Original Article

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Experimental investigation on the effect of accelerated ageing conditions on the pull-out capacity of compressed wood and hardwood dowel type fasteners

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Abstract: The widespread use of adhesives in timber construction has negative implications for the end-of-life disposal or re-use of the structural timber components. To promote the circular bioeconomy, it is preferable to substitute adhesives with more sustainable alternatives such as wood-based connectors. Today, robotic fabrication technologies facilitate the development of dowel-laminated timber (DLT) products whereby hardwood dowels are used to connect timber laminates as a substitute to adhesives. In recent years, thermo-mechanical densification of wood has resulted in significant improvements in the mechanical performance of the wood. This modified product often termed compressed wood (CW) has a shape-recovery effect which may be beneficial for the development of DLT products and timber-timber connections with improved friction fit with time. To test the hypothesis, accelerated ageing tests were carried out on CW-timber and hardwood-timber dowel type connections subjected to variable climate conditions. Finally, the capacity of the connections or friction fit was assessed using pull-out tests. Results show that the shape-recovery effect leads to the continuous expansion of the CW dowels and facilitates a friction fit with the timber substrate yielding higher pull-out loads when compared to hardwood dowels.

Keywords: accelerated ageing; compressed wood; dowel type connections; mass timber; pull-out capacity; shape-recovery.

1 Introduction

Recent advancements in timber engineering have led to the development of high-performance engineered wood products (EWPs) which are allowing for the construction of taller and more environmentally sensitive timber buildings. In the last two decades, the EWPs which are garnering attraction across the globe are termed massive or mass timber products. They are layered products comprising sawn timber boards (laminates) that are adhesively bonded/mechanically connected to produce thick panels or linear elements (Harte 2017; O'Ceallaigh et al. 2018; Ramage et al. 2017). These products are becoming increasingly used in building construction as they offer excellent load carrying capacity, fire performance, durability, reduced effect of natural defects and are easily customisable making them very suitable for construction purposes. On the sustainability side, they offer low embodied carbon solutions and provide excellent potential for recycling at the end of life of the buildings (Hough 2019; Skullestad et al. 2016; Sotayo et al. 2020; Tellnes et al. 2013). Although mass timber products are bio-based and sustainable, there is scope to further improve upon their environmental and health benefits by minimising the use of energy-intensive synthetic adhesives and metallic connectors during the manufacturing and assembly process of these products.

In recent years, hardwood dowels have been used as an alternative to adhesives and metallic fasteners in the manufacturing of laminated timber products commonly known as dowel laminated timber (DLT) or "Dowellam"

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(Dauksta 2014; El-Houjeyri et al. 2019; StructureCraft 2019). For DLT production, dried hardwood dowels (at a relatively low moisture content) are driven into softwood boards. Consequently, the hardwood dowels swell to establish moisture equilibrium with the surrounding timber and this facilitates form-and-friction locking of the dowel in the timber (StructureCraft 2019; TechnoWood 2021; Thoma et al. 2019; Thoma Holz 2018). Similar technology has been used in the manufacture of traditional hardwood dowelled timber-timber connections as hardwood dowels used in this manner are capable of transferring loads under shear between adjacent timber laminations and can be designed to form rigid structural elements and connections that can carry significant structural loads. However, the long-term behaviour of such connections is still unknown. During the in-service life of a timber dowelled connection, the moisture content of the individual components (hardwood dowels and softwood elements) varies with changes in the relative humidity of the surrounding environment. As a result, the contact pressure/friction fit between the hardwood dowels and softwood varies with time which can lead to degradation of the friction fit. Grönquist et al. (2019) reported that a continuous decrease in the relative humidity over time may lead to complete loss of contact pressure between connected components. In another study, Guan et al. (2010) reported that hardwood dowels in timber-timber connections have a high-stress relaxation feature, which causes the loosening of connection over time and necessitates tightening at regular intervals.

Recent studies have found that densified or compressed wood (CW) can be used as a potential alternative to adhesives and metallic connectors in structural timber applications (Conway et al. 2021; Grönquist et al. 2019; Hassel et al. 2008; Jung et al. 2008; Sotayo et al. 2020). CW is a modified wood product with improved structural properties. While there are many different types of modification treatments, such as chemical, thermal or physical modification, the densification of wood presented in this study is termed thermo-mechanical compression of wood which has been manufactured by subjecting timber to heat and pressure to increase its density. CW manufactured subjected to this modification treatment exhibits what is known as springback or shape-recovery behaviour, which is responsible for partial shape-recovery when subjected to moisture/heat or a combination of both (Gong and Li 2017; Kutnar et al. 2015; Namari et al. 2021; Navi and Pizzi 2015; Pelit et al. 2014, 2015; Wehsener et al. 2018; Welzbacher et al. 2008). As a result, during its in-service life, CW can exhibit both reversible and irreversible swelling. Reversible swelling occurs due to the hygroscopic nature of the wood and irreversible swelling occurs due to the shape-recovery behaviour, which can cause a partial or full return of the CW to its original dimensions. Inoue et al. (1992) reported that CW recovers 90% of its original shape when subjected to the temperature that was used during the compression process. Studies have also reported that continuous moisture absorption results in an increase in the thickness of CW (Anshari et al. 2011; Grönquist et al. 2019; Laine et al. 2013). The shape-recovery behaviour of the CW could be utilised as a beneficial trait in applications such as dowel-type timber connections where increased friction within a connection is desirable. CW dowels may be used to resolve issues associated with the loosening of hardwood dowelled connections. The continuous expansion of CW due to shape-recovery could prevent the loosening of connections during the service life. There are a few studies available on structural applications of CW as dowel material for the production of CW dowel laminated timber and jointing of structural members such as beams and columns (Jung et al. 2010; Mehra et al. 2018; O'Ceallaigh et al. 2021). However, the long-term performance of dowelled connections and the influence of the shape-recovery phenomenon in CW fasteners requires further investigation.

This paper details the experimental findings of tests, which were carried out to develop a better understanding of the long-term behaviour of CW fastened connections. The long-term relaxation of timber structures and particularly structural connections is a slow process, and long periods are required to study their mechanical behaviour. CW dowel laminated products and connections are relatively new and there is no actual life span data available. Therefore, it is beneficial to carry out accelerated ageing tests to obtain information on the long-term performance of the CW dowels by mimicking long-term moisture induced stresses in timber in a significantly reduced timeframe. In this study, test specimens were subjected to an accelerated ageing programme followed by an evaluation of the friction fit behaviour of these connections employing dowel pull-out tests. As seen in Figure 1, one CW dowel and one hardwood dowel are inserted within a timber section and pull-out tests are performed to assess the dowel-timber interaction. Prior to structural testing, the specimens are subjected to accelerated ageing treatments using variable conditions including constant temperature and relative humidity, and a series of pressure wetting and rapid drying cycles. The experimentally obtained pull-out test capacity of the CW dowels is compared to that of the hardwood dowels.

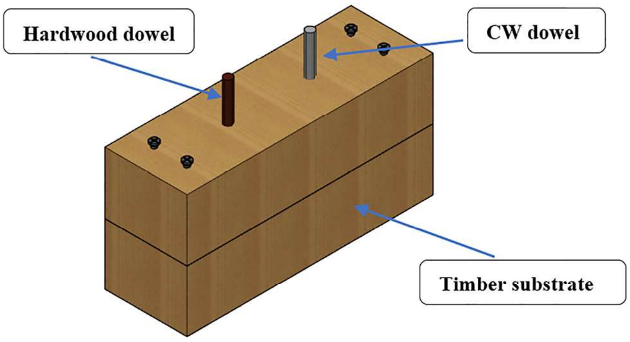


Figure 1: Test specimen containing one hardwood dowel and one CW dowel.

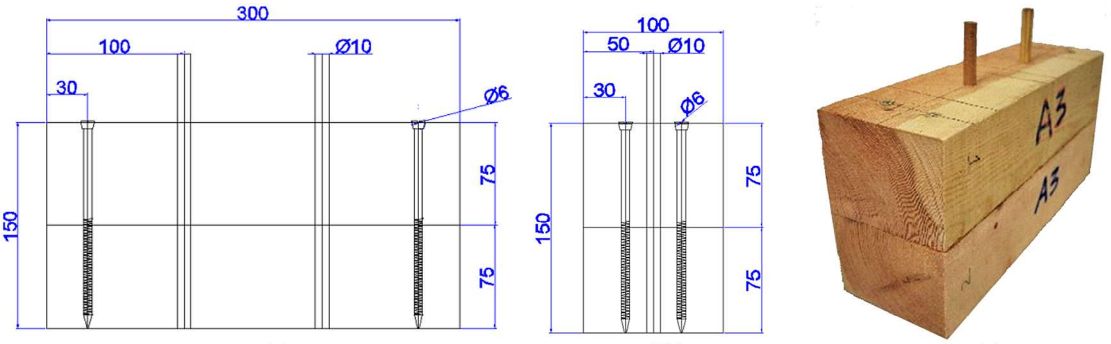
2 Materials and methods

In this study, several different materials were used to form the test specimens. One CW and one hardwood dowels were inserted into the same timber substrate to minimise its influence on the results. Commercially available kiln-dried Irish grown Scots pine (*Pinus sylvestris* L.) timber was used to form the substrate (Ó Fátharta et al. 2020). To further minimise the variations among the specimens due to the substrate, timber specimens with a density of between 520 and 540 kg/m^3 after conditioning at a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C for 30 days were selected for the test programme. The CW dowel material used in this study is manufactured from radially compressed Scots pine. The density of the uncompressed Scots pine specimens prior to compression varied from 500 to 700 kg/m^3 at 12% moisture content. The moisture content of the CW dowels post-compression varied between 5 and 6%. To ensure the moisture content remained constant and to prevent shape-recovery, the dowels were placed in air-tight plastic bags immediately after manufacture. The diameter of the dowels measured with a vernier calliper with an accuracy of ±0.01 mm varied from 9.95 to 10.31 mm with a mean value of 10.0 mm and a standard deviation of 0.16 mm and the length of 200 mm. The mean oven-dry density of the CW dowels used in this study was found to be 1238 kg/m^3 with a standard deviation of 30.1 kg/m^3. The CW dowels were sourced and manufactured at the University of Liverpool. The CW dowels were manufactured by subjecting the Scots pine timber to heat and compressing the Scots pine in the radial direction to a compression ratio of 54% where the compression ratio refers to the difference between the initial and final thickness of the wood as a percentage of the initial thickness. Further information on the manufacturing process is described by Sotayo et al. (2020). The hardwood dowels used in this study were formed using beech wood (*Fagus sylvatica* L.). The hardwood beech dowels were used to form a basis for comparison with the CW dowels. The diameter of the hardwood beech dowels varied from 9.80 to 10.37 mm with a mean diameter of 10.1 mm and a standard deviation of 0.09 mm. The mean oven-dry density of the hardwood dowels was 695 kg/m^3 with a standard deviation of 24.2 kg/m^3.

2.1 Test procedure

2.1.1 Preparation of test specimens: The test specimens comprise a Scots pine timber substrate in which the CW and hardwood dowels are inserted as presented in detail in Figure 2. The Scots pine substrate measuring 300 mm (L) × 100 mm (T) × 150 mm (R) was manufactured as per EN 1382 (CEN 2016). Each specimen comprised two laminates of 300 mm (L) × 100 mm (T) × 75 mm (R) connected using Spax universal partially threaded flat countersunk-headed screws of 6 mm diameter and 150 mm length as shown in Figure 2. It should be noted that screws were preferred over adhesives for lamination purposes as severe accelerating ageing could potentially cause delamination (Raftery et al. 2008; Sikora et al. 2015). Once laminated, holes, which extended the entire depth of the timber specimens, were bored in the specimens using a pillar drilling machine. Each dowel was 200 mm long, which includes a 150 mm effective length (embedded in the timber specimens) and a 50 mm section to facilitate the mechanical grips of the test machine. To ensure a tight fit without damaging the perimeter of the dowels, 10.2 mm holes were created for all CW dowels. For the hardwood dowels, holes between 10 and 10.2 mm were formed due to the variation in the dowel diameter. For both dowel types, the diameter of the hole was chosen based on the average diameter of the dowel. It should be noted that the moisture content of both the hardwood dowels and the CW dowels was less than that of the Scots pine timber prior to insertion as is the case in practice. In total, 12 specimens were manufactured with each specimen comprised of two dowels (one CW and one hardwood dowel).

2.1.2 Accelerated ageing treatments: Four different series were considered as outlined in Figure 3 which were chosen to examine the



(a) (b) (c)

Figure 2: Accelerated ageing test specimen preparation: (a) elevation, (b) end view and (c) test specimen (all dimensions in mm).

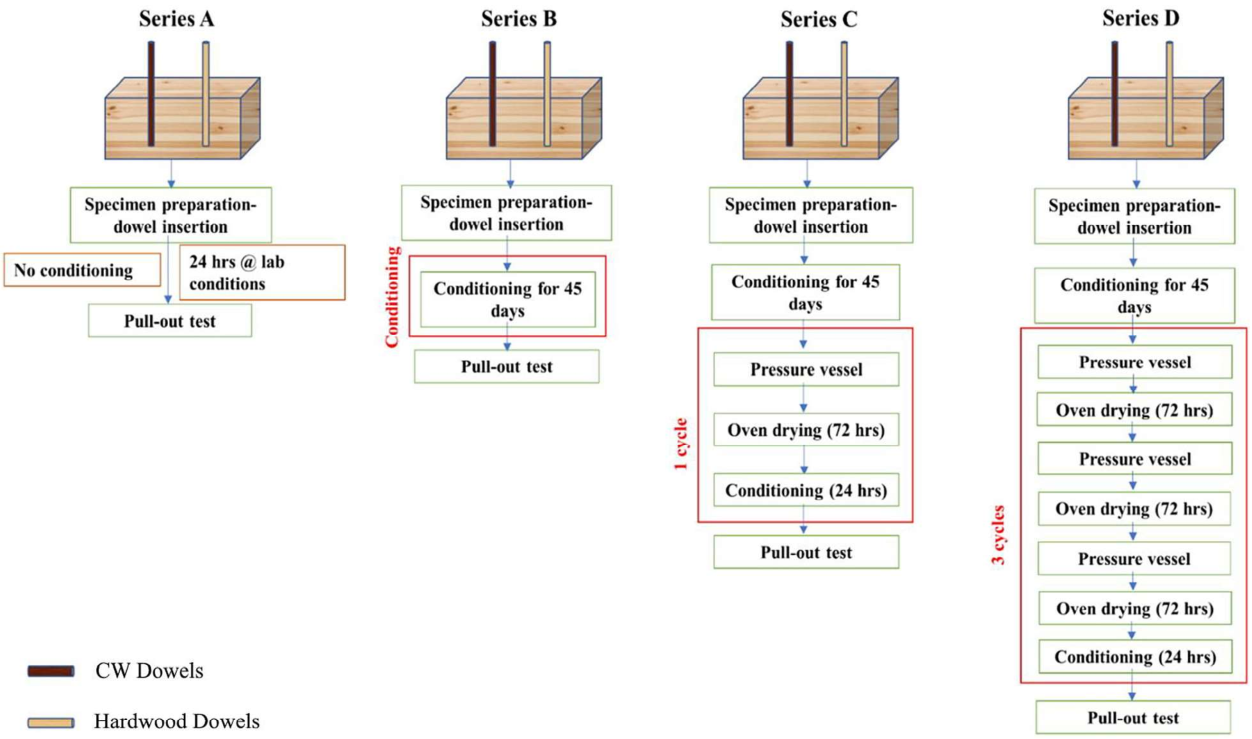


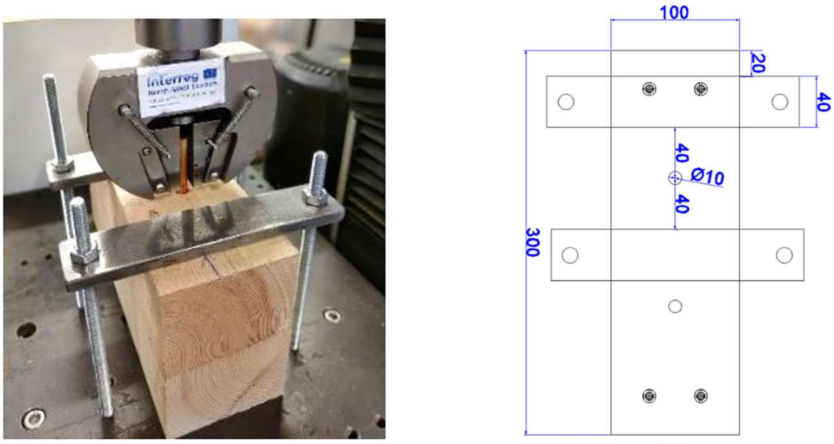
Figure 3: Scheme of accelerated ageing test procedures for Series A, B, C and D.

differential swelling/shrinkage of the dowel and timber substrate and its influence on the frictional forces between the dowel surface and surrounding timber. Series A examines the structural response of CW and hardwood dowels exposed to laboratory conditions with a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C for 24 h after dowel insertion. Series B examines the structural response of CW and hardwood dowels subjected to 45 days of conditioning at 20 ± 2 °C and a relative humidity of 65 ± 5%. The duration of 45 days was selected as an appropriate duration because preliminary tests on the swelling of unconstrained specimens of CW had shown that a significant proportion of the shape-recovery effect occurs in the first 10 days of exposure (Mehra 2020). Series C and D are subjected to the same conditioning as Series B, which was then followed by accelerated ageing treatments which were performed before the structural examination. As there is no standard protocol for accelerated ageing of wooden-dowel type connections, a pressure treatment in accordance with ISO 12580 (ISO 2007) was utilised for Series C and D.

The accelerated ageing process involved subjecting the specimens to a pressure soaking treatment to accelerate moisture diffusion in the timber and dowels, which in turn induced internal stresses in and around the connection. These specimens were cycled as per Method B of ISO 12580 (ISO 2007). Initially, specimens were placed in the pressure vessel and submerged in water at room temperature. Specimens were separated using a wire screen in such a manner that all end-grain surfaces were freely exposed to water. Then, the pressure vessel was closed and a vacuum of approximately 70 kPa was drawn and held for 30 min. Subsequently, the vacuum was released and a pressure of approximately 550 kPa was applied for 2 h. Specimens were then oven-dried at 70 °C temperature until the mass returned to 100–115% of the conditioned mass (mass on 45th day after conditioning). Once the aforementioned mass was attained, the cycle was complete and specimens in Series C were conditioned for 24 h at a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C before performing the pull-out test. The accelerated ageing cycle was repeated for specimens in Series D for a total of three cycles followed by 24 h of conditioning and experimental evaluation.

During the different treatments, the dowel diameter was measured at different intervals. As CW dowels tend to expand mainly in the radial direction, the diameter was only measured in the radial direction at a pre-marked point on each dowel (10 mm above the timber surface).

2.1.3 Pull-out tests: All specimens were subjected to pull-out tests as per EN 1382 (CEN 2016). Tests were performed using an Instron machine, model 4466, rated to 10 kN, under displacement control mode at a constant displacement rate of 1.5 mm/min. The testing rig comprised a 2716 series manual wedge action grip and two steel plates for clamping the specimen on the steel platform using threaded steel bars as shown in Figure 4a. The distance between the inner edges (nearest to dowel) of the steel plates and the axis of the dowel was 4*d* (40 mm), as shown in Figure 4b. Once the specimen was securely clamped on the testing rig, the grip was closed, and the dowel was axially loaded in withdrawal (tension) and the maximum pull-out load was recorded. It should be noted that the position of the clamp along the dowel length was noted to ensure no slippage was observed during the test.



(a) (b)

Figure 4: Testing rig: (a) test set up, (b) plan view of the test specimen showing edge distances of steel plate from the centre of the dowel (all dimensions in mm).

3 Results and discussion

3.1 Pull-out test results

This section presents the pull-out test results for all specimens of Series A, B, C and D. The test results for CW dowels and hardwood dowels were compared within each series to observe the differences due to the dowel type and between each series to examine the influence of the accelerated ageing treatment. Table 1 shows the pull-out test results of the individual specimens of Series A, B, C and D. When examining Series A, it can be seen that the mean pull-out load of the hardwood and CW dowels were 1.2 and 1.3 kN, respectively. As expected, there was no significant difference between the pull-out strength of the CW dowels and hardwood dowels in Series A because each specimen of this series was subjected to laboratory conditions for only 24 h after dowel insertion allowing a negligible amount of dowel expansion to occur. The load-displacement behaviour of the dowels in Series A can be seen in Figure 5a. For all the load-displacement graphs, a solid line indicates the CW dowels, and a dashed line indicates the hardwood (HW) dowels. The load-displacement behaviour is characterised by a linear elastic behaviour until the pull-out strength is achieved. The mean pull-out strength of the hardwood dowels was found to be 10% lower than that of the CW dowels.

In Series B, the hardwood and CW dowels were conditioned for a period of 45 days at a temperature of 20 ± 2 °C and relative humidity of 65 ± 5% prior to performing pull-out tests. Conditioning of the specimens allowed the dowels to increase in moisture content and resulted in the expansion of the CW dowels in the radial direction which facilitates form and friction locking. An investigation of the dowel expansion during this conditioning phase, which also included measurements from specimens in Series C and D, has shown that there is a continuous expansion of the CW dowels during this conditioning phase, whereas the expansion was negligible in the hardwood dowels. CW dowels showed an approximately 5.6% increase in radial swelling compared to only 0.8% for the hardwood dowels over the same period of 45 days. While not directly measured, both dowel types experienced a change in moisture content which results in some dowel expansion,

Table 1: Results of pull-out tests.

Series	Dowel	Specimen label	Pull-out load (kN)	Mean pull-out load (kN) (standard deviation)
A	HW	A1HW	0.9	1.2 (0.2)
		A2HW	1.3	
		A3HW	1.4	
	CW	A1CW	1.4	1.3 (0.3)
		A2CW	1.5	
		A3CW	1.0	
B	HW	B1HW	0.9	0.8 (0.2)
		B2HW	0.9	
		B3HW	0.6	
	CW	B1CW	3.8	3.8 (0.2)
		B2CW	3.6	
		B3CW	4.0	
C	HW	C1HW	3.4	3.4 (0.1)
		C2HW	3.4	
		C3HW	3.3	
	CW	C1CW	5.4	5.9 (0.5)
		C2CW	6.4	
		C3CW	5.9	
D	HW	D1HW	3.2	2.8 (0.4)
		D2HW	2.4	
		D3HW	2.8	
	CW	D1CW	5.7	6.9 (1.3)
		D2CW	6.7	
		D3CW	8.3	

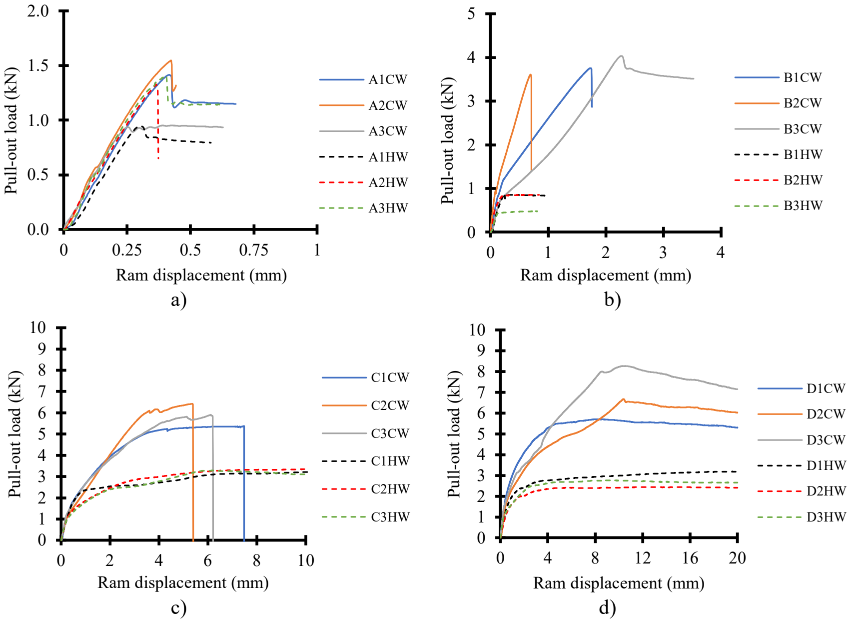


Figure 5: Load-displacement graphs for the pull-out tests: (a) Series A, (b) Series B, (c) Series C, (d) Series D. Note different scales presented for clarity.

however, the large increase in the CW dowel may be attributed to the shape-recovery effect. In Figure 6, the expansion of the CW dowel due to the shape-recovery effect can be seen to result in an elliptical shape while the hardwood dowels maintained their circular shape.

When examining the pull-out load of the specimens in Series B, it was found that the mean pull-out load for the CW dowels was 387% higher than that for the hardwood dowels with mean loads of 0.8 and 3.8 kN, for the hardwood and CW dowels, respectively. The load-displacement behaviour of the hardwood dowels and the CW dowels in Series B can be seen in Figure 5b and it is quite clear that there are significant improvements in the pull-out load of the CW dowels. While the load-displacement behaviour of the hardwood dowels is similar to that experienced in Series A, the load-displacement behaviour of the CW dowels is characterised by a bi-linear curve, initially demonstrating linear elastic behaviour followed by a reduced slope until the pull-out capacity is achieved. Interestingly, the pull-out loads observed for the hardwood dowels were less than that observed for the hardwood dowels in Series A. This would indicate that the expansion of the hardwood dowels observed during the Series B conditioning phase does not contribute significantly to increased friction between the hardwood dowels and the timber substrate.

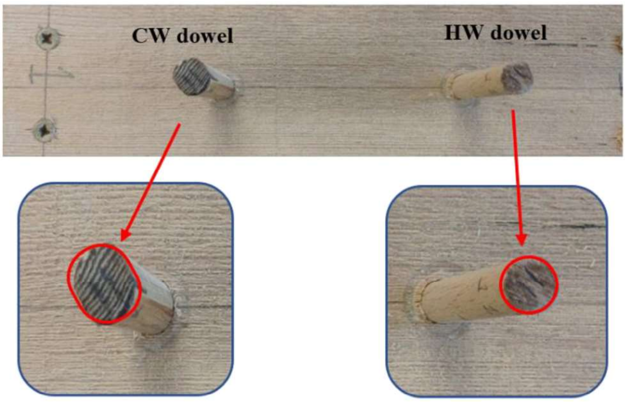


Figure 6: Typical shape of the dowels of Series B after 45 days of the conditioning phase.

In Figure 5c, the load-displacement behaviour of Series C can be seen. When subjected to an accelerated ageing treatment cycle, there was a significant improvement in the pull-out loads of both the hardwood and CW dowels. The mean pull-out load of the CW dowels (5.9 kN) was found to be only 75% higher than the loads achieved for the hardwood dowels (3.4 kN). The treatment applied to the dowels in Series C resulted in a mean increase of 34% in the radial dimension of the CW dowels and a mean increase of 2.3% in the radial dimension of the hardwood dowels when compared to their initial diameters. When compared with Series A and B, there were increases of 353 and 55%, respectively, in the pull-out strength values for the CW dowels in Series C. Similarly, when the hardwood dowels of Series C were compared with Series A and B results, increases of 184 and 331%, respectively, were observed. It can be seen in Figure 7 that the CW dowels expanded significantly during the accelerated ageing treatment due to shape-recovery in the radial direction and formed a funnel shape geometry.

Figure 7: Shape of the dowels of Series C after the treatment.

Figure 5d shows the load-displacement behaviour of Series D which subjected the CW dowels and hardwood dowels to three wetting-drying cycles. It was expected that repeating the ageing cycles may result in lower pull-out load values. However, increasing the number of ageing cycles positively affected the pull-out load of the CW dowels. A mean pull-out load of 6.9 kN was observed which is 145% higher than the mean pull-out load than connections with hardwood dowels. When compared with the pull-out strength of the CW connections of Series A, B and C, there were increases of 429, 81 and 17%, respectively, indicating that such cyclic changes in the surrounding environment do not adversely affect the performance of CW dowels but may actually be a beneficial trait for such applications.

When the pull-out load values for the hardwood dowels of this series were compared with hardwood connections of Series A and B, there were increases of 137 and 259%, respectively. However, when compared to hardwood dowels of Series C, which had a mean pull out load of 3.4 kN, specimens of this series resulted in a 17% lower mean pull-out load of 2.8 kN. This would indicate that repeated cycling has a negative effect on hardwood dowels and affects the dowel-timber interaction resulting in a potential degradation of the dowel performance with time. To investigate this further, Figure 8 presents the change in mean radial dowel diameter of the CW and hardwood dowels during the various steps of the accelerated ageing treatment in Series D. The CW dowels showed a mean increase of 42% of the initial dimension in the radial direction. Whereas the increase was only 2.5% for the hardwood dowels. It can be seen in Figure 8 that the first accelerated cycle results in a significant increase in the radial dimension when examined after the first cycle of drying (72 h) but there is a further increase with each additional cycle. The mean radial swelling of the CW dowels of Series D was 8.2% higher than the CW dowels of Series C as a result of two additional pressure soaking cycles. When examining the hardwood dowels the mean radial swelling of the Series D was negligible (0.2% higher) when compared to the hardwood dowels of Series C.

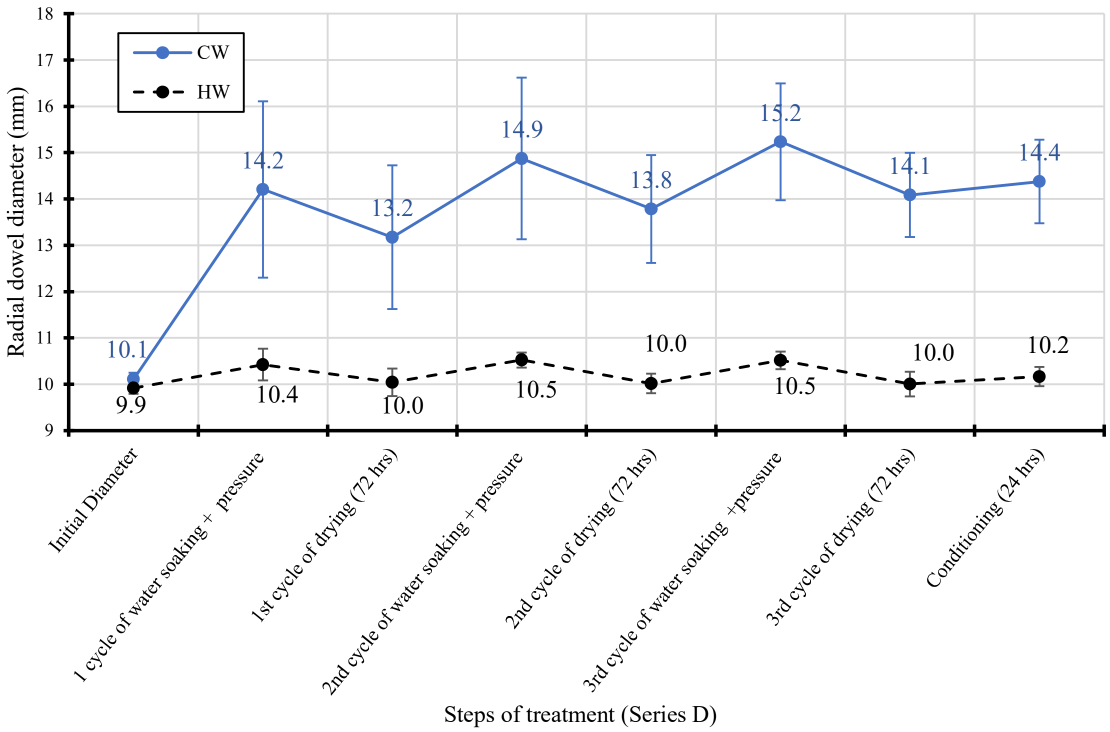


Figure 8: Change in dowel diameters of CW and hardwood dowels for Series D.

It is clear that the CW dowels expanded due to shape-recovery in the radial direction and formed a funnel shape geometry after the first cycle of the accelerated ageing treatment. For Series C, the mean radial dimension was 13.6 mm after completion of the corresponding ageing cycle, whereas this was 14.4 mm for Series D. These findings confirmed that the increase in the number of ageing cycles results in a significant swelling of dowels in a radial dimension. Consequently, with each cycle, an improvement in the tightness of the CW dowel-timber interaction is observed. However, the hardwood dowels maintained their cylindrical shape with negligible increases in diameter with subsequent accelerated ageing cycles. While the radial expansion of the hardwood dowels in Series D (2.5%) was slightly higher than hardwood dowels in Series C (2.3%) this did not result in a higher pull-out load and there appears to be some degradation of the hardwood dowel-timber interaction. It should also be noted that there are a number of characteristics influencing the pull-out behaviour of both the CW and hardwood dowels, such as differences in moisture expansion coefficients and diffusion coefficients which may results in differences under the common exposure conditions, but it is believed that the significant differences between the two materials are primarily due to the shape-recovery effect of the CW material which is a unique characteristic of the CW material.

4 Conclusions

The accelerated ageing tests, presented in the current study, have shown that shape-recovery leads to the expansion of CW dowels and facilitates form and friction fit with the timber substrate which can yield a higher pull-out capacity and improved long-term performance of CW dowels when compared to hardwood dowels. Therefore, there is a benefit to using CW dowels as a replacement for hardwood dowels in structural applications such as timber-timber dowelled connections which can take advantage of the shape-recovery of CW and may result in better long-term behaviour.

When examining the performance of the test specimens 24 h after dowel insertion, there was no significant difference in the pull-out load values of the two dowel types. Significant differences in pull-out load were only observed after the dowels were conditioned for a period at a standard temperature of 20 ± 2 °C and at a relative humidity of 65 ± 5% which allowed the shape-recovery effect to take place resulting in increased form and friction fit. Further increases in pull-out load were observed when the CW dowels were subjected to accelerated ageing tests under a series of different wetting and drying cycles which demonstrated improved pull-out performance. In comparison to this, connections with hardwood dowels showed no improvement in pull-out load when conditioned at a standard temperature of 20 ± 2 °C and relative humidity of 65 ± 5%, but improvements in the pull-out strength were observed when the hardwood dowels were subjected to accelerated ageing tests. However, the pull-out loads achieved with hardwood dowels were lower than the CW dowels irrespective of the number of cycles. Furthermore, while each cycle resulted in increased performance for the CW dowels, tests on the hardwood dowels indicated that increasing the number of cycles has a negative effect on the pull-out load and there appears to be some degradation of the hardwood dowel-timber interaction with repeated cycling.

This study has shown that the shape-recovery of CW dowels could be utilised as a beneficial trait for structural timber applications. During the in-service life, the use of CW dowels may retain/improve their performance when utilised in structural elements subjected to variations in the surrounding environment due to the shape-recovery behaviour of CW and the potential degradation in the performance of hardwood dowels may be avoided.

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