Experimental testing of plywood & OSB 'jigsaw' joints for structural characteristics

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Declaration

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Abstract

WikiHouse is an innovative open-source construction system operated by OpenSystemsLab, based upon the premise of a structural plywood frame split into separate blocks manufactured offsite and assembled onsite to form the structure. These blocks are comprised of individual plywood panels that interlock using timber-to-timber connections to join the panels together. Therefore, the aim of this project is to investigate the strength characteristics of the 'jigsaw' joint used in the design of the WikiHouse building system. The main reason for this is to contribute more fundamental understanding of the structural behavior and capacity of the WikiHouse Skylark 250 system, for it to be refined to be integrated into the current housing construction industry as a valid option alongside the more traditional options available.

Although the current design is based upon plywood being the choice material for construction, an alternative option is concurrently being investigated – Oriented Strand Board (OSB) – in order to provide a comparison and for an informed decision to be made on the ideal material for the WikiHouse design. There are still questions about the overall performance of the plywood WikiHouse design, particularly the failure mode of both the plywood and OSB connections.

Through analysis of the results obtained through monotonic tensile testing, it was found that the jigsaw joints failed at an average maximum force of 9.28 kN and 10.29 kN for plywood and OSB respectively. The overall stiffness of the joints were 1.2 kN/mm and 2.05 kN/mm for plywood and OSB joints respectively. Additionally, rotational deformation was observed for both material types, highlighted using Digital Image Correlation (DIC). The failure mode for the plywood specimens was ductile delamination of the veneers at the joint interface, whilst the OSB specimens demonstrated more brittle behavior, with crack failures occurring at the areas of highest displacement. Finally, an analytical model was investigated for the OSB specimen where clear cracking during failure was observed, and the failure stress of the specimen was found to be comparable to that of separate testing for strength characteristics conducted on plywood and OSB.

Acknowledgements

I'd like to thank my project supervisor, Marcus Perry, for his help throughout the year pointing me in the right direction and getting me going with the initial modelling and fabrication process. Thank you also to James Frances and Gavin Gibson in the Civil & Environmental Engineering labs, who were always available to lend a hand and offer encouragement during the fabrication and testing process.

A massive thank you also goes to Gabriele Granello at the University of Edinburgh who has gotten me through this last stretch of the writeup with his incredibly useful guidance on what to focus on and tolerated my constant barrage of WhatsApp messages without complaint. Gabriele also produced the DIC imagine shown in the report, so a huge thank you for that also Gabriele.

Finally, thank you so much to my friends and family for their love & support during this challenging year, and always reminding me to not compare myself to others and do my best in everything.

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1 Introduction

1.1 Focus of report

This report aims to investigate the structural performance of a specific castellated joint (coined the 'Jigsaw Joint') used in the Open Systems Lab WikiHouse design. Their current flagship design, the Skylark, is entirely constructed using timber panels such as plywood and OSB as the constituent material. The jigsaw joint (see **Figure 1**) uses a castellated locking mechanism to join two constituent panels together. The research conducted hopes to investigate the structural characteristics of the jigsaw joint under tensile loading, and subsequently derive key parameters relating to stiffness and overall strength. In doing so, this report hopes to contribute useful knowledge of the structural limitations of the WikiHouse design.

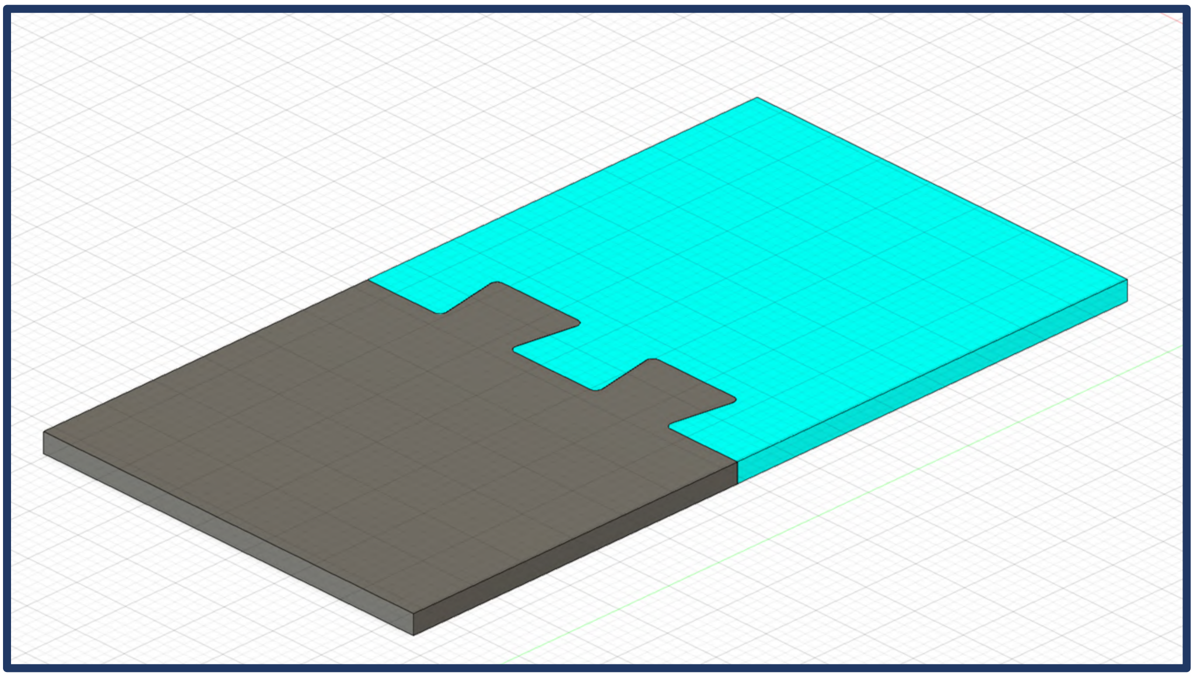

Figure 1: Jigsaw Joint

As the WikiHouse design is still in its development stage, research is being constantly conducted into its structural performance to continually optimize and improve it. It places an emphasis on the removal of the conventional joint fasteners used in housing construction, such as nails and screws, to reduce the dependence on traditional construction skills during the assembly stage. However, in doing so it brings heavy scrutiny on the structural integrity of the plywood panel connections used in their place.

Alongside the Skylark construction projects using plywood as its material of choice, investigation into the feasibility of OSB as an alternative material is being simultaneously conducted. Currently there is a full-scale Skylark house being assembled entirely using OSB as the construction material. Therefore, an identical investigation will be simultaneously conducted on OSB jigsaw joint specimens, allowing the functionality and the relative uncertainty between the two materials to be compared. With this analysis of the results, this report hopes to provide justification for the choice of material used in the WikiHouse design.

1.2 The research has the following objectives:

- To identify comparative examples of structural performance of similar timber-to-timber connections through the assessment of peer-reviewed literature on the topic.
- To conduct monotonic tensile testing to failure of the jigsaw joint specimens using the department's Tinius Olsen Model 25ST Universal Testing machine.
- To investigate the comparative stiffness values for the jigsaw joints comprised of both plywood and OSB.
- To identify the key failure modes for both material types.

1.3 Limitations & Assumptions

1.3.1 Limitations

The main limitations of the research conducted within this report were a result of the machinery used to fabricate and test the jigsaw joint specimens. The Ooznest CNC machine used to cut the joints constricted the maximum size of panels being cut to dimensions of 1.2m x 0.6m. This meant that the jigsaw joint specimens that were cut could not be replications of the full-length panels used in the WikiHouse design, and so had to be adapted to fit the constrictions of the CNC machine available to use. The Tinius

Olsen Universal Testing machine used to conduct tensile loading to failure of the joints had similar sizing limits, with a max permissible specimen length of 1.09m.

Both these limitations resulted in the specimens being adapted to conform with the sizing restrictions of the machinery being used to conduct the research.

Another limitation is the sample size used in the report. Due to time constraints, only 3 jigsaw joint specimens were manufactured and tested per material type. This limited the extent of analysis that could be conducted, as the sample size was deemed too small to be worthy of conducting a dispersion analysis of the results.

1.3.2 Assumptions

Any irregularities or defects in either the plywood or OSB panels used to cut the jigsaw joints for testing were not accounted for.

1.3.3 Ethical Considerations

The research conducted for the purposes of this report did not involve the gathering of any opinions from volunteer subjects. All activities and research that took place was purely scientific and all opinions expressed were that of the author, unless stated otherwise.

2 Literature Review

2.1 Off-site construction

In the UK, along with a rising population has come an exponential growth in the housing industry, with more people than ever looking to own their own home. Alongside this, there is an omni-present and ever growing pressure to develop more sustainable and carbon-friendly practices within the industry, as the UK has set itself the target of reaching net zero emissions by 2050 (Tannert, 2016). These demands have resulted in the need to streamline as many of the processes within the construction industry as possible (Švajlenka & Kozlovská, 2020) through methods such as off-site construction. This involves moving a portion of the work that would otherwise be done on the construction site to a workshop where assembly of some or all the constituent parts of the structure can be completed in a more controlled environment. The current WikiHouse structural design embodies this building technique, with the beams, columns and walls that make up the frame of their buildings.

One of the main advantages of prioritising off-site construction is the corresponding reduction in on-site construction time that is creates (Duncheva & Bradley, 2019). Building sites are expensive to operate and are subject to the prevailing weather in a way that more controlled environments like a workshop are not. A massive reduction in waste has also been often cited as another benefit of a shift to offsite construction, in some areas by up to 30% (Sandanayake et al., 2019).

This method of construction is not an entirely new concept, with concrete construction regularly utilising the offsite fabrication of key components such as primary load bearing beams. This process can also involve the application of stress to a reinforced concrete beam during the production phase, to provide strength against tensile force experienced during its life cycle. However, this system is complex and expensive and in the case of concrete construction is generally reserved for key, critical members under tremendous stress, both compressive and tensile. The WikiHouse design focuses on smaller scale housing, up to 3 storeys high, but maintains that preference of off-site fabrication. However, this not due to key strength criteria that can only be met through complicated methods (such as concrete pre-stressing), but because of the intention to make the on-site construction process as simplified as possible, reducing the demand for skilled labour at the assembly stage (Priavolou & Niaros, 2019).

2.2 WikiHouse design

Prioritising off site construction, the Skylark design involves the fabrication of its constituent blocks – be that beams, columns, or walls – in a controlled workshop environment. These blocks are typically made up of timber panels, engineered to lock together using connections known as integral mechanical attachment joints (Napier, 2022).

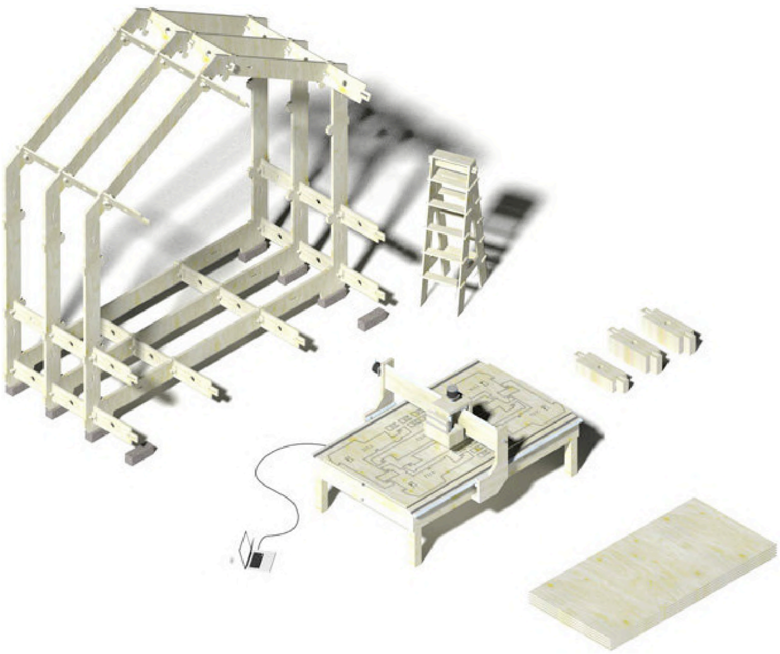

Figure 2: Visual of WikiHouse construction process (www.wikihouse.cc)

The WikiHouse design offers a sustainable solution to the demand for environmentally friendly housing alternatives, as the timber-based design trumps contemporary brick-and-mortar design on important sustainability criteria such as fabric heat loss, annual heating cost, and the upfront carbon cost of the structure (www.wikihouse.cc – see **Figure 3**)

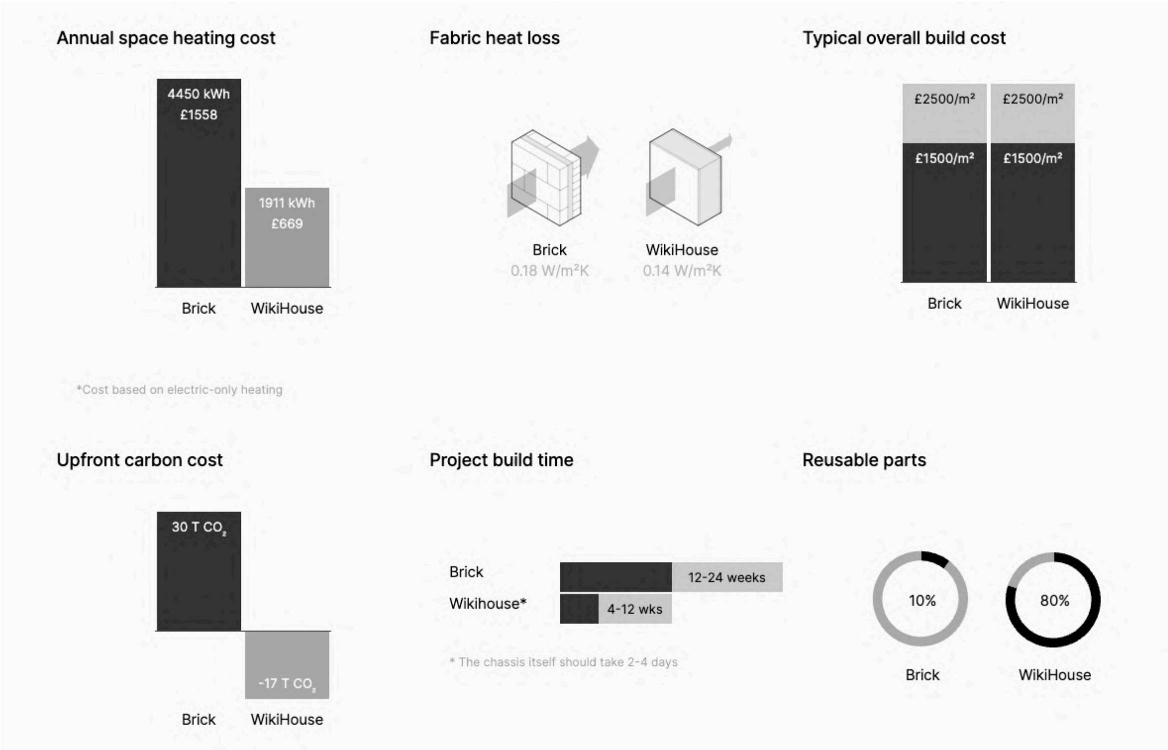

Figure 3: Energy & carbon modelling comparing WikiHouse & brick construction (www.wikihouse.cc).

WikiHouse initially focused on using plywood as the timber of choice for experimental construction and research into the strength properties of the design (Prest, 2021). However, there has been renewed interest within the WikiHouse team in the use of OSB as a potential alternative timber material to use in the design. This report examines both in the hope of providing useful insight into the difference in their structural behaviour and capacity.

2.2 Plywood & OSB in construction

Wood is one of the world's oldest construction materials. In previous centuries construction using timber was most often out of preference because of its workability – wood in general provides a lot of strength in proportion to its relatively light weight (Li et al., 2019). Since the onset of the industrial revolution, both steel and concrete have emerged alongside timber to form the trifecta of modern construction materials (Shollock et al., 2016). However steel and concrete are both carbon intensive (Van den Bulcke et al., 2009) to manufacture and therefore are a much less sustainable option, especially when compared to timber which is a regenerative material (Götmark et al., 2005).

Plywood is a manufactured timber consisting of wood veneers glued together. It embodies the same characteristics that historically made timber a favourable material, with its relatively high strength capacity in comparison to its low density (Jakob et al., 2020). It is used worldwide in construction, although has experienced some decline in use (Keegan et al., 1998) in favour of particle boards (such as OSB).

Oriented-Strand-Board (OSB) is a manufactured timber composed of wooden strands 'mashed' together under compression and bonded into a single panel using adhesives. It is also used worldwide in construction, with use growing rapidly in recent years. OSB consumption increased by 45% in Europe between 2010 and 2020 (Lille et al., 2022), and is used extensively in flooring, wall sheathing, and increasingly as an alternative to plywood in loadbearing scenarios (Li et al., 2019). In the United states, where timber construction dominates in comparison to the UK where brick-and-mortar is still largely preferred, OSB comprises 60% of the overall structural panel use (Aro et al., 2014). OSB, like all timbers, is subject to the "mechano-sorptive" effect, which is the relationship between variations in the moisture content of the given material and its performance under load. High fluctuations in moisture content during the lifetime of a timber structure can magnify the effect of creep deformation that occurs (Mohammad & Smith, 1994).

2.3 Fastener-less timber connection technology

The WikiHouse design does not rely on traditional fasteners such as nails and screws, placing emphasis on the mechanical integrity of the joints between panels and blocks that are used in the design. Such joints have been studied and experimented with in recent years. Within modern timber construction, there are generally three types of ways to join different structural members: bonding together with an adhesive (such as a phenolic resin), mechanical "dowel type" fasteners, or by direct member-to-member contact (Tannert, 2016). "Dowel-type" fastener is the general name given to a range of items such as nails, screws, staples, bolts with nuts and dowels (BS EN 14592: 2008). The jigsaw joint studied in this report, like several used in the WikiHouse design, does not utilise dowel type fasteners and falls under the latter of the three options described. The connection strength and security coming from the interface of the joint connecting the two panels. On the other hand, some of the joints in the WikiHouse design do utilise such mechanical dowel-type connections, such as the Bowtie joint (**Figure 4**). In this case, the Bowtie is a manufactured plywood component, designed and integrated into the WikiHouse design to piece together two of the timber panels that make up an individual block.

Figure 4: Bowtie joint used in WikiHouse Skylark design

For these types of connections that utilise dowel-type fasteners, there is established guidance within the British Standards Institution documentation (BS EN 14592) on their structural requirements. As of 2023 there is no specific guidance outlining the strength calculations for all-timber connections without fasteners (Bell, 2018) such as those used in the jigsaw joint. With this in mind, the focus of this report will be to contribute to the structural knowledge of plywood and OSB. WikiHouse is at the forefront of the push to have fastener-less connections such as the jigsaw joint standardised and fully integrated into the Eurocode and British standard publications on timber structures. This would be a big step in the right direction for the WikiHouse concept, and for timber housing in the n United Kingdom as a whole and would open the door for WikiHouse to potentially make that jump into widespread use.

2.4 Overview of peer-reviewed literature on timber-to-timber connections

For timber structures in general, the connections between members are important as they dictate the overall strength capabilities of the structure (Ottenhaus et al., 2021). Excellent connection design is therefore especially critical to the success of fastener-less connections such as the jigsaw joint, as all strength properties come directly from the connections themselves.

Granello *et al.,* (2022) investigated the structural performance of plywood WikiHouse beams using the castellated 'jigsaw' joint as part of their design. They found in their experimental results that the jigsaw joint introduced more flexibility to the beam. The average failure force across the 5 specimens was found to be 22.7kN. Furthermore, the displacement witnessed during the testing suggested that the deformity of the beams in question do not follow conventional monolithic beam theory, and that the observed deflection was a result of the rotation at each jigsaw joint. Throughout the testing, the failure of all plywood specimens during testing was observed to be ductile.

Granello also investigated the structural performance of the plywood bowtie joint individually under tension (Granello, 2023). They observed the stiffness for the joint shown in **Figure 4** to be between 1.44 kN/mm and 1.67 kN/mm, with an average of 1.54 kN/mm. The observed failure mode of the specimens was at the interface between panel and the bowtie component. Napier, (2022) also conducted research into the performance of the bowtie joint under tensile loading and derived an identical average stiffness value to Granello. Clear delamination of the plywood veneers was seen as the primary failure mode in the testing of the bowtie joints (see **Figure 5**).

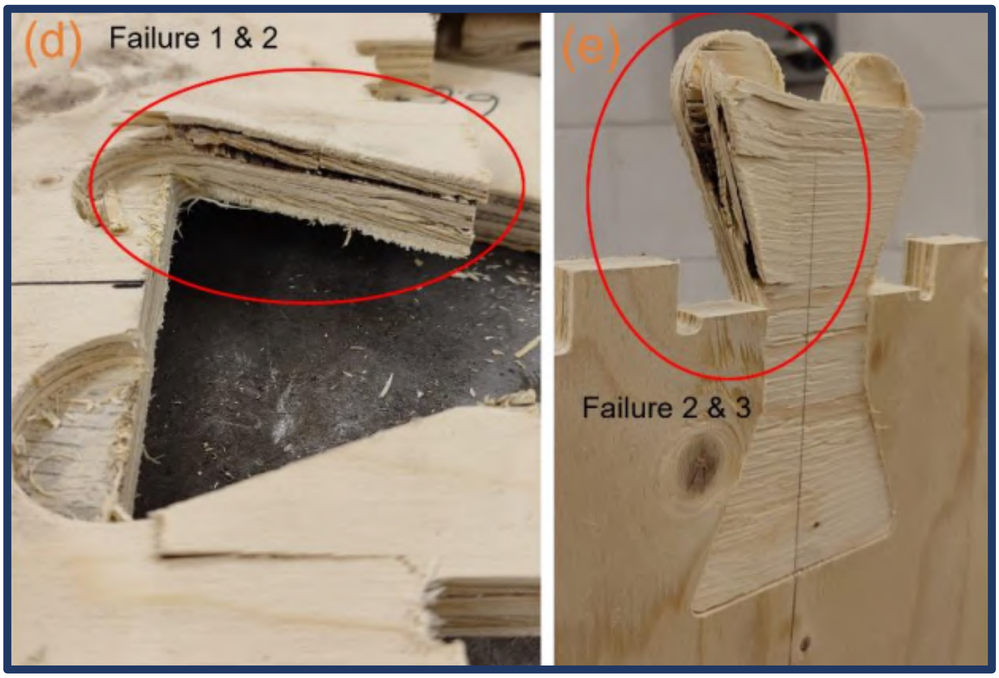

Figure 5: Delamination of plywood veneers observed in bowtie joint testing (Napier, 2022).

Chang *et al* (2010) focused on using plywood and oak to develop a new connection for beam members of timber structures. Their new connection involved joining two beams together using a 'Flitch Plate' and oak pegs (see **Figure 6**).

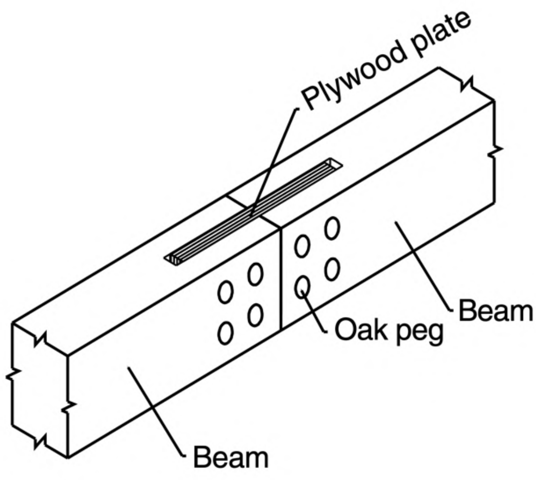

Figure 6: Beam-to-beam connection (Chang *et all*, 2010)

During their research the connection specimens were tested to failure using monotonic tensile loading, and from the data obtained the stiffness and strength parameters of the connections were able to be derived. The stiffness of the pegs affected the stiffness of the connection as a whole and was found to be 7.03kN/mm. It is also shown in their research that the guidance provided by Eurocode 5 generally gives a very conservative estimate of the capacity of timber-to-timber connections, as the strength capacity which was observed significantly exceeded the capacity value derived from EC5. It was found that EC5 gave a value that was between 60-98% of the values obtained from the experimental testing.

Because of the lack of standardisation of the fastener-less timber connections such as the jigsaw joint, attention can be paid to the research and guidance concerning dowel-type fasteners, which can be considered a similar connection type and one which has more established design protocols such as BS EN 14592. Dorn *et all* (2013) investigated the performance of a steel-to-timber dowel-type connection, using the design values outlined in Eurocode 5 to compare. They focused on five different criteria which influence the resulting strength characteristics of the joint; density, slenderness, dowel roughness, ed/edge distance and reinforcement. In their results they again found that the Eurocode 5 guidance tends to underestimate the strength capacity of a given joint. This could lead to overengineering of connection leading to them being underutilised. Furthermore, Dorn *et all* point out that connection width is not a factor that is accounted for within EC5, meaning that inaccuracies in the stiffness design values are at risk of being introduced.

Tannert (2016) experimented with different methods of increasing the stiffness of a specific timber-to-timber joint called the Rounded Dovetail Joint (RDJ) (**Figure 7**). The RDJ joint shares similarities with the jigsaw joint, in that it is a timber-to- timber connection comprised of a male part and female part that lock together to join two structural members.

Figure 7: Rounded dovetail joint (Tannert, 2016)

Tannert highlights how the rise in the capabilities of modern CNC machinery has made such fabrication techniques far more economical and allowed for growing exploration into new techniques and building designs that utilise CNC fabrication, such as WikiHouse. In order to supplement the structural capabilities of the RDJ, they explore the additional use of reinforcement to form a 'hybrid' connection to maximise the capacity of a given connection. Tannert specifically focuses on the use of two forms of reinforcement in their research - self-tapping screws and adhesives - and conducted testing with various combinations of reinforcement and tightness of the joint fitting in order to explore the performance in a variety of setups. The joints were tested by the application of a point load under monotonic loading in accordance with BS EN 26891. The analysis was also conducted in accordance with this guidance and allowed values of the joint stiffness to be extracted for each test. From their testing, Tannert found that the joint stiffness could be increased by increasing the size of the tenon (the male part) to allow for a tighter fitting joint. The addition of self-tapping screws was also found to increase the joint stiffness, however neither of these methods was found to increase the joint capacity – that is the maximum force it can withstand before failure. The stiffness was also found to be improved with the use of adhesives, albeit at the detriment of the deformation capacity of the joint.

Stitic et al., (2018) also conducted research into the performance of multiple tab-and-slot joints (MTSJ) which bear similarity the jigsaw joint in that they are both utilise a castellated joint to lock two panels together. However, whereas the jigsaw joint under scrutiny in this report is used to combine two constituent pieces into one straight member as part of a beam block, the MTSJ is used to join two panels which are at different angles and part of a larger folded surface structure. Because of the nature of the connection, Stitic et al. experiment with the use of adhesives and angle of connection in their testing. 3 main connection types were determined: MTSJ with open slots, MTSJ with closed slots, and the Miter joint (see **Figure 8**), with the latter utilising adhesives to achieve the necessary rigidity. Additionally, the force application used differed to that of this report, as a complex loading mechanism was used to mimic the uniformly distributed surface loading that folded surface structures experience.

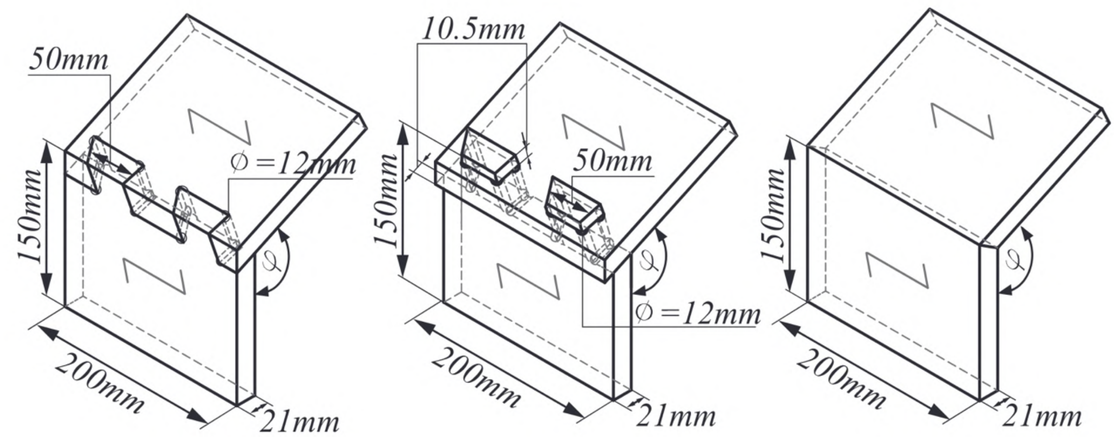

Figure 8: Multiple tab-and-slot joints (MTSJ) (Stitic *et al.*, 2018)

Analysing the force vs displacement behaviour of the various samples, Stitic *et al* found that the adhesively bonded joints provided the highest stiffness, values for which were obtained from the observation of the linear elastic region of the force vs displacement graphs. However, the connection type with the maximum achieved strength was the MTSJ with closed slots.

The calculated stiffness of the MTSJ with open slots specifically was found to be 1.65kN/mm. This is mentioned as it is the connection type which most closely resembles the jigsaw joint being focused on in this report. This stiffness value obtained in the research of Stitic *et al*. will be useful for comparison within the discussion of the results.

Hassanieh & Valipour (2020) investigated the performance of timber joints comprised of a combination of OSB and Laminated Veneer Lumber (LVL), using stapled connections as fasteners (see **Figure 9**). Two combinations of joint design were tested, utilising different staple lengths, and spacing between panels. Under monotonic tensile loading, a range of stiffness values were obtained. Through a normal distribution analysis, a characteristic stiffness value of 1.8 kN/mm was obtained in accordance with Eurocode 5.

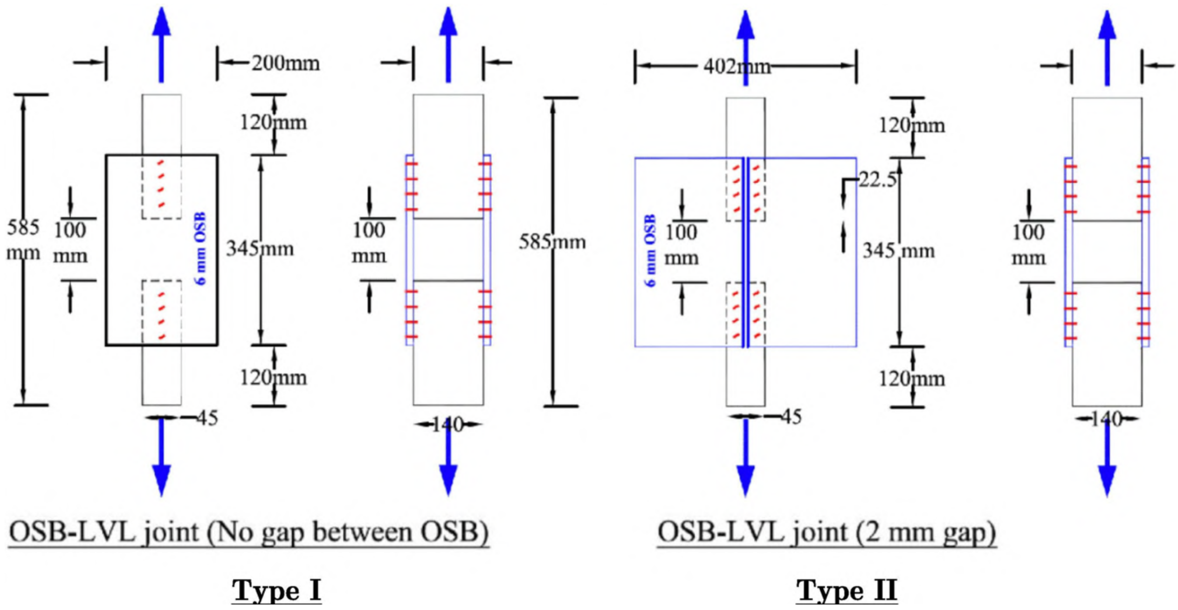

Figure 9: OSB/LVL testing setup(s) (Hassanieh & Valipour, 2020)

2.5 Overview of relevant standardised guidance available

Among the available documentation for structural engineering from the British Standards Institution (BSI) and the Eurocodes there are several specifically covering the design of timber structures. Eurocode 5 is very broad and covers the design of timber structures as a whole and is explained well in the 'Manual for the Design of Timber Building Structures to Eurocode 5' published by the Institution of Structural Engineers. This document provides specific guidance on joint slip that will be drawn upon later in this report.

As of April 2023, there is no specific standardised guidance either from the BSI or in Eurocode 5 on the fastener-less design of the jigsaw joint under scrutiny in this report.

Therefore, a degree of empiricism must be used at this stage, drawing on established guidance for similar connection types to see how they perform. An example of this will be seen later in the report, using guidance on the design of joints made with mechanical fasteners (BS EN 26891).

3 Methodology

3.1 Software & Machinery

The research conducted in this report can be split into 3 general stages: modelling, fabrication and tensile testing. Throughout each of these stages, a range of software and machinery were used. During the modelling stage of the jigsaw joint, two main software packages were used: AutoCAD 2023 & Fusion 360. Both software are provided by Autodesk and were used for free under the student licensing system. Additionally, Microsoft Excel was used to compile the data obtained from the tensile testing into graphs depicting the behaviour of the joints under loading.

During the subsequent fabrication and testing stages, all equipment was kindly provided by the Civil & Environmental Engineering Department within the University of Strathclyde. An Ooznest WorkBee Z1 CNC machine (**Figure 10**) was used for the cutting of the specimens, which had an approximate length and breadth working area of 1200mm x 600mm – well beyond the dimensions of the specimens being cut for this report.

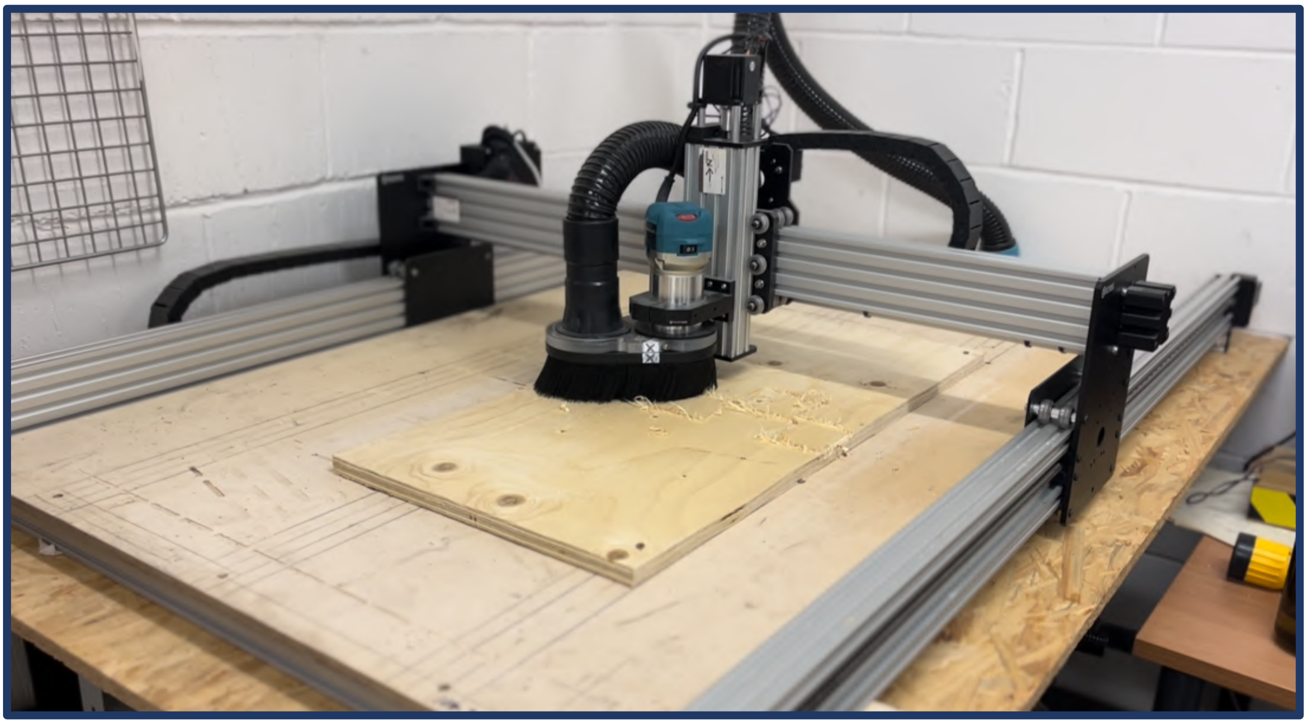

Figure 10: Oozenest Workbee Z1 CNC machine

A Model 25ST Tinius Olsen Universal Testing Machine (**Figure 11**) was used for monotonic tensile loading of each of the joints. This machine has a maximum force limit of 25kN for compressive and tensile loading - significantly higher than the expected failure load of both the plywood and OSB specimens based on historical testing of similar timber joints. The maximum specimen length including allowances for lengthening during tensile deformation is 1090mm, and so the design and fabrication of the specimens was conducted with these constrictions in mind.

Figure 11: Tinius Olsen Model 25ST universal testing machine

In addition, a purpose-built mounting clamp (**Figure 12**) was fabricated by the Design, Manufacturing & Engineering Management Department. This clamp was a replica of the clamp used for similar testing conducted within the department previously (Napier, 2022), kindly provided by the University of Edinburgh. The main demand of the clamp was for it to be well above the predicted strength of the specimens being tested. Being comprised solely of stainless steel, the clamp was deemed to satisfy this requirement. The limiting factor of the clamp strength was therefore determined to be the number of bolts used to fasten the specimen the clamp. Using 5mm diameter stainless steel bolts for mounting and with the maximum possible number of bolts being 52, the strength capacity of the mounting clamp was determined to be 52kN – well beyond either the predicted specimen failure load or the tensile testing capacity of the machine being used. Due to this, only 26 bolts were used to tether either end of the testing specimens to the mounting clamps. This provided ample shear strength for the purposes of the testing being conducted whilst also reducing the number of 5mm holes being drilled through the specimen to allow for mounting. In doing so, any potential impact of the mounting system on the structural integrity of the specimens was minimised. In addition, this reduction in number of holes being drilled and bolts being manually fixed and then removed for each specimen reduced the labour intensity and time consumption of the testing process significantly. The clamp (with dimensions of 140mm x 3000mm) was manually centred in the middle of the panel end edge to ensure centralised, uniform tensile loading of the specimen(s) during testing.

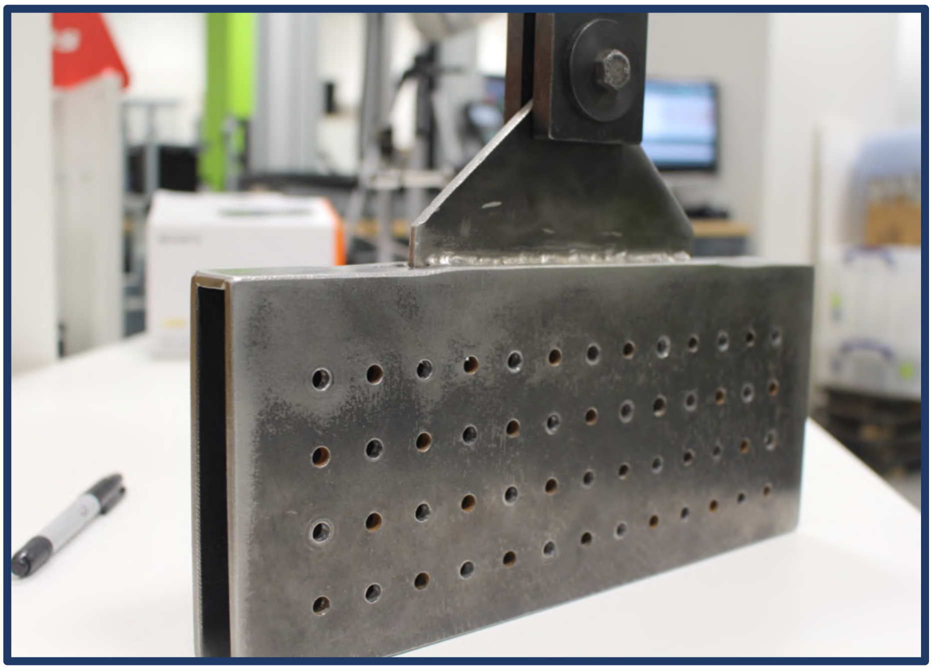

Figure 12: Mounting clamp used for tensile testing

To provide additional visualisation of the key areas of failure/ deformation during the tensile testing, Digital Image Correlation (DIC) was utilised. This involved close-up timelapse photography of the joints themselves during the tensile testing, at a rate 1 picture per 5 seconds. A random pattern of black dots was drawn onto each specimen around the area of the joint. Using the ParaView software available online, a visual representation of the deformation across the specimen was then be produced using the imaging captured during testing.

3.2 Material Specification & Panel Design

The research conducted in this report used Finnish Spruce plywood panels supplied by the University by Strathclyde, sourced from Metsä Wood. Each plywood panel is comprised of 6 bonded cross-bonded veneers, each 3mm thick, glued together to form each 18mm thick panel.

The OSB specimens were constructed from Sterling OSB3 panels provided again by the University of Strathclyde. OSB timber is formed using adhesives to combine and compress wood strands in s

3.2 Digital Modelling of Jigsaw Joint

Due to the open-source setup of the WikiHouse design, the relevant DWG file were easily obtained via the Library section of the WIkiHouse website. These DWG files contain three-dimensional models of the entire blocks that make up the Skylark 250 design including walls, beams, and columns.

The jigsaw joint is used across many of the different block options, but as only the joint itself was needed for modelling and fabrication, a representative block of 'Floor-M-1' was chosen as it utilises the jigsaw joint as part of its design. WikiHouse provides a description for this beam as 'A basic floor block that works with a 4.8m internal span. Suitable for upper floors.' (wikihouse.cc/blocks). With the Floor-M-1 DWG file downloaded, it was then opened within the AutoCAD software. All WikiHouse floor beams are essentially four-sided rectangular beams (**Figure 13**) with length, breadth, and height dimensions of 5436mm, 600mm & 380mm. Each beam has vertical sides being comprised of 3 separate sections, connected by two jigsaw joints. Of these three-section panels, two panels connected by one jigsaw joint were isolated and then exported separately as two DWG files.

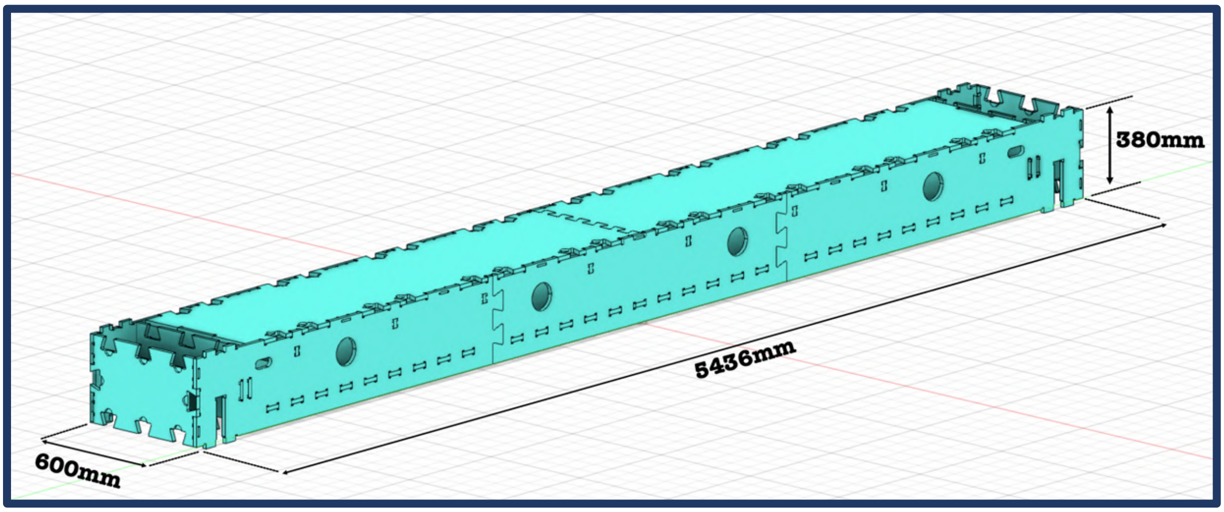

Figure 13: Floor M-1 Block

With the jigsaw joint panels isolated and saved as separate files, they could then be uploaded to Fusion 360. To produce a specimen within the limitations of both the departments CNC and tensile testing machines, the models for both panels were digitally shortened. Additionally, The Skylark 250 block arrangement involves an intricate design both in the edges and within the body of the panels themselves, to enable all the individual panels to lock together to form one unit (as can be seen upon inspection of **Figure 13**). As the scope of this report is focused solely on the structural performance of the jigsaw joint itself, both the edges and the holes within the body of the panels were removed to form the simplified jigsaw panel design shown in **Figure 14**.

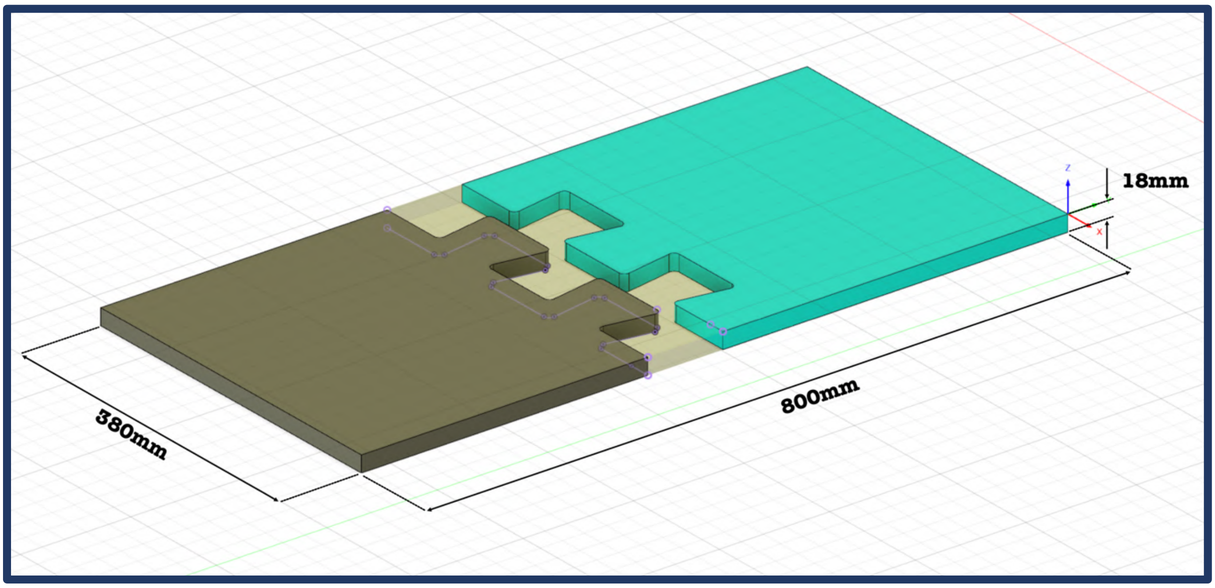

Figure 14: Simplified panel for jigsaw joint cutting

This simplified panel had length, breadth, and height dimensions of 800mm, 380mm, and 18mm respectively. The panel height dimension is specified upon inspection of the Skylark 250 design, which utilises 18mm thick structural plywood as the constituent timber for its panels. Similarly, the 380mm breadth dimension is specified as the width of the panels using the jigsaw joint in the Floor-M-1 block design. The 800mm panel length was chosen for several key reasons; firstly, to keep the panel dimensions within the limitations of both the machines being used for the subsequent cutting and testing, secondly, in order to be as economical as possible with the department's structural plywood resources, and lastly in order to leave ample space for the mounting clamps to be tethered at either end during the tensile testing phase.

As can be seen in **Figure 14**, an 85mm gap was included between the two constituent panels of the jigsaw joint. This was to allow for ample space for cutting without interference on the panel opposite.

3.3 Cutting of joints with CNC Machine

With the panel dimensions finalized as specified above, a toolpath corresponding to the layout of the digital model was then compiled within Fusion 360 (**Figure 15**). Key parameters needing specified within the toolpath included spindle speed & feed per tooth, whose values were obtained via available guidance from Makita – the tool manufacturer for the drill used as part of the CNC machine setup. Specifications of the toolpath settings used in the cutting for the specimens in this report can be found in the Appendices.

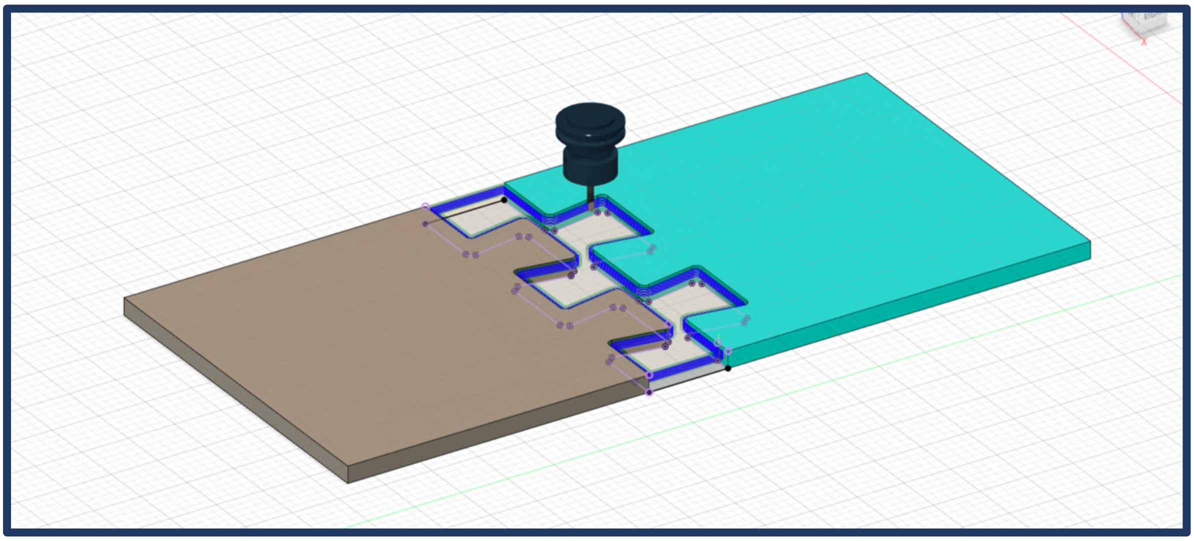

Figure 15: Toolpath used for jigsaw joint fabrication

With the toolpath finalized, it was then exported as a G-code file – the format that allows the CNC machine to compute the 3D layout of the toolpath. This toolpath was used for the cutting of both the plywood and OSB specimens. To maintain as precise a cut as possible, 1mm increments were specified (resulting in 18 total passes required to cover the 18mm depth of each specimen). Larger increments were available; however this can introduce a higher likelihood of thermal damage to the specimen. In addition, increasing the depth-per-cut increment and therefore the amount of material being removed per pass could introduce residual stress within the material located around the jigsaw joint (9). As this is expected to be the precise location of failure during the subsequent tensile testing, a conservative depth-per-cut increment of 1mm was decided upon, despite the extended runtime per cut.

Using the operating software provided by Ooznest for the WorkBee Z1, the toolpath G-code file was uploaded and tested on scrap material in the workshop. All specimens were then cut using the following steps:

(1) Fix specimen to CNC workbench using woodscrews, visually aligning panel edge parallel to the existing lines.
(2) Using the probe tool, centre the drill bit on the correct corner of the specimen (corresponding to the location specified within the toolpath).
(3) In this position, use the 'Home XYZ' feature within the Ooznest software to lock in the start point of the cut.
(4) Switch on power for vacuum, Makita power drill. (User to be wearing safety glasses whenever cutting is in progress.)
(5) Run G-code file.
(6) Switch off vacuum and power drill. Remove specimen from workbench.
(7) Repeat for all 6 specimens.

<u>Note</u>: After the first pass of each cut the process was paused temporarily to allow for screws to be drilled into the portion of material separating the two jigsaw panels (see **Figure 16**). This ensured that all sections of the specimens remained locked in place throughout the cutting process.

To assemble the component panels of each joint together, a soft-faced mallet was used to encourage the two pieces together with light taps. Particular care was taken with the plywood specimens, which are more susceptible to delamination in these circumstances. Additionally, sandpaper was used to refine any imperfections on the joint interface to allow for seamless connection of the panels.

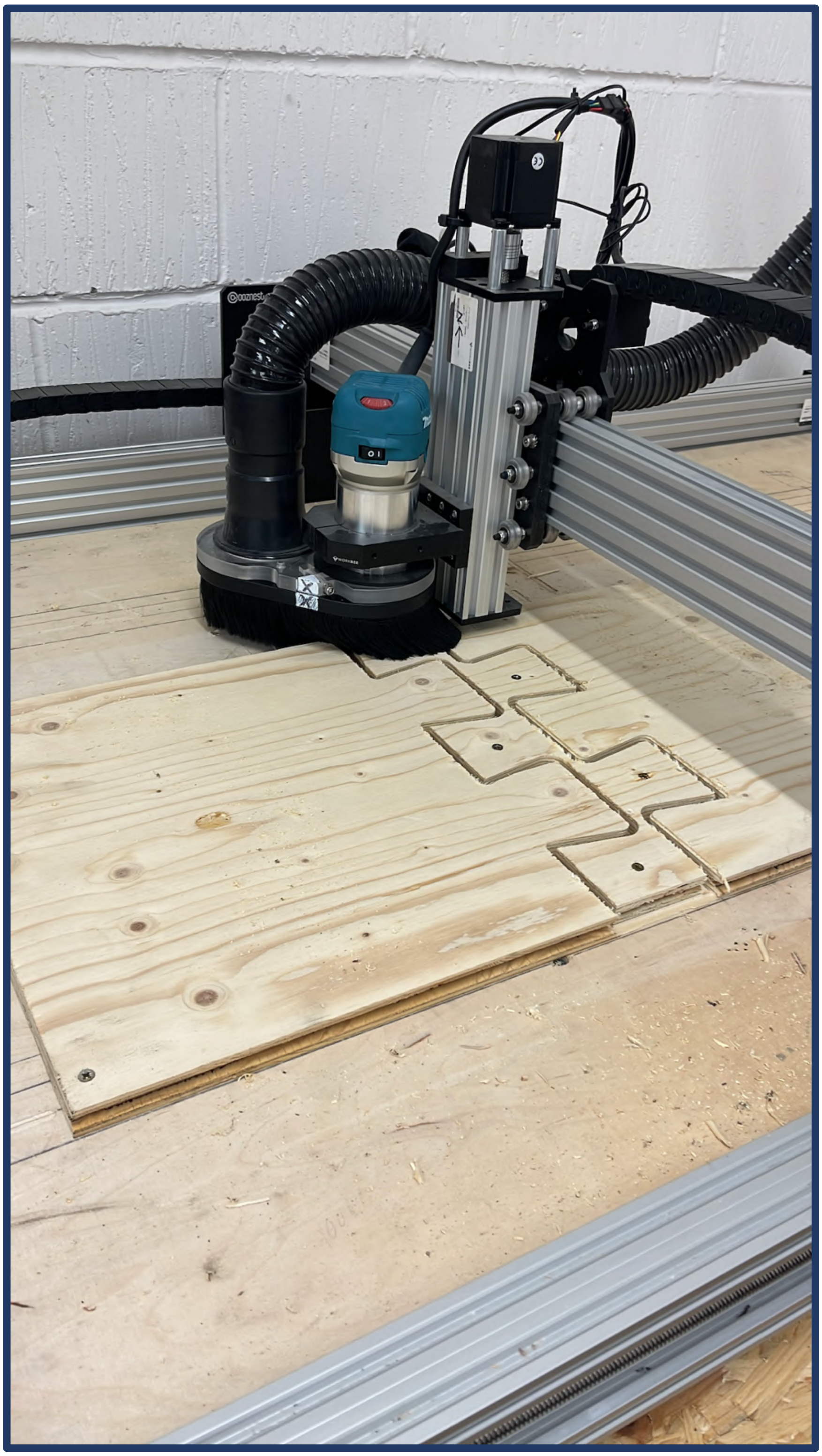

Figure 16: CNC fabrication of jigsaw joints

3.4 Tensile Testing of Jigsaw Joint

Monotonic tensile testing was then conducted with the department's Tinius Olsen Model 25ST machine. A loading rate of 3mm/minute was specified for the testing of all specimens, to maintain continuity with similar testing conducted previously using the same loading rate. Graphs of Force vs Displacement and Force vs Time were obtained for each of the 3 specimens for both material types. Testing was conducted using the following steps:

(1) Load and secure the panel into the machine using the mounting clamps.
(2) Setup and focus the DIC timelapse camera on the jigsaw joint. Set camera to rate of 1 photo per 5 seconds.
(3) Ensure Tinius Olsen software is setup for measurement of force, displacement, and time during monotonic loading of 3mm/min.
(4) Specify save location for data of individual test being conducted.
(5) Zero force (kN) and displacement (mm) readings.
(6) Start DIC timelapse photography.
(7) Safety glasses put on by all personnel present.
(8) Begin monotonic tensile loading.
(9) Maintain loading until a maximum force is reached and force value has dropped to at least half of this maximum force value.
(10) End monotonic tensile loading, saving data obtained as CSV file locally to computer hard drive.
(11) End DIC timelapse photography.
(12) Remove test specimen. Repeat for subsequent jigsaw joints specimens.

<u>Note(s)</u>: Tensile loading was continued for a period of ~ 10 minutes for the plywood tests (giving roughly 30mm of displacement) and ~ 5 minutes for the OSB tests (giving roughly 15mm of displacement). In both cases, all specimens had dropped were well beyond half of the maximum observed force. Additionally, all panels had visible failed and underwent significant plastic deformation by the end of the test period(s). Examples of the deformation observed for both material types can be seen in **Figures 18 & 19.**

4 Results

In this section the results obtained from the tensile testing will be presented. Physical observations of both during and after the testing process, along with the failure modes observed across all test samples will be also discussed, and key stiffness and slip modulus values calculated in accordance with Eurocode 5.

Having concluded testing on all 6 test samples, the data detailing the force vs displacement behaviour of the jigsaw joints was compiled using Microsoft Excel to produce Force (kN) vs Displacement (mm) graphs.

4.1 Observations during testing

Photo documentation of all specimens after the tensile testing can be seen in **Figure 17**. During the tensile testing of all 6 samples there was notable differences observed between the two materials. Across all specimens, there was a slight bias in deformation observed towards one side of the joint, which can be attributed to the accumulation of minute geometric imperfections in the specimens and the placement of the mounting clamp at either end which were centred by manual measurement and were therefore inevitably going to be somewhat imprecise, even by fraction of a millimetre. The subsequent loading was always going to accentuate any of these imperfections in the material specimen and loading setup, in turn focusing the point of maximum deformation to a certain point. This is not considered a significant impact on the scientific accuracy of the testing conducted, as the real-life application of the jigsaw joint within the WikiHouse beam does not involve perfect uniform loading along the grain direction of panels.

Figure 17: Jigsaw joint samples after failure (Left column: Plywood, Right Column: OSB)

It has been shown in testing conducted on such beams (Granello et all, 2021) that the jigsaw joint rotates under deformation in a similar manner to that seen across the specimens tested in the research for this report.

Visually, the plywood jigsaw joint specimens failed very smoothly in a ductile manner, with very little audible cracking or creaking under tension. As was expected from the literature discussing similar testing of plywood specimens (Napier, 2022), delamination of the individual veneers of the specimen occurred across the entire joint interface (see **Figure 18**), with the greatest degree of delamination located at the points of greatest displacement and deformation. The failure mode of the plywood samples can therefore be said to be delamination of the plywood veneers at the joint interface.

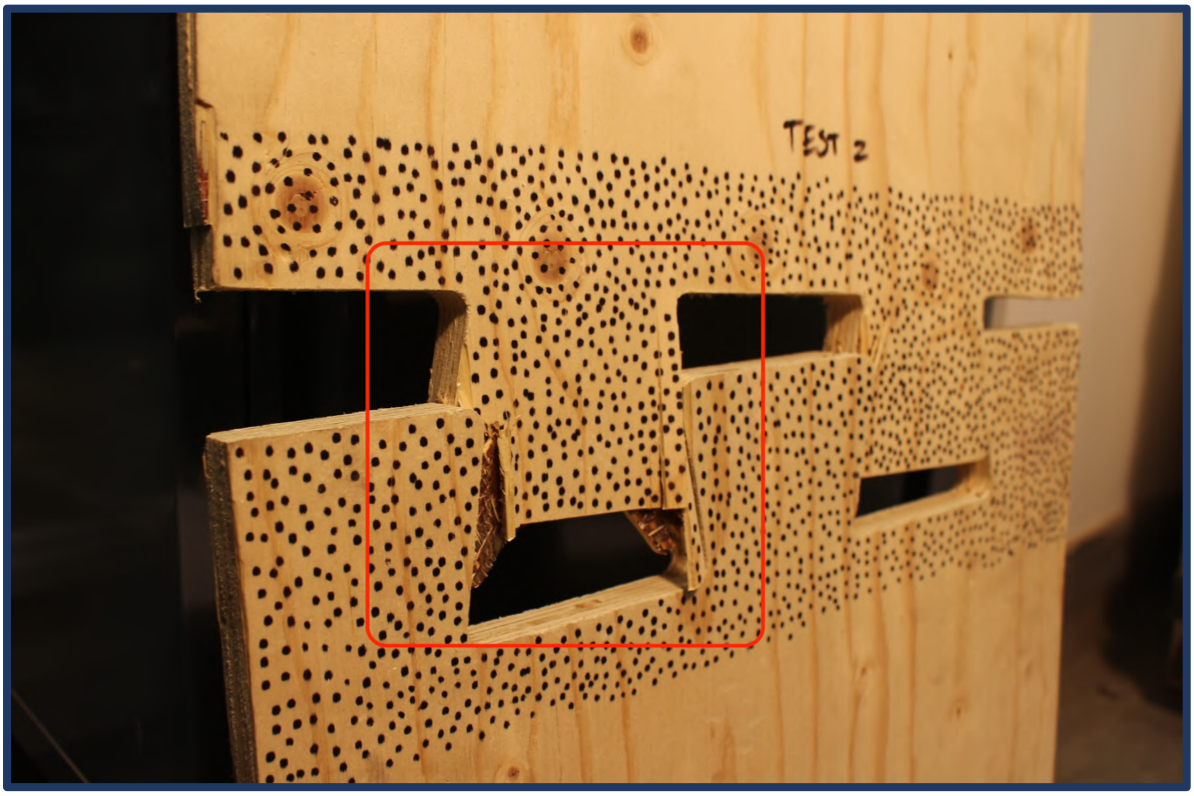

Figure 18: Plywood delamination at joint interface

The testing of the OSB specimens was audibly louder than that of the plywood, with significant cracking heard throughout the loading process. This is reflected in the noise seen in the force vs displacement graphs produced from the testing, which shows the relationship jumping around in an erratic fashion. This indicates the cracking heard was the internal composition of the OSB specimens stretching as the fibres pulled apart under loading. Similar rotational deformation to the plywood samples was observed in the testing of the OSB jigsaw joint specimens, however the failure mode seen was focused on the edge portion of the panel (**Figure 19**), with a visible crack being observed as the individual 'tooth' rotated out of position. This, along with audible erratic stretching of the fibres under tension, resulted in a more brittle failure manner than that of the plywood specimens.

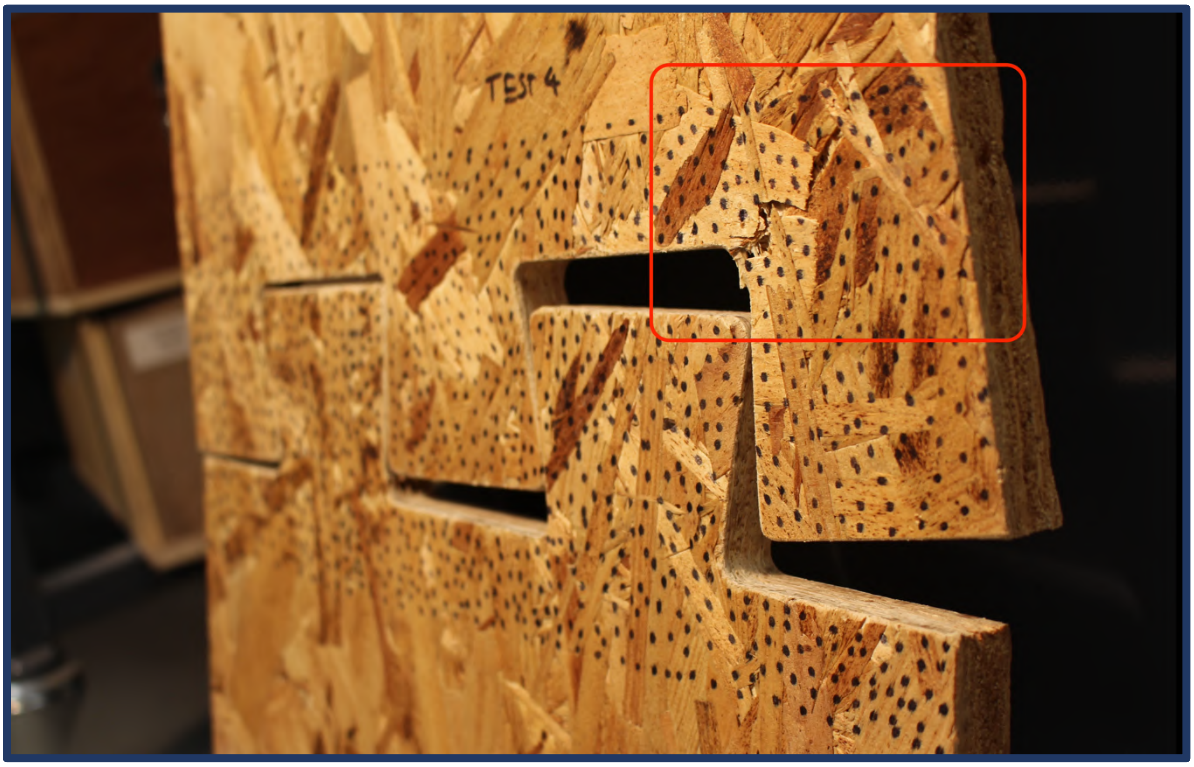

Figure 19: Crack failure observed in OSB specimens

4.2 Plywood Test Sample(s) Results

The tensile testing of the plywood jigsaw joint samples produced steady force vs displacement behaviour (**Figure 20**) for all 3 samples, with the predicted unsettled phase at the beginning of loading as the slack is taken up in the system and the bolts being used on the clamp lock into place for the remainder of the testing duration. After this phase, a period showing a linear relationship between force and displacement can be observed, reflected by the relatively straight, elastic behaviour of the graphs of all three samples immediately after the unsettled phase at the start of the loading.

The failure of the samples can be observed by the downturn of their respective graphs after the maximum force has been reached, shown in **Figure 20** as the force being applied to maintain the 3mm/min monotonic loading rate decreases. At this point the sample(s) could be considered to have failed, and continued to deform in a ductile manner as they underwent plastic deformation. The 3 plywood jigsaw joint specimens had an average maximum load (F_{max}) of 10.29kN.

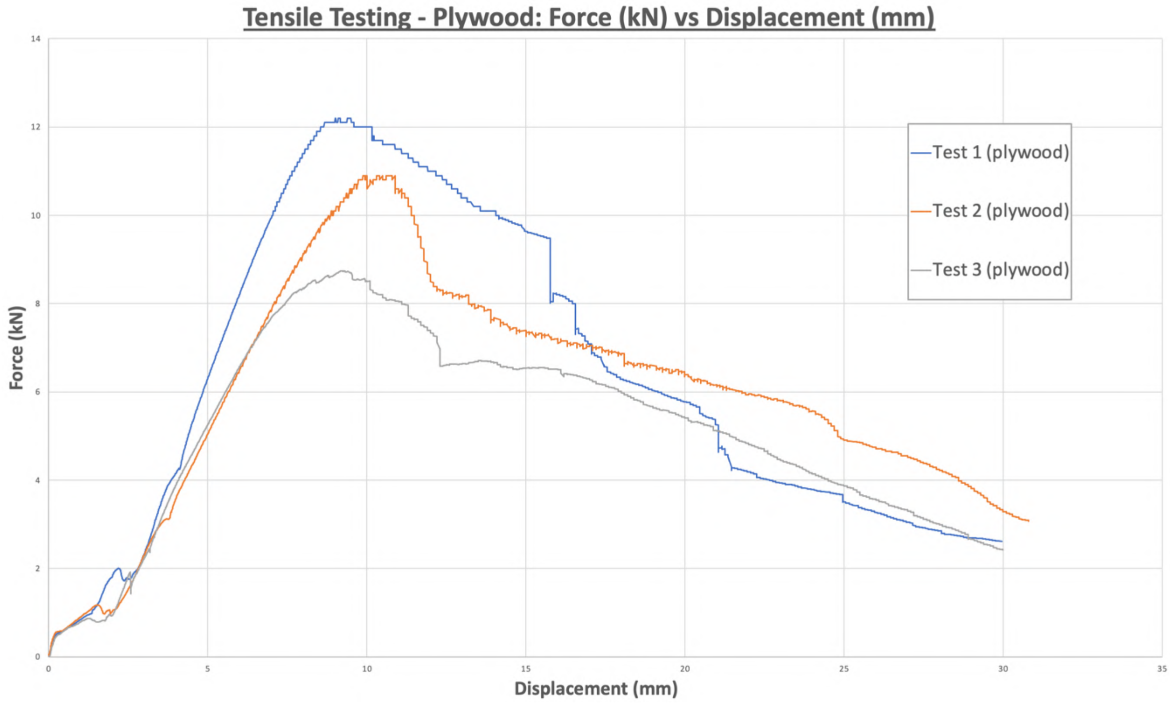

Figure 20: Force vs Displacement graph (Plywood jigsaw joints)

4.3 OSB Test Sample Results

The monotonic tensile loading of the OSB samples produced graphs similar in shape to those obtained from the plywood testing. The force vs displacement behaviour of these joints can be seen in Figure 21. The 3 OSB jigsaw joint specimens had an average maximum load (F_{max}) of 9.28kN. As discussed in the observations, the comparatively brittle behaviour of the OSB jigsaw joint under tensile loading resulted in visible noise in the force vs displacement graphs produced. Therefore, a moving average with an interval of 30 measurements was produced (**Figure 21**) to show a more readable graph and to allow for more straightforward extraction of data for analysis.

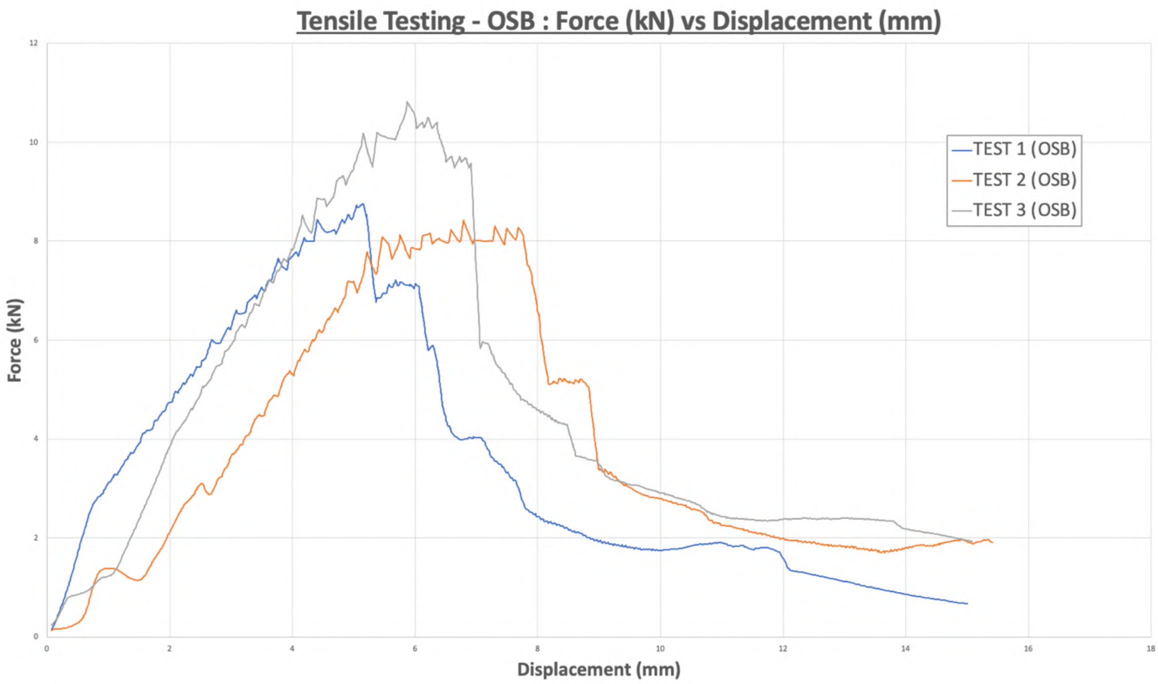

Figure 21: Force vs Displacement graph (OSB jigsaw joints)

4.3 DIC Imaging Results & Analysis

Using the timelapse photography taken during testing, the open-source DIC analysis software, and the black dot pattern drawn around the joint interface of each specimen; a visual representation of the deformation occurring in each specimen was produced. Examples of these are shown for both the plywood and the OSB tests in **Figure 22** and **Figure 23** respectively. The DIC analysis tracks the displacement of each black spot drawn onto the specimen individually. In doing so, areas of higher displacement and deformation in the joint can be identified.

Figure 22: DIC visual showing plywood jigsaw joint deformation

Inspecting **Figure 22**, the rotational deformations stated in the observations can be seen clearly. The DIC analysis uses the ParaView software and utilises a graduated colour scheme to delineate the differences in displacement across the specimens, with areas of low displacement shaded orange graduating to areas of high displacement shaded blue.

The strain (ε) experienced at a given point in the specimen can be defined as:

$$\varepsilon = \frac{\Delta \mathrm{L}}{L}$$

where $\Delta \mathrm{L}$ is the change in length, in this case displacement.

It can therefore be said that the areas of highest displacement correspond with those of highest strain. A convention of positive displacement being in the upward direction is applied, so any downward displacement tends towards red on the colour scale. This is clearly observed in the bottom diagram of **Figure 23**, where the rotational failure is conveyed by the red colouring of the right-side of the bottom panel, indicating clockwise rotation away from the starting position, and by the blue colouring of the right side of the top panel, indicating anti-clockwise rotation. The delamination of the plywood panels is not easily observed in the DIC imaging as the camera was taking pictures perpendicular to the face of the specimen. However the portion of the plywood sheared off from the upper panel during the failure under tension is visible in **Figure 22** (the strand of orange dots remaining in the right hand side gap formed by the displacement).

Overall, from the DIC imaging it clear the highest strain and tensile deformation of the plywood specimens is located at the joint interface on the right side – or more generally the side of maximum rotation - with delamination of the specimen to be expected at these points of maximum displacement.

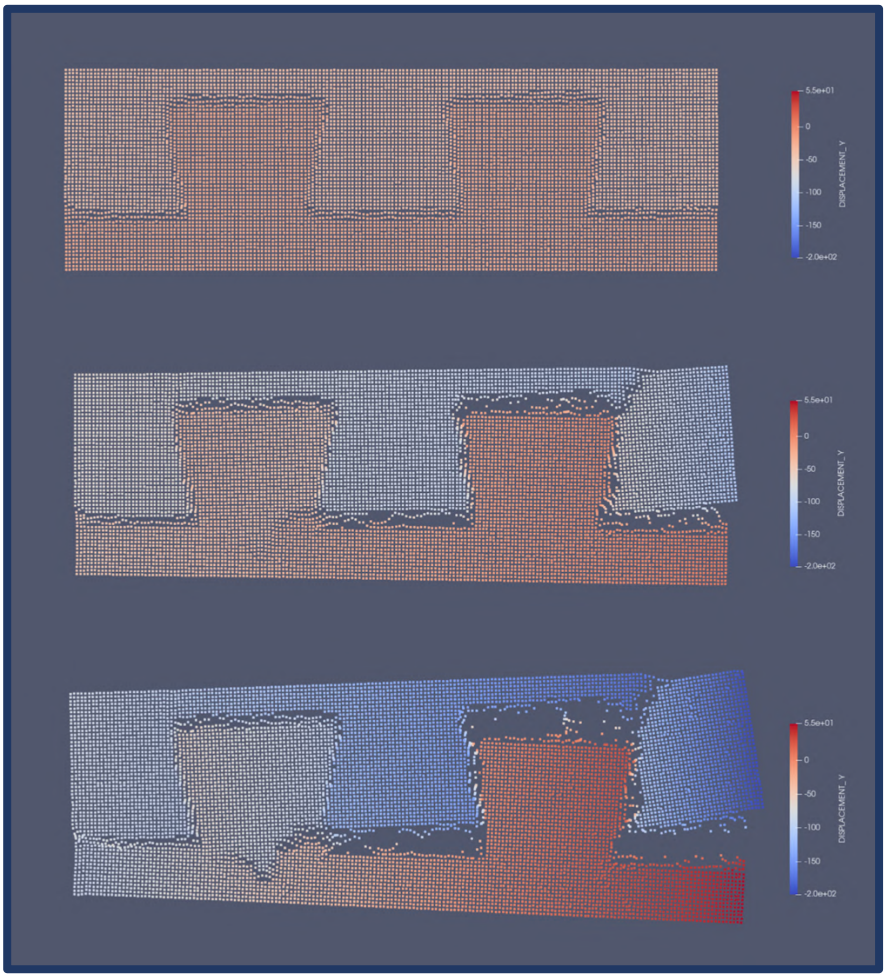

Figure 23: DIC visual showing OSB jigsaw joint deformation

The DIC imaging of the OSB jigsaw joint testing highlights the more brittle failure discussed in the observations, as the crack shown in **Figure 23** is also seen here in the top right corner of the last diagram. Additionally, a crack failure on the left side of the bottom panel is also shown in the same diagram. This was not immediately identified during the physical observation stage and provides more evidence for the brittle nature of the OSB specimens in comparison to plywood. Similar right-hand side rotation to that on the plywood imaging is also visible, as shown by the red colour profile on the bottom panel, indicating clockwise rotation downwards, and anticlockwise rotation upwards shown by the blue colour of the upper panel. This portion of the upper panel subjected to the highest rotational forces and displacement is also the portion that cracked and broke away, indicating that OSB panels will tend towards brittle failure when subjected to the tensile loading forces applied during the testing of this research.

4.4 Analysis of Results

4.4.1 Derivation of slip modulus to EN 1995:

Slip modulus and stiffness are both terms used interchangeably, and both quantify the ability of the connection to resist deformation under loading, measured in kN/mm. This is an important parameter to define for structural connections as it gives an indication of how the two constituents will interact under loading and allows for subsequent predictions of the effect this will have on the surrounding members.

Eurocode 5 (EN 1995-1-1) provides general guidance on the design of timber structures. As the design of fastener-less nature of the jigsaw joint is not specified within Eurocode 5, the following slip modulus calculations follow the guidance for dowel-type fasteners & timber connectors (Manual for the Design of timber structures to Eurocode 5), which are a similar type of connection and therefore it is reasonable to follow their available guidance.

The slip modulus can be determined for both the serviceability and ultimate limit states respectively, seen below in **Equations 1 & 2**:

SLS: $$K_u = \frac{2K_{ser}}{3} \qquad (1)$$

ULS: $$K_{ser} = \frac{\rho_m^{1.5}\, d}{23} \qquad (2)$$

Where: ρ_m = the mean density of timber

d = nominal diameter or side length of the timber connection

Metsä Wood provide specification on the weight per metre square of their 18mm thick plywood (metsägroup.com). From this value its density was derived to be **465.6 kg/m^3**. Sterling specify the density of their OSB3 panels as **640 kg/m^3** (falconpp.co.uk).

The value for d is taken in this case to be the length of the portion of the panel estimated to be a part of the connection itself (**Figure 24**), measured to be **140mm.**

Therefore, the slip moduli of the OSB and plywood specimens for both the ULS & SLS are as follows:

Plywood: K_{ser} = 1.88 kN/mm , K_u = 1.25 kN/mm

OSB: K_{ser} = 3.03 kN/mm, K_u = 2.02 kN/mm

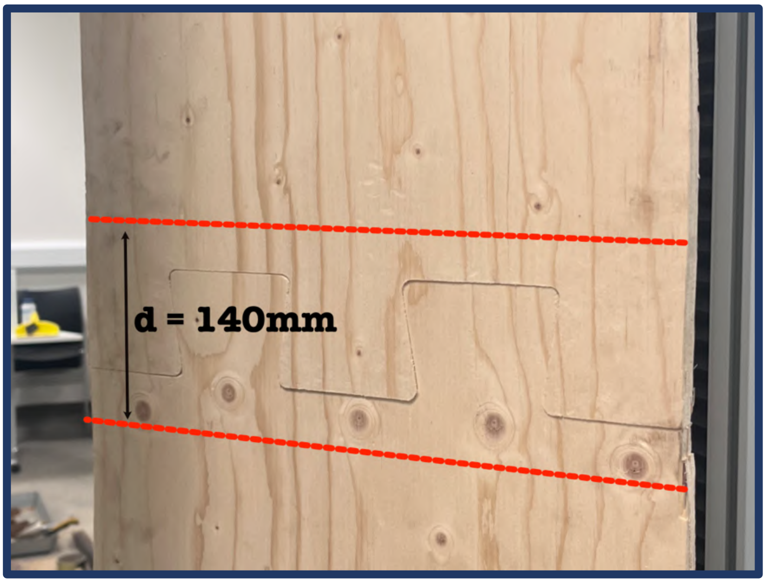

Figure 24: estimated d value used in K_{ser} calculation

4.4.1 Derivation of slip modulus to BS EN 26891

As can be seen in Section 4.4.1, the Eurocode 5 slip modulus equations do not take into account data obtained from the specific tensile testing of the jigsaw joints, as the connection length and material density are the only governing factors. Therefore BS EN 26891 will be used to calculate various values including the slip modulus, specifically using the force vs displacement data shown in Figures x & x. These values are shown for each test sample in **Table 1**:

Table 1: Slip parameters obtained in accordance with BS EN 26891

	F_{max} (kN)	v_i (mm)	$v_{i,mod}$ (mm)	v_s (mm)	k_i (kN/mm)	k_s (kN/mm)	$v_{0.8}$ (mm)	$v_{0.6}$ (mm)	$v_{0.1}$ (mm)
Plywood (Test 1)	11.23	4.34	3.69	0.65	1.035	1.22	6.88	4.15	1.57
Plywood (Test 2)	10.9	4.53	4.25	0.28	0.962	1.02	7.68	6.03	1.34
Plywood (Test 3)	8.74	3.75	3.27	0.48	0.932	1.07	6.34	4.99	1.3
OSB (Test 1)	8.76	1.26	1.27	-0.02	2.79	2.75	3.48	2.31	0.3
OSB (Test 2)	8.28	2.87	2.88	-0.01	1.15	1.15	4.69	3.79	0.71
OSB (Test 3)	10.8	2.2	1.88	0.32	1.96	2.30	4.38	3.29	0.79

Where:

v_i = *initial slip*

$v_{i,mod}$ = *modified initial slip*

v_s = *joint settlement*

k_i = *initial slip modulus*

k_s = *slip modulus*

$v_{0.8}$ = *slip at 80% of maximum force,* F_{max}

$v_{0.6}$ = *slip at 60% of maximum force,* F_{max}

$v_{0.1}$ = *slip at 10% of maximum force,* F_{max}

From the data above, the following average values for the slip moduli can be obtained:

Plywood: K_s = 1.103 kN/mm

OSB: K_s = 2.07 kN/mm

4.4.2 Elastic stiffness, K_{el}

The elastic stiffness can be defined as the secant at 40% of the failure force, F_{max} and is defined in Equation 3. It is represented by the portion of linear elastic behaviour shown in **Figures 20 & 21 and** gives an indication of the overall stiffness of the joint, i.e., its ability to resist deformation.

$$K_{el} = \frac{F_{40\%} - F_{10\%}}{d_{40\%} - d_{10\%}} \quad (3)$$

Using Equation 3, the slip modulus was calculated for each test sample and the results shown below in **Table 2**:

Table 2: Slip modulus, K_{el} calculated for each specimen

	F_{max} (kN)	$F_{40\%}$ (kN)	$F_{10\%}$ (kN)	$d_{40\%}$ (mm)	$d_{10\%}$ (mm)	K_{el} (kN/mm)
Plywood (Test 1)	11.23	4.88	1.12	4.34	1.57	1.36
Plywood (Test 2)	10.9	4.36	1.09	4.53	1.35	1.03
Plywood (Test 3)	8.74	3.496	0.874	3.75	1.81	1.35
OSB (Test 1)	8.76	3.504	0.876	1.26	0.31	2.77
OSB (Test 2)	8.28	3.312	0.828	2.87	0.71	1.15
OSB (Test 3)	10.8	4.32	1.08	2.22	0.79	2.27

From the data above, the following average values for the stiffness of the specimens can be obtained:

Plywood: K_{el} = 1.25 kN/mm

OSB: K_{el} = 2.06 kN/mm

4.4.3 Analytical model

As can be seen in **Figure 19** the comparatively brittle behaviour of the resulted in a crack failure, in comparison to the ductile deformation observed in the plywood specimens (**Figure 18**). Upon inspection of the jigsaw joint itself, it is clear under the applied uniform tensile loading that the force is split between the four locking interfaces along the entire connection length. This means that each a force of F/4 is applied in either panel at these points, shown below in **Figure 25**:

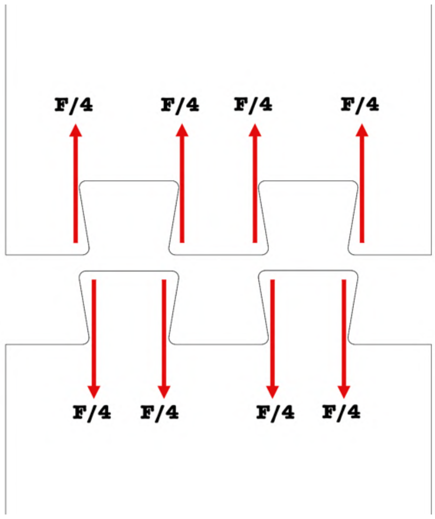

Figure 25: Distribution of applied tensile force in jigsaw joint specimen.

Examining the failure mode of the OSB specimens, the stress induced at the point of failure will be determined for both the tensile and bending moment cases. To determine the F/4 value, the average of the OSB specimens F_{max} values will be used, so: **F/4 = 2.32kN** The width of the portion that failed, as shown in **Figure 26**, is **66mm.**

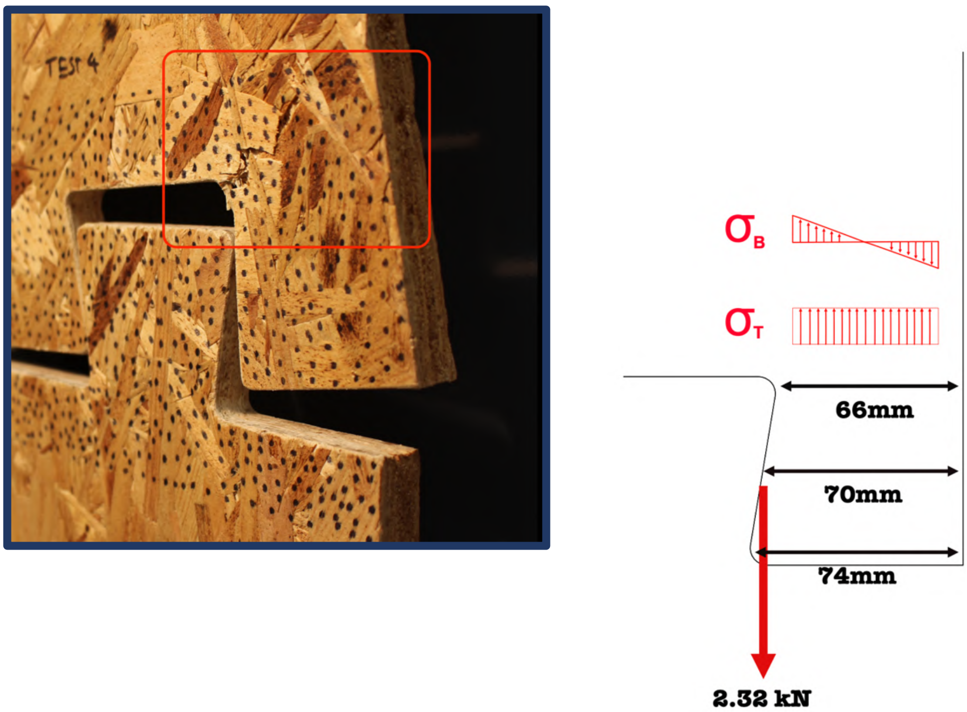

Figure 26: Bending and tensile stress experienced during failure.

The bending and tensile stresses experienced during failure can be defined by the following **Equations 4 & 5:**

$$\sigma_B = \frac{F\frac{L}{2}}{d\frac{w^2}{6}} \tag{4}$$

$$\sigma_T = \frac{F}{dw} \tag{5}$$

Where: $F =$ *the failure force applied, in this case 2.32 kN*

$L =$ *the lever arm for the bending stress, in this case the 70mm average width of the joint portion that failed*

$d =$ *the thickness of the specimen, in this case 18mm*

$w =$ *the section width of the at the point of failure, in this case 66mm*

Therefore, for the OSB specimens:

σ_B = 6.21 MPa

σ_T = 1.95 MPa

The sum of both the bending and tensile stress in the specimen gives the total stress at failure in the specimen:

$\sigma_{tot} = \sigma_B + \sigma_T$ = 8.16 MPa

5 Discussion

5.1 Strength capacity

Due to the low number of specimens tested, the level of analysis conducted on the maximum strength values was limited. It was found that the plywood specimens failed with an average maximum force of 11.29 kN, whilst the OSB specimens failed with an average of 9.28 kN.

5.1 Slip modulus / Stiffness

Using two available methods within the standardised guidance available, the slip modulus values were calculated. A summary of these results found in the analysis are shown in **Table 3** below:

Table 3: Summary of slip modulus results

	EN 1995		***BS EN 26891***	
	***K_{ser}* [kN/mm]**	***K_u* [kN/mm]**	***K_s* [kN/mm]**	***K_{el}* [kN/mm]**
Plywood	1.88	1.25	1.10	1.25
OSB	3.03	2.02	2.07	2.06

The serviceability limit state slip modulus values (K_u) calculated using the guidance within EN 1995 align roughly with the slip modulus values (K_s) calculated using BS EN 26891. The former is derived using non-experimental factors including the material density and connection length, whereas the latter utilises specific force vs displacement data obtained under tensile testing to derive a value. However, a limitation of the EN 1995 calculations is the estimation of the connection length , d used. More in depth analysis would need to be undertaken in the future to determined the exact portion of the join that can be considered to be a part of the joint itself.

Additionally, the elastic stiffness, K_{el} of the specimens was also determined. This represents the linear elastic region in the force vs displacement graphs of each material type. The average value for both plywood & OSB is shown in Table 3 also. These values closely align with the K_u & K_s values calculated using EN 1995 & BS EN 26891 respectively. Therefore, these three values of stiffness (*K_u, K_s , K_{ser}*) can be combined to form an average value for both material types:

Plywood: K = 1.20 kN/mm

OSB: K = 2.05 kN/mm

The ultimate limit state stiffness, K_{ser} calculated to EN1995 (shown in **Equation 2)** to be 1.5 times the size of the SLS slip modulus and shouldn't be included in the combined average as in the interest of conservative and safe design, the serviceability limit state should primarily be adhered to at this stage.

The values of slip modulus for both material types can be compared to similar research on timber-to-timber connections. Stitic *et al*., (2018) determined an average stiffness of 1.65 kN/mm in their research of the structural performance of MTSJ's. Granello (2023) determined an average stiffness of 1.54 kN/mm for plywood bowtie connections used in the WikiHouse Skylark design. Naper (2022) conducted tensile testing on identical bowtie joints to (D. G. Granello, n.d.-a) and obtained the exact same mean stiffness value.

The similar research discussed above was all conducted using plywood as the material of choice, and so comparing the plywood jigsaw joint stiffness value of 1.20 kN/mm determined within this report, it can be said that the plywood jigsaw joint resists deformation at a similar proportion to the other research. Comparing directly to the work of Napier (2022) and Granello (2023) - whose research was also specifically focused on WikiHouse timber connection testing – the plywood jigsaw joint performs at 22% less stiffness than that of the bowtie joint. Therefore, the plywood jigsaw joint can be said to perform similarly to the bowtie joint under tensile loading, albeit slightly less stiff.

Examining the average stiffness values obtained from the testing, the OSB specimens had a significantly higher overall stiffness than the plywood specimens, with a calculated average of 2.05 kN/mm as shown above, Comparing to similar research by Hassanieh & Valipour (2020), who obtained an average stiffness of 1.8 kN/mm in their testing of OSB and LVL joints, the OSB jigsaw joints can be said to perform comparatively to other research using the same material.

5.2 Material behaviour under loading & failure modes

The two material types showed markedly different behaviour under loading. The plywood specimens exhibited smooth deformation behaviour, shown in the force vs displacement graphs for each test, with little noise, allowing for an obvious portion of linear elastic behaviour to be observed. The OSB specimens tested showed a lot more noise on all graphs produced, resulting in moving averages of the results needing to be produced to extract clear results for analysis. Additionally, the OSB specimens were audibly cracking during testing as the material fibres showed brittle behaviour under the applied tensile load. This erratic material behaviour resulted in the noise seen in the graphs, discussed above.

The failure modes for both material types were markedly different, with the plywood joints undergoing smooth ductile failure at the joint interface via delamination of the veneers, whereas the OSB specimens showed brittle crack failure at the points of highest stress in the material, within the body of the panel itself.

This, along with the erratic force vs displacement behaviour, means it can be said that plywood exhibits more predictable, stable behaviour under loading than OSB in this scenario.

5.3 Analytical model

(Granello, 2022) shows in their research of the characteristics of Sterling OSB that the average maximum stress across 5 specimens was 8.3 MPa under tensile loading. From the calculations in Section 4.4.3, it was found the average failure stress in the OSB jigsaw joint specimens was 8.16 MPa. Therefore the analytical model of the OSB failure stress produced a value within 1.7% of the failure stress found by Granello (2022). This shows that the testing conducted produced comparable strength capacity results in the OSB specimens to separate research on the structural performance of the same material.

5.3 Limitations due to sample size

Due to the time constraints for this report, only 3 samples for each material type were manufactured and produced. This limitation introduces higher likelihood for inaccuracy within the testing results. Given a higher number of testing specimens, a more realistic average across all parts of the analysis could have been determined. A higher sample size would allow for worthwhile investigation into the distribution of the results obtained, including a standard deviation analysis to determine the dispersion of the failure results for each material.

Additionally, there is limited available literature of the testing of similar OSB timber-to-timber connections in comparison to plywood. Therefore, understanding of the general structural performance of OSB in this context would particularly benefit from additional research including a higher number of test specimens, in order to make the findings as robust and accurate as possible to be drawn upon during future research.

6 Conclusions

The jigsaw joints were successfully modelled and fabricated using available software and a CNC machine, with 3 specimens for each material type produced. The joints were then subsequently tested to failure through monotonic tensile loading. With the results obtained from the testing, and through reference to the available guidance on similar connections, stiffness values were obtained for both material types.

Through the assessment of peer-reviewed literature on similar timber-to-timber connections, comparative values of stiffness for both plywood and OSB joints were obtained. It was found that the jigsaw joint performed similarly to the research on joints using the respective material types, with the OSB joints exhibiting higher stiffness than the plywood joints. However, the plywood specimens failed at a higher average maximum force than the OSB specimens.

The behaviour of the specimens observed during testing highlighted that plywood generally fails in a ductile and predictable manner, whereas OSB specimens behaved more brittle and failed in a less ductile manner through cracking. In addition, the graphs of force against displacement obtained during the testing reflected the erratic behaviour of the OSB under loading.

Therefore, it can be said that OSB behaves in a less predictable manner than plywood in this case and is prone to brittle failure at the points of highest stress within the specimen. However, the OSB jigsaw joints on average showed a higher level of stiffness than their plywood counterparts.

OSB would benefit from further attention and research, in the case of WikiHouse and beyond. Significant research can be found within the WikiHouse library on the performance of plywood joints, and extensive research exists amongst the worldwide academic literature on the topic. However, there is noticeably less research on OSB joints used in similar connections to the jigsaw joint, limiting the ability to draw comparisons to other values from separate testing.

A recommendation for further research would be to conduct strength testing similar to that of Granello et al. (2022), using OSB as the material for the full size WikiHouse beams instead of plywood. This would obviously be useful for comparison to the plywood beam research and allow for more understanding of how the brittle behaviour of the OSB joints effects the structure as a whole.

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8 Appendices

8.1 Fusion 360 toolpath settings