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Robotic Integral Attachment

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1. Research Aims and Objectives

Integral joints provide a rapid, simple and mechanically strong connection between parts. Our investigation focuses on the assembly of cross-laminated wood veneer plates, where previous studies have shown that the strength of through-tenons is equivalent or superior to state-of-the-art fasteners such as screws or nails. This mechanical behavior is highly dependent on a precise fit of the joints, where no gaps are left between the parts.

However, the manual assembly of such tight-fitting joints can be complicated. Thanks to its rectangular cross-section profile, a single through-tenon joint is a sufficient assembly guide for an entire plate, but multiple through-tenons are required to establish a mechanically strong connection. This results in a kinematically over-constrained assembly motion. [Mantripragada et al. 1996] Additionally, due to fabrication- or material related tolerances, the joints can be too tight-fitting and manual assembly motions deviate from the precise insertion path. So called *wedging* occurs during the assembly of tight-fitting joints, especially with larger parts at a building scale (see figure 1). This requires high forces to be overcome.

Rather than leaving gaps between the parts, which presents one solution for the manual assembly of such systems, we investigate the assembly using an industrial robot. The robot allows for a more precise assembly motion and higher forces can be applied in the direction of assembly. The aim of this research is to use these benefits along with the compressibility of wood for the assembly of *oversized tenons*. While in regular through-tenon joints, the width of the tenon is equal to the width of the slot, the oversized tenons in this paper are slightly wider than their slot parts. This assembly will require a certain insertion force, squeezing the tenons into the holes, but the resulting connection will be tight-fitting without any gaps.

Figure 1: Large-scale robotic positioning of a timber plate.

2. Research Context

Robotic Integral Attachment demonstrates the advantages of combining Robotic Assembly [Helm et al. 2016] and Integral Mechanical Attachment, such as through-tenon joints (see Figure 2). Both methods are used to facilitate the assembly of complex architectural designs, for example freeform shells and space frames. While integral attachment embeds the instructions for manual assembly into the form of prefabricated components (see Figure 3) [Robeller 2015], robotic assembly integrates the assembly logic into the robotic positioning procedure. [Gramazio et al. 2014] The aim of this research is to investigate the combination of these seemingly contrary methods.

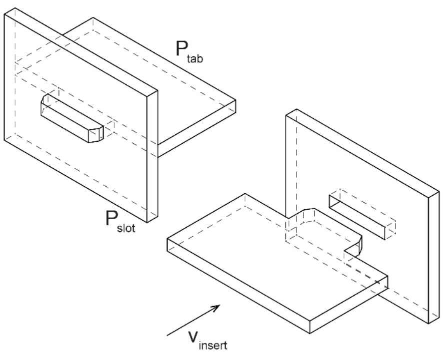

Figure 2: Through-tenon joint

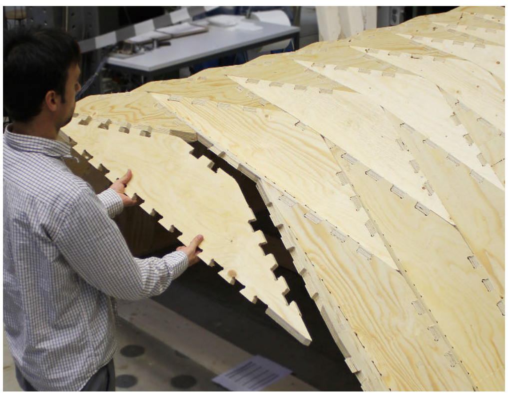

Figure 3: Timber folded plate built from 21mm LVL panels, assembled manually, IBOIS, EPFL, 2014

The two main benefits of Integral Joints for the design of timber plate shell and spatial structures are their so called locator and connector features. Locator features in the form of the joints reduce their mechanical degrees of freedom, and therefore also the relative motions between the connected parts. This allows to indicate the correct alignment and position of parts to one another. While some joint shapes such as finger joints will reduce the mobility of parts to three degrees of freedom and perform as partial assembly guides, other joints such as through-tenons will reduce the mobility of parts to only one insertion direction and perform as fully integral assembly guides.

Integral Mechanical Attachment allows for a simple, fast and precise on-site joining process. It is moving the complex and laborious part of assemblies into the prefabrication of the plates. This is made possible through computational design and automatic prefabrication technology. As a consequence of such improved joining strategies, more complex shapes can be produced and assembled efficiently. An example has been provided by Robeller and Weinand 2015, where a singly-curved folded surface structure using equally shaped parts and regular joints, was compared with a doubly-curved folded surface structure with individually shaped plates and integral joints. In a simulation, deflections were 39% lower on the double-curved structure, which was enabled through the integral joints.

At the same time, integral joints improve structures through the direct transfer of forces through the form of connectors. Roche et al. 2015a has shown that the shear strength of finger- and dovetail jointed plywood plates is similar to the shear strength of screwed connections. Li et al showed that the connectors can be combined with metal fasteners, and further research by Roche et al 2015b compared the rotational stiffness of joints at ridges, demonstrating the particular strength of through-tenon joints.

3. Research Questions

Aiming at the automated assembly of timber plates, and the elimination of any gaps which reduce the stiffness of the joints, the main questions were what forces would occur during the insertion of through-tenon joints with and without oversized tenons.

Since in the assembly of timber plate shell or folded plate structures, multiple joints must often be inserted simultaneously, further questions were how the insertion forces on individual joints could be reduced through modifications in their form, how the forces would add during such multi-joint assemblies, and how insertion forces and possible wedging could be reduced through custom-built vibration-inducing robot end-effectors.

- What force is required for the insertion of a through-tenon joint?
- What force is required for the insertion of a through-tenon joint with oversized tenon?
- Can the effect of wedging be reduced through optimizations in the form of the joints?
- Can the effect wedging be reduced through automated, robotic assembly?

4. Experimental Setup

The robotic assembly of *elastic* and *plastic* through-tenon joints (see Figure 4) for cross-laminated wood veneer plates was examined through physical assembly experiments. Using 40mm thick beech laminated veneer lumber (LVL) plates and a tenon width of 120mm for all specimen, different joint shapes and parameters were tested.

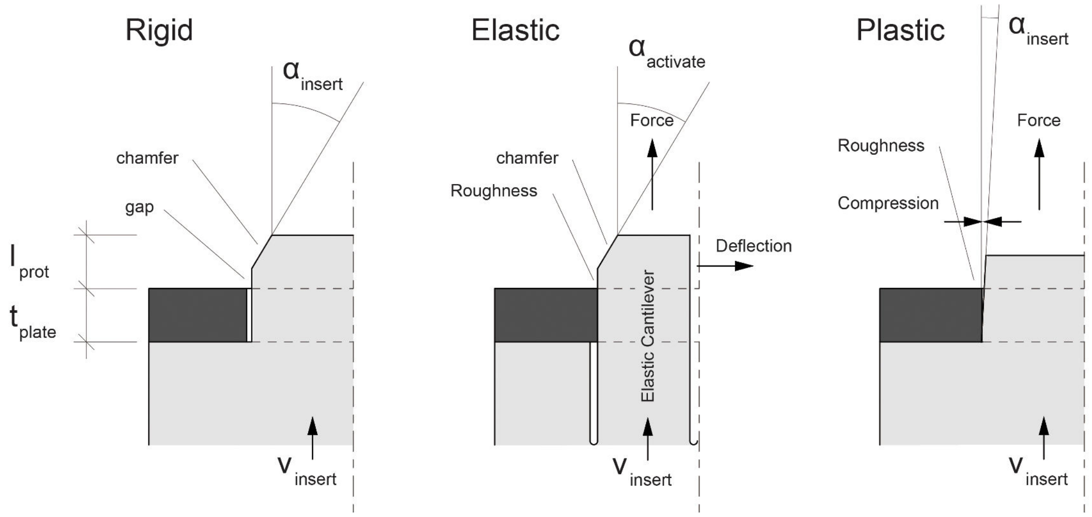

Figure 4: Through-tenon as rigid, elastic and plastic interlock.

Elastic joining techniques such as cantilever snap-joints are commonly used in other industry sectors, such as consumer electronics or the automotive industry. [Messler 2016] They can be generally applied to elastic materials. The application to cross-laminated wood panels has also been investigated previously [Robeller et al 2014].

Plastic joining techniques are also commonly used in various industrial applications, especially in the form of press-fit or friction fit joints. A well-known example using metal materials is staking, where an undersized boss in a regular sized hole is expanded through a staking punch. The resulting radial expansion will cause a physical interference fit between the two pieces. Metal screws work in a similar way: The thread of the screw creates a large friction surface, while pressure is applied through its inclination and rotation. In addition to the friction interference, the elasticity of the material plays an important role in plastic interlocks too. Through the press-fit, the parts of the joint are squeezed. The elastic recovery force will apply pressure on the contact surfaces, which further increases the friction interference.

The primary purpose of the plastic and elastic timber plate joints in this investigation is to eliminate gaps, which may be required for the assembly of joints. The regular rigid joints were added as a reference for comparisons. This elimination of gaps should be achieved through a press-fit assembly of tenons that are slightly wider than their slots. Multiple series of specimen were tested, where the tenon oversize was increased in small steps: 0.05mm, 0.10mm, 0.15mm, 0.20mm and 0.25mm. During the insertion of the joints, the oversized tenons should be able to fit into the slots primarily due to the material compressibility on the rigid-type through-tenons, and predominantly due to the material elasticity on the elastic-type through tenons. Here, cuts along the center line of the tenon allow for lateral deflections during the joint assembly.

Due to the center line cut on the elastic through tenons, their shear strength will be greatly reduced in comparison to rigid versions. However, the elasticity was also expected to greatly reduce the required insertion force. Such elastic joints may be particularly interesting in combination with rigid or plastic interlocks (see figure 5, the plate held by the robot), providing ideal locator features whilst requiring reduced insertion forces.

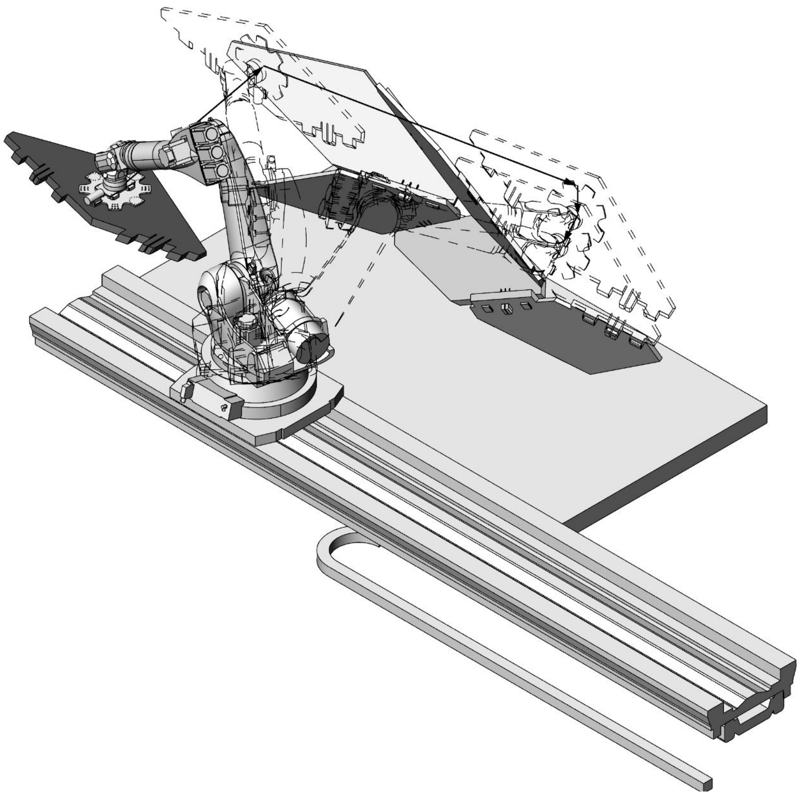

Figure 5: Simulation of the assembly sequence and plate insertion paths.

The primary challenge in the assembly of the oversized joints is the so called effect of "*wedging*", where a friction interlock is established between the two parts during the insertion, before the final position is reached. This occurs due to tolerances in the size of the parts, resulting from fabrication imprecision or dimensional changes due to changing environmental conditions, as well as imprecisions in the assembly motion, which must follow one precise path in the case of single-degree-of-freedom joints such as the through-tenons.

It was expected that the wedging could be reduced through a small inclination of 1° on the small contact faces across the edge on the through-tenons and on the slots. We can achieve an inclination on these faces using a 5-axis CNC router, where the tool is inclined at 1° for the cutting of the slot part. However, the other two contact faces along the edge of the joint cannot be inclined, as those lie on the top and bottom of the cross-laminated wood plate and cannot be easily cut without turning and re-clamping the work pieces.

For all assembly tests, a 6-axis industrial robot with a maximum payload of 150kg and an additional 7th linear axis was used to insert the trough-tenons (see Figure 5). In the first series of single-joint assembly tests, the slot plates were fixed to a concrete block. The insertion motion was then carried out parallel to the robot's additional linear axis for the single-joint assembly tests. A custom end effector was built with an integrated force measurement device, from which the pressure values were recorded during the assembly motion.

Following the first series of single-joint assembly tests, the assembly of multiple joints was tested on 6 full-scale plates out of a folded roof structure[1] (see Figure 6), which was generated with the computational tools presented in Robeller and Weinand 2016.

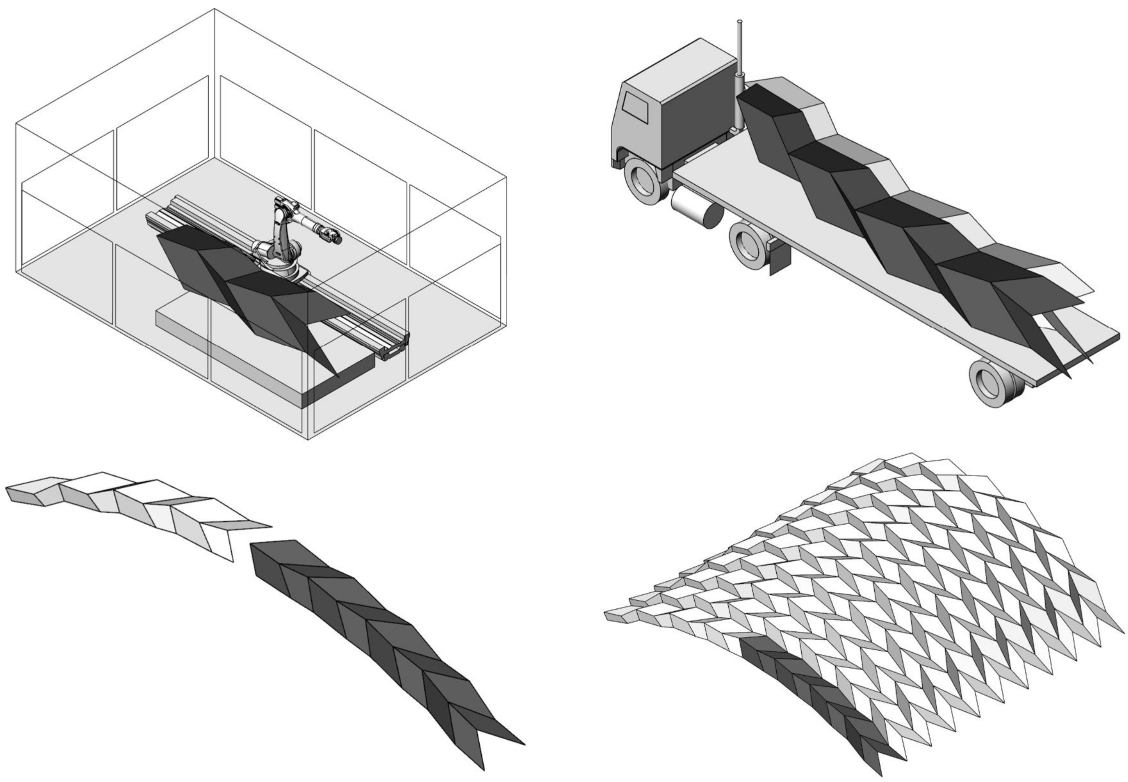

Figure 6: Case-study for dimensioning the large-scale prototype: A doubly-curved, lightweight structure (free-form folded plate roof) is segmented into prefabricated elements optimized for transport and handling.

The multi-plate robotic assembly experiment investigates the off-site robotic assembly of prefabricated segments, which would fit on standard-size trucks for the transport to the construction site. With such a prefabricated assembly, 85% of the total edge-joints in the case-study roof would be assembled automatically with robots, while the remaining 15% of the edges must be joined on site with state-of-the-art connectors.

The main challenge in this multi-plate assembly experiment was the cumulative force required for the insertion of entire plates, as well as an increased effect of wedging, due to the simultaneous assembly of 6 through-tenons per plate. A custom end effector was built to hold the plates with an integrated device for the measurement of forces (see Figure 7). This

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[1] The case-study roof structure covers an area of 700m2. Its doubly-curved surface spans over 20m between two 35m line supports, with a span-to-rise ratio of 4 in the center point and 8 at the front and end. The surface was segmented with a Miura-Ori fold pattern of 16 plates in the direction of span, 40 plates along the supports, and a static height of 650mm. The average dihedral angle between the 640 plates is 130°, with a maximum of 160° and the average edge length is 1.5m, with a maximum of 1.8m.

effector was also equipped with an integrated "vibration-assisted assembly" device for the introduction of vibrations into the plates, in order to reduce the effect of wedging.

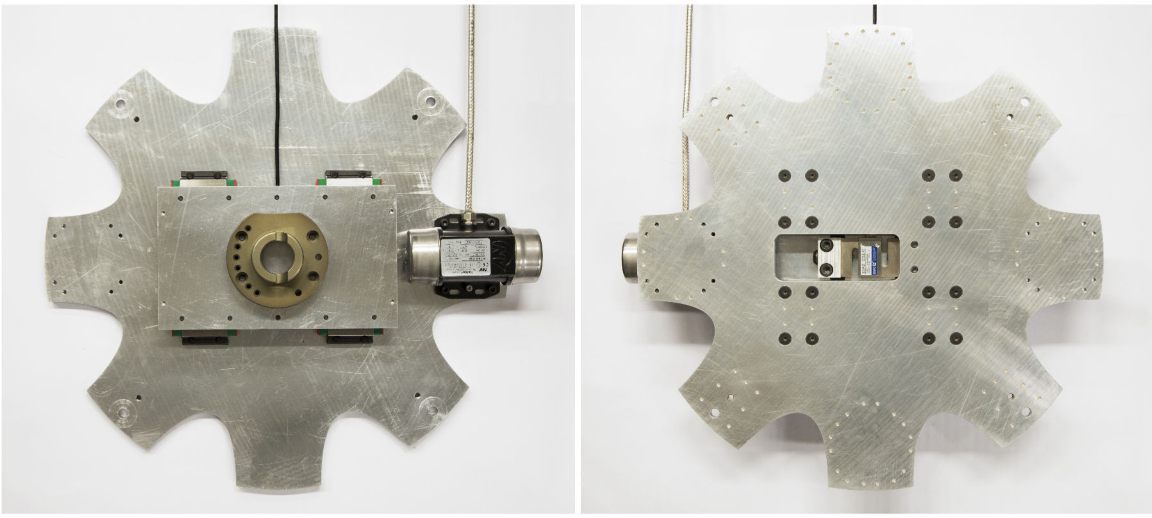

Figure 7: A custom built end-effector equipped with a load cell for force measurement and a vibration device.

5. Results

The first series of single-joint assembly tests showed the expected increase of insertion forces along with an increasing oversize of the plastic through-tenon joints (see Figure 9). The smallest oversize of 0.05mm would result in a required insertion force of 0.7 kN. At an oversize of 0.15mm we recorded 0.8kN, while the two largest oversizes of 0.20 and 0.25mm required much larger forces of 1.08 kN and 1.57 kN. Additionally, the effect of wedging was increasing along with the oversize value.

The inclination of the joints faces across the edge at an angle of 1° resulted in a greatly reduced effect of wedging. Figure 10 shows a comparison of two graphs for a specimen with and without the inclined faces.

The multi-plate assembly test showed that the simultaneous assembly of 6 through tenon joints require the vibration-device (see Figures 11, 12) to be activated in order to avoid a premature friction based interlock. Furthermore, the test showed that an additional "pulse" force in the joints assembly direction is beneficial in combination with the vibration device. During the tests this force was applied manually with a mallet. The plates used is this test featured two center elastic locator tenons (see Figure 13, left stack of samples) and four outer plastic connector tenons.

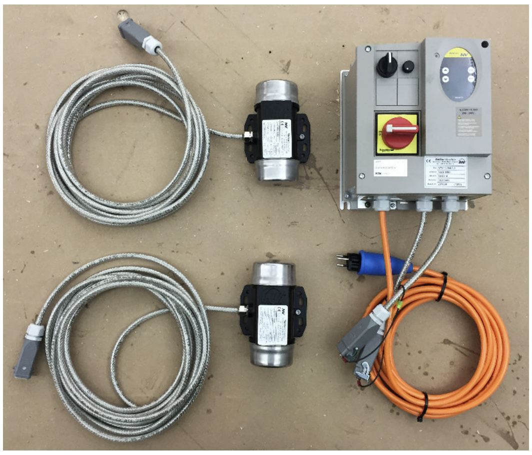

Figure 12: Vibration setup consisting of two vibrators and a frequency converter.

Figure 13: Specimen with different parameters, joint shapes and oversizes, 40mm thick Beech plywood.

6. Conclusion

With their locator and connector features, integral timber plate joints offer considerable benefits for the design of timber plate structures such as segmented plate shells or folded plates. While the mechanical strength of the joints requires a tight fit of the joints, it can be problematic for the assembly of such kinematically overconstrained joints.

The elastic and plastic interlocks presented in this paper demonstrate how the materials properties of compressibility and elasticity can be exploited for an assembly technique that fully eliminates any gaps, through the insertion of oversized tenons. While this basic concept of plastic interlocks is commonly used in mechanical fastening techniques such as screws and bolts, this paper first applies this concept to the integral attachment of through-tenon jointed timber plates. It is made possible through the precise assembly motion of an industrial robot, as well as its possibility to apply an insertion force. Here, the single-joint assembly test series first provides values on the required forces.

Since the assembly of structures such as timber plate shells requires the simultaneous assembly of multiple edges and therefore also multiple joints, it is crucial to estimate the total required insertion force per plate. The multi-plate assembly tests have shown that the assembly of building-scale plates from our case study project is possible with an additional vibration-inducing device. Further research is required into the addition of a pulse force, similar to a jackhammer, which can be induced in the plate's direction of assembly.

Acknowledgments

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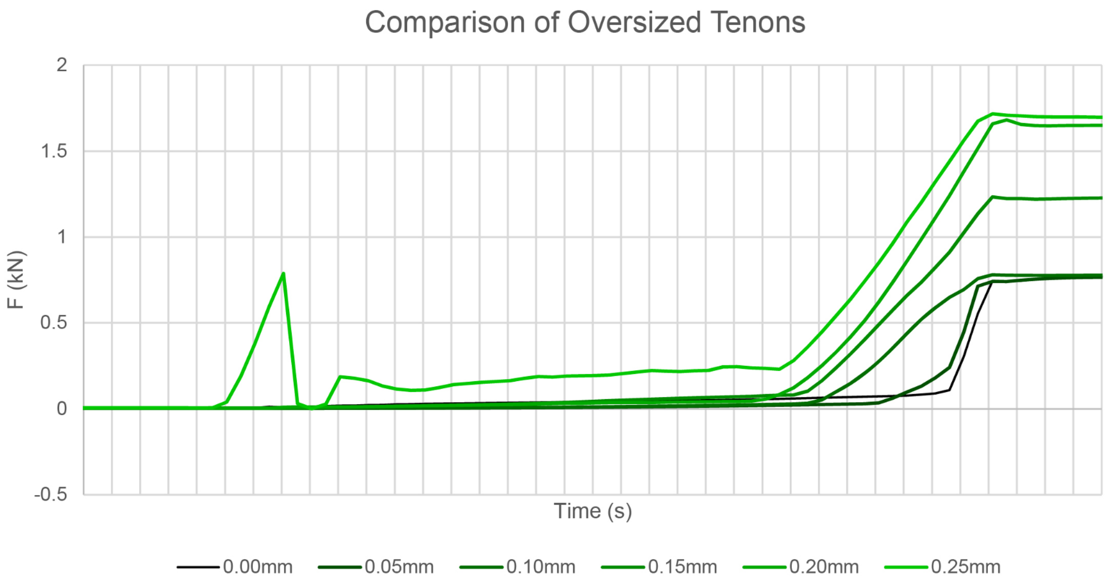

Figure 9: Insertion force graphs for five incremental steps of increased oversizes on non-elastic through-tenons.

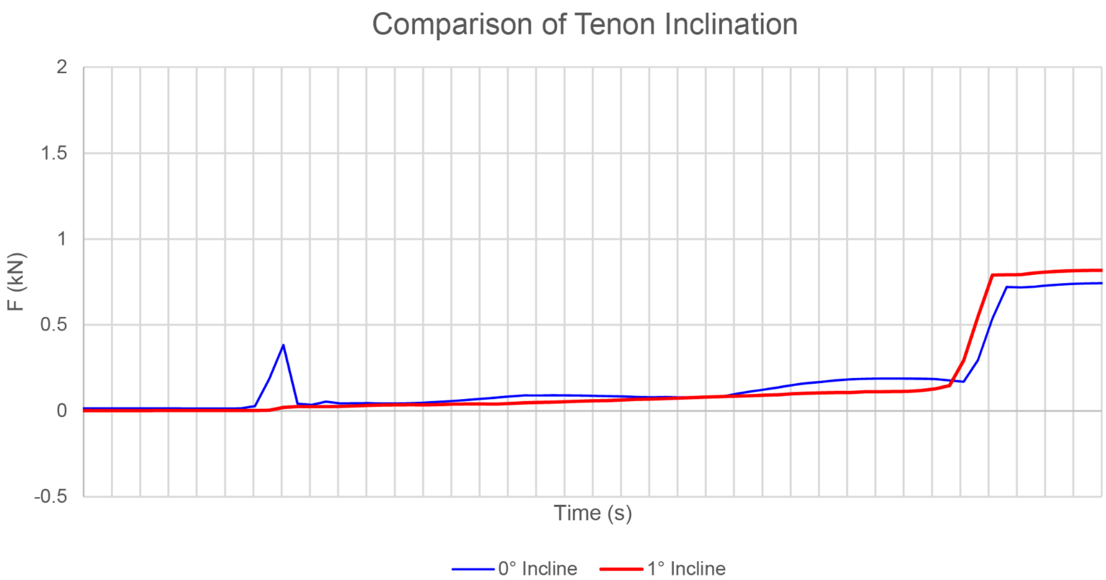

Figure 10: Graphs comparing different tenon geometry: The effect of wedging can be reduced through modifications in the joint shape.

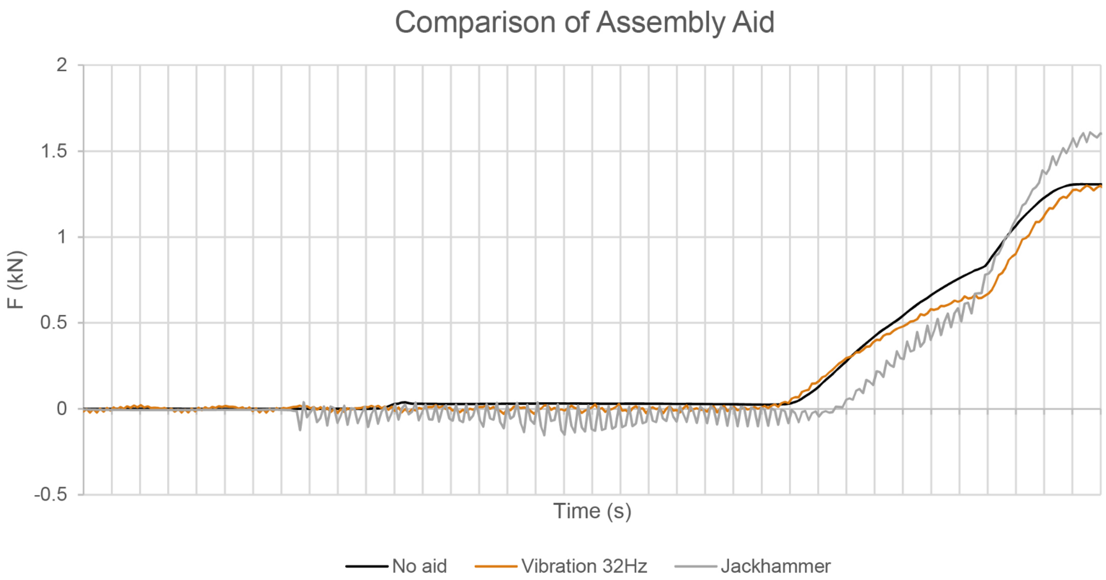

Figure 11: Graphs illustrating required insertion forces when coupled with assembly aid.