Mass Timber Joinery Design for Digital Fabrication and De-constructability

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Research Partners

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Consultant, Turner Construction Company

Overview

Overview

- Background
- Research Questions

Literature Review

- Timber Connections
- Digital Fabrication
- Timber FEA

Methodology

- Design
- Analysis
- Testing
- Metrics

Case Studies

- Setup
- Physical Study
- Mass Timber Simulations

Conclusion

- Lessons
- Future Work

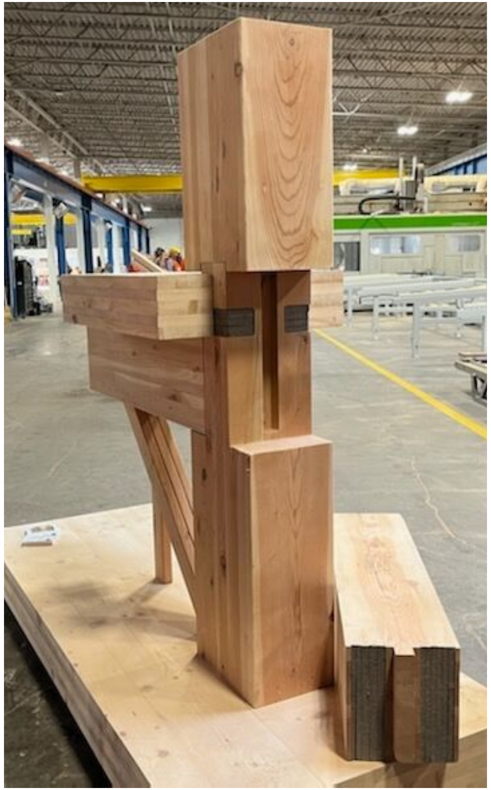
Research Overview | Mass Timber Connections

https://www.structuremag.org/?p=15654

http://studio-tm.com/constructionblog/?cat=224

Research Overview | Mass Timber Connections

https://leverarchitecture.com/innovation/mass_timber_beamtocolumn_seismic_testing



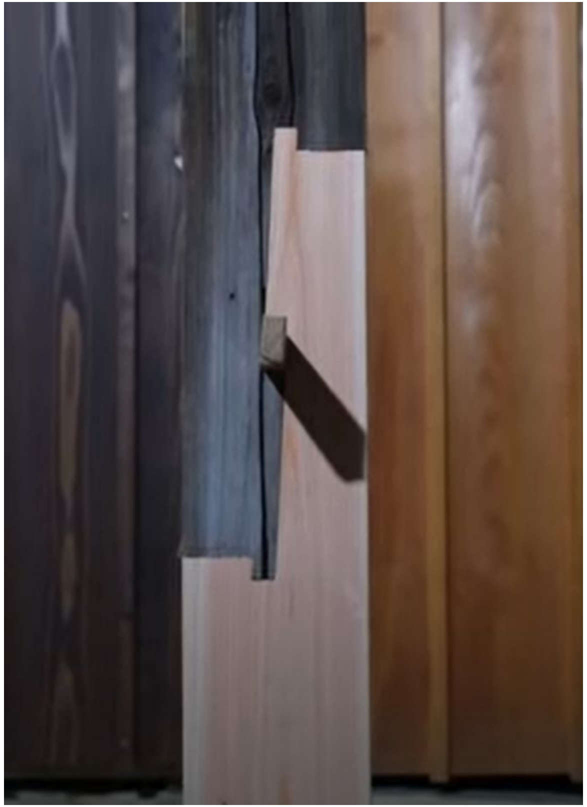
Atelier Jones

Timber Advantages | Deconstructible

https://archinect.com/news/article/150019184/2-500-year-old-chinese-wood-joints-that-make-buildings-earthquake-proof

https://www.stonebridge.com/post/the-meticulous-art-of-traditional-japanese-woodworking

Timber Advantages | Reusable



https://www.youtube.com/watch?v=oD_9Gy_KWo0&ab_channel=DylanIwakuni

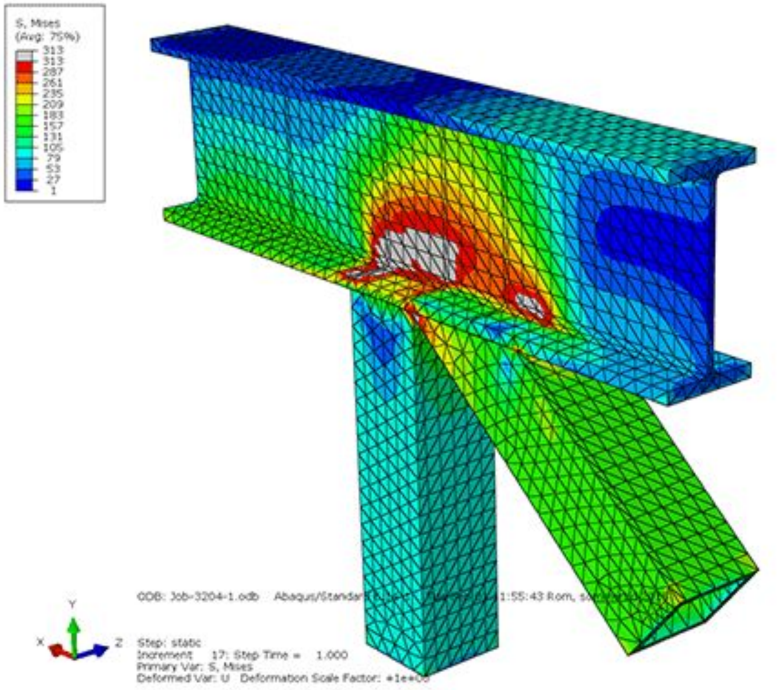
Modern Advancements | Mass Fabrication

https://kianejatian.medium.com/the-rise-of-prefab-construction-past-present-and-future-7f84abe08b3b

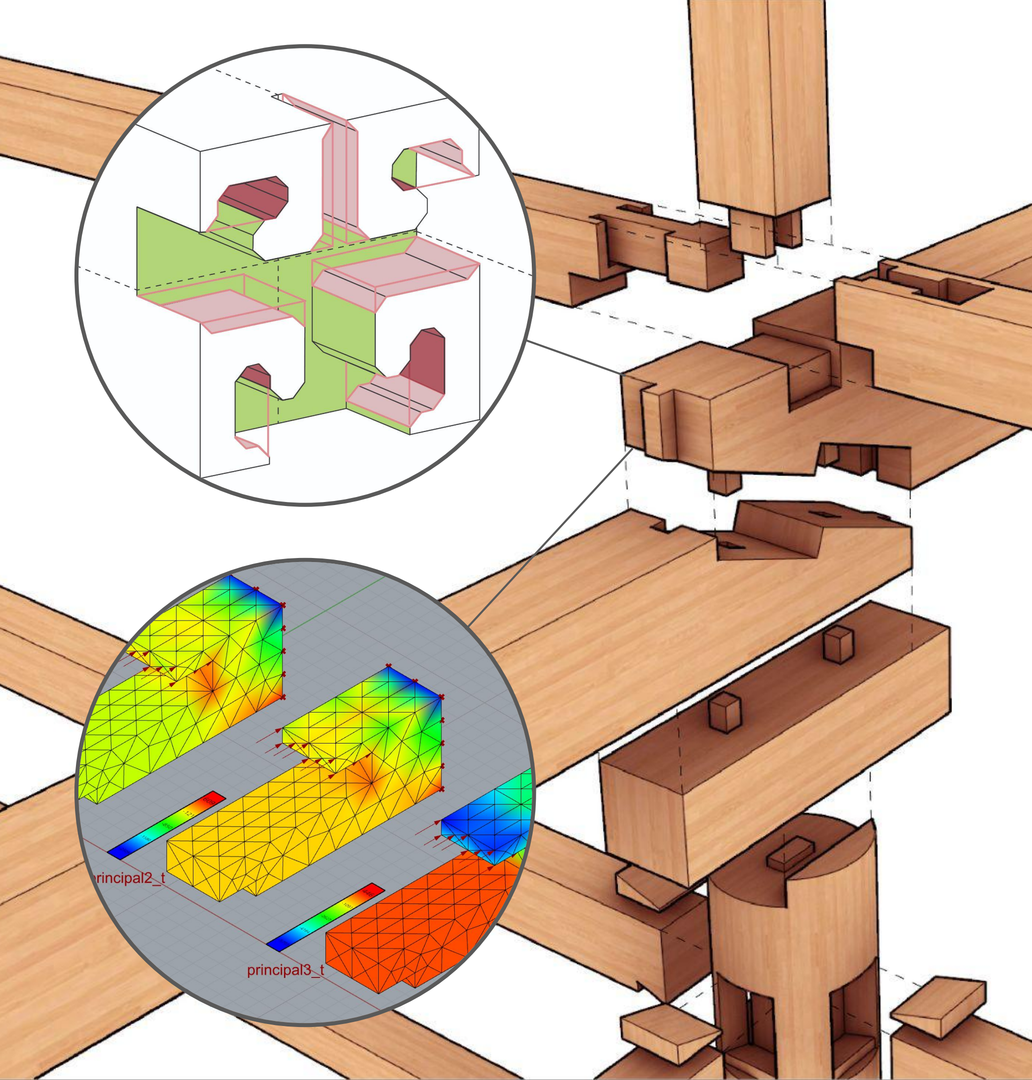
Modern Advancements | Mass Customization

Robeller et al. (2018)

Modern Advancements | Computational Design



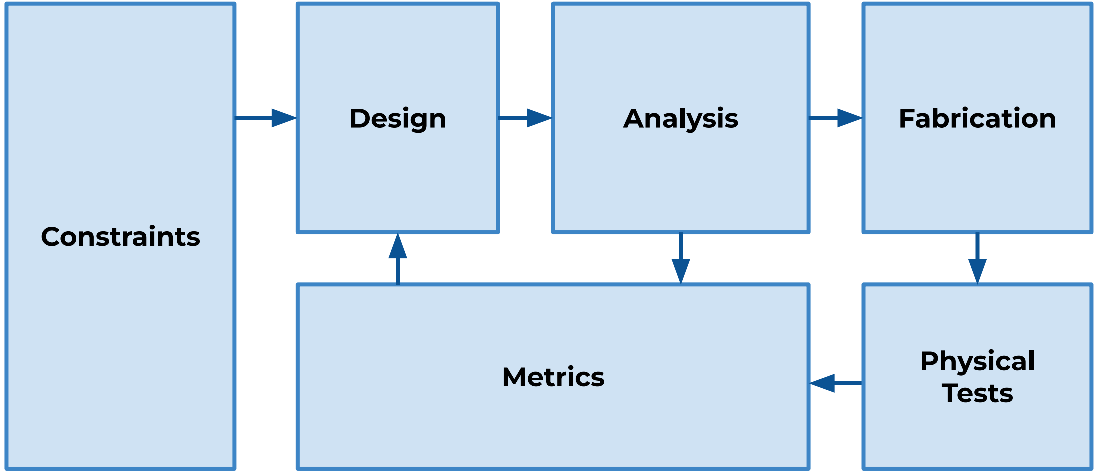
https://ki.dk/wp-content/uploads/2020/07/FEA-analyse_0004_Experimentarium-1.png



How can digital computation inform design and fabrication of mass timber joinery and what are the barriers for mass timber joinery in modern construction?

Research Goals

- Create a process for analysis and rapid prototyping of traditional timber connections
- Use tools to evaluate a case study for splicing reused timber beams for further process refinement
- Analyze large dataset for case study to find design guidelines that achieve multiple objectives



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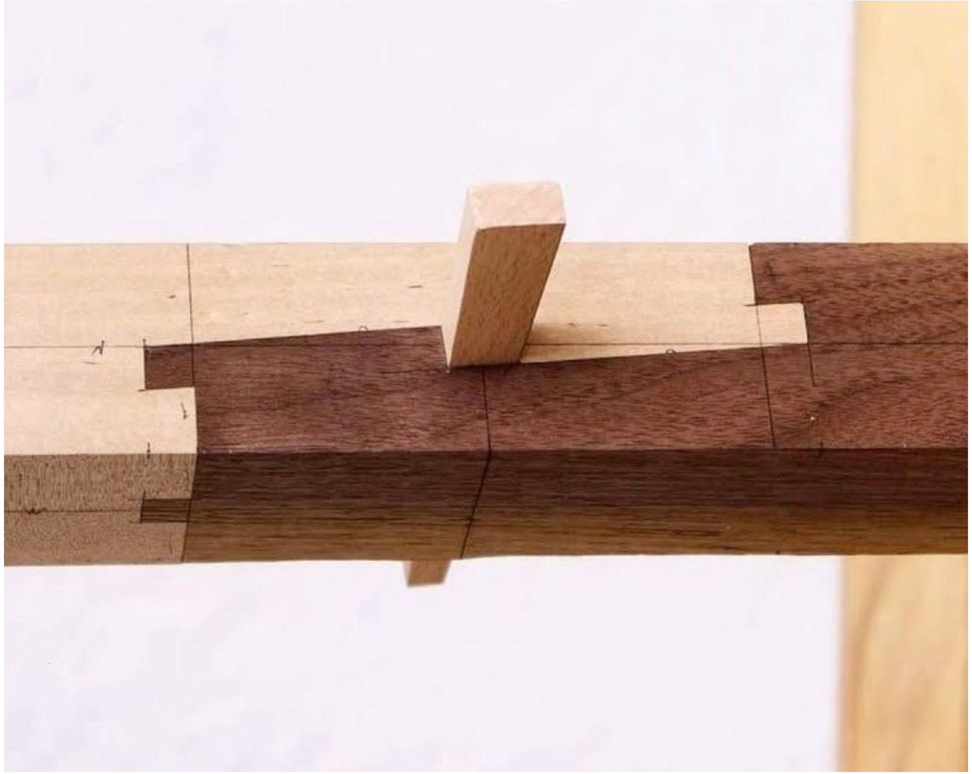

https://i.ytimg.com/vi/3KqIIOyuo1Q/maxresdefault.jpg

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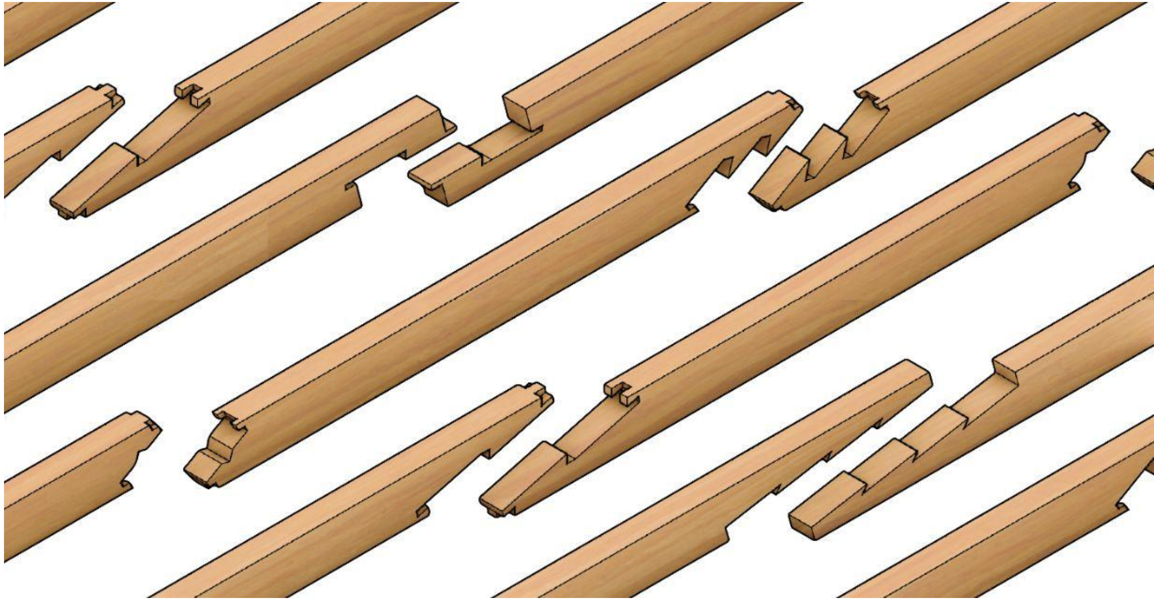

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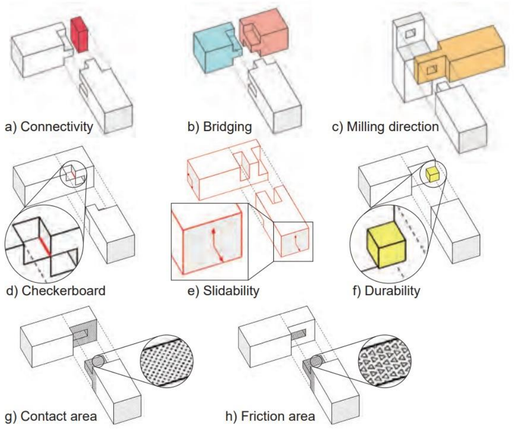
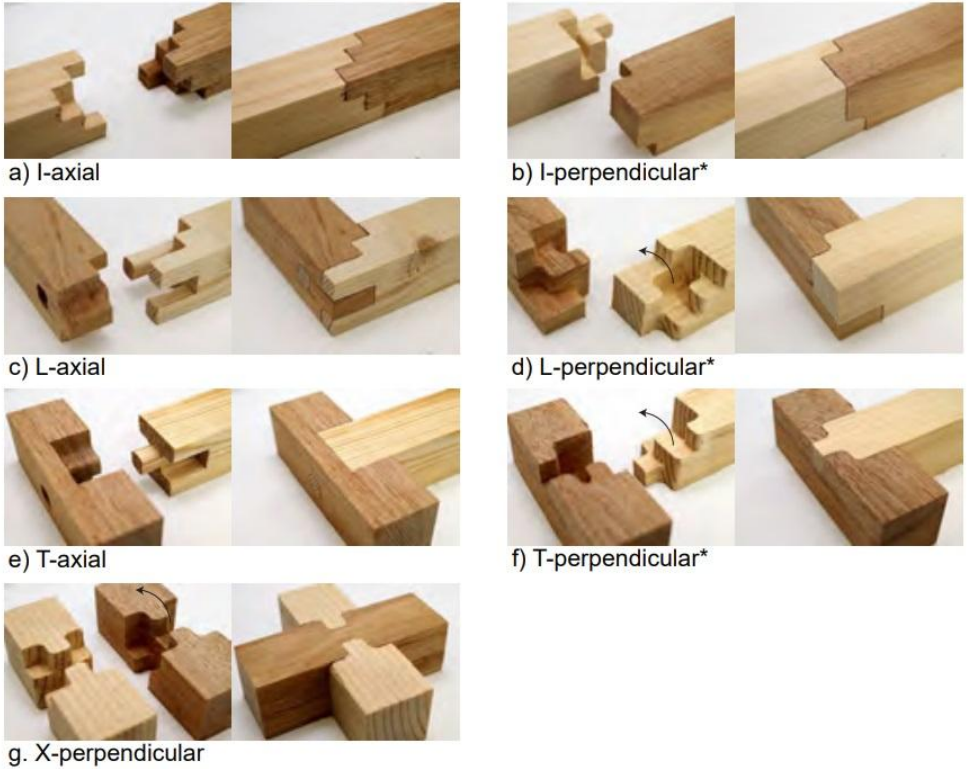
Literature | Timber Connections

Tsugite

- Tsugite uses metrics and user interfaces to inform design decisions
- Studies how users can use the design to to quickly wood-wood connections



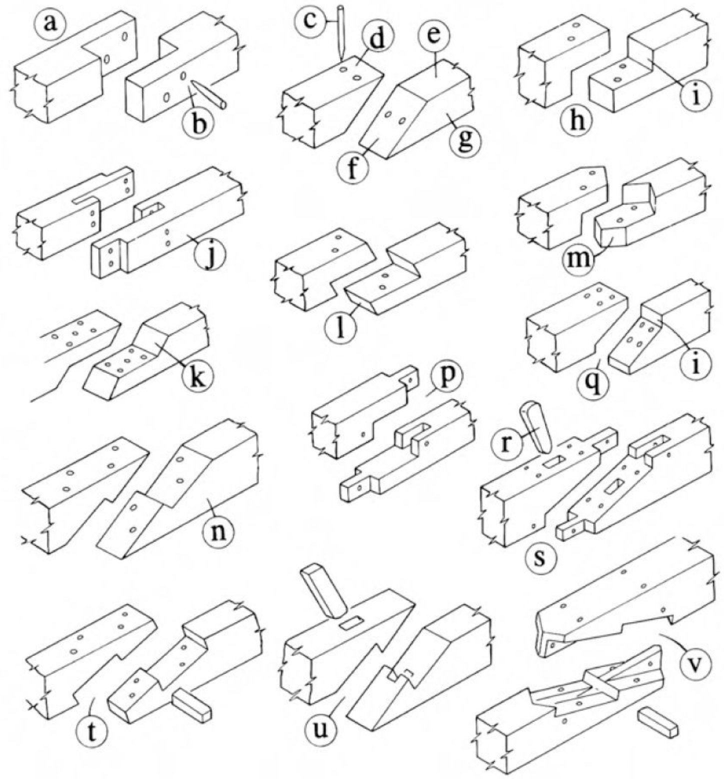


Larsson et al. (2020)

Literature | Timber Connections

Scarf Joint Vernacular

a) Face-halved scarf
b) Side-pegging
c) Peg
d) Face-pegging
e) Face
f) Splayed scarf
g) Side
h) Side-halved
i*) Vertical butt
j) Face-halved and bladed scarf
k) Squinted butt inside halved scarf
l) Under-squinted butt in halved scarf
m) Sallied butt
n) Through-splayed and tabled scarf (Trait de Jupiter)
p) Side-halved and bridled scarf
q) Stop-splayed scarf
r) Key
s) Stop-splayed scarf with bridled butts and face key
t) Stop-splayed and tabled scarf with key
u) Through-splayed and tabled scarf with face key
v) Stop-splayed and tabled scarf with sallied and undersquinted butt, internal tongues and key



https://www.vernacularbuildingglossary.org.uk/a-z/scarf-joint/through-splayed-scarf/#images

Literature | Digital Fabrication in Timber

Modern Fabrication

- Modern Projects such as the Heartwood building are beginning to use all timber connections.

- These projects require the use of digital fabrication in order to achieve the allowances necessary for these connection types.

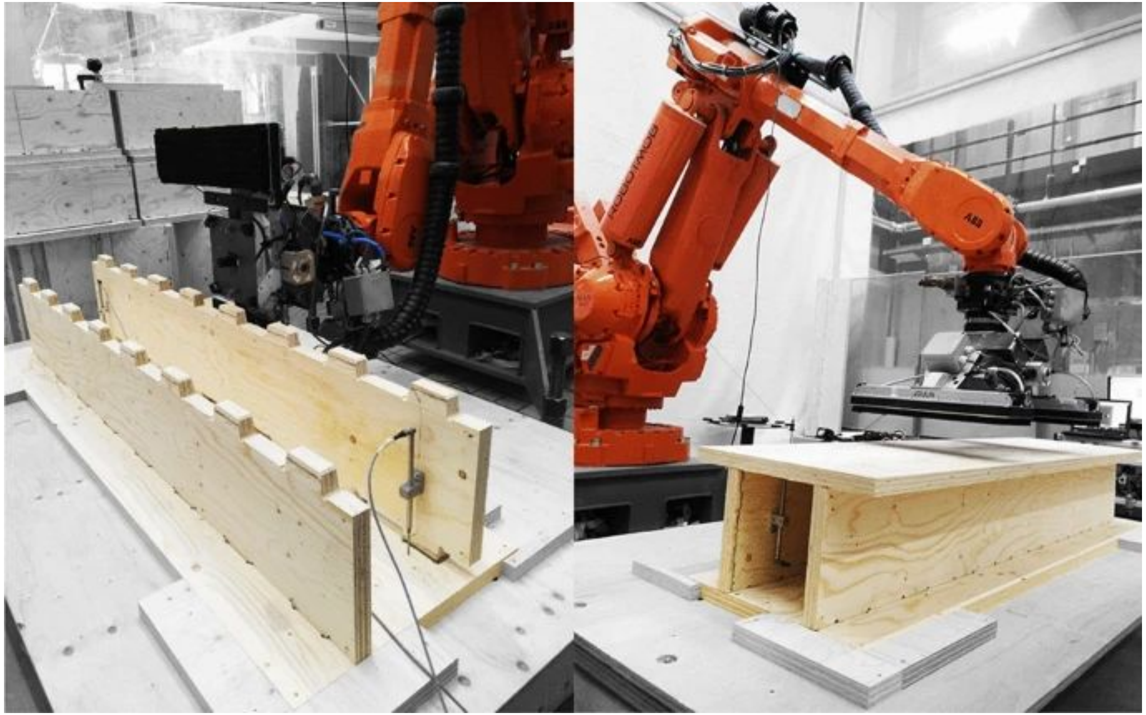
https://timberlab.com/projects/heartwood

Literature | Digital Fabrication in Timber

Digital Assembly

- Modern Research is looking into robotic assembly which create unique requirements and restrictions for fabrication.

- The study investigates the angle of cut for the mortise and allowance for robotic assembly.



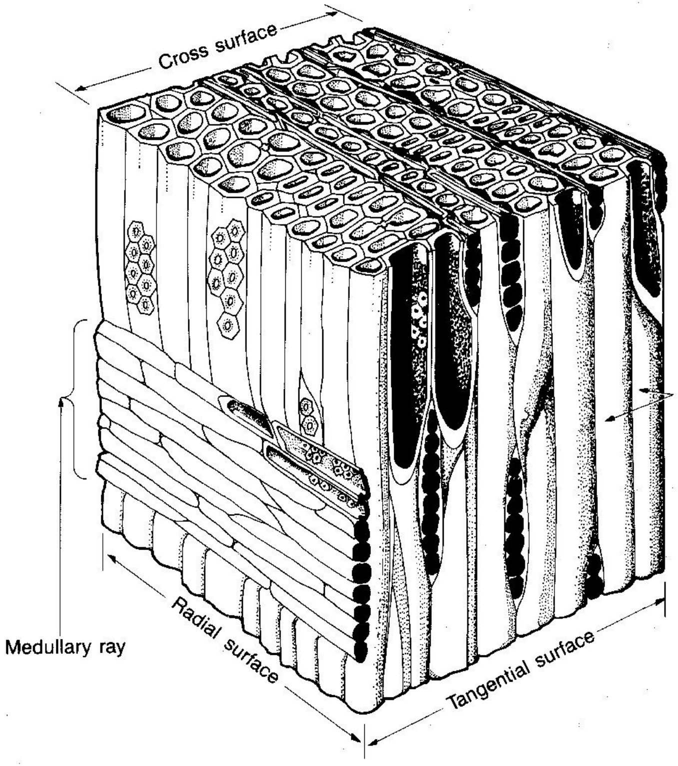
Rogeau (2022)

Literature | Finite Element Analysis with Timber Connections

Material Properties

- Orthotropic Materials Properties are required to properly study how timber reacts in timber connections

Properties	Literary Range	Variables Used					
E-Modulus	7 - 16 GPa	X	11 GPa	Y	0.4 GPA	Z	0.7 GPA
Poisson Ratio	0.4 - 0.6	XY	0.535	YZ	0.419	ZX	0.019
Friction	0.4 - 0.6	0.5					
Density	400 - 500 kg/m³	498 kg/m³					
Allowable Stress	11 - 14 MPa	13.8 MPa					



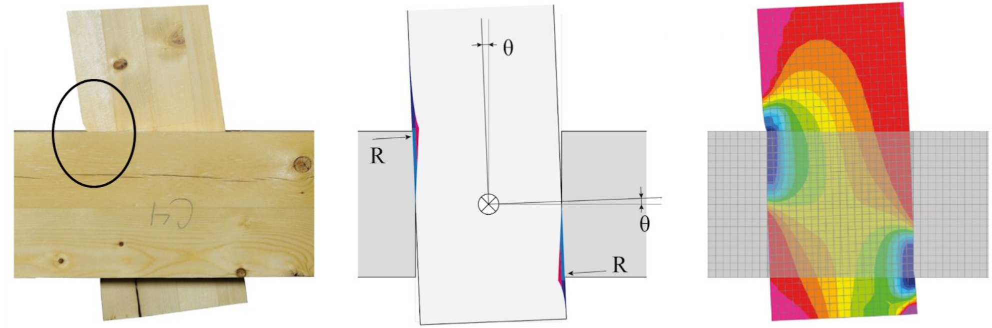
https://www.buyqldtimber.com.au/Images/Blog/softwoodmicro.jpg

Literature | Finite Element Analysis with Timber Connections

FEA

- Some research has shown that Finite Element Analysis of joints are possible with modern computational techniques

- Focus on specific joint typologies or loading conditions.



Fang (2018)

Moradei et al. (2018)

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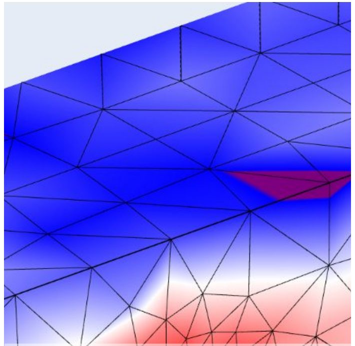

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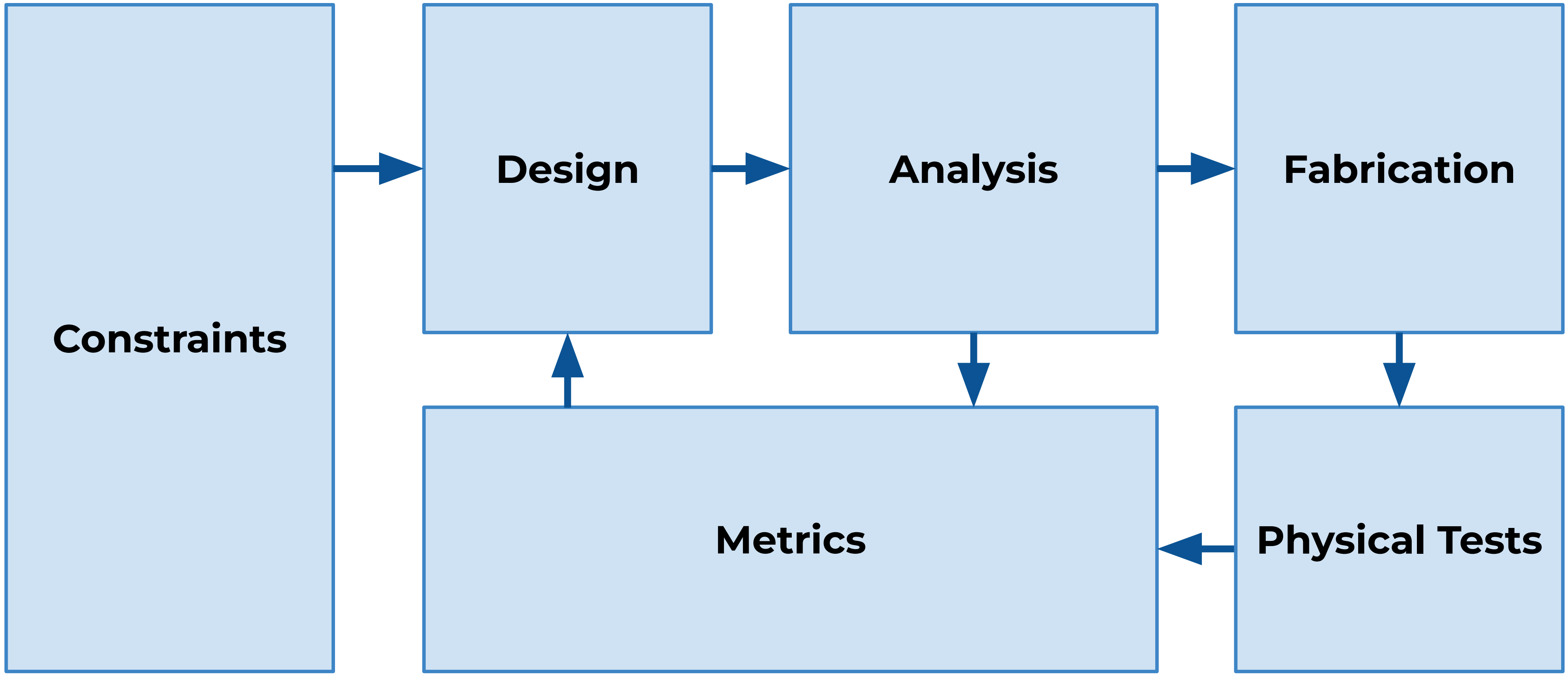
Constraints
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Fabrication
Metrics
Physical Tests

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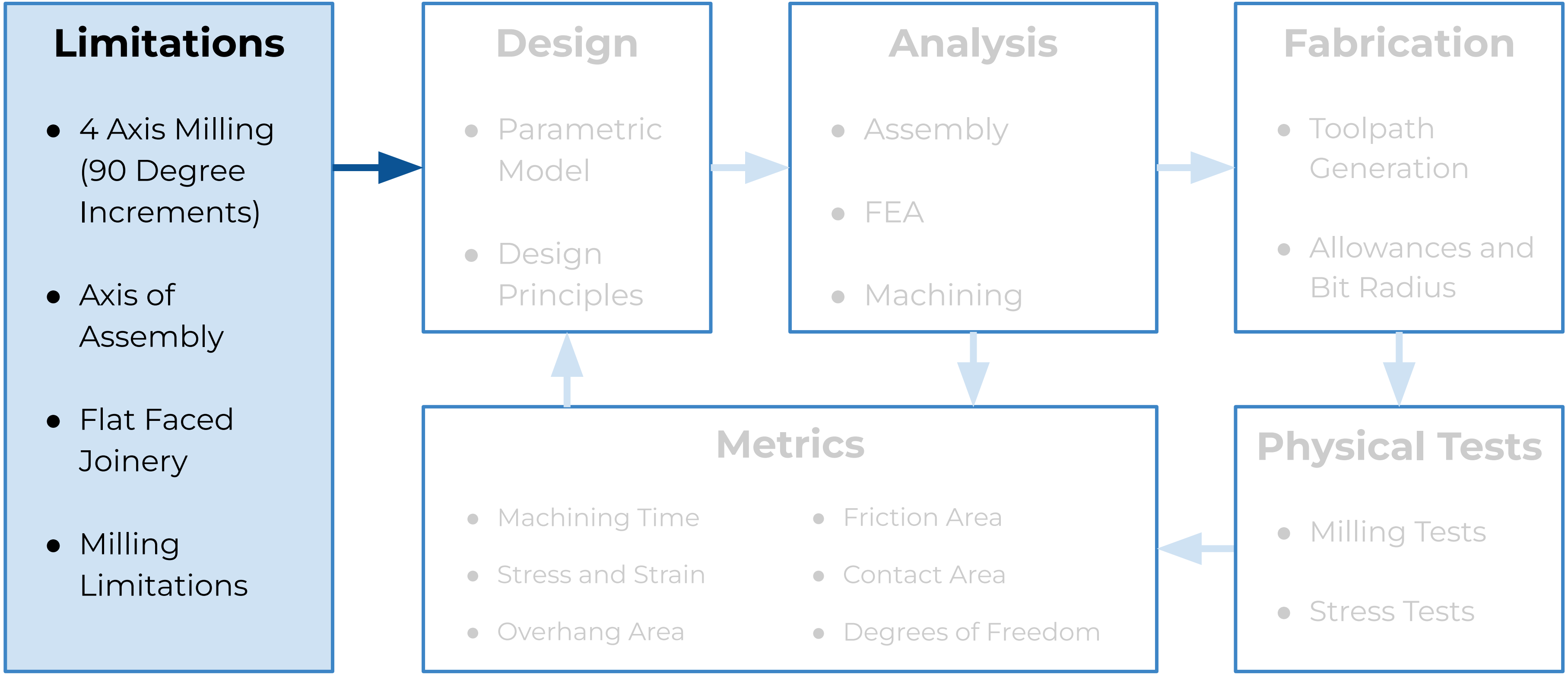
Limitations
4 Axis Milling (90 Degree Increments)
Axis of Assembly
Flat Faced Joinery
Milling Limitations
Design
Parametric Model
Design Principles
Analysis
Assembly
FEA
Machining
Fabrication
Toolpath Generation
Allowances and Bit Radius
Metrics
Machining Time
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Friction Area
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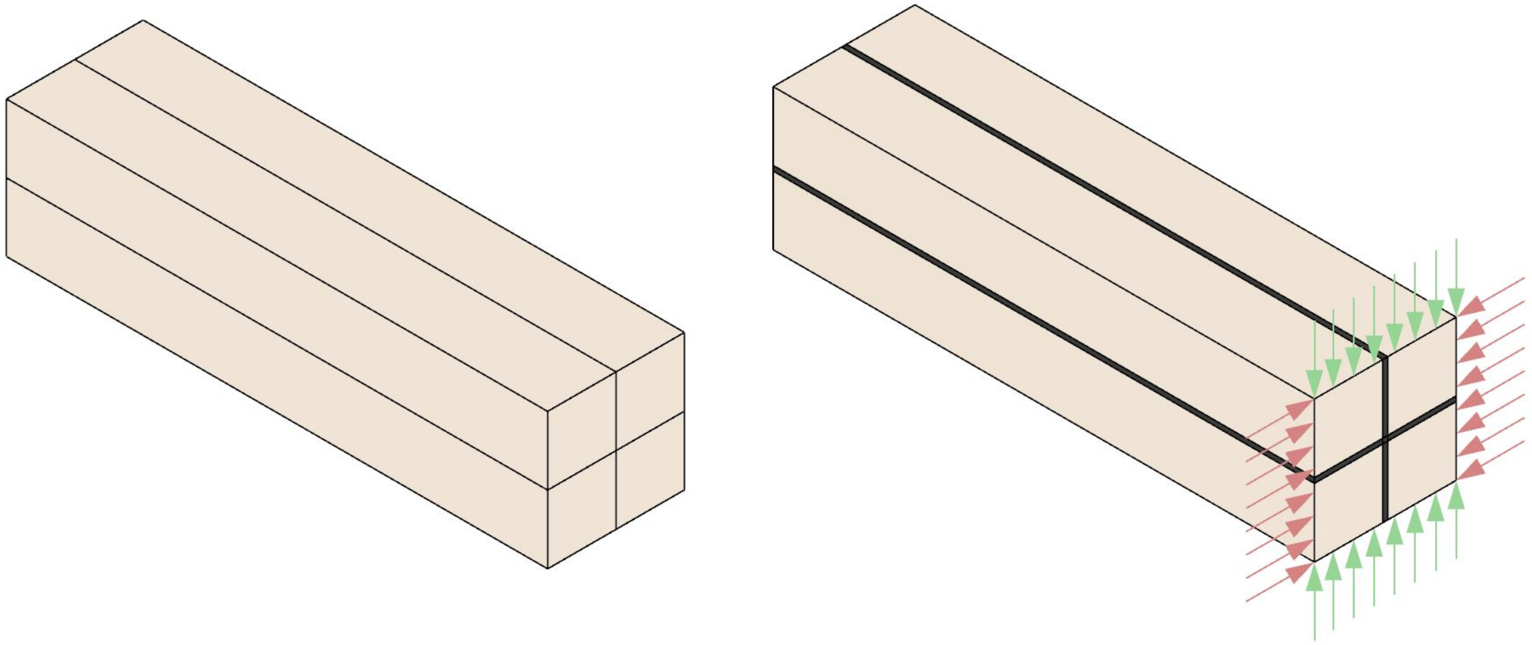
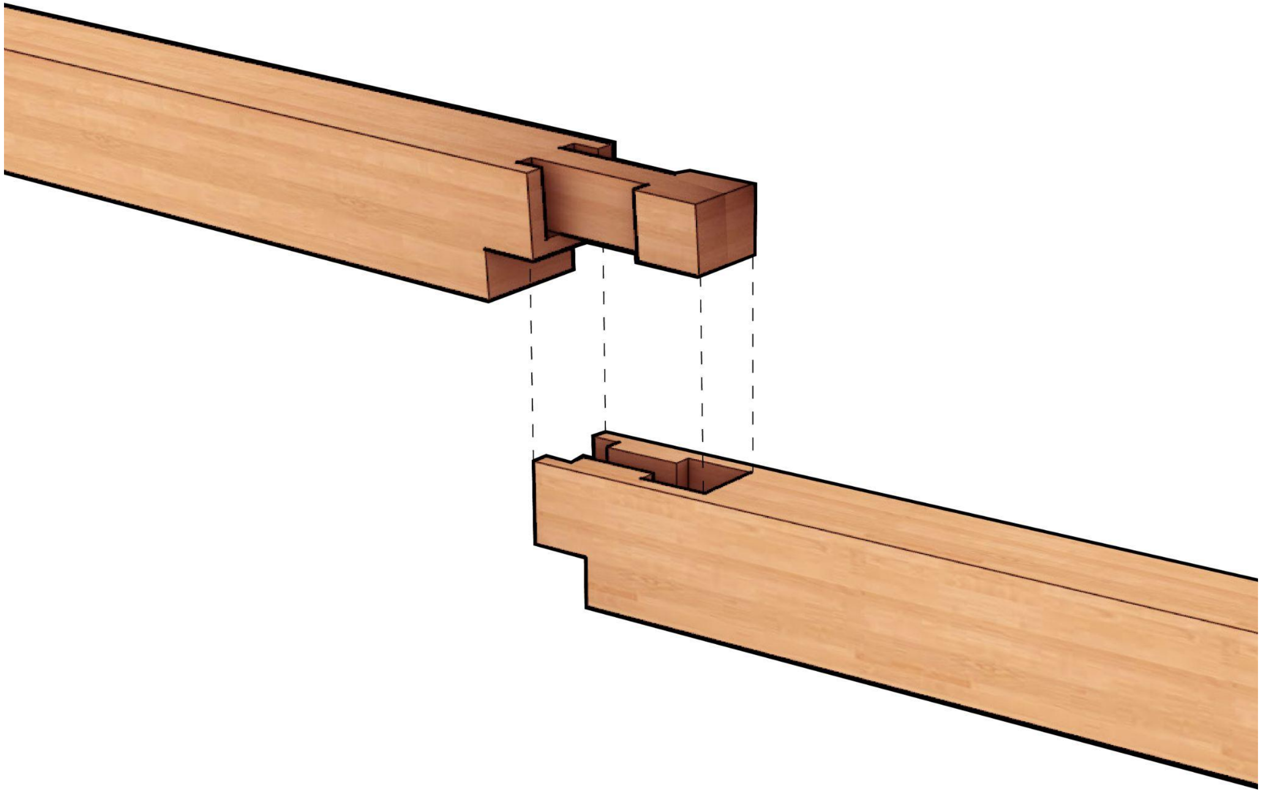
Milling Tests
Stress Tests

Constraints | Fabrication Oriented Design

Constraints | 4 Axis Milling



Constraints | Assemblable



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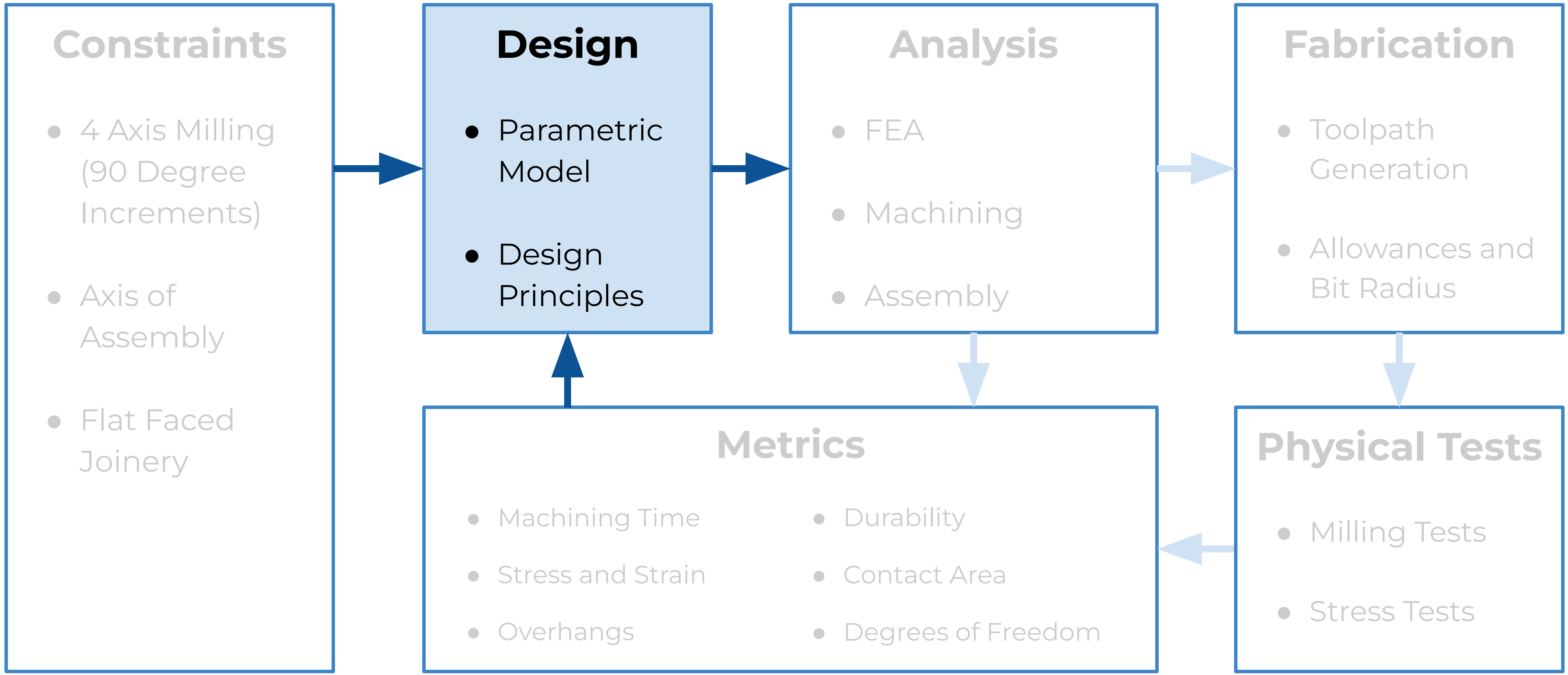
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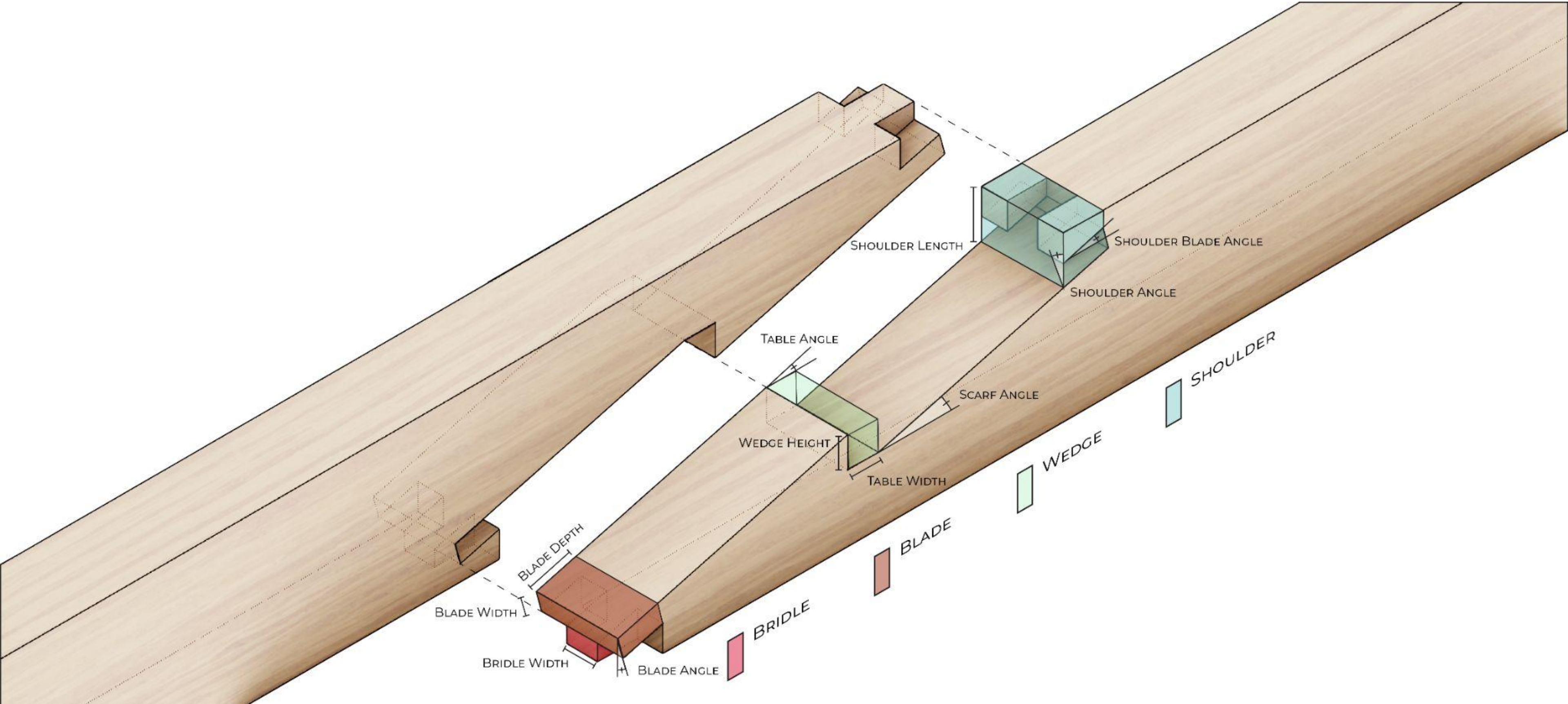
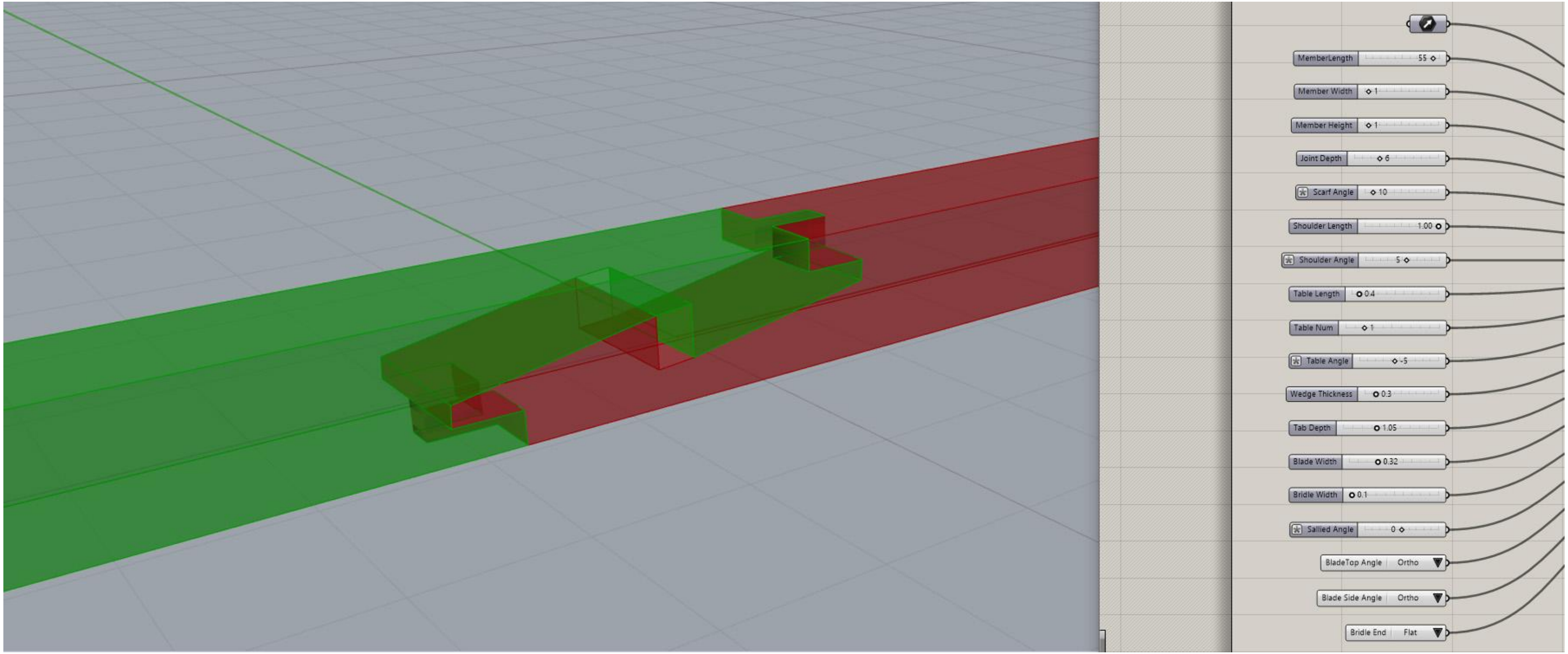
4 Axis Milling (90 Degree Increments)
Axis of Assembly
Flat Faced Joinery
Design
Parametric Model
Design Principles
Analysis
FEA
Machining
Assembly
Fabrication
Toolpath Generation
Allowances and Bit Radius
Metrics
Machining Time
Stress and Strain
Overhangs
Durability
Contact Area
Degrees of Freedom
Physical Tests
Milling Tests
Stress Tests

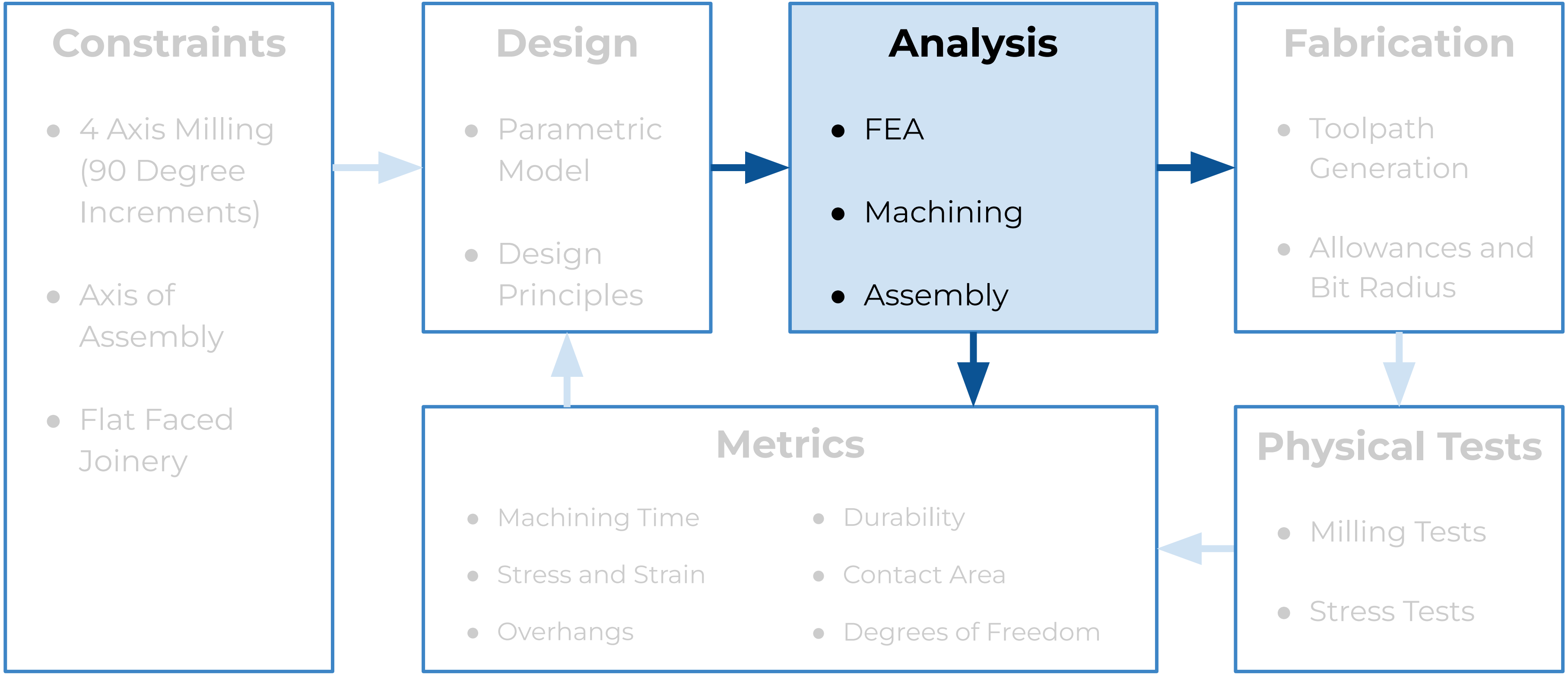
Design | Identify Variables



Design | Parametric Model



Framework



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4 Axis Milling (90 Degree Increments)
Axis of Assembly
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Design
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Design Principles
Analysis
FEA
Machining
Assembly
Fabrication
Toolpath Generation
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Metrics
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Overhangs
Durability
Contact Area
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Physical Tests
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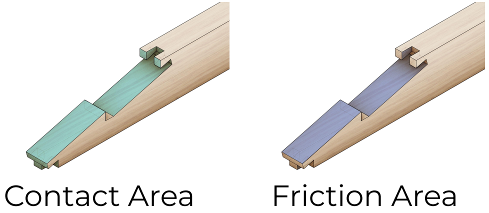
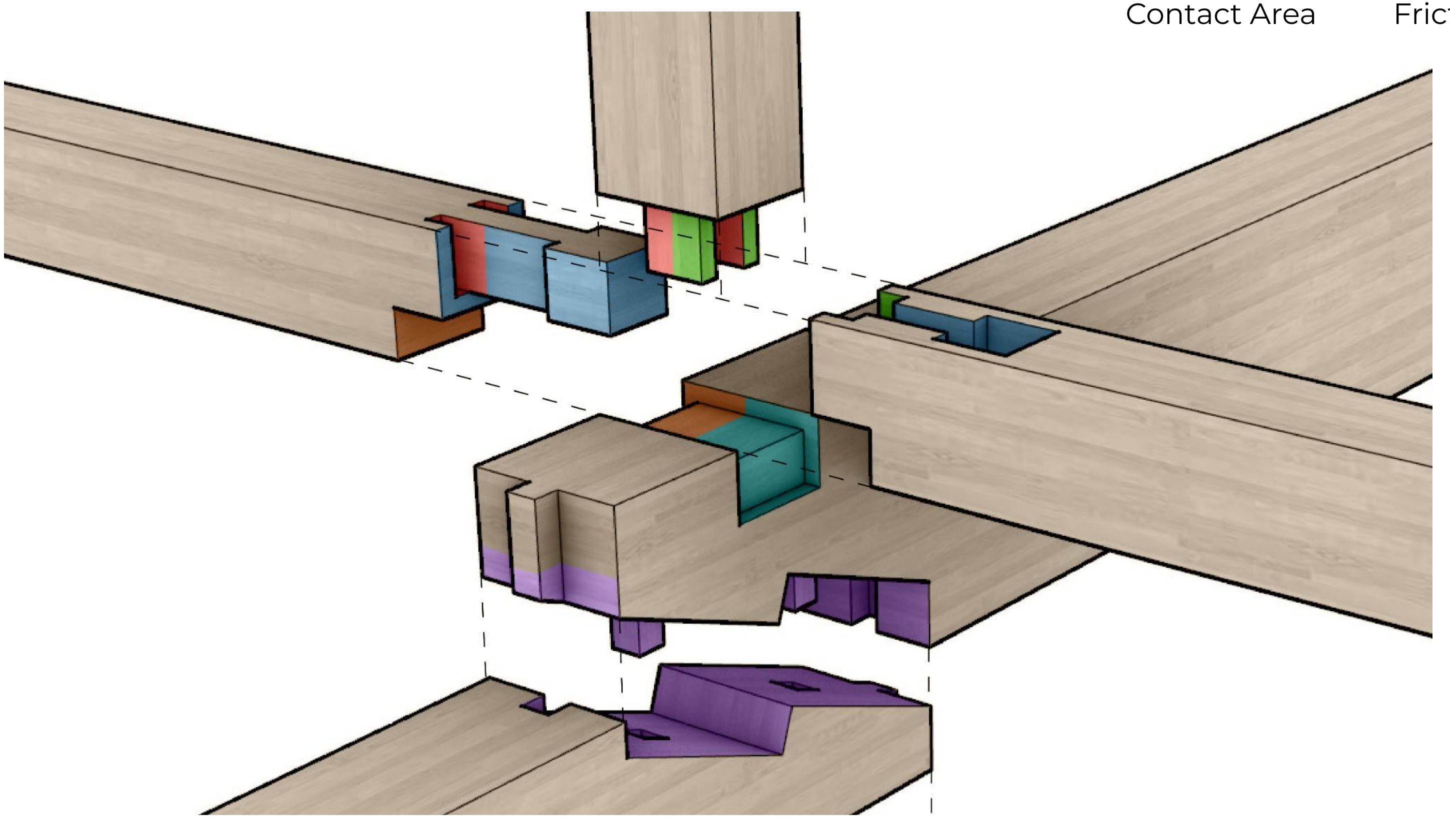
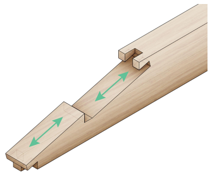
Analysis | Assembly - Contact

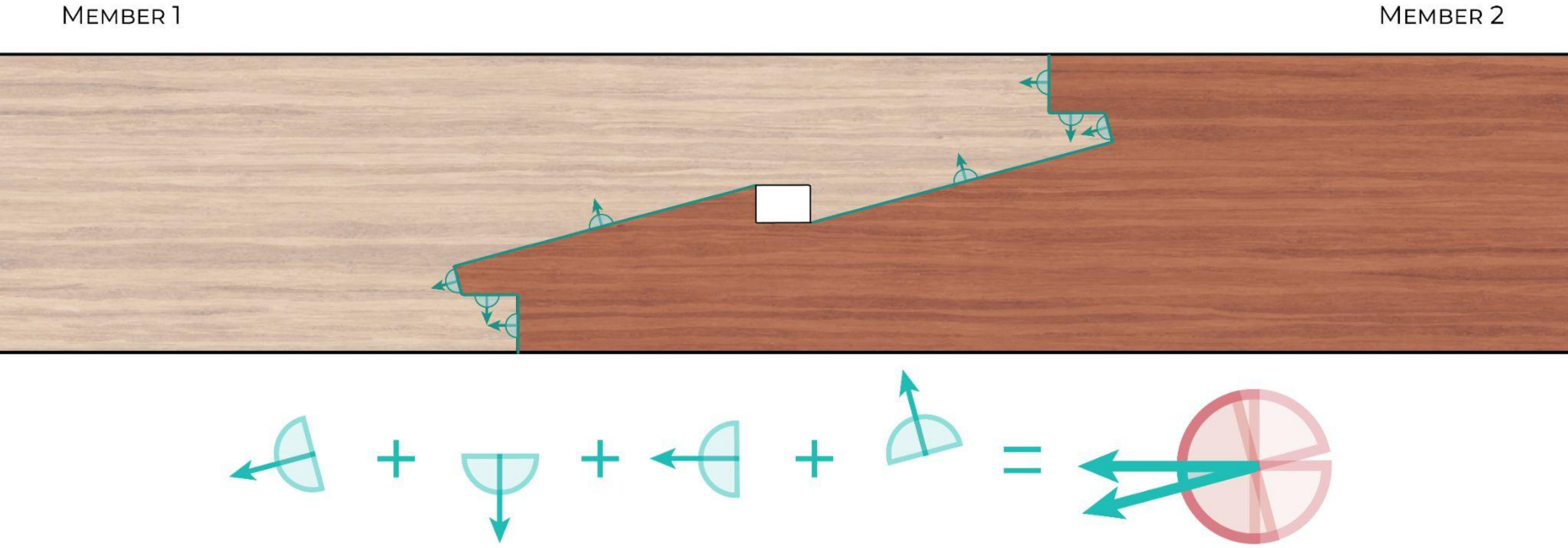




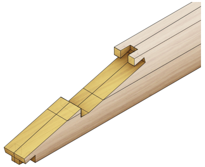
Analysis | Assembly - Axis of Assembly



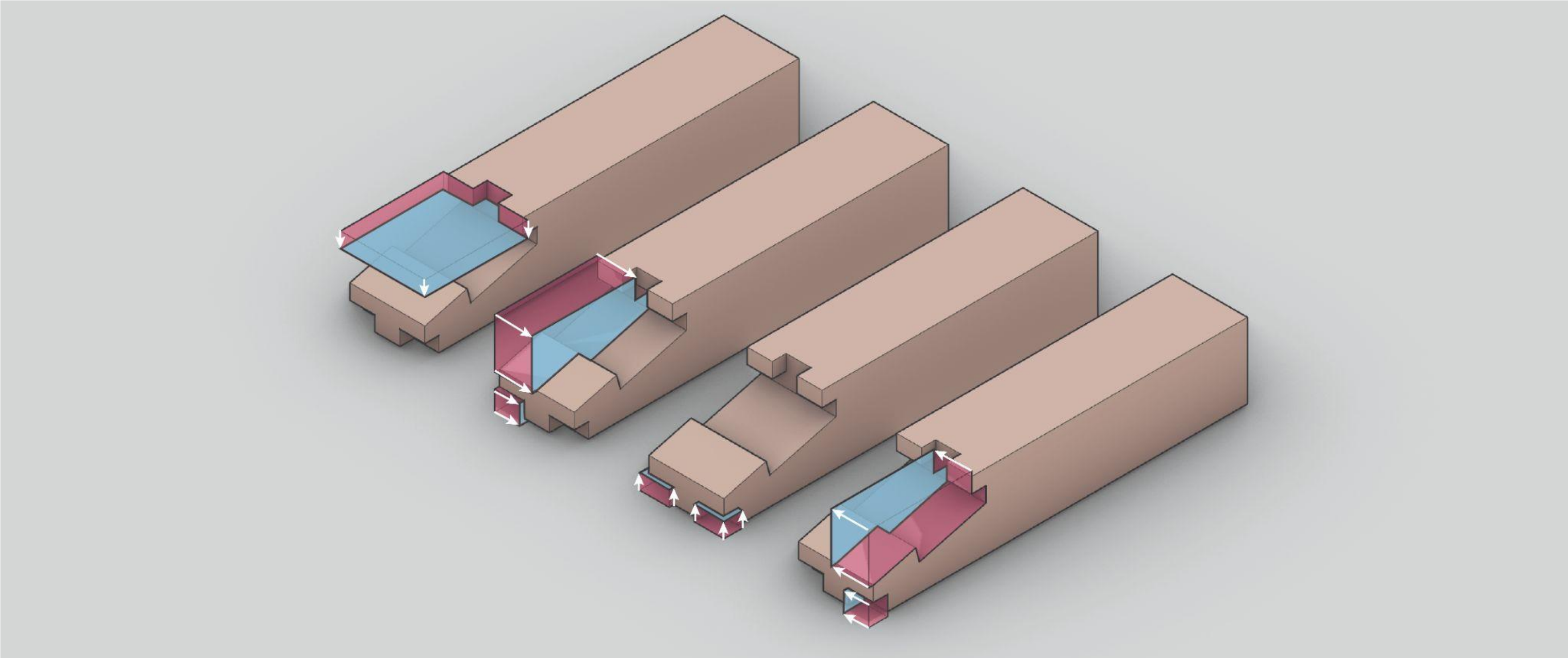
Degrees of Freedom



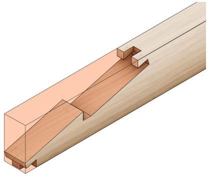
Analysis | Machining - Milling Curves



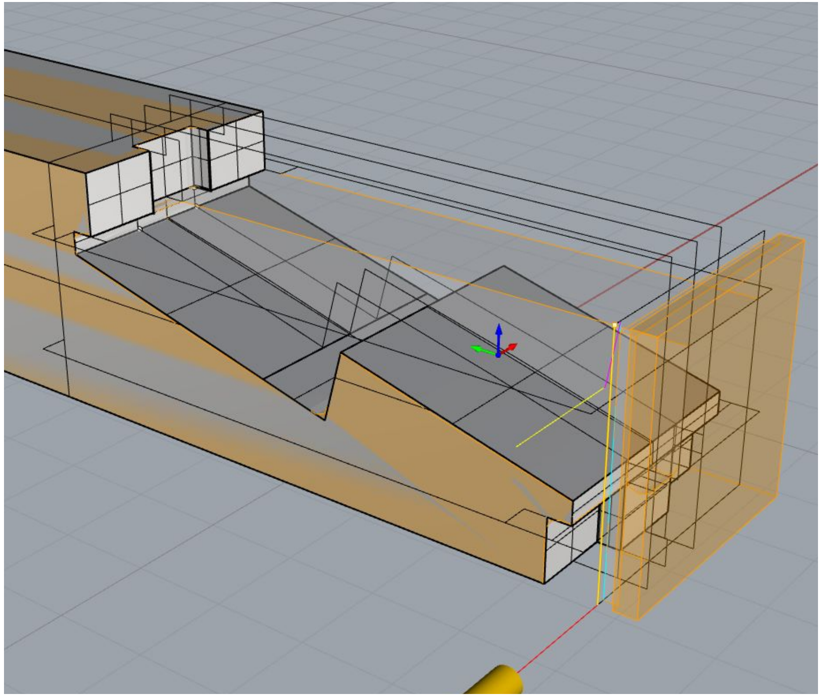
Millability

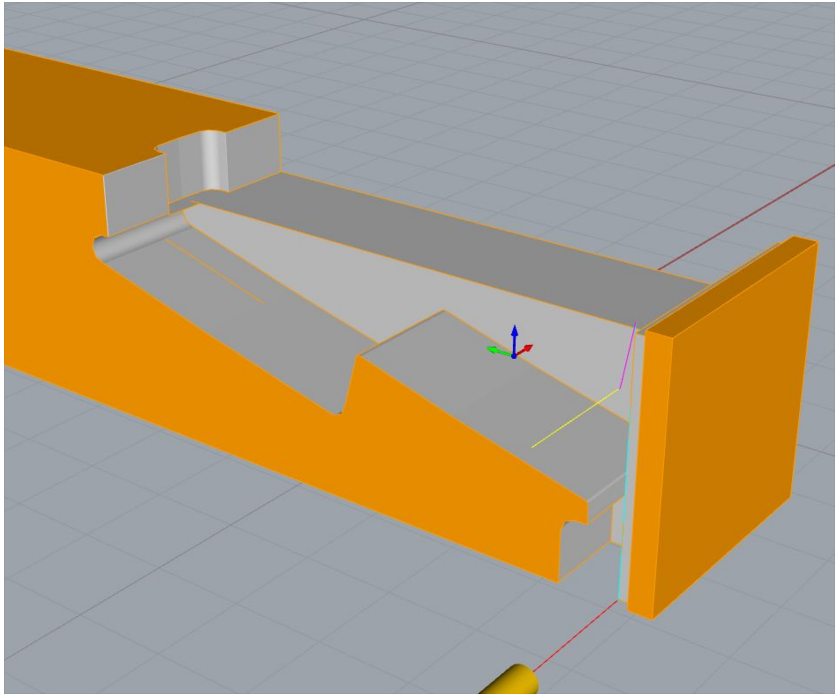


Analysis | Machining - Tool Paths



Milling Time





Analysis | FEA Constants

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Poisson Ratio	0.4 - 0.6	**XY**	0.535	**YZ**	0.419	**ZX**	0.019
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Density	400 - 500 kg/m^3	498 kg/m^3					
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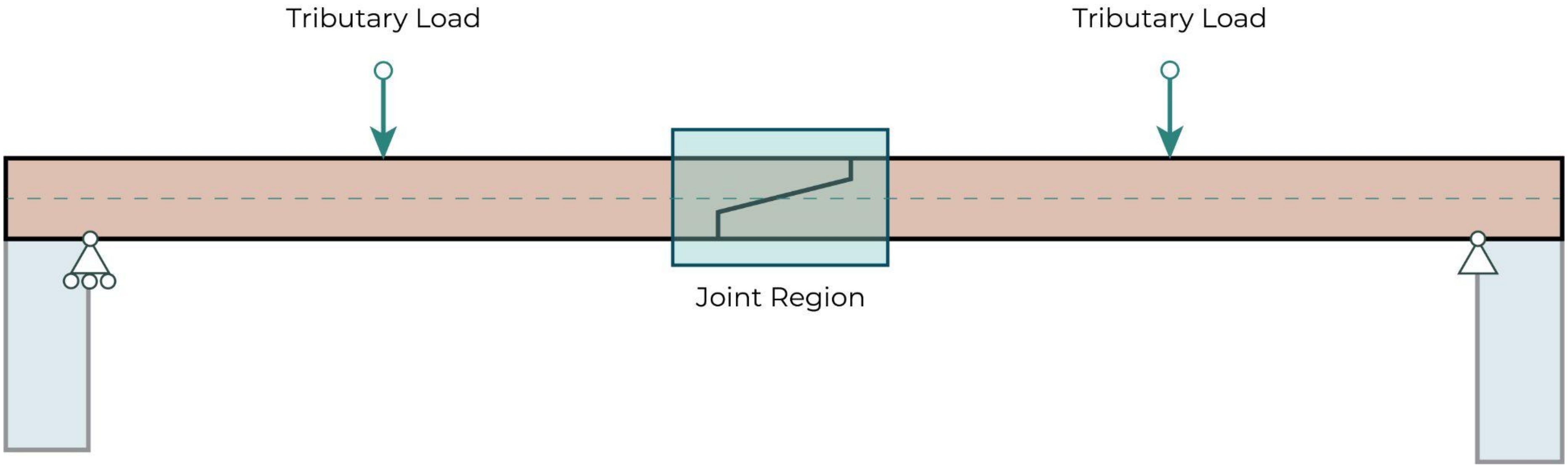
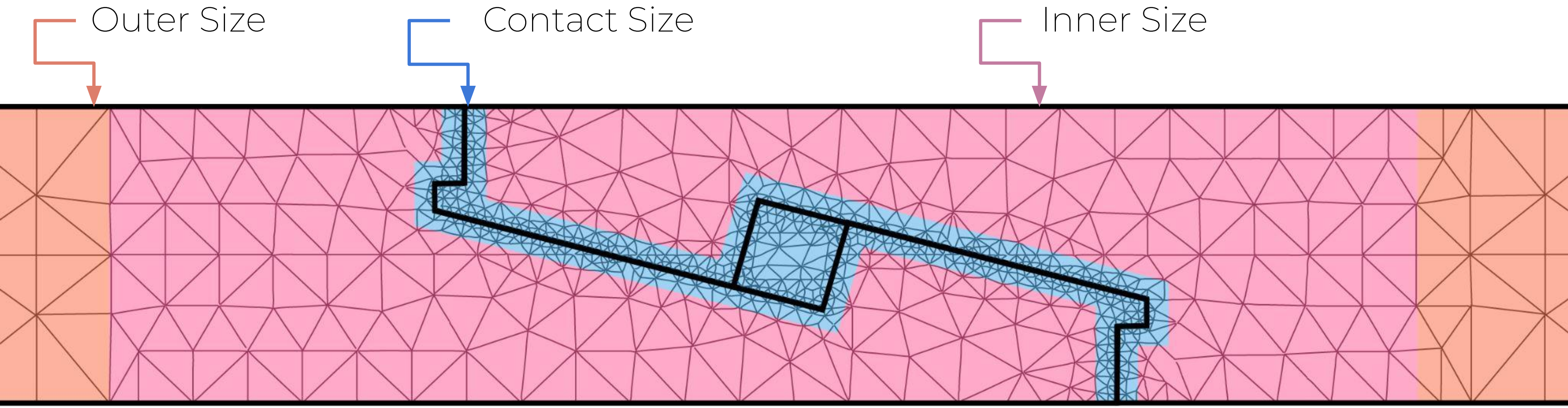
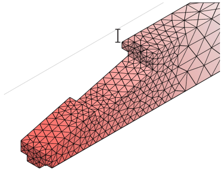
Analysis | FEA Setup

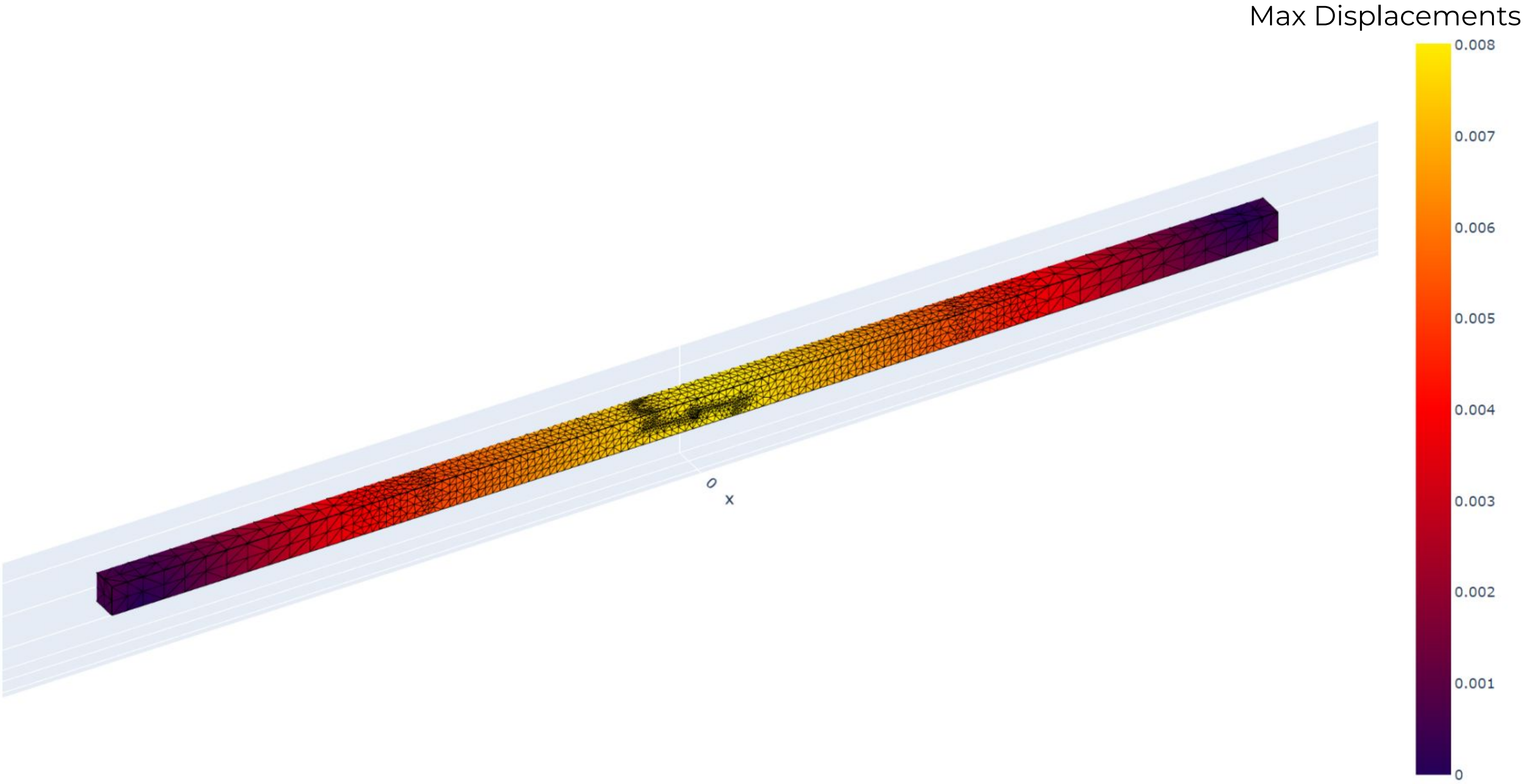


Analysis | Gmsh

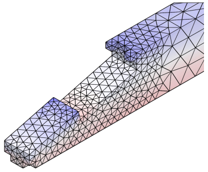


Analysis | FEA - Displacements



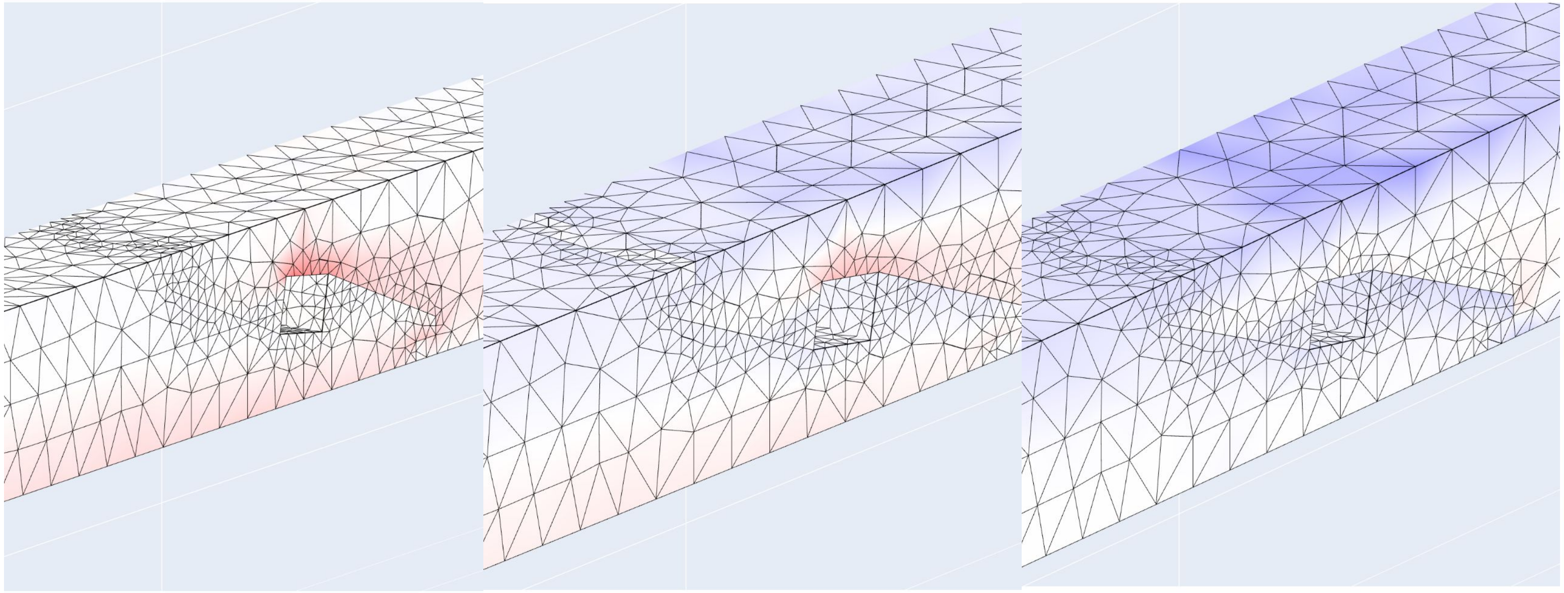


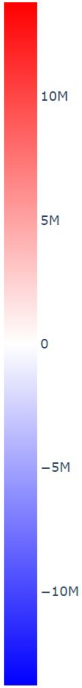
Analysis | FEA - Principal Stresses



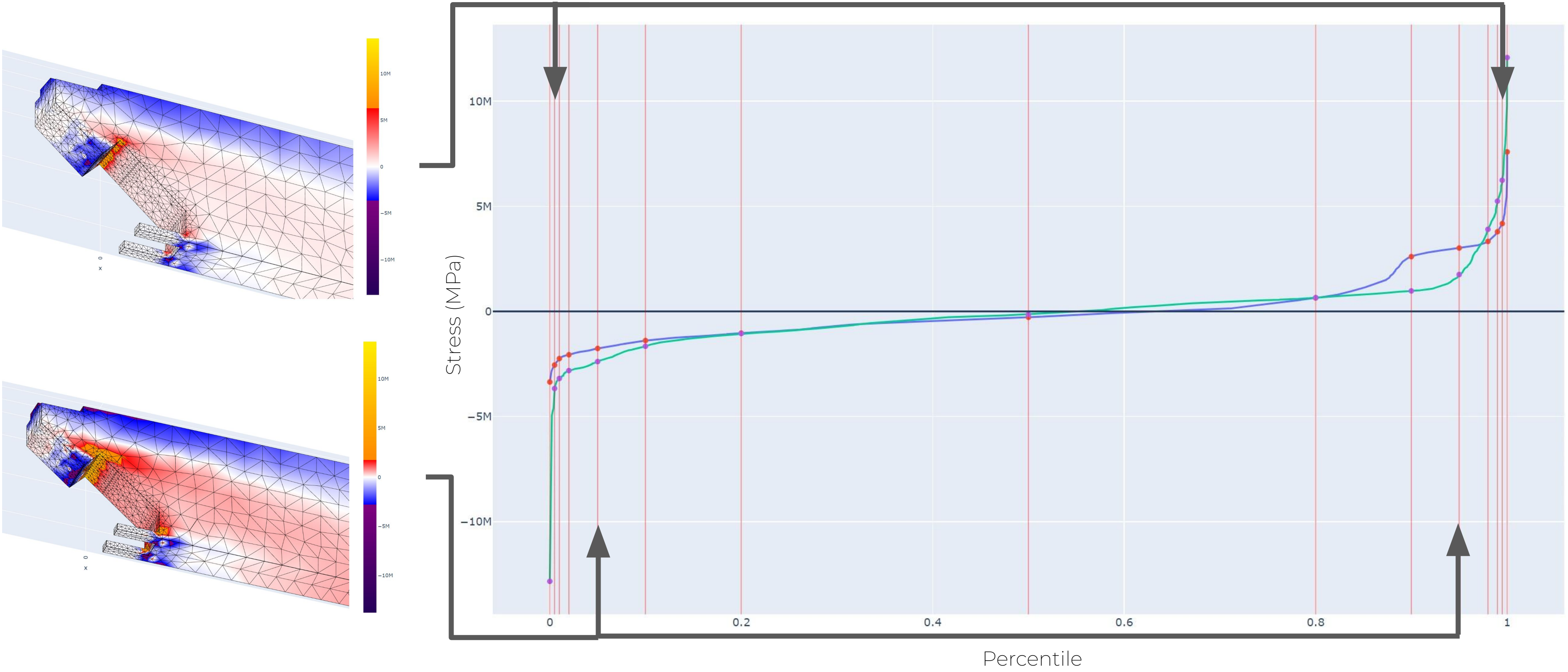
Max Stress

Principal 1 Principal 2 Principal 3





Analysis | FEA - Displacements



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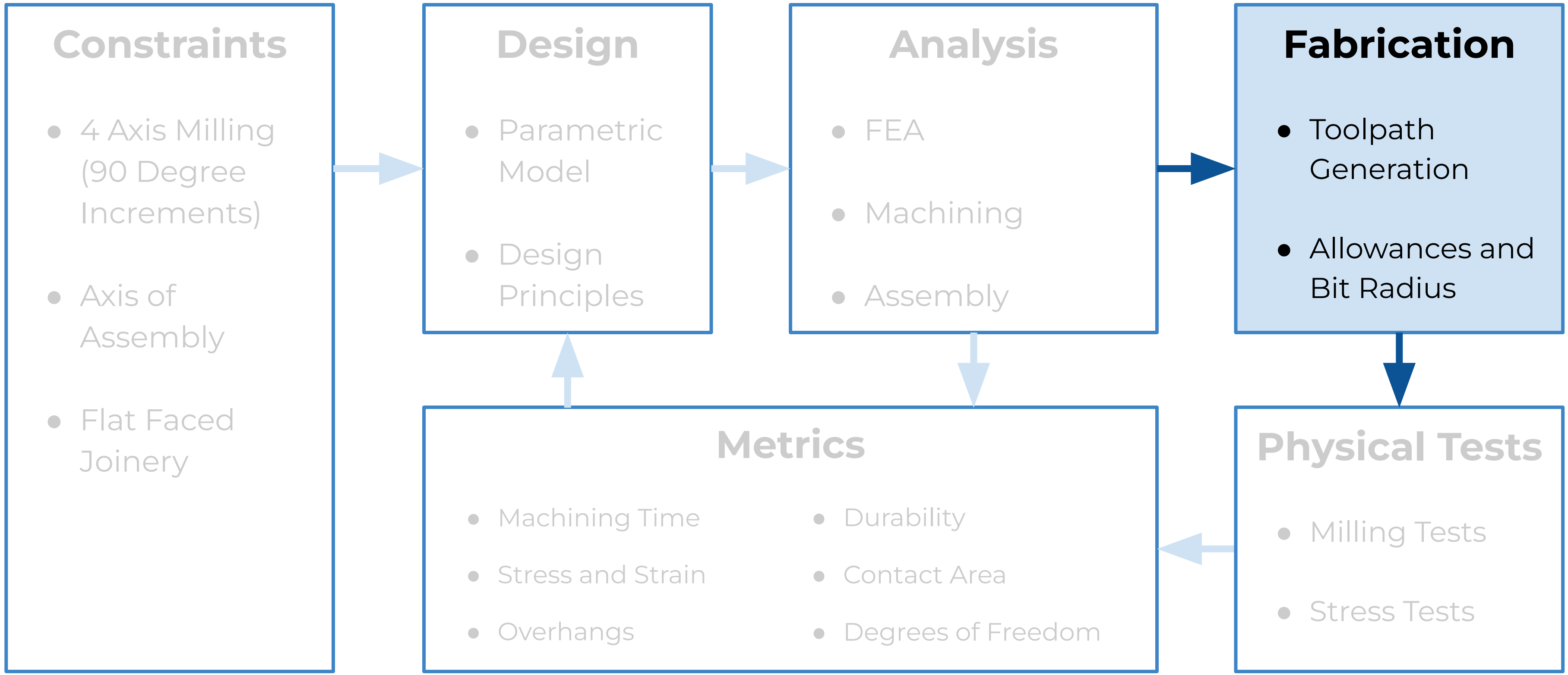
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4 Axis Milling (90 Degree Increments)
Axis of Assembly
Flat Faced Joinery
Design
Parametric Model
Design Principles
Analysis
FEA
Machining
Assembly
Fabrication
Toolpath Generation
Allowances and Bit Radius
Metrics
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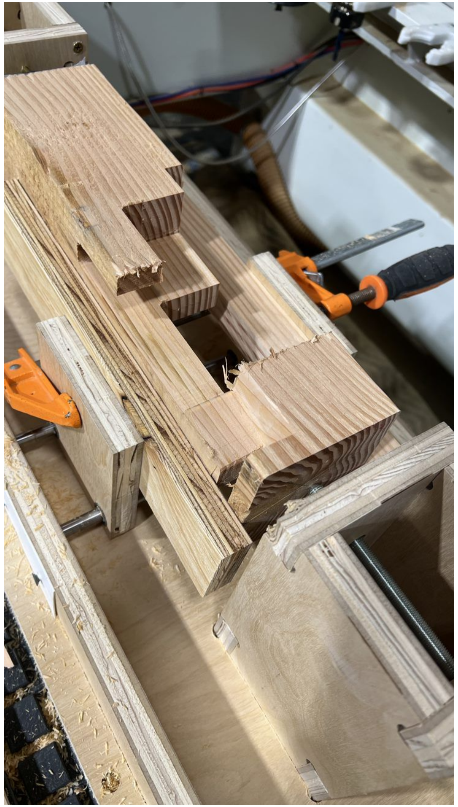
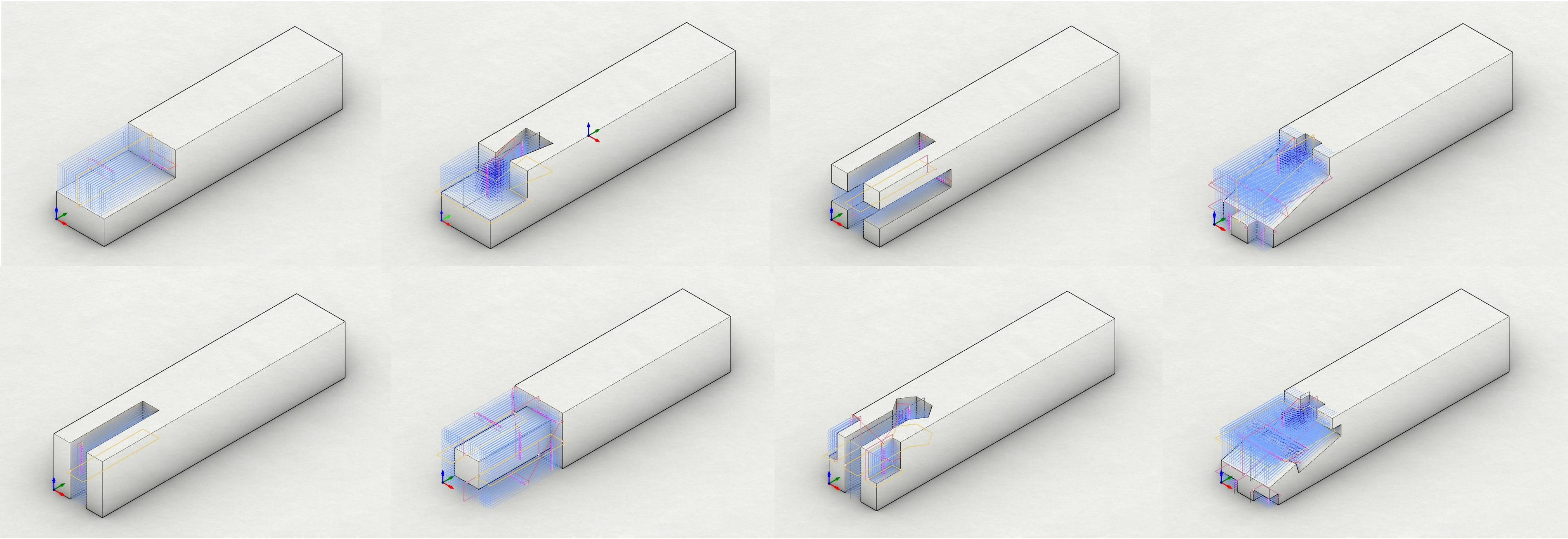
Stress and Strain
Overhangs
Durability
Contact Area
Degrees of Freedom
Physical Tests
Milling Tests
Stress Tests

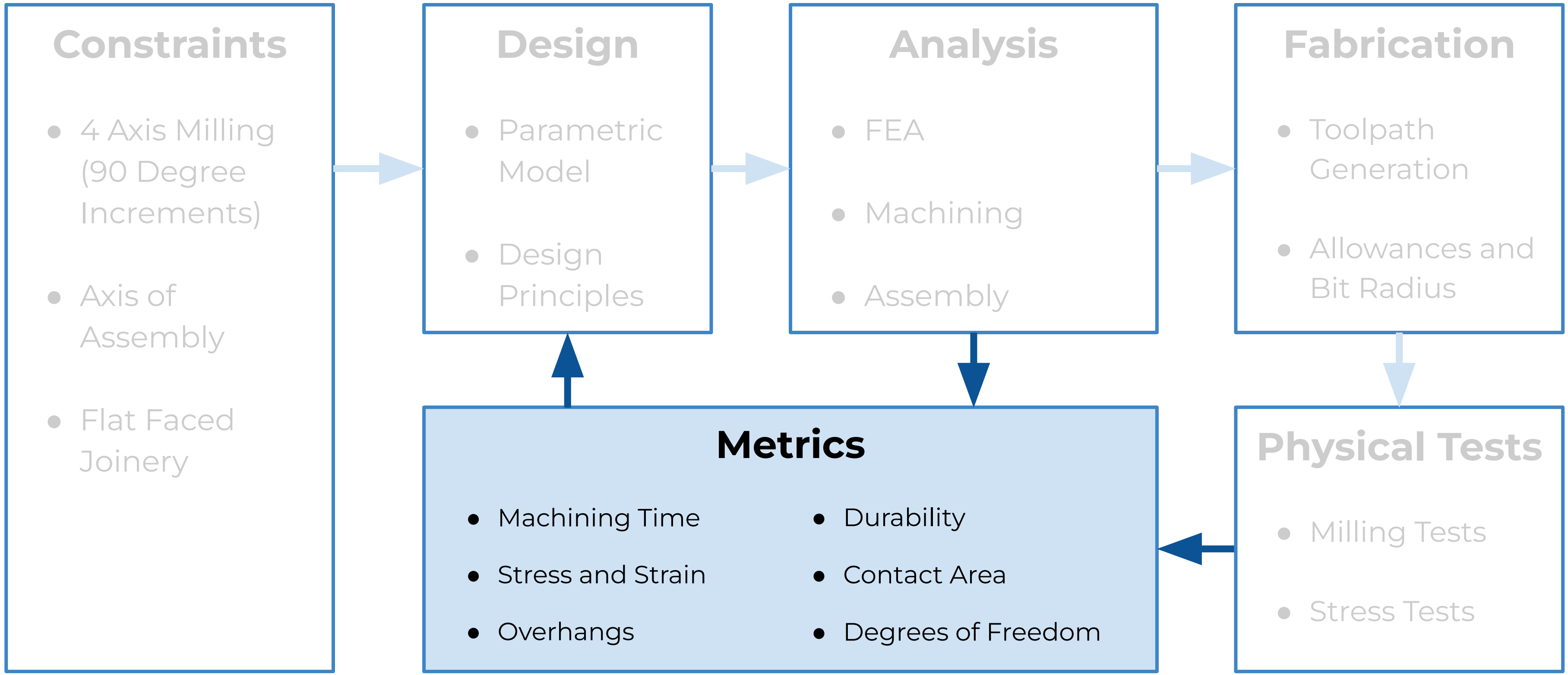
Fabrication | 4-Axis Milling



Fabrication | Mass Customization and Prototyping



Framework



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Flat Faced Joinery
Design
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Design Principles
Analysis
FEA
Machining
Assembly
Fabrication
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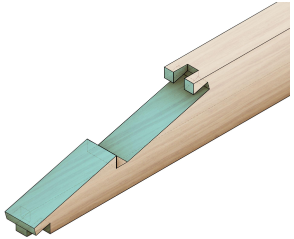
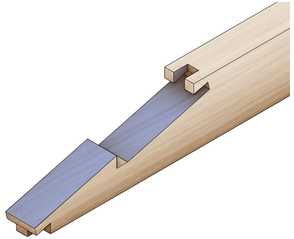
Metrics

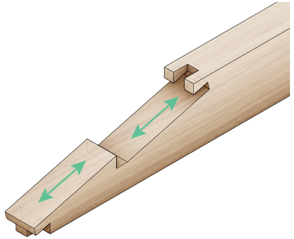
Assembly Metrics



Contact Area

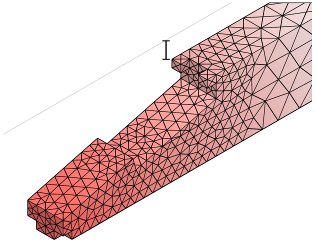


Friction Area

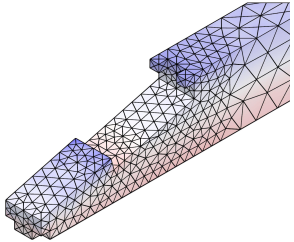


Degrees of Freedom

FEA Metrics

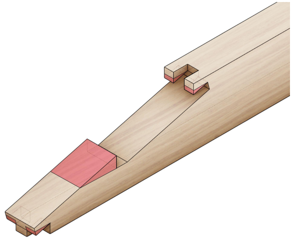


Max Displacements

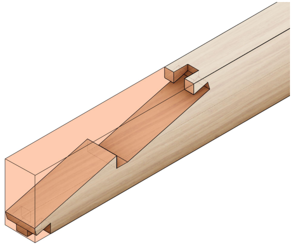


Max Stress

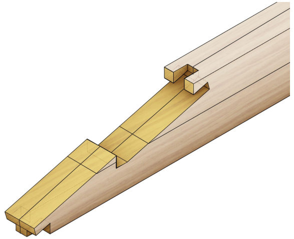
CAM Metrics



Durability (Overhang)



Milling Time



Millability

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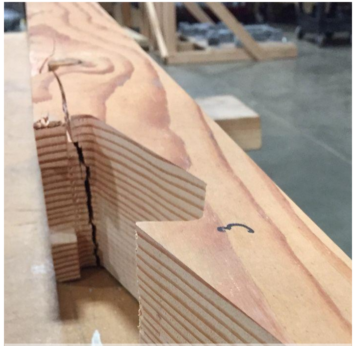
- Testing
- Metrics



Case Studies

- Setup
- Physical Study
- Mass Timber Simulations

Conclusion

- Lessons
- Future Work

Joint Design Case Study

Short Members have difficult being reused. Spliced timber beams provide a great case study for testing this new process.

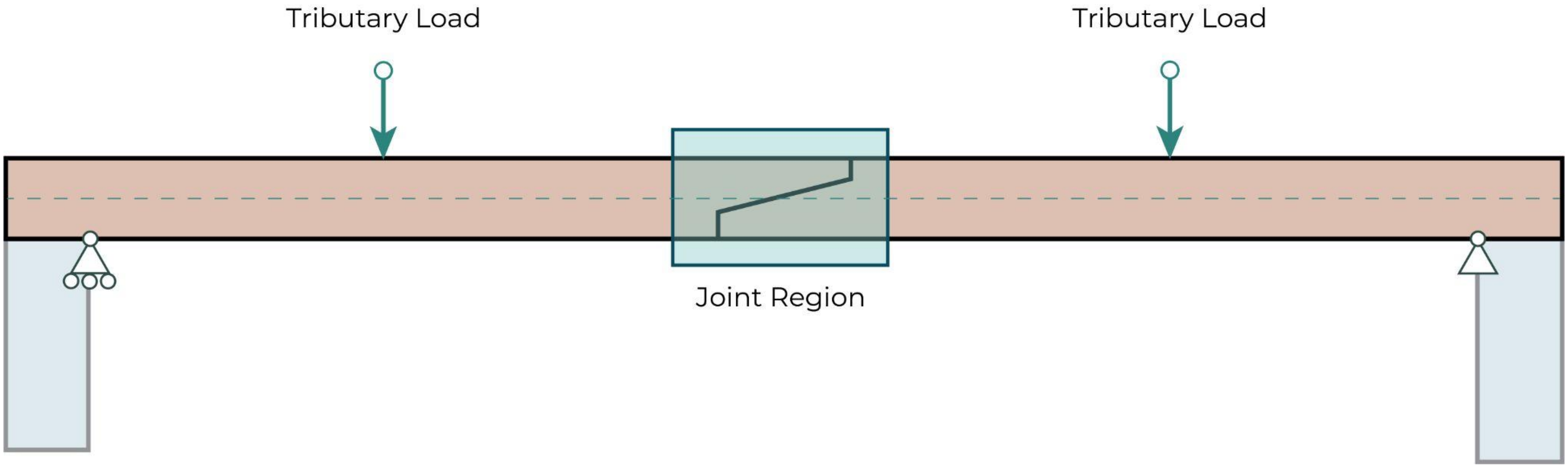
Methods

- Rapid Prototyping
- Design Intuition
- Simulations
- Physical Tests

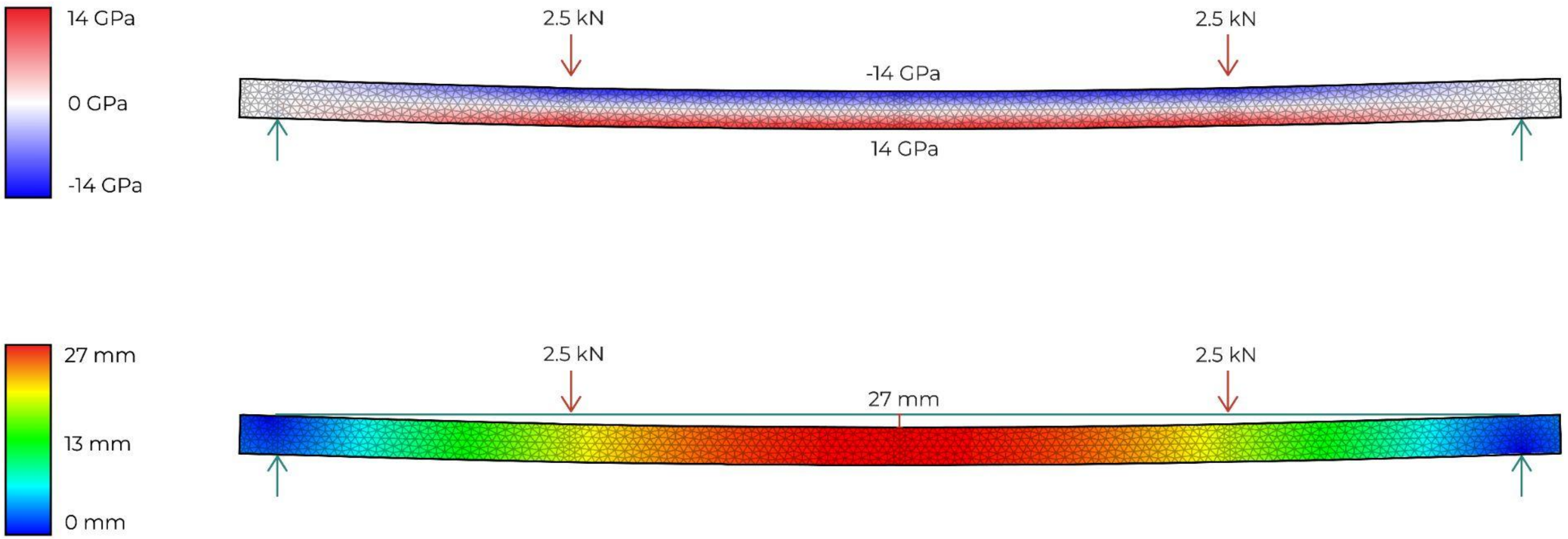
https://oldworldlumberco.com/wp/wp-content/uploads/2019/05/IMG_2283.jpeg

https://www.buildingconservation.com/articles/timber-roof-structures/scarf-repair-tie-beam.jpg

Setup | Load Testing Setup



Setup | Solid Beam Control

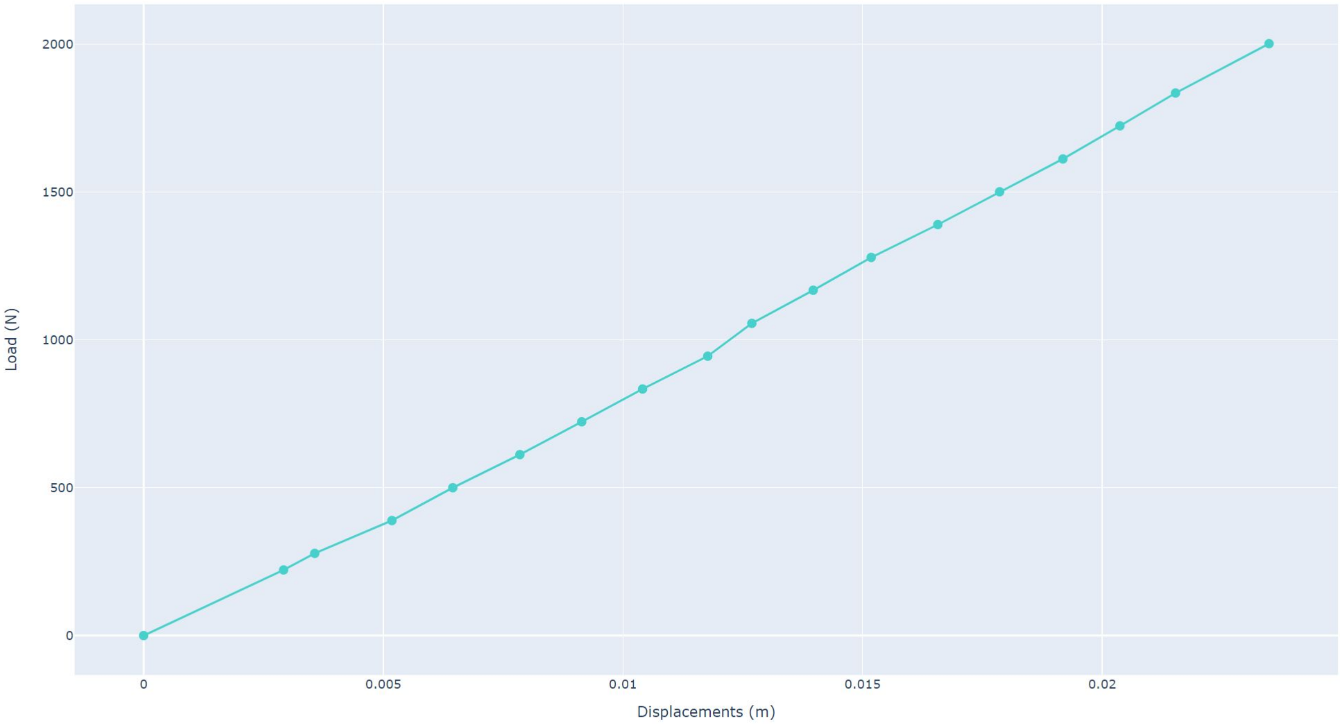


Setup | Solid Beam Setup

Setup | Solid Beam Loading

Setup | Solid Beam Results

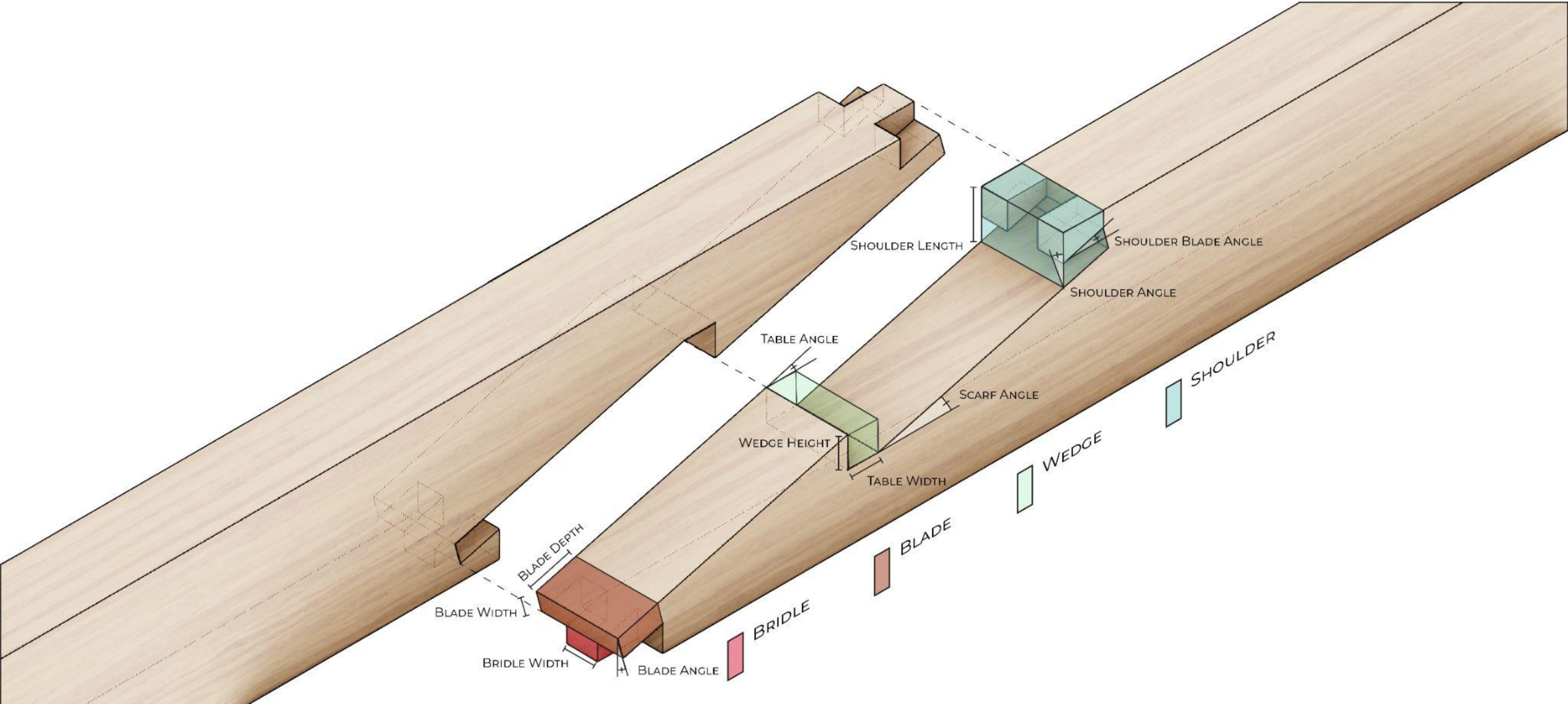
As the displacements scale linearly with the load up to plastic deformation, estimating the material properties using a Genetic Algorithm can assume a linear model



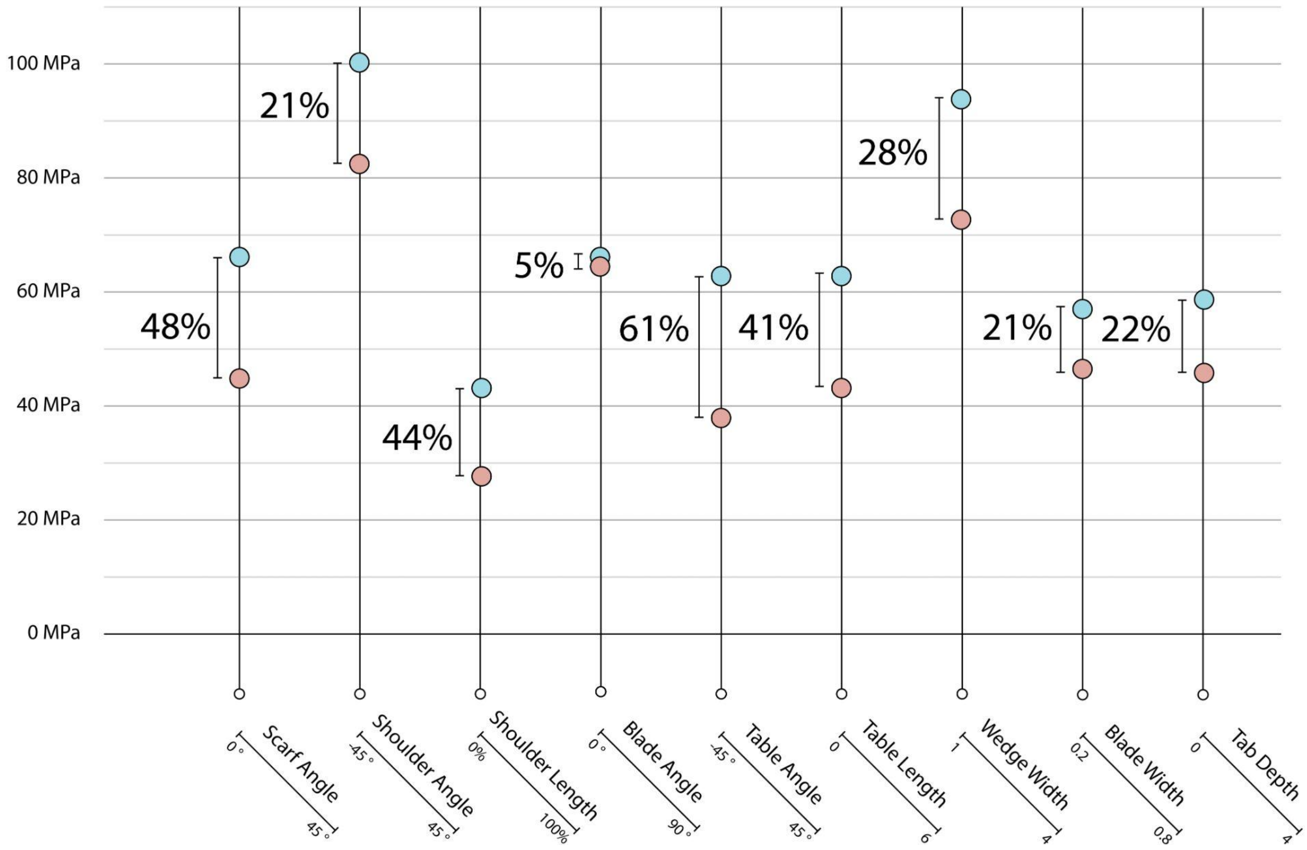
Setup | Solid Beam Material Properties

Properties	GA Range	GA Results
E-Modulus | X	7 - 13.5 GPa	7.74 GPA
E-Modulus | Y	3 - 7 MPa	5.59 MPA
E-Modulus | Z	5 - 10 MPa	9.29 MPA
Poisson Ratio | XY	NONE	0.535
Poisson Ratio | YZ	NONE	0.419
Poisson Ratio | ZX	NONE	0.019
Density	NONE	498 kg/m^3

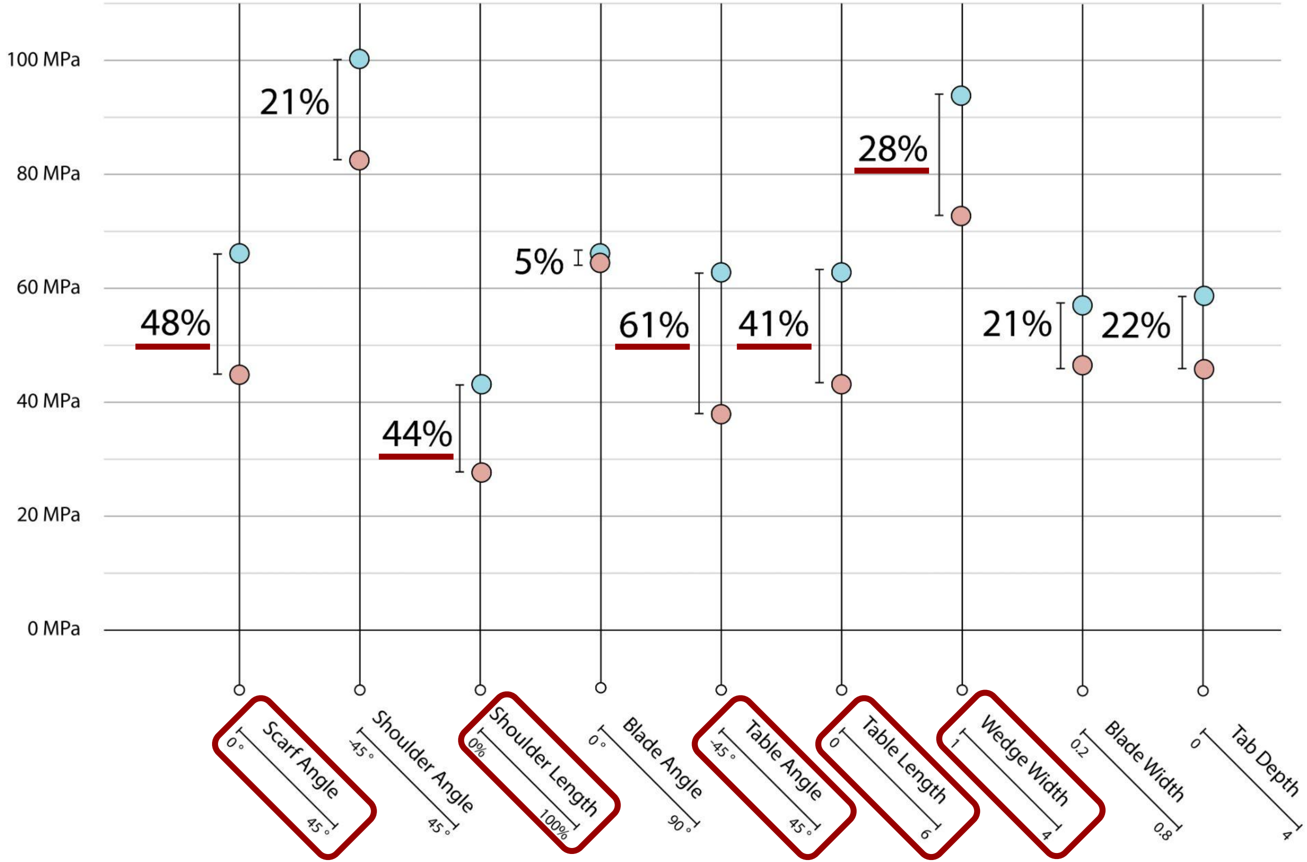
Setup | Scarf Joint Variables



Setup | Single Variable Comparison



Setup | Chosen Variables



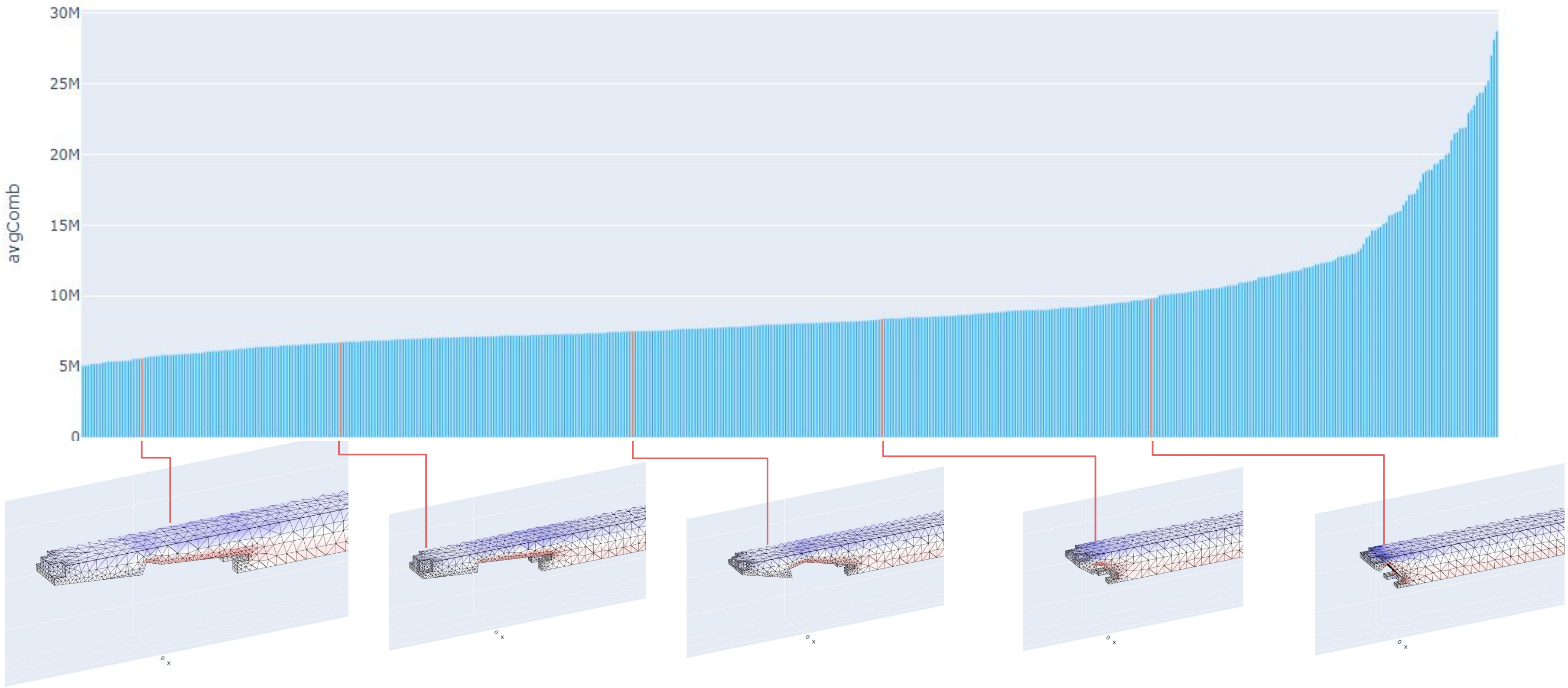
Case Study 1 | Member Properties

Properties	Variables Used					
Member Dimensions	**Height**	0.085 m	**Width**	0.085 m	**Length**	3 m
Gmsh Sizes	**Outer**	0.06	**Inner**	0.02	**Contact**	0.0075
Load	250 N					
Allowable Stress	13.8 MPa					

Case Study 1 | Simulation Variables

Variables	Range	Number of Variables
Scarf Angle	15° to 45°	5
Shoulder Length	0.4 to 1.0	5
Table Angle	-45° to 45°	5
Table Length	0.4 to 2.0	5

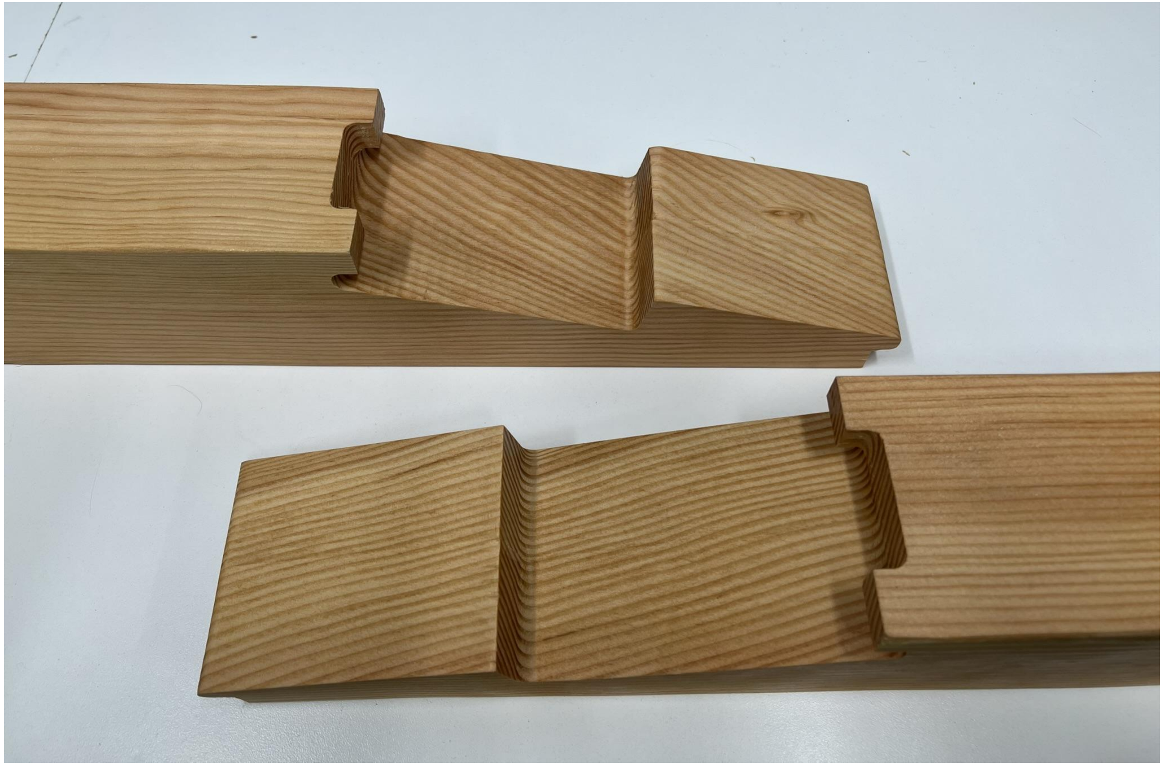
Case Study 1 | Simulated Plot



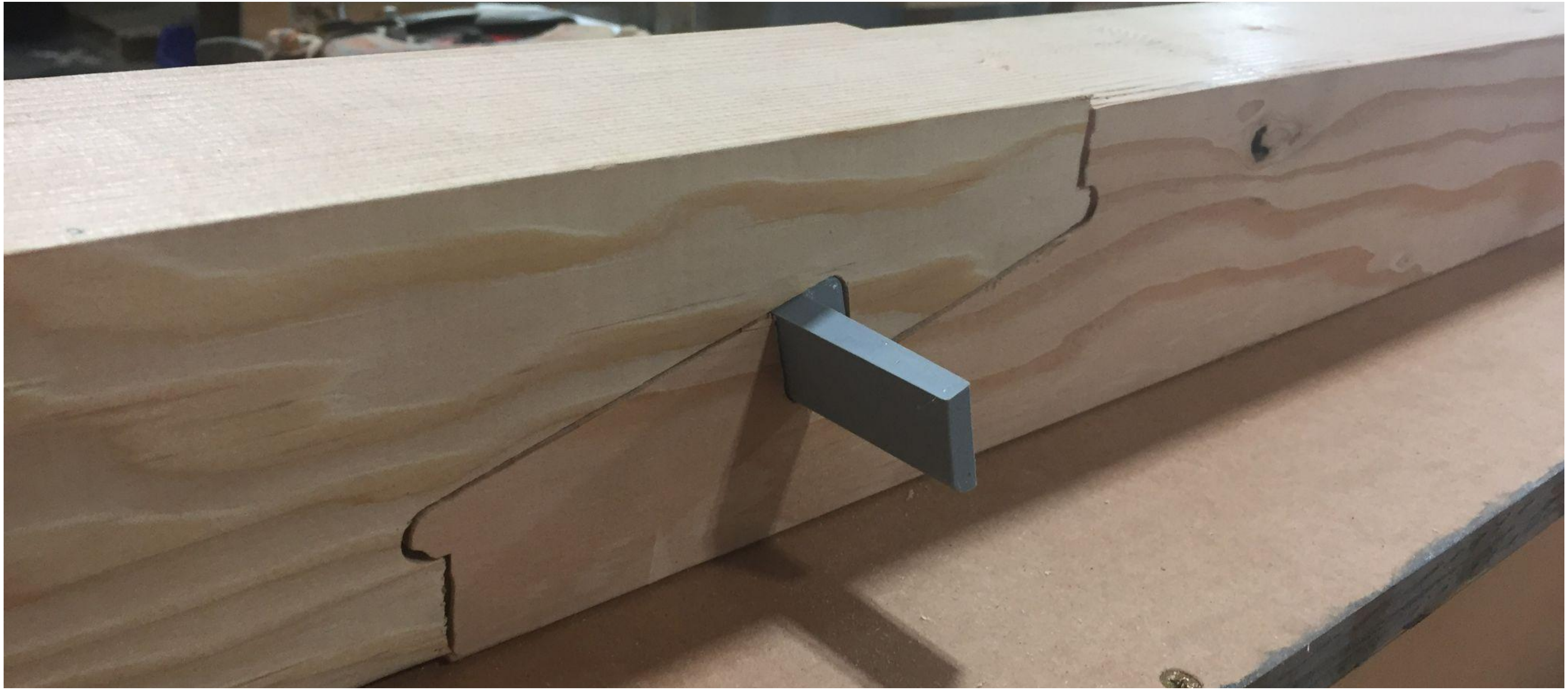
Case Study 1 | Assembly Fabrication



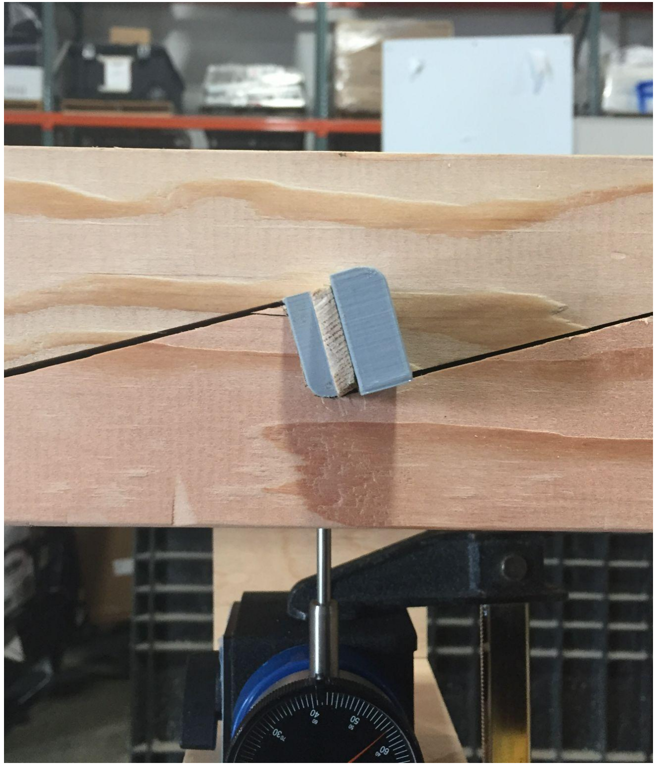

Case Study 1 | Assembly Fabrication



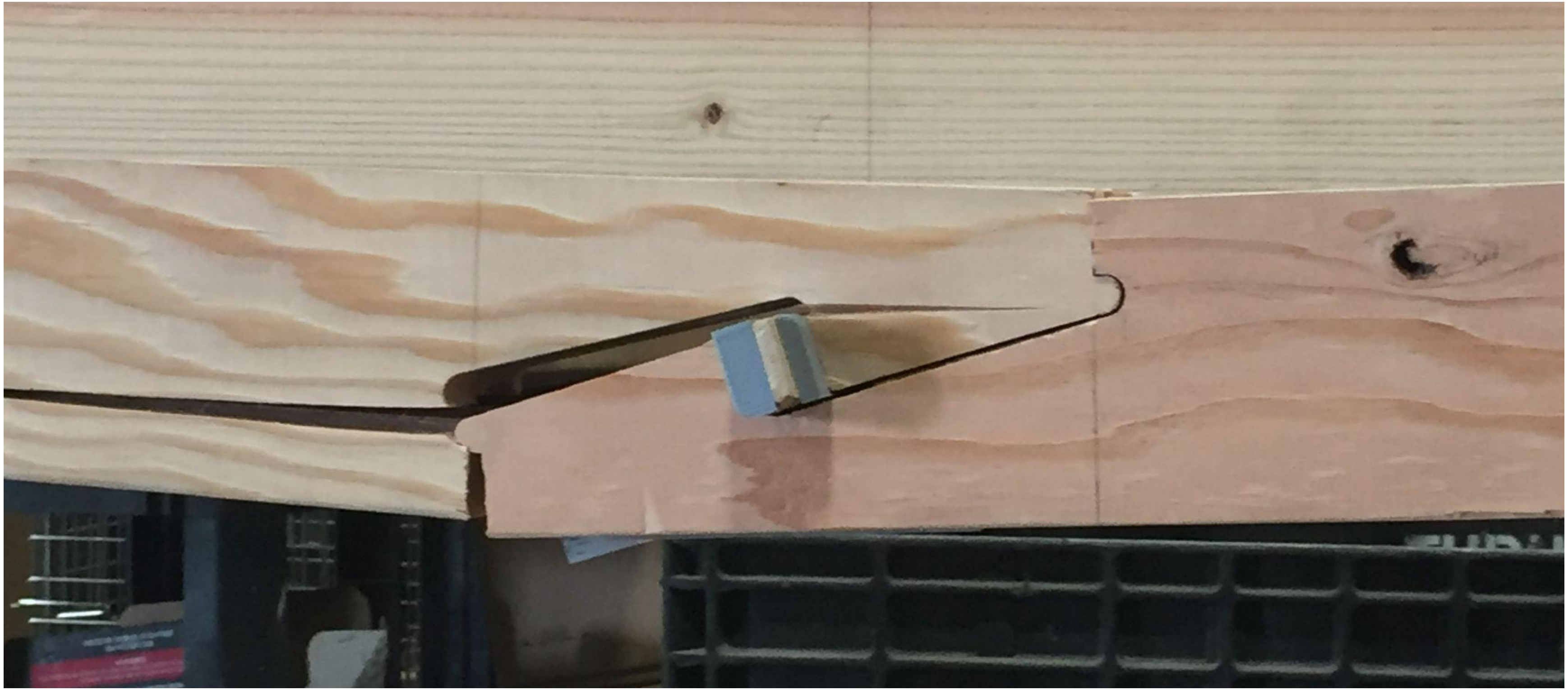
Case Study 1 | Joint Test Setup



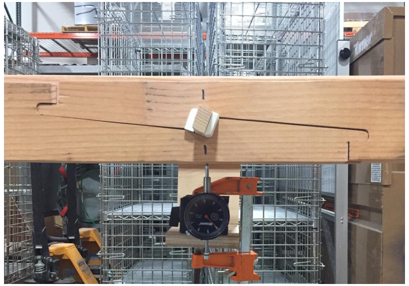
Case Study 1 | Joint Test Loading

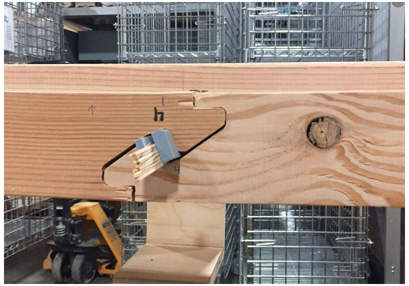


Case Study 1 | Critical Load Testing



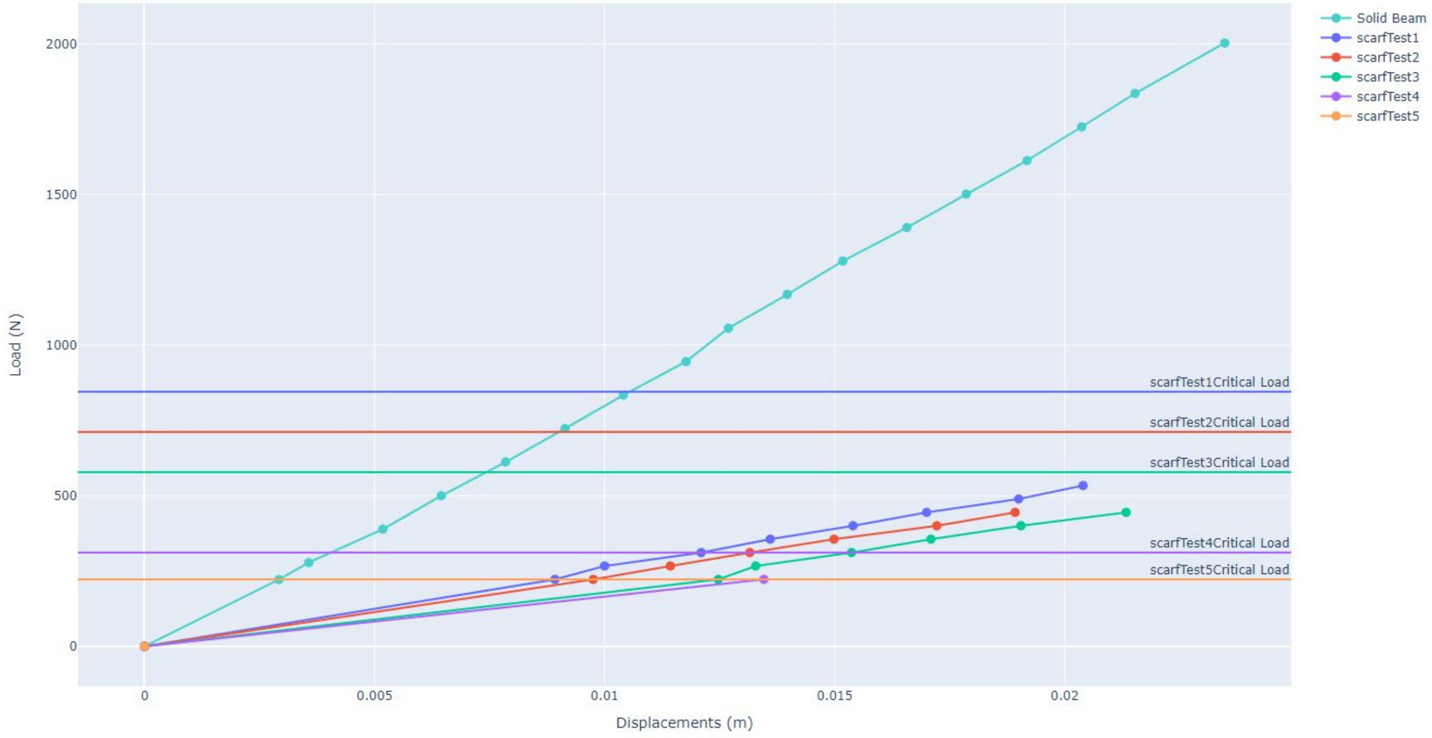
Case Study 1 | Physical Tests



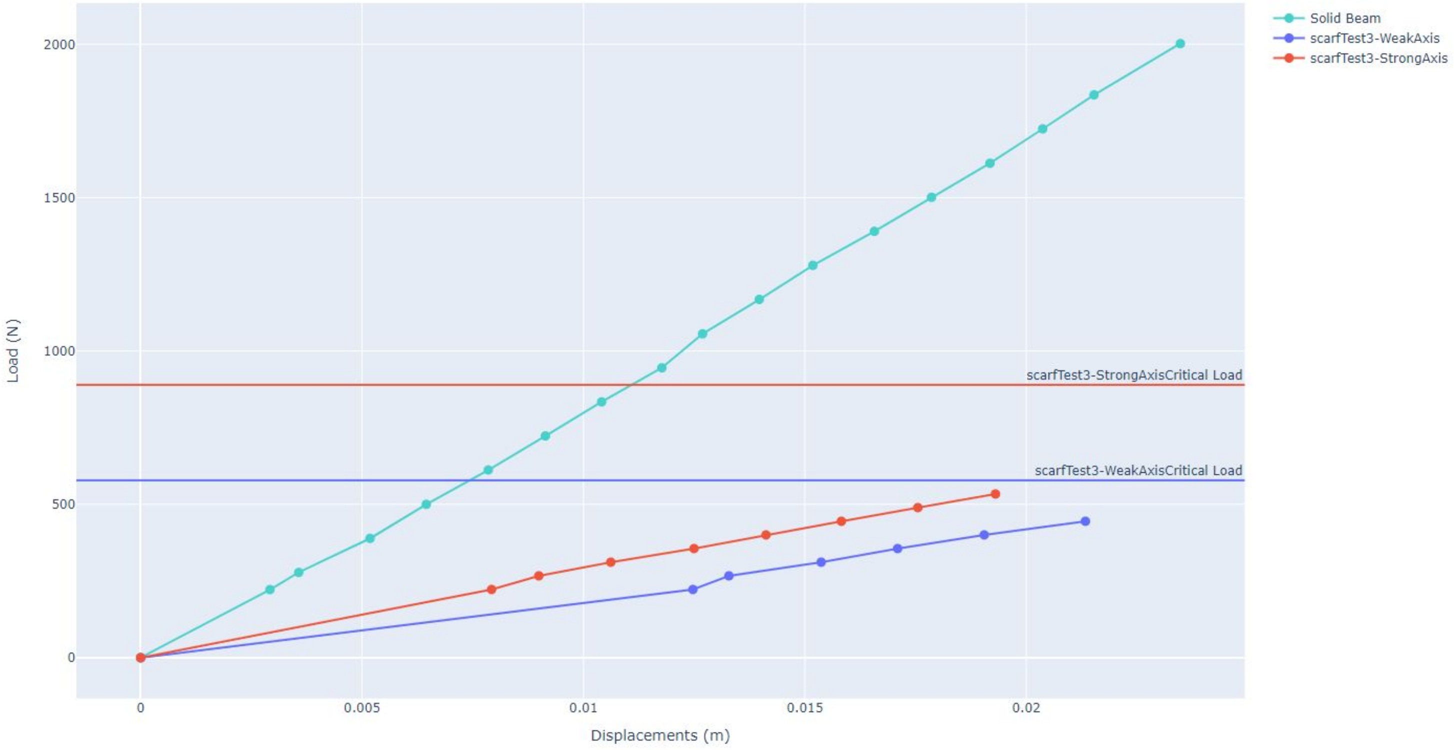


Case Study 1 | Physical Results



Case Study 1 | Material Axis (Face vs. Edge Grain)

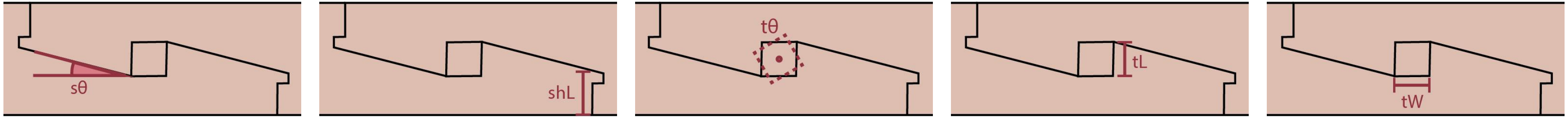
Case Study 1 | Material Axis (Face vs. Edge Grain)



Case Study 2 | Member Properties

Properties	**Variables Used**					
Member Dimensions	**Height**	0.3 m	**Width**	0.1 m	**Length**	6 m
Gmsh Sizes	**Outer**	0.12	**Inner**	0.04	**Contact**	0.01
Load	1.3 kN					
Allowable Stress	13.8 MPa					

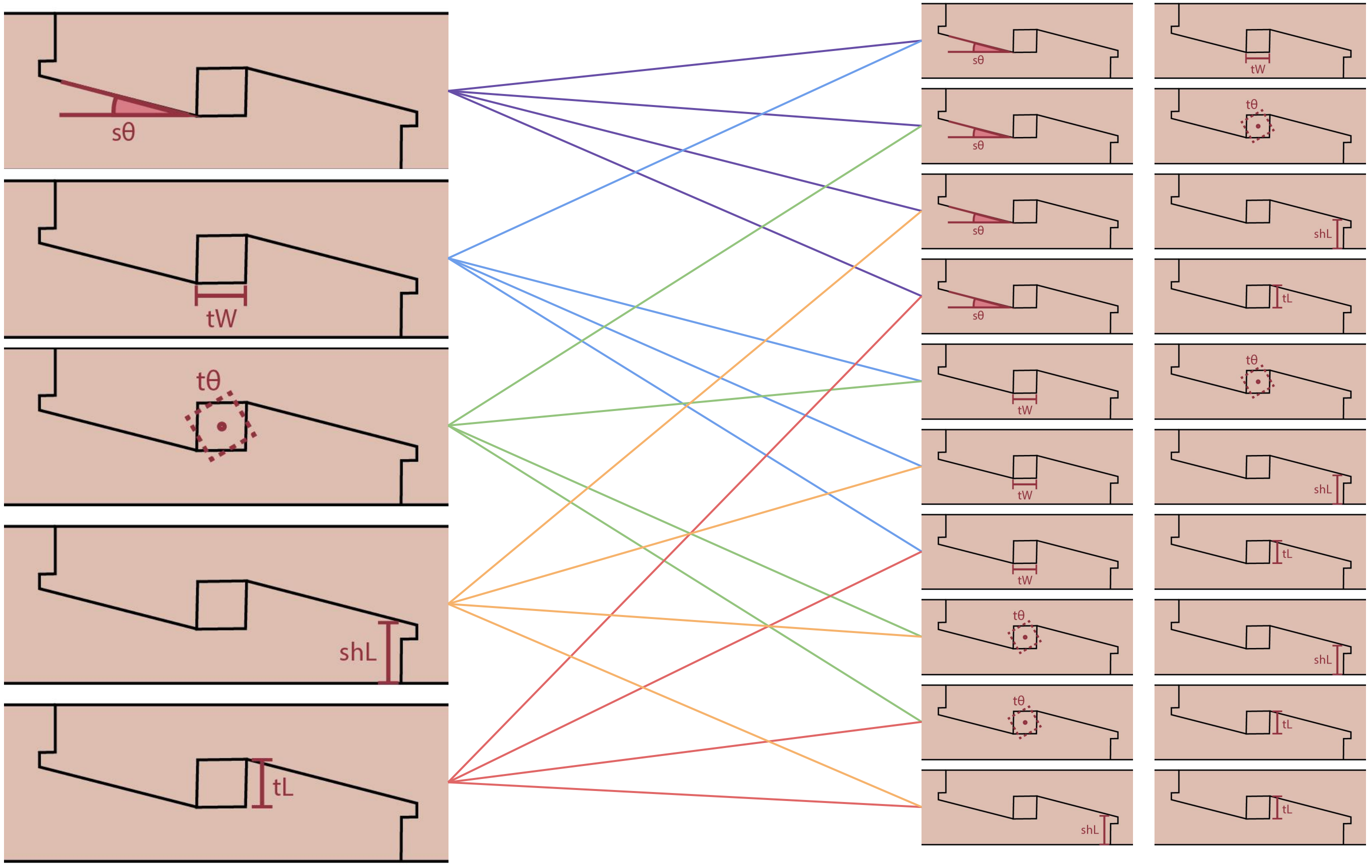
Case Study 2 | Variable Design Space



17 x 17 x 17 x 17 x 17

1,419,857
Combination

Case Study 2 | Variable Pairings



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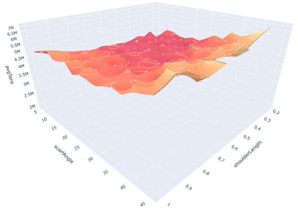
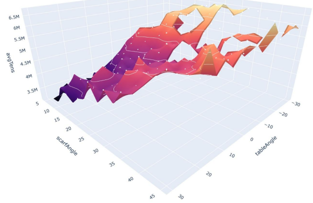
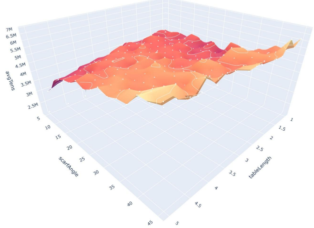
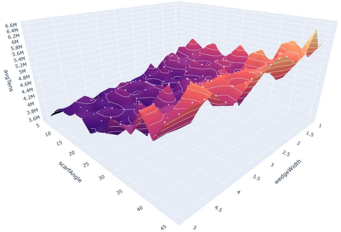
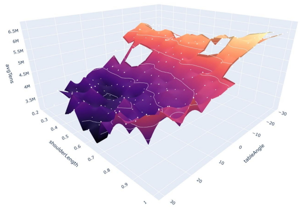
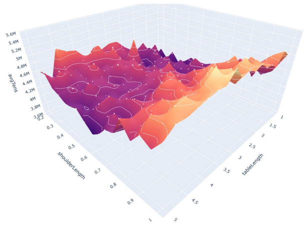
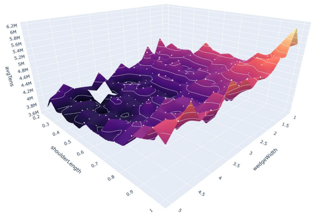
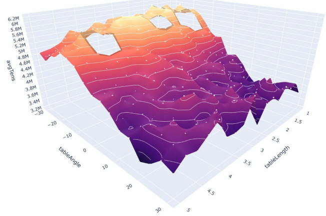
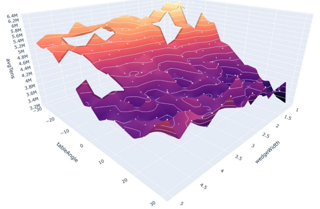
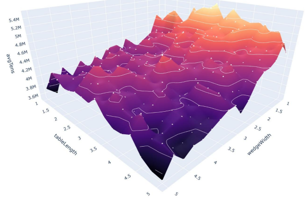
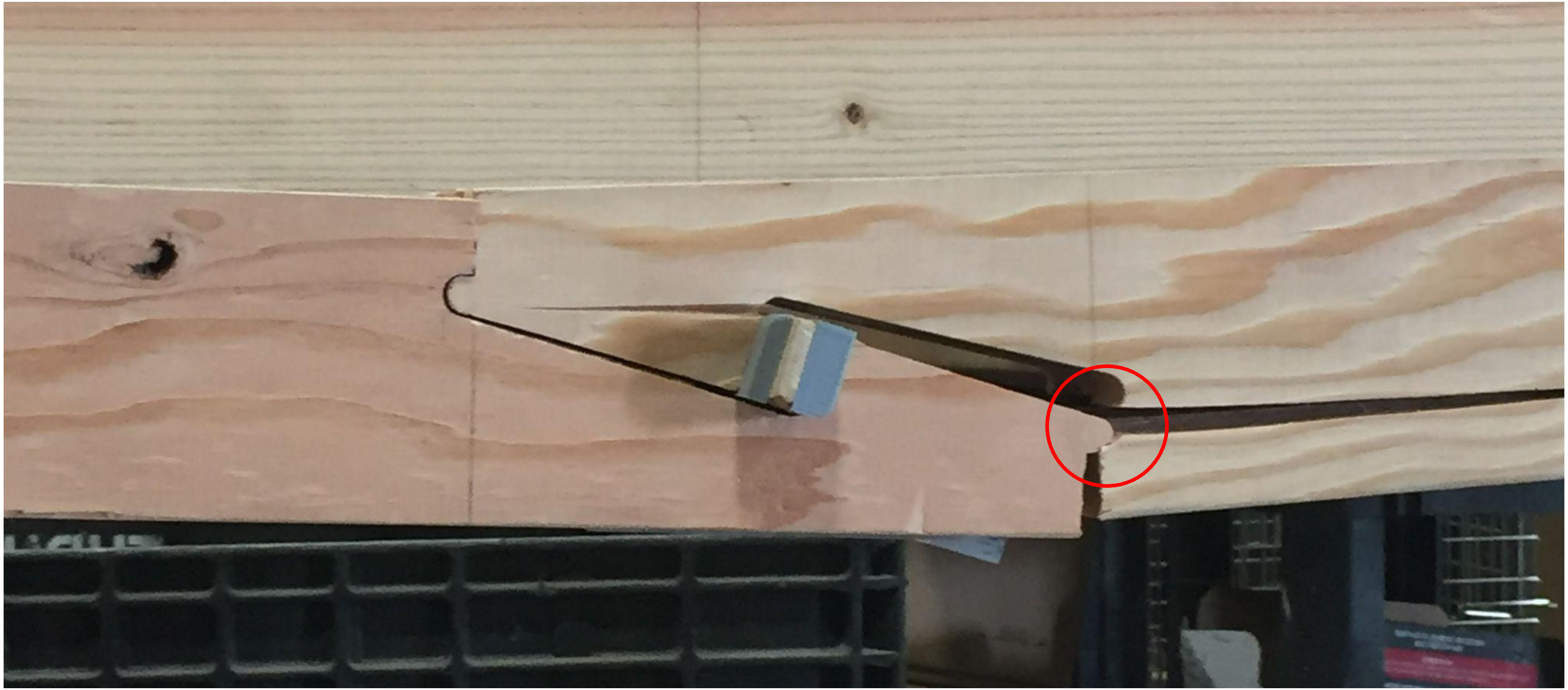
17 * 17 = 289
17 * 17 = 289

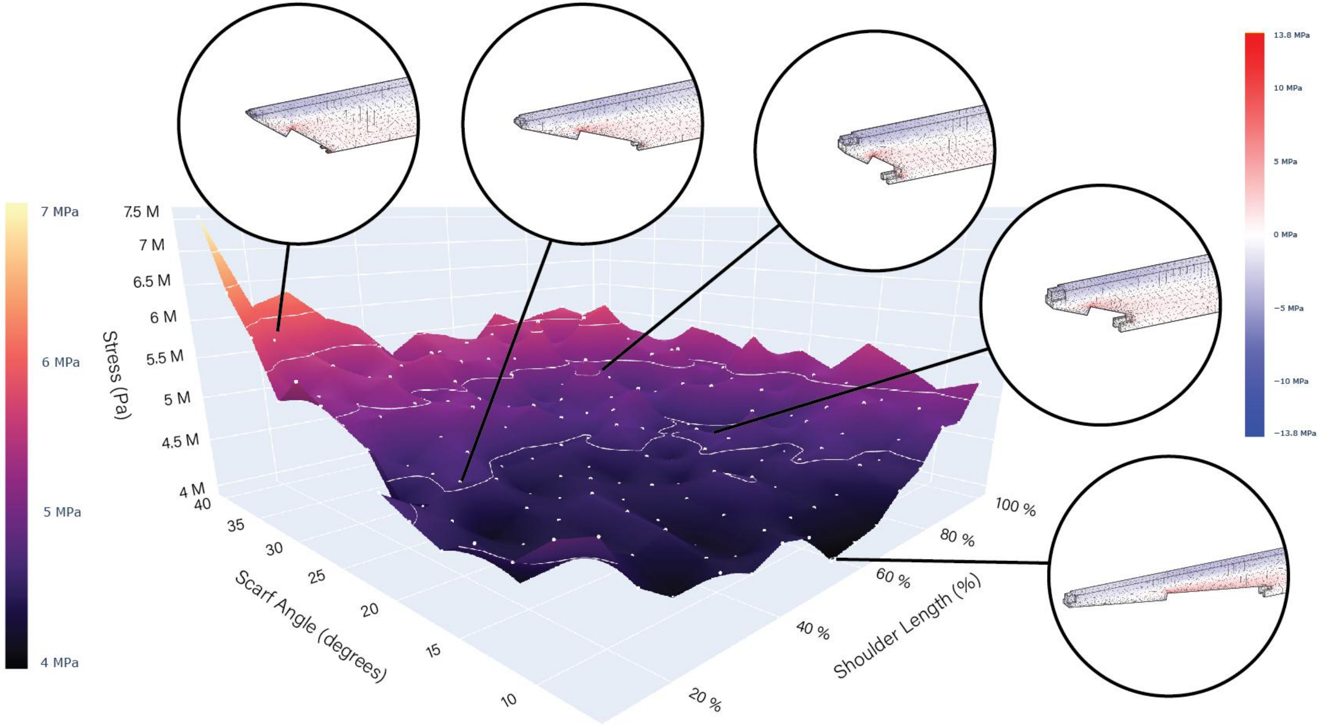
2890 Total

Stress Results	Shoulder Length	Table Angle	Table Length	Wedge Width
Scarf Angle				
Shoulder Length				
Table Angle				
Table Length				

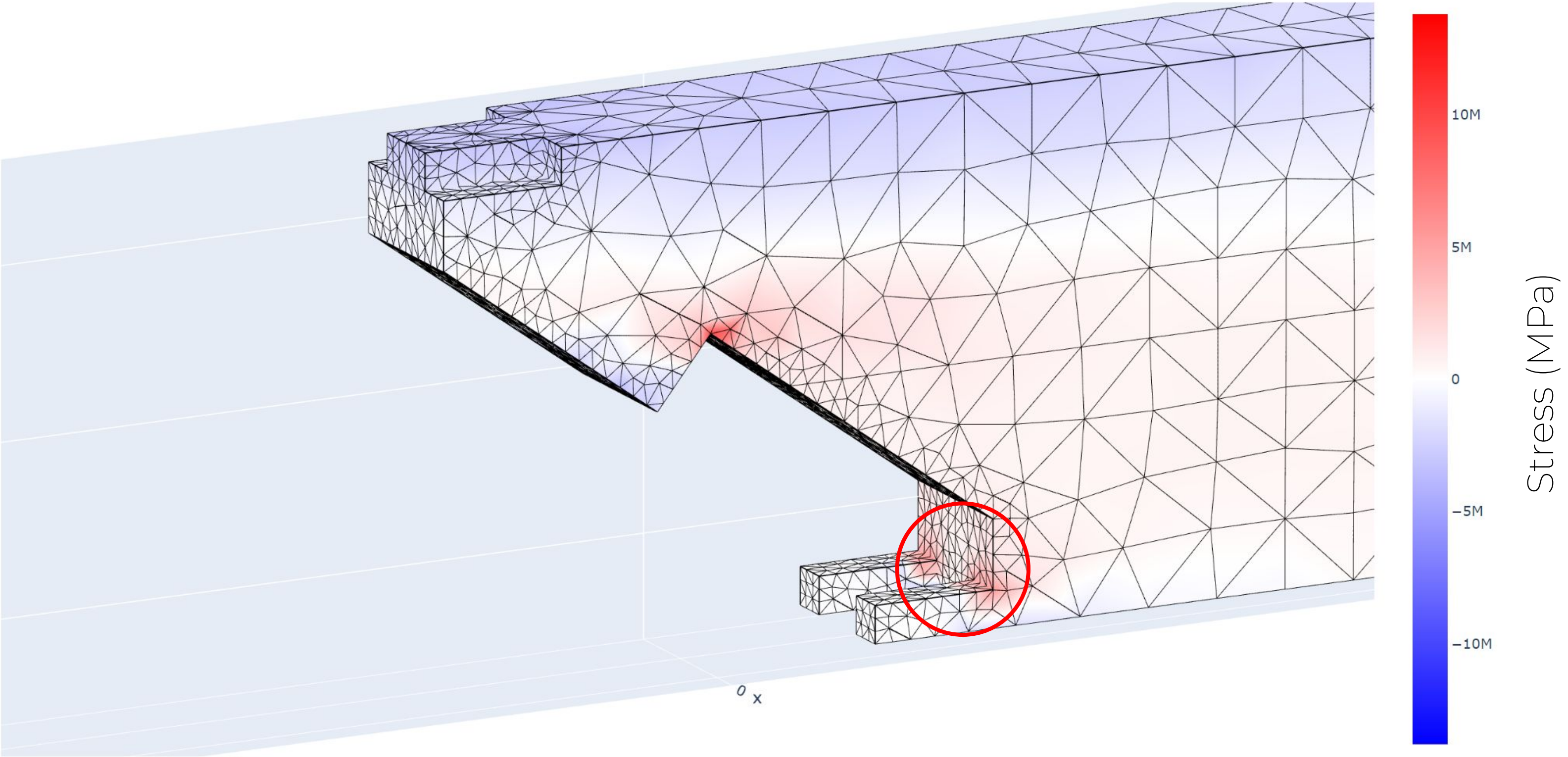
Blade Stress | Typical Joint



Case Study 2 | Blade Stress Solution



Blade Stress | Low Performance



Blade Stress | High Performance

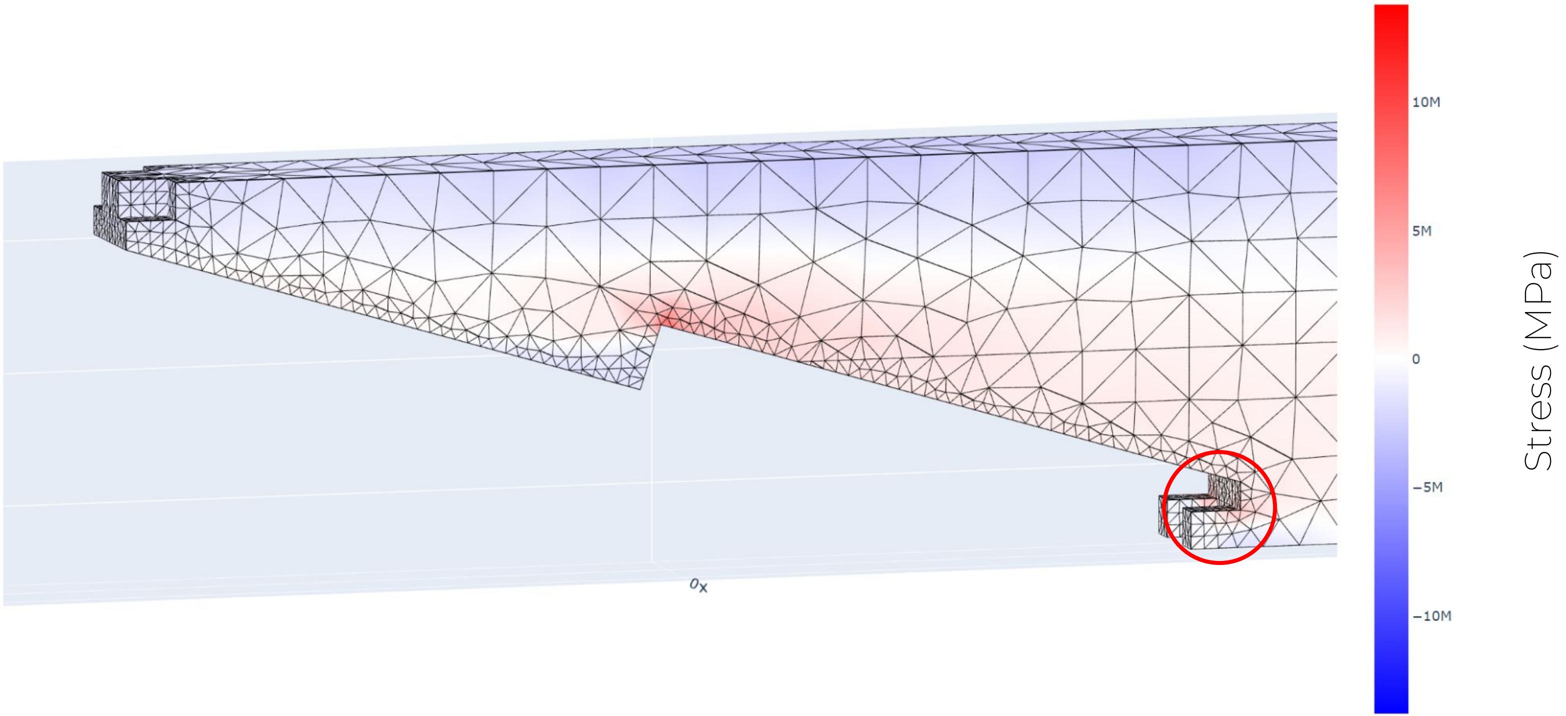
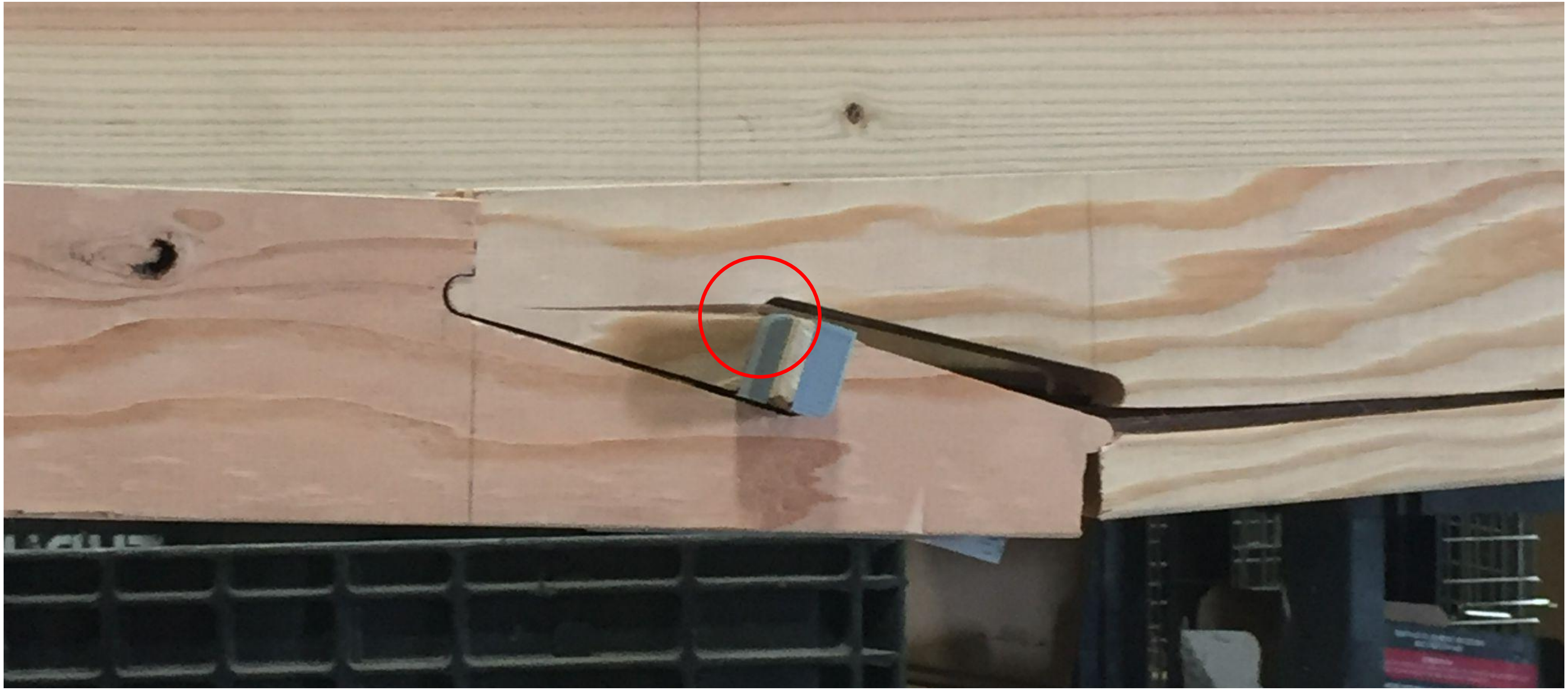


Table Stress | Typical Joint



Case Study 2 | Table Stress Solution

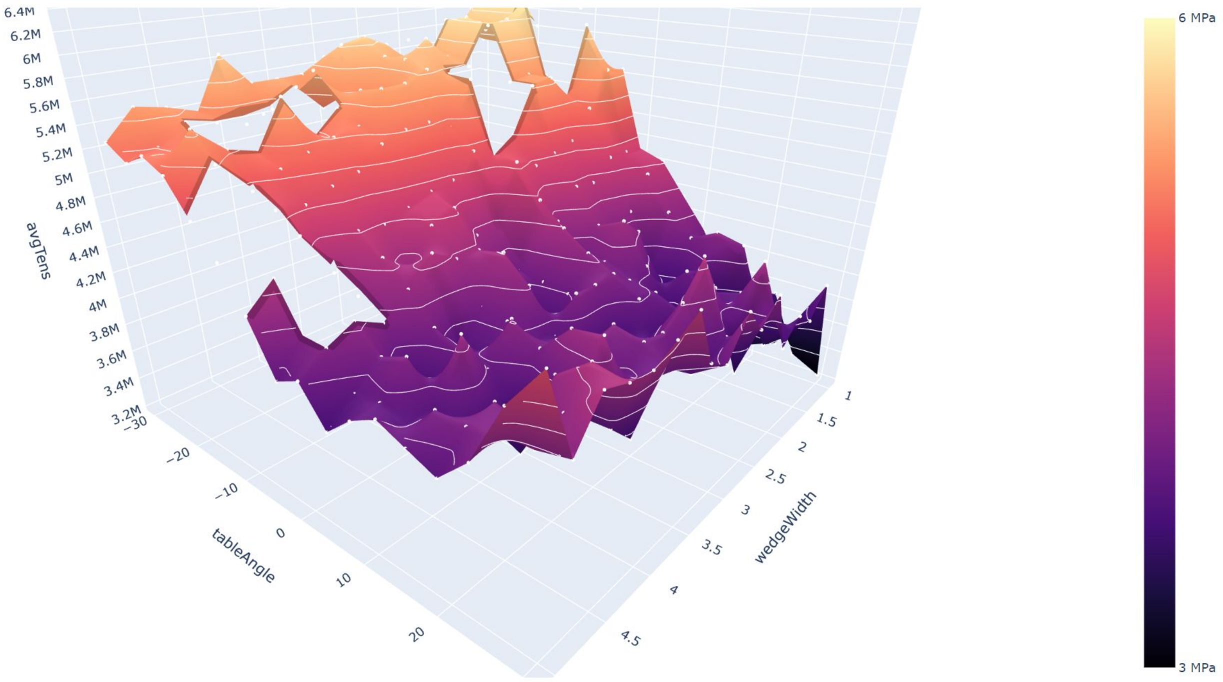


Table Stress | Low Performance

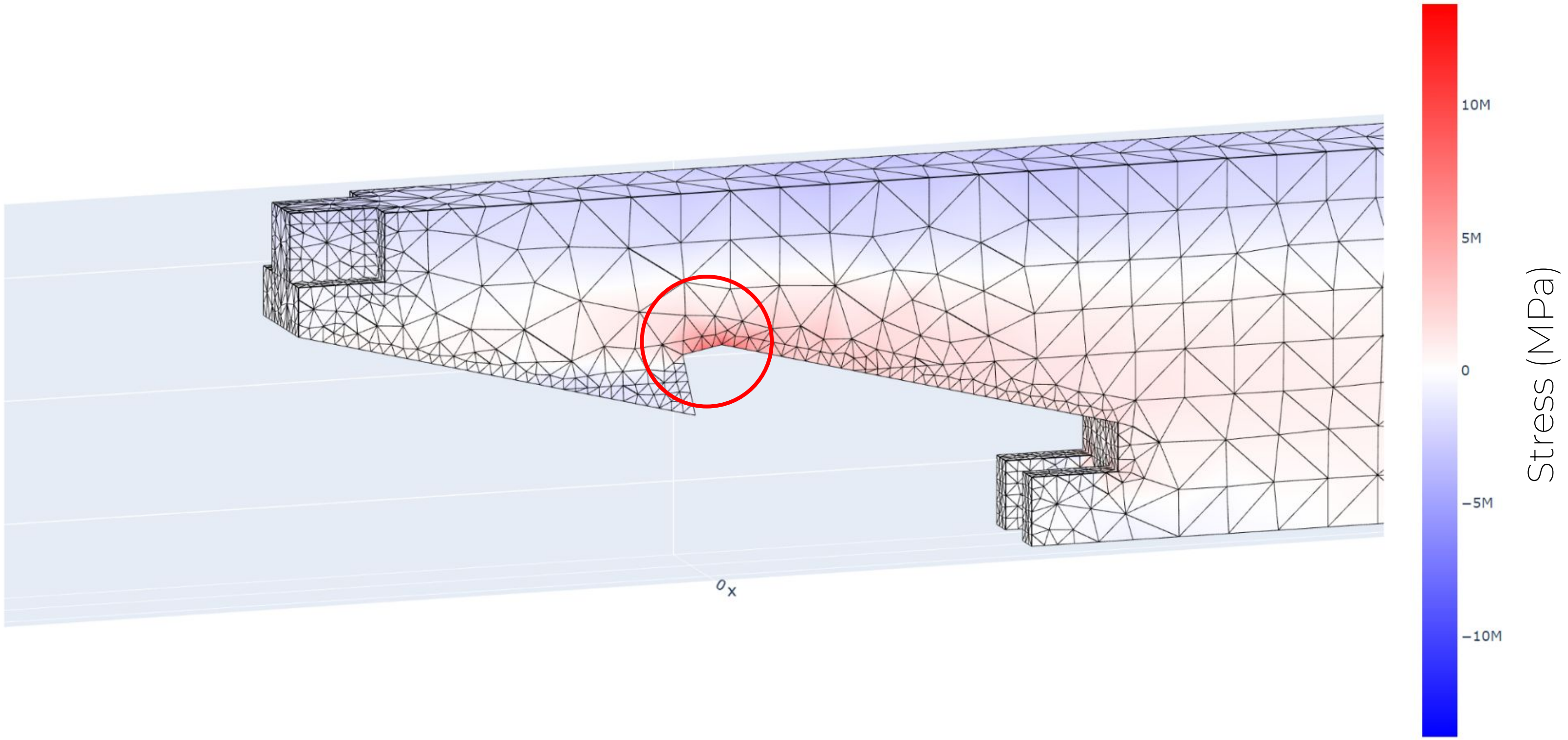
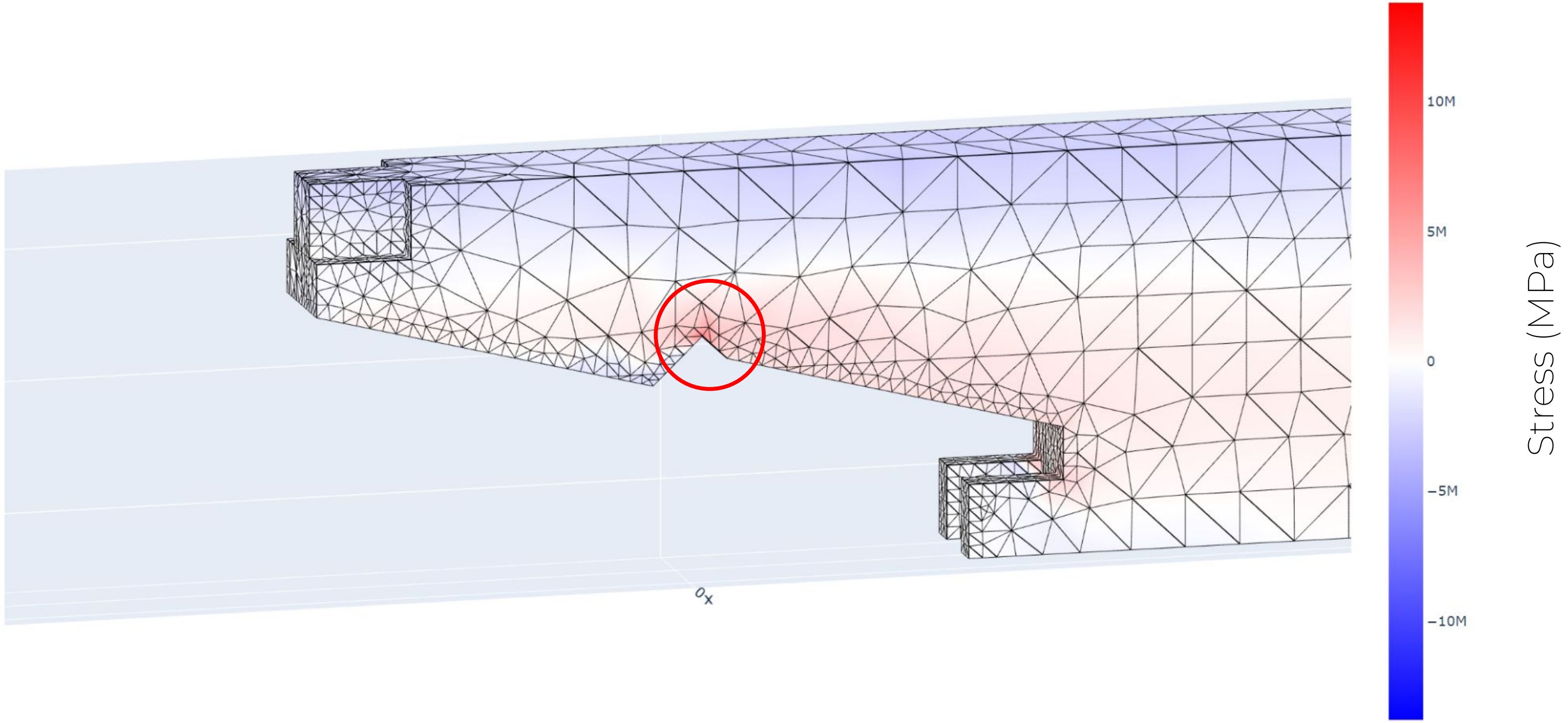
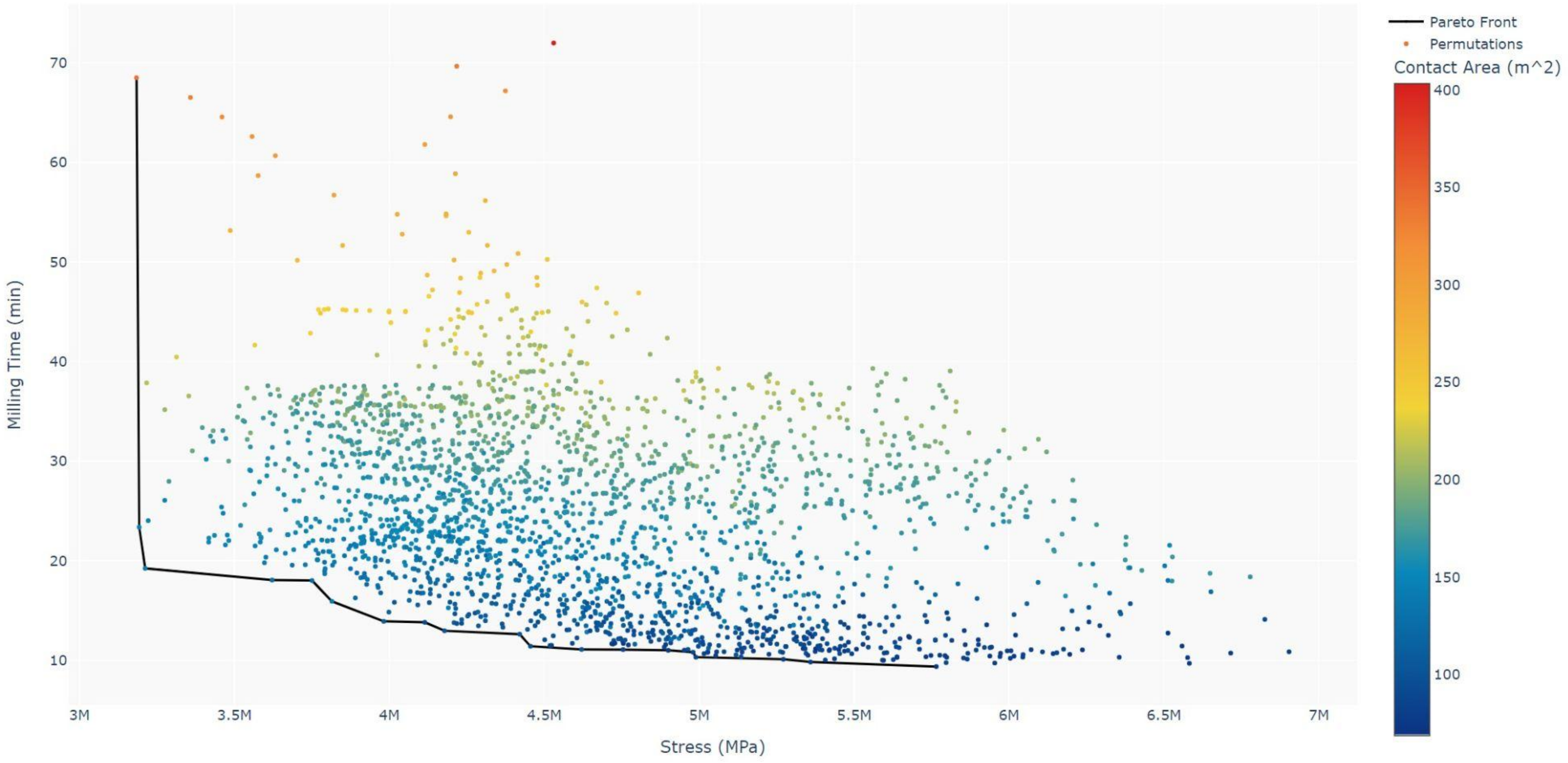


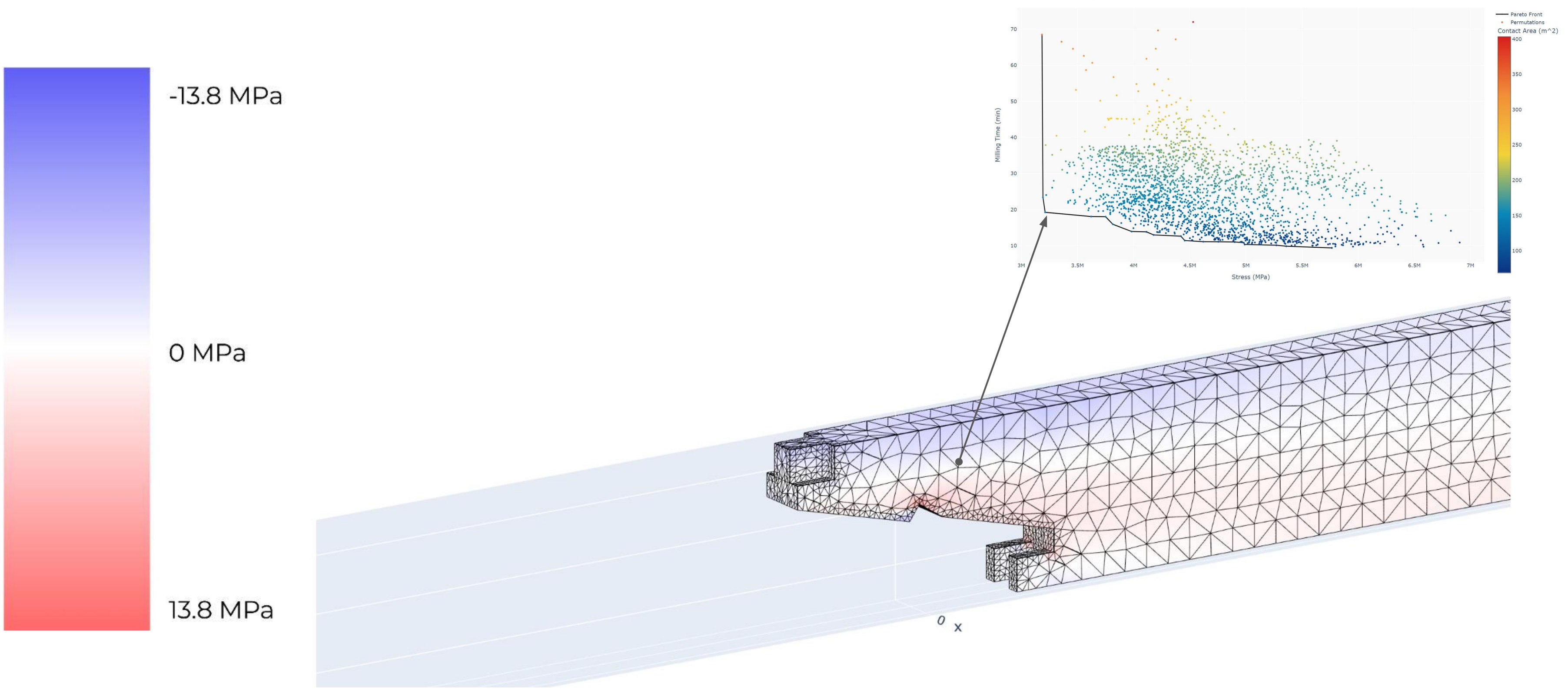
Table Stress | High Performance



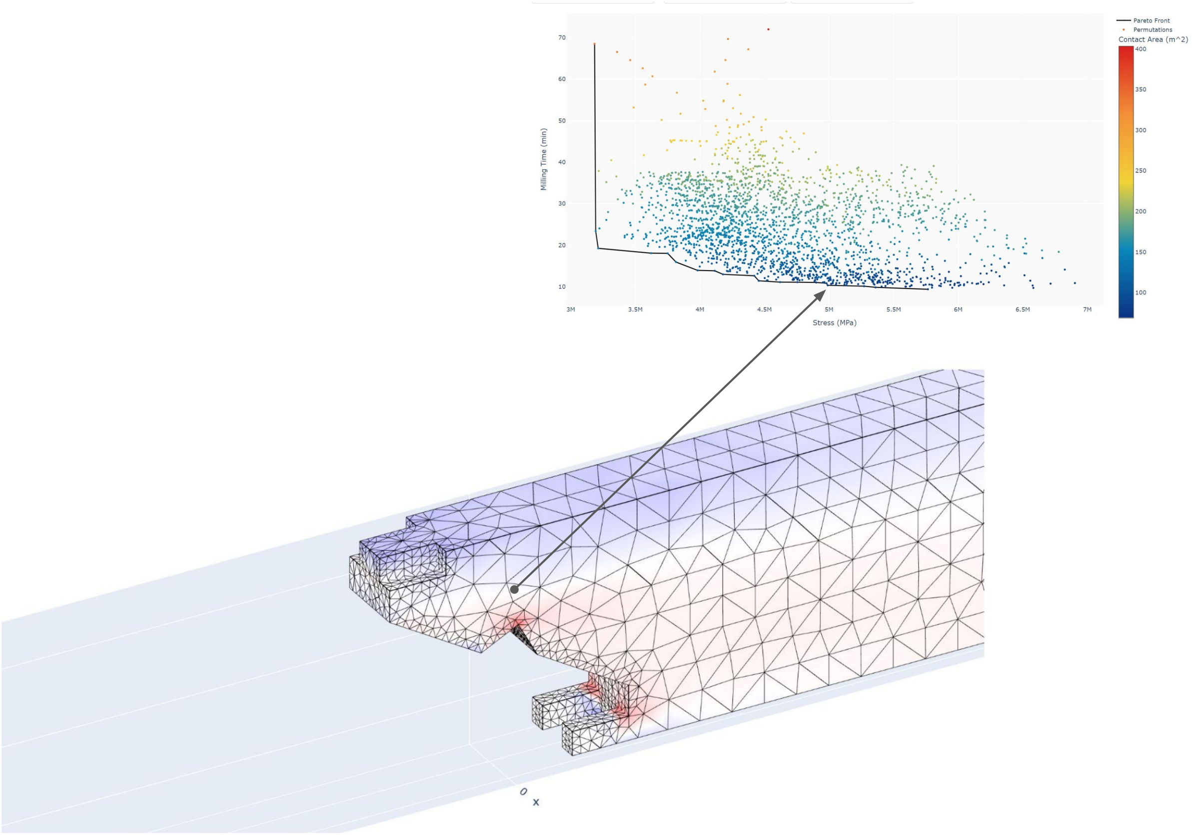
Case Study 2 | Observations - Pareto Front



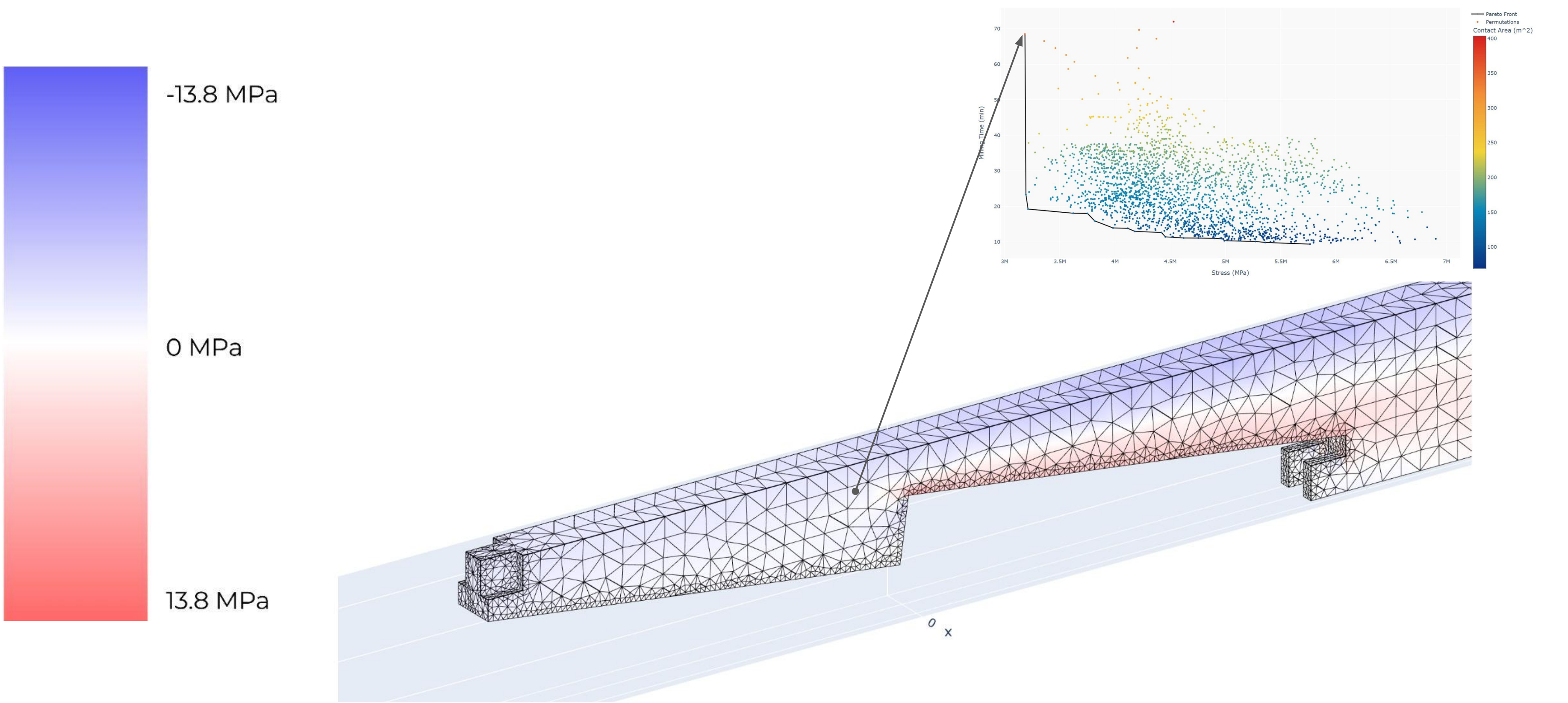
Case Study 2 | High Performance



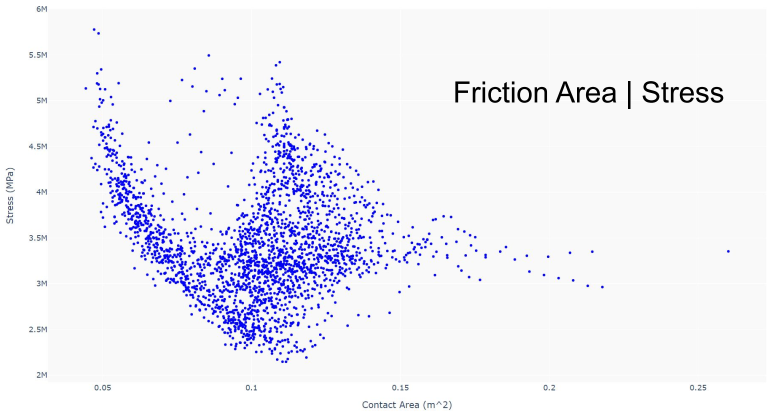
Case Study 2 | High Performance

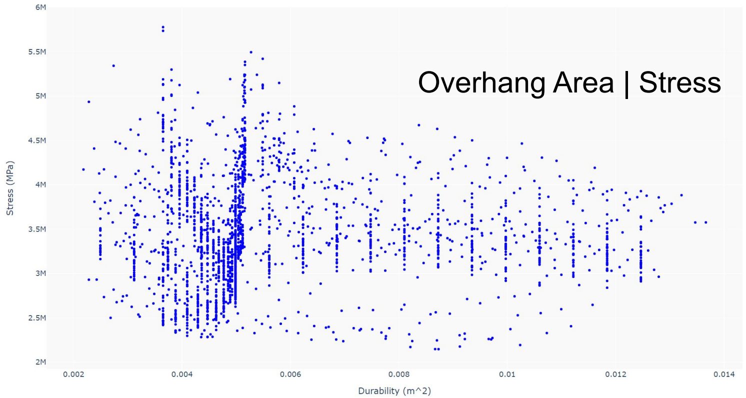


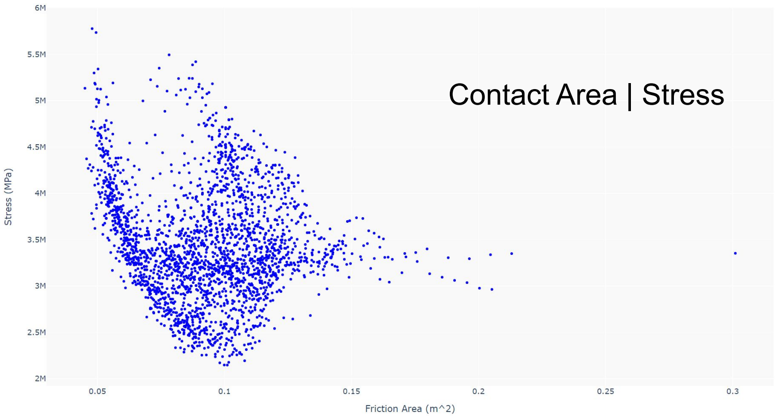
Case Study 2 | High Performance

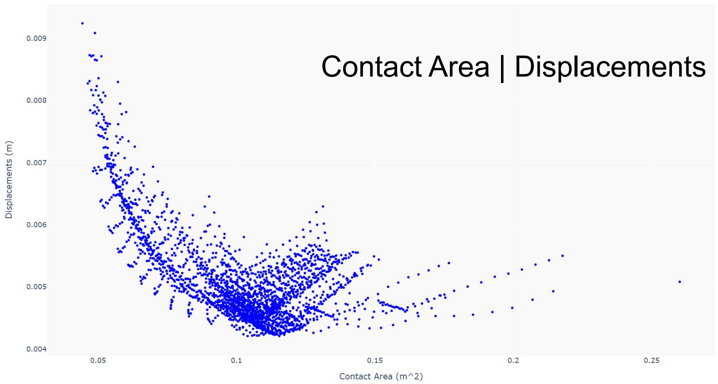


Case Study 2 | Observations - Midpoint Indicators









Conclusion

Overview

- Background
- Research Questions

Literature Review

- Timber Connections
- Digital Fabrication
- Timber FEA

Methodology

- Design
- Analysis
- Testing
- Metrics

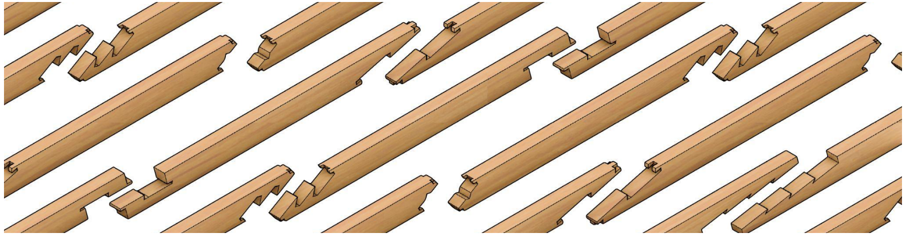
Case Studies

- Setup
- Physical Study
- Mass Timber Simulations

Conclusion

- Lessons
- Future Work

Conclusion | Lessons



- The Generative Tool and Framework was successful in creating a large design space and gathering data metrics for performance. By leveraging existing softwares and processes, we were able to investigate connection properties from a geometric and design perspective.

- Despite the robustness of our FEA model, inconsistencies were observed when introducing contact elements which caused convergence issues and data with increased noise. While culling was used to reduce the noise, this still limits the effectiveness of computational design for timber joinery.

- The framework could be used to distill individual characteristics from a large dataset and find design principles for a specific connection family. This seems to be an effective strategy for designers and researchers to investigate complex joint geometries.

Conclusion | Lessons

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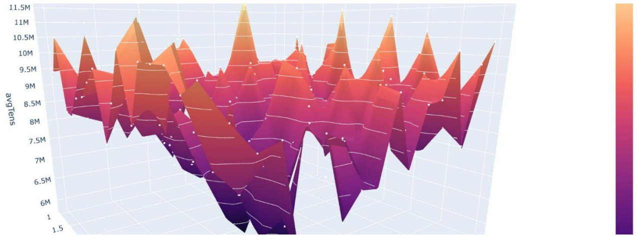

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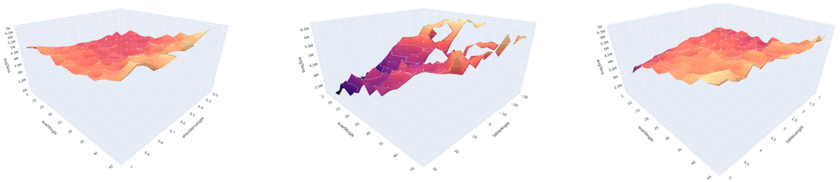
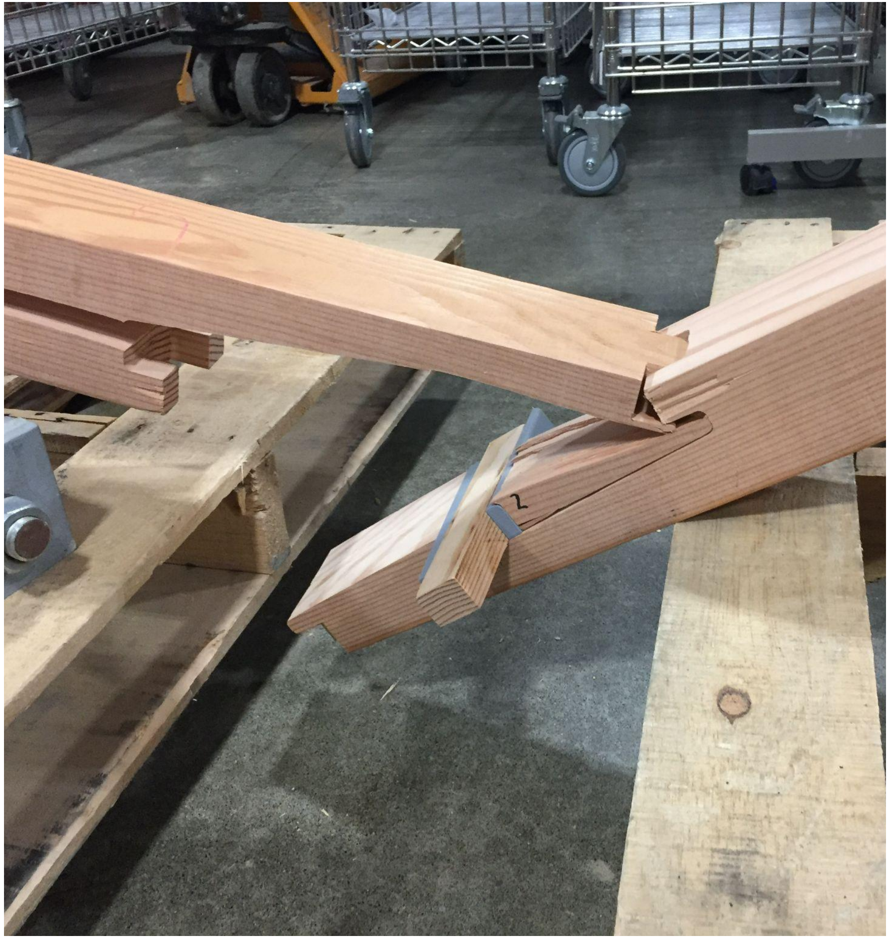


Conclusion | Future Work

- **More realistic FEA models**
  - Laminate Layers
  - Additional Load Cases
  - Load Steps for Wedges
- **Physical Testing**
  - Study Stresses within Timber
  - Multiple Tests to account for Natural Materials
- **Additional Use Cases**
  - CLT Connections
  - Seismic Resistance Studies



Analysis | Stress Smoothing vs. Culling