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Experimental Investigation for the Quantitative Assessment of Ungraded Timber in Floor Trusses

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Abstract

Using timber in construction is a pivotal strategy for decarbonising the building industry. While timber is a renewable resource, particular attention must be directed towards optimising material efficiency. In regions such as the UK, where the forest area is low and the timber market heavily relies on imports, the supply chain is elongated, incurring additional financial costs, extra timing for procurement, and embodied carbon impacts through transportation. This study concentrates on the potential of English homegrown timber, relegated to short-term applications, to identify sustainable and material-efficient construction products within a short supply chain. The research introduces an experimental methodology to test structural applications of underutilised ungraded timber, working with small section boards to assess the performance and feasibility of floor trusses. Two alternative connection systems are proposed for the trusses: the conventional steel punch plate and the robotically manufactured finger joint. Truss samples are evaluated structurally and environmentally and comparatively benchmarked against proprietary industry standard steel web floor trusses. This analytical study sheds light on the viability of ungraded and underutilised timber for applications in construction, offering insights into potential value-added resources for the local construction and timber processing industries.

Keywords: material efficiency, robotic timber manufacturing, local resources, floor wood trusses, ungraded timber, underutilised timber

1. Introduction

In recent years, there has been a global trend towards the increased use of timber in construction, which has been identified as one of the solutions to decarbonise the building sector [1]. However, as the adoption of timber expands, questions regarding future sustainable sourcing and potential challenges arise [2], making it crucial to promote the efficient use of this resource in the construction industry [3]. In the UK, about 300,000 new residential units per year are needed [4], representing an opportunity for decarbonising the construction industry, which, according to the UK Green Building Council, is responsible for about 25% of the direct greenhouse gas emissions [5]. As timber is identified as a viable solution to address these challenges, this study aims to focus on a resource-efficient use of the wood from the tree, exploring the application of ungraded timber in long-term structural building products, looking in particular at potential pathways to add value to homegrown English resources.

In this research, ungraded timber refers to UK-harvested resources that have not been graded because their current prevalent uses in local industry, such as fencing and pallets manufacturing, do not require graded timber. Ungraded timber can be in- or out-of-grade depending on its properties, for a conservative analysis this research considers it as out-of-grade, therefore falling below the minimum strength class of C14. In England, about 77% of the forest stock is predominantly hardwoods (mainly composed of Oak, Ash, Birch, Sycamore and Beech), and there is limited use for products from these resources, with around 80% of what is harvested burned for biofuel (0.7 million tonnes in 2022) [6]. The remaining forest stock comprises softwood species, mainly Sitka Spruce and Scots Pine, from which around 1 million m^3 of sawn wood per year is produced, and only about 11% is used in construction [6]. Despite the prevailing trend of using these resources for short-lived products, prior studies have shown their potential for structural building applications such as timber framing [7] and other innovative experimental products such as stress-laminated columns from UK-harvested timber [8].

This study aligns with the recent publication of the UK's roadmap for timber in construction [9], which aims to stimulate the demand for domestic planting stock, reduce the reliance on imported timber, and foster the country's increase of forest area from the current 13.4% [10] to 16.5% by 2050. The UK has a high import-oriented wood and wood products market, being the third global importer in 2021 [11], and the internal production of about 3.1 million m^3 of sawn softwood is allocated for more than two-thirds for short-lived products.

This research is funded by the UK Government through the Forestry Commission to examine potential applications of ungraded timber in timber framing. We look at the construction of new houses and low-rise dwellings in England, where there is projected demand [12]. The National House Building Council (NHBC) reports that most of the residential typologies built in the UK are suitable for adopting timber framing. For reference, in 2023, around 105.000 new homes were built in the UK, with 75% of the typologies consisting of detached, semi-detached and terraced houses [13]. This study focuses on floor trusses, widely employed in timber framing, through designing, manufacturing and testing samples that utilise ungraded timber, assessing their structural and environmental performance. Initial conventional market standard floor trusses are analysed and are followed by two proposed alternative prototypes, one employing a novel robotic manufacturing approach and another based on a more traditional assembly technique.

2. Methodology

The research builds off earlier work from the Authors [14], and two studies are presented herein. In study one, floor truss designs were developed to look at the potential for ungraded sawn boards and tested against a proprietary system where performance characteristics were analysed. Structural assessment occurred through full-scale six-point bending tests, while environmental attributes such as the embodied carbon (EC) are investigated through a life-cycle assessment (LCA) considering stages A1-A3 following the methodology of the Institution of Structural Engineers (IStructE) [15] without accounting for the biogenic nature of wood. The second study's further development focuses on the joints of floor truss design. It looks at enhanced connections and specific material properties for locally sourced homegrown sawn boards and their implications for overall performance characteristics through additional testing and analysis. The results of both studies are converged, and the implications for both timber building design and value adding to local resources are synthesised in the closing discussion.

2.1. Study One: Design & Manufacturing of Floor Trusses

2.1.1. Truss Design

Three types of floor trusses, one proprietary and two developed (Figure 1), were manufactured with a total span length of 3m. This distance was determined by the constraints of the robotic cell used for manufacturing the floor trusses, although it falls in line with average span lengths in residential dwellings, which are found to be in the range of 2-5m. Performance assessment of the trusses considers the overall structural load-bearing capacity and environmental attributes by using LCA to determine the EC across stages A1-A3 and overall material efficiency considering the material volume. The Inventory of Carbon & Energy (ICE) database was referred to for material data [16], and the Environmental Product Declaration (EPD) from the producer for the steel webs. The applied loads considered for a residential floor were 1.5kN/m2 for live loads, 0.85kN/m2 for dead loads, and a safety factor of 1.5, resulting in 3.52 kN/m2, which for a single truss to support an area of 300x60 cm, translates to 6.34 kN in total. The deflection values recommended by Eurocode 5 [17] are span/250-350. In this case, for a 3m truss beam, the acceptable displacement results in 12-8.5mm.

A proprietary steel-web joist has been set as the benchmark (BM) for the study. Steel-web joists have top and bottom chords of softwood sawn boards 47x72mm sourced from the Scandinavian region. The boards are structurally graded TR26, a structural strength class for trusses in the UK, comparable to C27 in C-strength classes [18]. The chords are linked by diagonal steel webs connected to the timber with a series of teeth pressed into the wood, similar to steel punch plates or gang-nail plates in roof trusses. The benchmark steel-web truss EC is evaluated through an LCA.

The developed truss designs consider environmental attributes and material efficiency using the smallest possible timber cross-sections and a minimal quantity of steel in the connections. The benchmark domain (300x25cm) and load distribution spacing (60cm) were maintained to keep the same node positions for the testing. Karamba3D in the Rhino-Grasshopper environment was used to simulate structural performance, applying the smallest commercially available cross-section of 45x45mm. In this research ungraded timber is considered to be out-of-grade for a conservative analysis, therefore the structural parameters for the digital simulation were adapted by applying a reduction factor of 0.7 to sawn boards of Strength Class C16 to allow for the selection of sawn boards classified as ungraded. With the reduction factor, the material characteristic values come to Young's Modulus 560 (kN/cm2), compressive strength 1.19 (kN/cm2), tensile strength 0.59 (kN/cm2), and density 250 kg/m^3, falling below Strength Class C14.

The designed floor trusses were simulated and found to have a maximum utilisation factor of the members of 97% (compression in the midspan of the top chord), an average utilisation factor of 41% for the whole truss, and 7 mm of deflection. The joints were simulated as hinges, and no bending stresses were evaluated. We found these values acceptable for proceeding with manufacturing the designs.

2.2.2. Truss Manufacturing

The floor truss designs were manufactured by testing two types of connections: truss punch plates (PP) and finger joints (FJ). In the first case, 38x76mm truss Punch-Plates (PP) (also known as truss Gang-nail Plates, steel Nail-Plates, truss Connector Plates, etc.) are applied to tension webs and rotated parallel to the direction of the webs and the tension force, while the compression webs are glued with Polyurethane-based (PUR) wood glue. This assembly method aims at increasing the contact area of the plates with the chords while minimising the steel plate coverage to minimise the EC of the final product. In the second case, Finger-Joints (FJ), common to join short lengths of sawn boards together, are used in North America to join timber elements at an angle for the manufacturing of all-wood floor trusses [19], [20]. FJ connection has some advantages, such as the removal of steel connectors, and the possibility of using short-length sawn boards, whilst conversely, with the use of glue, in this case PUR wood glue, it does pose difficulties for disassembly and reuse.

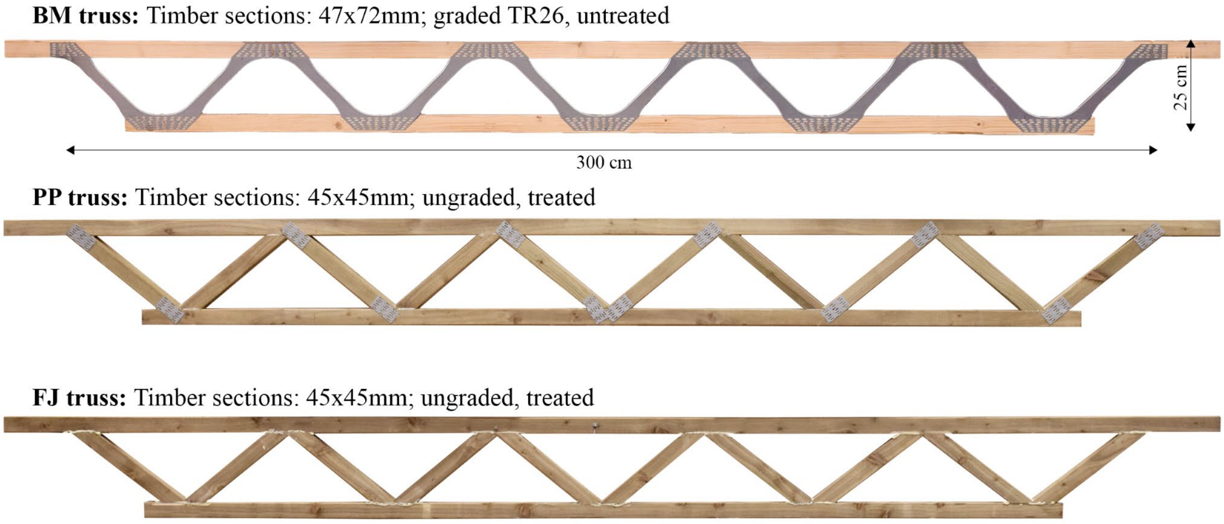

Figure 1: Elevations of the different types of trusses analysed

The manufacturing of FJ connections requires highly specialised machines and processes, particularly for the connections between webs and chords in floor trusses, which are proprietary and little information about the manufacturing is available [19], [20], [21]. In this research, a robotic manufacturing approach is introduced to test and assess the applicability of such connections in an academic laboratory environment. ABB IRB 6400R 6-axis robot equipped with an HSD spindle mounting a standard FJ router bit with eight fingers 8mm deep is used to manufacture the FJ trusses. To design the FJ connections, the joints were reverse-engineered through parametric modelling in Grasshopper, linking the geometry of the blade to the joints to generate a 3D model of the connection and be able to verify the proper fit of the timber. The robotic simulation of the manufacturing was divided into two steps with different z-axis spindle orientations and clamping layouts: one set up for the chords and one for the webs. The chords were manufactured by clamping the boards on a high-precision welding table and approaching the part with the spindle z-axis oriented horizontally and perpendicular to the board's main direction (Figure 2). The webs were produced in batches, clamped overhanging from the welding table, and the spindle z-axis was positioned vertically (Figure 2).

The structural performance is assessed via 6-point bending mechanical testing of specimens at the Structures Lab facility of the Civil Engineering Building at the University of Cambridge. The test set-up is composed of modular steel components (I-beams and posts) assembled as a portal frame to support the hydraulic actuators Instron PL160N on which two spreaders are applied to evenly distribute the load on the trusses in correspondence with the nodes at top chord. This layout is maintained the same for testing all the truss samples.

2.2. Study Two: Truss Joint Development

Following the full-scale testing of the trusses, individual tests on the joints were conducted to evaluate potential enhancements in the truss design. The timber cross-sections were adjusted from 45x45mm to 47x75mm, the type of timber was changed to locally sourced ungraded pressure-treated Corsican Pine, and British-grown C16 pressure-treated. The FJ connections were revised from 8mm to 15mm and PP connections were revised from 38x76mm to 150x63mm. A deeper 15mm router blade was implemented to manufacture the FJ connections (Figure 2).

Figure 2: Robotic setup for finger joint production. Left and centre: spindle orientation for chord manufacturing. Right: spindle orientation for web manufacturing.

These tensile tests were carried out using an Instron 5567 machine, capable of applying a maximum tensile strength of 30kN. Three types of joints were tested with 47x75 sections coded as follows: 1) FJ, Ungraded, English Corsican Pine, glued with PUR glue (FJ_47x75_U_EN); 2) PP, Ungraded, English grown Corsican Pine (PP_47x75_U_EN); 3) PP, C16 graded, UK grown softwood (PP_47x75_C16_UK). The testing process allowed us to anticipate the feasibility of further prototypes applying these parameters.

While existing literature presents studies on the performance of finger joints connecting two consecutive linear elements [22], [23] this study introduces a strategy for the robotic manufacturing and testing of angled finger joints between webs and chords in wooden trusses, assessing their ultimate tensile strength (UTS). In literature, some examples present the test of steel plates in perpendicular or parallel timber connections [24], [25] but there is limited information about testing connections at 45°. Moreover, the behaviour of the steel plates not only depends on the wood fibres and plate orientation but also on the wood species and grade [25]. Therefore, further investigation was necessary to understand how angled connections could be tested to quickly assess the feasibility of larger-scale prototypes.

The analysis focused on the joints near the supports at the top chord, where the webs are subject to the highest tensile stresses. Since the truss and the load applied are symmetrical, the first and the last webs are subject to the highest tensile stresses. The analysis considers the reaction force at the support (R_A) as half of the load applied to the truss, transposed to the adjacent web as tensile force $F_{T,w} = R_A/\cos(\alpha)$, where α is the angle between the vertical reaction and the web (Figure 3). The tests allowed us to assess the ultimate tensile force F_T, which applies to the three types of the analysed nodes.

3. Results

The structural performance assessments for both the truss and joint studies were done at the Department of Engineering, University of Cambridge. In this section, the results from both studies are analysed and presented.

3.1. Trusses test results

Three benchmark trusses (BM) were tested, and the average performance was consistent. The maximum ultimate load was approximately 14.8 kN (Figure 3), and 17mm displacement at the midspan. Regarding the workload for residential floors, we considered 3.5 kN/m^{2,} which translates to 6.3 kN per truss. The displacement observed is around 6-7 mm, which is in line with the prescription of Eurocode 5 [17]. The failure mode observed was ductile in two of the examples, given by the steel webs bending, while in the third a longitudinal splitting of fibres at one of the two supports occurred.

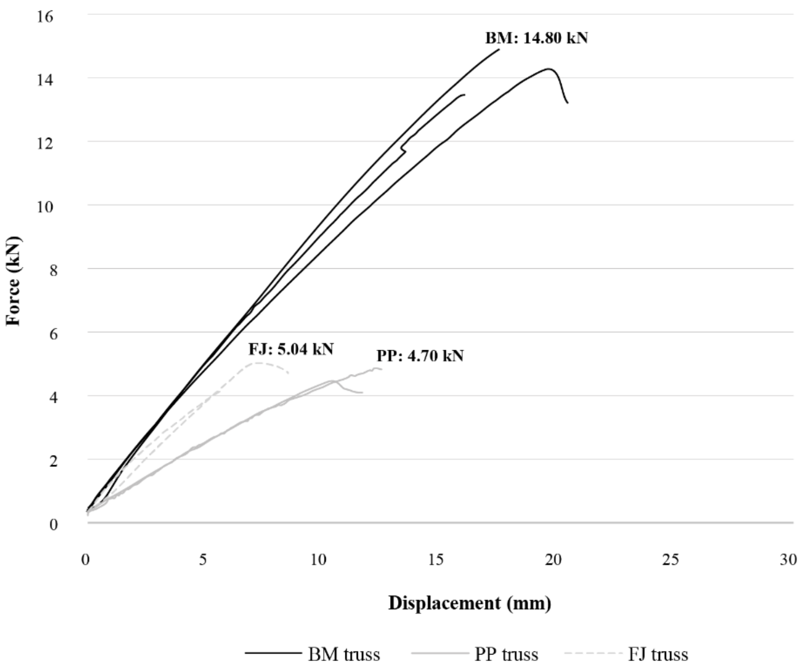

Figure 3: Load-Displacement graph plotting the results of the six-point-bending tests of the BM, PP and FJ trusses. The BM truss is represented in black, and the PP and FJ are in greyscale proportional to the reduced EC compared to the BM truss.

The two PP trusses performed the worst; the principal failure mode observed was the plate detachment at the top chord for the connections near the supports; the ultimate load reached was about 4.7kN, and a deflection of 12mm, below the design values. The two FJ trusses performed slightly better and were demonstrated to be stiffer; the ultimate load reached approximately 5.04 kN and 6 mm of deflection, closer to the design value. The failure occurred near the supports because of the higher tensile stresses in the first and last webs, causing the detachment of the finger-jointed connections (Figure 4). The failure modes observed highlighted that the connections needed further studies. In fact, in the PP truss, the area of the plate attached to the chord is 14 cm^2, while on the BM truss, the area of the plate in contact with the chord is almost double, 29 cm^2. Similarly, the FJ truss with a finger depth of 8mm did not provide enough glueing surface, as it was also highlighted by the failure modes observed where the fingers were detaching.

Figure 4: Failure points occurred on the different samples: left BM truss, middle FJ truss, right the PP truss.

3.2. Joints test results

The results obtained in the first study of the floor trusses were taken as a reference for improving the design of the subsequent experiments for the study of the joints. Given the total ultimate load applied to the best-performing steel-web trusses of 14.8 kN, the two vertical reactions at the supports near the failure points would result in R_A=7.4 kN. Consequently, the tensile force at the adjacent diagonal web is $F_{T,w}=R_A/\cos(\alpha)$=10.47kN, for α=45° (Figure 5). Hence, for an improved performance of the prototypes, the tensile strength of the joints, along the direction of the web, had to reach the threshold of $F_{T,w}$=10.47kN.

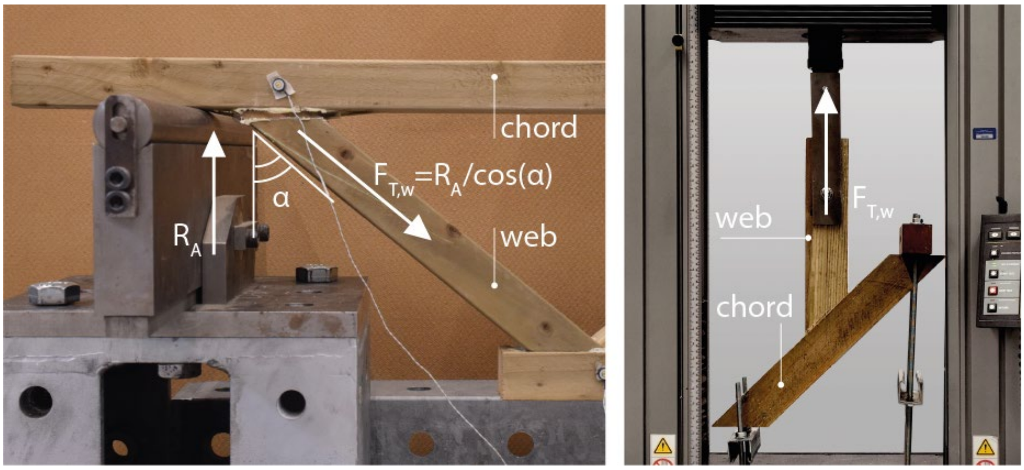

Figure 5: Diagram of the forces at the failure point (left) and tensile test setup (right) prepared accordingly.

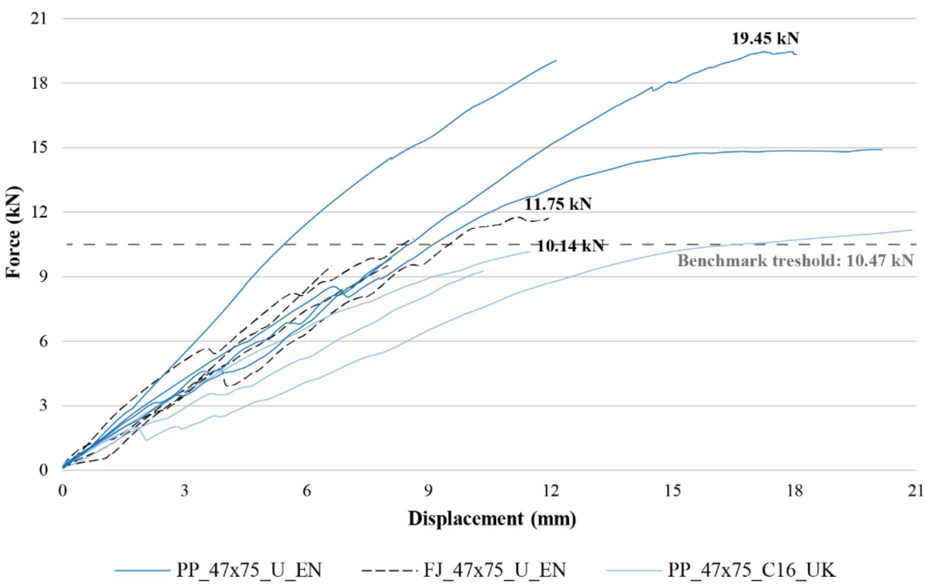

Figure 6: Load-Displacement graph of the tension tests performed on the joints. The continuous lines indicate PP connections and the dashed lines indicate FJ connections.

All three types of joint samples tested showed a UTS close to or above the set threshold; in particular, the worst were the samples coded as PP_47x75_C16_UK, with PP connections applied on 47x75 mm softwood C16 graded and grown in the UK, that reached an $F_{T,w}$=10.14 kN. In this case, the timber failed before the plate, with no plate detachment observed, and failure occurred at the clamping points of the test setup rather than at the joint between the web and chord.

The strongest performance was achieved by PP_47x75_U_EN, which consists of sections 47x75 mm of locally sourced ungraded English Corsican Pine. The UTS was $F_{T,w}$=19.45 kN in the web direction, and the failure occurred because the timber broke either at the joint web/chord or at the lock points of the test setup, with no plate detachment observed.

The finger-jointed connections FJ_47x75_U_EN, also consisting of sections 47x75mm of locally sourced ungraded English Corsican Pine, reached an ultimate tension $F_{T,w}$=11.75 kN, with failure observed regarding the tear up of the wood fibres.

3.3. Environmental performance assessment

The environmental performance of the PP and FJ trusses is assessed and compared against the BM truss expressed in the percentage of difference of the EC (kgCO_2eq) and the volume of timber (m^3). For a 3m long BM truss, the total EC results in 9.71 kgCO_2eq for the stages A1-A3 of the LCA without accounting for the biogenic carbon of the wood. The timber volume for the BM truss accounts only for the top and bottom chords, resulting in a relatively low value since the webs are not made with timber and consist of 0.0203 m^3. When comparing this with the developed PP and FJ trusses, it's important to note that for a steel-web truss, like the BM, the chords are typically constructed from high-strength class timber, such as TR26 grade. Consequently, the section size when using lower-grade timber would be larger. The environmental performance is evaluated for both the manufactured PP and FJ trusses, utilising 45x45mm sections of ungraded softwood, and for the trusses that would incorporate the examined joints, with 47x75 mm sections and larger PP and FJ connections. The EC values for the PP and FJ truss 45x45mm are 65% and 80% lower, respectively, with timber volume being close to the BM truss. For the 47x75mm sections, the EC for the PP and FJ trusses are about 13% and 67% lower, respectively, and the volume is approximately 58% more than the BM truss since larger sections of timber would be used in the webs as well (Figure 7).

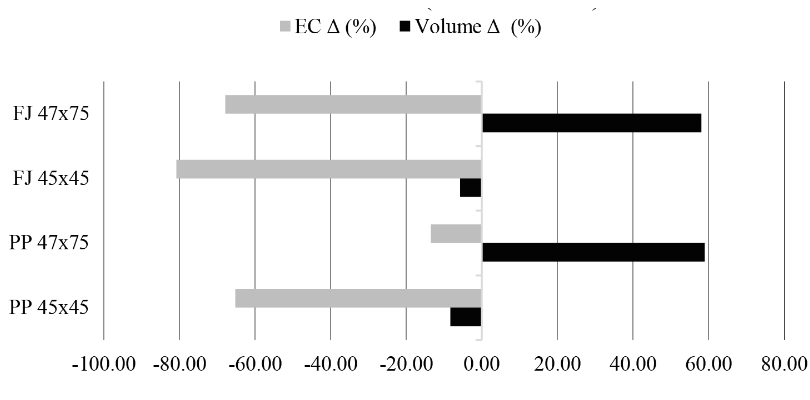

Figure 7: Comparative environmental analysis of the manufactured trusses with 45x45mm sections and 47x75mm for both PP and FJ connections. EC values are measured on LCA stages A1-A3.

4. Discussion and conclusions

This research presented a method to assess the application of ungraded timber in structural products such as floor trusses, evaluating their environmental and structural performance compared to the industry benchmark, steel-web floor trusses. The study was conducted in two parts; in the first part, floor trusses were designed, manufactured and tested to assess their structural performance and understand the overall behaviour; in the second part, a closer analysis of the joints typology was conducted through tensile testing varying some parameters. The trusses were developed and manufactured by experimenting with two types of connections between webs and chords: steel punch-plate (PP) and finger joints (FJ).

In the first study, 45x45mm ungraded timber sections were used. The PP connections consisted of 38x76mm steel plates applied to join only webs in tension to minimise the use of steel and oriented parallel to the main axis of the webs to maximise the contact area with the wood. The FJ connections consisted of 8mm deep fingers robotically manufactured. Mechanical tests revealed that PP and FJ truss samples had about one-third of the ultimate load capacity of the benchmark.

The second study involved small-scale tensile tests on the joints, experimenting with larger timber sections (47x75mm), steel plates (150x63mm), and deeper fingers (15mm) to enhance structural performance. For PP connections, using 47x75mm ungraded English timber and larger steel plates increased the contact area to 47 cm^2, resulting in a UTS almost double compared to the benchmark. For FJ connections, increasing finger size to 15 mm on the same sections of ungraded English timber improved the UTS by about 10% better than the benchmark. These changes can enhance structural performance in new truss designs using ungraded English timber, potentially surpassing the benchmark.

Trusses with 45x45mm timber sections showed 65-80% lower environmental impact and similar timber volume than BM trusses. Adding analysed joints increases timber volume by 58% compared to the benchmark, with EC savings ranging from 13-67%.

In conclusion, while the study found that using ungraded timber in small sections of 45x45mm may not be optimal for substituting the BM trusses, further examination of larger sections and enhanced connections suggests the potential viability for utilising ungraded English timber in these products. Additional analysis and testing on full-scale specimens incorporating the enhanced PP and FJ joints and homegrown wood are necessary to validate this potential.

Adding value to homegrown wood could represent an opportunity for the local timber industry. It contributes to extending the overall lifespan of this material and the carbon storage capacity. In addition, as the UK is one of the largest wood and wood-based products importers in Europe, a shift in the application of homegrown timber can not only catalyse local forestry practices, fostering a more robust and dependable supply chain, but it could also yield economic advantages to the internal timber industry.

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