Adhesive-Free Timber Buildings

Summary of Results

Introduction

The *Towards Adhesive Free Timber Buildings* (AFTB) project has brought together leading researchers from six European countries with the aim of developing building systems made entirely out of natural renewable raw material. One- and two-dimensional building elements in the form of dowelled laminated beams/columns and panels have been created and optimised using local timber species and high-performance compressed-wood dowel connectors. In addition, novel connection systems, which enable the building of structures from these elements, have been designed and developed using compressed-wood plates and dowels giving the possibility to create not only adhesive–free (AF) but also metal-free structures.
This brochure summarised the key findings of the AFTB project.

Timber Compression

Using high pressure and temperature, sustainable, fast-growing, softwood timber can be transformed into a material with greater strength, stiffness and hardness than some of the most valuable tropical hardwoods. By accurately controlling the temperature and pressure in a hydraulic press, the timber plasticises and can be compressed and densified without damage to the wood.
Applying a pressure of 16 MPa at a temperature of 130°C for several hours, softwood timber can be compressed by up to 68% giving a modified wood product with a density of up to 1400 kg/m^3 (*Fig.1*).

Fig. 1 - Western Hemlock timber sections before and after compression from 400 kg/m^3 to 1400 kg/m^3 [U Liverpool].

Properties of Compressed Wood

A comprehensive programme of material characterisation tests was carried out to establish a database of the necessary properties for design of structural elements and connections using compressed-wood dowels and plates. The following properties have been established: density, flexural strength and stiffness, shear strength and yield moment for dowels, embedment strength and impact bending strength.

In tests carried out at different partner institutions on a variety of wood species, it has been demonstrated that the densification of wood by thermal compression significantly enhances the mechanical properties.
As seen in *Fig. 2*, the level of enhancement in the density, flexural modulus and flexural strength is significant and varies with species. For compressed Western Hemlock, each of these material properties increased by over 200% compared to the uncompressed wood. For Scots pine and Douglas fir, the increases were lower but always above 70%.

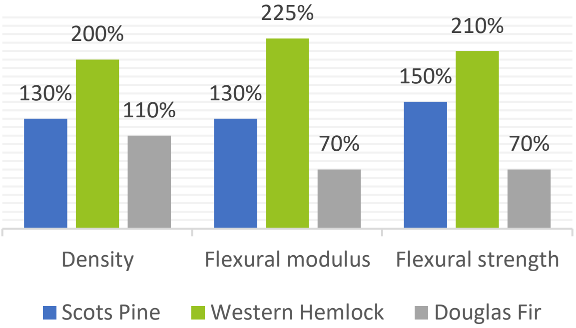

Fig. 2 - Increase in density, flexural modulus and strength due to compression of different wood species [U Liverpool].

Compressed-wood is subject to a shape-memory effect whereby it will revert to its original shape over time, at a rate determined by temperature and relative humidity. This can be prevented by heat treatment of other measures. However, the AFTB project takes advantage of this characteristic behaviour as it ensures that dowel connectors in CW structural elements and connections remain tight over their lifespan.

CW Dowel-laminated Engineered Wood Products

Several types of engineered wood products (EWPs), connected using thermally compressed wood dowels, have been manufactured and tested including:

- *Beams and columns (Fig. 3)*
- *Dowelled laminated floor and wall panels (Figs. 4 & 5)*

Fig. 3 - AF dowelled-laminated beams [U Liverpool].

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Fig. 4 - Testing of dowelled-laminated floor panel [U Liverpool].

The systems investigated included softwood and hardwood laminations and compressed hardwood and softwood dowels. These EWPs have been tested to failure to determine the allowable design loads and stresses. The dowel orientation and spacing has also been examined. This has allowed the optimum dowel spacing to be identified. Tests on AF dowelled-laminated beams with different dowel spacing were compared to glued laminated beams of the same cross-sectional size. The AF EWPs where found to be significantly less stiff than their glued laminated equivalents, and were found to fail at significantly lower loads. However, the research has also shown that by optimising the design and particularly the dowel spacing and lamination thickness, the stiffness and failure load may be significantly improved. The dowel material itself does not appear to be the determining factor in the flexural behaviour of the AF EWPs but our laboratory-scale tests indicate that there will be an improved long-term performance for EWPs using compressed-wood dowels as a result of the shape-memory effect ensuring an exceptionally tight-fit throughout its service-life.

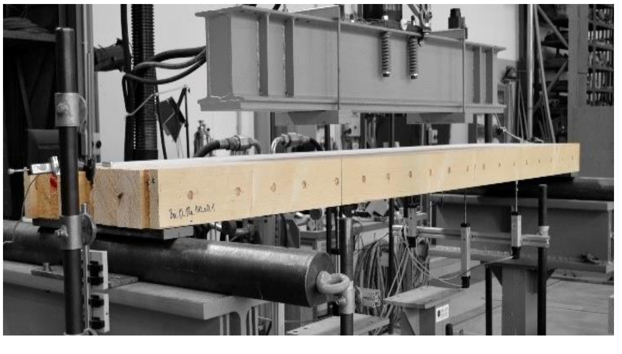

Fig. 5 - Flexural testing of Brettstapel wall element [TU Dresden].

Adhesive-free and non-metallic connections

The feasibility of all-wood moment connections was assessed for typical beam-beam and beam-column connections. The connection systems comprised compressed-wood plates inserted in grooves routed in the beams and columns and connected using compressed-wood dowels as illustrated in *Fig. 6*.

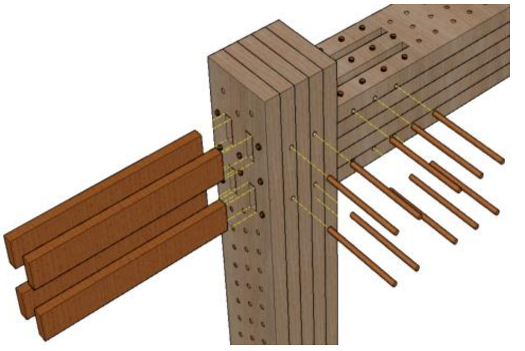

Fig. 6 - Adhesive-free (AF), non-metallic beam-column connection [NUI Galway].

A combined experimental and numerical modelling approach was used to determine the AF connection capacity. A series of connection configurations were examined, and the results have allowed the performance of the beam-beam and beam-column connections to be optimised. For beam-beam connections, the mean failure load achieved for AF-timber connections was 80% of that achieved by comparable steel-wood connections. The mean rotational stiffness of the steel-timber connection is 19% higher than that of compressed-wood-timber connection. For the AF beam-column connections, a series of connection configurations were examined experimentally, and the design was optimised using finite element methods to determine the optimum connection geometry, dowel arrangement, number of dowels and compressed-wood plate thickness. *Fig. 7* shows a local finite element model of an AF beam-column connection (beam section removed for clarity) which uses four compressed-wood plates and 10 compressed-wood dowels (six dowels in the beam section and four dowels in the column section).

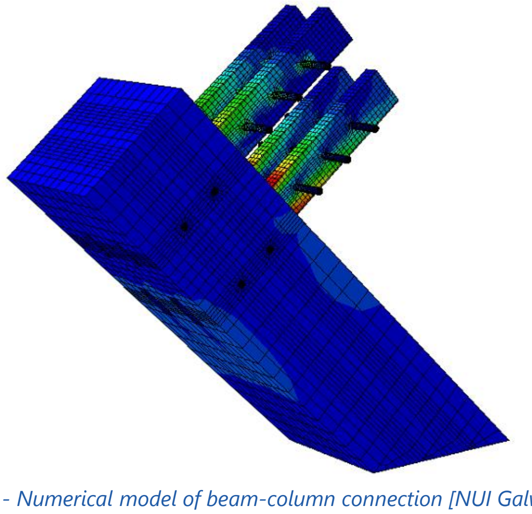

Fig. 7 - Numerical model of beam-column connection [NUI Galway].

Fig. 8 presents the testing of a large-scale timber frame which utilises the optimised adhesive-free, non-metallic connection design.

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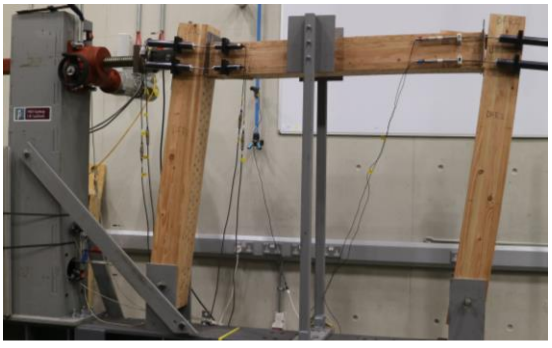

Fig. 8 - Racking test on adhesive-free, non-metallic timber frame [NUI Galway].

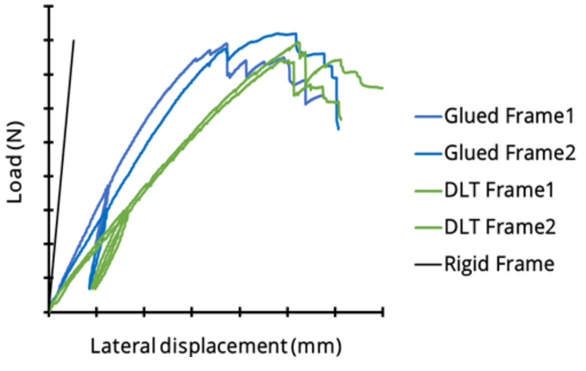

Fig. 9 - Comparison of AF & glued laminated timber frame with AF connections [NUI Galway].

The semi-rigid response of the AF connections is illustrated in *Fig. 9*, which shows racking test results for glued and AF elements connected with AF connections compared to theoretical predictions for a rigid frame. The failure load for the tested frames is about the same. The difference in stiffness is due to the lower stiffness of the AF beams and columns.

In tests on small-scale specimens, CW connections using dowelled laminated timber members showed approximately similar load carrying capacity and moment resistance to connections using glued members.

The research has shown that compressed-wood connectors are a viable alternative to steel and adhesives in timber connections. These all-wood connections will be 100% recyclable after the end-of-life of the structure. The research has shown that AF connections are also suitable for connecting solid wood and glued laminated members.

Structural Design Tool

The size, number and arrangement of dowels in adhesive-free compressed-wood dowelled-laminated beams and panels have a significant influence on their structural performance. Analysis of such components is complex generally involving a numerical modelling approach, which can replicate the complex geometry and also account for the highly anisotropic behaviour of the timber material.

This approach is time consuming and requires the user to have significant modelling expertise. To overcome this, an advanced Structural Design Tool has been developed as part of the AFTB project at the Luxembourg Institute of Science and Technology.

The tool has a user-friendly interface permitting the user to easily specify the lay-up and dowel arrangement for laminated beams and dowelled laminated panels (*Fig. 10*). The tool will then generate the complex model input file for the finite element package ABAQUS which may be run to produce numerical results (*Fig. 11*). The geometry generated can also be exported for use in other software packages. This easy-to-use tool can be used to quickly modify the geometry, examine the numerical results and enable the optimisation of the design.

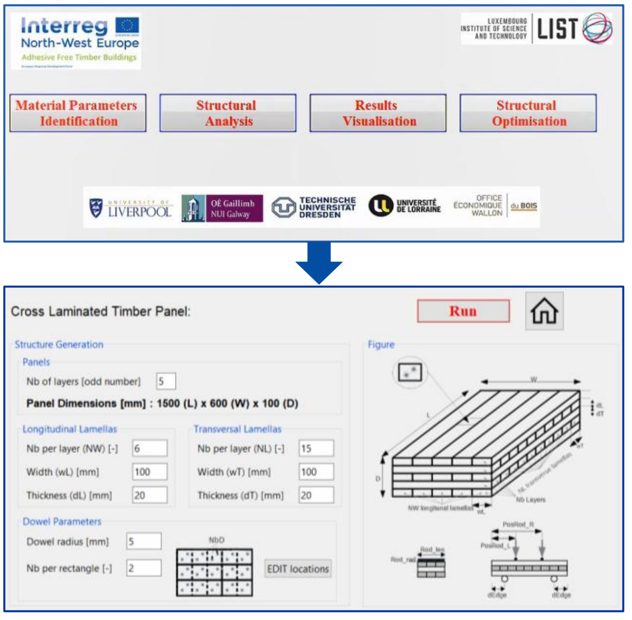

Fig. 10 - User Interface of the Structural Design Tool used to design a cross laminated timber panel [Luxembourg IST].

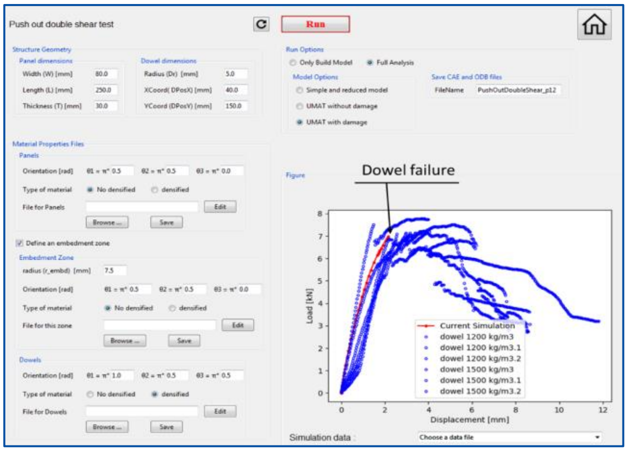

Fig. 11 - User Interface of the numerical results of a push out double shear tests [Luxembourg IST].

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Vibration Performance

An investigation of the vibration properties of adhesive-free, dowelled-laminated timber beams and panels was undertaken at the University of Lorraine using experimental, numerical and analytical approaches. *Fig. 12* shows an AF dowelled-laminated timber panel subjected to vibration testing and the results of a numerical simulation.

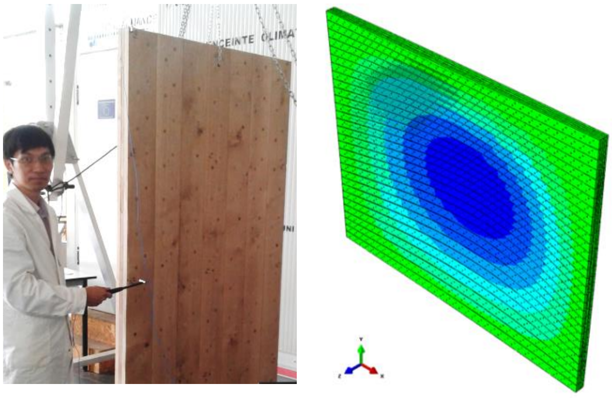

Fig. 12 - Experimental testing and numerical simulation of vibration characteristics of AF panel [U Lorraine].

This study has demonstrated that both AF dowelled-laminated beams and panels perform well within the vibration limits of Eurocode 5. In fact, the vibration properties of the dowelled-laminated beams were shown to be comparable to those of their glulam equivalents.

Fire Performance

Experimental testing and numerical modelling were used to compare the fire performance of compressed-wood and uncompressed wood. Due to the lack of internal voids, the compressed-wood displayed significantly better fire performance with lower charring rates, and longer ignition times and relatively quick extinguishment times. Compressed-wood dowel connections were also shown to outperform steel dowel connections in a fire test on a loaded frame (*Fig. 13*). In *Fig. 14* it can be seen that the time to failure of steel dowels was 10 minutes shorter due to greater heat conduction to the interior of the connection and rapid loss of mechanical properties of the steel dowel.

Fig. 13 - Fire test performed on AF connection [U Lorraine].

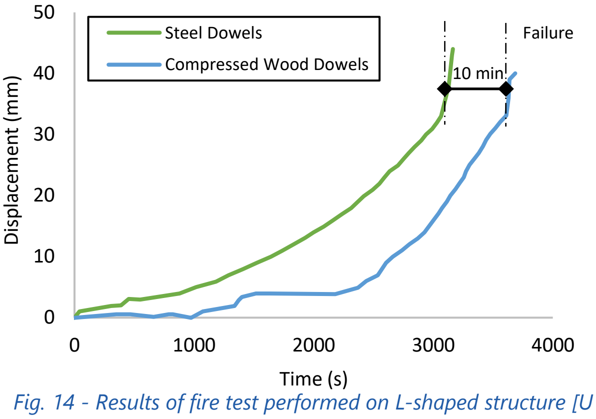

Fig. 14 - Results of fire test performed on L-shaped structure [U Lorraine].

Life-cycle Assessment (LCA)

The use of steel connectors and synthetic adhesives in the construction industry is often associated with high embodied energy and has a negative impact on the environmental performance. To characterise the environmental benefits of AF EWPs and compressed-wood connections, which are 100% reusable and recyclable after end-of-life, a Life Cycle Inventory Assessment (LCIA) was carried out. The LCIA data was developed for three different products, compressed-wood dowels, compressed-wood dowelled-laminated panels and compressed-wood dowelled laminated beams. The system boundary of the analysis for the CW dowels in cradle to factory gate (A1-A3) and the system boundary for the dowelled-laminated panels and beams is cradle to factory gate (A1-A3) with options to consider end-of-life effects (D) in accordance with ISO 14040 and ISO 14044.
The analysis has characterised the environmental impacts of AF EWPs and has shown that net negative impacts under categories such as global warming potential may be achieved when considering the end-of-life effects. The compressed-wood dowel production was shown to be significantly affected by the energy input for thermal compression. In a sensitivity analysis, it was shown that a 50% reduction in the energy consumption of the press can result in a 36% reduction in global warming potential and ozone layer depletion potential associated with the dowel manufacture. It was also shown to have a significant influence on the environmental impacts of the AF EWPs.
A comparative study, which compared the environmental impacts (A1-A3, D) associated with producing the Ness Gardens demonstrator using AF timber elements and a comparable CLT structure designed to carry the same loads, showed that the cradle-to-gate global warming potential (GWP) of both structures was similar when the efficiency of the dowel productions is optimised. When the end-of-life stage is included, the GWP associated with the AF structure is significantly lowered.

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Demonstrator Structures

A key outcome of the AFTB project is the delivery of three demonstrator structures. A 12m x 8.6m and 7.6m high warehouse style structure at the University of Lorraine, Épinal, France incorporated compressed-wood dowelled oak columns and roof trusses (*Fig. 15*). The second is a 35 m^2 field station at Ness Botanical Gardens, Liverpool, UK (*Fig. 16*). This building showcases compressed-wood dowelled-laminated beams, columns, panels and connections. The final demonstrator is an engineering art installation at the University of Dresden, Germany utilising steam-bent timber in the form of a space structure (*Fig. 17*).
These demonstrator structures will provide an opportunity for stakeholders and the general public to visit an adhesive-free structure and see the technology in use.

Fig. 15 - Spruce dowelled roof structure at Épinal [U Lorraine].

Fig. 16 - Research office at Ness Botanic Gardens [U Liverpool].

Fig. 17 - Engineering art installation at Dresden [TU Dresden].

Conclusion

This summary of results provides a brief overview of the topics and outcomes of the research activities of the AFTB project. The AFTB project set out to examine the potential to utilise modified wood to manufacture structural timber products without the use of adhesive or metallic fasteners. Through experimental, statistical and numerical methods, the AFTB project has successfully characterised the behaviour of the AF EWPs and have constructed three demonstrator structures which will serve to inform stakeholders such as architects, engineers and construction professionals as well as members of the general public who are interested in using this technology for environmentally friendly and sustainable timber structures.

For more information:

Further information on various aspects of the project available in a comprehensive set of Technical Notes and other reports, which can be downloaded from the project website http://www.nweurope.eu/AFTB.

Technical Note 1 - Market Survey
Technical Note 2 - Timber Compression
Technical Note 3 - Properties of Compressed Wood
Technical Note 4 - Compressed Wood dowel-laminated EWPs
Technical Note 5 - Vibration
Technical Note 6 - Fire Performance
Technical Note 7 - Adhesive-Free and Non-metallic Connections
Technical Note 8 - Numerical Modelling
Technical Note 9 - AFTB Demonstrator Structures
Technical Note 10 - CE Marking

Stakeholders Welcome

A key aim of the project is to engage with businesses, regulators and other interested parties. Adhesive-free timber building technology could be of interest to your business. Please get in touch via the e-mail addresses below:

For more information please visit the Adhesive Free Timber Buildings (AFTB) project website http://www.nweurope.eu/AFTB or use the contacts.

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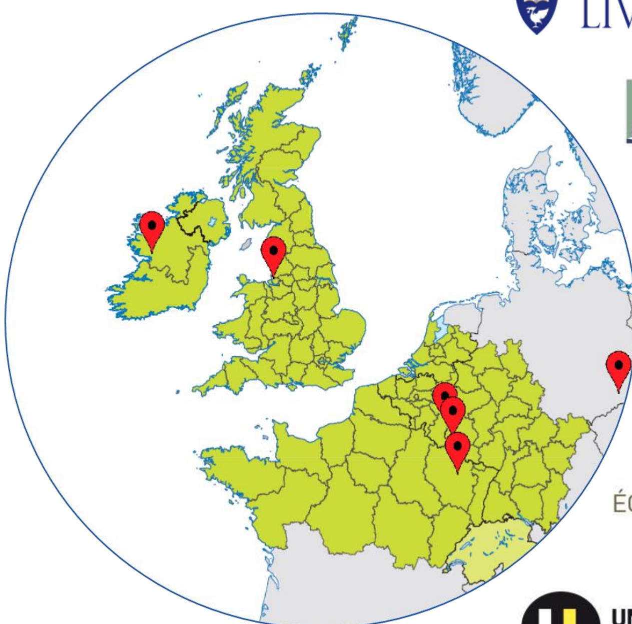

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