Robotic Fabrication of Kinetic Finger Joints for Modular Timber Systems

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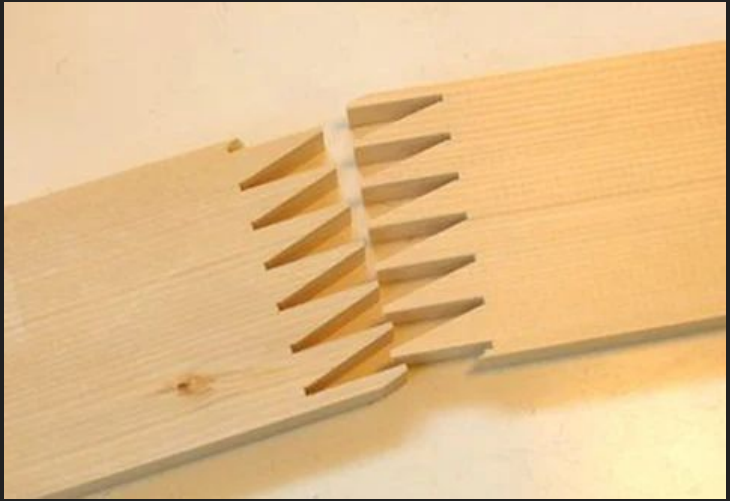
Agenda

1] Introduction
2] Case Study: Finger Joints in Guitar Necks
3] Case Study: Buga Wood Pavilion
4] Project
    a] Research Question
    b] Methodology
    c] Results

1] Introduction

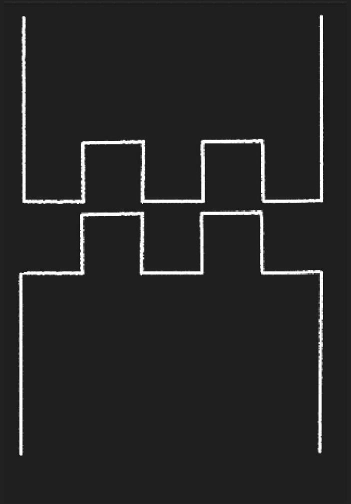
Finger Joints



Source: FindBuyTool, “The Ultimate Guide to Finger Joints in Woodworking,” 2025.

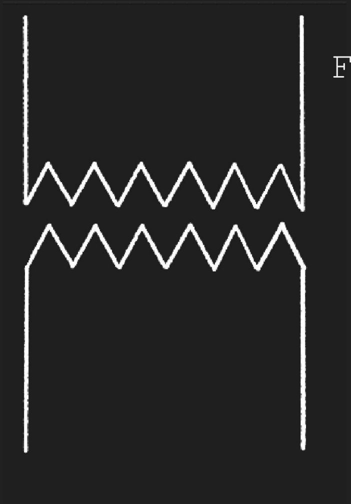
- Interlocking “fingers” of material that mesh together
- Increased glue surface area improves strength and load distribution
- Used in:
  - Right-angle joints
  - End-to-end extensions
  - Side-to-end connections

Finger Box Joints vs. Finger Joints



Box joints:

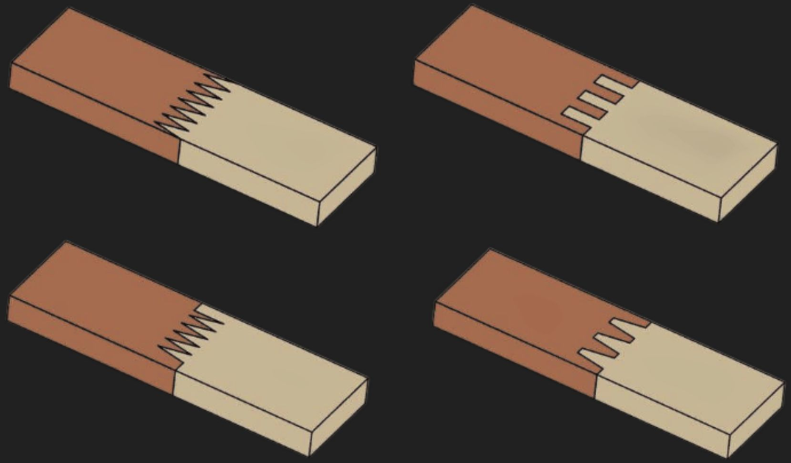
- Specific application at right-angle corners
- Common in boxes, drawers, and cabinets



Finger joints:

- Broader category
- Used linearly, structurally, and decoratively

Finger Box Joints vs. Finger Joints



- All box joints are finger joints
- Not all finger joints are box joints

Non-Structural Finger Joint

- Short fingers primarily for alignment and appearance
- Decorative or low-load applications (boxes, trim, cabinetry)

Sub-Structural Finger Joint

- Medium-length fingers providing moderate strength
- Furniture frames and secondary load-bearing elements

Source: DIY Doctor, “How to Make a Finger Joint Step by Step,” 2025.

Structural Finger Joint

- Long, tapered fingers designed for high load transfer
- Engineered timber systems such as glulam beams (higher strength-to-weight ratio than steel)

Traditional Techniques

Cut by hand using:

- Extremely high precision required
- Small errors in spacing or depth compromise strength

Saws

Chisels

Layouts

Led to adoption of:

- Machine-cut joints
- CNC milling

Industrial Finger Joints

Widely adopted after 1970s expansion of engineered timber

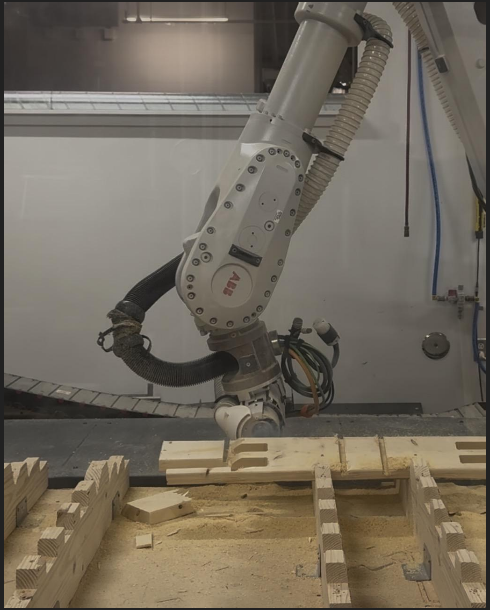
Advantages:

- Enables removal of defects for more uniform structural performance
- Produces predictable, gradual failure rather than sudden joint breakage
- Supports standardized lamellas for CLT and mass-timber systems
- Reduces internal stresses by joining shorter, pre-dried segments
- Integrates easily with CNC and robotic fabrication workflows

Limitation: Visible joint patterns can be aesthetically restrictive

Robotically Fabricated Finger Joints

- Achieve higher geometric precision than manual or CNC-only methods
- Enable complex joint geometries beyond standard rectangular fingers (dog bone)
- Allow multi-axis machining without manual repositioning of material
- Improve repeatability and consistency across large production runs
- Support integration of movement-enabled joint designs

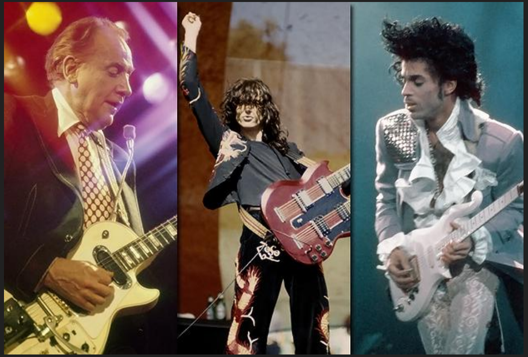


Source: Freepik (zirconicusso), n.d.

2] Case Study: Guitar Necks

Why the Neck Matters

- The neck is a beam under constant string load (~60-90 lbs)
- Drives playability (feel, action, fret access), stability (tuning), and tone (stiffness & damping)
- Design is a balance of ergonomics, materials, geometry, and joinery

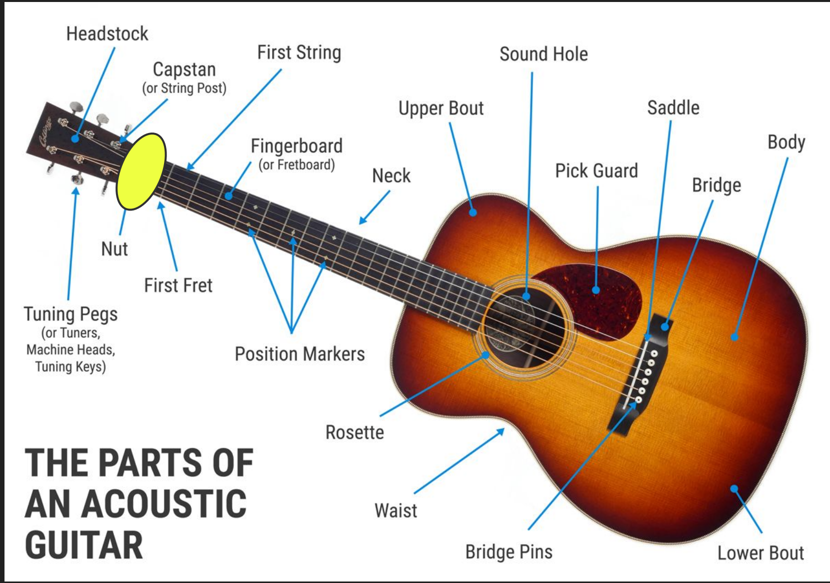


Source: Rolling Stone, RollingStone.com.

Anatomy of the Neck

Finger joint:

area between the headstock and the fingerboard



Source: The Parts of an Acoustic Guitar, SoundPure.com, n.d.

Materials/Grain Orientation

Common neck woods: Maple, Mahogany, Roasted variants, Rosewood, Ebony, Maple

Quarter-sawn vs flat-sawn: (the way wood is cut) quarter-sawn is typically more dimensionally stable and stiffer edgewise

Source: Guitar Fretboard Wood Choices, LeftyFretz.com, n.d. (LeftyFretz).

Source: Flat Sawn or Quarter Sawn Neck, UpFrontGuitars.com, n.d.

Quarter/Flat Sawn

Flat-sawn (a.k.a. plain-sawn):

- The growth rings are more horizontal (0–30° to the surface)
  - Pros: cheaper, shows wide “cathedral” grain patterns, easier to cut from logs
  - Cons: tends to warp, cup, or twist more with humidity changes

Quarter-sawn:

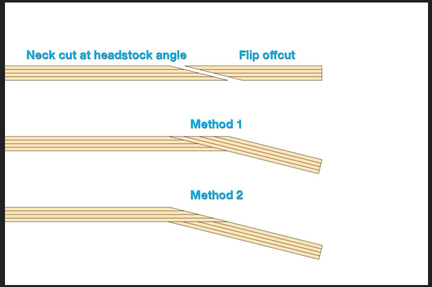
- The growth rings are nearly vertical (60–90° to the surface)
  - Pros: dimensionally more stable (doesn’t warp as much when humidity changes), stiffer edgewise (across the neck depth), often prettier “straight grain” or “ray fleck” patterns
  - Cons: more expensive, more waste in sawing

Source: FlooringDetective.com, Sliced Cut Oak vs. Sawn Cut Oak Veneer, n.d.

Joint Options

- **One-piece:** headstock and neck carved from a single blank
- **Scarf joint:** angled headstock made from two pieces; grain runs straighter, less waste
- **Finger joint (box joint):** interlocking “fingers” join short pieces into a longer, stable blank

Source: Archtop Guitar Build: Headstock and Neck, Scotts-Workshop.blogspot.com, 2012.



Source: Choosing Headstock Type, TalkBass.com, n.d.

Source: Wood Seasoning Chamber (product document), IM & IM, 2025.

Tools Used in Guitar Necks

- **CNC Routers:** cut fret slots, truss rod channels, carve back profiles
- **Robotic Arms:** multi-axis shaping, sanding, and assembly tasks
- **Laser Cutters:** templates, finger joint test pieces
- **3D Scanners:** digitize legacy neck shapes for reproduction

Source: FARO Scanner v3, CADDJM.com, n.d.

Source: Eurolaser XL-1200, Treatstock.com, n.d.

Source: Walmart.com, FoxAlien CNC Router Machine Vasto 3-Axis, 2025.

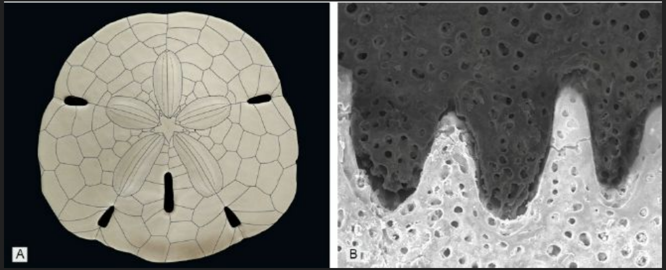
Source: ICD/ITKE, University of Stuttgart; photograph by Roland Halbe, 2019.

3] Case Study: BUGA Wood Pavilion

Overview

- Designed by ICD and ITKE
- Inspired by natural segmented shells (sand dollar)
- "Less material, more form."
- Double-curved segments, robotically fabricated with only 10 days of on-site assembly
- Both organic and precise in architectural expression

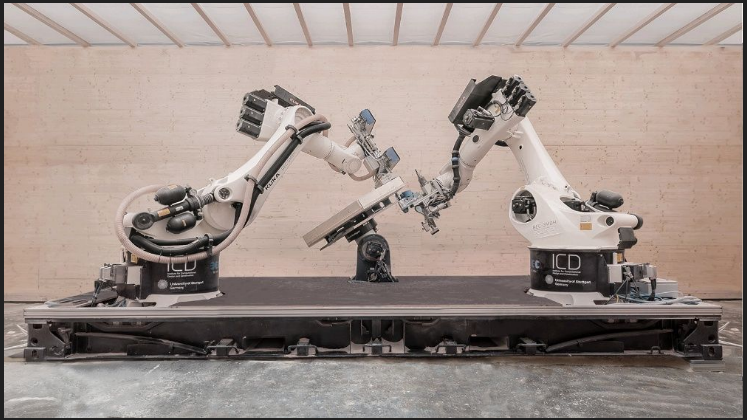
Hollow wood cassettes used in assembly. Source: ICD/ITKE.



Source: Gerber & Nebelsick / Nebelsick & Grun, University of Tübingen.

Fabrication

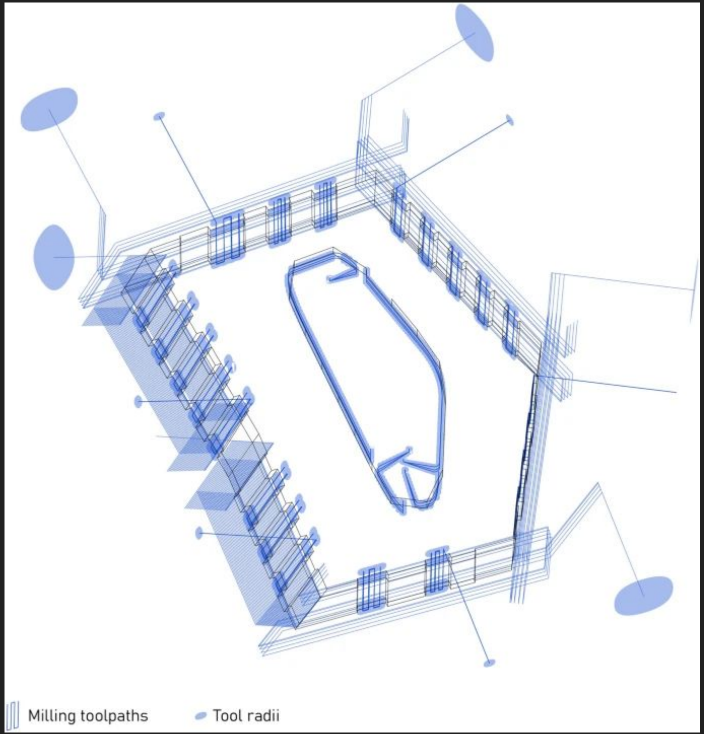
- CNC-milled w/ KUKA robots from thin spruce plywood sheets and laminated into 2-layer plates
- Cassette built from 2 LVL plates and edge beams
- Modular “skill” subroutines, e.g. tasks like “apply adhesive,” “pick beam,” “drill hole,” etc.
- Enumerated and sequenced tasks w/collision simulation



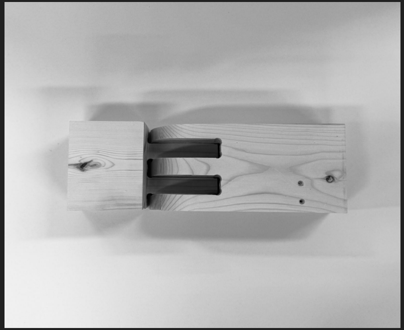
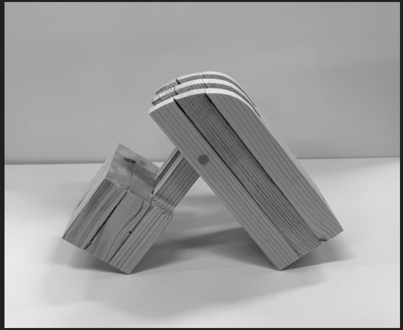
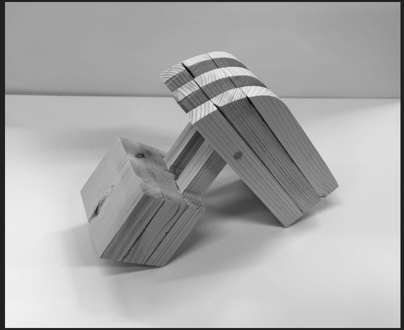
Source: ICD/ITKE University of Stuttgart.

Fabrication Cont.

- Edge profiling for curved outlines
- Finger joint milling along edges (interlocking geometry)
- Cassettes were built up: large interior voids meant less material



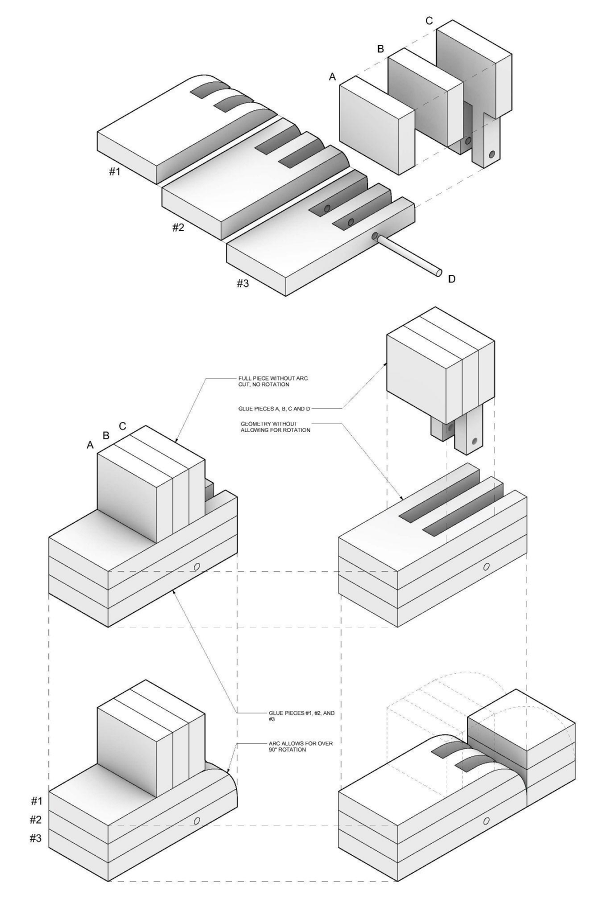
Source: Wagner, H.J., Alvarez, M., Groenewolt, A. et al. Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion. Constr Robot 4, 187–204 (2020). https://doi.org/10.1007/s41693-020-00038-5

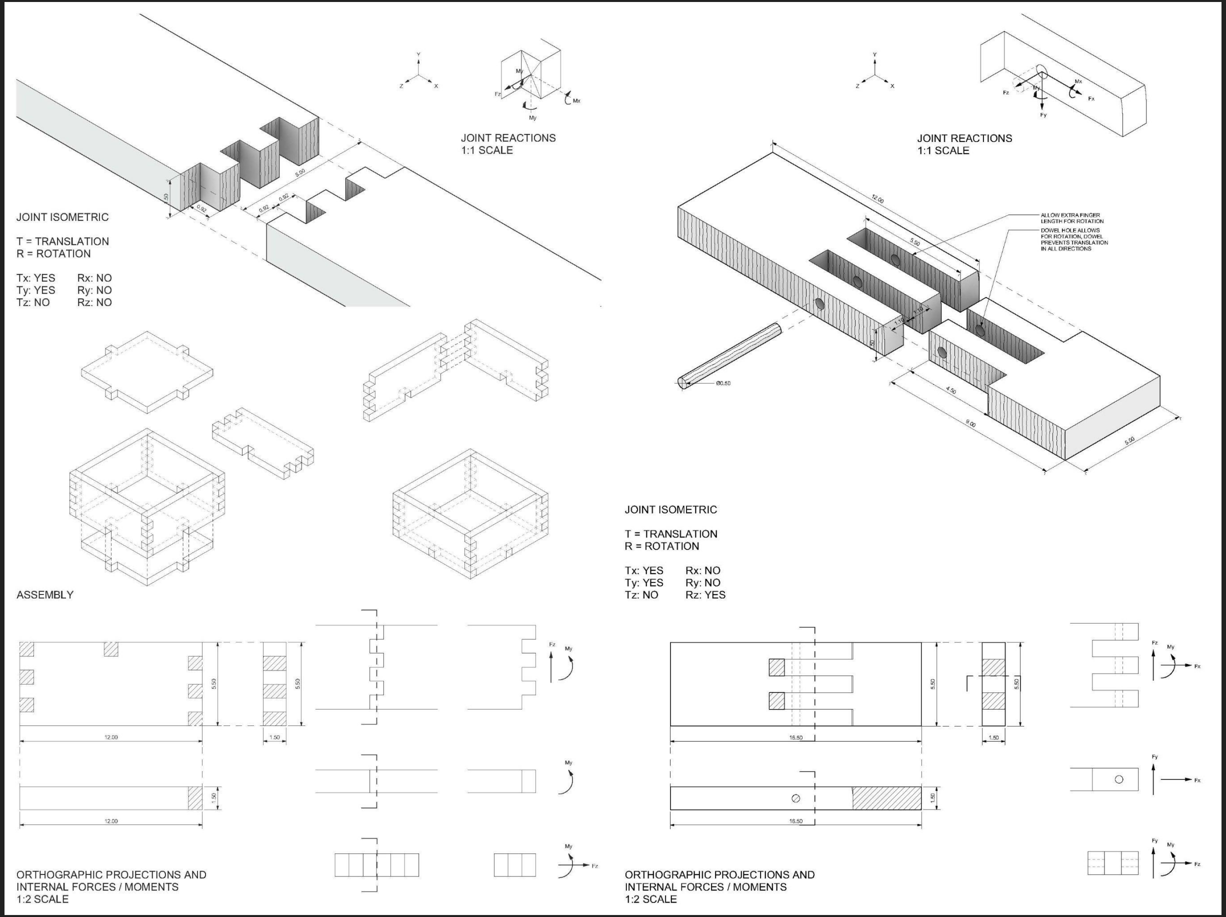
   

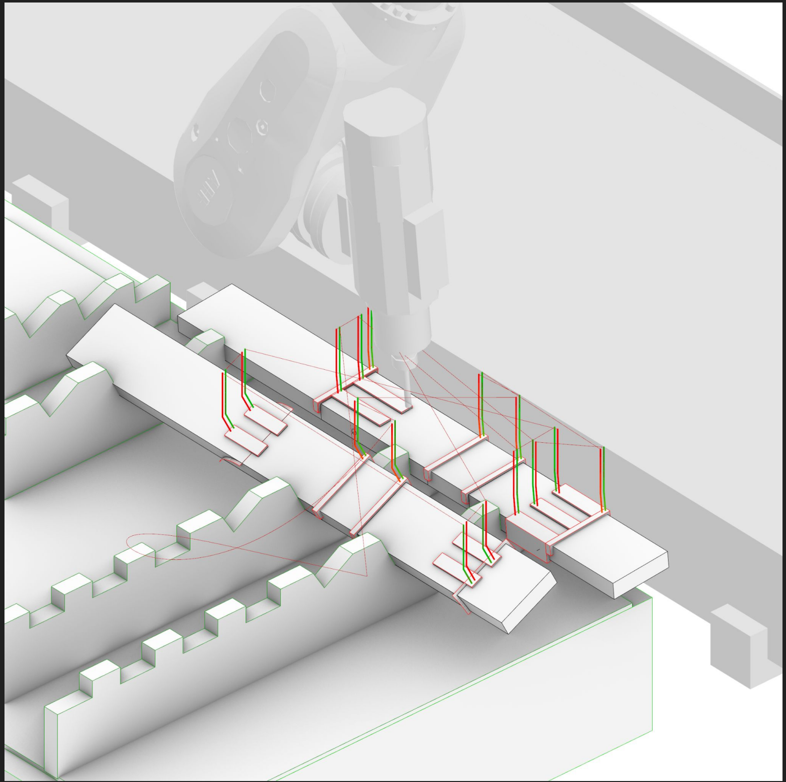
4] Project

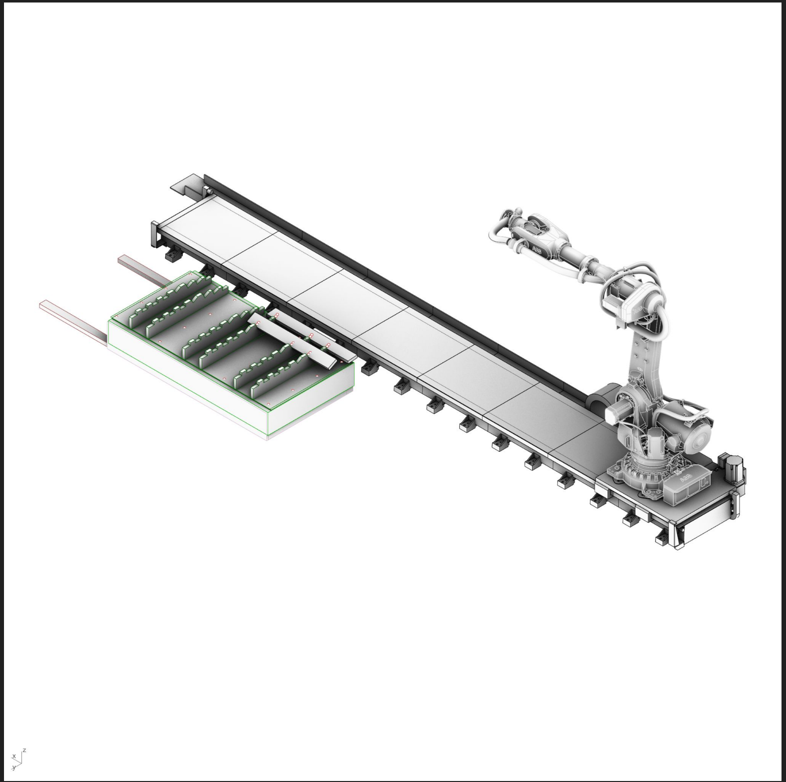
How can **robotic fabrication** be used to design and produce **finger joints** that maintain **structural integrity** while enabling **controlled kinetic motion** in modular timber systems?

Research Question

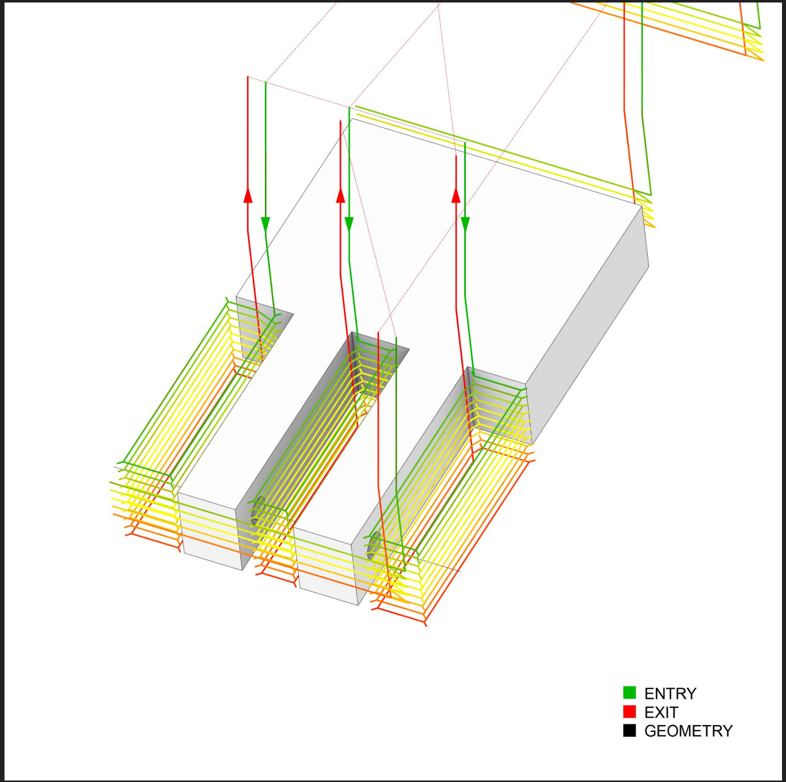

C
B
A
#1
#2
#3
D
FULL PIECE WITHOUT ARC CUT, NO ROTATION
GLUE PIECES A, B, C AND D
GEOMETRY WITHOUT ALLOWING FOR ROTATION
A
B
C
GLUE PIECES #1, #2, AND #3
ARC ALLOWS FOR OVER 90° ROTATION
#1
#2
#3

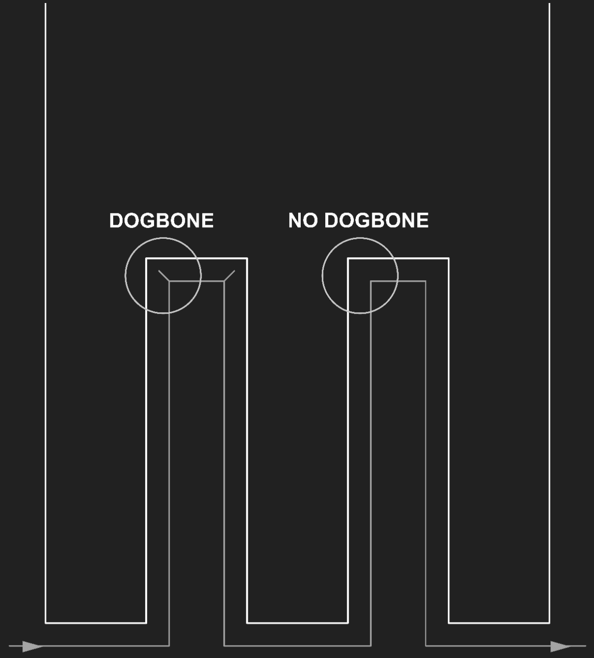

JOINT REACTIONS
1:1 SCALE
JOINT ISOMETRIC
T = TRANSLATION
R = ROTATION
Tx: YES Rx: NO
Ty: YES Ry: NO
Tz: NO Rz: NO
ASSEMBLY
ORTHOGRAPHIC PROJECTIONS AND
INTERNAL FORCES / MOMENTS
1:2 SCALE
JOINT REACTIONS
1:1 SCALE
ALLOW EXTRA FINGER LENGTH FOR ROTATION
DOWEL HOLE ALLOWS FOR ROTATION, DOWEL PREVENTS TRANSLATION IN ALL DIRECTIONS
JOINT ISOMETRIC
T = TRANSLATION
R = ROTATION
Tx: YES Rx: NO
Ty: YES Ry: NO
Tz: NO Rz: YES
ORTHOGRAPHIC PROJECTIONS AND
INTERNAL FORCES / MOMENTS
1:2 SCALE



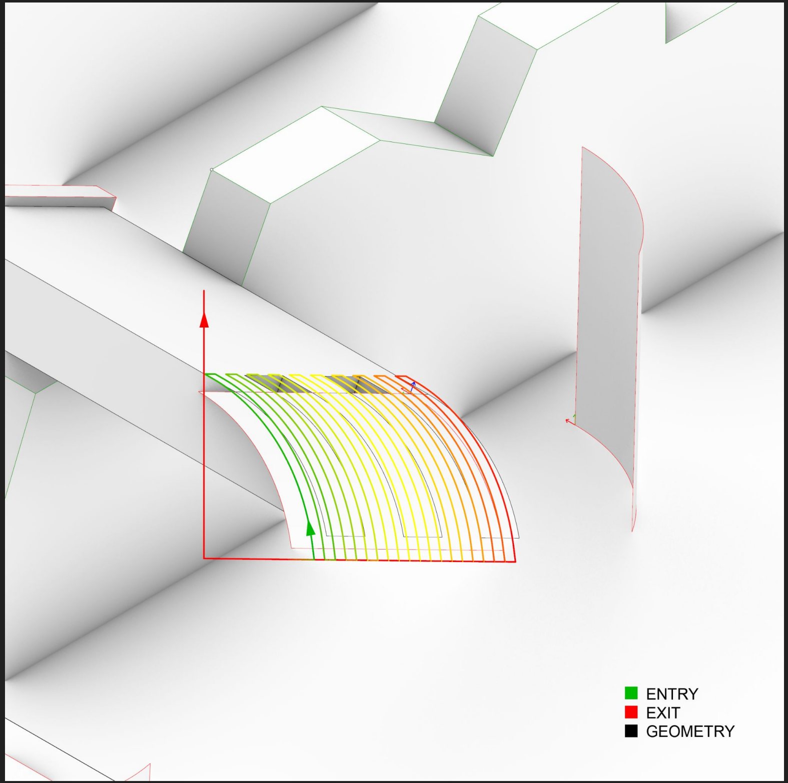


Robot Setup

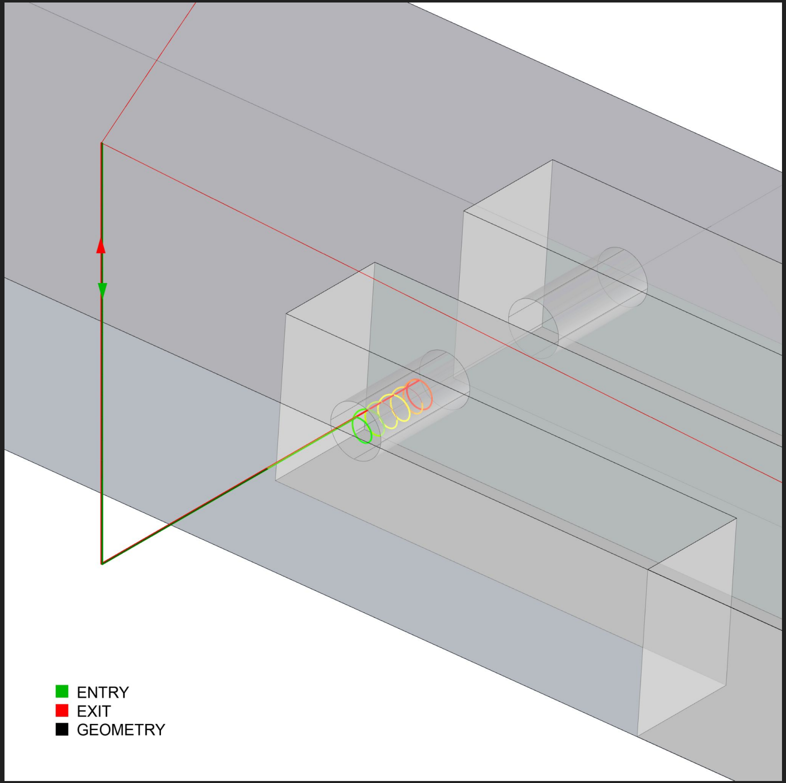




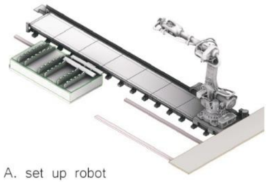
Dogbone Profiling



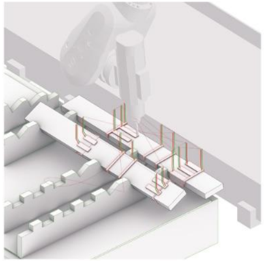
Swarfing



Hole Profiling

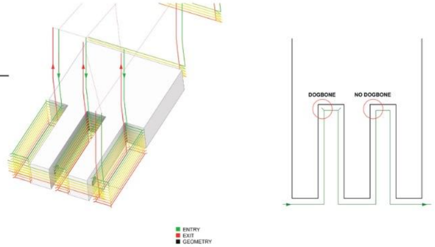


A. set up robot

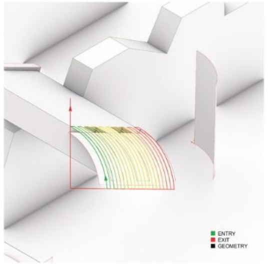


B. drill in stock material for milling
*areas shown in color are scripted cuts with a 1/2” endmill

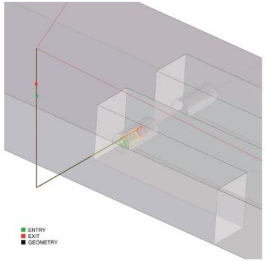
C. detail of finger mill pathway
*dogbone feature is implemented to ensure interior corners of all fingers align



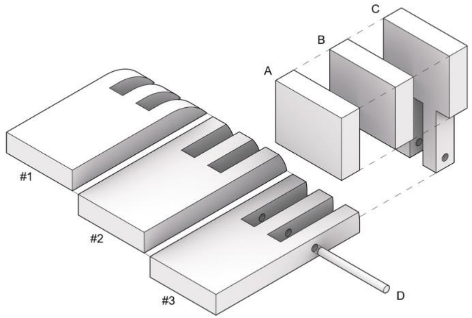
D. swarfing component implemented to allow rotation and curvature

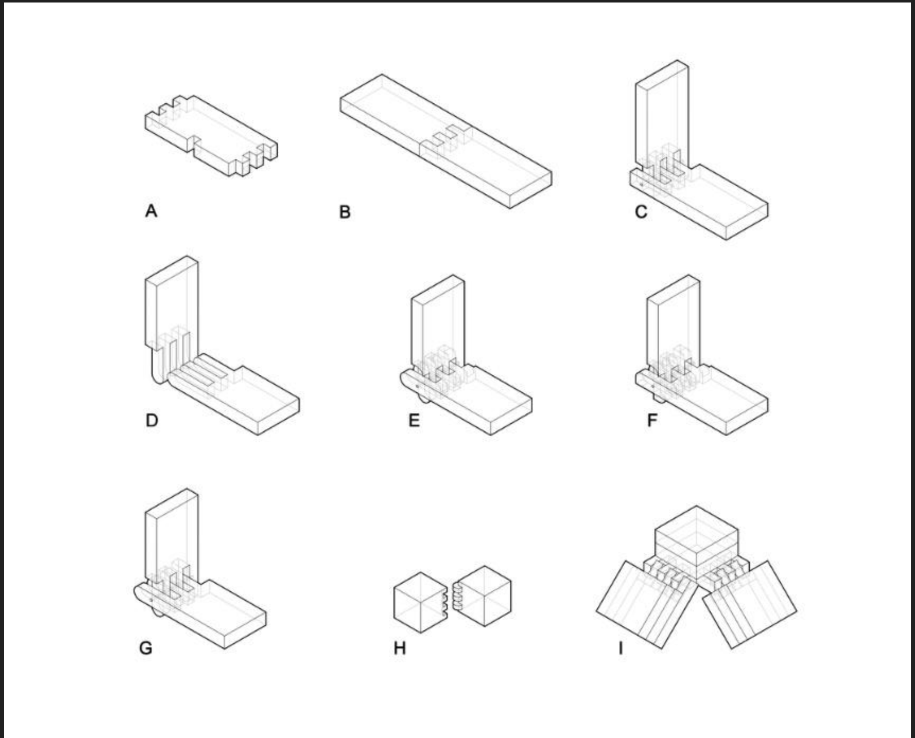


E. finish with hole profiling（1/4” endmill）to locate hole positions

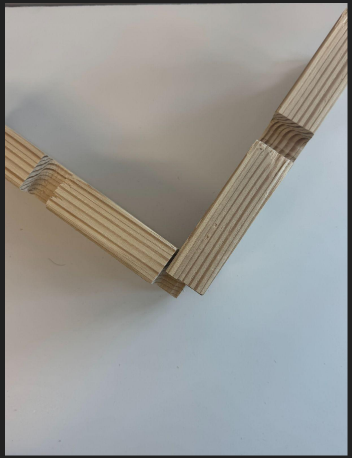


F. completed panels for assemblages





Iterations

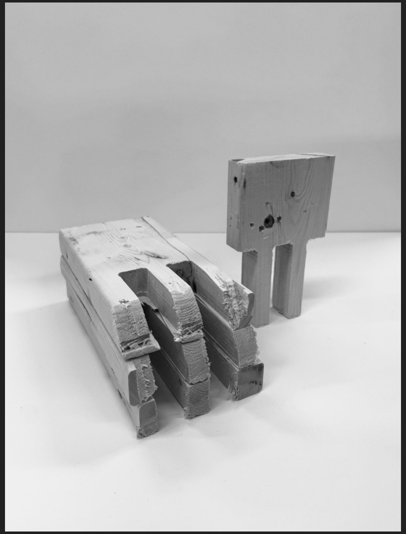
First Mill





Second Mill

Third Mill



Fourth Mill

1. Cut 2 x 6 wood with circular saw into approximately 3’ lengths

Methodology

2. Place both panels into the robot setup, make sure one has an overhang of 250mm and the other 200mm, drill in to secure

← 250mm and 200mm overhang side

Methodology

3. Jog robot to confirm mounting position alignment, warm up the spindle, send script to robot via Grasshopper or RobotStudio.

    a. Grasshopper script featuring dogbone profiling + swarfing with a ½” end mill and a ¼” end mill to help profile ½” holes, exported as RAPID code for execution

Methodology

4. Cut wood to final size and clean up wood with sanding blocks, sand paper, circular rasps, powered hand sander, and oscillating multi-tool

Featured:
A. oscillating multi-tool

B. powered hand sander

C. sanding block

Methodology

5. Mark hole position on each finger and drill a ½” hole following the drill profile

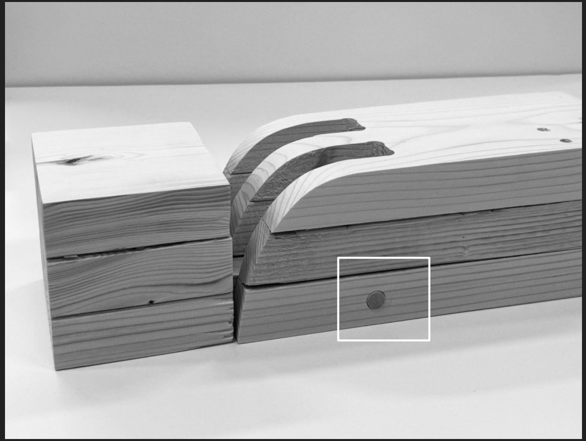
Shown:
marking cut lines for smaller panels

Methodology

6. Glue and clamp each panel securely to one another (24 hrs wait time)

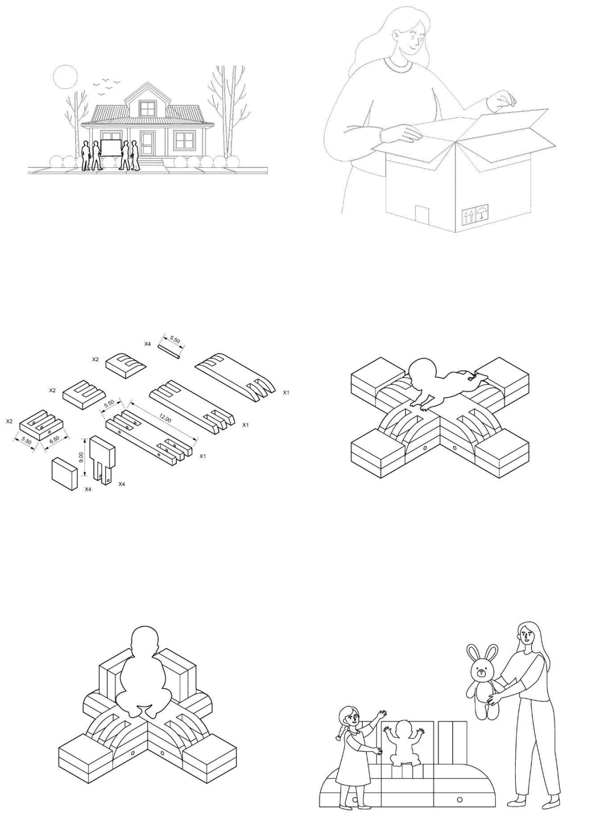
Methodology

7. Cut dowel down to right length with pull saw, insert through each finger hole



← dowel insert

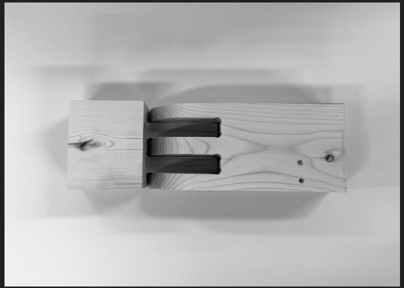
Methodology

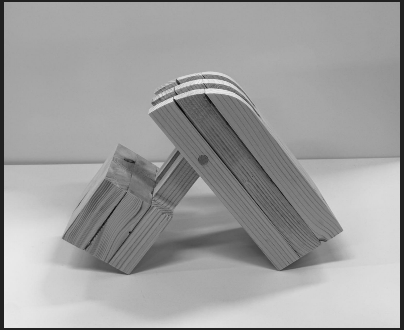

X4
5.50
X2
X2
X1
5.50
12.00
X1
X2
5.50
6.50
9.00
X1
X4
X4

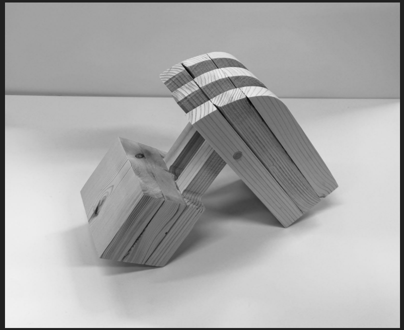
Displayed is the finished piece.

Throughout the fabrication process, we milled two wooden panels using a robotic arm equipped with a half-inch end mill that moved in the x- and y-axes.

A major challenge arose from a tolerance issue in our robotic script, which caused the finger joints of one panel to be slightly misaligned with the other panel. Luckily, a bit of sanding helped resolve the issue. Moving forward, we plan to refine our fabrication script by tightening the tolerance parameters, and to experiment with more angular cuts using the circular saw.. These next steps will help us push the boundaries of dynamic wooden joinery and continue blending craftsmanship with automation in meaningful ways.







Results