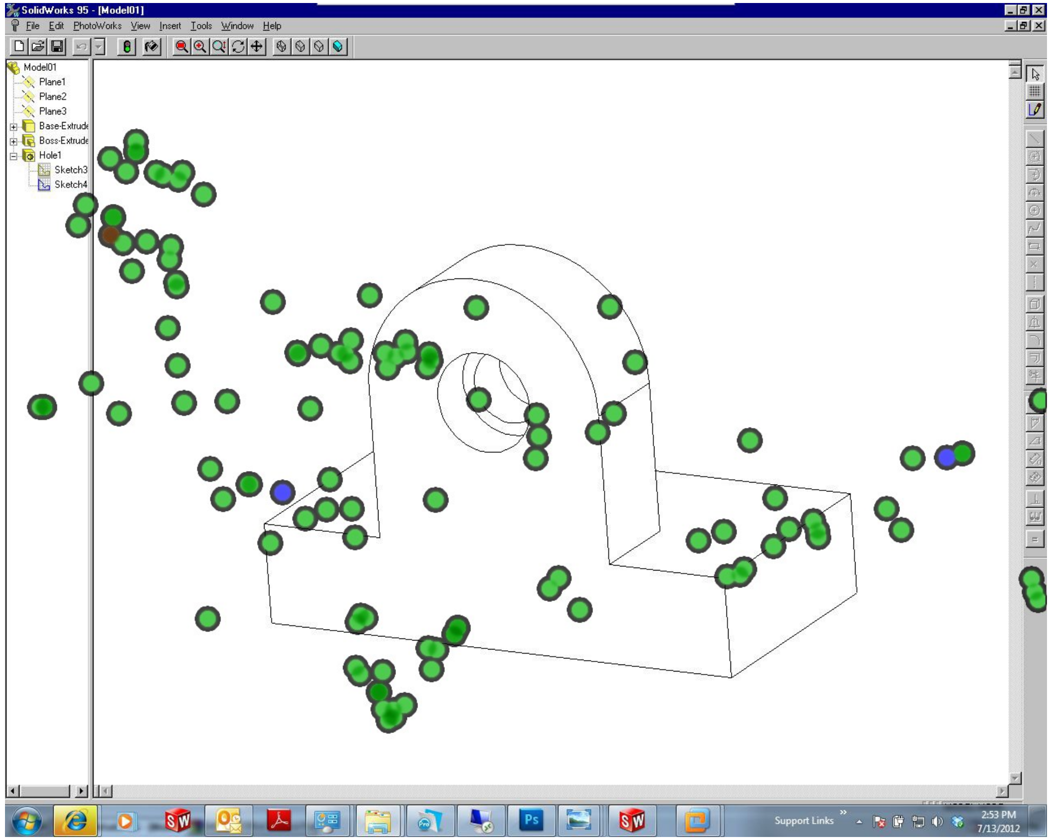


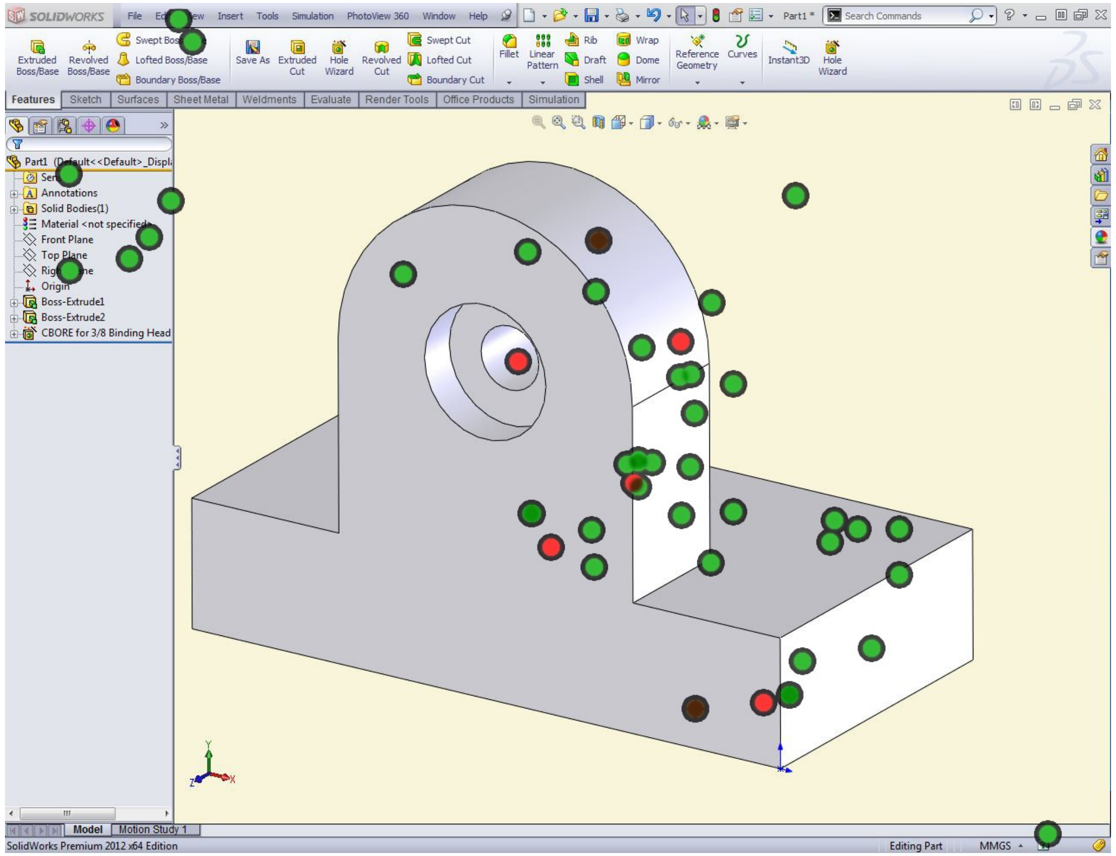


- Next big step came in 1983, when AutoCAD was created

History (cont'd)

- 3D modelling came into effect in 1987 with Pro/ENGINEER
- SolidWorks was released in 1995





History (cont'd)

- Siemens NX is the CAD package we use
  - Started out as Unigraphics in 1978 (initially for drawings)

UNITED COMPUTING CORPORATION PRODUCT BULLETIN

UNI-GRAPHICS®

UNI-GRAPHICS PROGRAMMING CONSOLE

MACHINING AND DRAFTING APPLICATIONS

UNIAPT® COMPATIBLE GRAPHICS PROGRAMMING SYSTEM

UNI-GRAPHICS PHILOSOPHY

United Computing set a number of high goals for the design of the UNI-GRAPHICS system. Primary among these goals was the commitment to provide the user with the most powerful system available for graphics programming of part and drawing specifications associated with computer aided design and manufacturing. However, this powerful capability could be rendered useless if the system were not both easy to understand and use. Thus the second most important design goal was to provide a system which would automatically lead the user through the programming sequence without the need for complicated menus and burden on the programmer's memory.

Other priorities for the UNI-GRAPHICS design demanded a system whose hardware components could be rapidly field serviced thus assuring the maximum uptime possible from installed equipment. United also wanted to provide a system which would give the user easy economical entry into the field of graphics programming and at the same time interface this new capability with existing methods of doing business, such as part programming with the UNIAPT N/C language. Last, but not least, this system must provide a foundation to advance into future applications of computer aided design and manufacturing. The system presented in this brochure exceeds these goals.

UNI-GRAPHICS SYSTEM FEATURES

- Graphic definition of basic geometry (point, line, circle, plane, etc.)
- Graphic definition of extended geometry (developable, ruled, mesh surfaces, etc.)
- Complete graphics manipulation capability.
- Automatic scaling, dimensioning, labeling, line fonts, etc.
- Two to Five axis N/C programming.
- Extensive pocketing, profiling, swarf cutting and machinability.
- Dynamic tool path display.
- Compatible with UNIAPT post processors.
- Handles up to four interactive design stations.
- Can produce APT source programs from graphics input.
- Separate CRT for tutorial operator messages (eliminates graphics rewrite following message area erase.)
- Accepts APT geometry definition from non-graphic media.
- Programmed function key lights guide user programming sequence.
- Pattern and drawing library storage and recall.
- Hard copy options.
- Computer and drafting machine independence.
- Extensive field service support.

THE TWO-CRT, FUNCTION KEYBOARD CONCEPT

Most graphic programming systems utilize a single CRT and a typewriter like keyboard for geometry and command input and display. Associated with this gear is a listing, called a menu, which contains code numbers representing the various functions the system is capable of performing. The user looks up the code number of the particular function to be performed and types this number into the system through the keyboard to activate the operation. Single CRT graphics systems divide the display surface into two areas, the graphic or drawing area and an alphanumeric command message area.

There are three major disadvantages to the single CRT/Keyboard design.

1. When the command message area is full, the entire display must be erased, including the graphic area. The graphics must then be re-drawn. This is very time consuming and greatly limits the speed of graphics programming.
2. The menu approach requires the operator to remember (or repeatedly look-up) abstract codes for the various functions to be performed.
3. There is a lack of guiding of the operator as to which keys should be depressed following a given sequence of operations. Thus he is required to revert time and again to his menu to determine options available.

The UNI-GRAPHICS system eliminates all of these problems by utilizing two CRT's and a function keyboard entry device. A typewriter like keyboard is also connected to the system to facilitate entering alphanumeric data to the graphics area.

The TEKTRONIX Display Terminal is the main unit to construct the graphic presentation. This high resolution CRT provides bright, accurate display of alphanumeric and graphic data. Its design eliminates costly extra circuitry required by refreshed terminals. Its simpler circuitry also means a new high in equipment reliability.

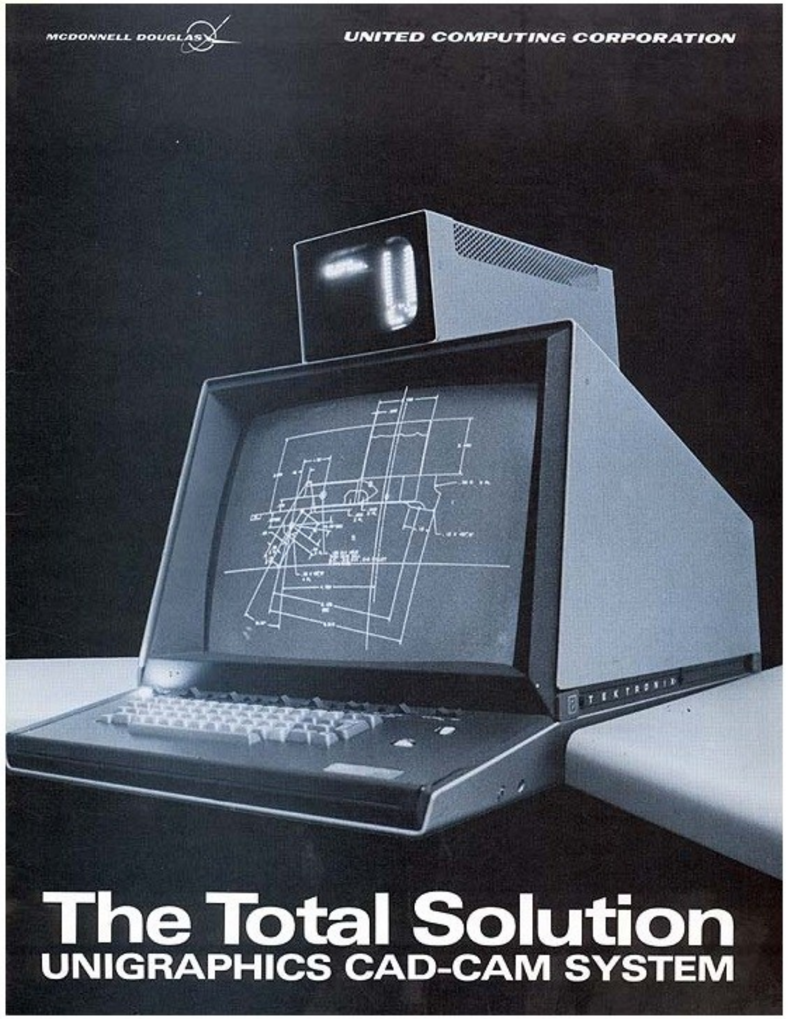
GRAPHICS DISPLAY TERMINAL

The Message Monitor provides for the display of tutorial command data to the operator. It is a high speed, refresh, ASCII display device with a 5½" diagonal, 32 x 16 matrix screen and an independent RS-232 interface. Redrawing of the graphics image each time the command data is changed is virtually eliminated. The 5 x 7 dot matrix characters and uncluttered display format result in an extremely ledgible and uncomplicated presentation which is easily read without fatigue.

MESSAGE MONITOR

A Programmable Function Keyboard is also a part of each UNI-GRAPHICS terminal. The unit has 32 keys which are lighted under program control. Each key is labeled and represents a given function which is to be performed by the system such as communication (yes, no, etc.), definition (line, circle, etc.) or operation (label, rotate, etc.). The computer lights certain keys following a given operation thus indicating options available to the user.

PROGRAM FUNCTION KEYBOARD

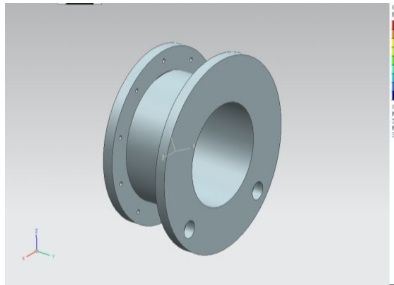
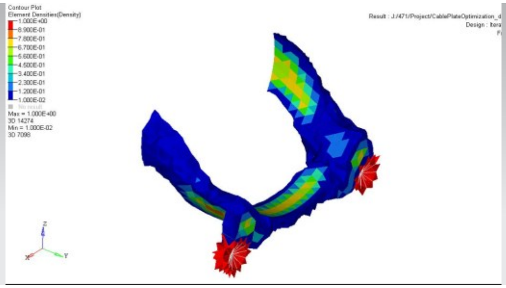
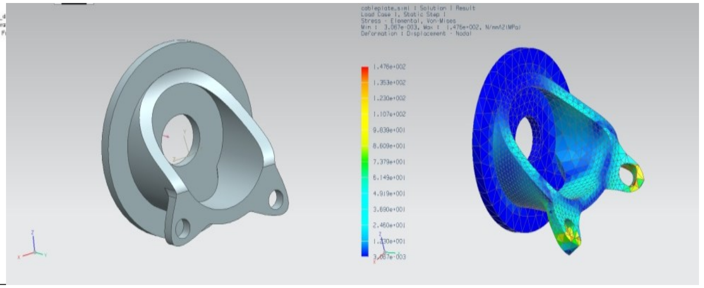


Benefits of CAD

- Time and cost
- Space
- More designs and creativity
- Higher accuracy
- Design testing
- Shared designs
- Customer relations
- 3D previews
- etc

Product Lifecycle Management

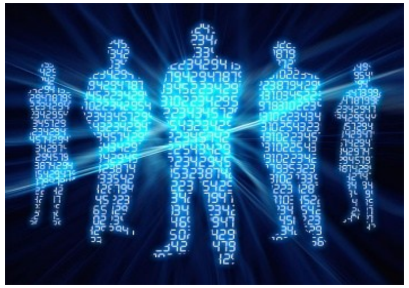
- Product Definition

- Product Production




- Operation Support




Product Definition

Product definition is primarily concerned with managing knowledge as an intellectual asset that is comprised of the product's total definition, including product specifications, conceptual design, part geometry, analysis results, engineering drawings, assembly drawings, and so forth. Thus, product definition encompasses all CAD, CAE, and CAM information.

Activities related to product definition information include:

- **Product configuration management.** As the product design and configuration evolve, the resulting information must be managed in an effective way to ensure its availability on a timely basis to whoever needs it.
- **Change management.** This is a crucial activity. Any change that is made by a member of the product team must be documented and made available immediately. If an organization has offices in different locations, no office should work with obsolete information.
- **Product design and design optimization.** This is a major activity of product definition. All engineering, design, and analysis tools are used here to ensure the proper design and product dimensions.
- **Material selection.** Engineers choose material based on design calculations.

Product Production

Product production is primarily concerned with the physical operations that are performed to produce the product itself. Activities related to product production information include:

- **Material purchasing.** This activity requires an awareness of suppliers and what they offer. Here, SCM tools should come in handy.
- **Production planning and scheduling.** This is an outcome of the process planning.
- **Equipment design.** Some organizations design their own production equipment in-house. This equipment is highly specialized and is not available off-the-shelf in mass markets.
- **Equipment ordering.** This is off-the-shelf equipment. SCM tools should help decision makers in ordering this equipment.
- **Facilities planning.** Facilities planning must be done before equipment can be installed and operated.
- **Equipment installation and operations.** This signals the beginning of production. This is the ultimate outcome of all of the preceding activities.
- **Maintenance.** Production facilities must be maintained on a scheduled basis to prevent unpredictable shutdowns and failures during critical production times.
- **Manufacturing and quality assurance (QA).** QA tests the accuracy of the production and manufacturing processes. It is an important part of customer satisfaction. QA uses various statistical methods and tools, including Six Sigma.
- **Delivery.** At last, the product can be shipped to customers. Delivery is part of the material handling and logistics problems.
- **Support and customer service.** This activity is the beginning of product revisions and future changes. Customer feedback, field service, and service data often provide a valuable measure of the success of product design and manufacturing.

Operation Support

Operations support includes activities directed at managing finances, human resources, and organizational structure design and management.

The conclusion that we can make now is that a product is synonymous with generating information and managing information. Without information, organizations cannot innovate or create new products; they cannot grow. Therefore their demise and collapse becomes a matter of time. Without information management, organizations cannot compete as their time-to-market lead time becomes excessive. Therefore they cannot make profit nor survive in the marketplace, although they may have excellent products.

Without successful information generation and management, the productivity of individuals and their organizations suffers and declines. Productivity leads to growth, growth leads to profitability, and profitability leads to survival in the marketplace.

Having realized the importance, the complexity, and the heterogeneity of product information, and having realized the importance of its management, the central question can be stated as follows: How can we manage this information effectively? We now can appreciate that the scope of the sum of the product information is much bigger and more complex than the scope of any individual area, including CAD, CAE, CAM, and so forth. One effective answer to the question is PLM.

PDM, PLM

- PDM and PLM are used to manage CAD files in a larger organization
  - Manages who is working on CAD to prevent anyone from overwriting edits

- While designing PF24, we did use Teamcenter
  - Lost it due to $$$

Parametrized CAD

What is Parametrized CAD?

- Parameters
  - Aspects about your design that you’ll maybe want to change
  - Examples: height, width, length, depth, etc

- Why parameterized CAD?
  - Allows you to make quick design changes to make multiple variations of a similar component
  - Quick tweaks to mass optimize (running FEA)
  - Scalability
    - RC cars, etc…

Assemblies

Intro to Assemblies

- CAD Assembly
  - Digital representation of a system
  - Made up of components

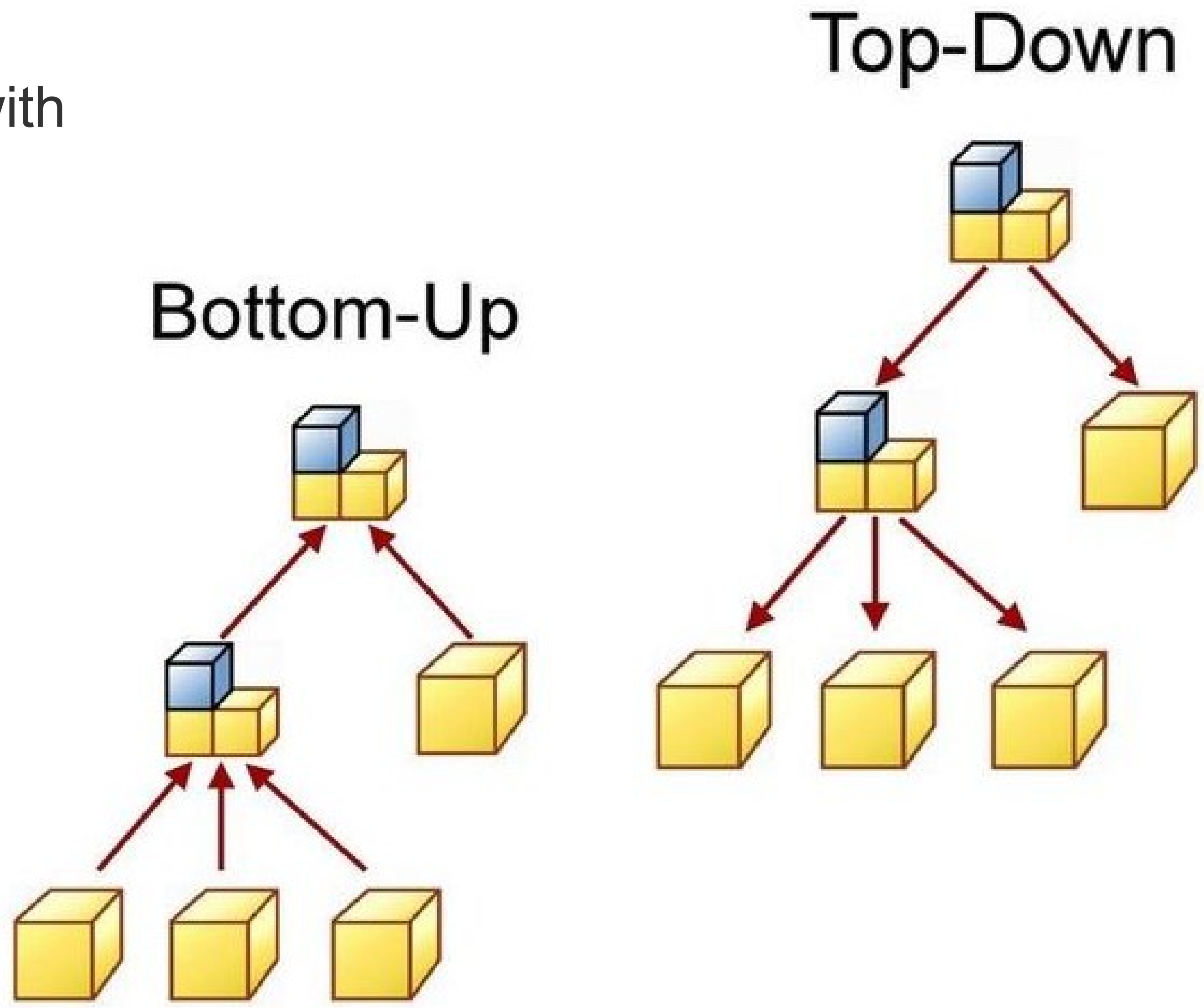
- Think back to General Onboarding:
  - Bike Pedal Assembly
    - Frame
    - Pedals
    - etc

Benefits of CAD Assemblies

- Visualization
- Design Intent can be conveyed
- Analysis and Simulation:
  - Carry out assembly level FEA
  - CFD (Aero)
  - Motion Studies
  - Clearance Checks
  - etc
- All other benefits of CAD carry over as well

Top-Down vs Bottom-Up

- Top-Down Assembly
  - Define assembly skeleton with relevant geometry
    - More than just datum planes
  - Model assembly before modelling components
- Bottom-Up Assembly
  - Model components before modelling assembly



Assembly Constraints (in NX)

- Touch Align
  - Prefer touch
  - Touch
  - Align
  - Infer Center/Axis
- Angle
- Center
  - 1 to 2, 2 to 1, and 2 to 2
- Bond → Constrains objects to act as a rigid body
- Distance
- etc

Notes About Constraints

- Use the minimum amount to be able to constrain components
  - Avoid overconstraining your components
  - A big benefit comes when changes have to be made (happens a lot more than you think

- There is a correct order to doing assemblies
  - You'll slowly figure this out as you do more CAD

CAD Demo

Drivetrain CAD

Before Modelling

- Bounding “Box”

Before Modelling

- Bounding "Box"
  - Chassis Tubes
  - Hubs
  - Suspension Points

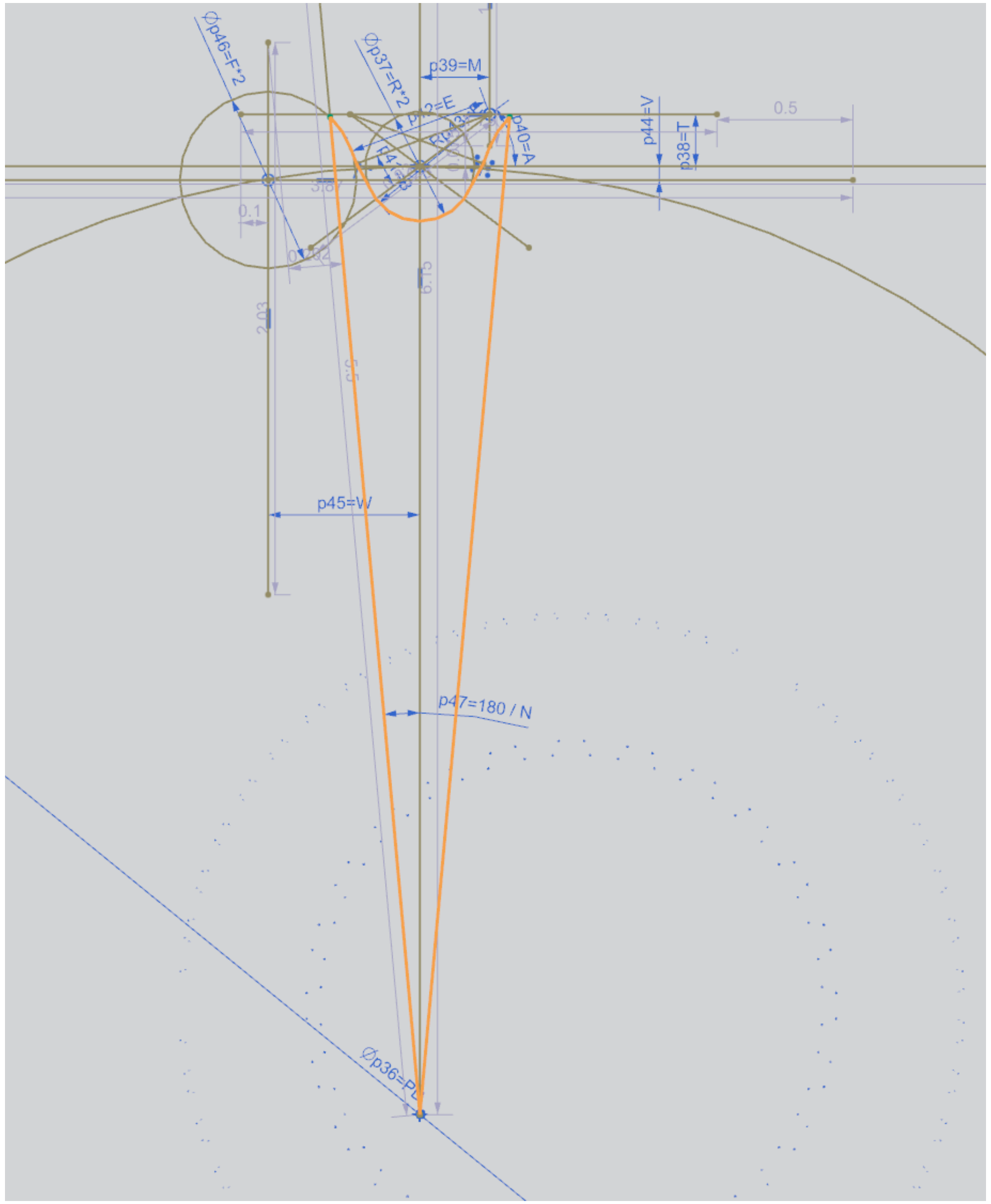
- Made up of datum planes, solid bodies, datum points, etc

- Next: Slides are broken down by component (all assume that the skeleton is set in place)

Sprocket

- Follow this guide:
  - http://www.gearseds.com/files/design_draw_sprocket_5.pdf
  - Until step 15
- Put your parameters in place
  - Think about where to put these (component level or assembly level)

Sprocket



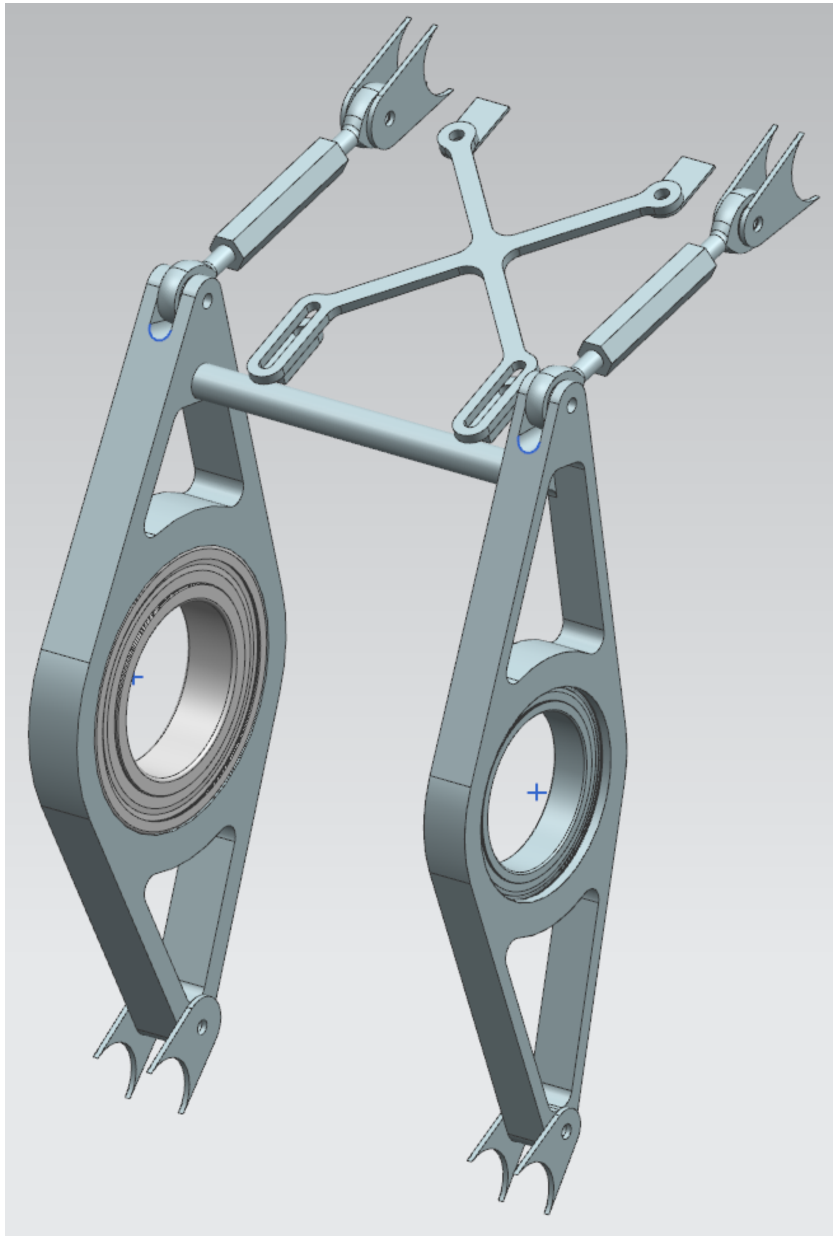
- Make other teeth:
  - Pattern in sketch + extrude
  - Extrude then pattern

Sprocket

- From there, do your cutouts

Differential Carriers

- Bearing Selection
- Functional Requirements:
  - Fix differential with respect to chassis
  - Differential should be allowed to rotate
- 3 Nodes
- Accommodate Bearings

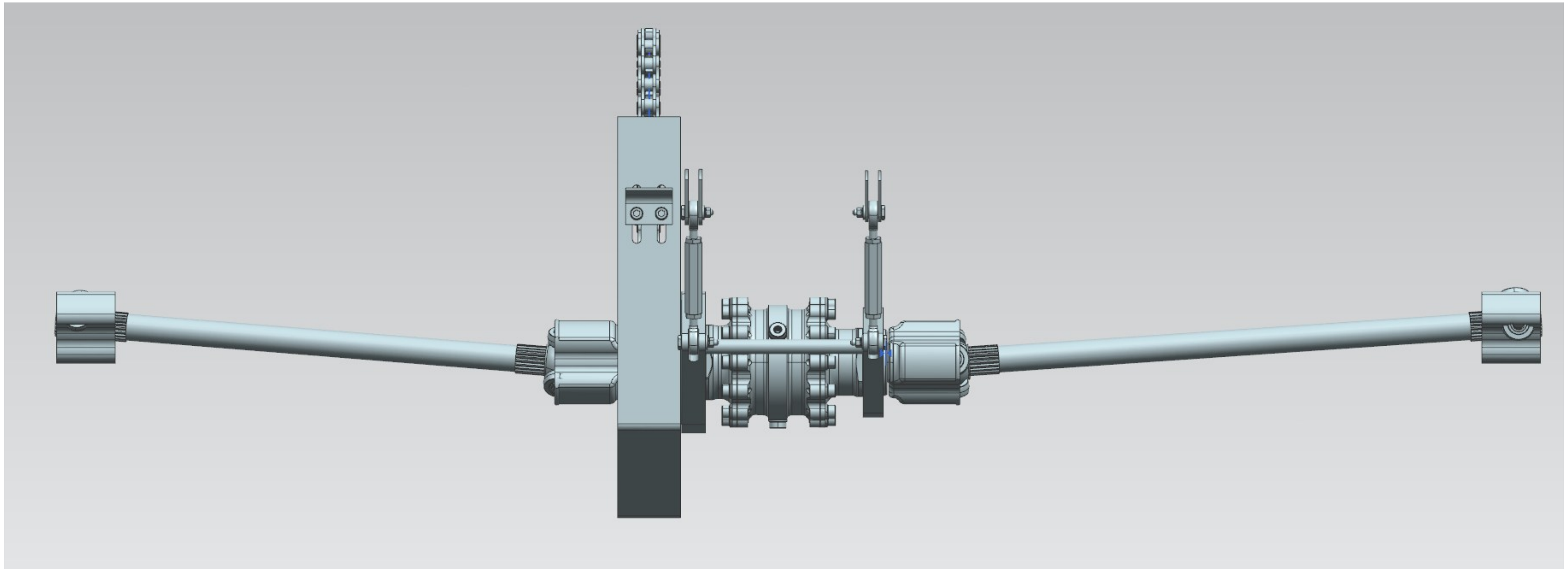


Halfshafts

- Not designed but have to be modelled in CAD
  - Visualize entire assembly
  - Checking for initial halfshaft angles and clearance checks
    - Will change over time due to manufacturing tolerance stackup but not by a significant degree
- How to check for halfshaft angles?
  - Check when wheels are on ground and 1 inch above and below (for suspension travel)
  - Goal is to have enough plunge to allow movement but not restrict car movement
    - Don’t want to destroy the hubs and/or inboard differential housing

Halfshafts

- How to model halfshafts?
  - RCV gives CAD
  - Model as a cylinder and make it steel
  - Place CV’s according to manufacturer specification (reference RCV for this)

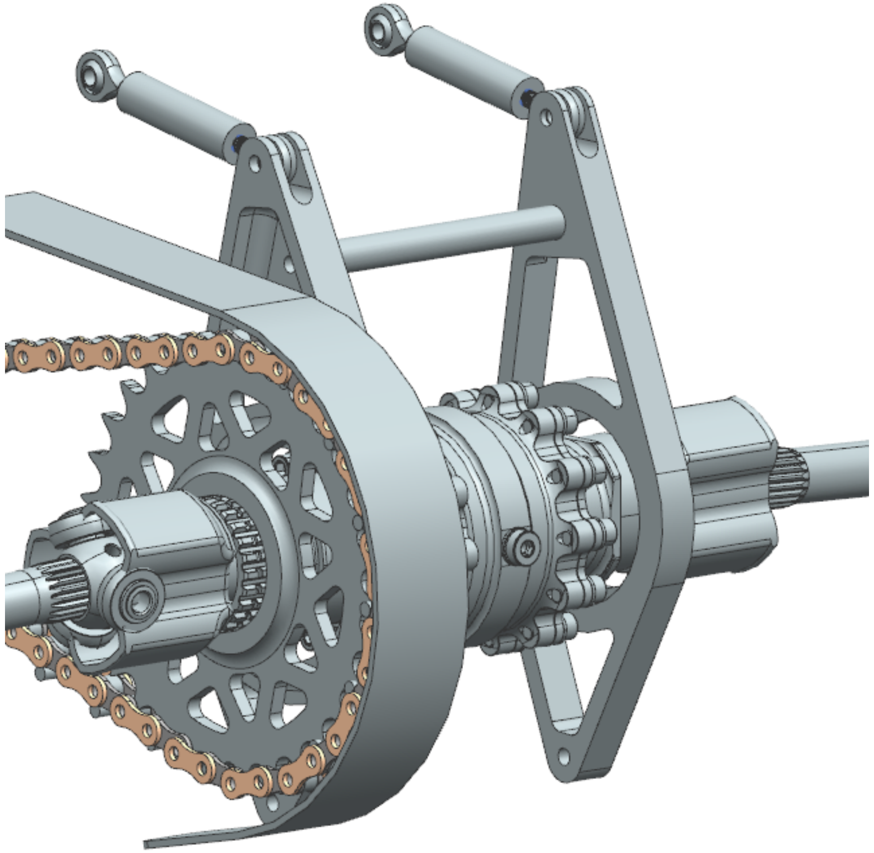


CV's and Boots

- CV CAD also provided by RCV
- Boots
  - Depending on whether custom boot is being used of another one is being acquired, you can model it yourself or get one from online

Differential

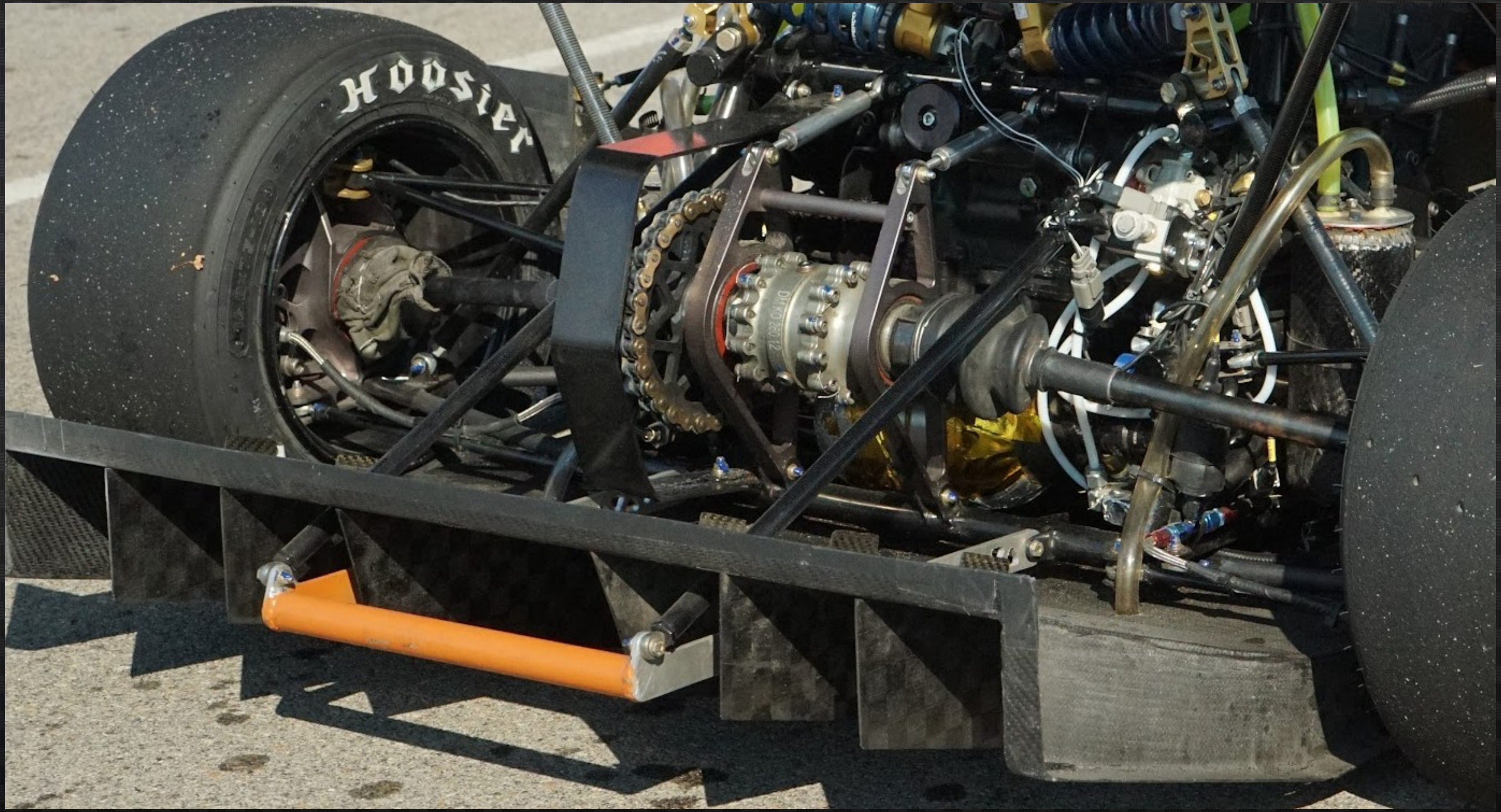
- Not designed put in CAD
- Team Drive has CAD files with differential assembly
  - Components
  - Hardware
  - Mass
  - etc



Miscellaneous Components

- Turnbuckles
- Chain
- Chain Guard
- Stability Bar
- Hardware (including rodends)

Drivetrain Education: Lecture 3



03/03/2025

Quick Notes

Notes

- I will be out of town next week (3/10)
  - No meeting
  - No help hour
- This will be the last time you see me before spring break
- As always, if you have any questions, feel free to reach out to me
- You can message me on Teams if you have questions, but I may be slow to respond over the next week

Projects

Project List (Final)

- Sprocket Design
- Differential Carrier Design
- Titanium Halfshaft Manufacturing Guide
- Misc Projects
  - Remaking calculators
  - CV Insert Study
  - Halfshalft Endcaps
  - Custom Boots

- I am still open to ideas. These documents will be written up next week along with a form to fill out.

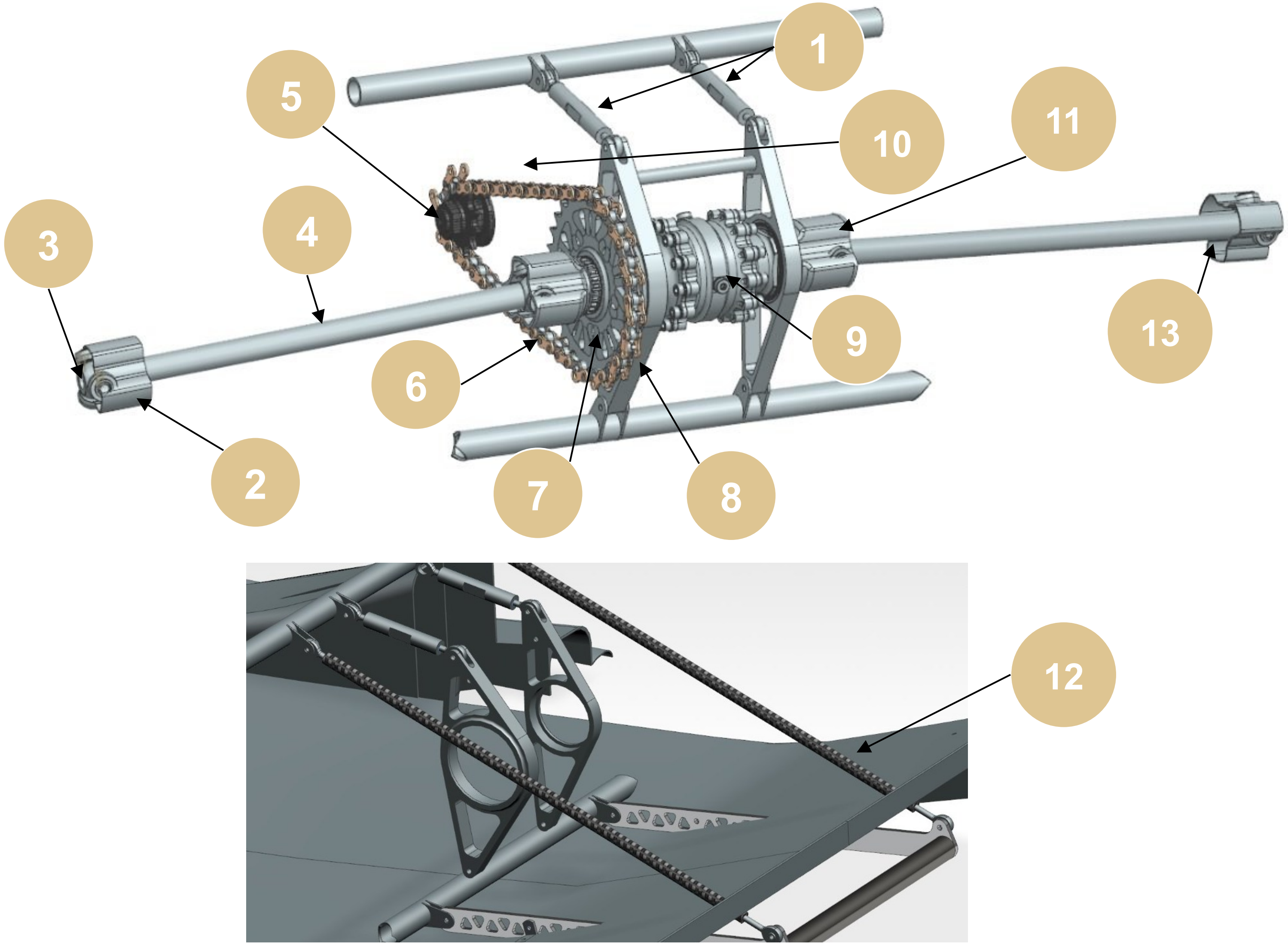
Questions?

- Any questions about what was covered last time?

- Any other questions?

Architecture

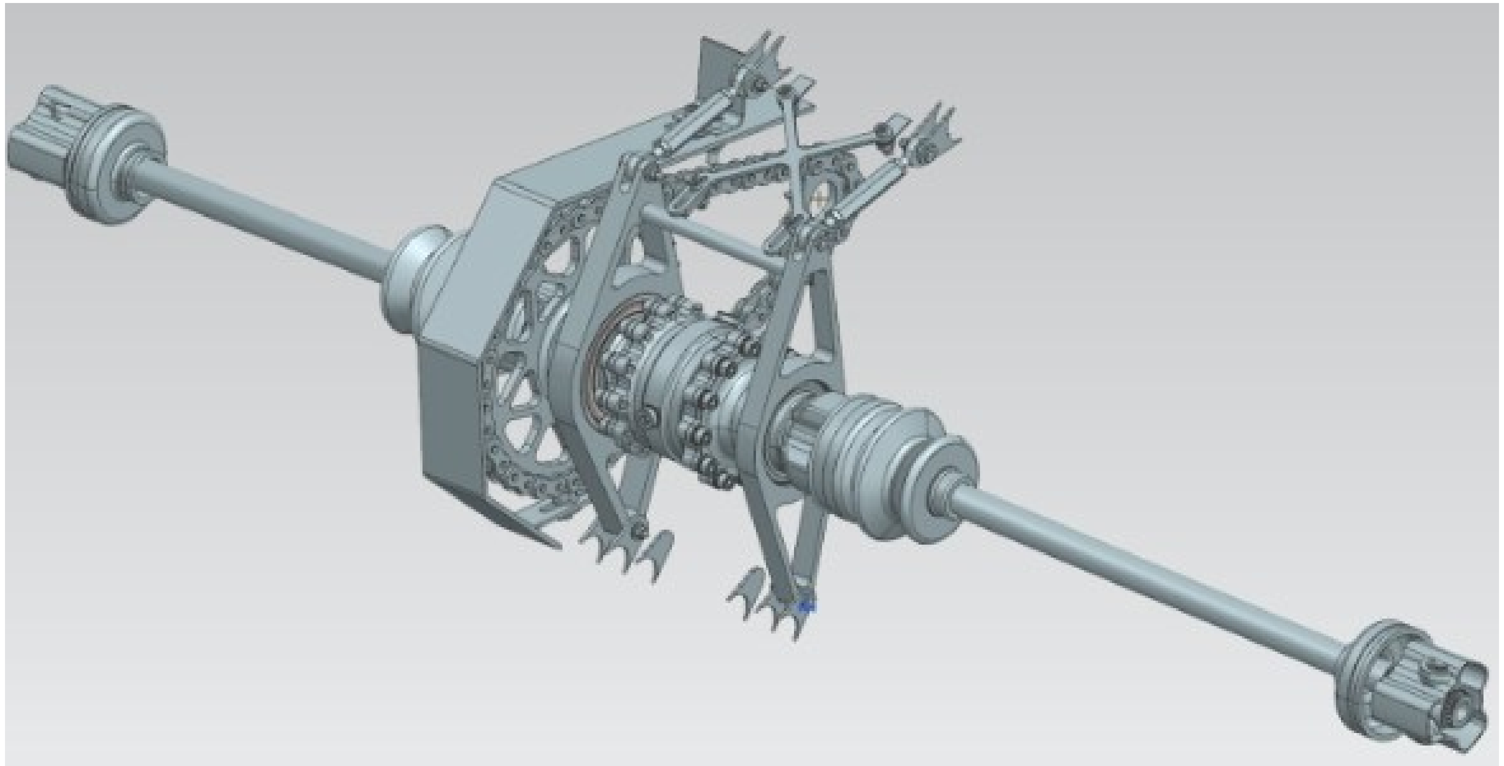
PF24 Drivetrain



1. Turnbuckles
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard (not pictured)
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots (not pictured)

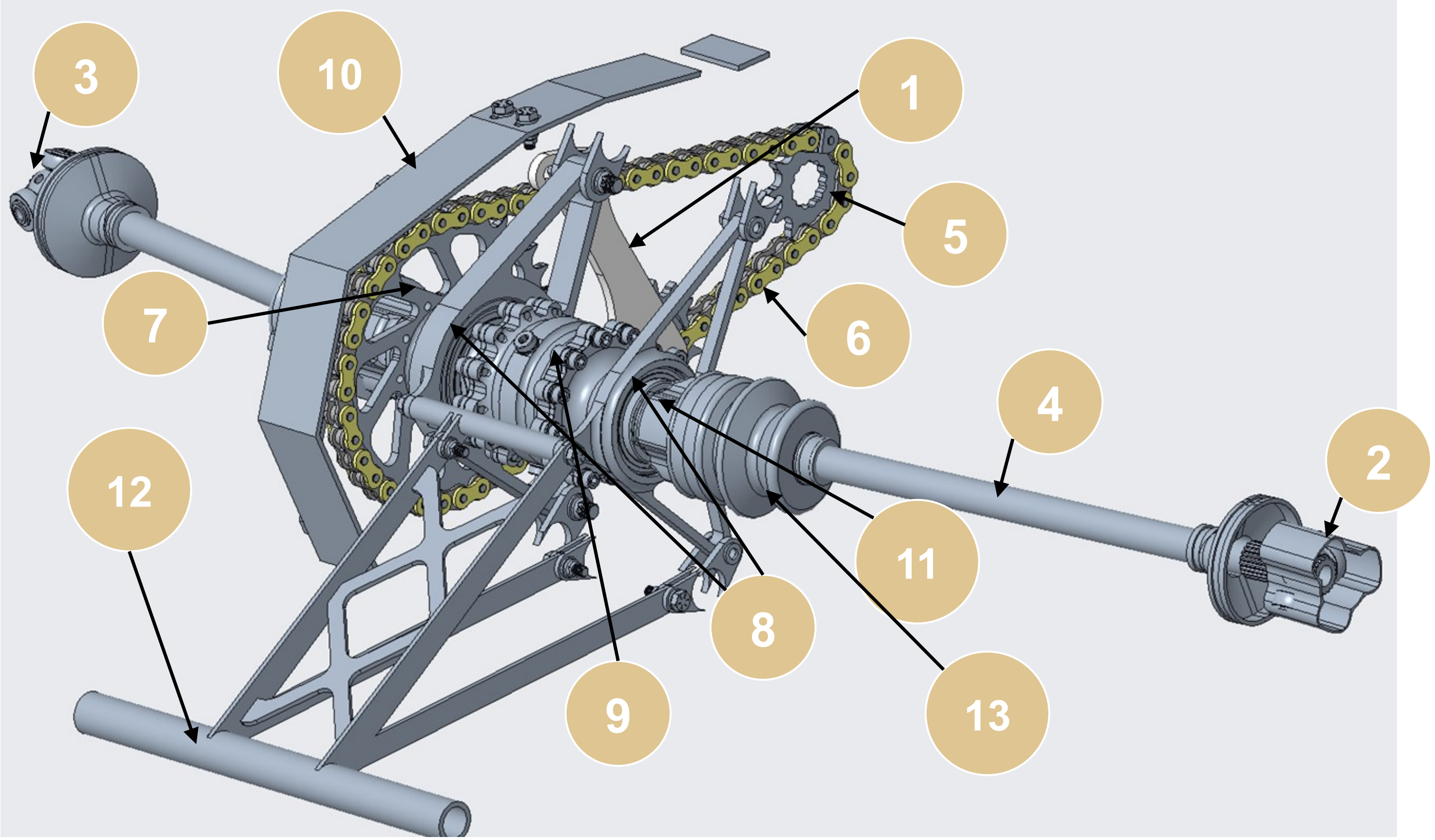
PF20 Drivetrain

- Final Drive = 34/11 = 3.09
- Architecture and philosophy between PF24 and PF20 very similar
  - Similar architecture ran for 5 seasons (PF20-24)
- Differences:
  - Higher FDR compared to PF24
  - Slight design differences



PF19 Drivetrain

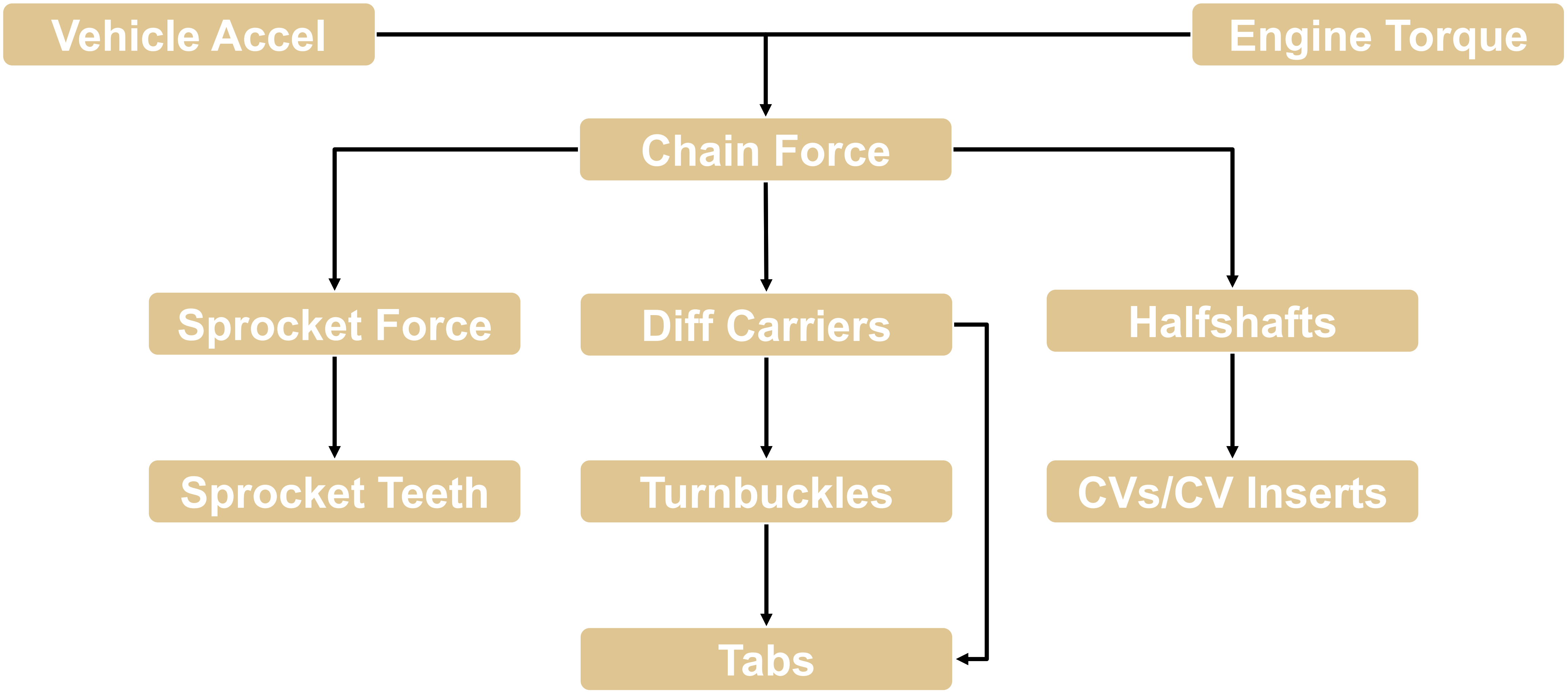
- Final Drive = 34/11 = 3.09



1. Chain Tensioning System
2. CV Inserts
3. CV's (Tripods)
4. Halfshafts
5. Front Sprocket
6. Chain
7. Rear Sprocket
8. Differential Carriers
9. Differential
10. Chain Guard
11. Inboard Tripod Housing (Tulips)
12. Towbar
13. Boots

Loads

Loads Flow Map



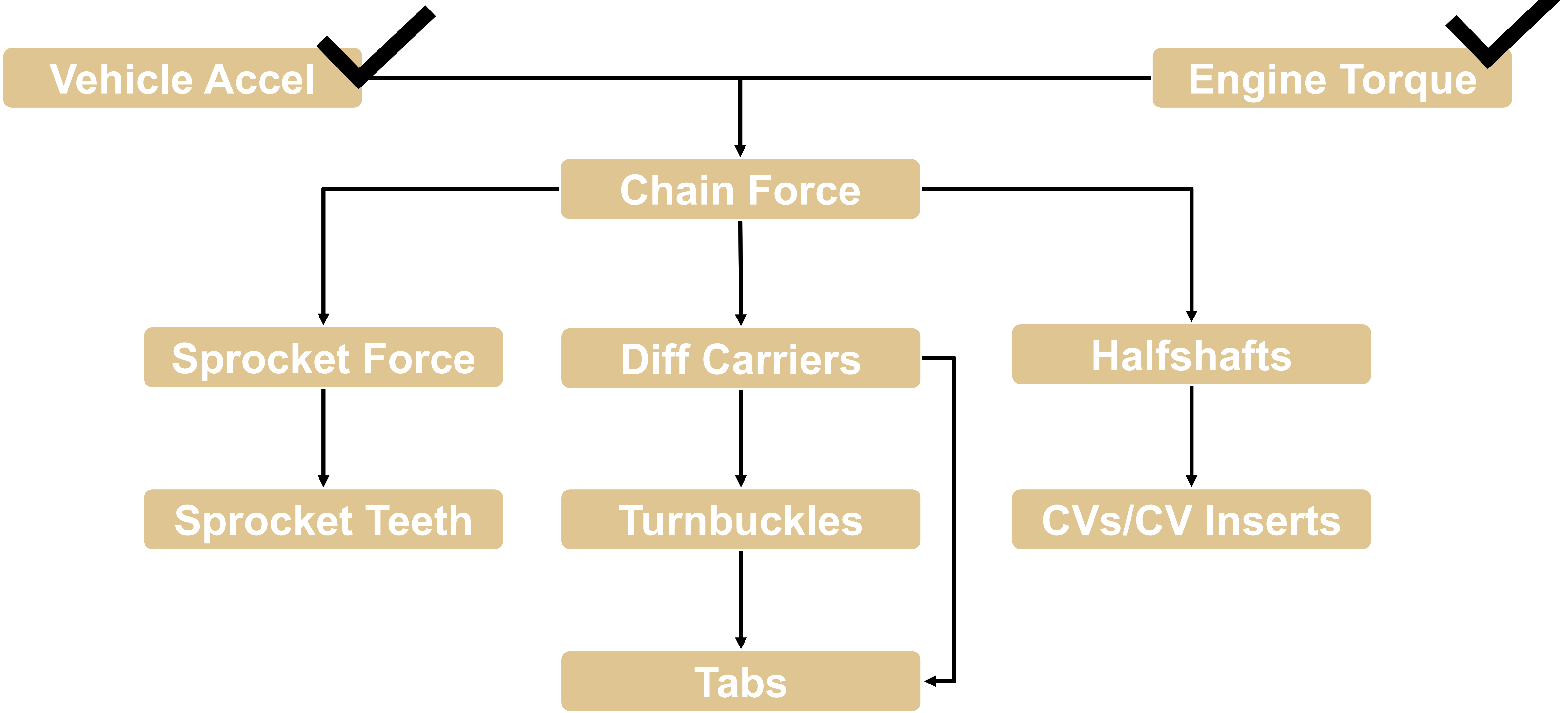
Knowns/Unknowns?

- Knowns:
  - Loads philosophy
- Unknowns:
  - A lot….

Global Inputs

- Vehicle Parameters
  - Vehicle weight, tire diameter, max accel
- Sprocket Parameters
  - Number of teeth, FDR, pitch, etc
- Launch Parameters
  - 1st gear, 2nd gear

Loads Flow Map

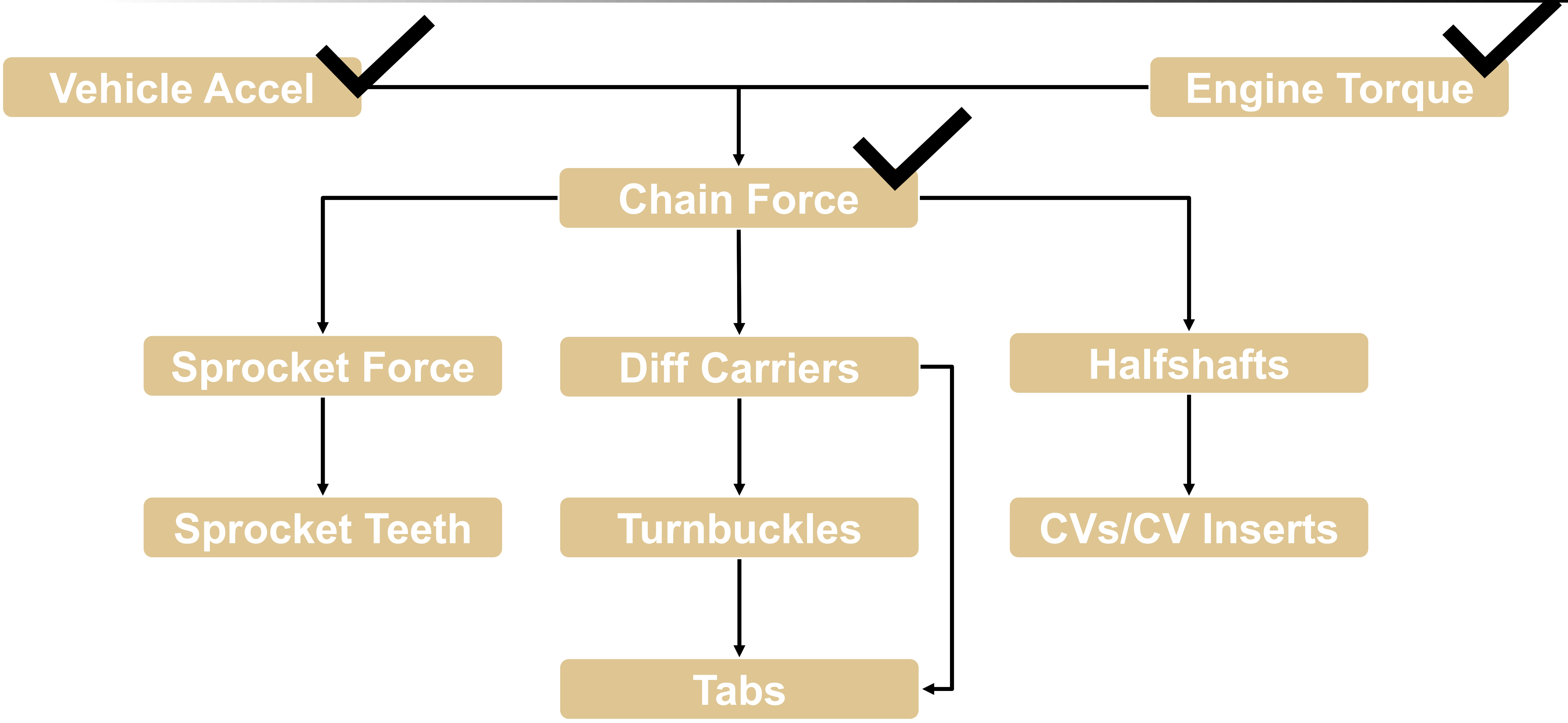


Chain Force

- Three methods to determine chain force
  - Max of these three methods is taken as the load going through chain
    - PF25 → Tire Launch and 2nd Gear Inertia

Chain Load		
Method 1: Tire Launch and Average Inertia		
Tire Launch	703.828125	ft-lbf
Average Inertia	131.7441191	ft-lbf
Chain Load	3246.084167	lbf
Method 2: Tire Launch and 2nd Gear Inertia		
Tire Launch	703.828125	ft-lbf
2nd Gear Inertia	186.3839263	ft-lbf
Chain Load	3458.352363	lbf
Method 3: 1st Gear Inertia + 1st Gear Torque		
1st Gear Inertia	77.104	ft-lbf
1st Gear Torque	760.7935913	ft-lbf
Chain Load	3255.119035	lbf
Max Chain Load	**3458.352363**	**lbf**

Loads Flow Map

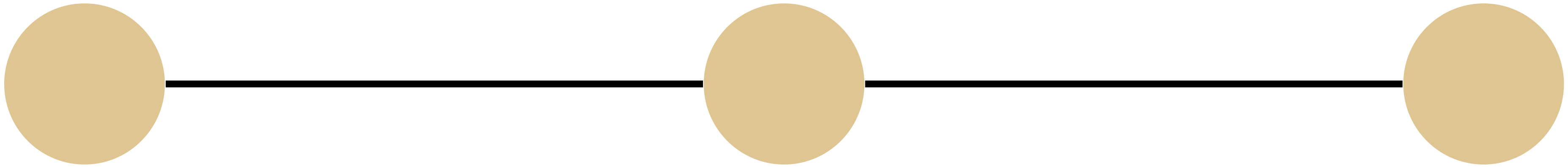


How can we proceed?

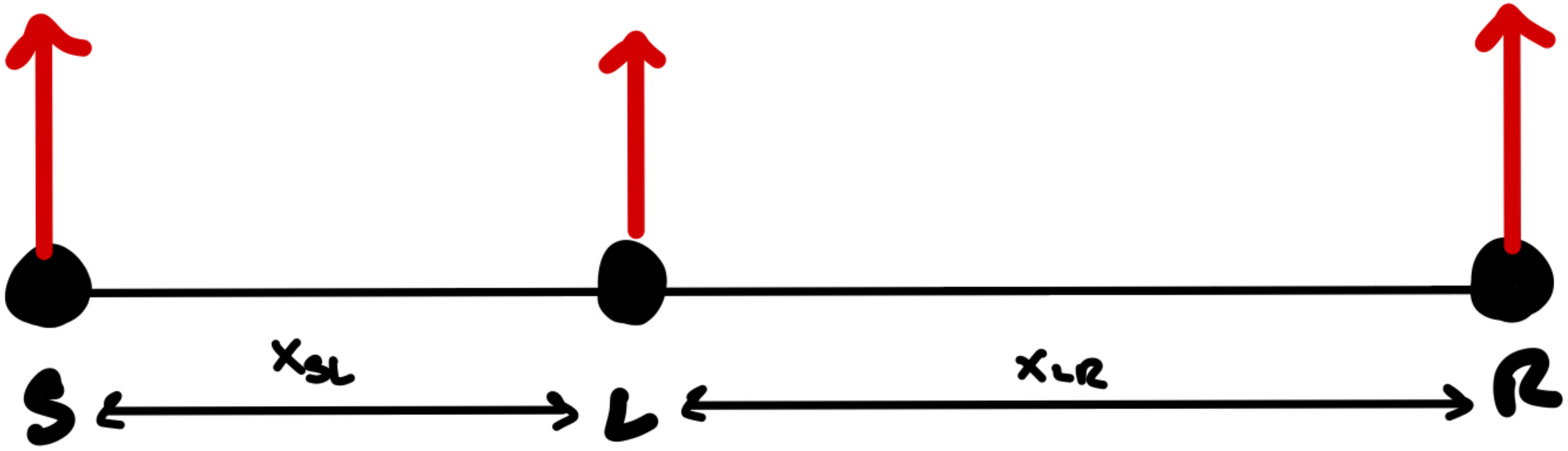
- Thoughts?

- Hint: this is where we have to “model” the system as maybe something else so we can proceed (remember Lecture 1)

Beam Model



Beam Model – Derivation



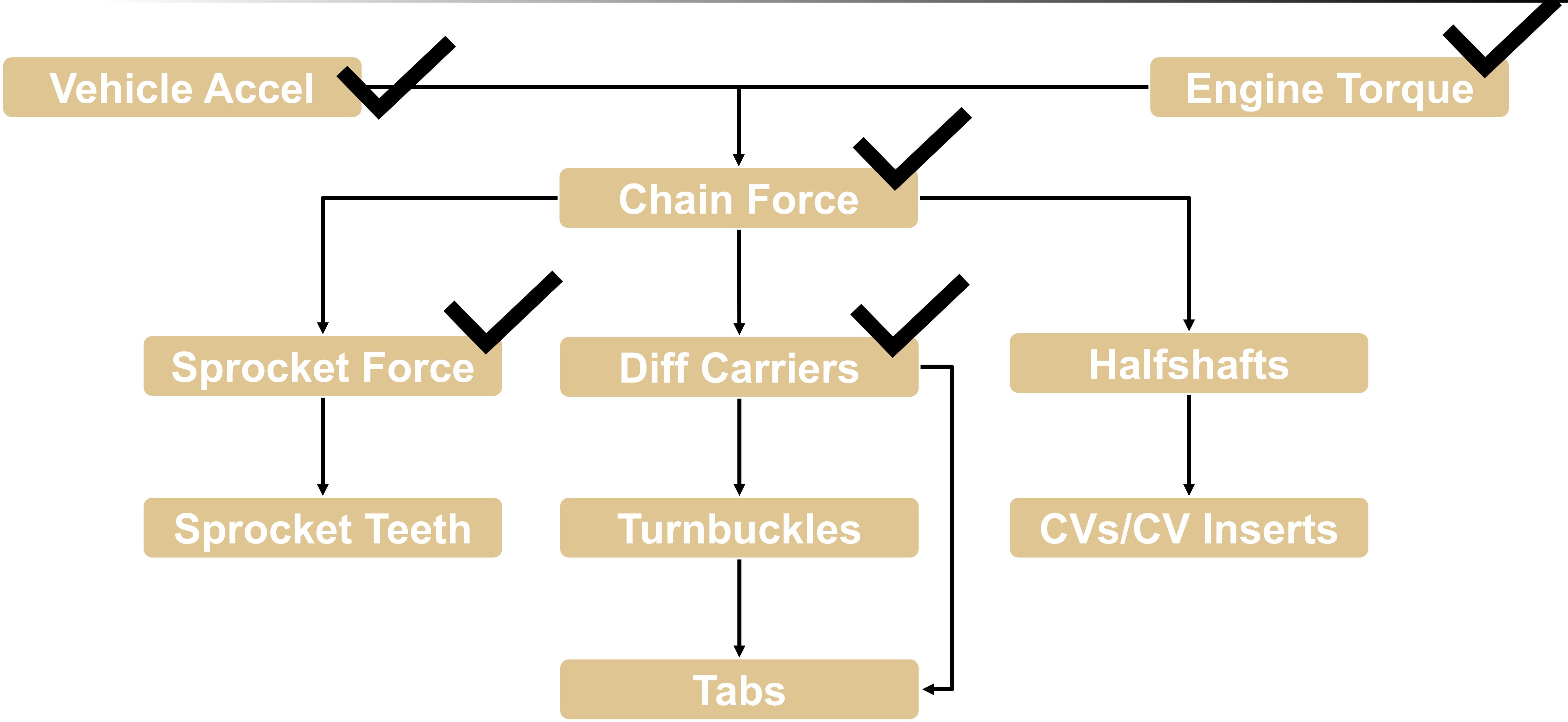
$$\Sigma F = F_S + F_L + F_R = 0$$

$$\Sigma M_L = -F_S x_{LS} + F_R x_{LR} = 0$$

$$F_R = F_S x_{LS} / x_{LR}$$

$$F_L = -F_S - F_R = -F_S - F_S \, x_{LS}/x_{LR} = -F_S (1 + x_{LS}/x_{LR})$$

Loads Flow Map



Sprocket Force

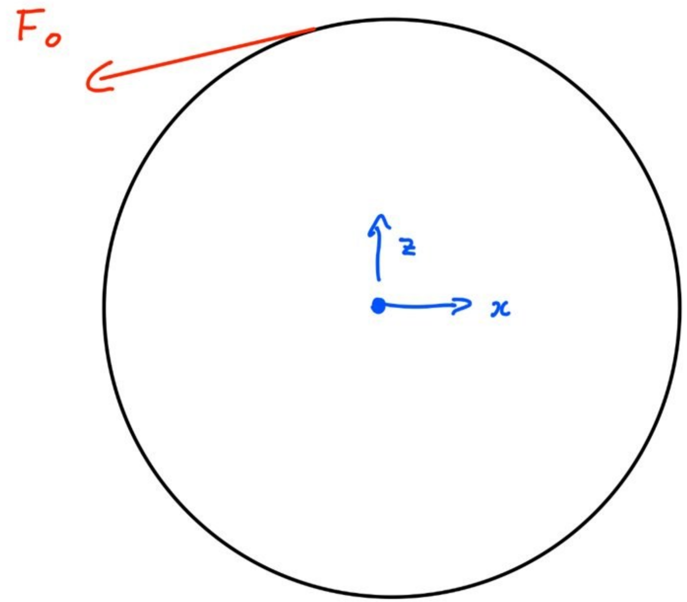
- Using equations (RC Binder Chain Calcs) and the input (chain force) the force on each tooth can be determined.

$$F_n = F_o * (\frac{sin(\phi))}{sin(\phi+\gamma)})^{n-1} * (\frac{sin(\gamma)}{sin\phi+\gamma})$$

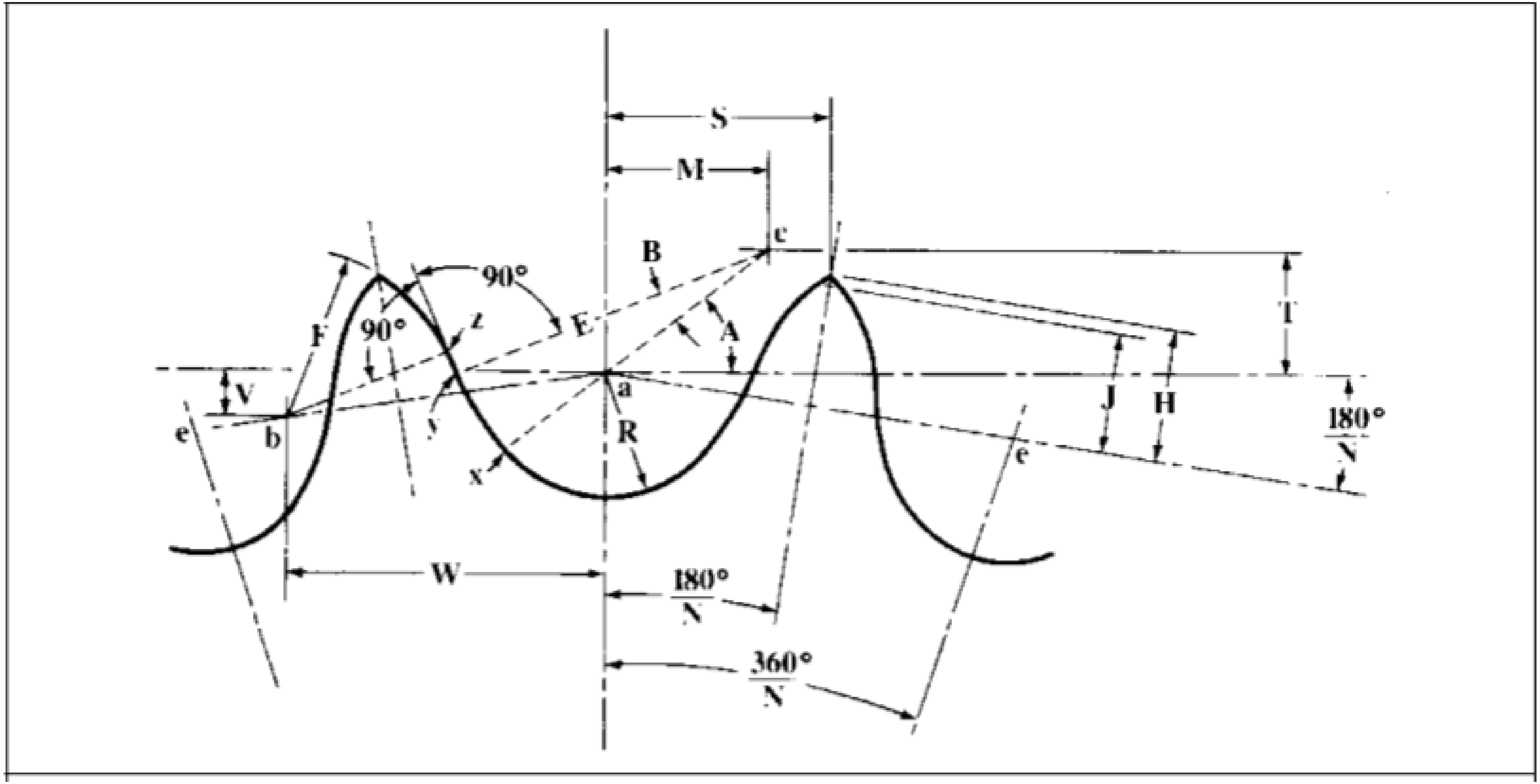
$$Pressure\ Angle\ (deg) : \phi = 35 - \frac{120}{N}$$

$$Articulation\ Angle\ (deg) : \gamma = \frac{360}{N}$$

N : Number of sprocket teeth
n : n_{th} tooth
F_o : Chain tension (lbf)



Sprocket Force



Sprocket Teeth Force

Tooth Table					
Tooth	Force Mag (lbf)	% Force	Pressure Angle	X Force (lbf)	Z Force (lbf)
1	1025.731396	29.65953983	-0.543	-878.0314531	-530.2694268
2	781.3046602	22.59181767	-0.341	-736.4167429	-261.0121698
3	595.1236105	17.20829887	-0.138	-589.4709618	-81.82968238
4	453.3085873	13.10764606	0.065	-452.3587718	29.32945458
5	345.2873852	9.984158609	0.267	-333.0135751	91.24328537
6	263.0071031	7.604982821	0.470	-234.4753459	119.1387781
7	200.3338067	5.792752898	0.673	-156.6774953	124.8430878
8	152.595248	4.412368433	0.875	-97.75688226	117.1703959
9	116.2325525	3.360922783	1.078	-54.97191401	102.4114003
10	88.53490808	2.560031448	1.281	-25.31250012	84.83930273
11	67.43747585	1.949988572	1.484	-5.877563297	67.18085589
12	51.36745773	1.485315906	1.686	5.915520551	51.02570265
13	39.12684573	1.131372446	1.889	12.23742032	37.16390185
14	29.80311124	0.861771969	2.092	14.8288396	25.8520977
15	22.70117672	0.656415956	2.294	15.02789087	17.01487351
16	17.29159819	0.499995269	2.497	13.82139333	10.39078701
17	13.17109557	0.380848861	2.700	11.9055384	5.63346375
18	10.03248841	0.290094454	2.902	9.746653823	2.377722227
19	7.64179587	0.220966376	3.105	7.636679346	0.27959379
20	5.820793578	0.168311177	3.308	5.740694225	-0.962324115

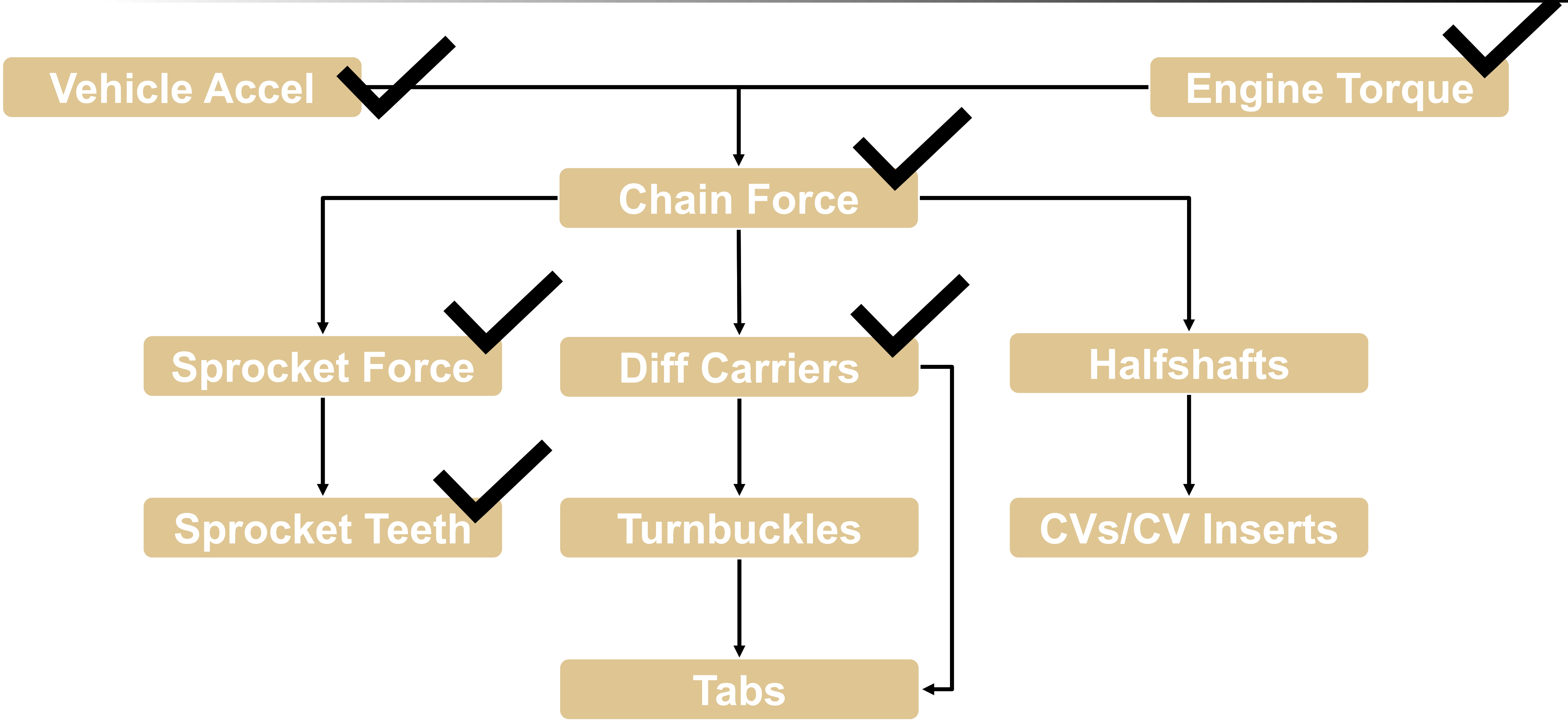
Sprocket Teeth Force

- First 7 teeth put into ANSYS to a significant portion of the loading (defined as a percentage of the max chain load)
- Table below displays error between using first 7 teeth vs all teeth in ANSYS

Rear Sprocket Loading (from Tooth Table)		
Net X Force	-3380.444346	lbf
Net Z Force	-508.5566732	lbf
Net Force from Tooth Table	3418.484147	lbf

Net Force Validation		
Max Chain Load	3458.352363	lbf
Force from Tooth Table	3418.484147	lbf
Error	1.152809521	%

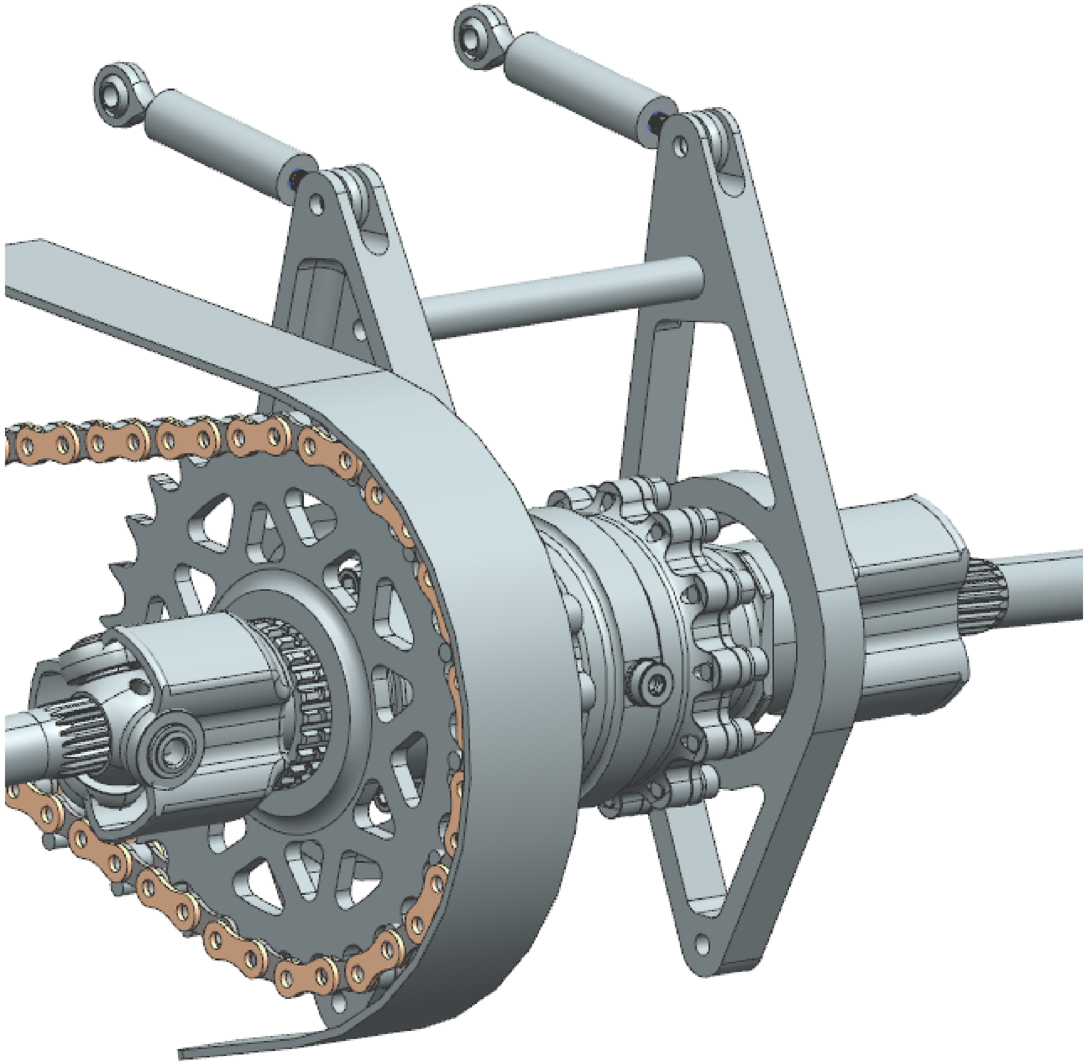
Loads Flow Map



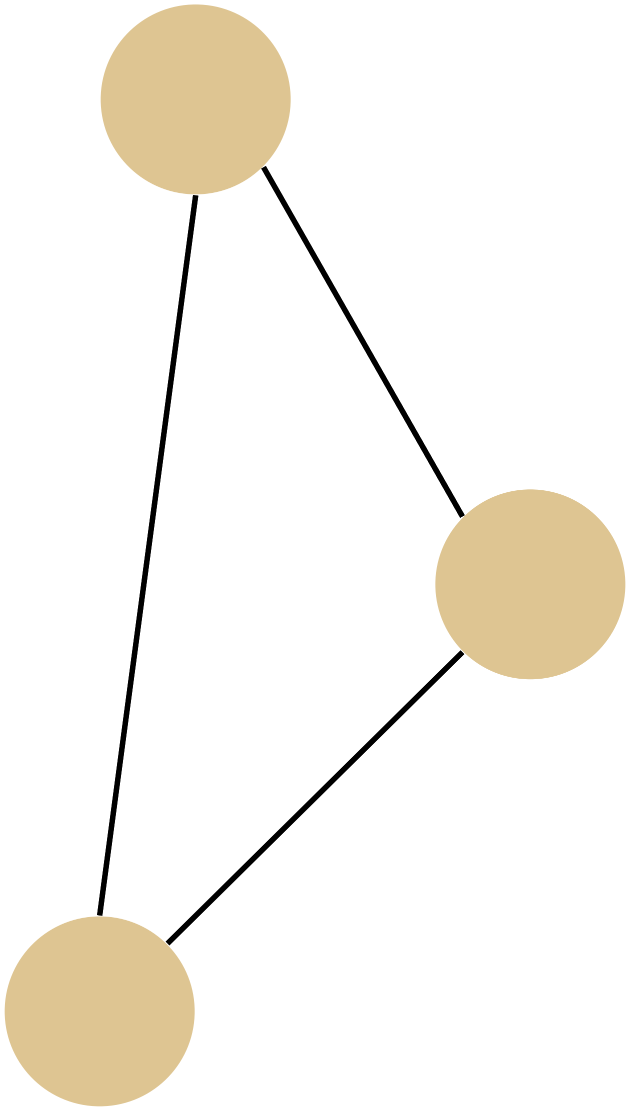
How can we find turnbuckle loads?

- Thoughts?

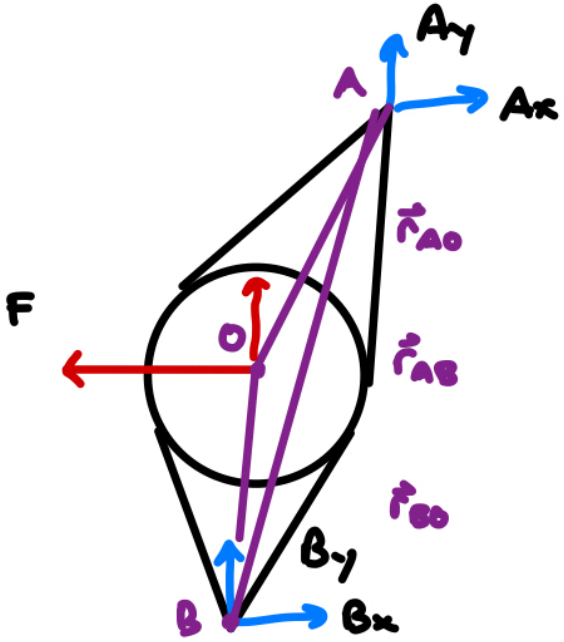
- Knowns:
  - Left Diff Carrier Force
  - Right Diff Carrier Force
- Unknowns:
  - Turnbuckle Force



3 Node Model



3 Node Model – Derivation



$$\Sigma F_x = -F_x + A_x + B_x = 0$$

$$\Sigma F_y = A_y + B_y + F_y = 0$$

$$\Sigma M_B = \vec{r}_{AB} \times \vec{F}_A + \vec{r}_{AO} \times \vec{F}_O = 0$$

$$\vec{r}_{AB} \times \vec{F}_A = [r_{ABx}, r_{ABy}] \times [F_{Ax}, F_{Ay}]$$

$$F_{Ay} \cdot r_{ABx} - F_{Ax} \cdot r_{ABy}$$

$$\vec{r}_{AO} \times F_O = [r_{BOx}, r_{BOy}] \times [F_{Ox}, F_{Oy}]$$

$$-F_{Ox} \cdot r_{BOy} + F_{Oy} \cdot r_{BOx}$$

$$F_{Ay} \cdot r_{ABx} - F_{Ax} \cdot r_{ABy} - F_{Ox} \cdot r_{BOy} + F_{Oy} \cdot r_{BOx} = 0$$

$$F\,(\sin\theta_B\, r_{ABx} - \cos\theta_B\, r_{ABy}) - F_{Ox}\, r_{BOy} + F_{Oy}\, r_{BOx} = 0$$

$$F_B = F_{Ox}\, r_{BOy} - F_{Oy}\, r_{BOx} / (\sin\theta_B\, r_{ABx} - \cos\theta_B\, r_{ABy})$$

$$A_y = -F_y - F_B \sin\theta_B$$

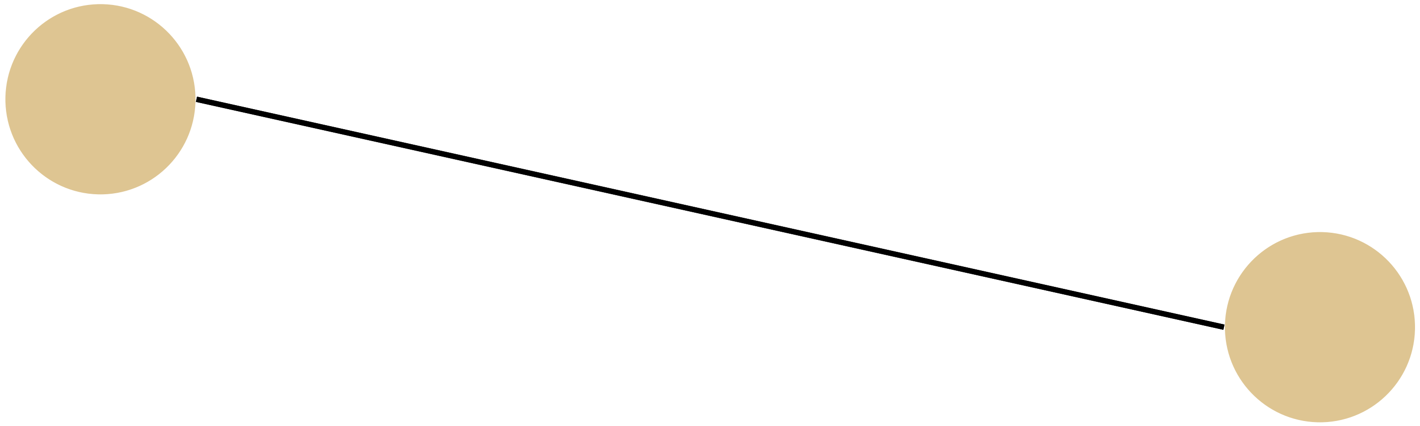
$$A_x = -F_x - F_B \cos\theta_B$$

What is the turnbuckle load?

- Turnbuckle on an angle…..
- How can we move from here?

- Hint: this is where we have to “model” the system as maybe something else so we can proceed

Turnbuckle Node Zoomed In



Differential Carriers Loads

Uprights Load Calculator

Inputs		
Sprocket Force:	3458.35236	
Dist Sprocket to Upleft:	1.32	in
Dist Upleft to Upright:	5.36	in
Upright Force:	851.683791	lbf
Upleft Force:	-4310.0362	lbf
Chain Angle:	9.7011	deg
Turnbuckle Angle:	10	deg

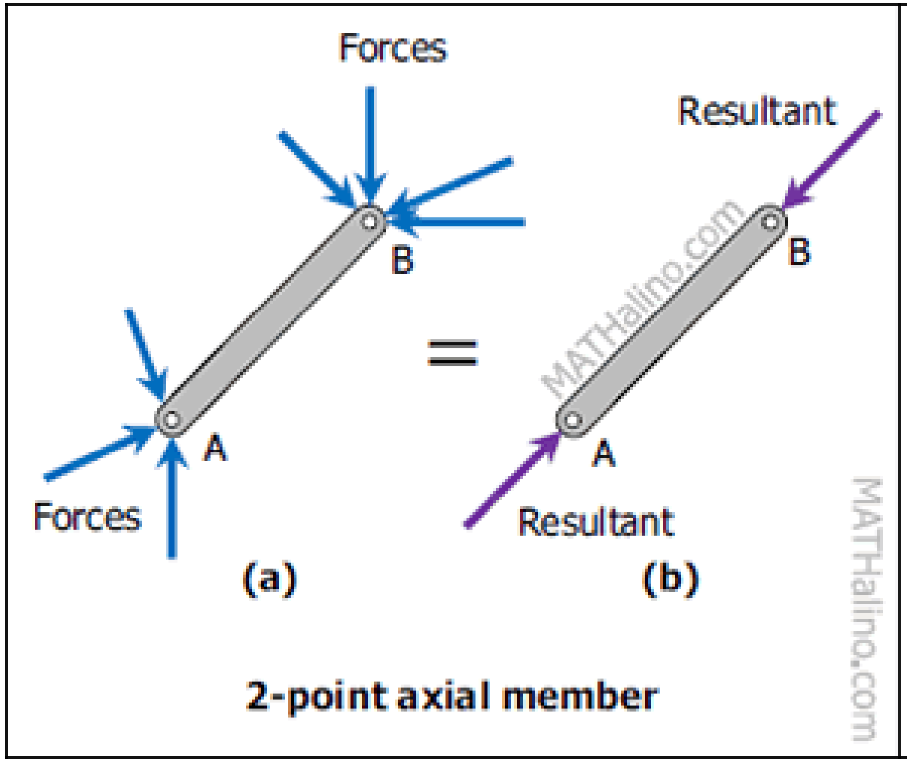
Coordinates		
Node	X	Z
Center	30.9	9.125
Top	30.2742	14.6621
Bot	30.668	5.4892

Upright		
Upright X Force:	-839.50491	lbf
Upright Z Force:	143.515791	lbf
Dist Bot to Center X	-0.232	in
Dist Bot to Center Z	3.6358	in
Dist Bot to Top X	0.3938	in
Dist Bot to Top Z	9.1729	in
Top Node Resultant Force:	331.641921	lbf
Upright Top Node X:	326.603535	lbf
Upright Top Node Z:	57.5890153	lbf
Upright Bottom Node X:	512.901377	lbf
Upright Bottom Node Z:	-201.10481	lbf

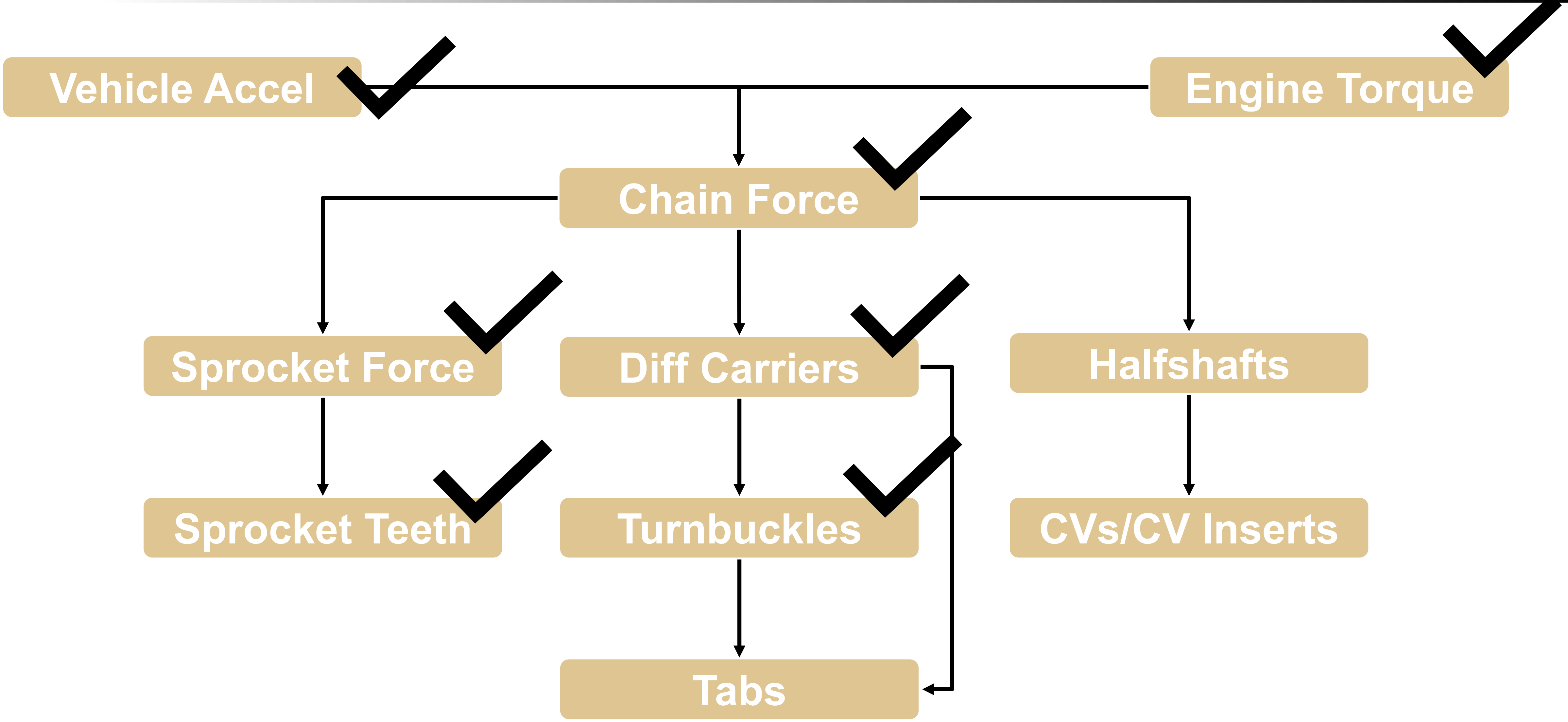
Upleft		
Upright X Force:	4248.40365	lbf
Upright Z Force:	-726.27688	lbf
Dist Bot to Center X	-0.232	in
Dist Bot to Center Z	3.6358	in
Dist Bot to Top X	0.3938	in
Dist Bot to Top Z	9.1729	in
Top Node Resultant Force:	1704.13569	lbf
Upright Top Node X:	1678.24604	lbf
Upright Top Node Z:	295.920056	lbf
Upright Bottom Node X:	-5926.6497	lbf
Upright Bottom Node Z:	430.356825	lbf

Turnbuckles

- Two force member
  - Forces on the turnbuckles are the components of the reaction forces from the differential carriers calculator.



Loads Flow Map

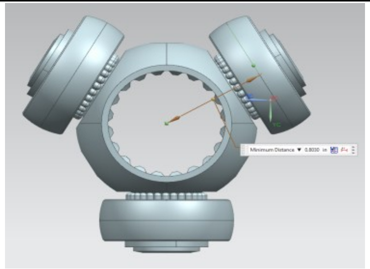


Analysis – CV Insert Force

- Two Methods:
  - Vehicle Weight
  - Engine Torque

- Assume that 2/3 rollers are in contact at launch

CV Insert Loads



Global Inputs		
Vehicle Weight	650	lbm
Max Proj Accel	1.65	G
Tire Diameter	15.75	in
Launch Torque	55	ft-lbs
CV Roller Radial Distance	0.803	in

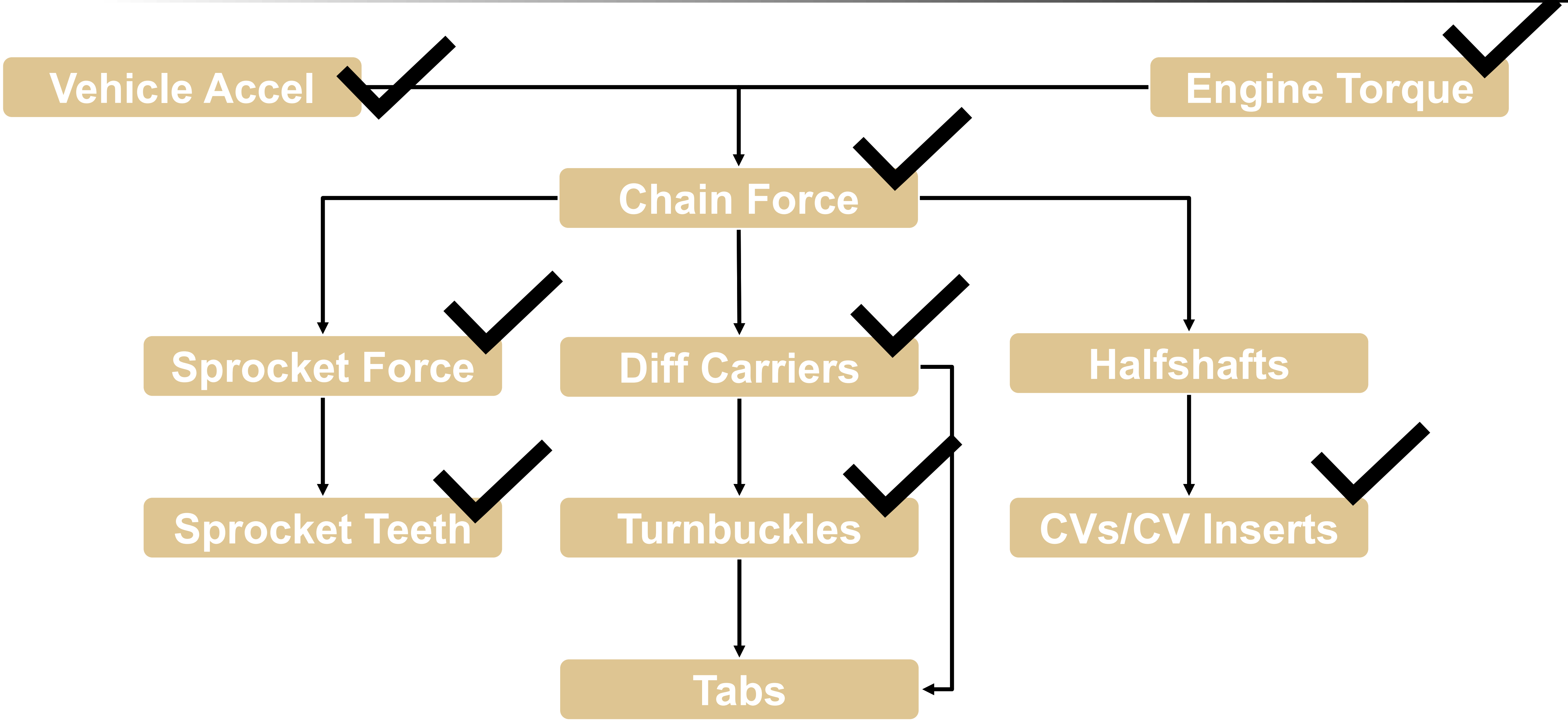
Engine Gearing Parameters		
Primary	2.073	out:in
1	2.583	out:in
2	2	out:in
3	1.667	out:in
4	1.444	out:in
5	1.286	out:in
6	1.15	out:in
Final Drive	2.5833333	out:in

Differential Parameters	
Ramp Angle (deg)	Lock up %
30	88
40	60
45	51
50	42
60	29
From Drexler manual	

Vehicle Weight Method		
Vehicle Acceleration Force	1072.5	lbf
Rear Axle Total Torque	8445.9375	in-lbs
Acceleration Ramp Angle	45	deg
Associated Accel Bias Case	51	%
Maximum Single Wheel Torque	4307.4281	in-lbs
Radial Roller Bearing Force	2682.0848	lbf

Engine Torque Method		
Chosen Launch Gear	1	-
Adjusted Engine Torque	760.793591	ft-lbs
Acceleration Ramp Angle	45	deg
Associated Accel Bias Case	51	%
Maximum Single Wheel Torque	4656.05678	in-lbs
Radial Roller Bearing Force	2899.16362	lbf

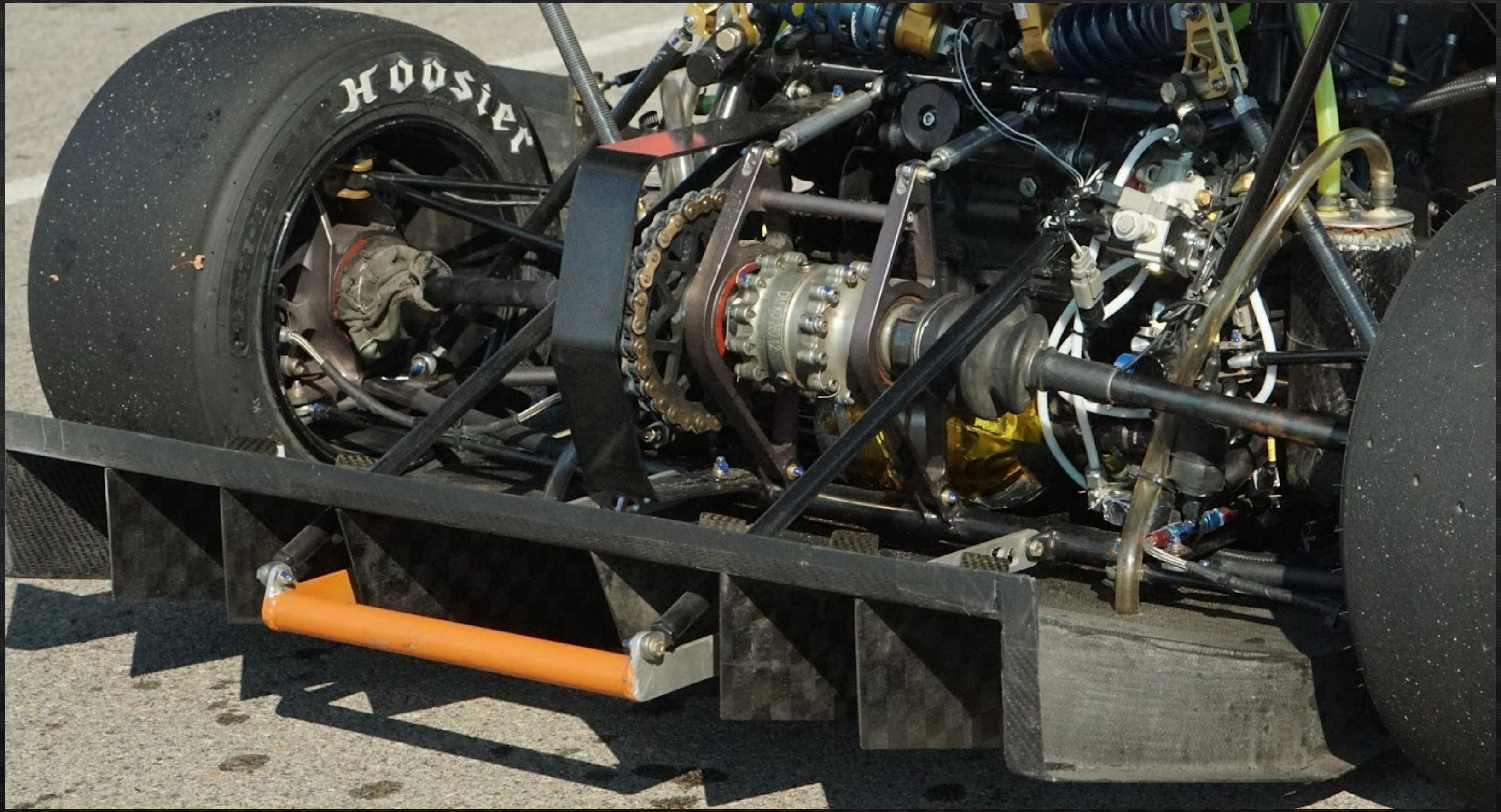
Loads Flow Map



Recap of Steps

- Global Inputs
- Chain Force
- Beam Model
  - Sprocket
  - Left Differential Carrier
  - Right Differential Carrier
- 3 Node Model
- Turnbuckles
- CV Inserts

Drivetrain Education: Lecture 4



04/07/2025

Quick Notes

Notes

- Project assignments are out, talk to me if you have any other questions.
- For those of you doing multiple projects, you are free to drop one if you need to reduce your workload.
- Anyone assigned to multiple projects, see me after or send me a Teams messages.
    - I just want to know if you indicated more than one as options to choose from or you want to do both simultaneously.

Calculators

- I am providing you with calculators to use for this project

- I will walk through these now
  - Message for those who see this after the live lecture: Send me a message if you are confused about any aspect of the calculators. I will be happy to demo these again.

Introduction to Material Testing

What is Material Testing?

- Process of evaluating material properties under various conditions

- Relevant across many industries:
  - Construction
  - Automotive
  - Aerospace
  - Manufacturing
  - etc…

Why Test Materials?

- Any thoughts?

Why Test Materials?

- Safety and Reliability
- Regulatory Compliance
- Quality Control in Manufacturing
- Prevent critical failure in critical applications

Basics of Material Behavior

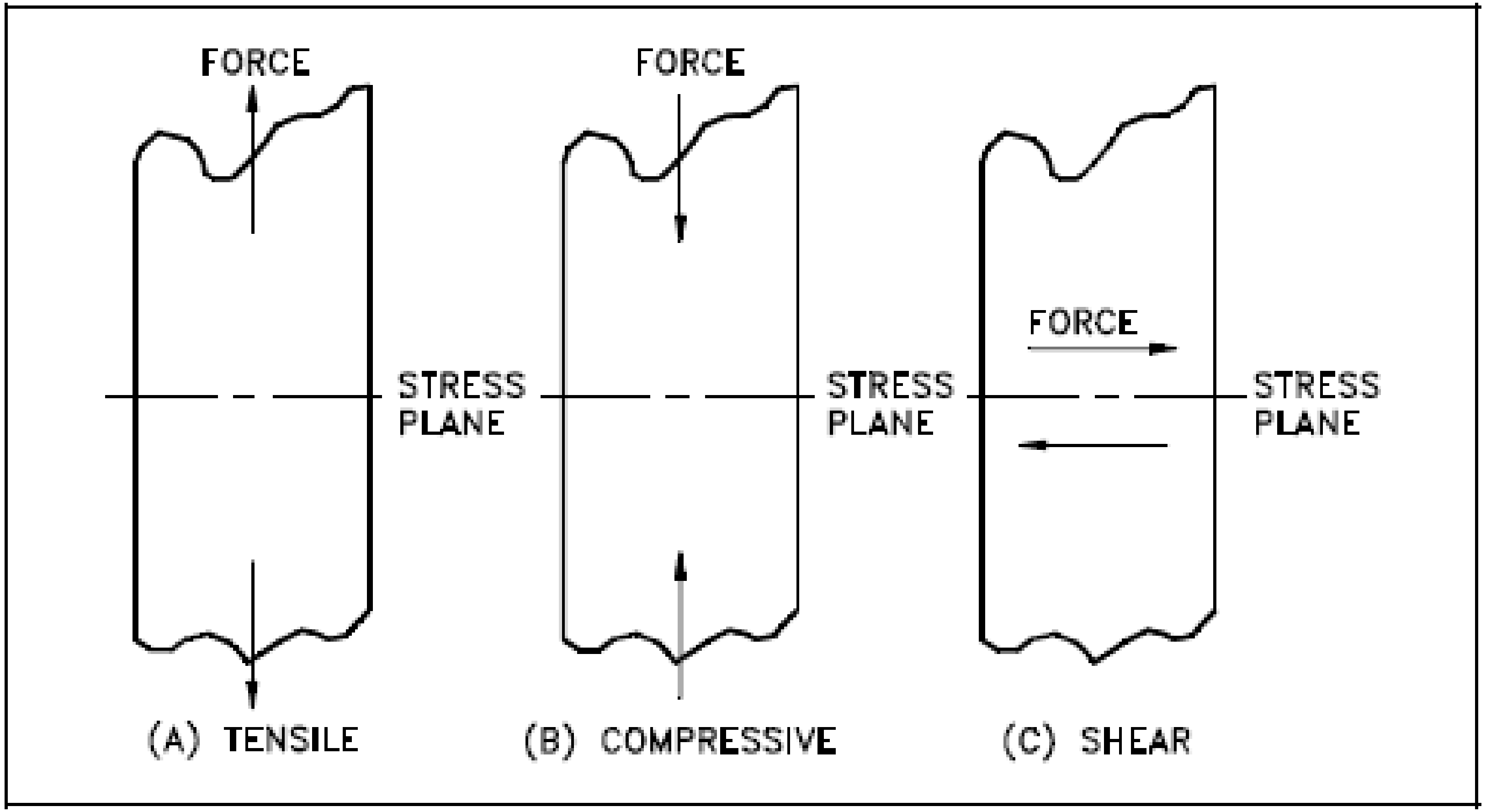
Stress and Strain

- Stress refers to force per unit area ($\sigma = F/A$)
  - Pretty useless to just provide force values when reporting operating environment of a part or system
  - Stress provides more context

- Strain refers to deformation per unit length ($\varepsilon = \Delta L/L_0$)
  - Raw displacement values are also useless without knowing original length
    - Provides insight into deformation with respect to the original length; standardizes it so it can be quantified for a variety of parts

Types of Applied Stress

- Forces can be applied in the following manners:
  - Tensile
  - Compressive
  - Shear



Types of Stresses

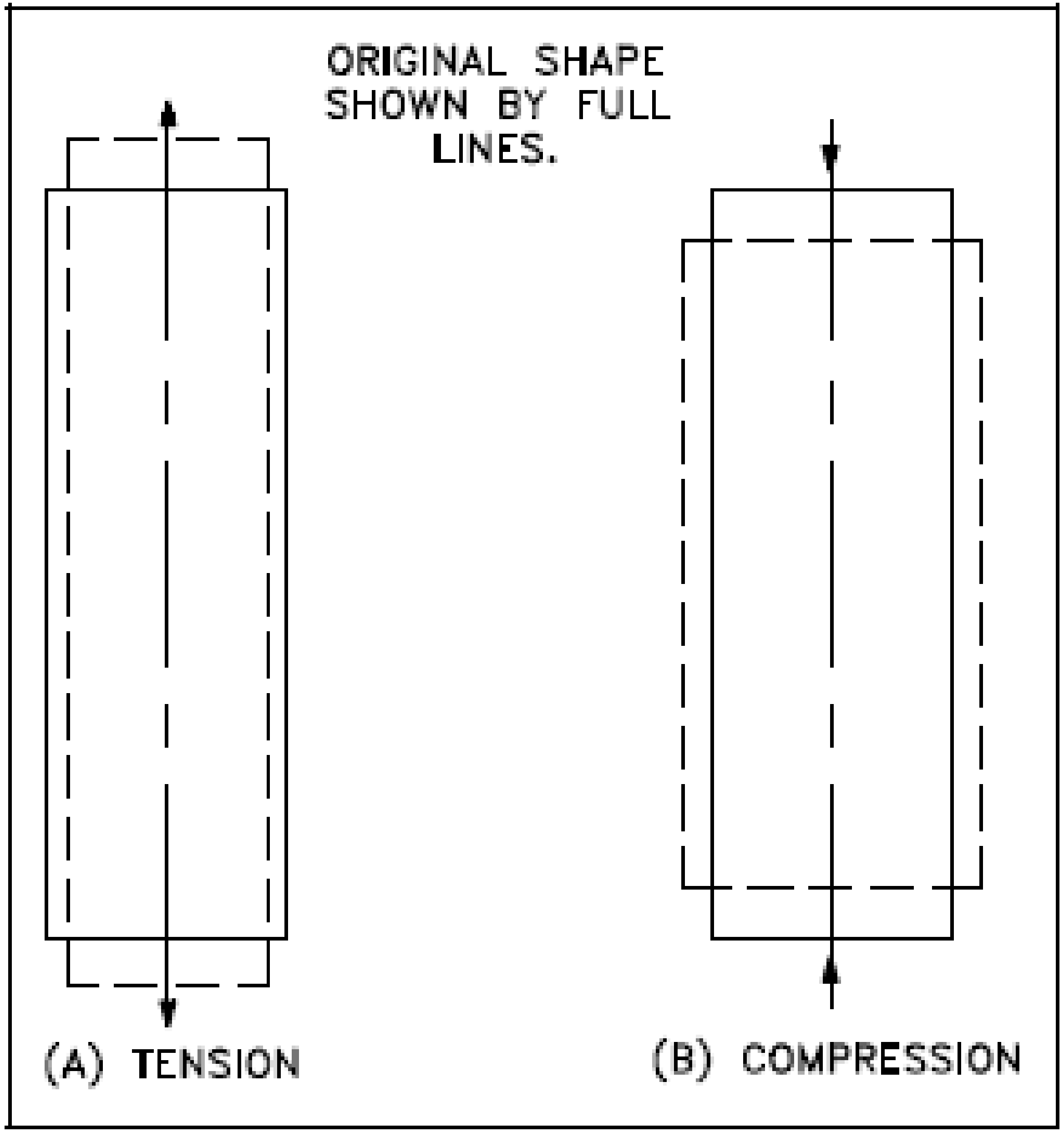
- Normal Stresses
- Principal Stresses
- Von Mises Stresses
- Shear Stresses
- Residual Stresses
- Thermal Stresses
- Fatigue Stresses

- and more….

Types of Strain

- Elastic Strain
  - Dimensional change is reversible
- Plastic Deformation
  - Dimensional change is irreversible

Deformation of Cubic Structures



Hooke's Law

- Valid for the elastic deformation region of a material
- Notes about the experimental data:
  - Strain is proportional to stress
  - Elongation is directly proportional to tensile force and length of bar
  - Elongation is inversely proportional to the cross-sectional area and modulus of elasticity

$$\delta = \frac{PL}{AE}$$

Young's Modulus (E)

- Ratio of unit stress to unit strain
- Quick Derivation:

$$\sigma = \frac{P}{A} \qquad \varepsilon = \frac{\delta}{L}$$

$$\varepsilon = \frac{\sigma}{E}$$

Tensile Testing

Video

Click here

Stress Strain Curve

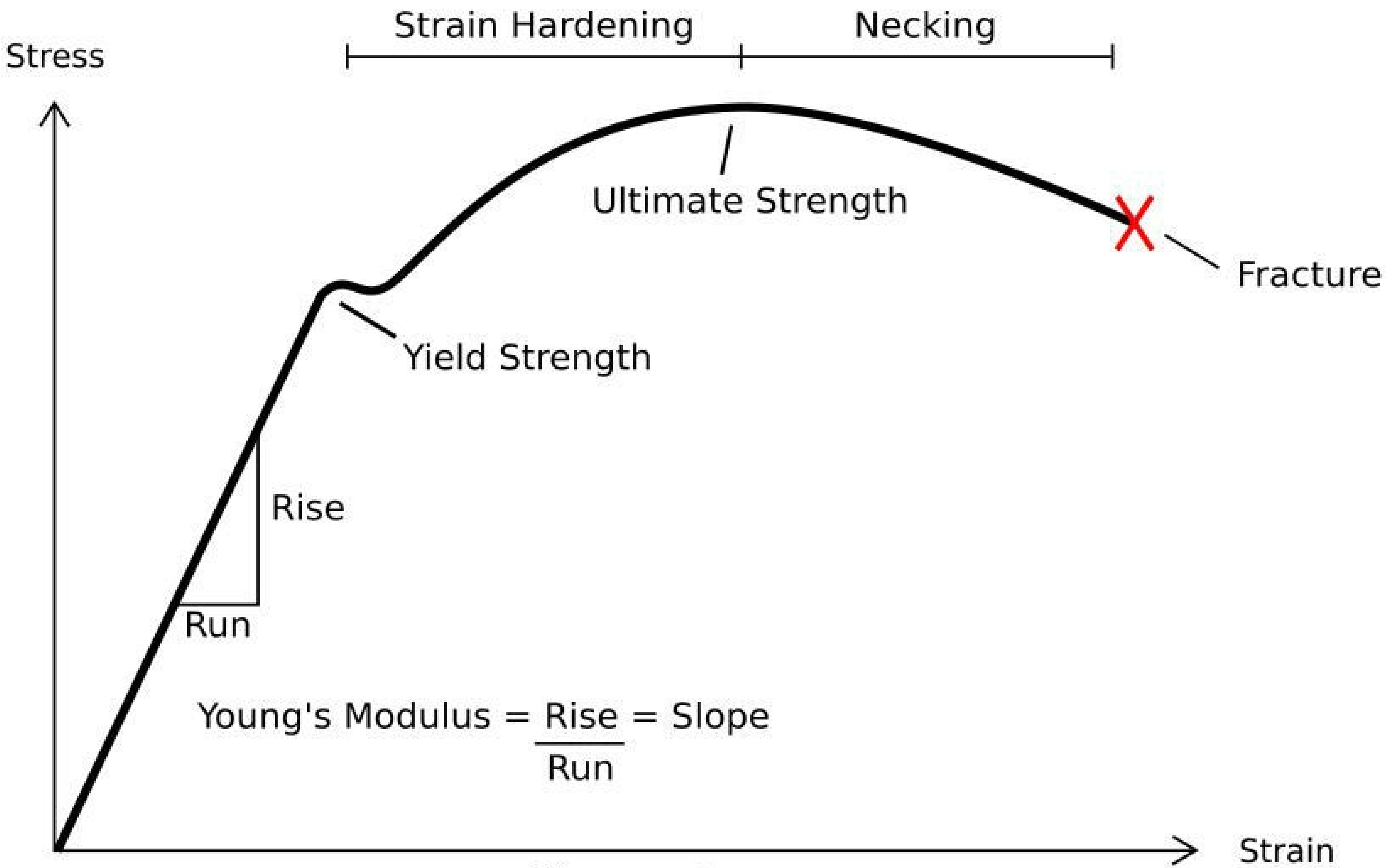
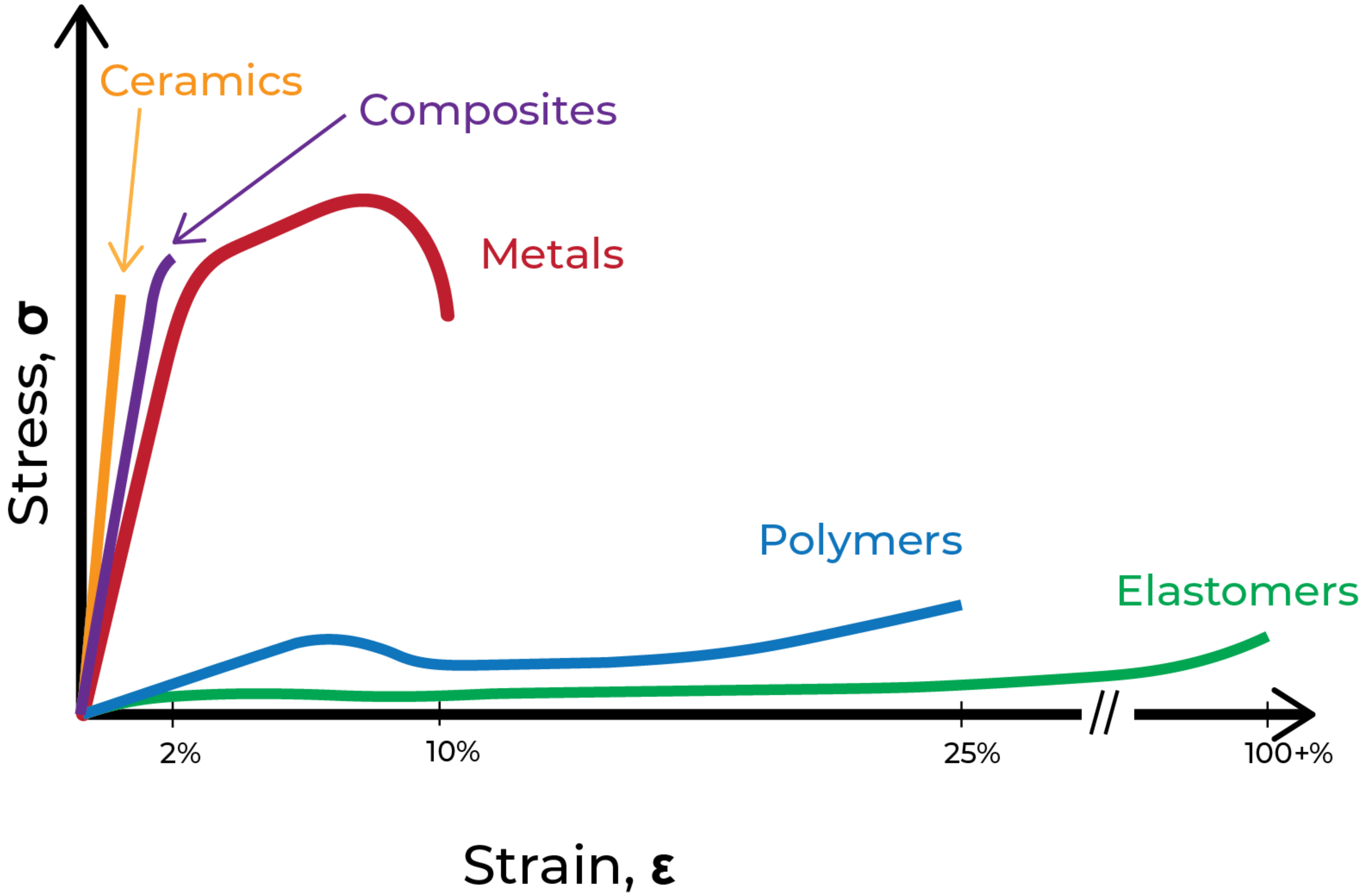


Figure 9

What can you get from the curve?

- Yield Strength
- Ultimate Tensile Strength
- Fracture Point
- Toughness
  - Describes the way a material reacts until sudden impacts
  - Area under the stress-strain curve

Stress Strain Curve



Other properties

- Lots of properties that you can get from metals, but are not present in tensile testing; examples below:
  - Hardness
  - Fatigue
  - Fracture Toughness
  - etc…

Overview of Testing Categories

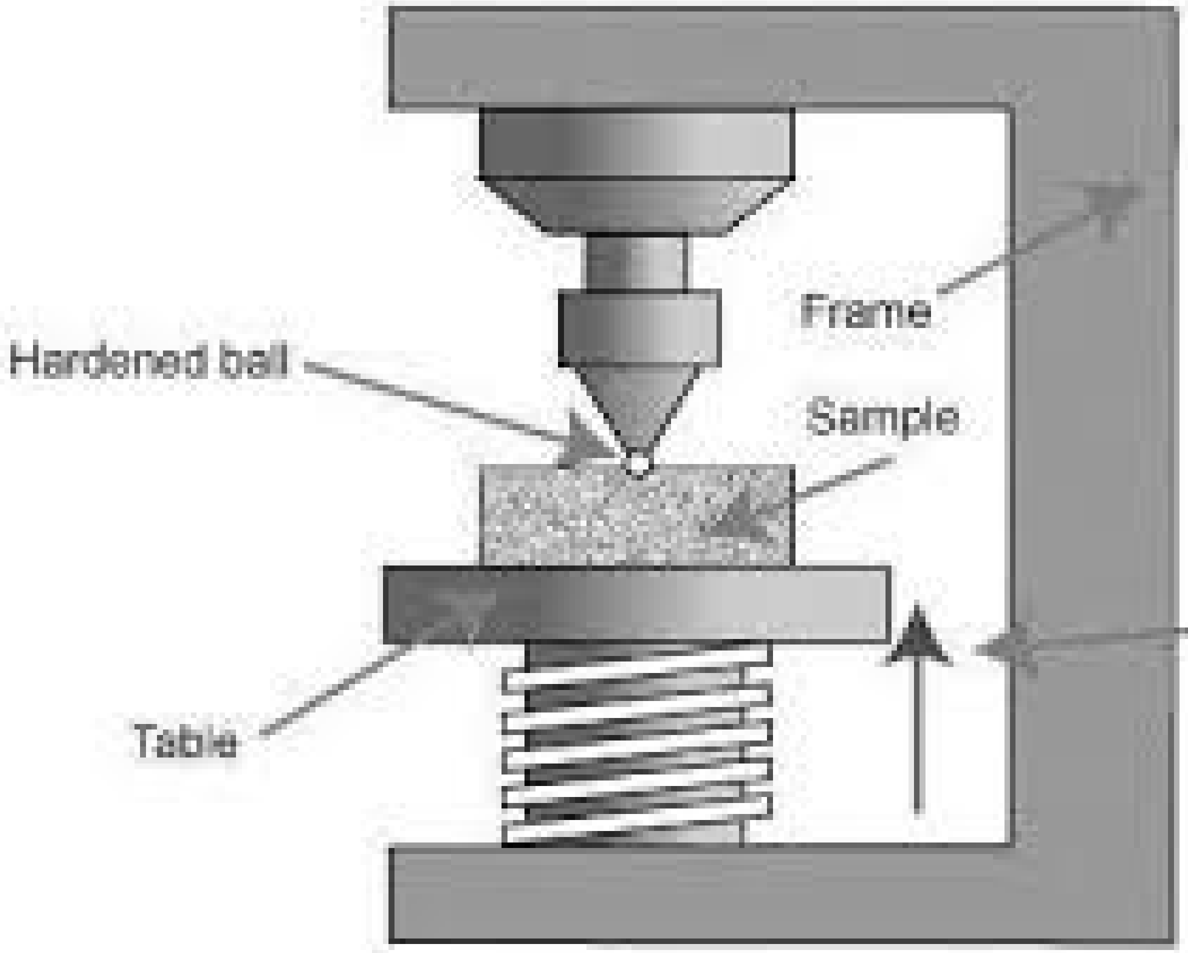
Overview of Testing Categories

- Destructive Testing
- Non-Destructive Testing
- Chemical Analysis

Common Destructive Tests

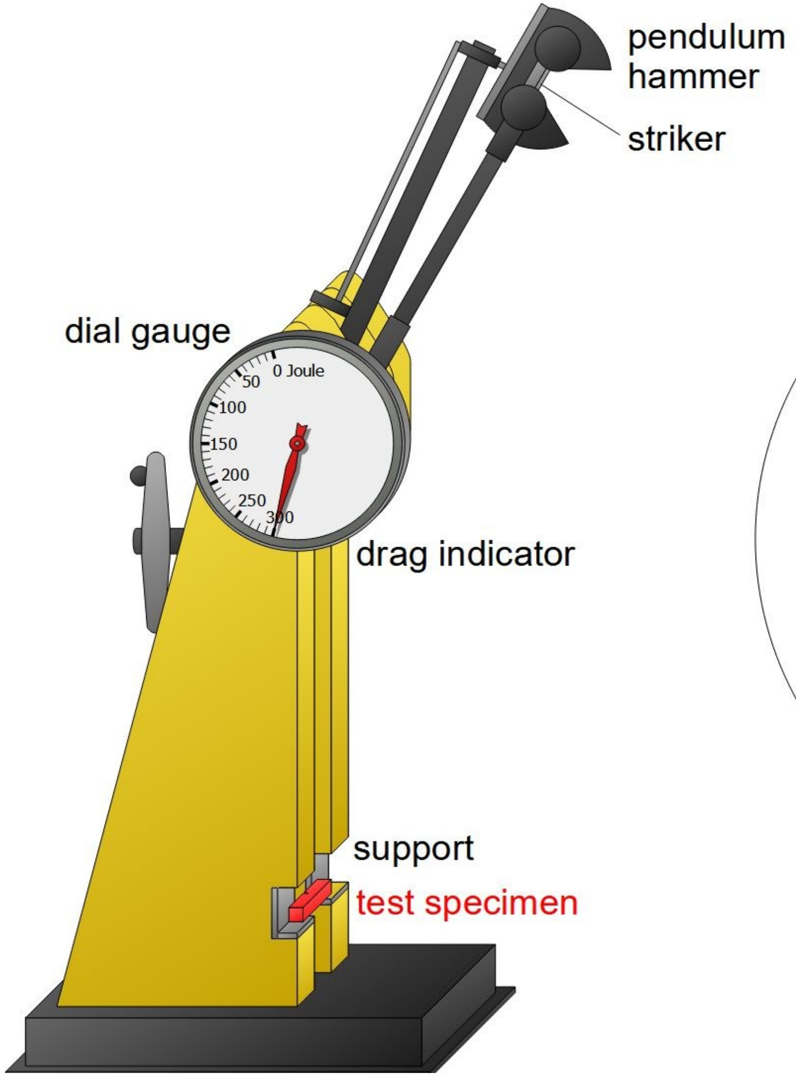
- Tensile Testing
  - Determines yield strength, ultimate strength, elongation, etc
- Hardness Testing
  - Brinell, Rockwell, Vickers methods
- Impact Testing
  - Used to test fracture toughness of a metal
  - Charpy-V
- Bend Tests
  - Used to test weld quality
- etc…

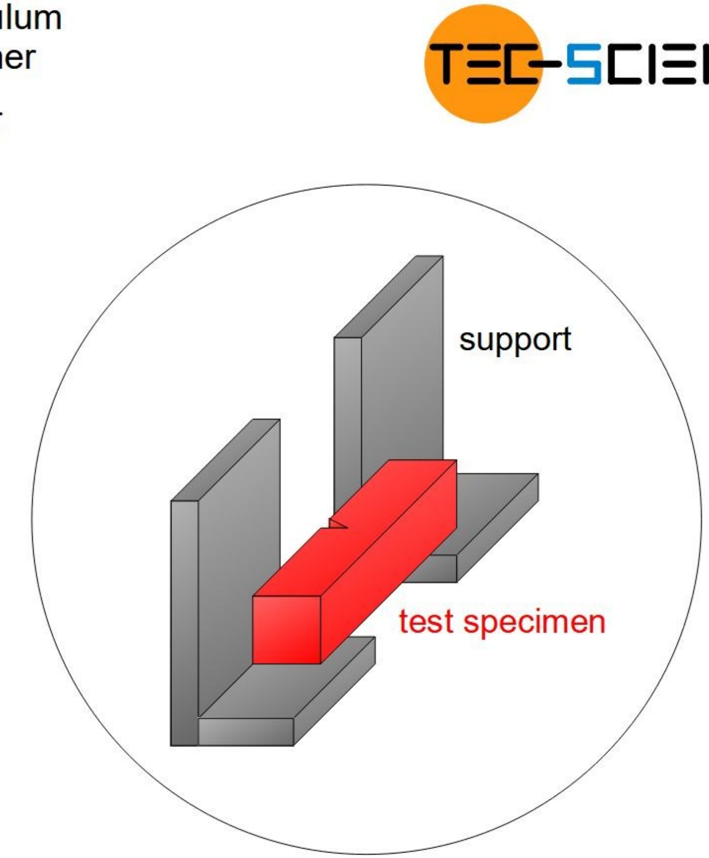
Hardness Testing



Screw forces ball into sample

Charpy-V Testing





Common Non-Destructive Tests

- Ultrasonic Testing
- Radiographic Testing
- Magnetic Particle Testing
- Liquid Penetrant Testing

- Why perform non-destructive testing?

Common Non-Destructive Tests

- Ultrasonic Testing
- Radiographic Testing
- Magnetic Particle Testing
- Liquid Penetrant Testing

- Why perform non-destructive testing?
  - Preserve test specimen
  - Can test on the field

Common Chemical Analysis

- Spectroscopy
  - OES
  - LECO
  - XRF
  - etc..
- Corrosion Testing
  - Salt spray to test coatings

Industry Examples

- Companies who work in the Testing, Inspection, and Certification (TIC) sector will use a combination of these tests every day
  - I worked at such a company, feel free to ask me for more insight on this

- Generally used on large scale construction projects
  - Airports
  - Bridges
  - Public Transit Systems
  - etc….

Standards and Regulating Bodies

- Methodology to test is usually carried out in accordance with certain standards published by certain bodies:
  - ATSM
  - ASME
  - ISO
  - AWS
  - AISC
- Ensures consistent, repeatable results that are broadly accepted

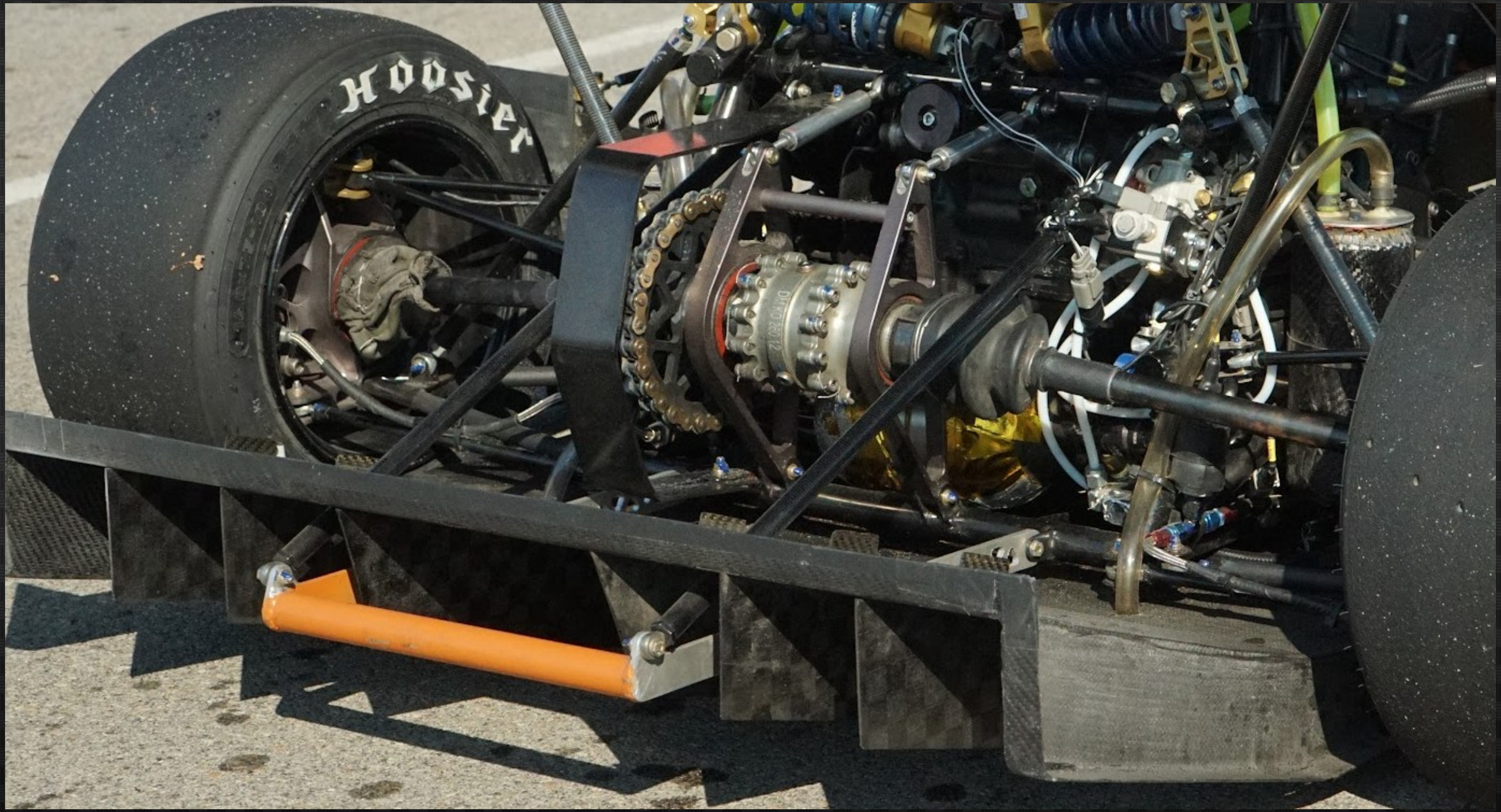
Case Study: Titanic

- Article: https://www.nist.gov/nist-time-capsule/nist-beneath-waves/nist-reveals-how-tiny-rivets-doomed-titanic-vessel

- Rivets were unexpectedly brittle in cold conditions
  - Massive oversight

Questions?

Drivetrain Education: Lecture 5



04/21/2025

Project Check-In

Status

- Where are you at in the process?
  - Initial Calculations?
  - Modelling?

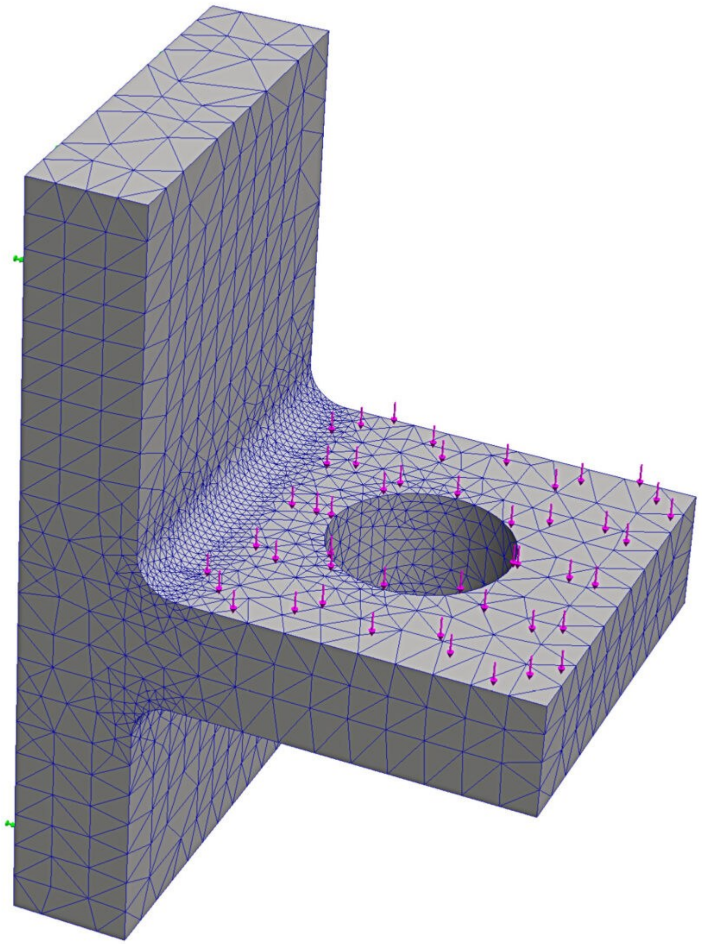
Recap of Calculators

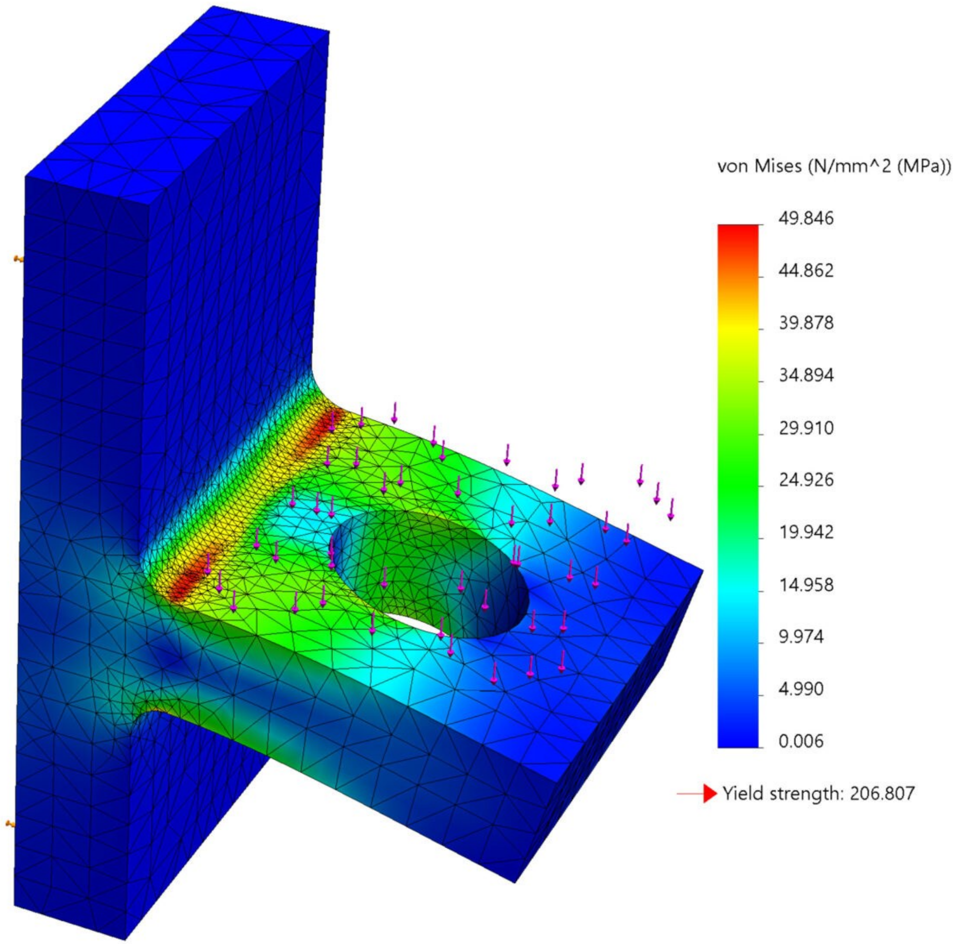
- I am providing you with calculators to use for this project

- I will walk through these now if anyone has questions

Introduction to FEA

Pretty Pictures





1940-1960

- **Alexander Hrennikoff (Russia/MIT/Canada)**
  - **lattice analogy** which models membrane and plate bending of structures as a lattice framework (1940)
- **Richard Courant (German/US)**
  - Solution of torsion problems with multiple domains
- **Feng Kang (China)**
  - Analysis of dams (1950-60)

1960-1970

- "The Finite Element Method In Plane Stress Analysis"
  - Ray Clough, UC Berkeley
  - Presented at the 2nd ASCE Conference on Electronic Computations in September of 1960
- J.H. Agyris (Stuttgart), O.C. Zienkiewicz (UC Berkeley), R. Gallagher (Cornell), Hinton (Swansea), Ciarlet (France)
- *Strang, Gilbert; Fix, George (1973). An Analysis of The Finite Element Method. Prentice Hall. ISBN 0-13-032946-0.*

Early Codes

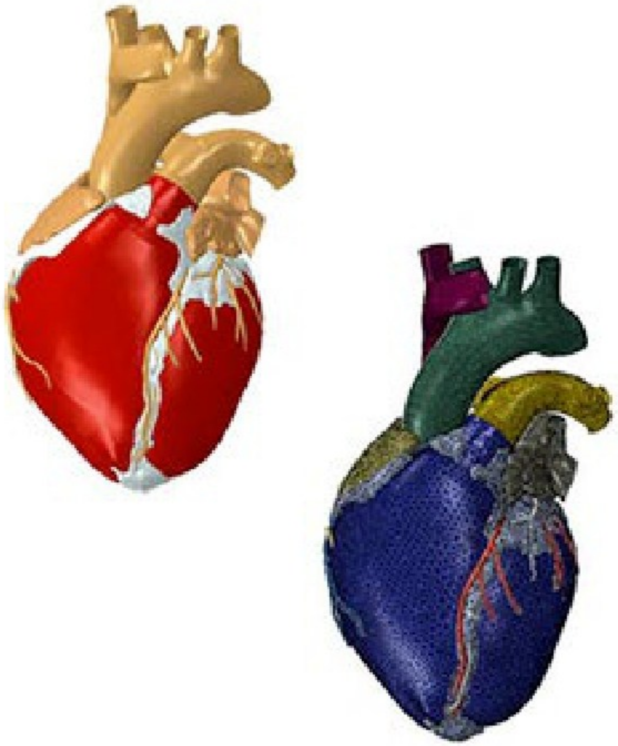
- NASTRAN (NASA)
- SAP (UC-B)
- SESAM (Norway)
- FEAP (UC-B)

Emergence of Commercial FE Codes

- Start late 1970s
- From start ups in 1990s to commercial success in 2000
  - ABAQUS, ANSYS, NASTRAN, COMSOL, DYNA, etc.
- Open source codes
- Widespread use now

Classical ME Domain: Automotive

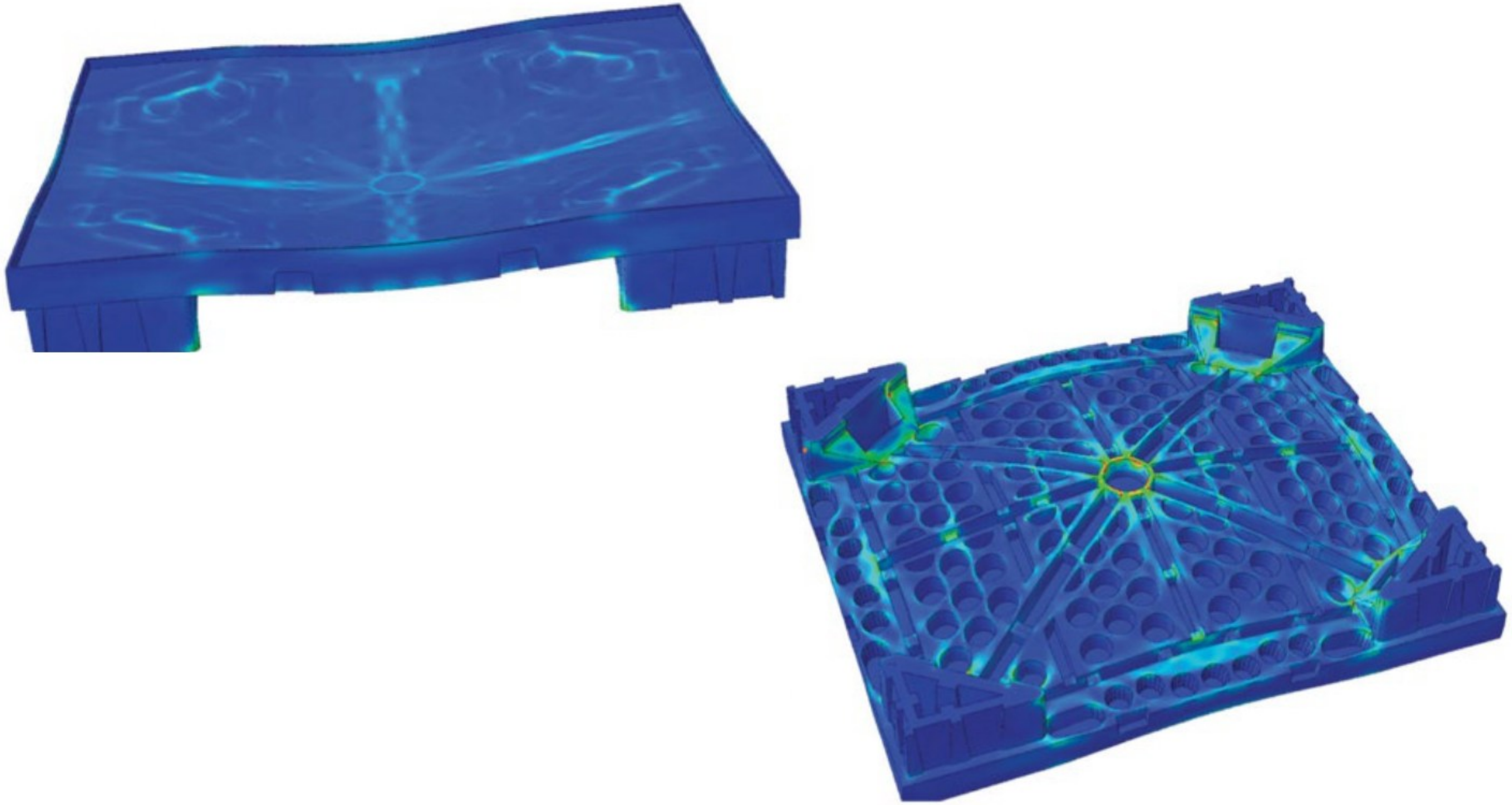
Biomechanics and Biomedical



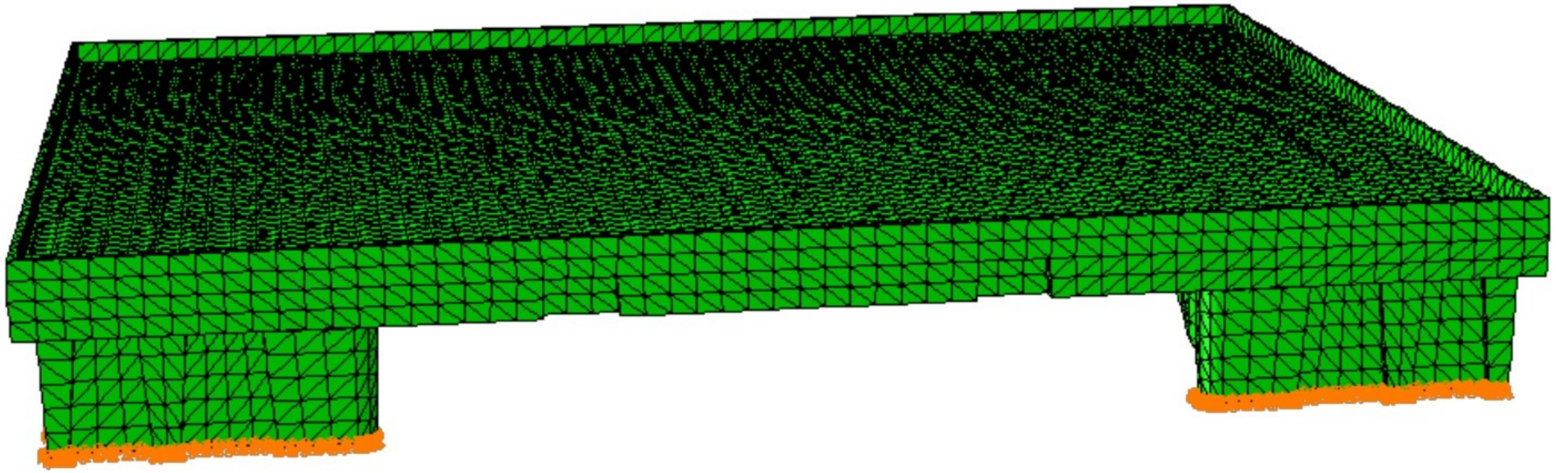
Unexpected ME Domain: The Oscars 2015

- *To Ben Cole for the design of the Kali Destruction System, to Eric Parker for the development of the Digital Molecular Matter toolkit, and to James O'Brien for his influential research on the finite element methods that served as a foundation for these tools.*

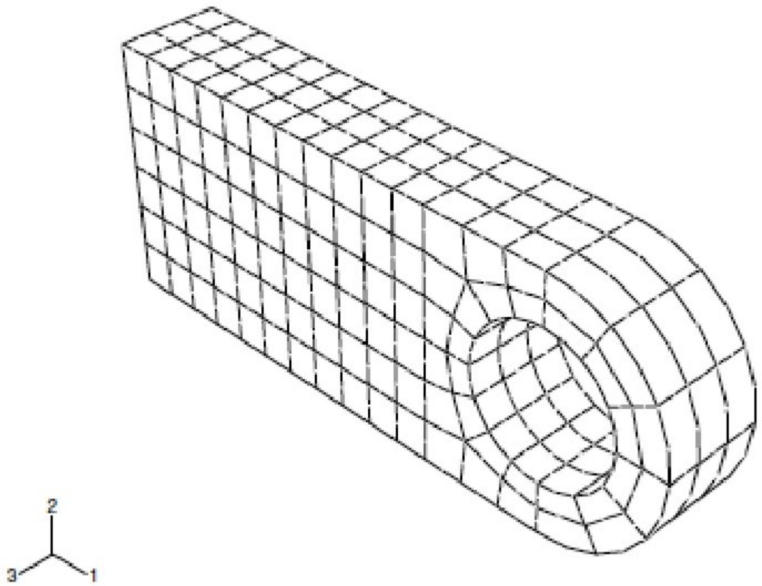
A colorful picture

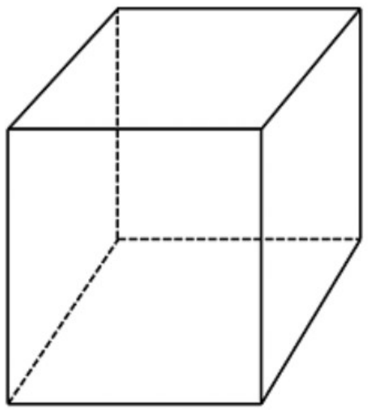


Underlying is a grid (mesh)

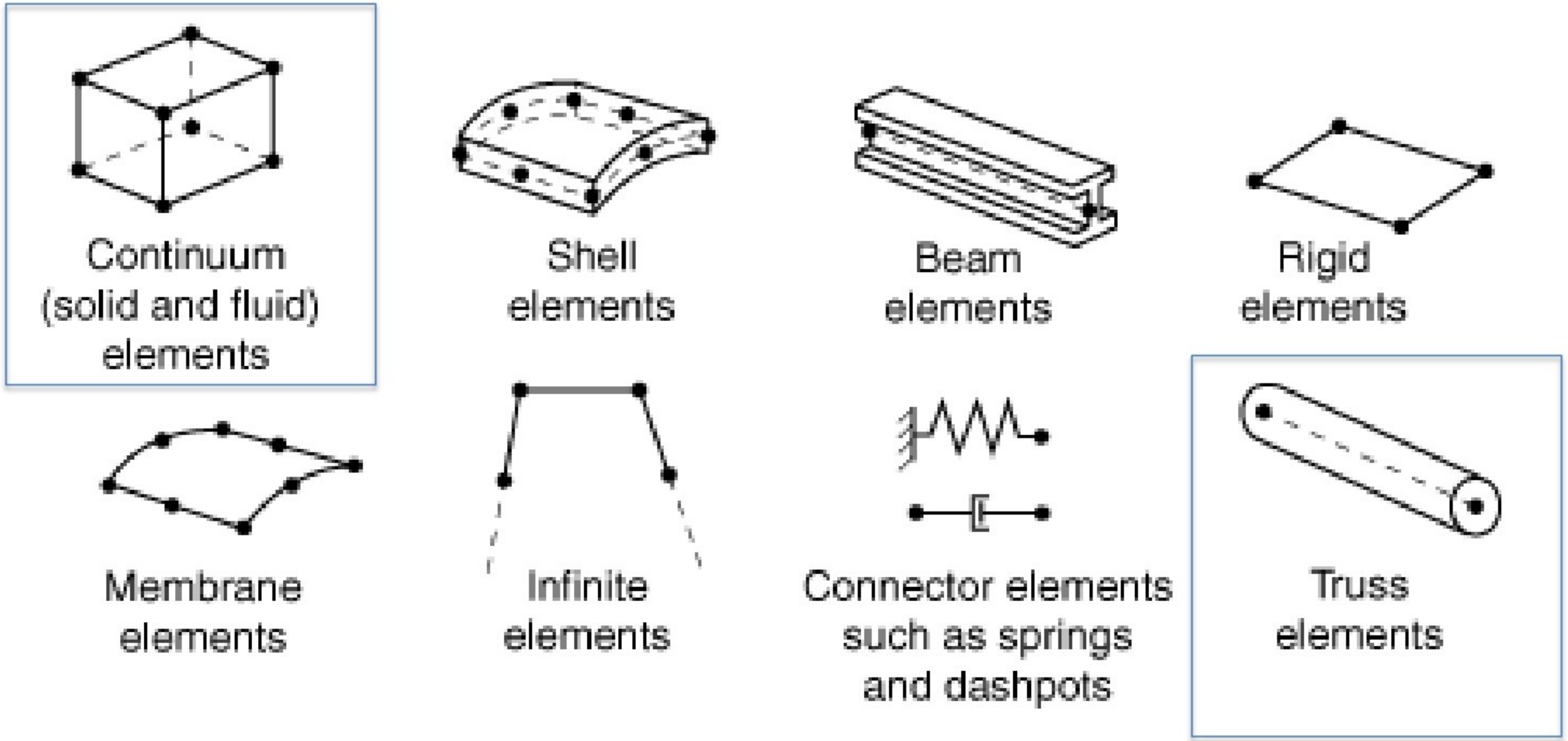


Mesh Consists of Elements

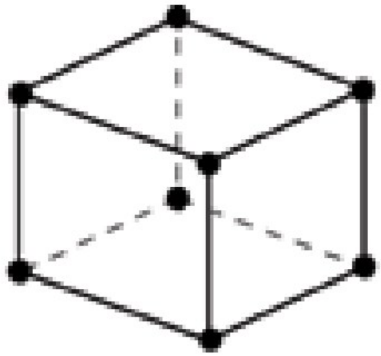




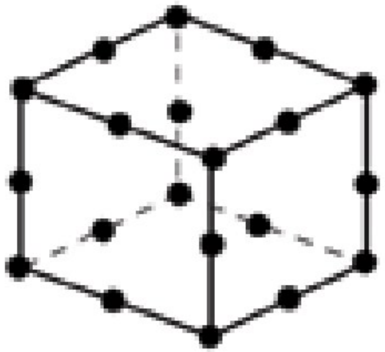
Element and Nodes



Elements

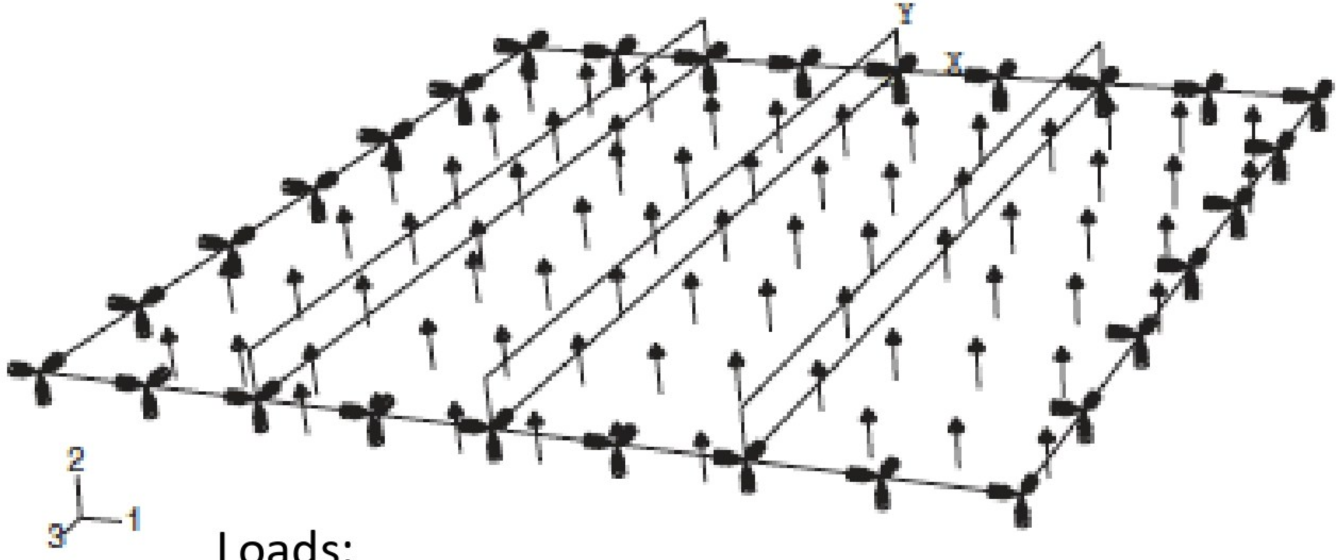


(a) Linear element
(8-node brick, C3D8)



(b) Quadratic element
(20-node brick, C3D20)

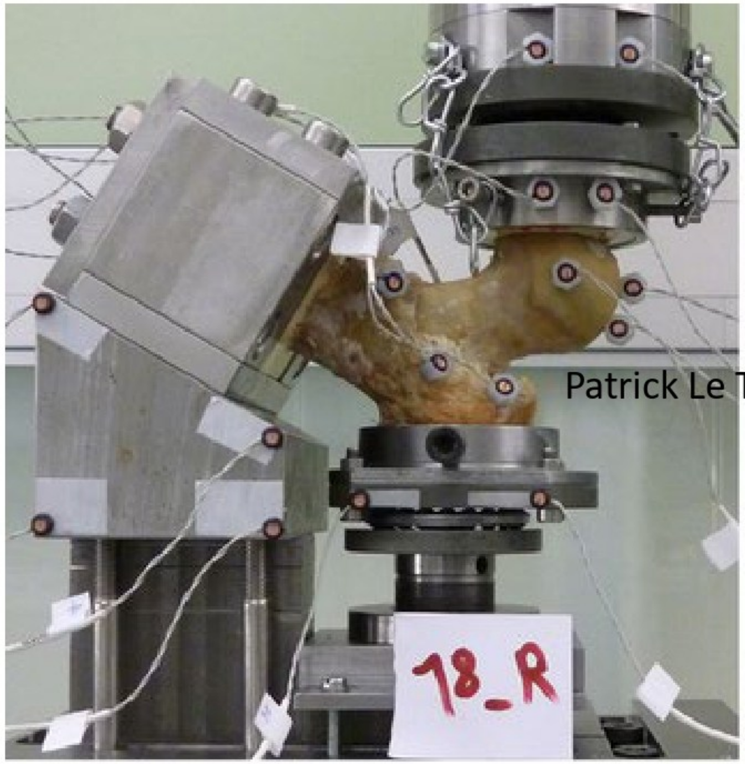
Boundary Conditions and Loads



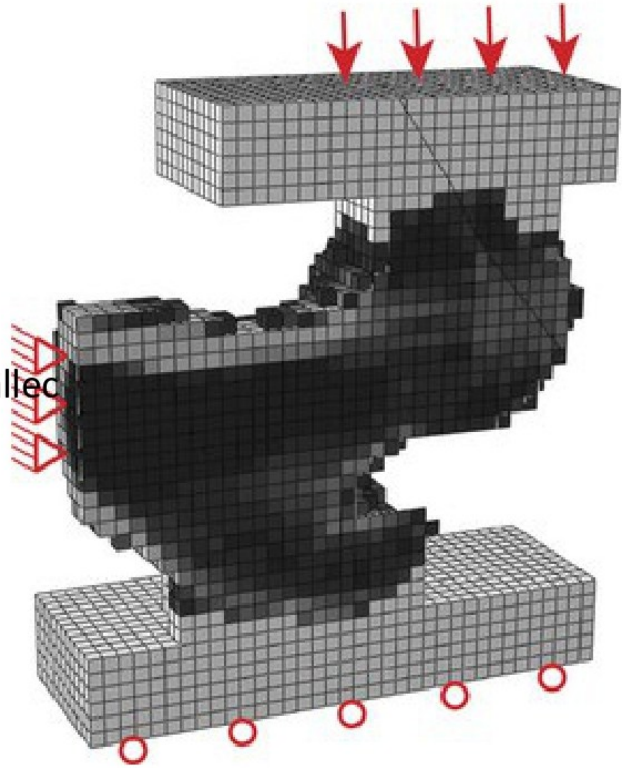
Loads:
Pressure on faces
Forces at nodes
Gravity

Boundary Conditions:
Constraints on displacments
Or rotations nodes

Boundary Conditions and Loads



Patrick Le Tallec

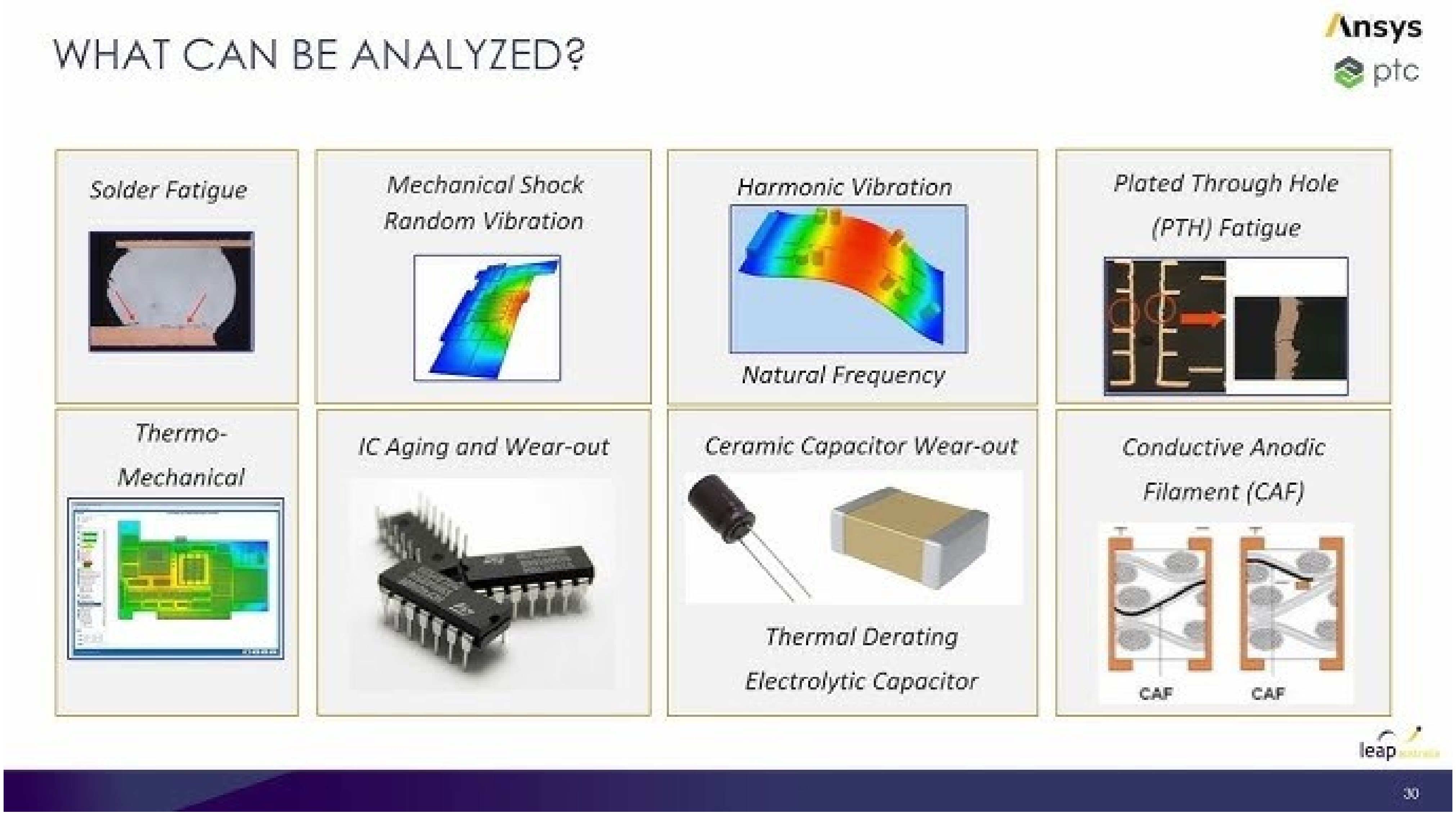


http://www.nature.com/bonekeyreports/2013/130807/bonekey2013120
/full/bonekey2013120.html

Materials Behavior

- Here: Elasticity, Heat Transfer
  - Modulus, Possion's ratio, strength
  - conductivity
- Also: Plastic, creep, fracture,

FEA is broad… and cool

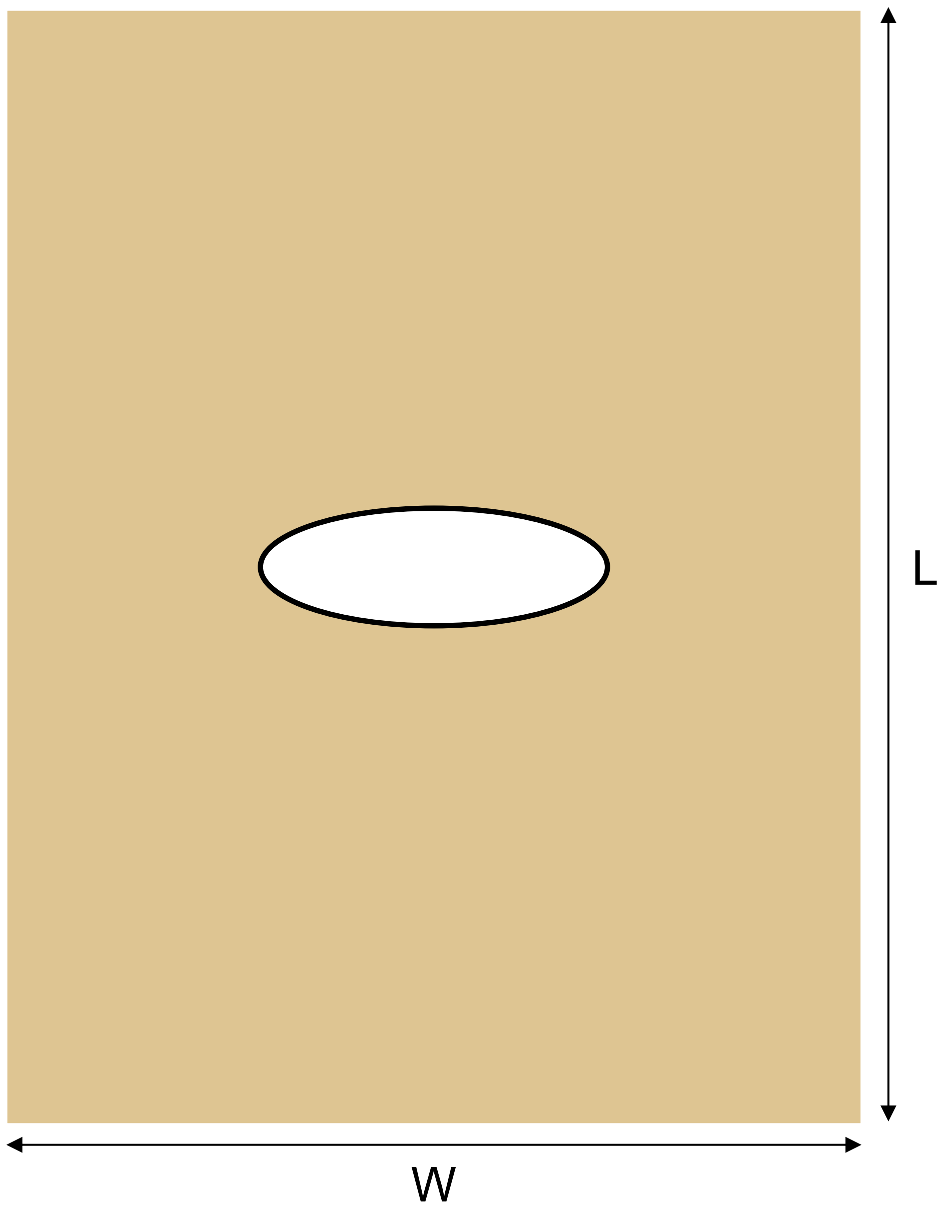


FEM and FEA

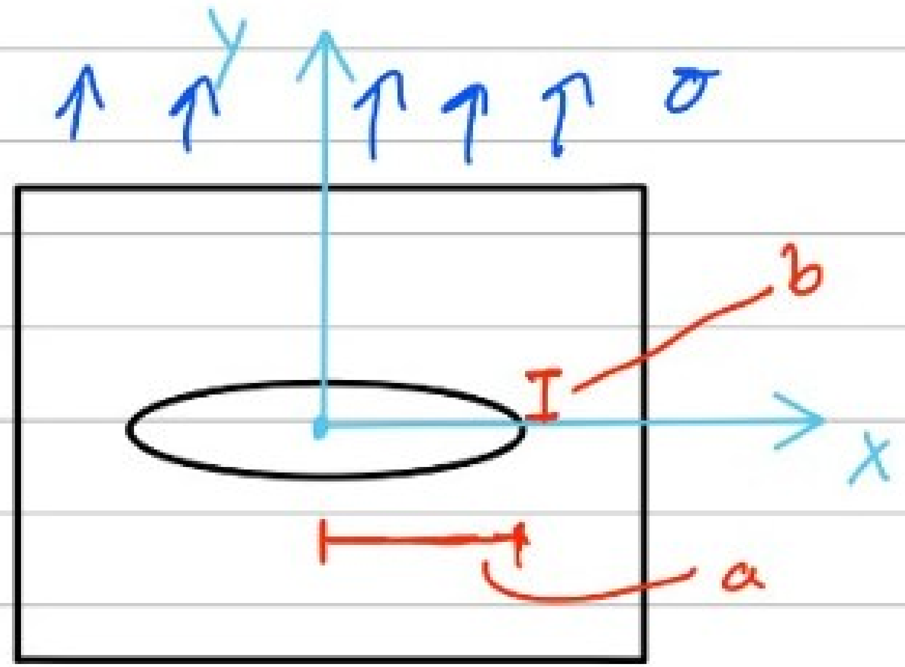
- FEM → Mathematical approach to solving a complex engineering and physics problem, which involves discretization of your system

- FEA → Application of FEM using software to model and analyze a system

Example



Example



Example

$$\sigma_{max} = K_s \cdot \sigma$$

$$\sigma = \varepsilon E$$

$$= \frac{1.25\text{ mm}}{125\text{ mm}} \cdot \frac{70000\text{ N}}{\text{mm}^2} = 700\text{ MPa}$$

$$K_s = 1 + 2\frac{a}{b}$$

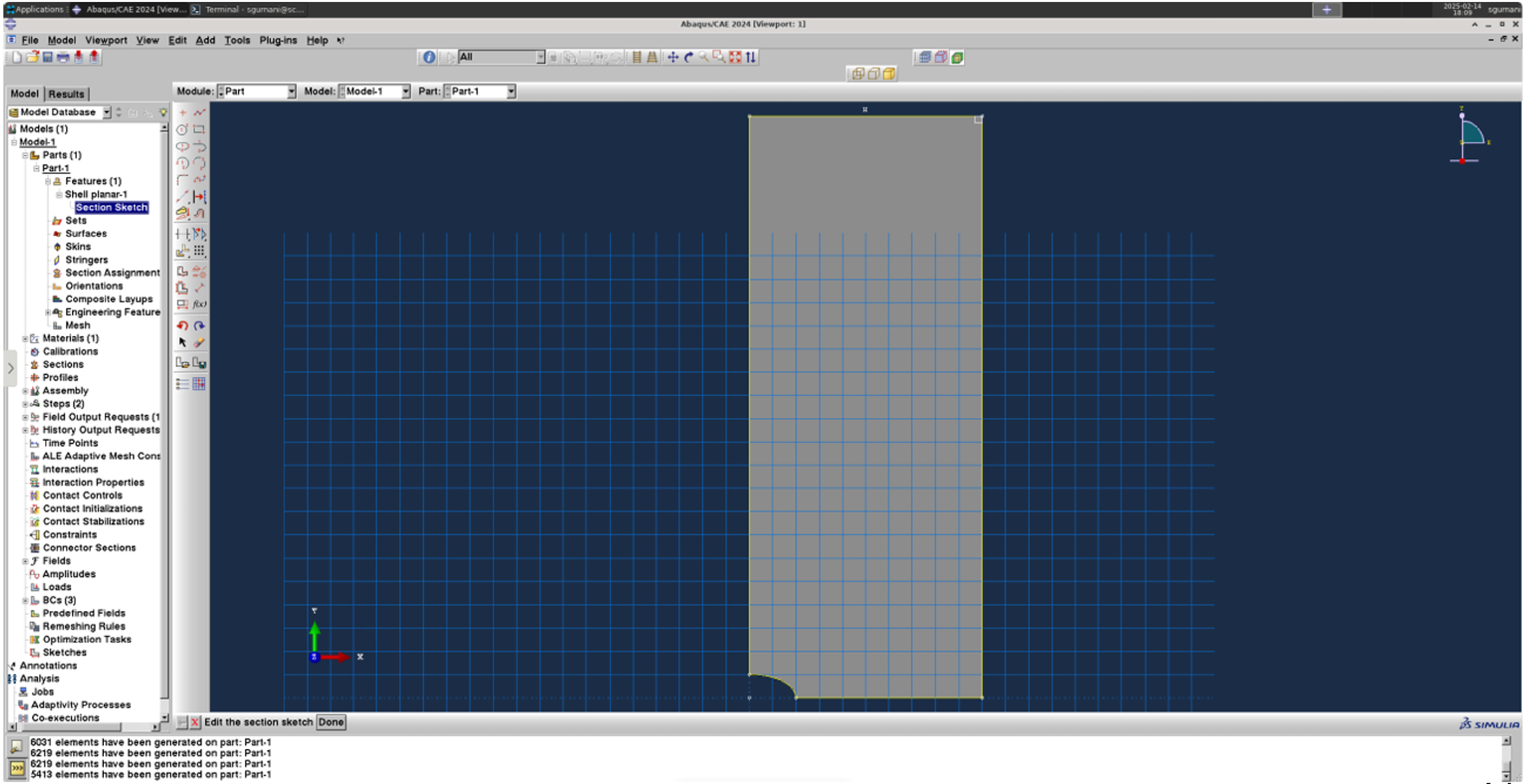
$$= 1 + 2\left(\frac{10}{5}\right) = 1 + 4 = 5$$

$$\sigma_{max} = 5 \cdot 700\text{ MPa}$$

$$= 3500\text{ MPa}$$

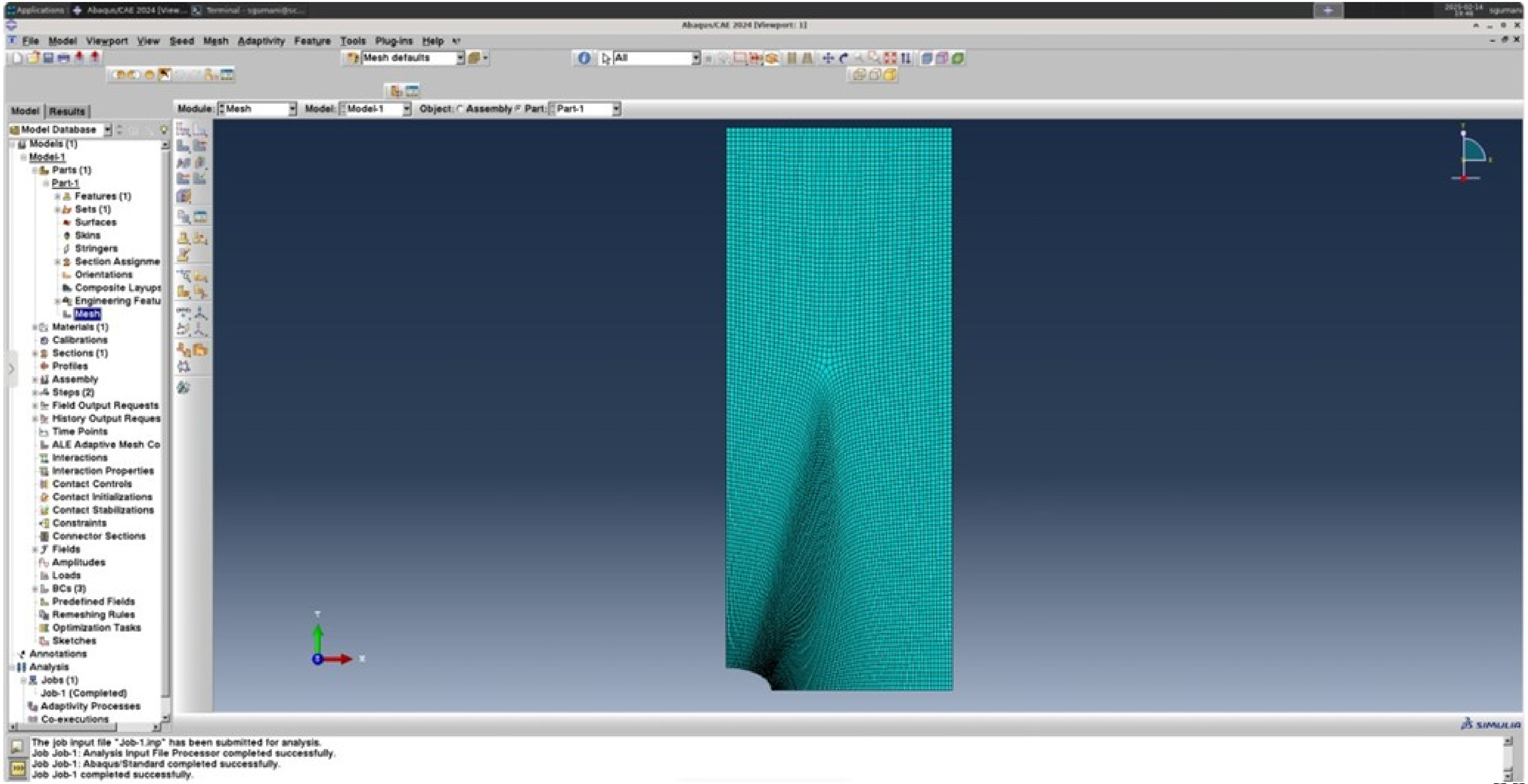
$$\boxed{\sigma_{max} = 3500\text{ MPa}}$$

Example



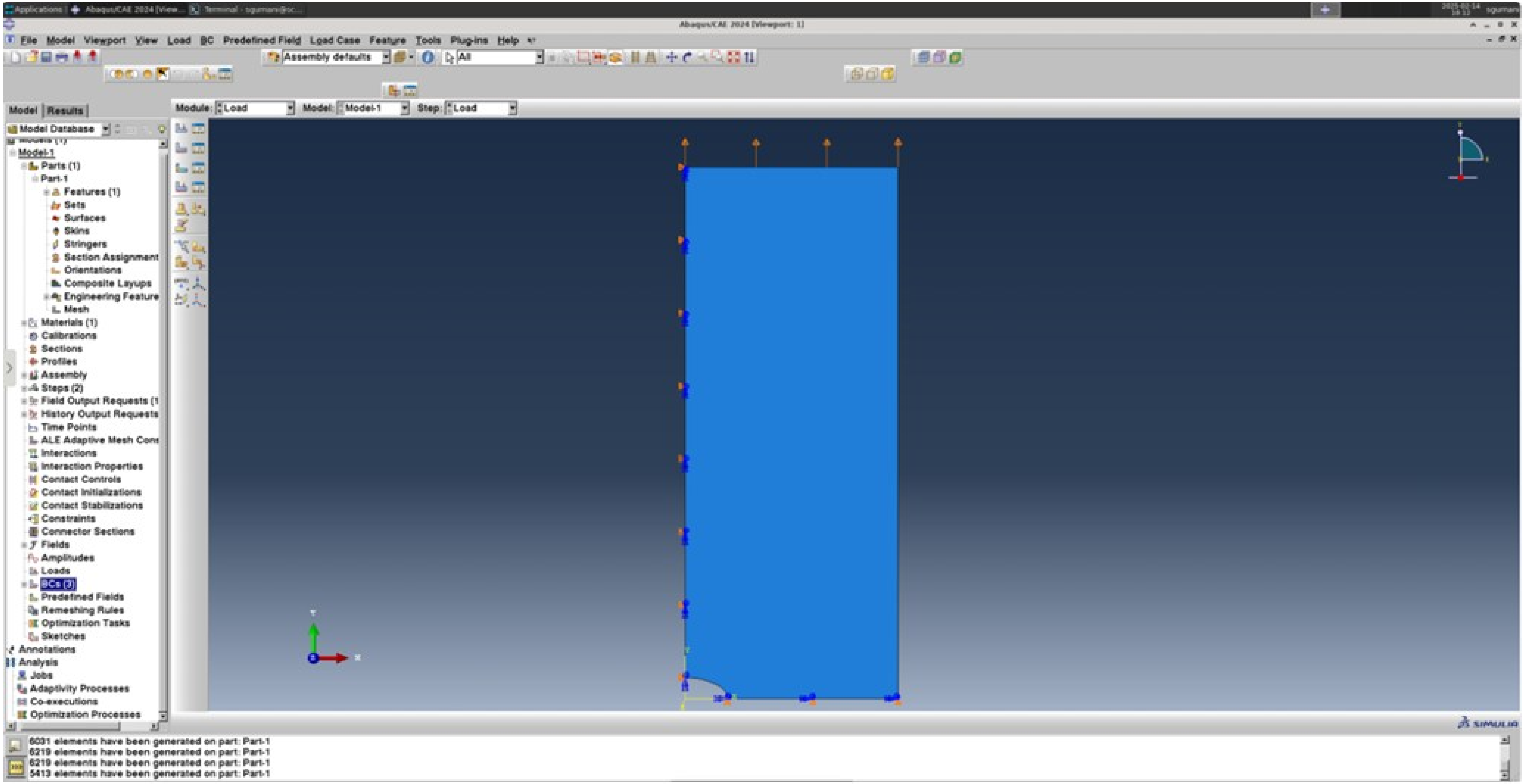
Abaqus/CAE 2024 [Viewport: 1]
File Model Viewport View Edit Add Tools Plug-ins Help
Model Results
Module: Part
Model: Model-1
Part: Part-1
Model Database
Models (1)
Model-1
Parts (1)
Part-1
Features (1)
Shell planar-1
Section Sketch
Sets
Surfaces
Skins
Stringers
Section Assignment
Orientations
Composite Layups
Engineering Feature
Mesh
Materials (1)
Calibrations
Sections
Profiles
Assembly
Steps (2)
Field Output Requests (1
History Output Requests
Time Points
ALE Adaptive Mesh Cons
Interactions
Interaction Properties
Contact Controls
Contact Initializations
Contact Stabilizations
Constraints
Connector Sections
Fields
Amplitudes
Loads
BCs (3)
Predefined Fields
Remeshing Rules
Optimization Tasks
Sketches
Annotations
Analysis
Jobs
Adaptivity Processes
Co-executions
Edit the section sketch
Done
6031 elements have been generated on part: Part-1
6219 elements have been generated on part: Part-1
6219 elements have been generated on part: Part-1
5413 elements have been generated on part: Part-1

Example



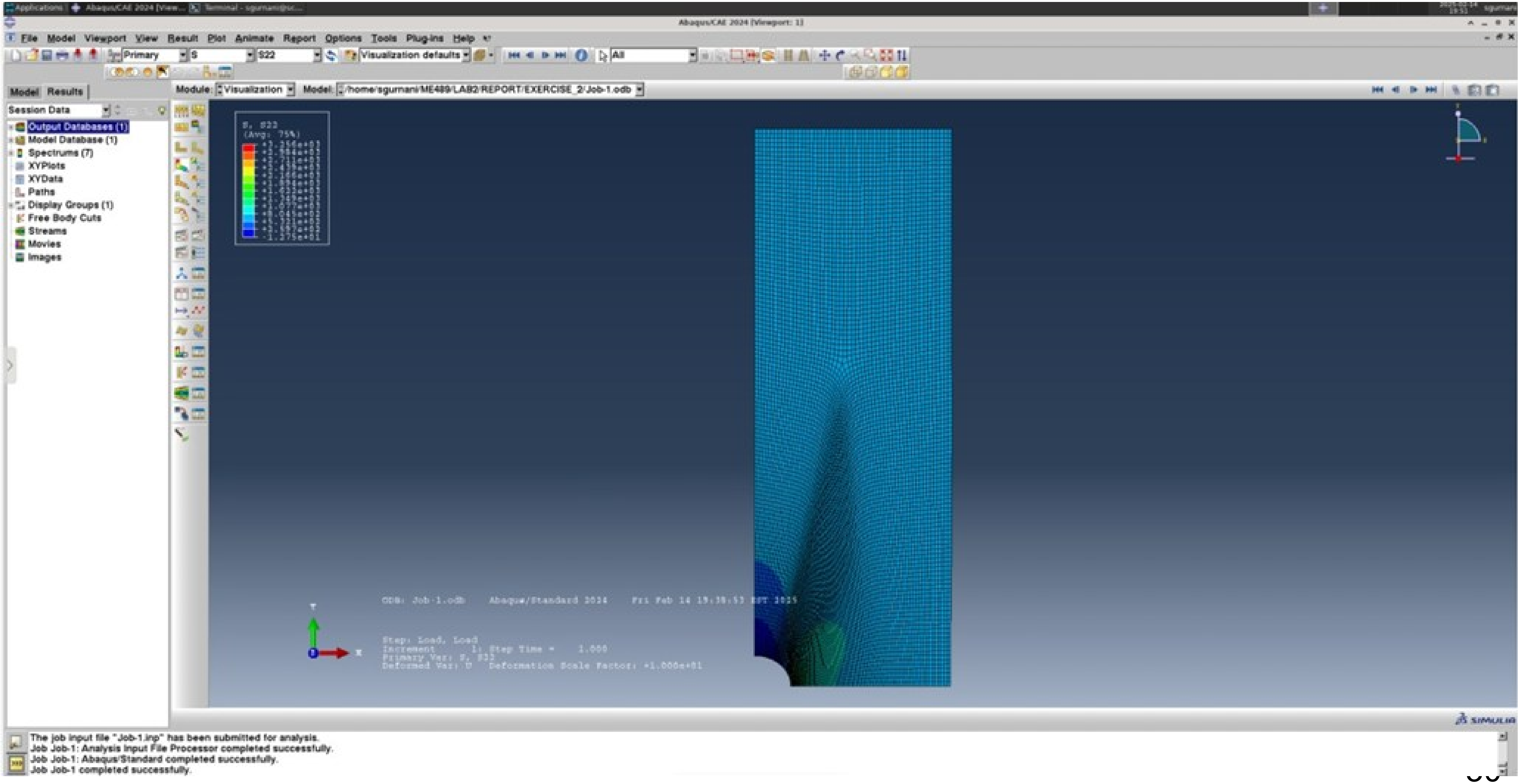
Abaqus/CAE 2024 [Viewport: 1]
File Model Viewport View Seed Mesh Adaptivity Feature Tools Plug-ins Help
Mesh defaults
All
Module: Mesh Model: Model-1 Object: Assembly Part: Part-1
Model Results
Model Database
Models (1)
Model-1
Parts (1)
Part-1
Features (1)
Sets (1)
Surfaces
Skins
Stringers
Section Assignme
Orientations
Composite Layups
Engineering Featu
Mesh
Materials (1)
Calibrations
Sections (1)
Profiles
Assembly
Steps (2)
Field Output Requests
History Output Reques
Time Points
ALE Adaptive Mesh Co
Interactions
Interaction Properties
Contact Controls
Contact Initializations
Contact Stabilizations
Constraints
Connector Sections
Fields
Amplitudes
Loads
BCs (3)
Predefined Fields
Remeshing Rules
Optimization Tasks
Sketches
Annotations
Analysis
Jobs (1)
Job-1 (Completed)
Adaptivity Processes
Co-executions
SIMULIA
The job input file "Job-1.inp" has been submitted for analysis.
Job Job-1: Analysis Input File Processor completed successfully.
Job Job-1: Abaqus/Standard completed successfully.
Job Job-1 completed successfully.

Example



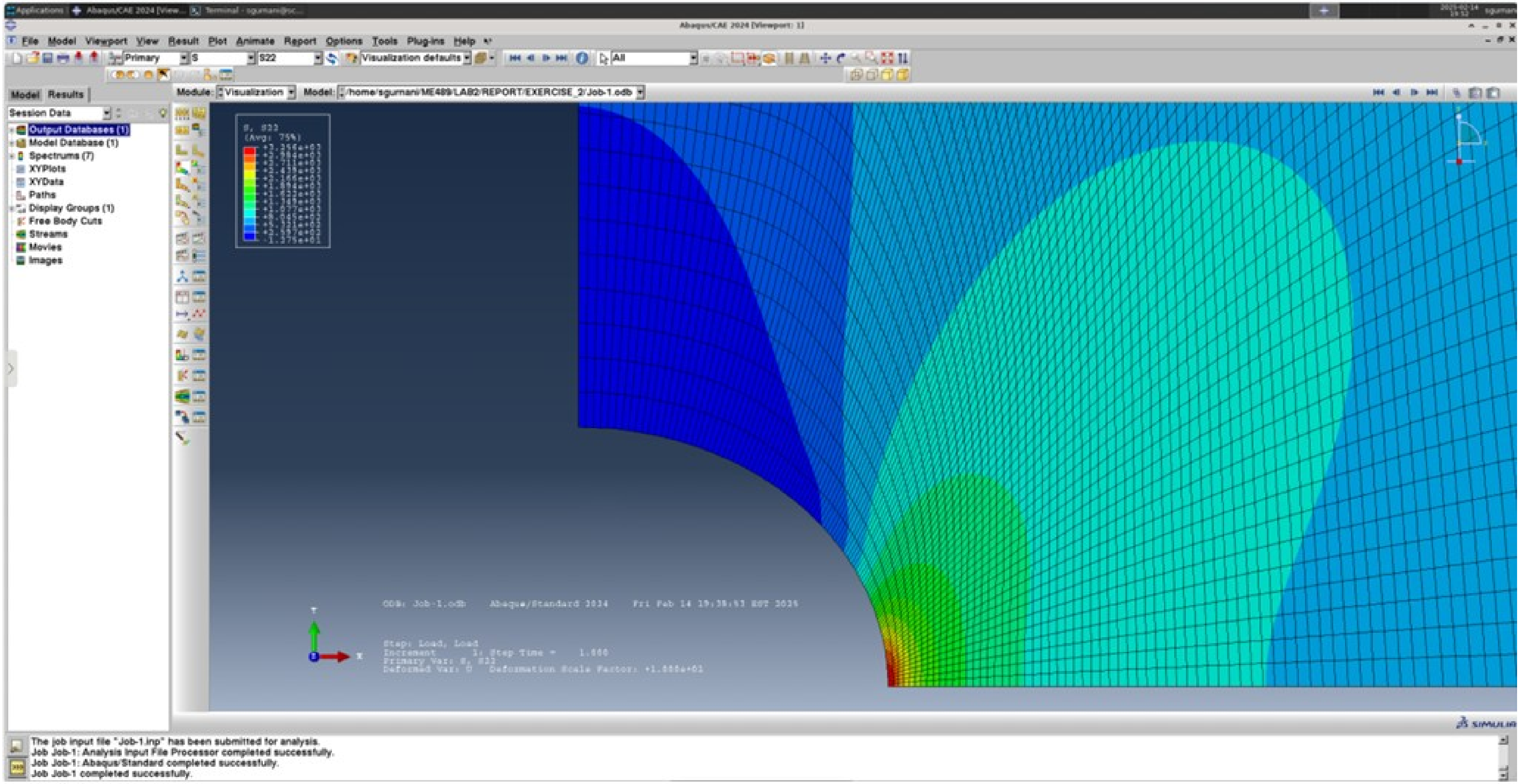
Abaqus/CAE 2024 [Viewport: 1]
File Model Viewport View Load BC Predefined Field Load Case Feature Tools Plug-ins Help
Assembly defaults
All
Model Results
Module: Load Model: Model-1 Step: Load
Model Database
Model-1
Parts (1)
Part-1
Features (1)
Sets
Surfaces
Skins
Stringers
Section Assignment
Orientations
Composite Layups
Engineering Feature
Mesh
Materials (1)
Calibrations
Sections
Profiles
Assembly
Steps (2)
Field Output Requests
History Output Requests
Time Points
ALE Adaptive Mesh Cons
Interactions
Interaction Properties
Contact Controls
Contact Initializations
Contact Stabilizations
Constraints
Connector Sections
Fields
Amplitudes
Loads
BCs (3)
Predefined Fields
Remeshing Rules
Optimization Tasks
Sketches
Annotations
Analysis
Jobs
Adaptivity Processes
Co-executions
Optimization Processes
6031 elements have been generated on part: Part-1
6219 elements have been generated on part: Part-1
6219 elements have been generated on part: Part-1
5413 elements have been generated on part: Part-1

Example



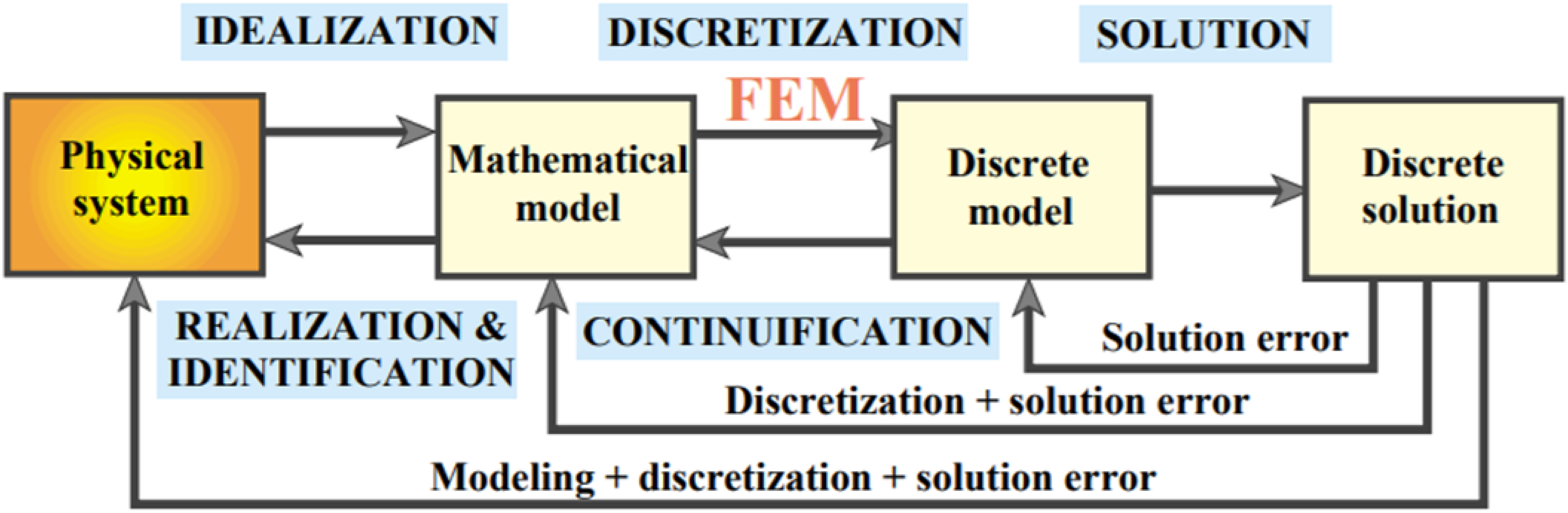
Abaqus/CAE 2024 [Viewport: 1]
File Model Viewport View Result Plot Animate Report Options Tools Plug-ins Help
Primary
S
S22
Visualization defaults
All
Model Results
Module: Visualization
Model: /home/sgumani/ME489/LAB2/REPORT/EXERCISE_2/Job-1.odb
Session Data
Output Databases (1)
Model Database (1)
Spectrums (7)
XYPlots
XYData
Paths
Display Groups (1)
Free Body Cuts
Streams
Movies
Images
S, S22
(Avg: 75%)
ODB: Job-1.odb Abaqus/Standard 2024
Step: Load, Load
Increment 1: Step Time = 1.000
Primary Var: S, S22
Deformed Var: U Deformation Scale Factor: +1.000e+01
The job input file "Job-1.inp" has been submitted for analysis.
Job Job-1: Analysis Input File Processor completed successfully.
Job Job-1: Abaqus/Standard completed successfully.
Job Job-1 completed successfully.

Example

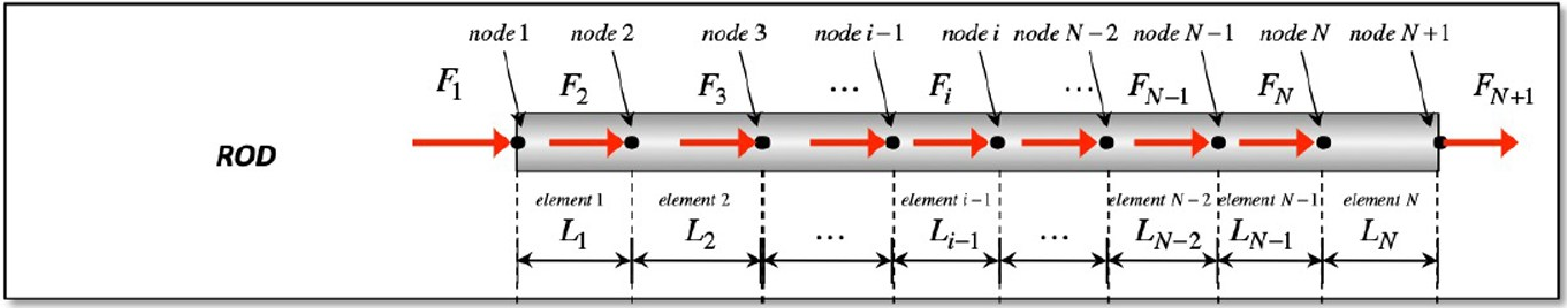


Max Stress → 3256 MPa

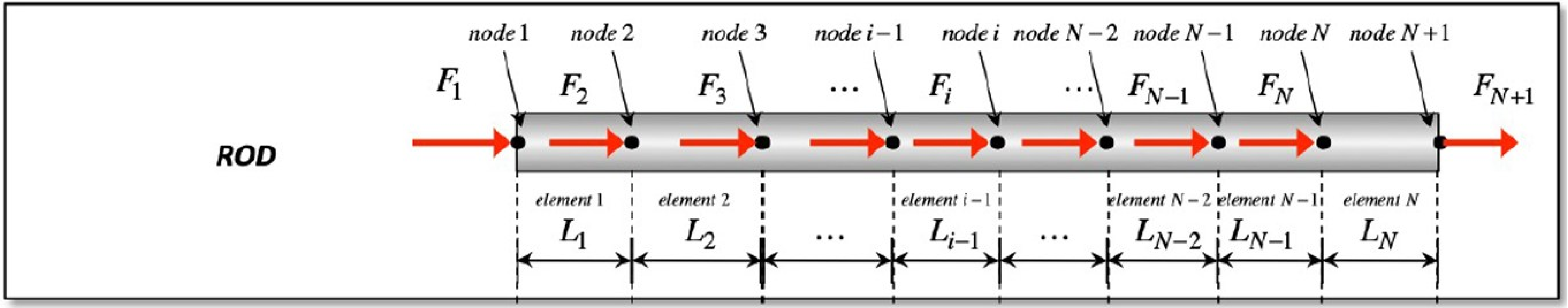
Sample Workflow

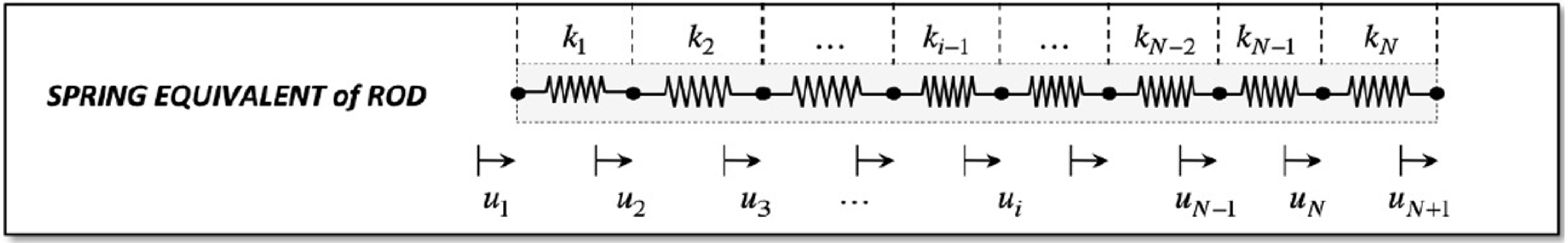


C. Felippa, *Introduction to Finite Element Methods*



ROD
node 1
node 2
node 3
node i − 1
node i
node N − 2
node N − 1
node N
node N + 1
F_1
F_2
F_3
F_i
F_{N-1}
F_N
F_{N+1}
element 1
element 2
element i − 1
element N − 2
element N − 1
element N
L_1
L_2
L_{i-1}
L_{N-2}
L_{N-1}
L_N


node 1
node 2
node 3
node i − 1
node i
node N − 2
node N − 1
node N
node N + 1
F_1
F_2
F_3
…
F_i
…
F_{N-1}
F_N
F_{N+1}
ROD
element 1
element 2
element i − 1
element N − 2
element N − 1
element N
L_1
L_2
…
L_{i-1}
…
L_{N-2}
L_{N-1}
L_N


k_1
k_2
…
k_{i-1}
…
k_{N-2}
k_{N-1}
k_N
SPRING EQUIVALENT of ROD
u_1
u_2
u_3
…
u_i
u_{N-1}
u_N
u_{N+1}

Strain energy in terms of nodal displacements

For N elements and $N+1$ nodes:

Lecture Book: Ch. 17, pg. 12

$$[K]=\begin{array}{c}
\begin{array}{cccccccc} 1 & 2 & 3 & & & N-1 & N & N+1 \end{array}\\
\left[\begin{array}{cccccccc}
k_1 & -k_1 & & & & & & \\
-k_1 & k_1+k_2 & -k_2 & & & & & \\
 & -k_2 & k_2+k_3 & -k_3 & & & & \\
 & & -k_3 & \ddots & & & & \\
 & & & \ddots & \ddots & -k_{N-2} & & \\
 & & & & -k_{N-2} & k_{N-2}+k_{N-1} & -k_{N-1} & \\
 & & & & & -k_{N-1} & k_{N-1}+k_N & -k_N \\
 & & & & & & -k_N & k_N
\end{array}\right]
\end{array}
\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \\ \\ N-1 \\ N \\ N+1 \end{array}$$

element 1

element 2

element 3

element N-2

element N-1

element N

Aarnav’s FEA Presentation

Structural FEA Presentation

- Aarnav (Sometimes may analyze things elementally in a finite manner)
    - May also perform infinite element analysis (IEA Lecture coming soon)

Always remember: People spend their whole lives learning and improving their FEA skills. We've got a few years, a degree to earn, a car to design and build, and multiple models to overconstrain

So What Actually is FEA? (makes pretty colors?)

1. **Geometry**
   Break geometry into little pieces. Each piece can stretch based on it's "spring constant" (Young's Modulus)

2. **Boundary Conditions**
   Lock down geometry that shouldn't move. Define how different parts can interact. Apply loads to geometry.

3. **Linear Algebra**
   FEA converts your geometry and boundary conditions into a bunch of differential equations

4. **Propagate Forces/Deflections**
   FEA calculates how applied loads propagate through the system

5. **Stress, Strain, Deflection**
   FEA outputs the solutions

6. **Iterate**
   Adjust geometry as needed if you don't like the results

STOP! Before you run FEA, ask yourself: *should I?*

Some questions to ask:

- Can I verify this or check this another way?
  - Beam calculations, Hertzian contact, Shigley's, etc
  - Rules of thumb for bolt-hole tab thickness or size
  - Common sense or past experience (**eyecrometer**)
  - Predictions from calculators
- Do I understand how this should behave?
  - What are my loads?
  - Draw a free body diagram?
- How much can I simplify this before that expected behavior falls apart?
  - What parts do I care about, and what parts do I not care about?

The basic workflow

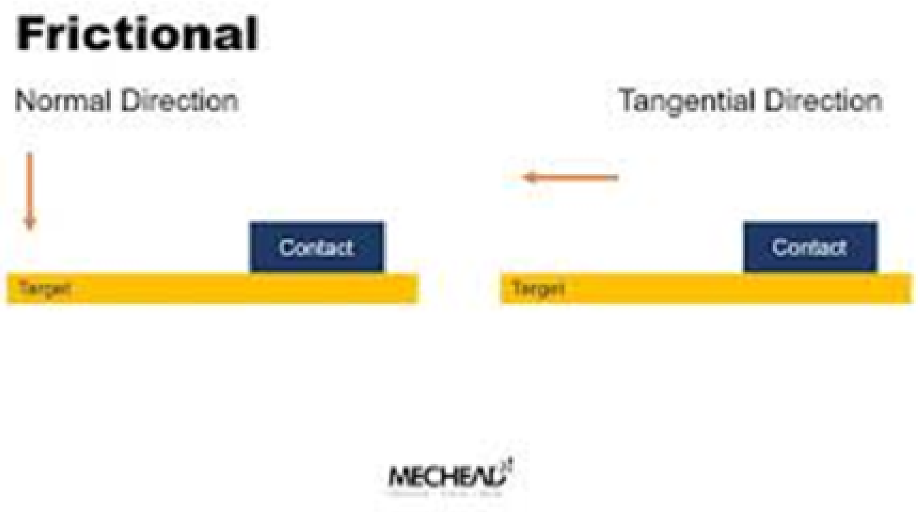
1. Figure out: what exactly you're trying to do and how to set it up to obtain the most realistic results
2. Import your part into Geometry (STEP 203 files typically work)
3. Spaceclaim!!! Clean up messy faces, simplify bolts, add reference coordinate systems, add reference parts
4. Mechanical: assign materials, named selections, etc.
    a. If it's an assembly, save yourself grief later, and rename/relabel all the components
5. Contacts:
    a. Stop and think about what constraints and contacts should be in the system
    b. **THEN** Implement these Constraints and contacts
6. Meshing:
    a. Start out coarse for the first run
7. Set up your load steps and change analysis settings as appropriate
8. Double check everything
9. Save
10. Run the analysis
11. Interpret the results
12. Iterate as necessary

Connections

Contacts, Beams, Springs, and Joints

Contacts

- **Bonded:** Bonds surfaces together as is if it was one piece. Initial gaps closed, initial penetration ignored.
- **No Separation:** Objects can slide without friction, but cannot separate
- **Frictionless:** Objects can slide without friction and seperate. May need to add “weak springs” to stabilize
- **Frictional:** Objects slide with friction and separate
- **Rough:** Objects can separate but not slide (infinite μ). Initial gaps not closed, initial penetration solved for.

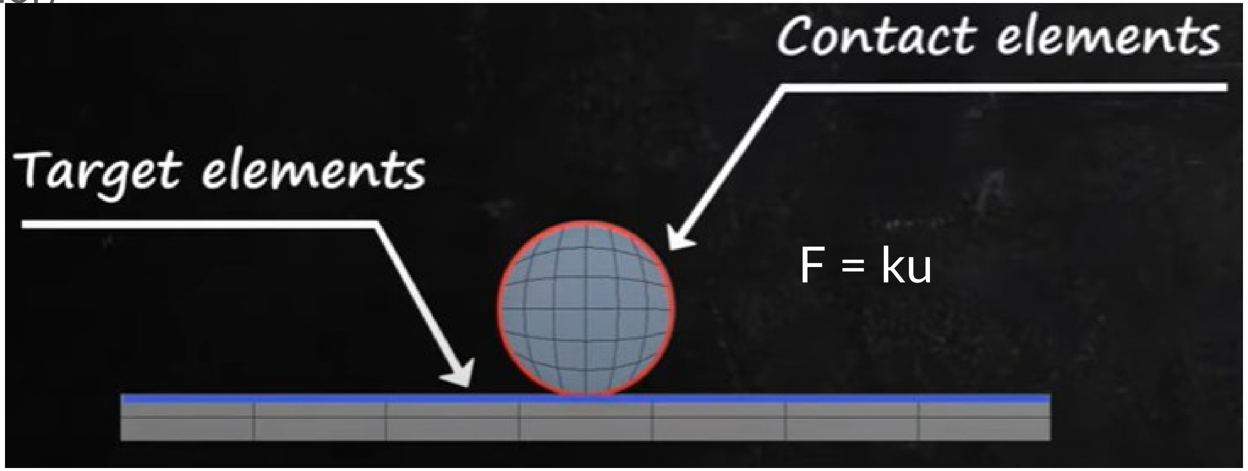


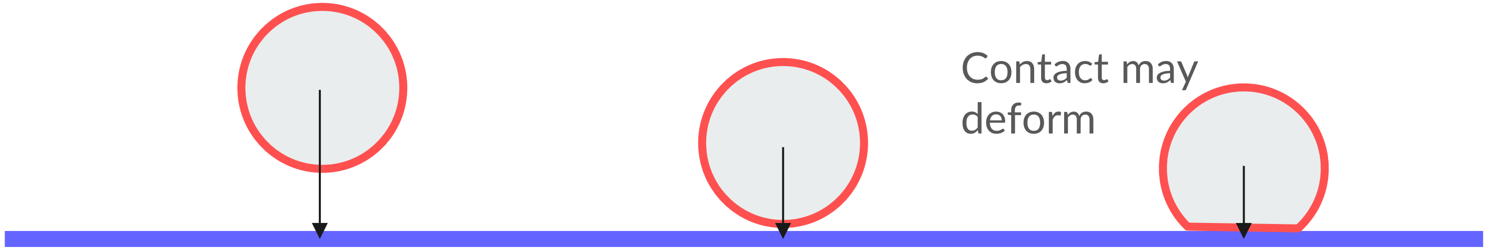
Note: Objects that do not have contacts cannot “see” each other

Bonded	No Separation	Frictionless	Frictional	Rough
No Separate	No Separate	Separate	Separate	Separate
No Slide	Slide w/o friction	Slide w/o friction	Slide **with** friction	No Slide

Contact vs Target

Contact Bodies: Cannot be rigid bodies with Asymmetric behavior (default behavior)



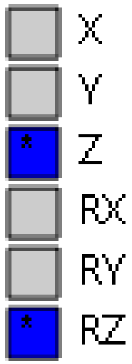


Target cannot be penetrated

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	support 2\Solid1
Target Bodies	Boss-Extrude1\Boss-Extrude11
Protected	No
Definition	
Type	Bonded
Scope Mode	Manual
Behavior	Program Controlled
Trim Contact	Program Controlled
Suppressed	No
Display	
Element Normals	No
Advanced	
Formulation	Program Controlled
Small Sliding	Program Controlled
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Pinball Region	Program Controlled
Geometric Modification	
Contact Geometry Correction	None
Target Geometry Correction	None

Joints

Fixed: 0 DOF
Revolute: 1 DOF - RZ
Cylindrical: 2 DOF - Z, RZ
Translational: 1 DOF - X
Slot: 4 DOF, X, RX, RY, RZ
Universal: 2 DOF - RX, RZ
Spherical: 3 DOF - RX, RY, RZ
Planar: 3 DOF - X, Y, RZ
Bushing: Creates a bushing using stiffness and damping coefficients
General: 0 DOF (basically build your own joint)

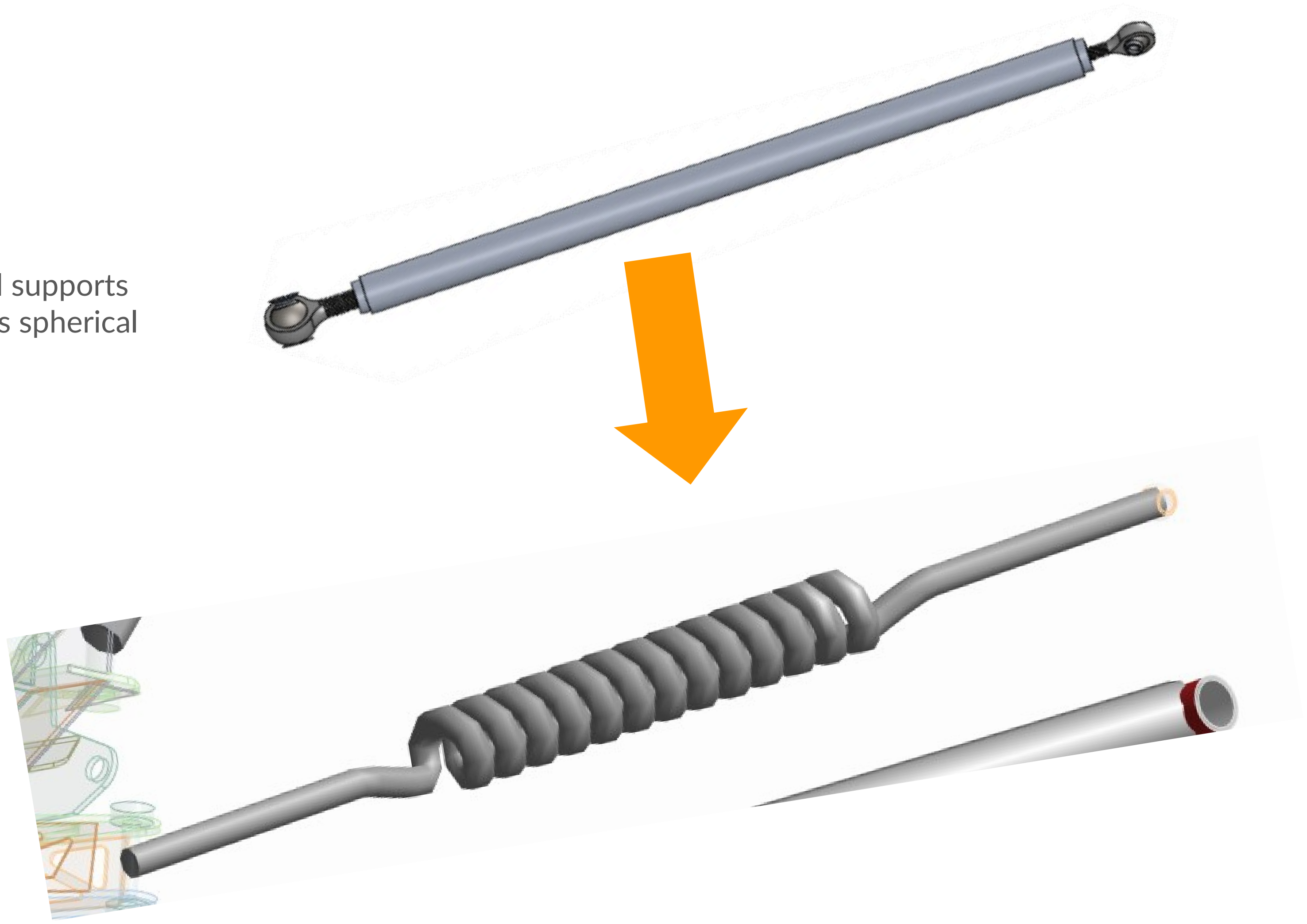


Details of "Cylindrical - Ground To Revolve1\Revolve1"

Definition	
Connection Type	Body-Body
Type	Cylindrical
Torsional Stiffness	0. lbf·in/°
Torsional Damping	0. lbf·in·s/°
Friction Coefficient	0.
Radius	0. in
Element APDL Name	
Suppressed	No
Reference	
Scoping Method	Geometry Selection
Applied By	Remote Attachment
Scope	No Selection
Body	No Selection
Coordinate System	Reference Coordinate System
Behavior	Rigid
Pinball Region	All
Mobile	
Scoping Method	Geometry Selection
Applied By	Remote Attachment
Scope	1 Face
Body	Revolve1\Revolve1
Initial Position	Unchanged
Behavior	Rigid
Pinball Region	All
Stops	
Z Min Type	None
Z Max Type	None
RZ Min Type	None
RZ Max Type	None

Beams and Springs

Beams: A rigid body with two ends that act as fixed supports
Springs: A deformable body with two ends acting as spherical joints



Less Calculations than adding contacts and bodies for similar results.

Meshing

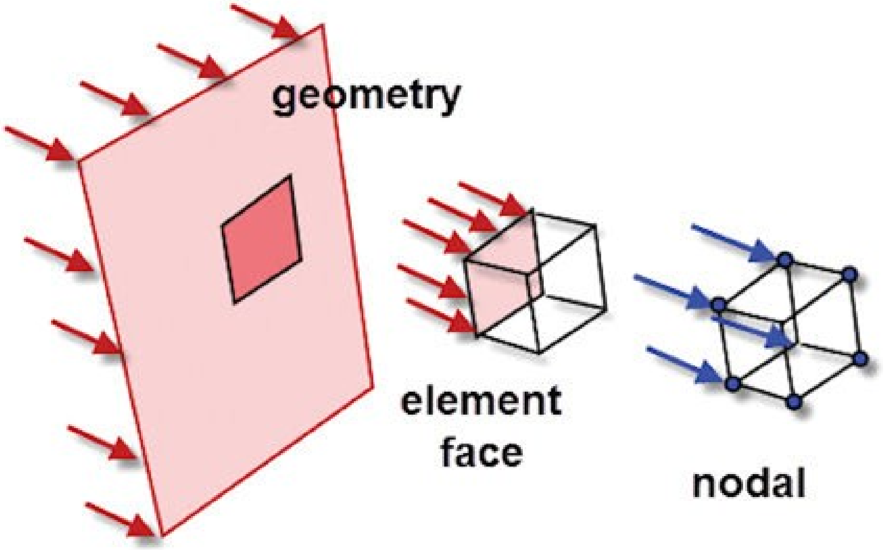
“finite” element analysis

Why Meshing?

- Geometry is split into small 3D pieces
- Vertices are known as nodes
- Boundary conditions are applied to these nodes. These remove degrees of freedom (DOFs)
- As the name “Finite” suggests, essentially you perform calculations at a limited number of points and then interpolate the results for the entire domain

Qty Equations = Qty Nodes * DOF per node

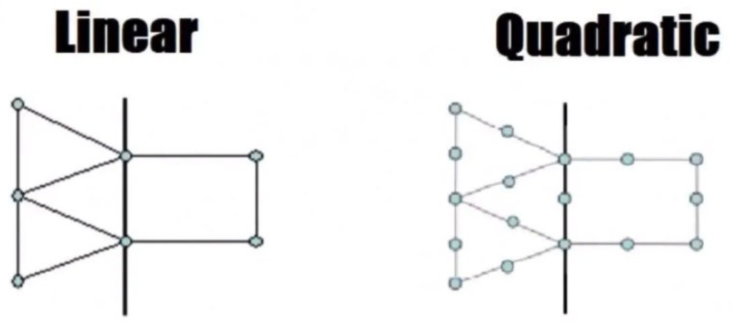
- Nodes = 8
- DoF = 6
- Total Equations = 48
- You can see why you might not want to have an ***infinite*** element analysis



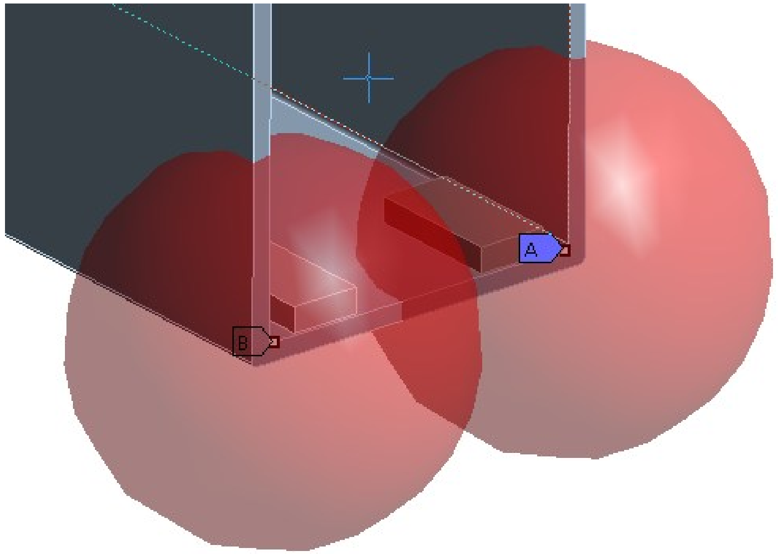
Solid Meshing

- For simple parts use hex dominant mesh
  - Will lead to convergence with far fewer elements than tetrahedral mesh
- Complex parts will generally require a tetrahedral mesh as it's hard to get good hex elements
  - Use element order quadratic even though it's more computationally intensive
    - This means that there will be less interpolation across a given element thus capturing stress gradients better
- If refinement is required in a very specific location, generally mesh sizing with sphere of influence/influence volume is a good option

Element Order

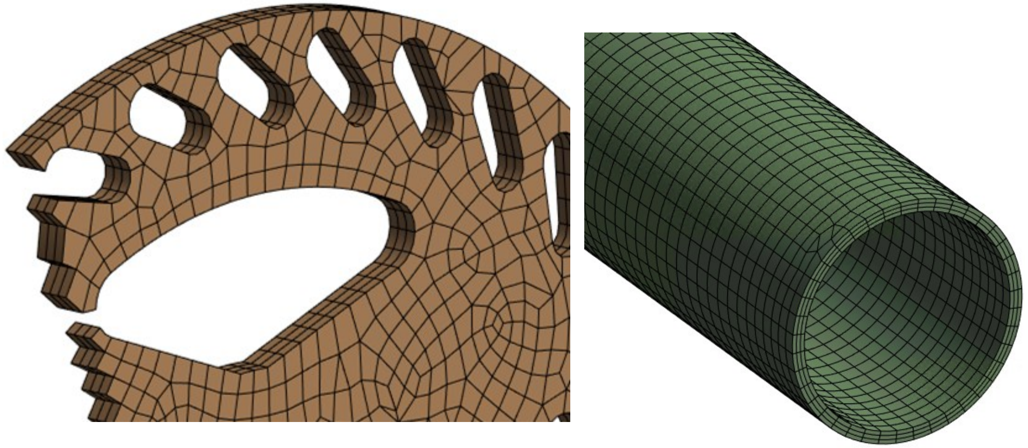


Sphere of Influence

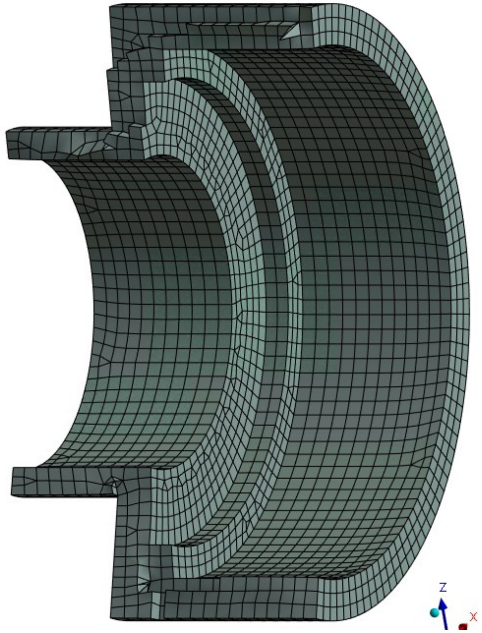


Mesh Methods

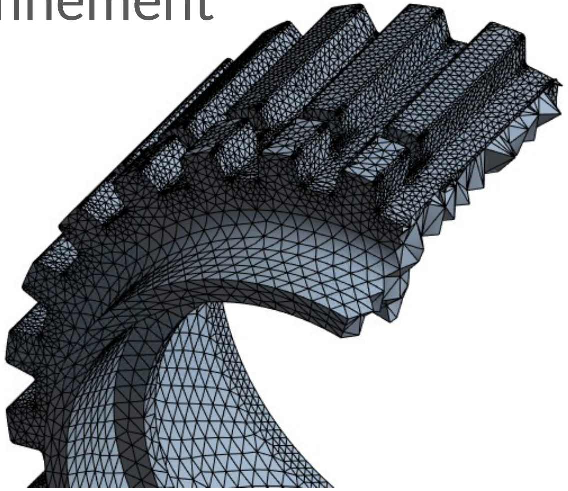
Sweep



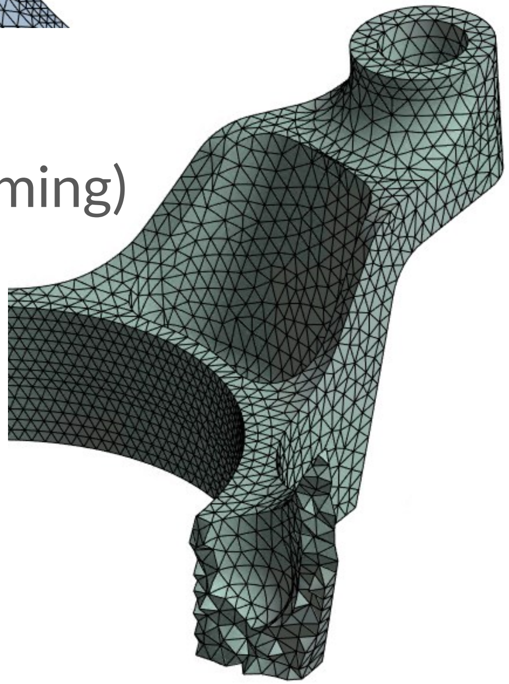
Hex dominant



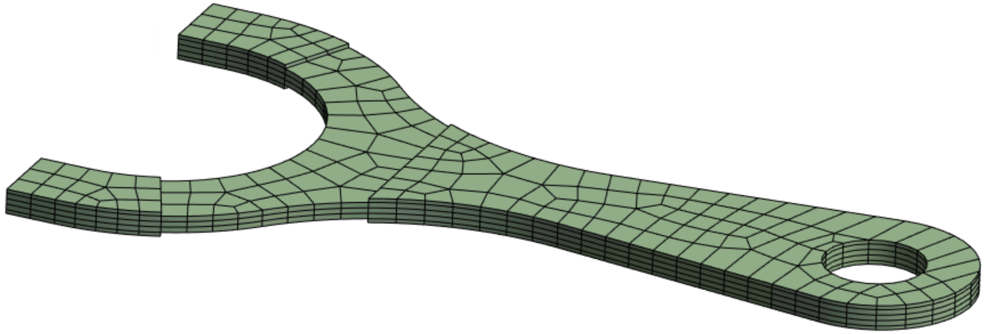
Refinement



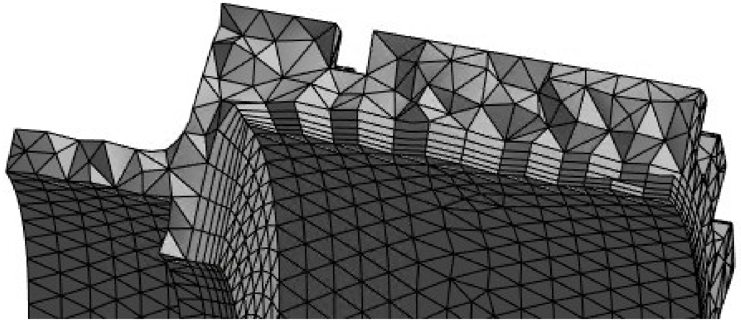
Tetrahedron
(Patch Conforming)



Multizone



Inflation



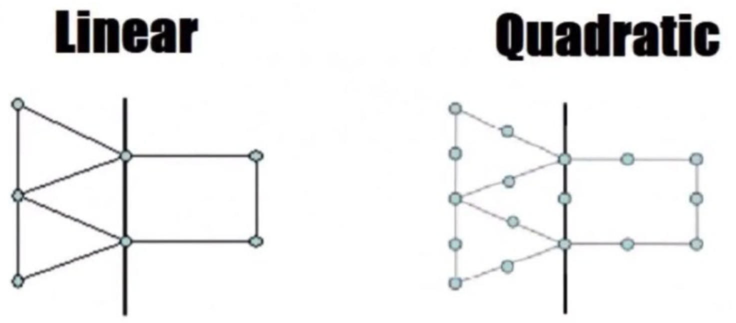
Meshing Hierarchy

1. Sweep
   a. If body is sweepable it will be easier to analyze as elements are all same thickness
2. Hex Dominant
   a. 6 contact faces for further fidelity
3. Multizone
   a. Increased contact faces than Tetrahedron
4. Tetrahedron
   a. Last choice if all else fails
   b. 4 sided pyramids (including bottom face)

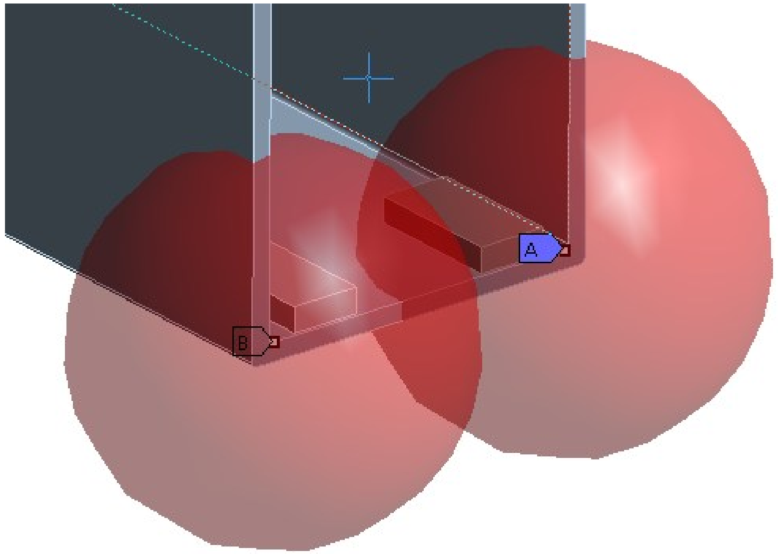
ENSURE QUADRATIC ELEMENTS

PLEASE FOR THE LOVE OF GOD DON'T USE CARTESIAN

Element Order

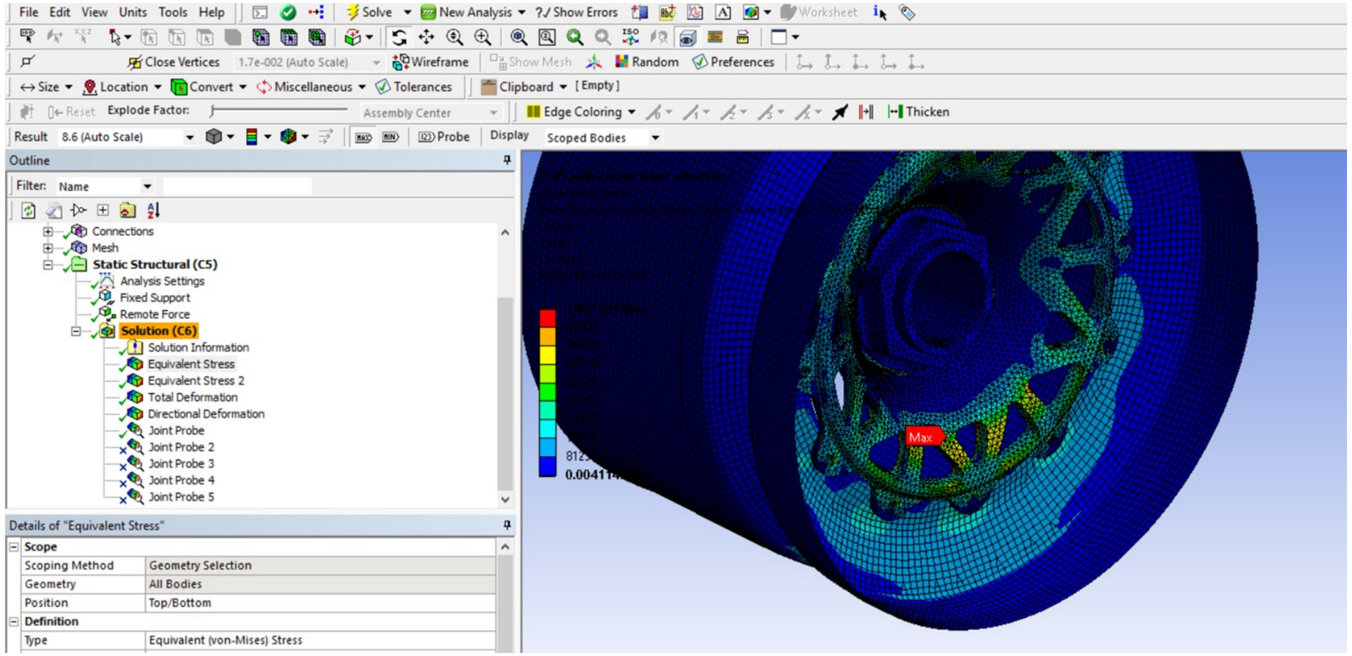


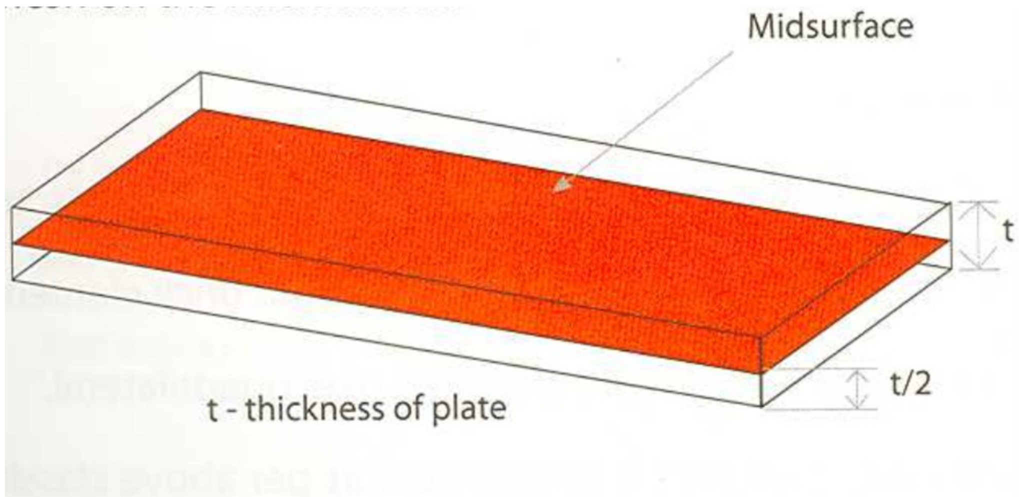
Sphere of Influence



Shell Meshing

- For single surface, constant thickness part, you're in luck a shell mesh can be used (think sheet metal)
    - Accurately captures behavior the shape with far fewer elements than a solid mesh
- In either CAD software or Spaceclaim, the mid-surface of the part must be grabbed
    - Element thickness specified by user
    - ANSYS automatically recognizes a shell mesh is desired if surfaces are brought in

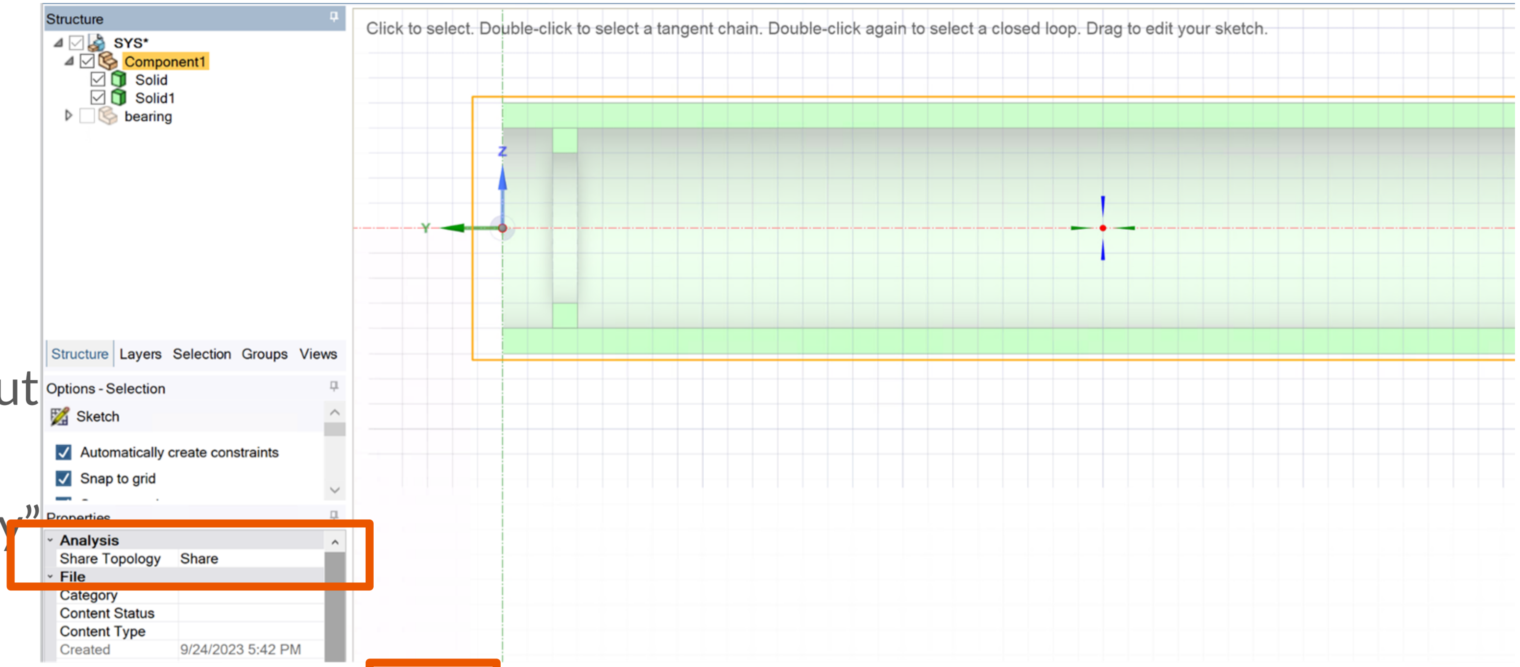




Shared Topology

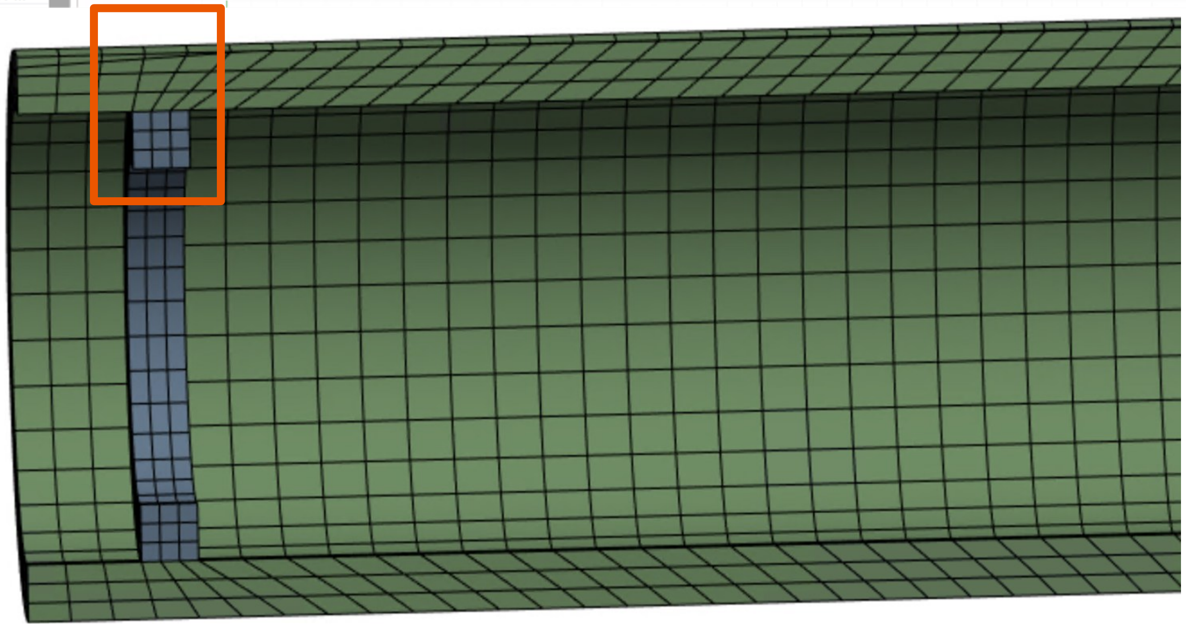
SpaceClaim

- Split almost-sweepable bodies but put them in the same component
- Select “Share” under “Share Topology”



Connections/Meshing

- Ansys will treat these as one component while making connections (no need to bond them)
- Mesh will be shared between shared faces
- Mesh may be assigned by body, so you can sweep them separately

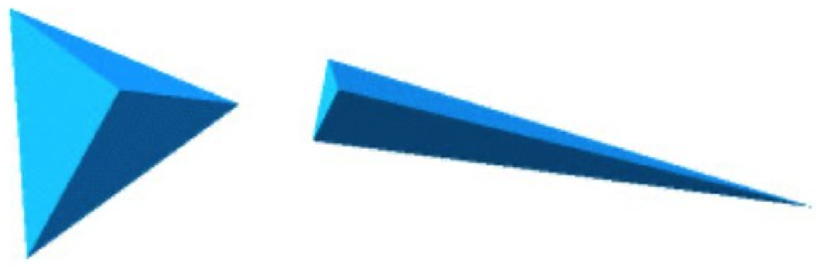


1D vs 2D vs 3D Element

- Exercise to show you guys difference and why you should simplify model where you can
- Cantilever beam that's 250x20x5mm (I don't know why I chose mm, it was very late at night) subject to 35N Force at the end
- Long story short, having the an insane mesh on a part doesn't necessarily get you any better results

	Nodes	Elements	Stress (N/mm^2)	Displacement (mm)
Analytical	-	-	105	4.23
1D	2	1	105	4.23
2D	909	800	103	4.21
3D	17,448	9,569	104	4.21

Mesh Quality Check



Element with aspect ratio close to 1.0

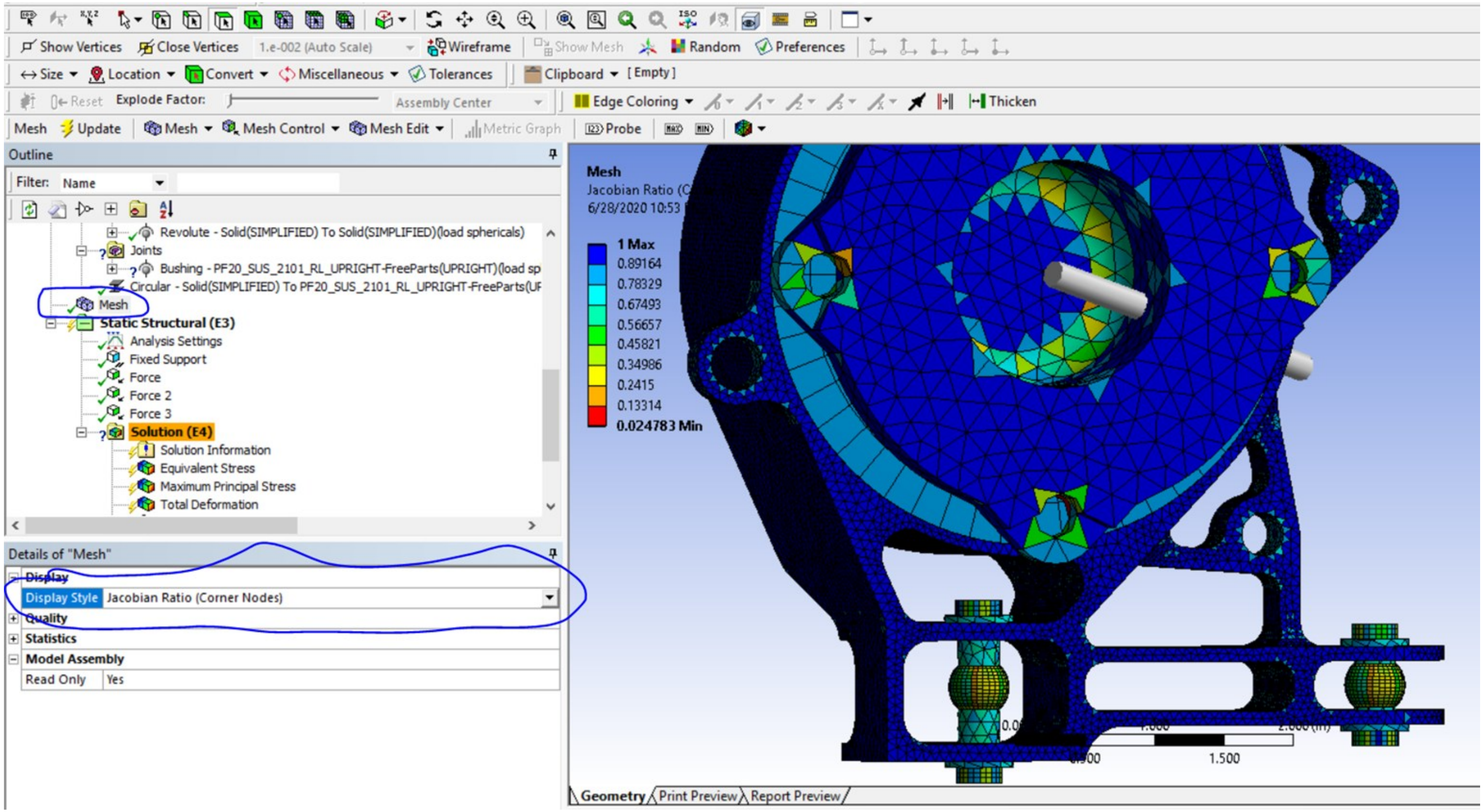
Element with large aspect ratio

Jacobian = 1

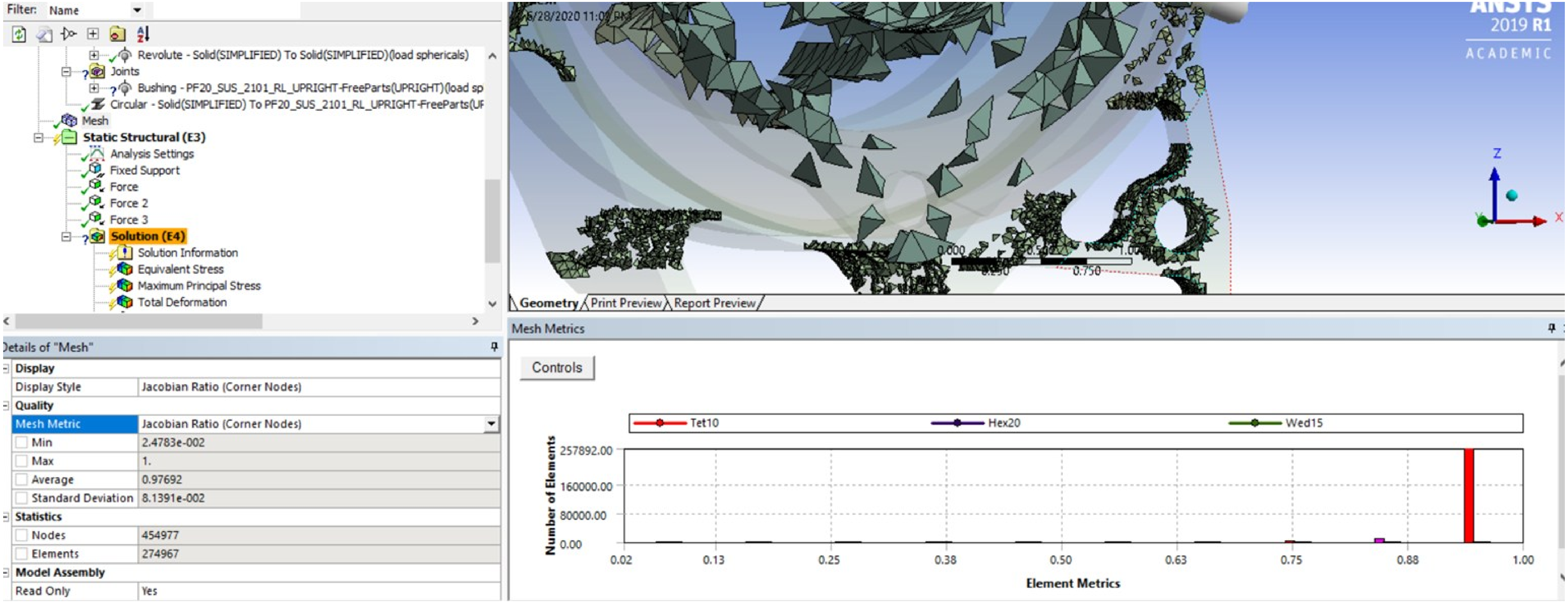
Jacobian approaching zero

- Mesh -> Display Style
- Aspect Ratio
  - Max element edge length / minimum element edge length
  - Target: < 5
  - Ideal: 1
- Jacobian Ratio (Gauss Points)
  - Deviation of given element from “ideally” shaped element for given geometry
  - Target: > 0.66
  - Ideal: 1
- There will always be a few bad elements, just gotta make sure they aren’t bunched up together and are far from critical locations
- NOTE: If you bond two bodies together make sure the contact area has the same element size for both bodies. It saves time!

Mesh Check: Visually



Mesh Check: Histogram



Meshing rules of thumb

- Remember Solving time is a function of the element size cubed! Keep meshes coarse where you can and refine where needed
- If possible, try to get at least three elements across the thickness for bending accuracy
- Start out with sizes around ~.15 in"
- Having elements sizes for touching parts being the same or multiples of each other can increase robustness (ie, for touching parts, have fine detail in .1, and larger mesh being .2, .3, etc)
- If you're having issues with solving or meshing issues, look at the highlighted parts, and often the failed mesh will be much finer around where the mesh is. Try looking in your part in spaceclaim for tiny funky stuff going on at the edges.

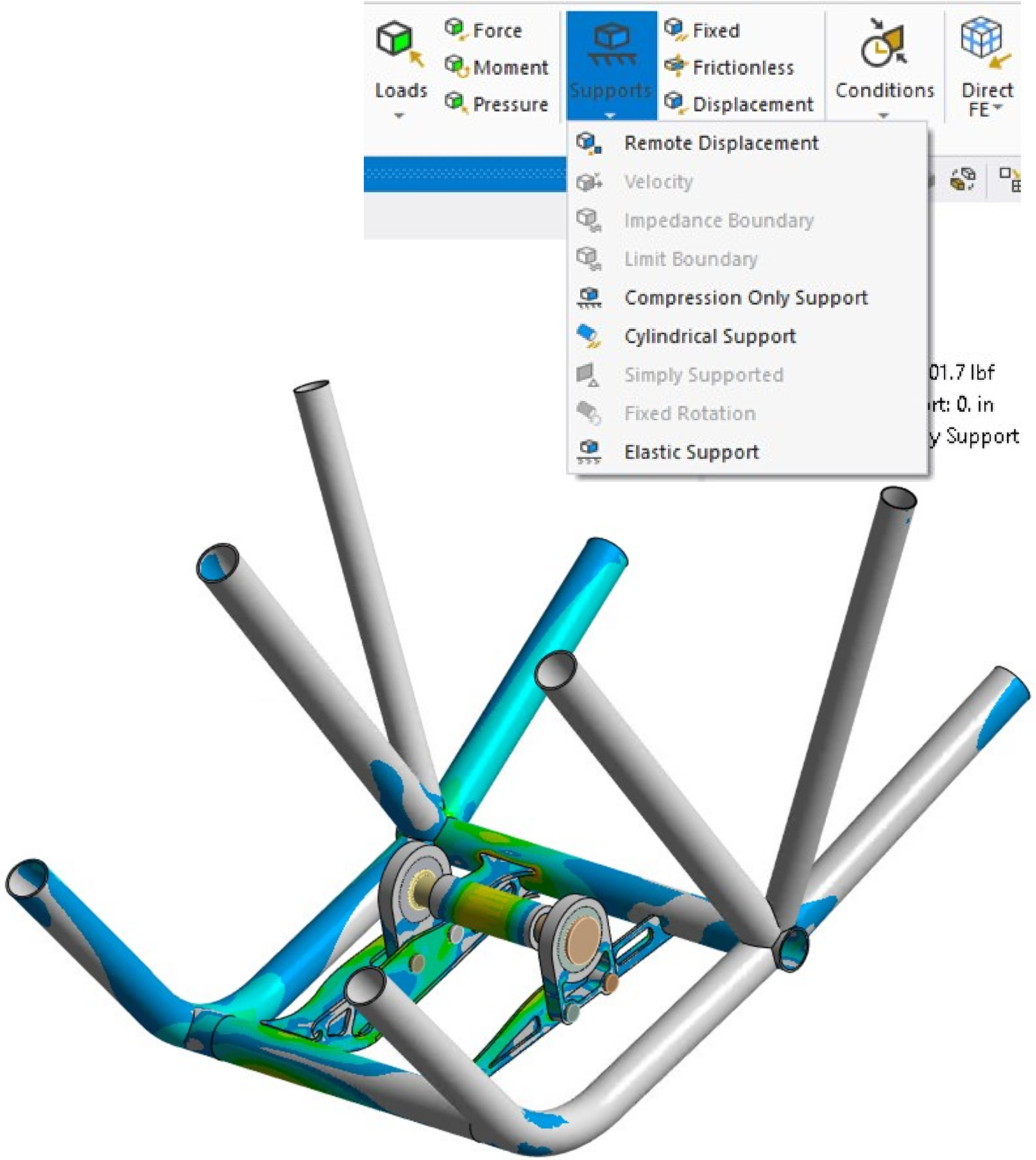
Constraints

Types of supports

- **Remote Displacement:** most generic, works on rigid bodies
- **Fixed:** face will not move or deform in space
- **Frictionless:** face cannot move or deform out-of-plane
- **Displacement:** impose movement in XYZ (or 0 movement)
- **Compression Only:** face cannot move or deform into plane
- **Cylindrical Support:** radially, tangentially, and/or axially fixed
    - Bad for large deflection
- **Elastic Support:** not sure, I’ve never used it

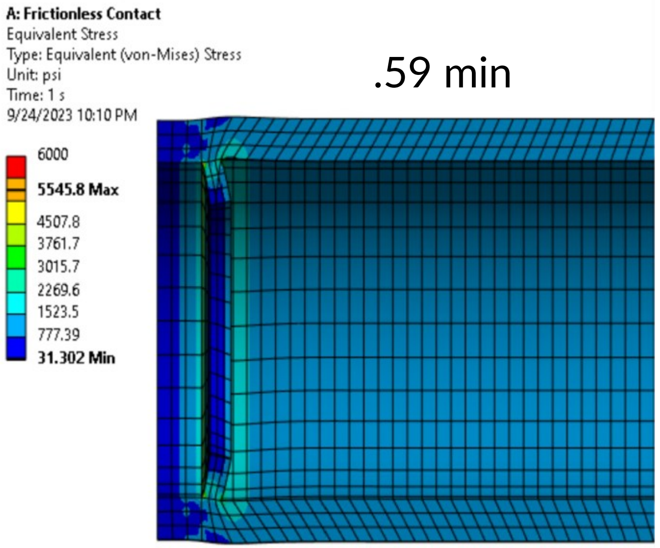
Try not to use supports directly on the part you’re analyzing unless you’re sure it’s correct.

Situate your part in reference to the rest of the car →

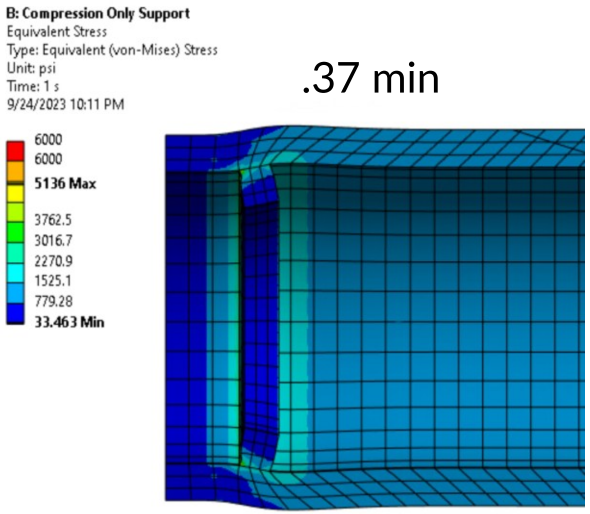


Support Case Study - compression only supports added axially as needed

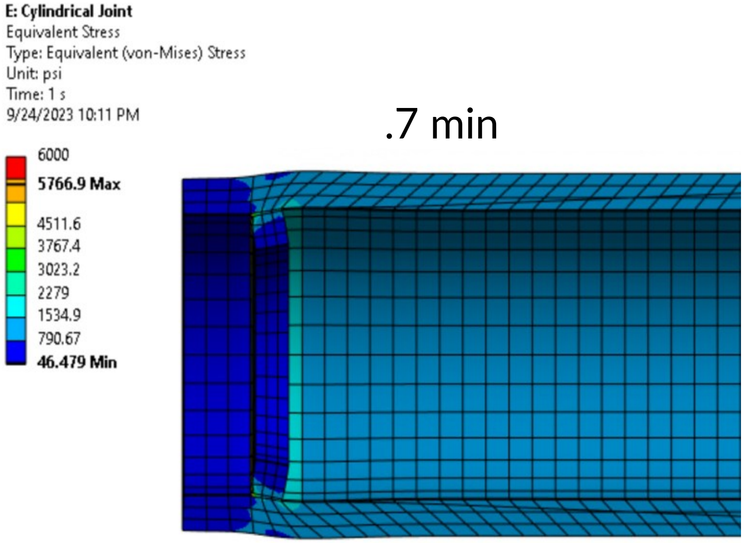
.59 min



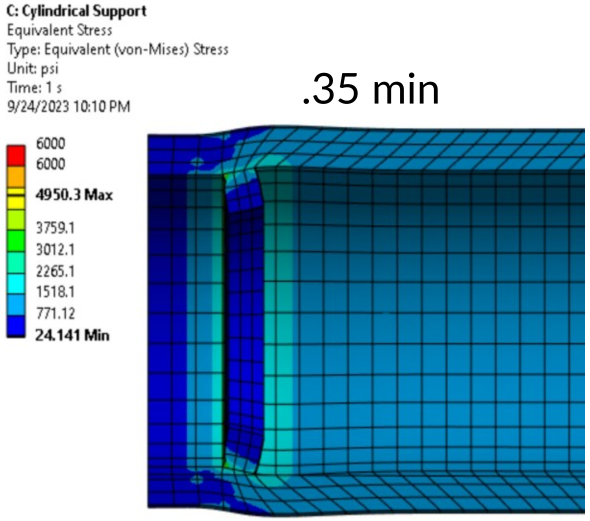
.37 min



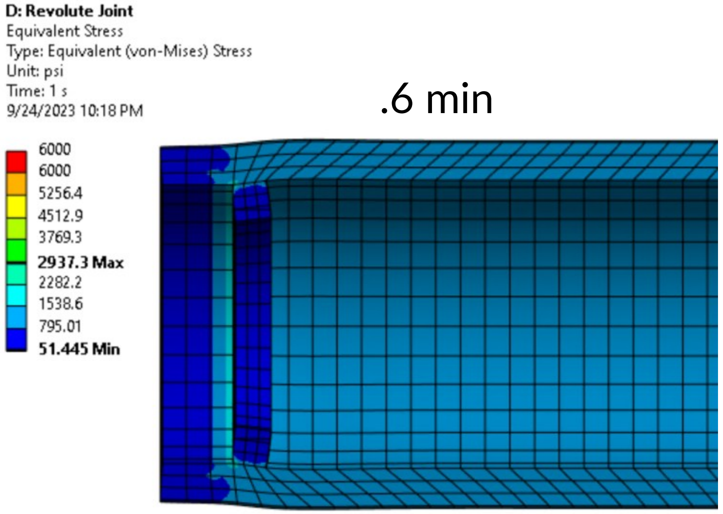
.7 min



.35 min



.6 min



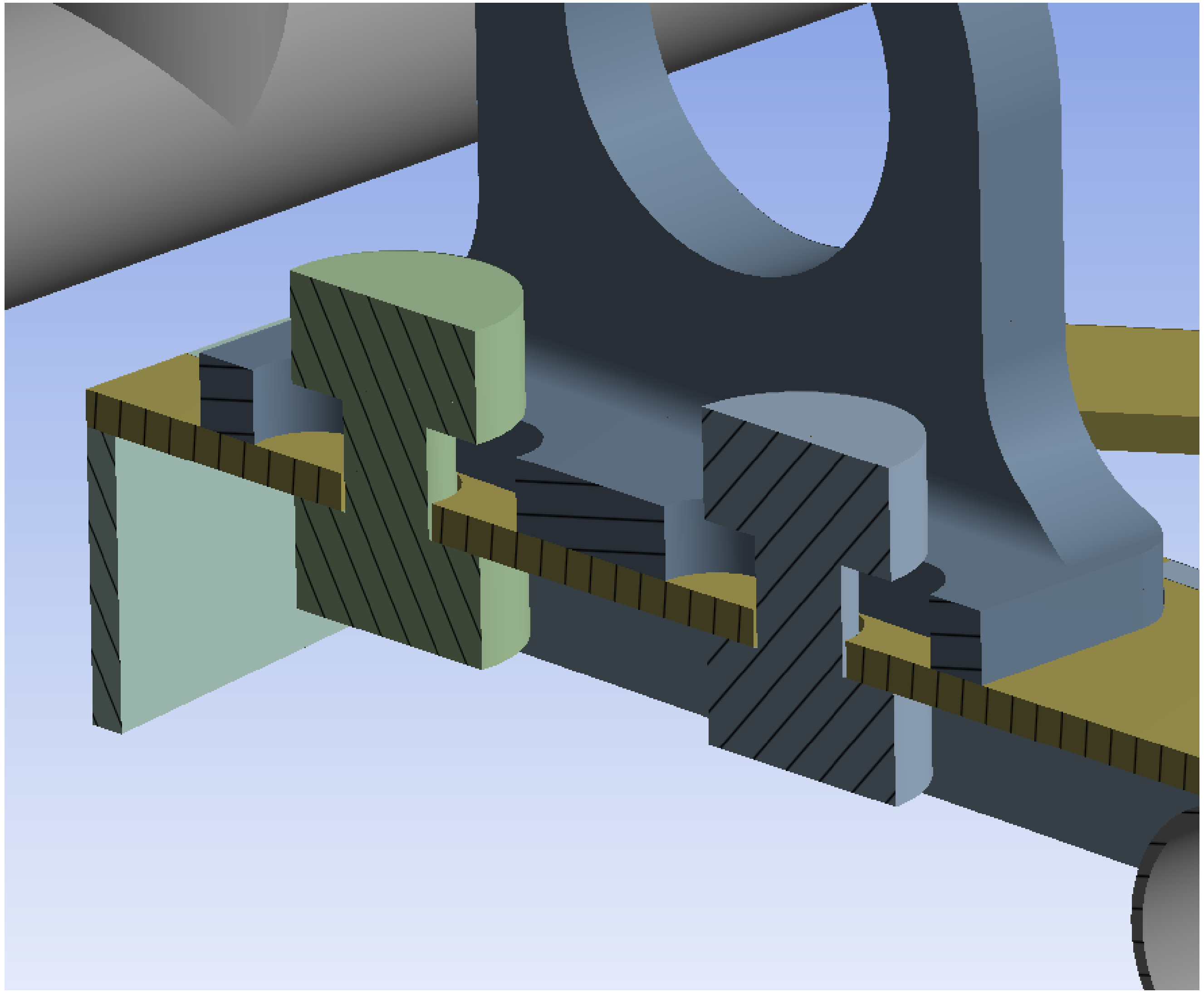
Bolted Contacts

aka “that’ll bolt out”

Bolted Contacts

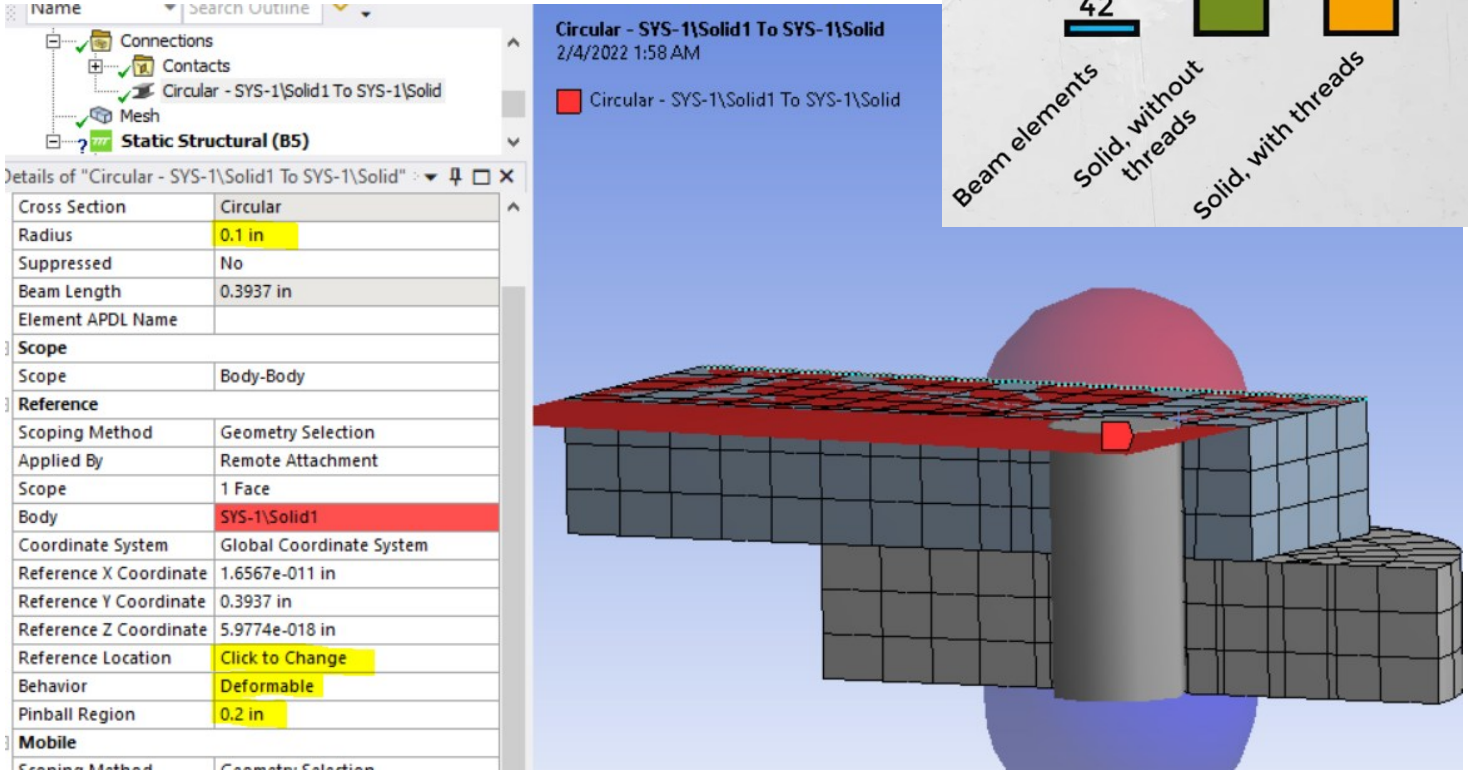
3 ways of modeling bolted joints

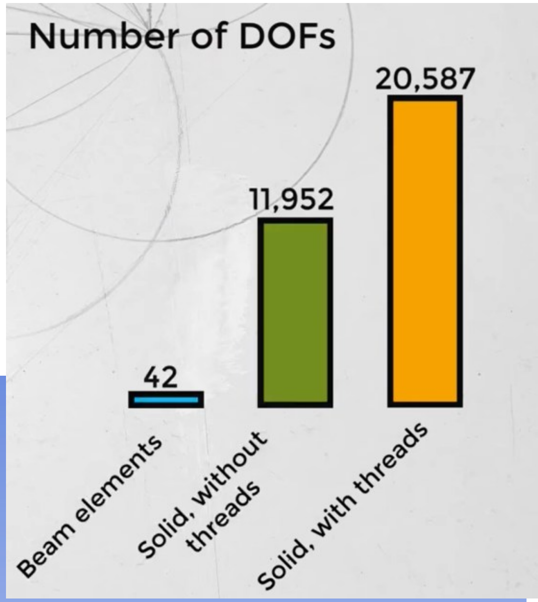
- The right way - modeled pretension
  - Captures stresses in bolts and around the bolts most accurately
  - Can be quite slow and add unnecessary complexity



Bolted Assemblies - The faster way (beams)

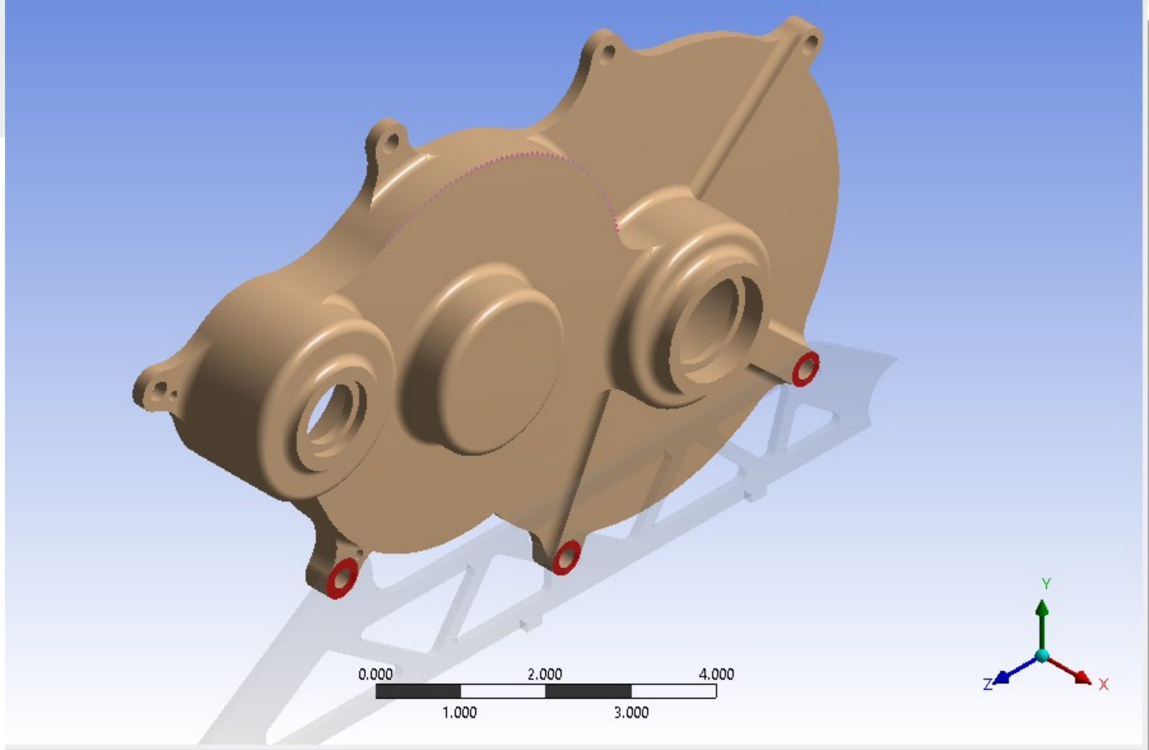
- Almost as accurate as long as the parts of the joint being bolted together aren't thin in comparison to the bolt
- Can still find issues such as slipping and clamp-load failure
- Can solve more quickly and be easier to set up, especially if you don't have bolts in the assembly

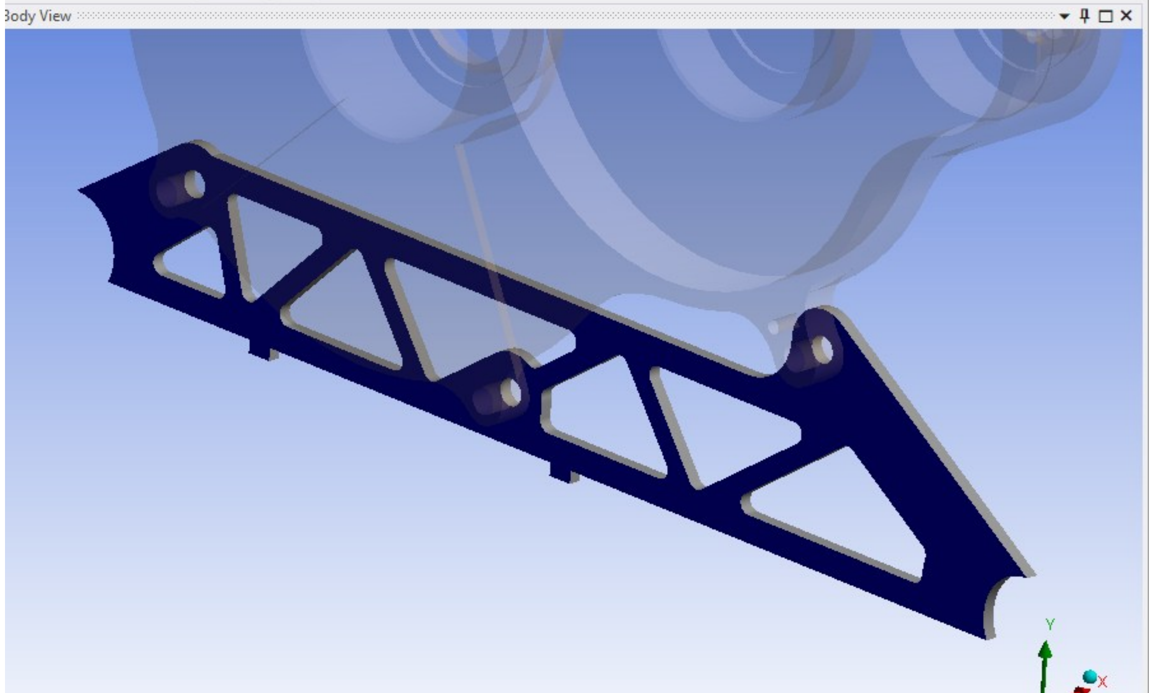




Bolted Assemblies - The ~~wrong~~ Baja secret to hitting deadlines way

- Bonded connections
- Very quick to set up, can remove frictional contacts, remove the preload step and make the solve very quick
- Good for quick iteration
- Always start with a better bolting technique, and ideally end with a better one too, to make sure your model is behaving similarly.





Where do pretension forces come from?

- Check the catalog for bolt pretension values
- This is where a torque specification comes from
- Since we never document which bolts have torque specs, set clamp load to ~70% of recommended

Nominal Dia. (in.)	Threads per inch	307A ASTM A307 Grade A				SAE J429 Grade 5					SAE J429 Grade 8				
		Clamp Load (Lbs.)	Tightening Torque			Clamp Load (Lbs.)	Tightening Torque				Clamp Load (Lbs.)	Tightening Torque			
			K = 0.15	K = 0.17	K = 0.20		Ecoguard™	K = 0.15	K = 0.17	K = 0.20		Eco-guard™	K = 0.15	K = 0.17	K = 0.20
Coarse Thread Series															
1/4	20	859	32 in-lbs	37 in-lbs	43 in-lbs	2029	61 in-lbs	76 in-lbs	86 in-lbs	10 1in-lbs	2864	86 in-lbs	107 in-lbs	122 in-lbs	143 in-lbs
5/16	18	1416	66	75	88	3342	125	157	178	209	4719	177	221	251	295
3/8	16	2092	10 ft-lbs	1 1 ft-lbs	13 ft-lbs	4940	19 ft-lbs	23 ft-lbs	26 ft-lbs	31 ft-lbs	6974	26 ft-lbs	33 ft-lbs	37 ft-lbs	44 ft-lbs
7/16	14	2870	16	18	21	6777	30	37	42	49	9568	42	52	59	70
1/2	13	3831	24	27	32	9046	45	57	64	75	12771	64	80	90	106
9/16	12	4912	35	39	46	11599	65	82	92	109	16375	92	115	130	154
5/8	11	6102	48	54	64	14408	90	113	128	150	20340	127	159	180	212
3/4	10	9030	85	96	113	21322	160	200	227	267	30101	226	282	320	376
7/8	9	12467	136	155	182	29436	258	322	365	429	41556	364	455	515	606
1	8	16355	204	232	273	38616	386	483	547	644	54517	545	681	772	909
1-1/4	7	26166	409	463	545	53786	672	840	952	1121	87220	1090	1363	1545	1817
1-3/8	6	31182	536	607	715	64096	881	1102	1249	1469	103939	1429	1768	2025	2382
1-1/2	6	37942	711	806	949	77991	1170	1462	1657	1950	126473	1897	2371	2688	3162

https://www.fastenal.com/content/merch_rules/images/fcom/content-library/Torque-Tension%20Reference%20Guide.pdf

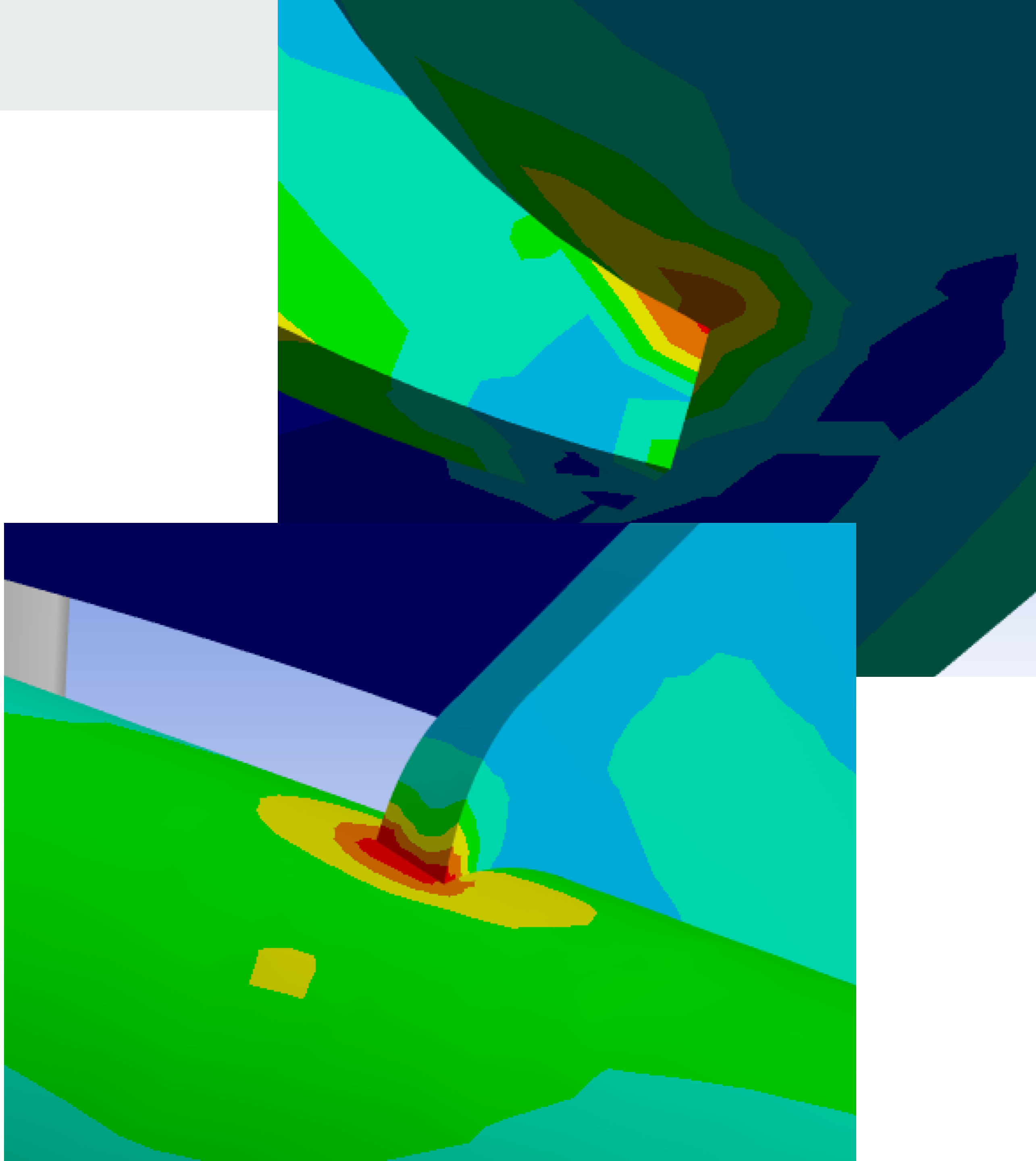
Stress Concentrations

aka “what to ignore” and “what not to ignore”

Inside Edges

Stress concentrations form at hard inside edges. This is *primarily* caused one of three ways

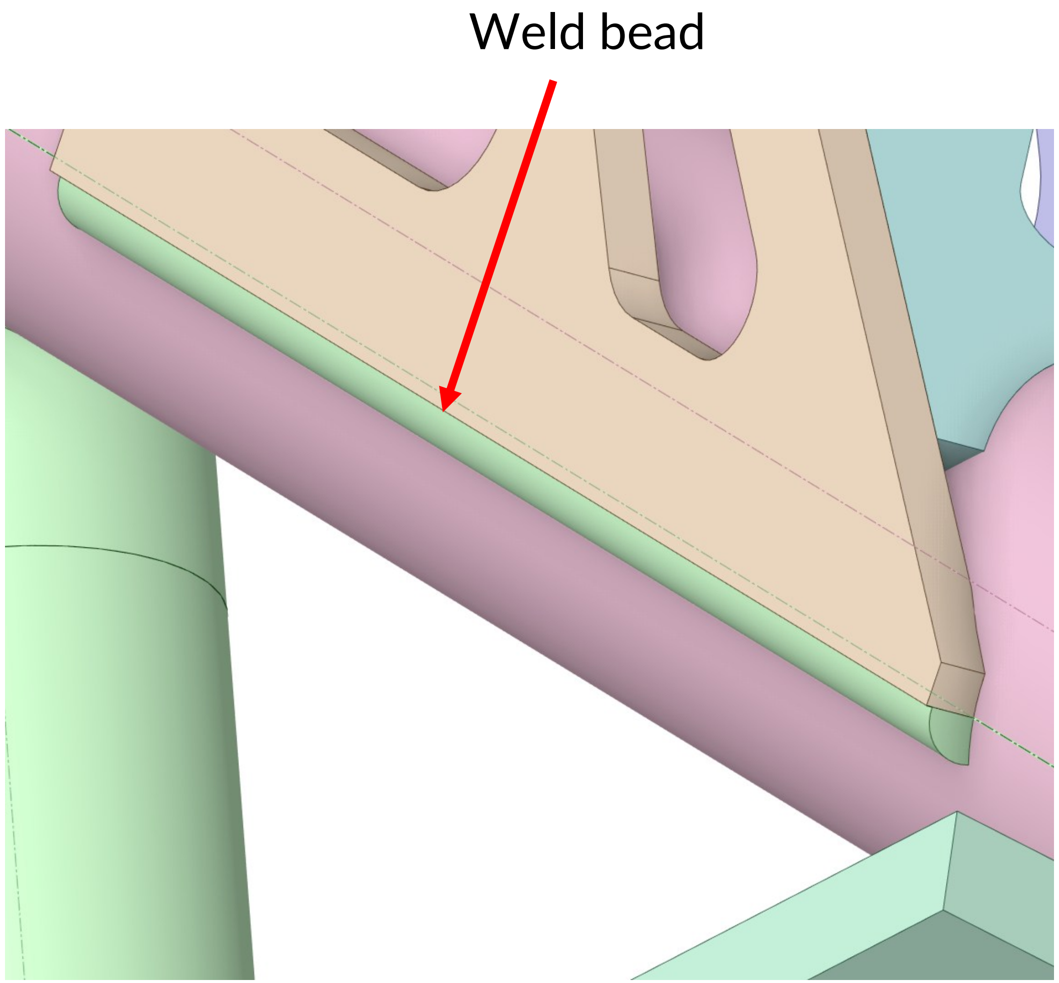
- Poor design -> add a fillet (or increase radius) to a CNC'd part
- Lack of weld modeling (shown to the right) -> add a fillet to represent the weld bead (or ignore if it's small)
- Mesh is too coarse -> decrease element size or change method (this will help tell you if the high stress is real or a result of the corner)



Modeling Welds Continued

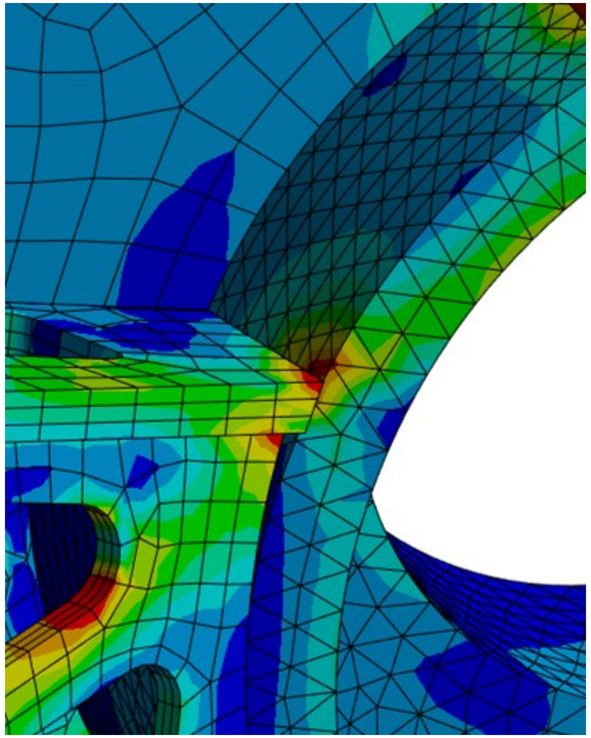
Ways to model welds

- Do not use chamfers to model welds as the edges will have singularities
- Use fillets **that are smaller than the expected weld** which is acceptable because of the ductility of metal. It is a reasonable assumption that any discontinuities will yield out
- PSA: **Analyze weld with correct tensile and yield strengths for given fill rod.**
- A separate body can be added to represent the bead

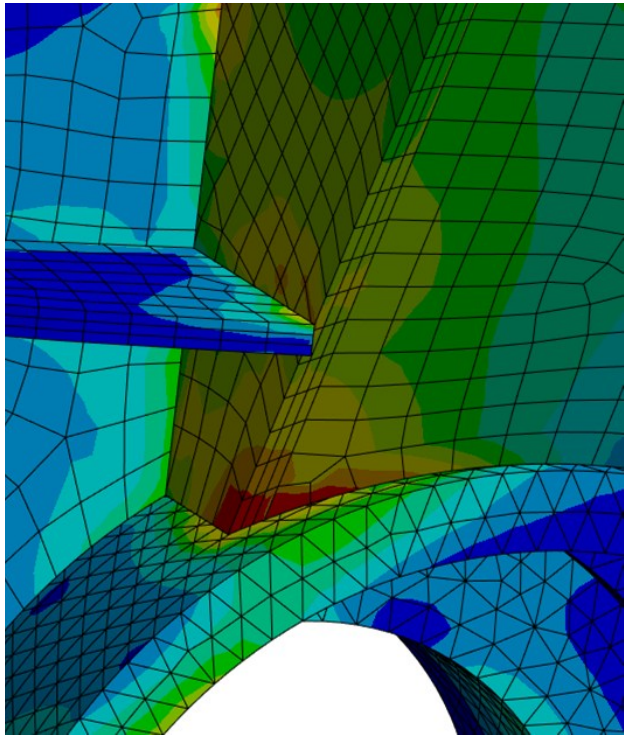


Modeling Welds Continued

Will this weld out?



Probably



Probably not

- Modeling welds is generally more complicated due to the strength knockdown associated with the heat affected zone
- For an annealed metal, it is acceptable to directly model in welds
    - No strength knockdown associated with heat effect
- When analyzing welds on a cold worked or heat treated metal, the same process could be used if you assumed that the material becomes annealed at the weld .... otherwise, you have some work to do.

How to read your solution information

aka “Should I kill this?”

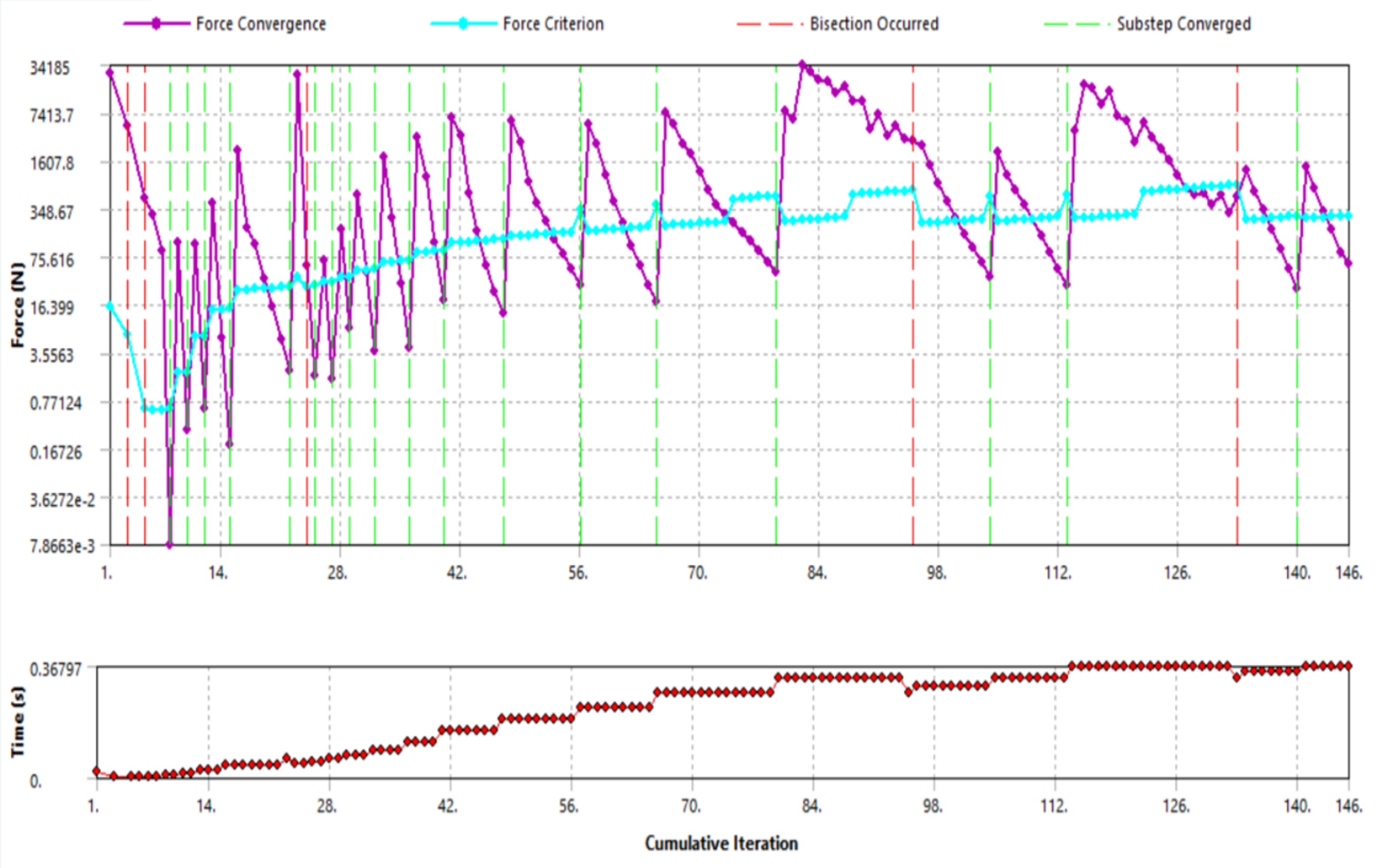
Force Convergence

Substep Convergence happens when the Force Convergence reaches the Force Criterion. Moves on to the next step.

Bisections happens when it can't converge. Cuts the step in half.

3 Bisections? Kill it.

Your FEA is done when the Time reaches 1



Solution History

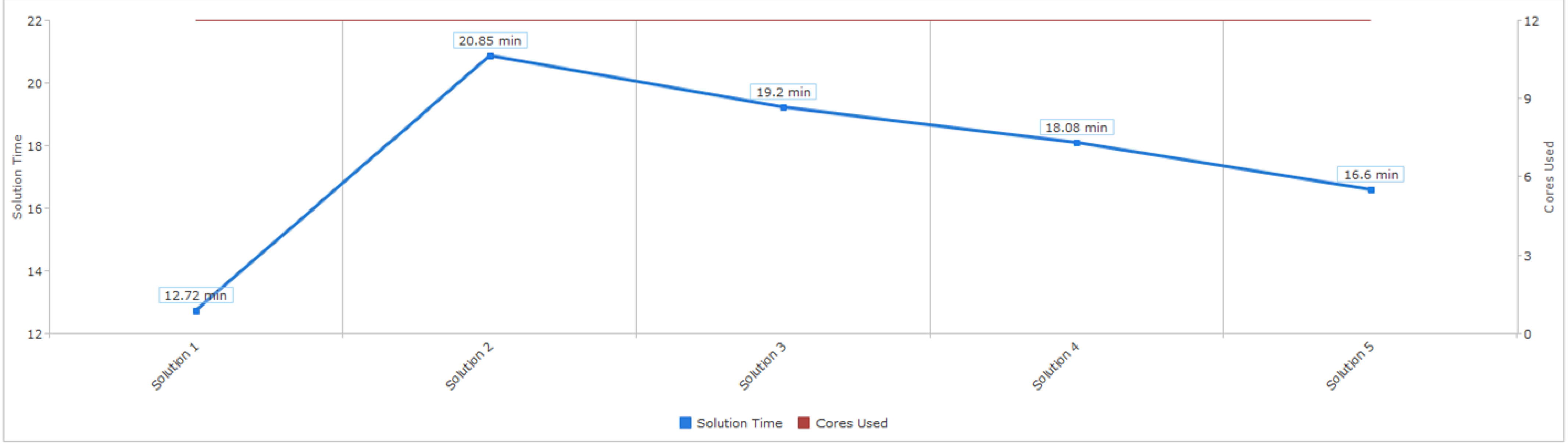
- Can see how long past solves took
- Be suspicious of drastic changes

Solution History

Solution Tracking | Result Tracking

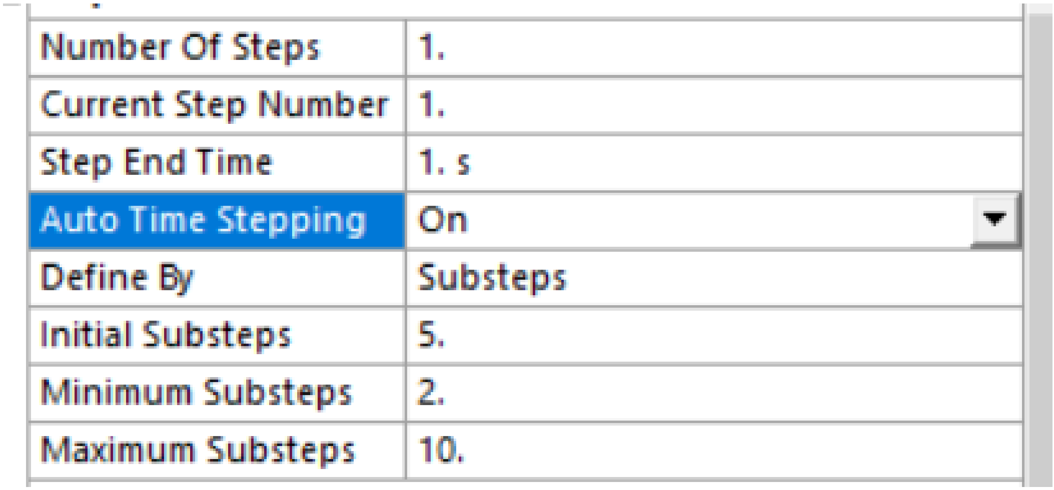
	☐ Nodes	☐ Elements	☑ Solution Time	☐ RAM Used	☑ Cores Used	☐ IO Write	☐ IO Read	☐ Element Load Balance Ratio
Solution 1: 11/03/2022 01:25 PM	394,122	244,029	12m 43s	13.46 GB	12	22.20 GB	54.50 GB	1.093
Solution 2: 11/05/2022 06:26 PM	394,099	242,323	20m 51s	14.09 GB	12	23.20 GB	59.40 GB	1.087
Solution 3: 11/07/2022 01:29 AM	544,932	330,508	19m 12s	18.79 GB	12	32.10 GB	86.10 GB	1.103
Solution 4: 11/07/2022 09:31 AM	540,501	329,530	18m 5s	18.80 GB	12	32.00 GB	84.10 GB	1.11
Solution 5: 03/02/2023 12:15 PM	544,858	330,577	16m 36s	19.06 GB	12	32.10 GB	84.90 GB	1.13

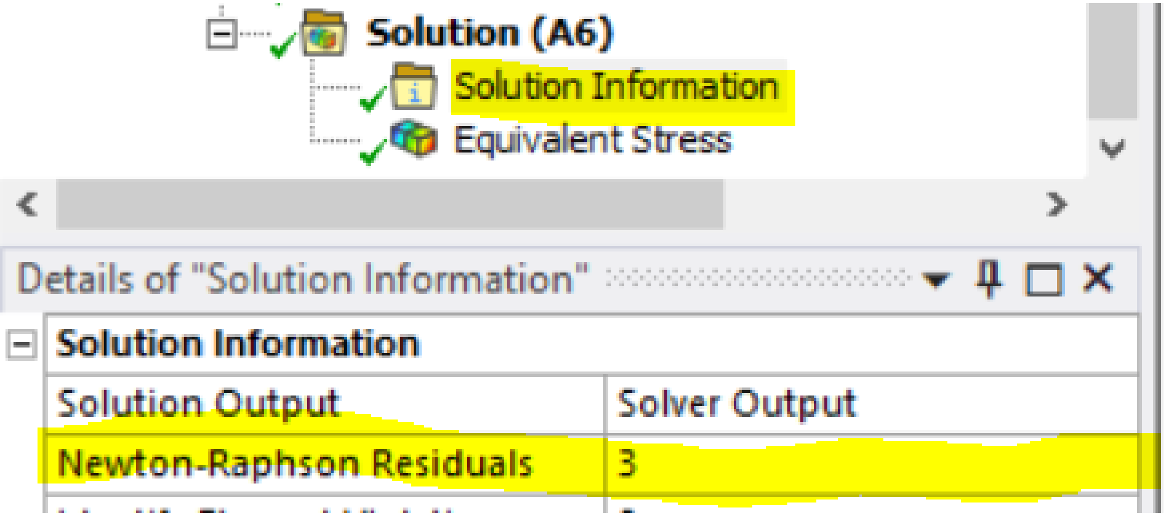
Go to page: 1 Show rows: 20 1-5 of 5



Load Steps and Analysis settings

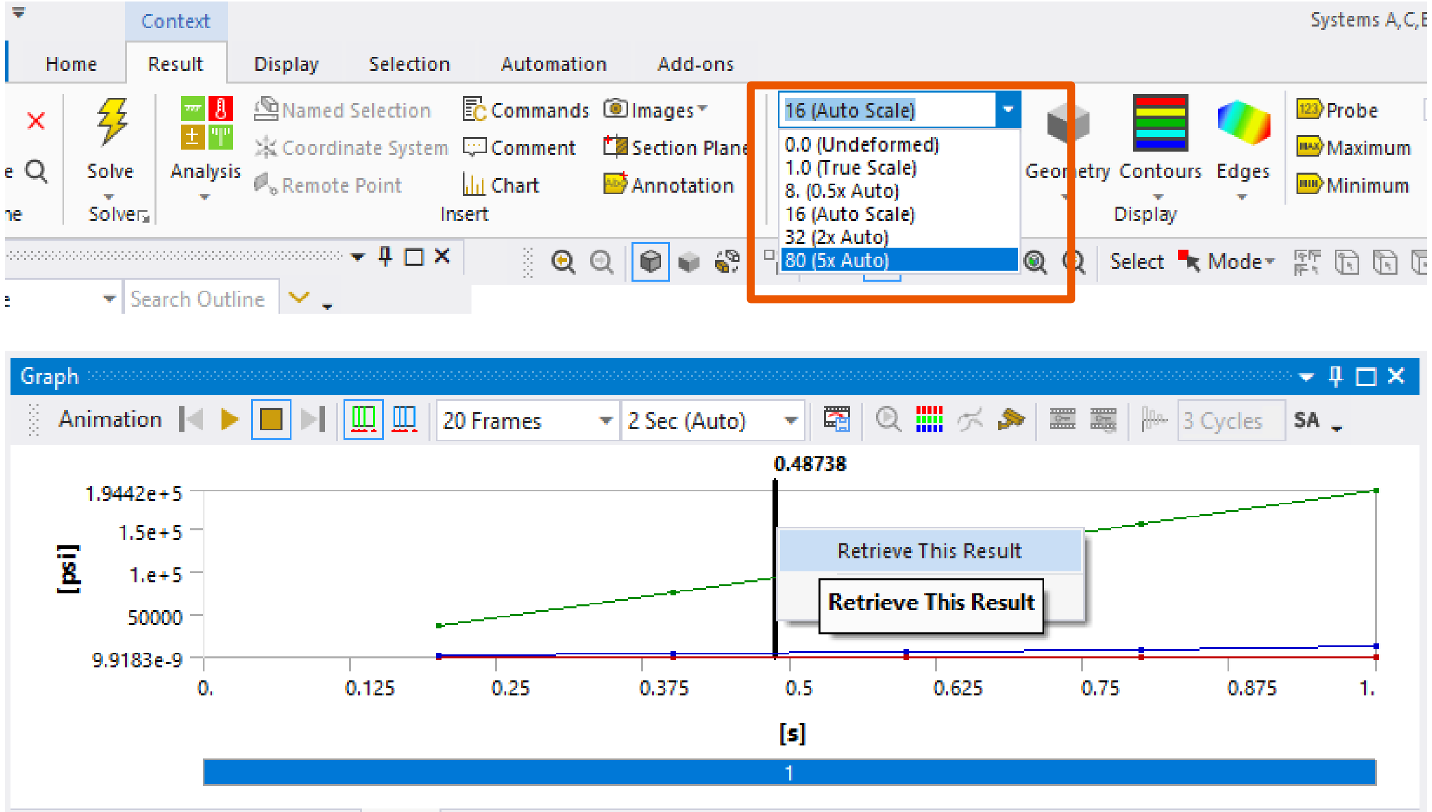
- You can force Ansys to take smaller steps to improve solving for complicated assemblies
- ***LARGE DEFLECTIONS SHOULD TYPICALLY BE ON***
- Newton-Raphson residuals can be a good way to troubleshoot convergence issues





Results Video

- Turn up your scale
- Play the animation to make sure the part moves as expected
- If the solution failed to converge you can still load the last solved step to see what's going wrong

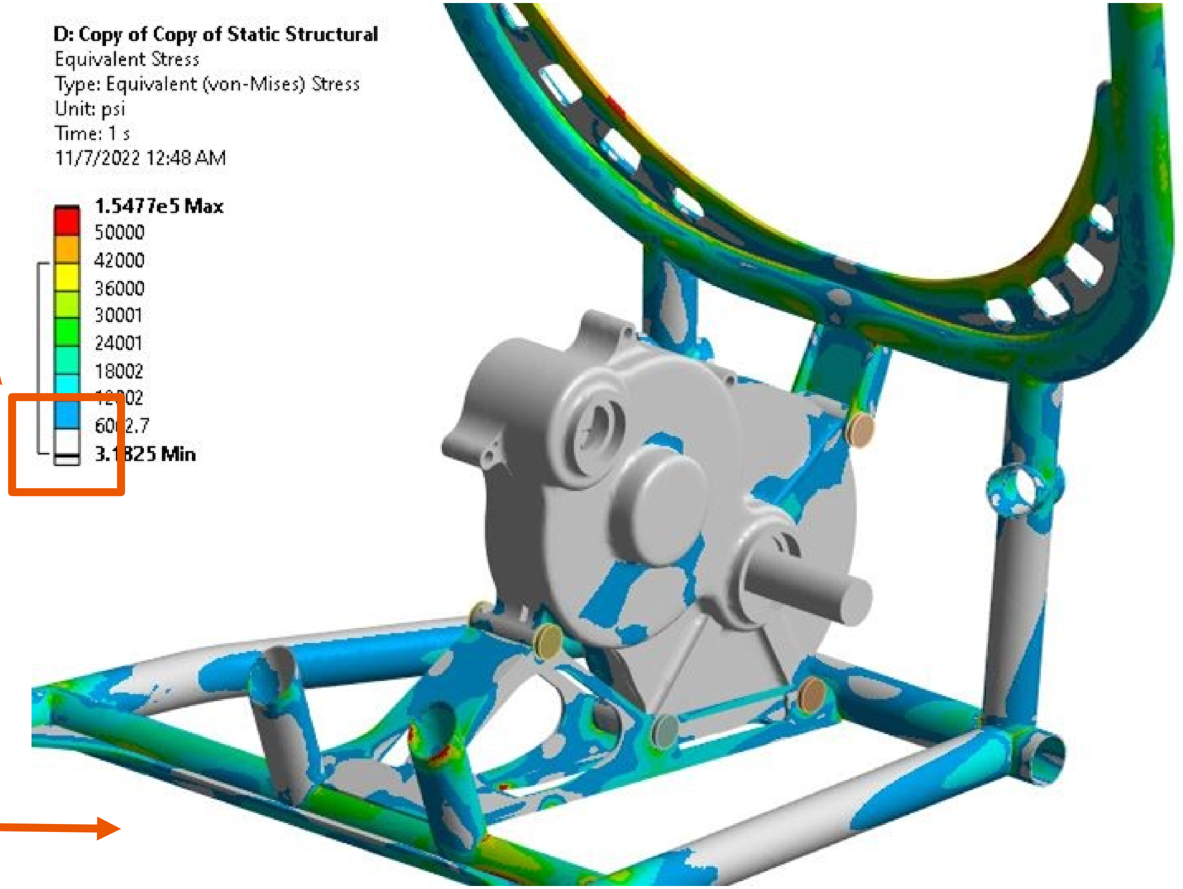


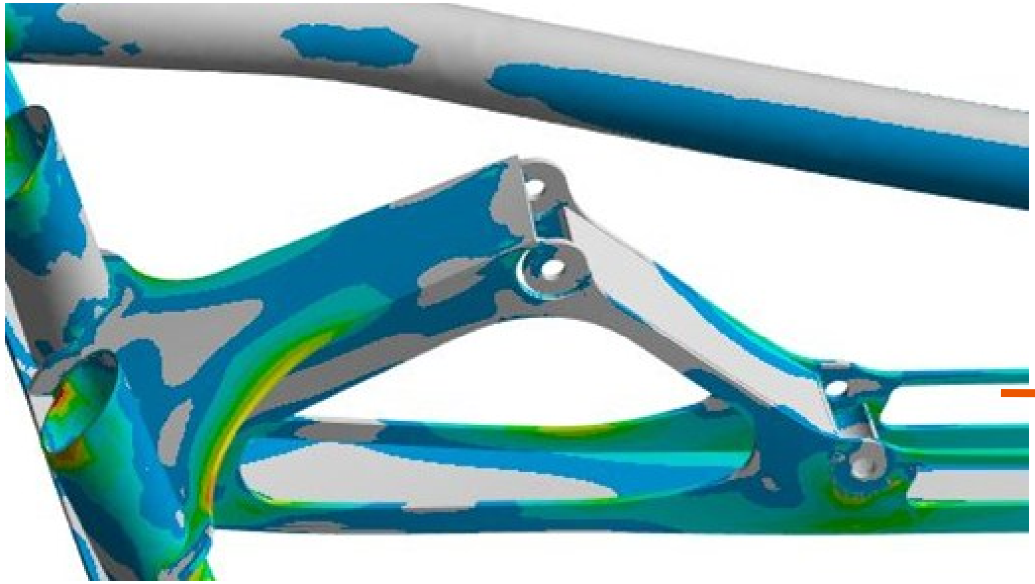
How to iterate

Where to put holes or add material

Where to cut material

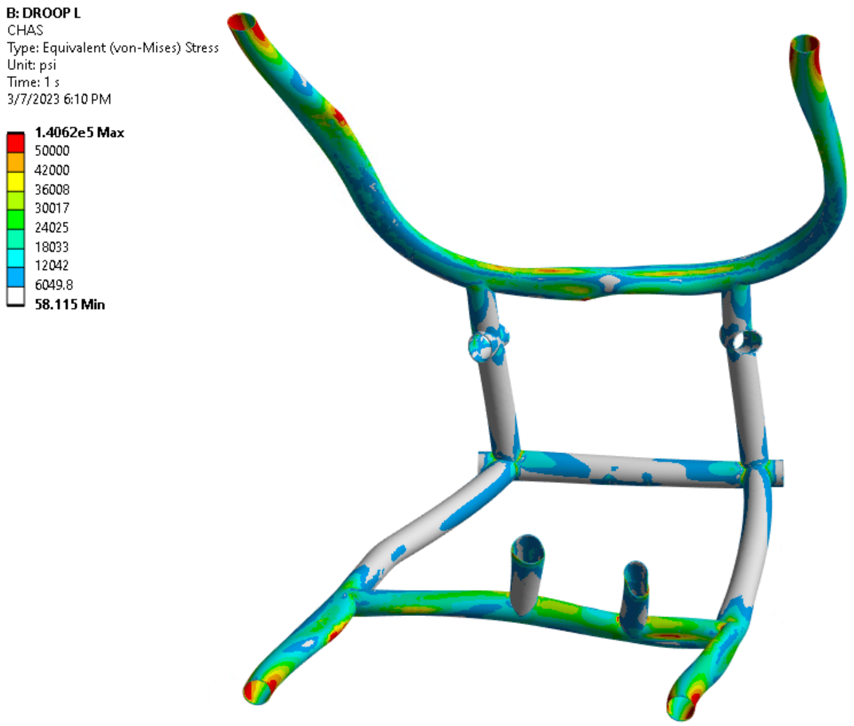
- Making the low stress areas white helps show places to cut weight
- Make sure area is white on both sides, otherwise it is in bending

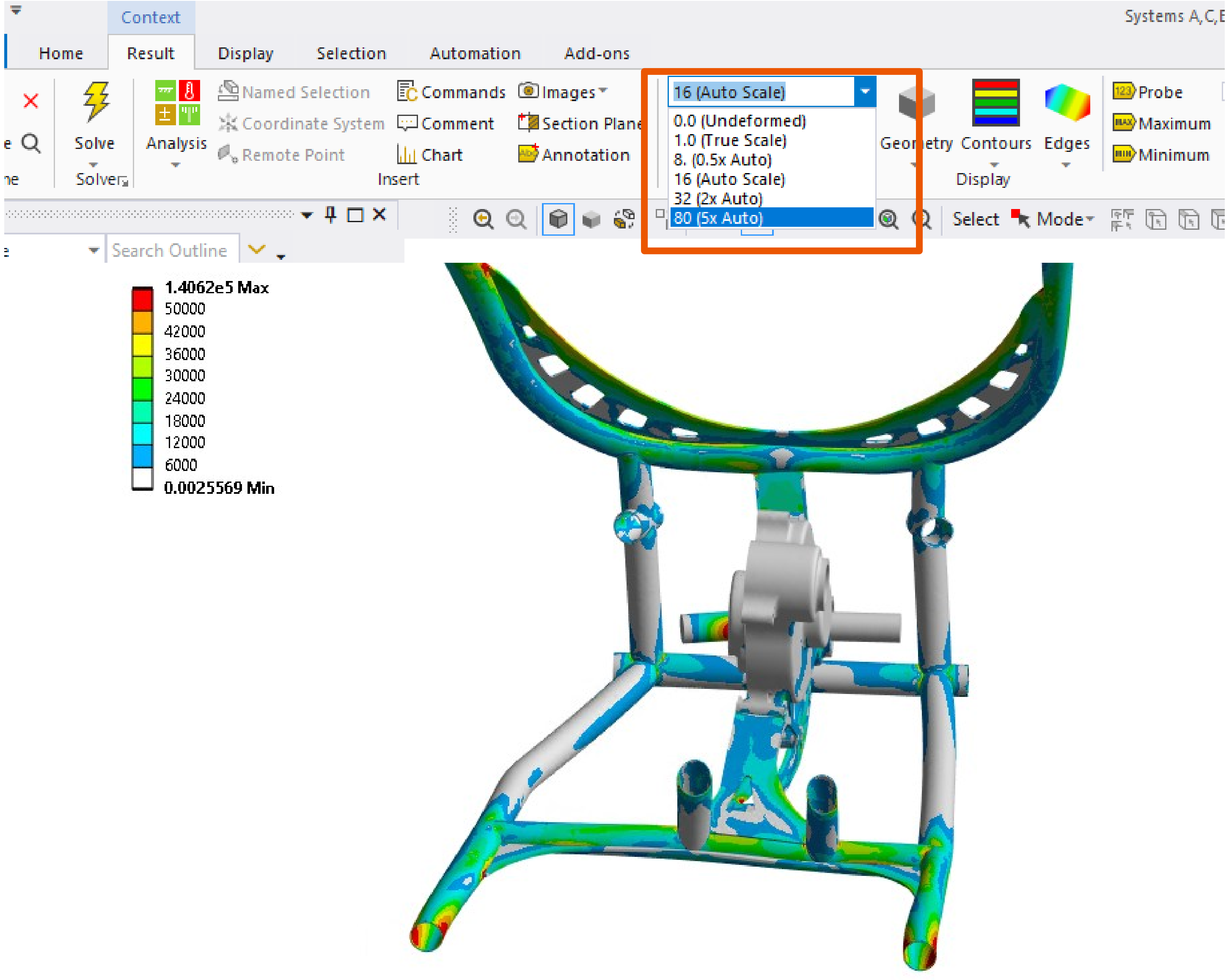




Where to add material

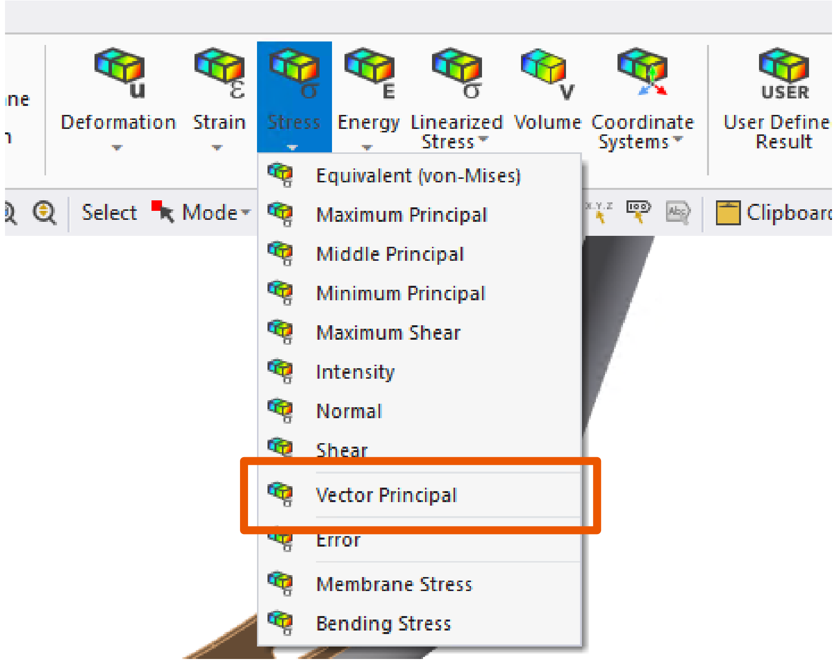
- Turn up Deformation Scale
- Only add material in the plane of deflection

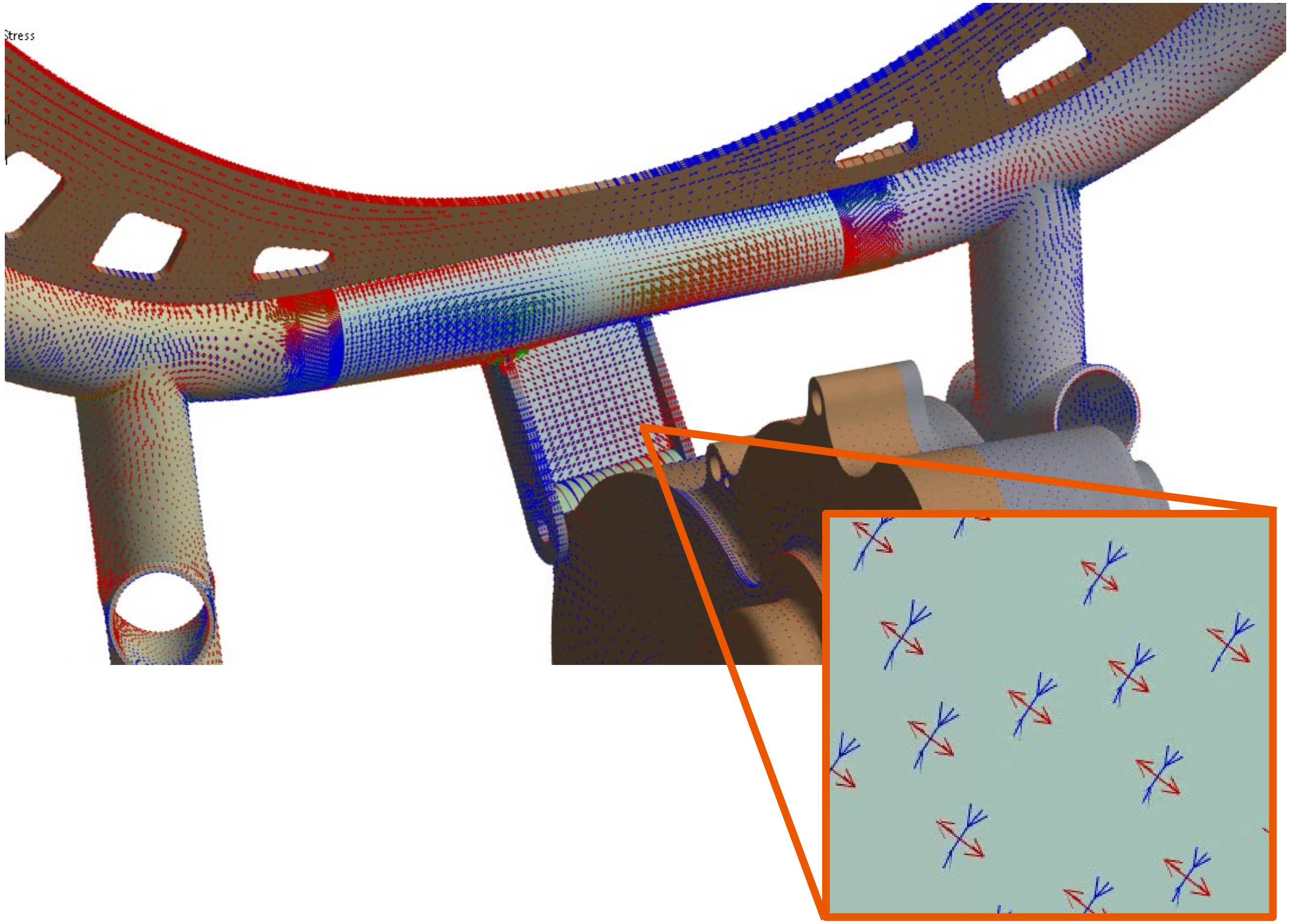




When you can't tell...

- Use Vector Principle Stress to see compression/tension
- Good when you can't tell what's going on





How does this all apply to your projects?

FEA – Sprocket

- Notes
  - FEA ran without splined section to ease meshing
    - Calculations carried out on spline stress calculator as previously defined
  - Loading from tooth table applied onto first 7 teeth
    - Represented under 5% of the max load that is seen
      - Ran sim using first 13 teeth, but proved to be no more useful than 7 in terms of peak stresses obtained

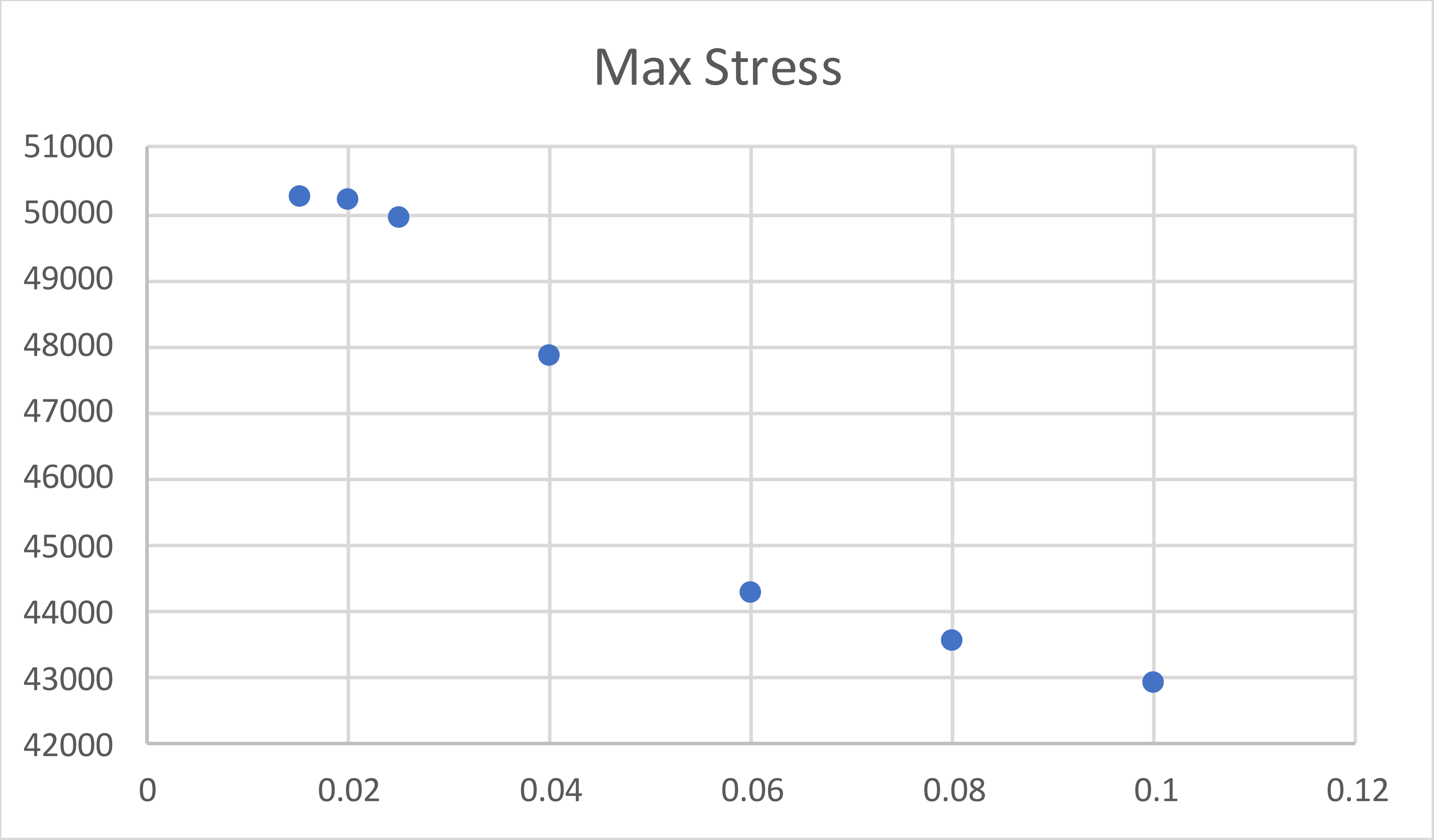
FEA – Sprocket

- Setup:
  - First seven tooth forced modeled as point loads on surface of tooth
  - Frictionless supports on the sides
  - Cylindrical support where spline would be
    - Changed from PDR (based on IDR feedback)
    - Sprocket is fixed relative to the differential, but the differential is free to rotate. Thus, a cylindrical support was recommended

FEA – Sprocket

- Mesh Convergence Study:
  - Element size changed to perform study

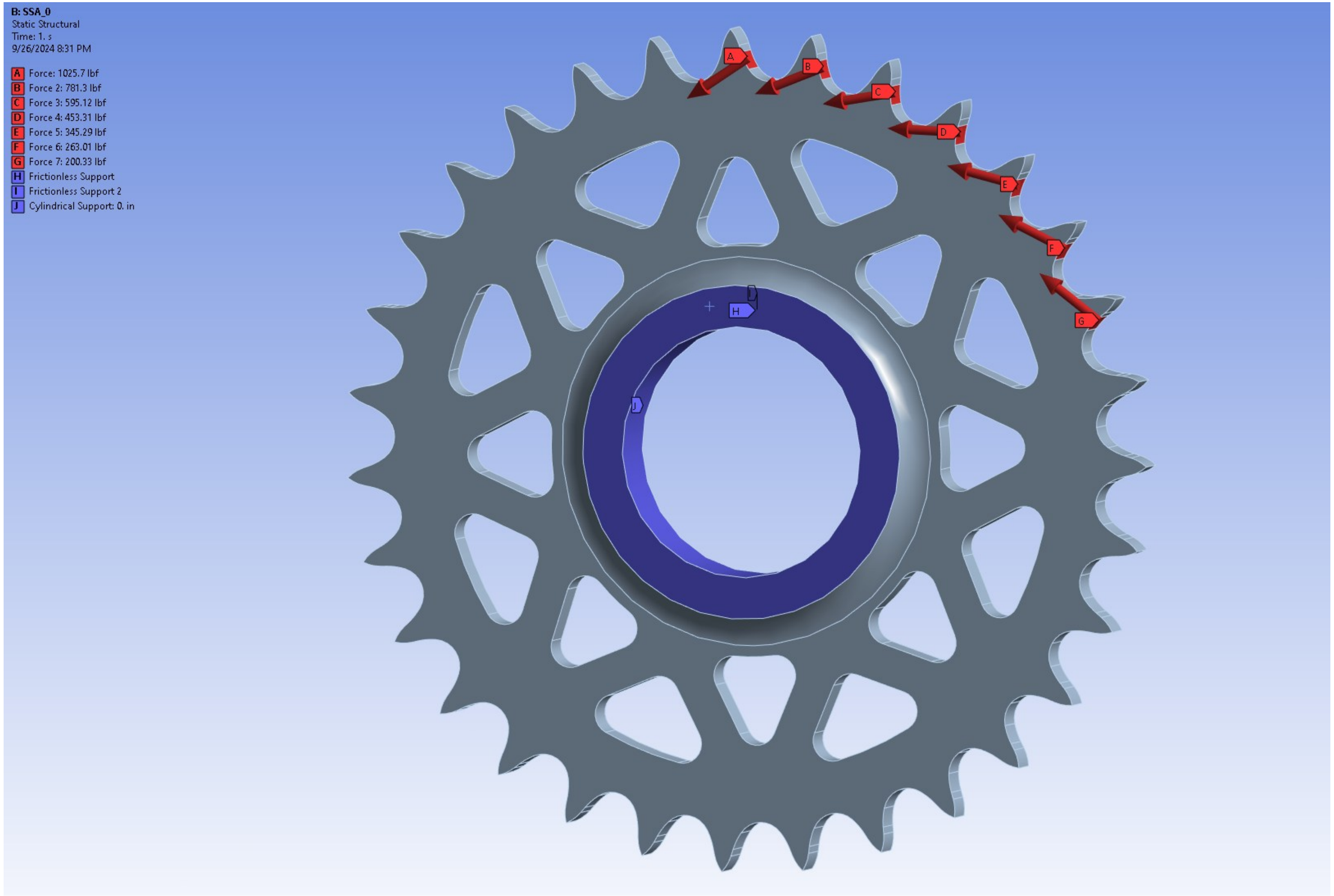
Element Size	Max Stress
0.1	42946
0.08	43621
0.06	44311
0.04	47911
0.025	49960
0.02	50242
0.015	50283

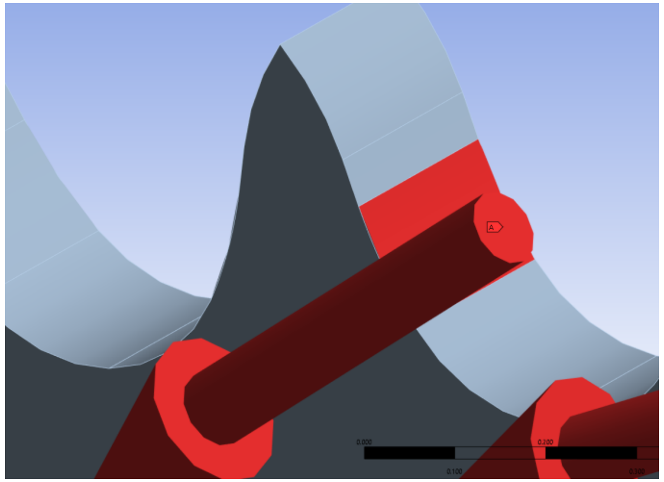


FEA – Sprocket

- Final Mesh Parameters:
  - General:
    - Element Size – 0.025 in
      - Ran SOI where needed
      - Decided on upon results from mesh convergence study
    - Element Order – Program Controlled
  - Patch Conforming Method
    - Tetrahedrons
    - Patch Conforming Algorithm
    - Quadratic Element Order

FEA – Sprocket

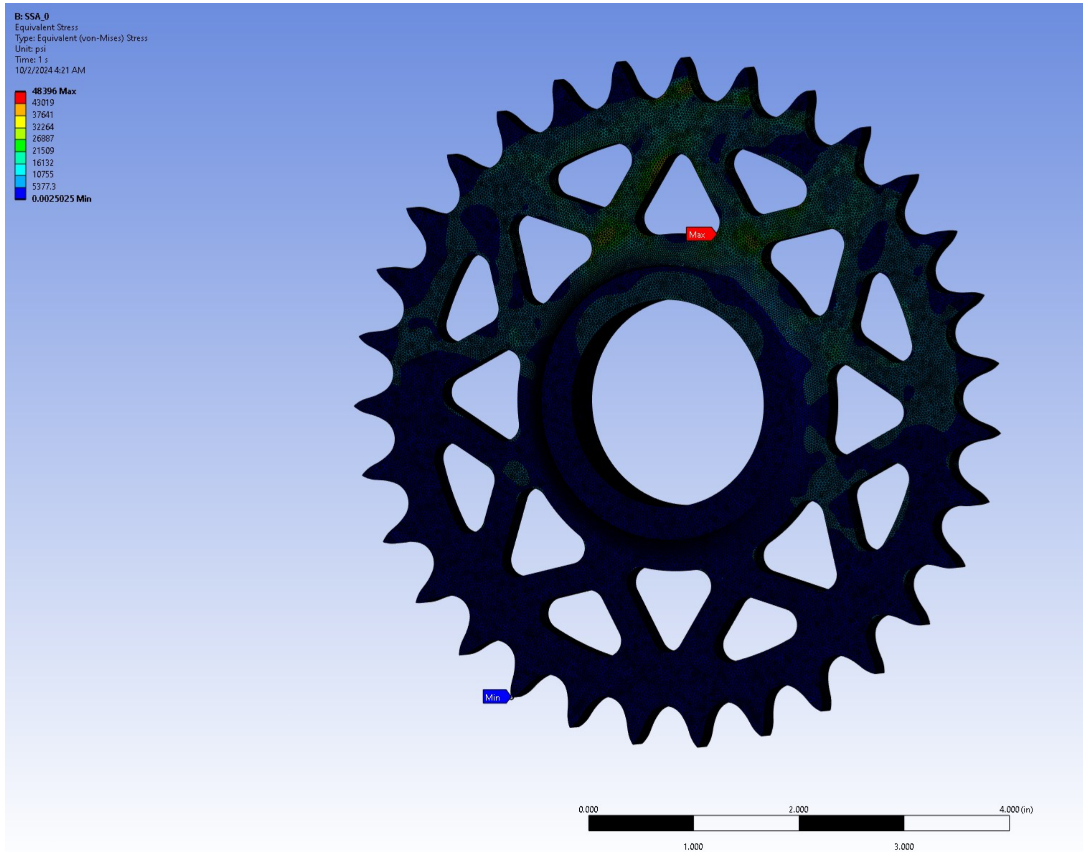


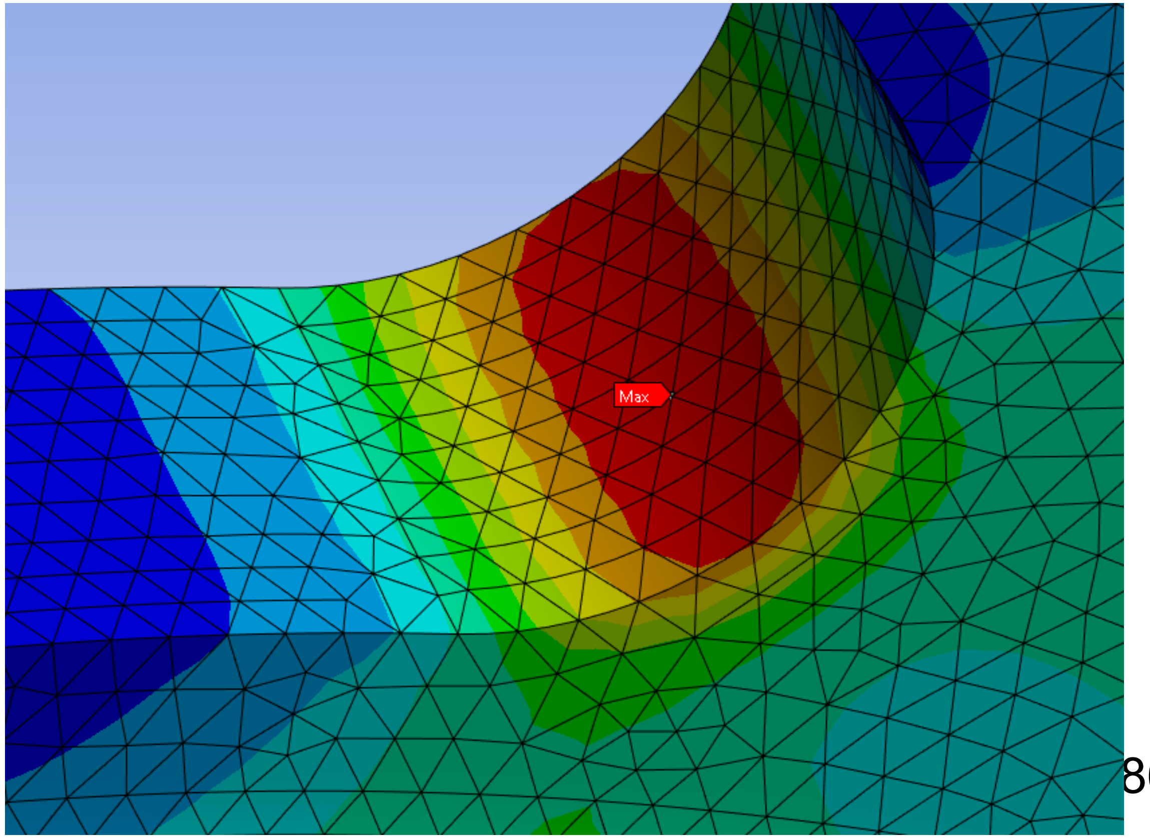


FEA – Sprocket SSA_0

Load Case: SSA_0	Solver: Ansys	Material: Al 7055-T77511	Geometry: Linear
Safety Factor Ultimate: 1.4	Safety Factor Yield: 1.2	Temperature: 71.6 F	Notes:

Section	Max Stress	Failure Mode	Material	Yield Allowable (with knockdowns)	Ultimate Allowable (with knockdowns)	MS_Yield	MS_Ultimate	Jacobian Ratio (Gauss Points) Avg	Aspect Ratio Avg
	43896 psi		Al	61600 psi	57000 psi			0.99844	1.8946

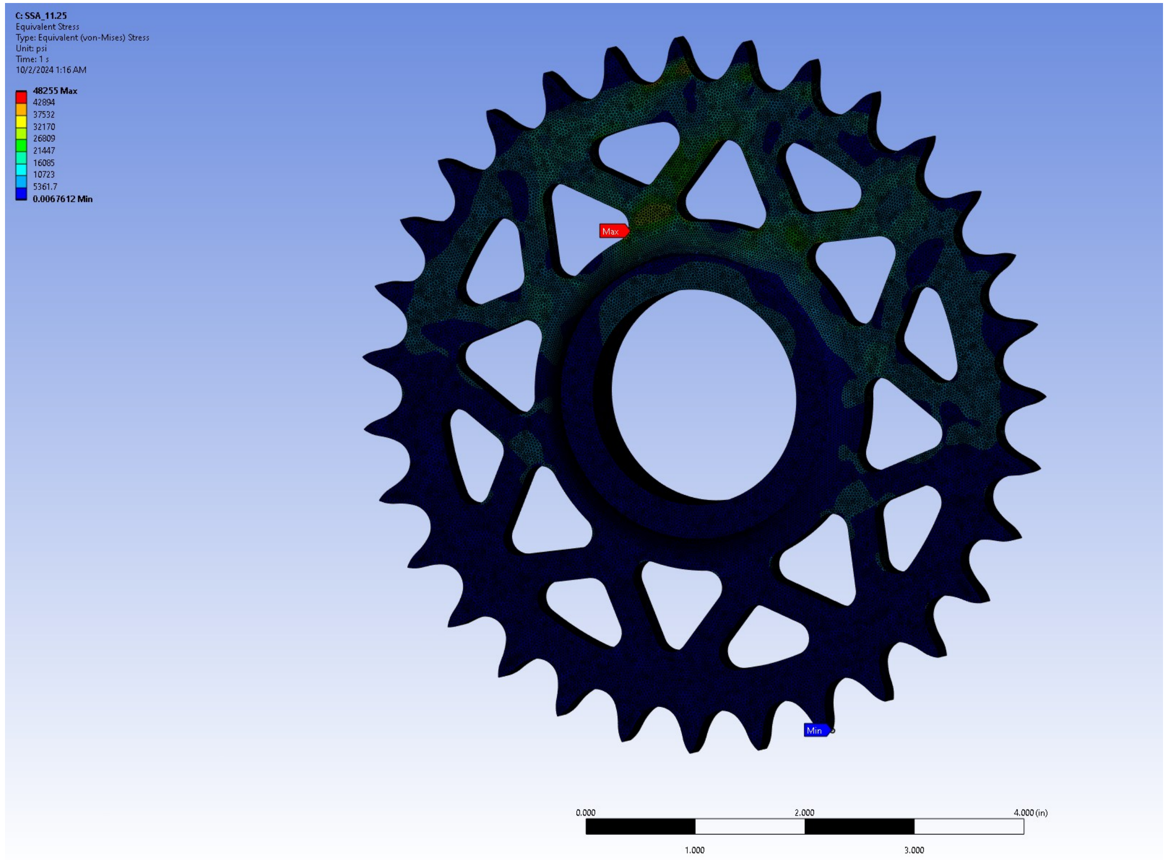


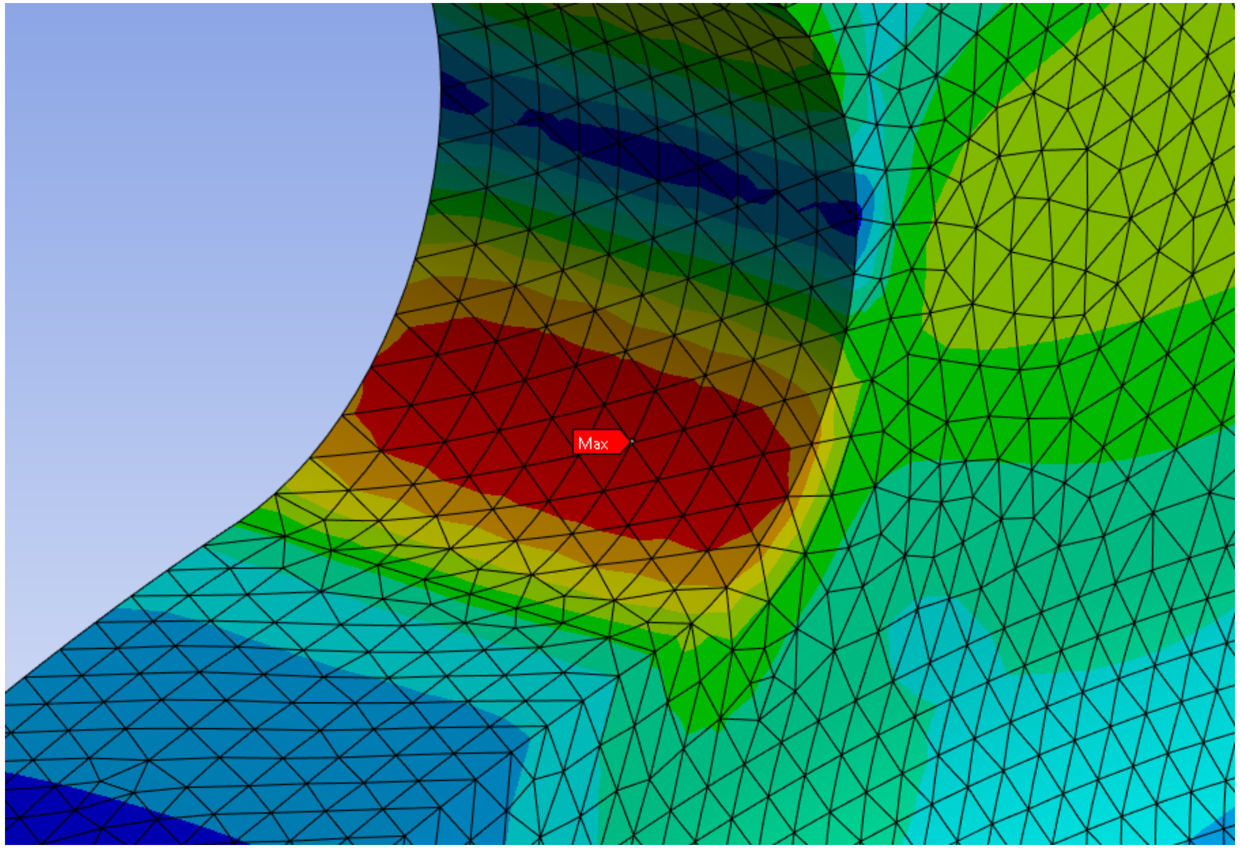


FEA – Sprocket SSA_11.25

Load Case: SSA_11.25	Solver: Ansys	Material: Al 7055-T77511	Geometry: Linear
Safety Factor Ultimate: 1.4	Safety Factor Yield: 1.2	Temperature: 71.6 F	Notes:

Section	Max Stress	Failure Mode	Material	Yield Allowable (with knockdowns)	Ultimate Allowable (with knockdowns)	MS_Yield	MS_Ultimate	Jacobian Ratio (Gauss Points) Avg	Aspect Ratio Avg
	48255 psi		Al	61600 psi	57000 psi			0.99843	1.8941

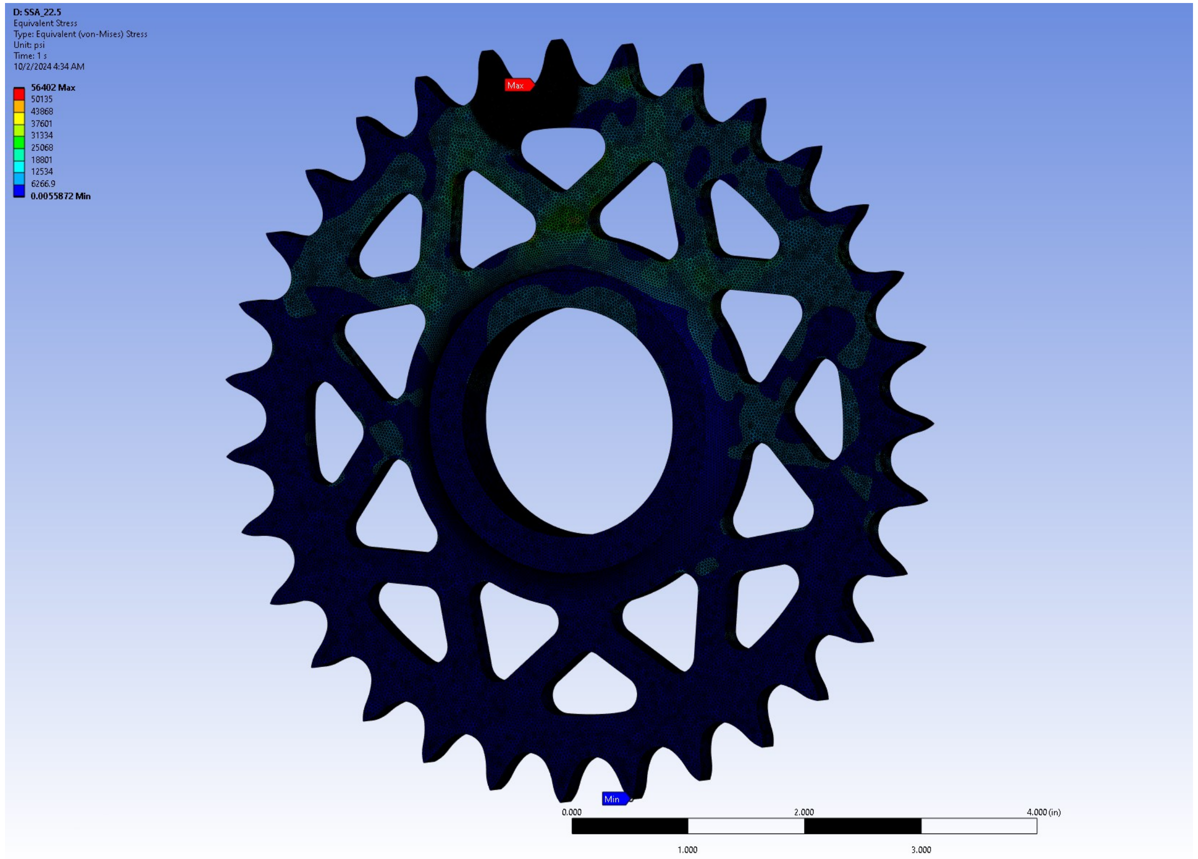


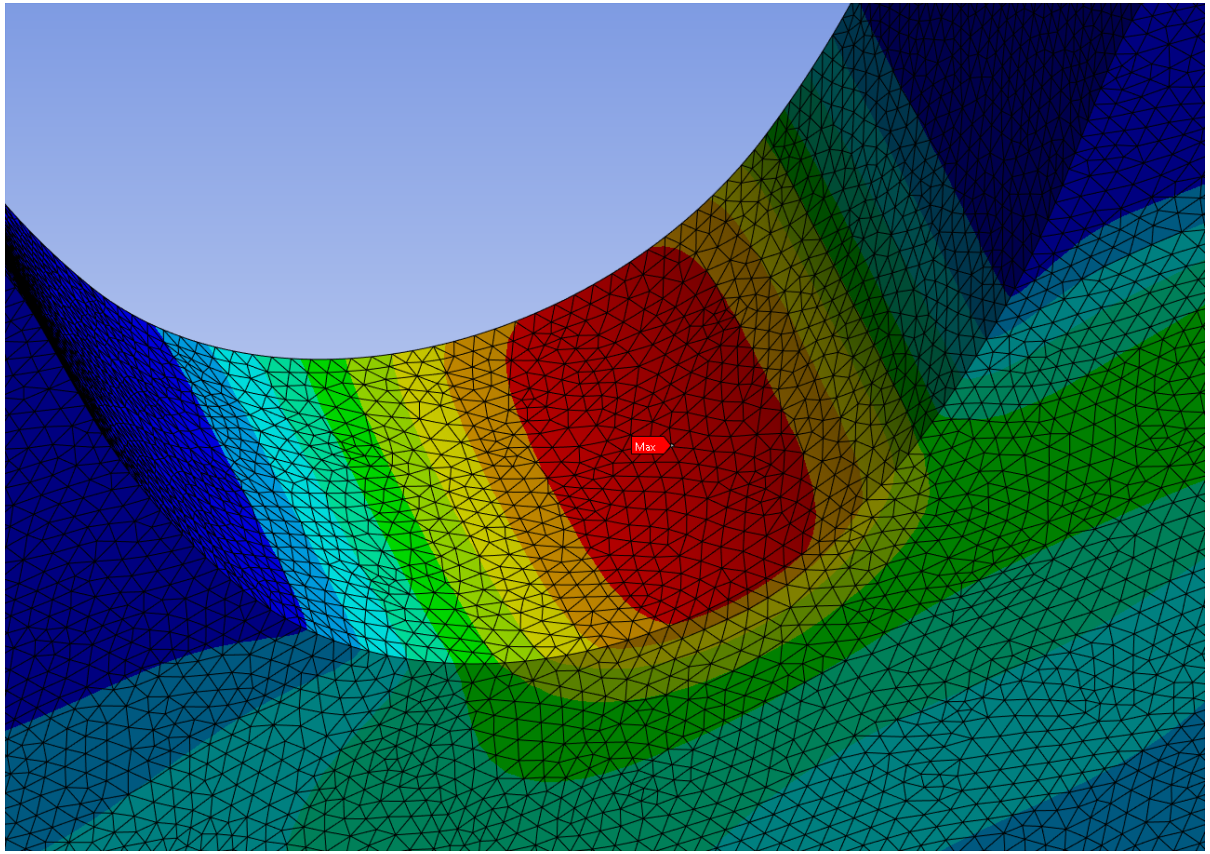


FEA – Sprocket SSA_22.5

Load Case: SSA_22.5	Solver: Ansys	Material: Al 7055-T77511	Geometry: Linear
Safety Factor Ultimate: 1.4	Safety Factor Yield: 1.2	Temperature: 71.6 F	Notes: Ran SOI

Section	Max Stress	Failure Mode	Material	Yield Allowable (with knockdowns)	Ultimate Allowable (with knockdowns)	MS_Yield	MS_Ultimate	Jacobian Ratio (Gauss Points) Avg	Aspect Ratio Avg
	56402 psi		Al	61600 psi	57000 psi			0.99905	1.8477

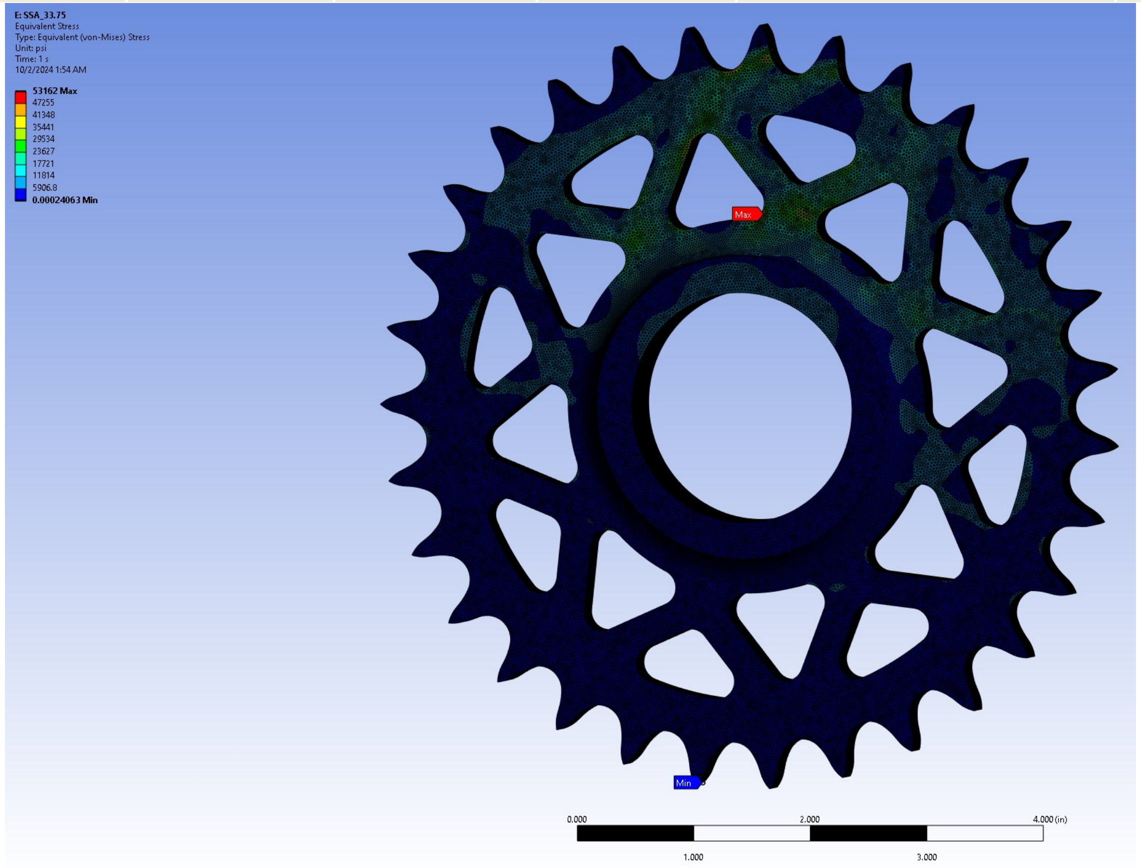


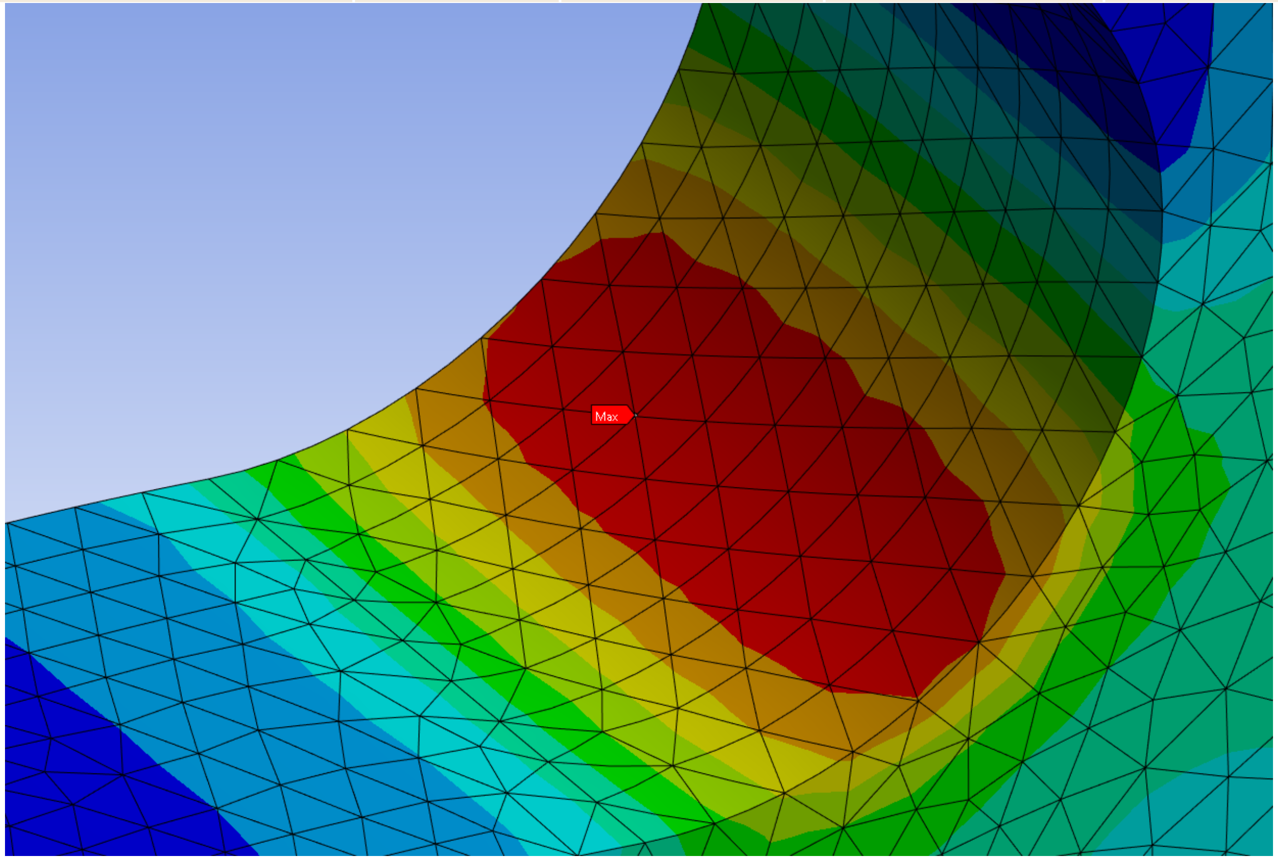


FEA – Sprocket SSA_33.75

Load Case: SSA_33.75	Solver: Ansys	Material: Al 7055-T77511	Geometry: Linear
Safety Factor Ultimate: 1.4	Safety Factor Yield: 1.2	Temperature: 71.6 F	Notes:

Section	Max Stress	Failure Mode	Material	Yield Allowable (with knockdowns)	Ultimate Allowable (with knockdowns)	MS_Yield	MS_Ultimate	Jacobian Ratio (Gauss Points) Avg	Aspect Ratio Avg
	53162 psi		Al	61600 psi	57000 psi			0.99844	1.894





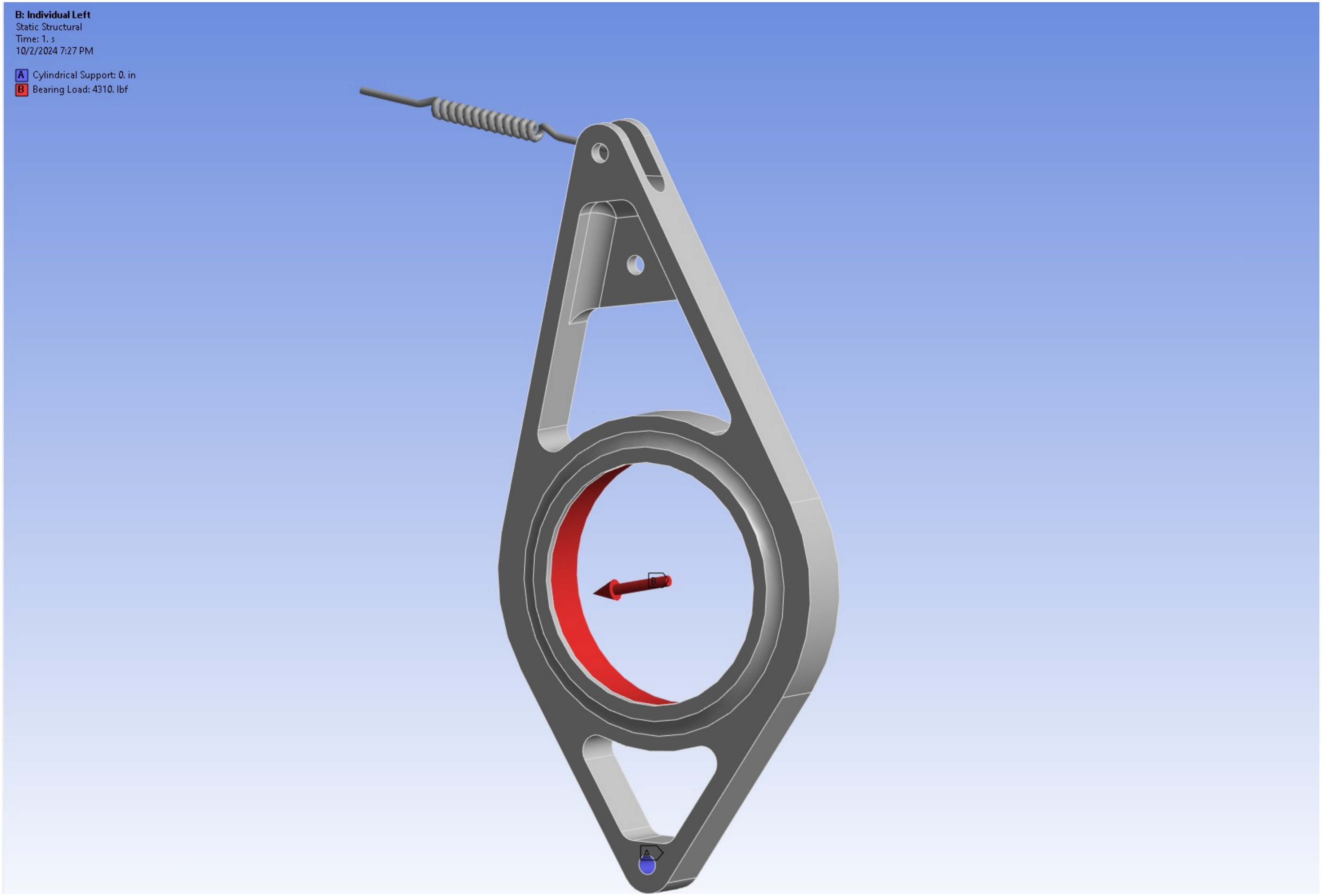
FEA – Diff Carriers

- Mesh:
  - Mesh convergence not carried out for this one
    - Peak stresses remain in similar spots so it is better to run a coarser mesh all around and a sphere of influence where there is peak stress (usually the bottom fillet)
  - Settings:
    - General element size at 0.1 in
    - SOI element size at 0.02 in
      - Ran at the bottom fillet for both
- Note:
  - Mass is not fully optimized
  - Eigenvalue buckling not ran due to length of time running on lab computers
  - Combined setup not run due to issues with individual right case
    - Ran once, went to change a relatively normal parameter, sends carrier's stress to basically infinity… something I have to investigate before I can run a combined case (I did both carriers exact same way, so any input would help here)

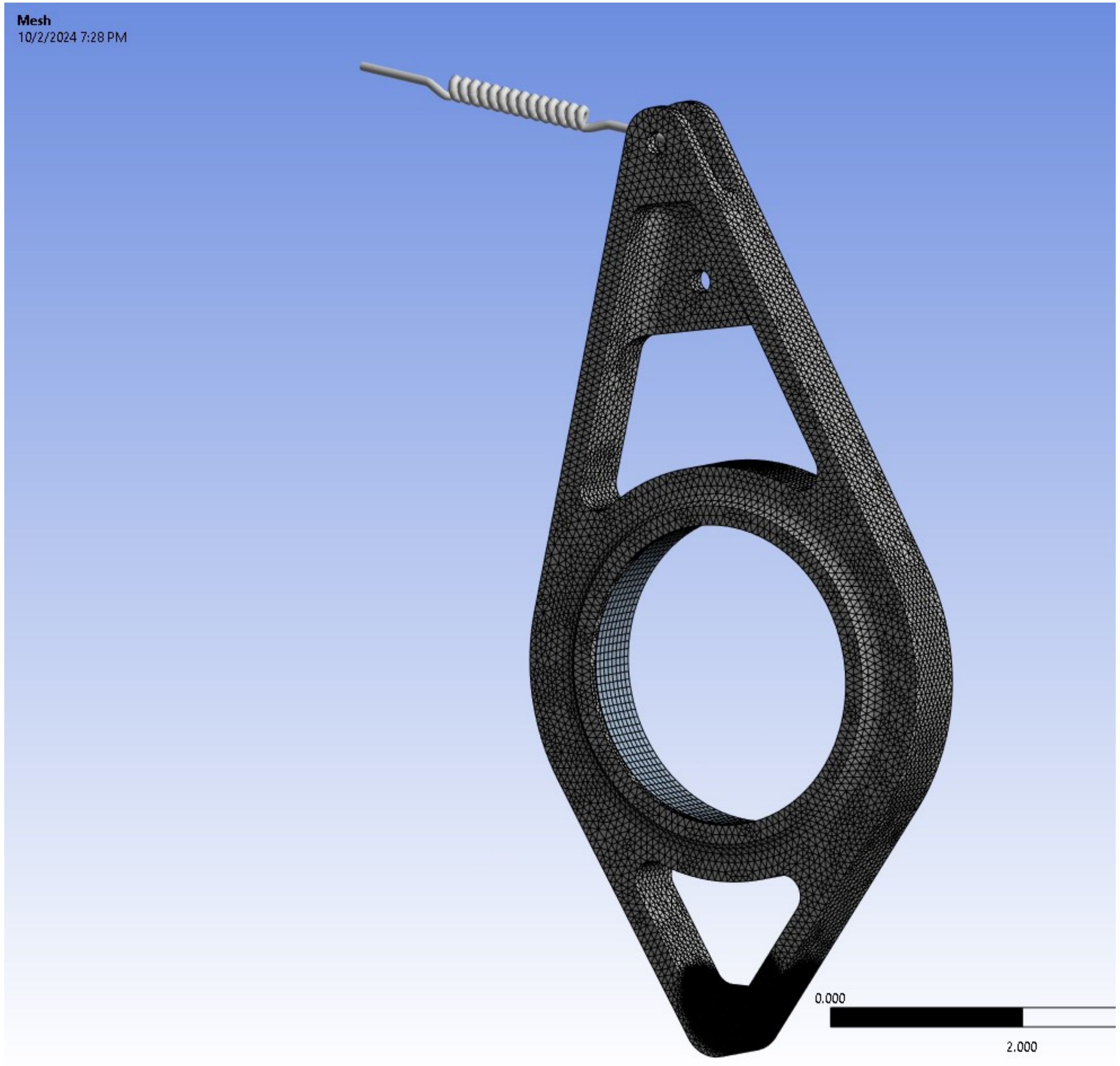
FEA – Diff Carriers

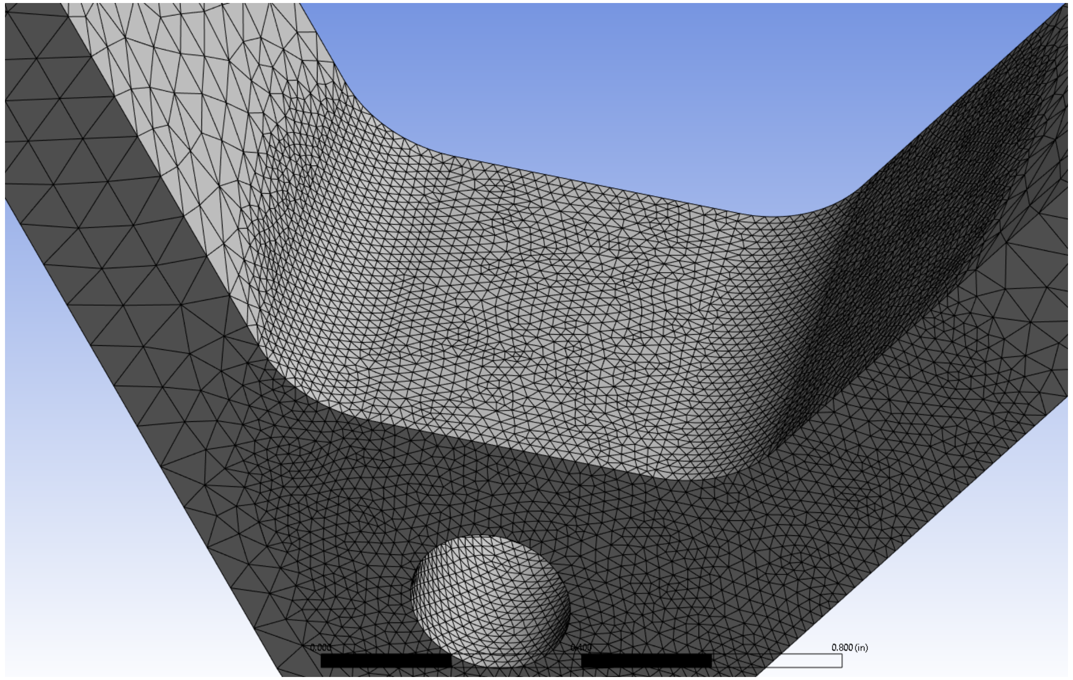
- Setup:
  - Turnbuckles modelled as spring with stiffness calculated
  - Cylindrical Support on Bottom Nodes
  - Bearing Loads
    - Load applied onto a mock bearing face to simulate a bearing load going through the part
  - Testing for overall system stresses and reaction probes to get bolt and lug calcs → Can do this in a combined scenario

FEA – Diff Carriers (Individual)



FEA – Diff Carriers

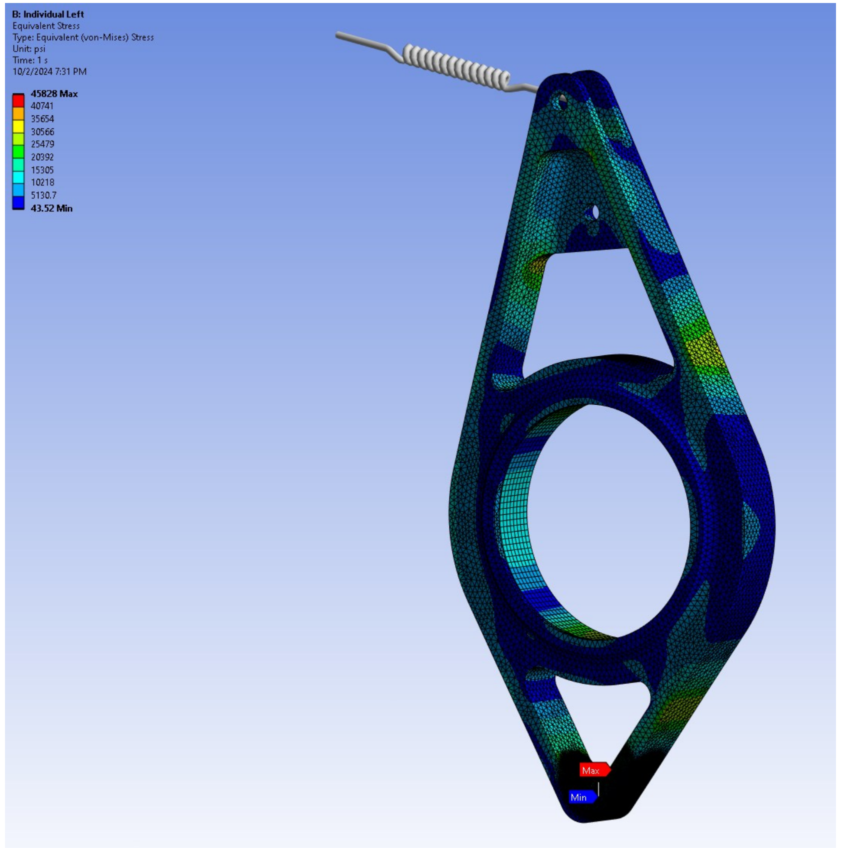


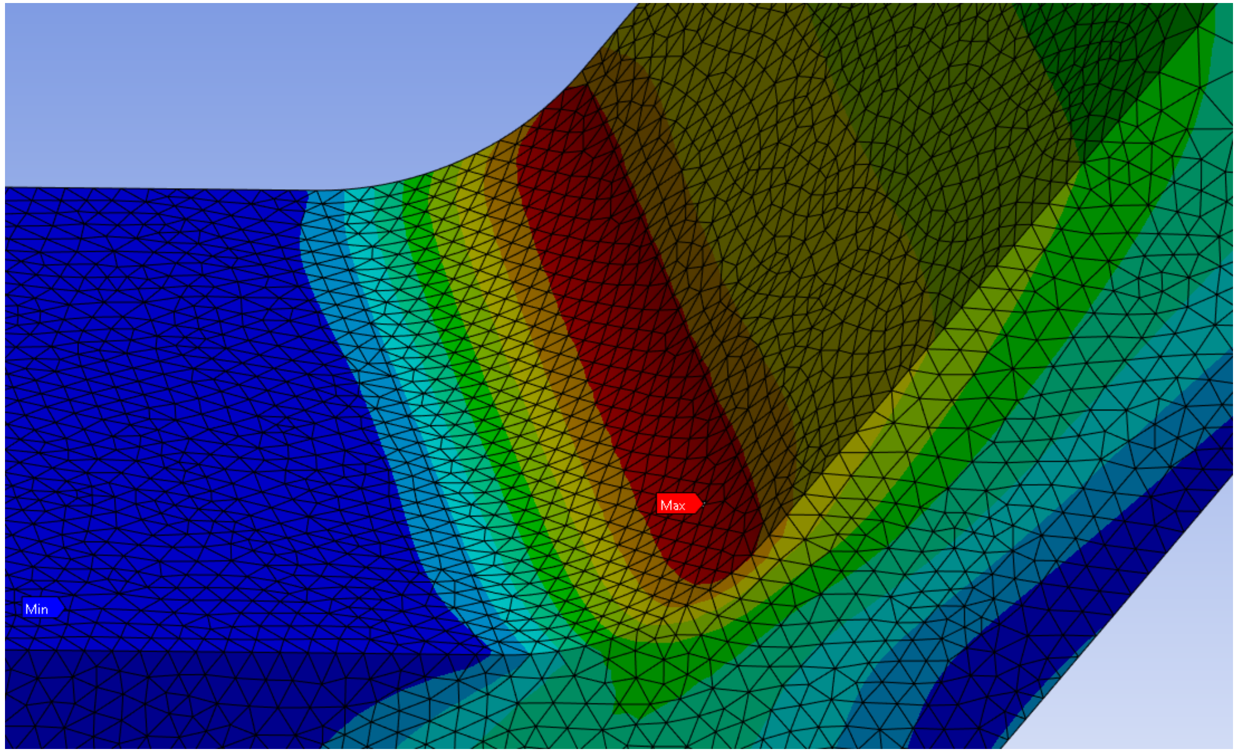


FEA – Left Carrier (Individual)

Load Case: LC	Solver: Ansys	Material: Al 7055-T77511	Geometry: Linear
Safety Factor Ultimate: 1.4	Safety Factor Yield: 1.2	Temperature: 71.6 F	Notes:

Section	Max Stress	Failure Mode	Material	Yield Allowable (with knockdowns)	Ultimate Allowable (with knockdowns)	MS_Yield	MS_Ultimate	Jacobian Ratio (Gauss Points) Avg	Aspect Ratio Avg
			Al	61600 psi	57000 psi			0.99854	1.8052





Questions?