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FINITE ELEMENT MODELLING AND TESTING OF TIMBER LAMINATED BEAMS FASTENED WITH COMPRESSED WOOD DOWELS

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ABSTRACT: Engineered Wood Products (EWPs) are materials used for structural applications worldwide. However, there are concerns with the adhesives typically used in these EWPs, which are usually toxic and harmful to the environment. As sustainability remains a major goal of the current environmental agenda, this paper describes the design, manufacture, finite element modelling and testing of laminated timber beams fastened with compressed wood dowels which can be used for structural applications. These Adhesive Free Laminated Timber (AFLT) beams manufactured from timber laminae and fastened with compressed wood dowels, offer a potential alternative to conventional glulam beams. Finite Element (FE) models were developed using a commercial software (ABAQUS) to aid the design and optimisation of the AFLT beams. The results from the FE analyses are compared and validated with those from the experimental tests. Furthermore, the results obtained from this research give a useful understanding of the development and testing of a new and sustainable adhesive free engineered wood product.

KEYWORDS: Compressed wood dowels, Finite element Analysis, Adhesive Free Laminated Timber (AFLT)

1 INTRODUCTION

The use of timber has been increasingly used in the design of building structures such as Metropol Parasol in Spain and HAUT in the Netherlands. These timber structures have provided the drive for both the academic and industrial communities to research novel timber structures with increased interest to develop an improved understanding of their structural properties and to transform such knowledge into useful structural design guidance. More precisely, Engineered Wood Products (EWPs), such as glue-laminated timber (glulam), are increasingly being used as structural materials for built environment applications globally due to their enhanced dimensional stability, increased durability, consistent mechanical properties and the fabrication of large sections [1, 2]. Although there are advantages associated with glulam, there are also several issues related to their manufacture and use, which include energy-intensive processing stages and the presence of toxic Volatile Organic Compounds (VOCs) in adhesives [3, 4]. The release of these Volatile Organic Compounds (VOCs) and other greenhouse gas emissions are harmful to the environment. Furthermore, according to Hammond and Jones [5], the embodied energy (which includes the extraction, refining and processing stages) for sawn softwood and glulam are 7.4 MJ/kg and 12 MJ/kg, respectively. These values reflect that the embodied energy for glulam is about 62 % greater than that of sawn softwood partly due to energy-intensive processing stages of glulam.

To address those issues, this study aims to develop, test and model (using ABAQUS FE software) a novel Adhesive Free Laminated Timber (AFLT) beam fabricated from timber laminae and fastened with compressed wood dowels, which provides a possible alternative to EWPs especially glulam.

First, details of the manufacturing processes for both the compressed wood dowels and the AFLT beam are presented. In the next section, the loading, boundary conditions, mesh and mechanical properties used for the FE modelling are given. After that, the experimental test setup on the AFLT and glulam beams are explained. The FE and experimental results are then analysed and compared. Finally, the main conclusions derived from the results of the study are summarised alongside future work.

2 MANUFACTURING METHOD OF THE COMPRESSED WOOD DOWELS AND AFLT BEAM

The making of the compressed wood dowels and the AFLT beam was carried out in the Structures Laboratory at the University of Liverpool.

The species used to make both the dowels and the three laminae of the AFLT beam was C24 Scots Pine (Pinus Sylvestris), which were obtained from a timber supplier, namely Buckland Timber, UK. The timber sections were visually graded and dried to moisture contents within the range of 10 – 15 %. In order to make the compressed wood dowels, clear timber sections which did not have

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knots and/or other visible defects were used. Figure 1 gives an overview of the processing stages involved in the fabrication of the compressed wood dowels.

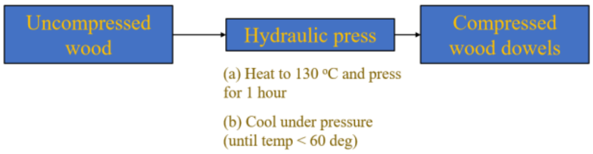

Figure 1: *An overview of the fabrication processes for the compressed wood dowels*

The timber sections were compressed radially via an in-house designed aluminium mould placed in a 2000 kN hydraulic press at 130 ºC. Figure 2 shows the image of the 2000 kN hydraulic press that was used to process the uncompressed wood into compressed wood dowels.

Figure 2: *A photograph of the 2000 kN hydraulic press used for processing the compressed wood dowels*

The timber was compressed from an average initial density of 572 kg/m^3 to a final density of 1285 kg/m^3. Studies [6-9] have also shown that the hot-press compression process significantly enhances the mechanical properties of timber. When the compressed wood dowels were removed from the aluminium moulds, their moisture content was 5%, and the dowels were placed in air-tight plastic bags to prevent moisture dependent swelling. Figure 3 shows a photograph of the compressed wood dowels

Figure 3: *A photograph of the compressed wood dowels*

The AFLT beam was manufactured by inserting the compressed wood dowels into pre-drilled holes of clamped timber laminae. Figure 4 shows the assembly processes for the AFLT beam.

The beam comprised of two rows of evenly distributed compressed wood dowels that were inserted perpendicularly with respect to the longitudinal direction of the timber laminae. The spacing between the dowels along the length and across the width of the beam were 50 mm and 23 mm, respectively.

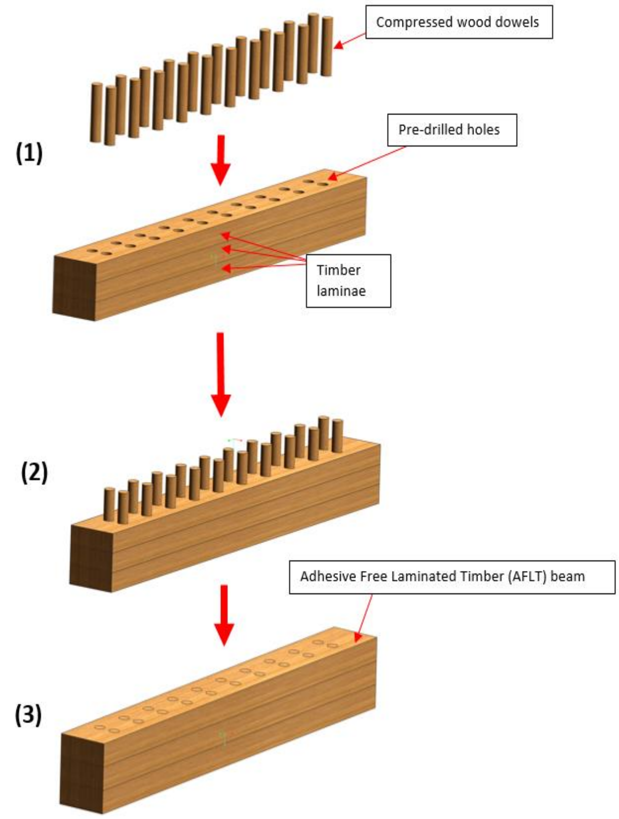

Figure 4: *Flow diagram showing the assembly processes involved in the fabrication of the AFLT beam*

The dimensions of the beam were 70 mm x 64.5 mm x 1350 mm, and Figure 5 shows a photograph of the actual AFLT beam. Together with spring back, the moisture-dependent swelling of the dowels helps to gain a tight fit in the laminated beam. The benefits of these AFLT beams over glulam are increased sustainability and recyclability through the use of environmentally-friendly compressed wood dowels, and subsequently, reduce harmful compounds and greenhouse gas emissions as well as a reduction in the quantity of EWPs going to landfill [10].

Figure 5: *A photograph of the assembled Adhesive Free Laminated Timber (AFLT) beam*

3 FINITE ELEMENT MODELLING

Prior to testing the AFLT beam, three-point bending tests were carried out on the uncompressed timber and compressed wood dowels to determine their longitudinal elastic flexural moduli. The test samples were conditioned in an environmental chamber at a temperature of 20ºC and 65% relative humidity, as recommended by BS EN 408 [11].

Using these results, a Finite Element (FE) model was developed using ABAQUS software [12]. The model was used to simulate the structural behaviour of the

AFLT beam. The model was also used to assist designing and optimising the AFLT beams. The four-point bending setup (i.e. loading and boundary conditions) is in accordance with BS EN 408 [11] and is shown in Figure 6.

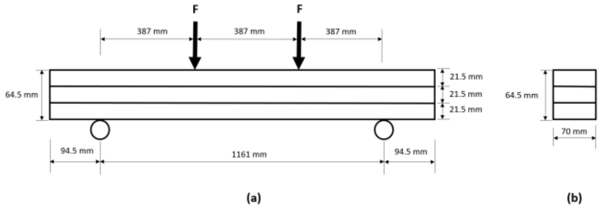

Figure 6: *The sketches and dimensions of the four-point bending test setup: (a) Side-view and (b) Cross-section view*

The longitudinal elastic flexural moduli of the uncompressed wood and compressed wood dowels were 10.8 GPa and 24.8 GPa, respectively. The results show that the flexural modulus of the compressed wood was about 130 % greater than the uncompressed wood. Also, the average densities of the uncompressed wood and compressed wood dowels were 572 kg/m^3 and 1285 kg/m^3, respectively. Loading was applied through displacement controlled loading of 25 mm according to the setup shown in Figure 6.

The contact and interaction properties are given in Table 1. The interaction between the holes of the timber laminae and compressed wood dowels were modelled with contact pairs and were defined using both tangential and normal contact behaviours.

Table 1: *Contact and interaction properties of the FE model*

Master component	Slave component	Coefficient of Friction
Dowel	timber laminae	0.8
Roller	timber laminae	0.1
timber laminae	timber laminae	0.2

The hard contact in pressure-overclosure was set for the normal behaviour and a friction coefficient of 0.8 was set for the tangential behaviour.

The three timber laminae and compressed wood dowels were meshed with C3D8R elements, which is an 8-node linear brick, reduced integration with hourglass control element. Relatively finer mesh was generated for the compressed wood dowels and an image is shown in Figure 7. Figure 8 also shows an image of the mesh generated for the AFLT beam fastened with compressed wood dowels, which was based on preliminary mesh sensitivity studies.

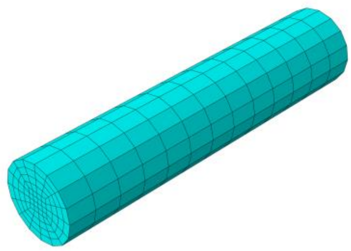

Figure 7: *Mesh used in the FE model of the compressed wood dowels*

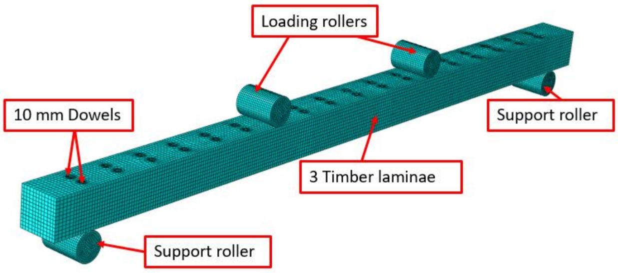

Figure 8: *Mesh, loading and boundary conditions of the AFLT beam*

On the other hand, a tie constraint (i.e. fully bonded) was used between the timber laminae to represent glulam in order to make transverse stiffness comparisons.

4 FOUR-POINT BENDING TESTS ON AFLT BEAM

A schematic drawing showing the loading arrangement and geometry of the beam is shown earlier in Figure 6. After the AFLT beam was fabricated, it was left for seven days before it was experimentally tested (via four-point bend testing) as shown in Figure 9. This was to make sure that there was a tight fit between the three timber laminae and the compressed wood dowels, which occurs from the moisture dependent swelling of the compressed wood dowels.

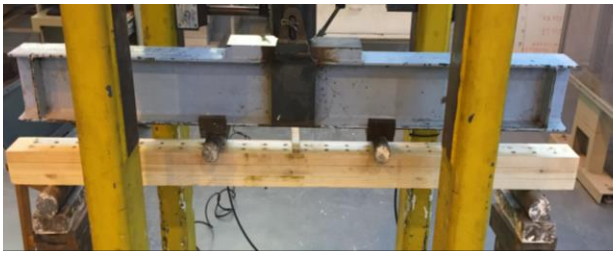

Figure 9: *AFLT beam setup for four-point bending*

In addition, for the purpose of comparison, four-point bending test was also carried out on a glue-laminated (glulam) beam with similar dimensions in accordance with BS EN 408 (2010). The glulam beam was manufactured and supplied by Buckland Timber, Devon, UK. C24 Scots Pine (Pinus Sylvestris) was also used as the timber laminae for the glulam for consistency.

The four-point bending tests were carried out on the AFLT and glulam beams to determine their initial stiffnesses, which were computed from the applied loads and the centre deflections. The beams were subjected to incremental static loading. 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.

5 RESULTS AND DISCUSSION

Figure 10 and Figure 11 show contour plots of the deflection response and stress distribution of the AFLT beam, respectively. As expected, the relatively larger deflections occurred at the centre of the beam between the loading points, shown in Figure 10. Figure 12 and Figure 13 also show the deflection response and stress distribution of the glulam beam modelled with 'tie' constraint (i.e. fully bonded).

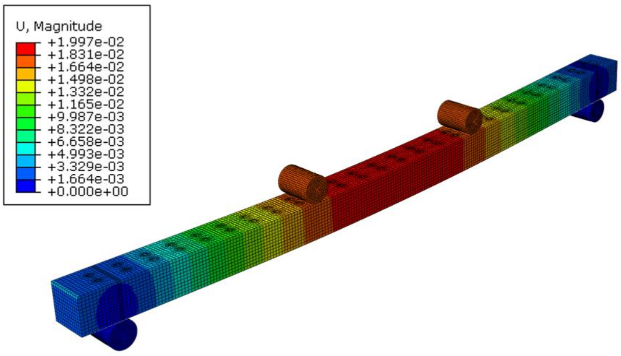

Figure 10: *Contour plot showing the deflection response of the AFLT beam*

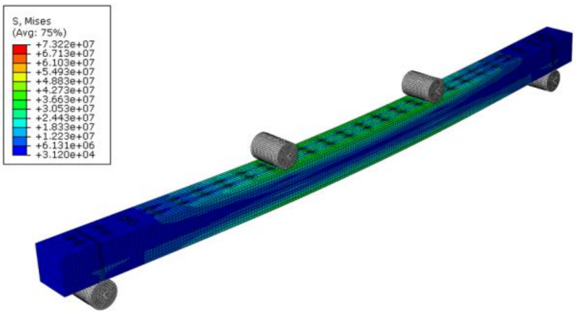

Figure 11: *Contour plot showing the stress distribution of the AFLT beam*

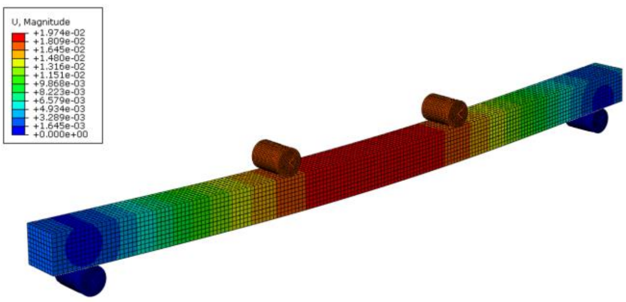

Figure 12: *Contour plot showing the deflection response of the glulam beam (tie constraint)*

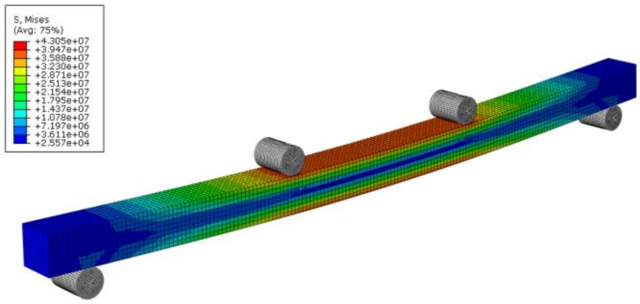

Figure 13: *Contour plot showing the stress distribution of the glulam beam (tie constraint)*

Figure 14 shows the contour plot of the stress distribution of the compressed wood dowels. The aforementioned figure indicates that there were lower stress distributions between the dowels located around the centre of the AFLT beam (between the loading points). Also, higher stress concentrations occur at the interface between the internal edges of the timber laminae and compressed wood dowels, which are highlighted in Figure 15.

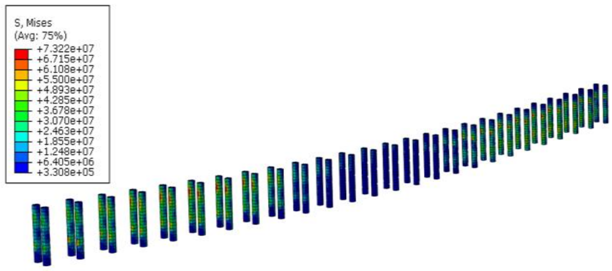

Figure 14: *Contour plot showing the stress distribution of the compressed wood dowels*

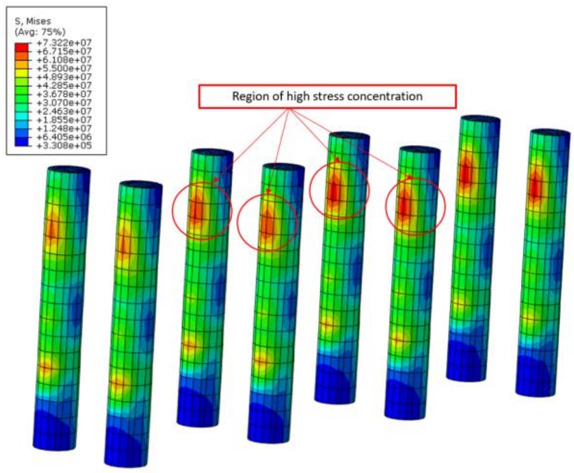

Figure 15: *Close-up view showing the region of high stress concentrations of the compressed wood dowels*

From the FE model, the initial transverse stiffness of the AFLT beam was 336 N/mm and the glulam was 995 N/mm. The results show that glulam beam which was modelled with a tie constraint (i.e. fully bonded) between the timber laminae was about three times greater than that of the AFLT beam. As the FE analysis was intended to aid the design of the beam in order to attain good structural properties, a parametric study which involved increasing the dowel spacing along the longitudinal direction of the beam from 50 mm to 100 mm was carried out. This was carried to determine its influence on the stiffness properties of the AFLT beams, as shown in Figure 16.

Figure 17 shows a plot of the initial transverse stiffness versus the dowel spacing for the AFLT beam. The results show that an increase in the dowel spacing (along the longitudinal direction) from 50 mm to 100 mm, resulted in a reduction in the initial transverse stiffness. These results are also in agreement with an experimental study by O'Loinsigh et al.[3], which showed that increasing the number of dowels led to an increase in the stiffness of the beams.

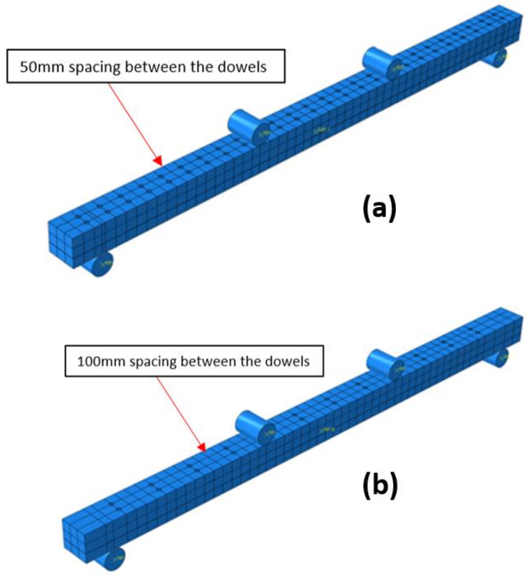

Figure 16: *Images showing AFLT beams with 50mm and 100mm dowel spacing*

It should, however, be noted that the dowels in O'Loinsigh et al.[3] were inserted at a 60º angle via a mechanical-induced high-speed rotation wood welding in O'Loinsigh et al. [3]. However, additional FE model will be carried out to aid optimisation in an aim to attain higher structural properties of the AFLT beam.

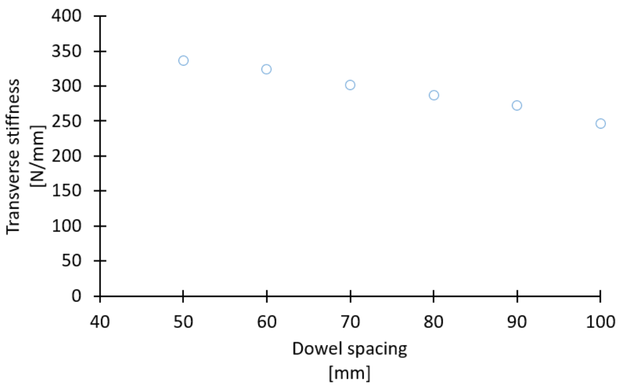

Figure 17: *A plot of the initial transverse stiffness versus the dowel spacing for the AFLT beam*

Also, the results from the experimental tests showed that the initial transverse stiffness of the AFLT beam was 323 N/mm. Figure 18 shows the load versus centre deflection plot of the AFLT beam under four-point bending. This shows that the AFLT beam can withstand reasonably large loads, however, the glulam beam with similar dimensions showed a greater stiffness of 909 N/mm. The result shows that the initial stiffness of the AFLT beam is about a third of glulam.

The results show that the FE model stiffness was about 4% greater than the stiffness obtained from the experimental four-point bending test. On the other hand, the FE model's initial transverse stiffness for the glulam was 9% greater than that from the experimental four-point bending test. Overall, the results show that the FE model predictions show good agreement with the experimental results.

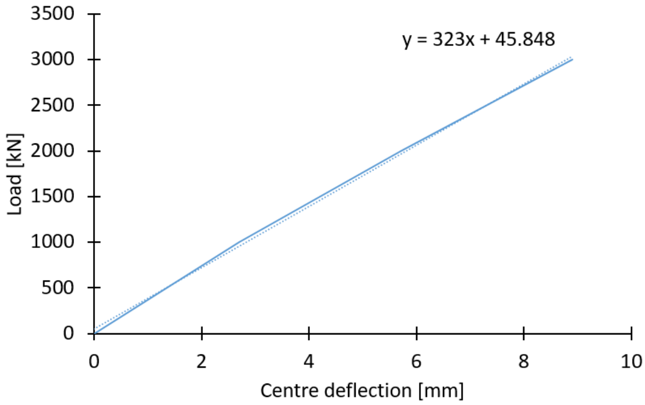

Figure 18: *Load versus centre deflection plot of the AFLT beam under four-point bending*

6 CONCLUSIONS

This study has demonstrated the development of an AFLT beam (novel timber assembly), which can be potentially used in structural applications as an alternative Engineered Wood Products (EWPs). This is because the use of novel EWPs in structural applications continues to rise as awareness of their potential amongst the structural engineering community increases.

An adhesive free laminated timber (AFLT) beam was manufactured from timber laminae and fastened with compressed wood dowels. The manufacturing method has been described, and details of the FE analyses have been presented. The experimental tests carried out are also described, and the test results have been analysed and discussed. Relevant images of the work have also been presented. Finite Element analyses of the beams have been carried out, and compared with the experimental test results. Good correlation between the FE model analyses and experimental test results has been demonstrated.

Three-point bending tests were carried out on the uncompressed wood and compressed wood dowels, and their longitudinal elastic flexural moduli were evaluated to be 10.8 GPa and 24.8 GPa, respectively. The results show that the flexural modulus of the compressed wood was about 130 % greater than the uncompressed wood.

Also, the average densities of the uncompressed wood and compressed wood dowels were 572 kg/m^3 and 1285 kg/m^3, respectively. Using these results alongside the geometric properties, FE analyses were carried out four-point loading to simulate the load-deformation response of AFLT and glulam beams. The results were validated with experimental tests, with the FE results being about 4 – 9 % greater than the experimental results.

The experimental tests results show that the AFLT beam has a potential for structural load-bearing applications. Although, the transverse stiffness of the AFLT beam (323 N/mm) is lower than that of glulam (909 N/mm), design optimisation via geometric changes and parametric studies (via FE modelling) will enable the use of the AFLT beams in structural applications.

Furthermore, the outcome of the research will bring about environmental benefits and increased sustainability. Therefore, these study therefore merits further investigation through additional FE modelling and more experimental testing and will be carried out under the auspice of the Interreg North-West Europe (NWE) programme.

As there are currently limited studies on the structural properties of timber beams fastened with compressed wood dowels, the FE and experimental results provide newly acquired knowledge and fresh insight into the development of a novel and sustainable adhesive free engineered wood product.

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