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DEVELOPMENT OF ADHESIVE FREE ENGINEERED WOOD PRODUCTS – TOWARDS ADHESIVE FREE TIMBER BUILDINGS

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ABSTRACT: Over 5 million m^3 of engineered wood products (EWPs) are produced in the EU annually and the market is rising. However, EWPs have a high degree of petrochemical use in their manufacturing. In addition, throughout the life span of these EWP products from manufacture to disposal, they emit formaldehyde and other volatile organic compounds (VOCs), which makes recycling very difficult. In this paper, preliminary experimental work on Adhesive Free Engineered Wood Products (AFEWPs) is presented, which covers (1) manufacture of compressed wood (CW) dowels, (2) fabrication of adhesive free laminated beams and connections, (3) structural testing of AFEWPs. Also, the finite element models are being developed to assist designing of AFEWPs in terms of size of compressed wood dowel and dowel patterns in order to maximise their stiffness and load carrying capacities.

KEYWORDS: Compressed wood fastener, adhesive free laminated beam, adhesive free timber connection, finite element

1 INTRODUCTION

There are more than 5 million m^3 of Engineered Wood Products (EWPs) produced in the EU annually and the market is growing, as EWPs provide a 'green' alternative to steel and concrete in construction. However, EWPs have a higher degree of chemical use incorporated in their manufacturing process compared to standard sawn timber. This chemical use mainly involves the adhesives being used to bond the wood laminates and finger joints in order to make laminations of the required length. In general, the production of one cubic meter of glulam timber requires 5 kg of phenol-resorcinol-formaldehyde (PRF) and 1 kg of melamine-urea formaldehyde (MUF) [1, 2]. These adhesives tend to be organic adhesives that use aldehydes in their base chains. Throughout the extended life span of these products from manufacture to disposal, they emit formaldehyde and other volatile organic compounds (VOCs) [3]. The manufacturing process for those products is also complicated with attributing to a higher embodied energy count, 10.75 MJ/kg for EWPs as opposed to 7.60 MJ/kg for sawn timber [2]. Certain air emissions contribute to global warming, acid rain, and smog formation throughout the life cycle of a current engineered wood product. Recycling is generally difficult for such wood products (structures) due to their composition (adhesives and metallic fasteners) and the end of life is typically disposal in landfill sites, which is considered an emission to land. In addition, structural EWPs and sawn timber elements are usually connected by steel plates or dowels and the manufacture of these traditional fasteners uses large amounts of energy. This in turn produces significant emissions of CO_2.

In order to tackle the above problems, an alternative and more environmentally friendly method of connecting wood laminates and joining structural members would be to use compressed wood (CW) dowels and fasteners. This form of connection and joioning systems helps to deliver low impact buildings whilst potentially increasing the market for thousands of hectares of sustainably managed farmgrown timber. There are many other advantages which include: reductions in VOCs during manufacturing and CO_2; easy to reuse, recover and recycle; improved fire resistance due to CW dowels being hidden inside wood; improved joint tightness (due to moisture-dependent swelling and spring-back of compressed wood). Therefore, a consortium with members from six European countries was formed to develop adhesive free engineered wood products (AFEWPs) and connections throughout a joint project supported by the Interreg North-West Europe (NWE) Programme. The aim is to achieve novel use of natural fibre building materials and to tackle sustainability of the fundamental building materials to help deliver sustainable future built infrastructures. The outcomes of the research work will help re-naturing cities with the above benefits and significant added-value to tackle

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various societal challenges such as climate change, air pollution on human health and resource management.

In the early stage of the study, compressed wood blocks were used to pre-stress glulam beams to generate useful precamber [4]. Figure 1 shows such beams pre-stressed. A series of material tests on compressed wood with various compressive ratios were also carried out to characterise the material and to provide basic material parameters for the finite element modelling [5]. Those tests include moisture-dependent swelling, compression and shear in three main directions. The finite element analyses were further undertaken to simulate the precamber and subsequent destructive tests of the pre-stressed glulam beams [6]. Some feasibility studies were also carried out at the University of Liverpool. Figure 2 shows the beam and CLT panel connected by compressed wood dowels.

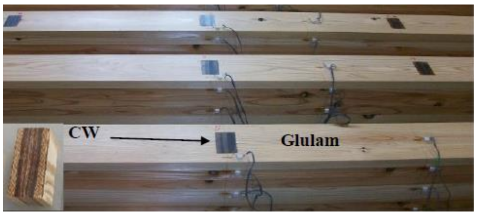


Figure 1: *Glulam beams pre-stresses by compressed wood*

Figure 2: *Small beam and CLT panels connected by compressed wood dowels*

In this paper, some preliminary work will be presented, which includes compressed wood dowel manufacturing, fabricating and testing of CW dowel connected short beam, beam-beam connection, double-shear joints, as well as the finite element modelling work.

2 EXPERIMENTAL WORK

2.1 Manufacturing CW dowels

The manufacturing of the compressed wood dowels was carried out in three partners, i.e. University of Liverpool, University of Loraine and Technical University of Dresden. Here, only the manufacturing work carried out in the Structures Laboratory at the University of Liverpool is described. The main processing equipment items used included a 200-tonne, 400^{o}C Hydraulic Press, belt linishing machine, band saw and in-house designed aluminium moulds. The aluminium moulds are illustrated in Figure 1, together with CW dowels after press.

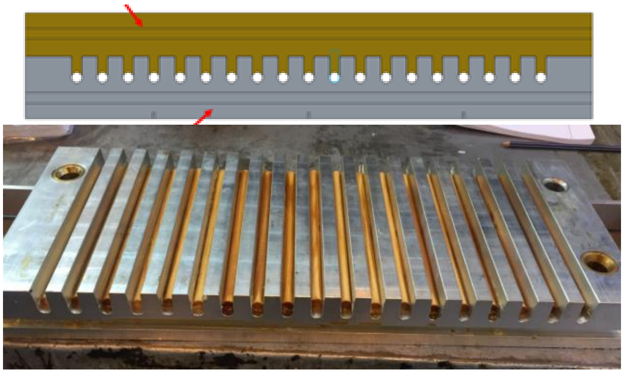


Figure 1. The moulds and CW dowels produced.

C24 Scots Pine (Pinus Sylvestris) was the species used and was supplied by Buckland Timber, Devon, UK. The timber had been visually graded and kiln dried to moisture contents of 10 – 15 %. Clear timber (i.e. without knots and other visible defects) were used for the production of the compressed wood dowels, and the mass densities of the timber blocks ranged from about 400 – 700 kg/m^3. Hence, the timber blocks were initially sorted according to their mass densities into three different groups: 400 – 500 kg/m^3, 500 – 600 kg/m^3 and 600 – 700 kg/m^3, and are referred to as Group A, B and C, respectively. Thereafter, samples from the three groups were cut using a band saw into timber sections with the corresponding dimensions shown in Table 1, with the aim of making 10 mm dowels.

Table 1: Groups, densities and dimensions of the uncompressed timber sections

Group	Density [kg/m^3]	Dimensions of timber sections [Height x Width x Length] [mm]
A	400 – 500	28 x 9 x 200
B	500 – 600	22 x 9 x 200
C	600 – 700	18 x 9 x 200

The densities of the compressed wood dowels are ranged from 1200 – 1500 kg/m^3 and the 10 mm dowels have a tolerance of ± 0.5 mm.

2.2 Preliminary testing the CW connected beam

The fabrication of the adhesive free laminated timber (AFLT) beams was carried out in the Structures Laboratory at the University of Liverpool. C24 Scots Pine (Pinus Sylvestris) was used as the lamina and was supplied by Buckland Timber, Devon, UK. The timber had been visually graded and kiln dried to moisture contents of 10 – 15 %.

The AFLT beam comprised of only three laminae in the early stage of the study, with each lamina (or layer) in dimensions of 70 mm x 21.5 mm x 1350 mm. The locations of the holes were pre-marked on the top lamina before G-clamps were used to hold the three laminae together. The clamped laminae were also clamped to a drilling machine before drilling, as shown in Figure 3. The holes in the AFLT beam are all 10 mm in diameter to produce a tight fit with the 10 mm compressed wood dowels. The spacing between the dowels along the longitudinal and transverse directions of the beam is 50 mm and 23 mm, respectively.

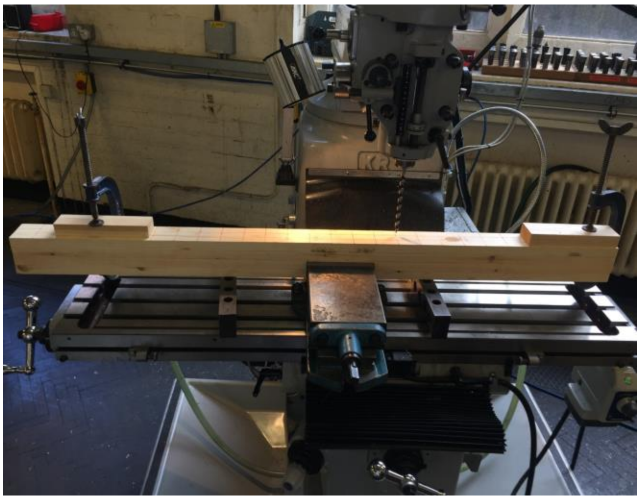


Figure 3. Image showing the AFLT beam setup for drilling

The compressed wood dowels had an average density of 1300 kg/m^3 and were chamfered, Figure 4, before being hammered into the laminae. In addition, after drilling the holes, the sawdust in the holes was removed with the use of a compressed air blow gun.

Figure 4. The chamfered compressed wood dowels before insertion into the AFLT beam

The AFLT beam has two rows of dowels. The dowels were evenly distributed, and the total number of dowels used for the AFLT beam was 54. The dimensions of the AFLT beam were 70 mm x 64.5 mm x 1350 mm. Figure 5 shows a fabricated AFLT beam.

Figure 5. A fabricated adhesive free laminated timber beam

The AFLT beam fabricated was left for seven days before it was tested to ensure a tight fit between the compressed wood dowels and the timber laminae as a result of the moisture dependent swelling and spring back of the compressed wood dowels. Four-point bending tests were carried out on the AFLT beam and a glue-laminated (glulam) beam with the similar dimensions in accordance with BS EN 408 (2010). The glulam beam was also manufactured and supplied by Buckland Timber, Devon, UK. C24 Scots Pine (Pinus Sylvestris) was also used as the timber laminae for the glulam.

The four-point bending test records the applied loads and central deflection of the beam, from which the initial stiffness and failure load can be determined. Figure 6 shows the sketches with dimensions of the four-point bending test setup. The beams were simply supported on steel rollers, and a laser displacement sensor was used to measure the vertical deflection of the beams under loading. The four-point bending setup on the test rig is shown in Figure 7.

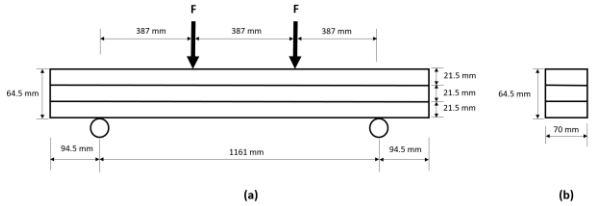


Figure6. Sketches of the four-point bending test setup: (a) Side-view and (b) Cross-section view

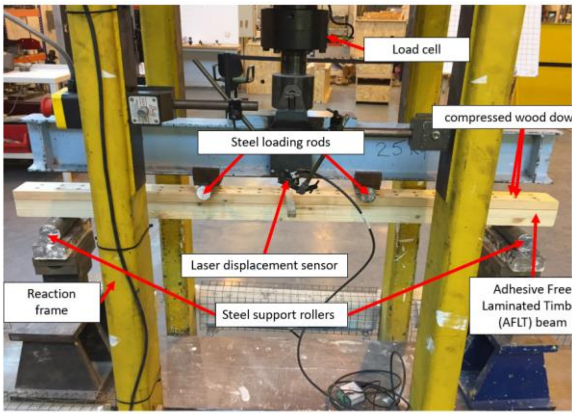


Figure 7. Test setup for four-point bending

Figure 8 shows the failed beam. As can be seen, the AFLT beam was failed prematurely due to a big knot at the tension extreme fibre. As the result, the failure load of the AFLT beam is only 6 kN, which is less than half of its glulam counterpart (14 kN). It is worth pointing out that the glulam beam did not have the defect shown in Figure 8.

Figure 8. The failed beam.

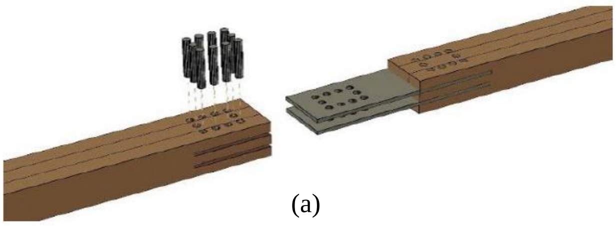
This preliminary test only covers a beam with three laminates and a short span. AFLT beams with 7 laminates and 3.15 m span are being prepared.

2.3 The beam-beam connection

National University of Ireland Galway is responsible for beam-beam and beam-column connections using compressed wood dowels and plates. At this point, a total of four test specimens were produced comprising two replications of a steel fastened connection system and compressed wood fastened connection system. The dimension lumber used in this study was Douglas Fir (*Pseudotsuga menziesii*). There were eight glulam beams manufactured. Each beam is consisted three laminates of 1575 mm long and 52.5 mm thick. The cross-section area of each beam is 115 mm x 157.5 mm.

Each glulam beam in the test programme was routed at one end to accommodate two compressed wood and steel plates with 10 mm thickness. The routed slot was 11 mm in thickness. The S275 grade steel plates dimensions were 480 x 152 mm and the compressed wood plates dimension were 480 x 157.5 mm.

The fabrication of the beam-beam spliced connection system can be seen in Figure 9. The step by step schematic image of spliced beam-beam connection can be seen in Figure 2a. In Figure 1b, the beams are fixed in position using clamps while the CW plates are positioned prior to dowel insertion. Once aligned, the dowels were driven into position to form the connection. In Figure 2c, the completed timber-steel connection and the timber-timber connection systems can be seen.



(a)

(b)

(c)

Figure 9. Spliced connection system: (a) 3D view of spliced beam-beam connection, (b) fabrication processes, (c) completed steel and compressed wood connections.

The connections were subjected to 4-point bending with the same loading and boundary conditions. The peak average loads for steel and compressed wood fastener connections are 10.8 kN and 8.7 kN, respectively. However, the CW dowel and plate based connection shows more ductile failure. This is an encouraging outcome.

2.4 Double shear joint and laminated beam connected by CW fastener

Up to date, University of Loraine has undertaken experimental work on manufacturing compressed wood fasteners and small compressed wood beam, fabricating double shear joints using CW dowel for push-out test and three laminate beam connected by CW dowels for relaxation test. Figure 10 shows a 3-laminate beam fastened by compressed wood dowels under relaxation testing.

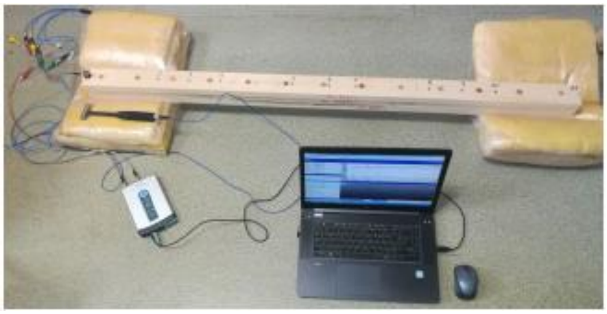


Figure 10. Testing on CW dowel connected beam under free boundary conditions.

A push-out test is shown in Figure 11 to investigate shear and embedding behaviour of compressed wood dowel against soft wood.

Figure 11. Push-out shear test under monotonic loading.

In comparison to other traditional timber structures, the adhesive free structural elements under developing must be designed to meet the requirements of the current European timber building standards and more specifically the safety and serviceability requirements. This is regarded as a crucial argument that will have a decisive impact on industrial adoption of such structural elements.

To this end, the following studies are undertaken:

(1) Vibration serviceability performance: adhesive free CLT floors must be designed to meet the Eurocode 5 requirements with respect to the vibration that can annoy human beings;

(2) Ductility and energy dissipation capacity: CW dowel connections must be designed to meet the Eurocode 5 regarding the stiffness and strength characteristics as well as the Eurocode 8 ductility classes. This is crucial for the assessment of the seismic performance. Thus monotonic and cyclic tests are to be undertaken on connections made with CW dowels;

(3) Fire performance: because fire represents a threat to life, property and the environment, there is a need to control its impact in such a way that life is fully protected, and damage to property and the environment are minimized. Fire safety is the means by which infrastructures are designed in a manner that these goals are achieved. In this context, experimental tests are undertaken to access both the physico-thermal properties of CW dowels and relative fire performance of timber connections made with CW dowels.

2.5 Experimental work on shape memory and dynamic response of compressed wood

In the project "Towards Adhesive Free Timber Buildings (AFTB)", Technical University of Dresden has been manufacturing of compressed wood dowels and undertaking a series of experimental work to cover shape memory, dynamic response, tension, compression, bending and double shear tests. Figure 12 shows the manufacturing of compressed wood plate using hot press machine. Once the CW plate was produced, it was turned into CW dowels.

Figure 12. A wood plate is in pressing stage.

A compressed wood dowel under 3-point bending is shown in Figure 13, which can be used to characterise flexural behaviour of the CW dowel and may also provide results for validating numerical models developed later on.

Figure 13. A compressed wood dowel under 3-point bending.

As the compressed wood fastener is the only connection mechanism to integrate wood laminates together to make beams, panels and columns, a lot of push-out tests were planned. This is to gain insight into failure mechanisms of CW dowel under shear. Figure 14 shows the assembled specimens.

Figure 14. Specimens for push-out tests.

Moreover, a large scale samples will be designed and tested, with a CW connected panel in dimensions of approximately 600mm (width) x 4000mm (length). This kind of panel will be likely used for a demonstrator in Germany.

3. Numerical modelling

Within the AFTB project, numerical simulation will contribute to design and manufacture damage tolerant adhesive free engineered wood products (AFEWPs). This implies code development and finite element implementation of the models to describe the wood behaviour subjected to hydro-mechanical loading. Here, a rheological model describing the hydro-mechanical behaviour of wood material is implemented using the finite element method, including effects of swelling/ shrinkage (hygro-expansion), mechano-sorption and the multi-yield surface plasticity. Wood presents a brittle behaviour in tension and shear, while it shows a plasticity and damage in compressive loading, especially in embedding situation. To take this behaviour into account the local stresses within the material are split to tensile and compressive stress component tensors. Then a damage model that considers the tensile and shear brittle failure and the compressive ductile damage are introduced.

The preliminary modelling to test the code on a CW dowel connected beam under 4-point bending is shown in Figure 15. Here, the bending stress distribution is displayed.

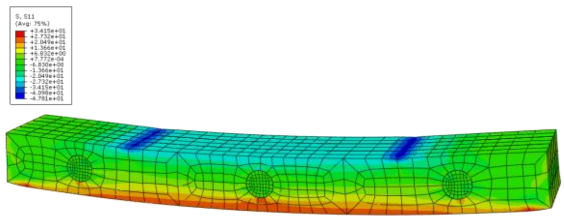


Figure 15. Bending stress distributions on a CW dowel connected beam.

Towards structural optimisation of AFEWPs, a user friendly interface is being developed for building adhesive free engineering wood structures where the number of laminates, number of dowels and position of dowels may be used as optimisation parameters.

4. Work in the near future

There are two types of adhesive free beams to be tested, i.e. one is 3 laminated (70 x 67.5 x 1350 mm) and another is 7 laminated (115 x 157.5 x 3150 mm). The former is being tested and the latter is under prepration. These beams are connected by compressed wood dowels with two diameters (10 and 15 mm). Figure 16 gives schematics of the beams.

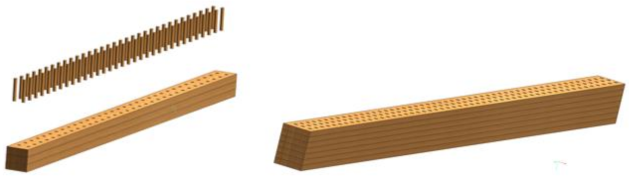


Figure 16. Adhesive free laminated timber beams

Figure 17 shows schematics of adhesive free cross laminated timber panels. Here, one panel is of dimensions of 600 x 60 (3 laminates) x 1200 mm, another 600 x 100 (5 laminates) x 2000 mm. Again, there will be two dowel sizes considered. Adhesive free column (180 x 180 (6 laminates) x 3600 mm) is also shown in Figure 18.

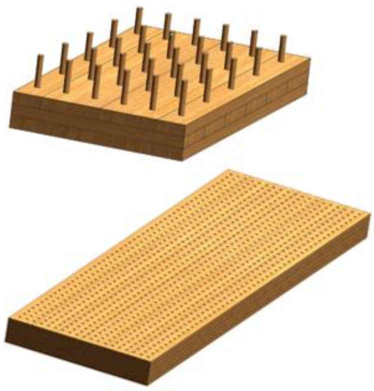


Figure 17. Adhesive free CLT panels

Figure 18. Adhesive free laminated timber column

Destructive structural tests are to be carried out to obtain the structural behaviour of all adhesive free engineered wood products manufactured, together with their adhesive counterparts.

In addition, more beam-beam and beam-column connections as well as grid systems using compressed wood fasteners are to be tested, together with their metallic fastener counterparts.

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REFERENCES

[1] Puettmann ME, Wilson JB. Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science 2005;37:18-29.

[2] Puettmann ME, Wilson JB. Gate-to-gate life-cycle inventory of glued-laminated timbers production. Wood and Fiber Science 2005;37:99-113.

[3] Wilson JB. Life-cycle inventory of formaldehyde-based resins used in wood composites in terms of resources, emissions, energy and carbon. Wood and Fiber Science 2010; 42: 125-143.

[4] Anshari, B., Guan, Z. W., Kitamori, A., Jung, K. and Komatsu, K. Construction and Building Materials, 2011, 29: 24-32.

[5] Anshari, B., Guan, Z. W., Kitamori, A., Jung, K., Hassel, I and Komatsu, K. Construction and Building Materials, 2011, 25(4): 1718-1725.

[6] Anshari, B., Guan, Z.W. and Wang, Q.Y. Composite Structures, 2017, 165: 160-170.