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Influence of Weathering on the Structural Performance of Sheathing-to-Timber Connections

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Abstract: The sheathing-to-timber connection (STC) is a critical component of timber-framed shear walls. The STC provides the shear wall system with its racking resistance, while anchors and tiedowns provide resistance to sliding and overturning, respectively. Because building materials are exposed to weathering during construction, this study aims to quantify the influence of weathering on the structural performance of STCs. To achieve this aim, a total of 117 small-scale specimens were fabricated with 5 different sheathing types and 2 different timber species. Each specimen comprised 2 panels of sheathing connected to 2 short lengths of pine timber (90 × 35 mm cross-section), with a total of 16/2.8(ϕ) × 30 mm (l) galvanised clouts at 45 mm spacings. Some specimens were tested under the EN 594 monotonic loading protocol and others were tested under the ISO 16670 cyclic loading protocol. Some specimens were exposed to the weather for a period of 6 months before being tested, while others were stored in an air-conditioned environment before being tested. The results show that weathering reduces the ultimate and yield capacity of STC connections by 3% and 5% on average, respectively; however, this result is not statistically significant for most sheathing types. The results varied, with some configurations having an ultimate capacity up to 16% higher and others having an ultimate capacity as much as 20% lower for weathered specimens compared to unweathered specimens. However, weathering reduces the stiffness of STCs by 61% and ductility by 50%, a statistically significant result. For most sheathing types, these findings do not support reductions to the design capacity of STCs that have been exposed to weathering.

Keywords: weathering; connections; shear capacity; sheathing; plywood; OSB; hardboard; particleboard

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1. Introduction

Timber and engineered wood products (EWPs) can be exposed to the weather for weeks or months during the construction phase, allowing moisture to penetrate the materials. If moisture becomes trapped it can promote decay and rot [1], which rapidly degrades the material and can have catastrophic consequences, as happened, for example, in the fatal 2015 Berkeley balcony collapse [2]. Even if excess moisture is removed prior to commissioning of the building and timber is protected from decay and rot, the process of weathering can lead to degradation of timber and EWPs [3], which may have some effect on structural performance (e.g., [4,5]).

The amount of weathering of timber and EWPs depends on several factors, including level of exposure, period of exposure, and climatic conditions. While designers and builders have some control over exposure level and time, they have no control over the climate. With extreme climatic conditions expected to increase in frequency and severity because of climate change [6], there is an increasing need to better understand the effect of weathering on the structural performance characteristics of timber buildings and their components.

Historical studies, reported in [7], have shown that, in the absence of decay and rot, weathering processes primarily affect the outer layers of wood and have little effect on the structural performance of solid wood. The structural performance of plywood and particleboard in these historical studies, however, was substantially affected. Assemblies comprising EWPs should therefore be subjected to weathering and tested in the laboratory to quantify the influence of weathering on their structural performance.

Timber-framed shear walls are assembled with timber and EWPs and are designed to resist lateral loads from wind and earthquakes on timber-framed buildings. The sheathing-to-timber connection (STC) is a critical component of timber-framed shear walls. The role of the STC is to resist the racking load, while overturning is resisted by tiedowns and sliding is resisted by anchors. Structural performance characteristics which are used in the design of timber-framed shear walls and STCs are based on experimental testing using materials that have typically been stored under cover (e.g., [8–10]).

The decision to use unweathered materials in an experimental study, rather than weathering the specimens, is a pragmatic one. Weathering takes a long time and requires a secure outdoor location for the storage of specimens and data logging equipment. Researchers are often constrained by cost, time, and availability of secure outdoor space, which is perhaps why most experimental work is performed on unweathered specimens. Accelerated weathering is a technique used by some researchers to emulate weathering in a timely fashion (e.g., [4,11]).

Here, we report on our experimental test plan to quantify the influence of weathering on the structural performance of sheathing-to-timber connections. Following a brief review of the relevant literature, the test methods are described and the results are presented. Analysis and discussion of the results show that weathering does not significantly affect the ultimate and yield capacity of STCs; however, it does reduce their stiffness and ductility. This paper includes a brief evaluation of the influence of loading protocol and timber species on the structural performance characteristics of STCs. We conclude the paper with a reflection on the relevance of our findings to industry.

The results from this study have been used in the development of new products and systems in Australia and have provided input to the industry technical literature.

2. Literature Review

The critical component in a typical timber-framed shear wall is the connection between the bracing diaphragm, usually plywood or oriented strand board (OSB), and the timber framing. The sheathing material is fastened to the timber framing with nails or screws, and it is this connection that usually fails in racking tests. The most common failure modes of timber-framed shear walls to be found in the literature relate to the nail connection: that is, nail pull-through, nail pullout, and nail fracture. Localised failures of the timber framing and sheathing are less common: that is, splitting of timber, shear failure at tiedown points, tearing of sheathing, and buckling of sheathing (e.g., [8,12]).

Given the importance of STCs in timber-framed shear walls, and given the fact that building materials are exposed to the weather during construction, it is somewhat surprising that relatively little research has been undertaken on the effects of weathering on the structural performance of STCs. Before looking at the literature on weathering of STCs, it is helpful to provide a broad overview of weathering of timber and wood-based composites.

2.1. Weathering of Timber and Wood-Based Composites

Feist [7] synthesised a great deal of scientific research from the mid-20th century, finding that weathering of solid timber primarily affected the timber surface and had little effect on structural performance. Feist showed that weathering of solid timber is caused by (1) ultraviolet radiation decomposing the timber surface, (2) erosion from wind and water removing decomposed and abraded material, and (3) movement of moisture through the timber causing shrinkage and swelling which opens cracks, allowing further erosion.

While the structural performance of solid wood is affected little by weathering (a point also acknowledged in [1,3]), Feist [7] reported that weathering of plywood and particleboard products, over a period of just one or two years, was found to cause substantial strength loss. The more recent work of Evans [3] reports on advances in adhesive technology leading to improved weathering performance of wood-based composites, including plywood, oriented strand board, particleboard, fibreboard, wood fibre cement composites, wood plastic composites, glulam, and laminated veneer lumber. However, Evans notes that the status of research on weathering of wood-based composites is not as mature as that of solid wood. Evans concludes that "[w]ood composites are more susceptible to the deleterious effects of moisture than solid wood" [3] (p. 188). There is, therefore, an established need to learn more about the influence that weathering has on the mechanical properties of wood-based composites and the assemblies that use them.

2.2. Weathering of Sheathing-to-Timber Connections

There are a handful of studies on the types of weathering processes (i.e., flooding, wetting, artificial weathering, and natural weathering) and their effects on the structural performance of shear walls or sheathing-to-timber connections [4,5,11,13–18]. The following review is presented in chronological order.

Leichti et al. [13] tested nine (9) 2.4 × 2.4 m timber-framed shear walls under three different scenarios ($n = 3$): (1) dry then tested with a monotonic loading protocol, (2) dry then tested with a cyclic loading protocol, and (3) submerged in 1 m of water for seven days, then air dried and tested with a cyclic loading protocol. The test panel framing comprised 38 × 89 mm Douglas fir double top plate, single bottom plate, studs at 406 mm spacings, and double studs at the ends of the test panel. The test panel sheathing was 11.9 mm Exposure-1 OSB panels fixed to the framing with 2.9 (ϕ) × 60.3 mm (l) 8d gun-driven nails at an unspecified spacing. The test panels in the monotonic and cyclic control groups achieved a mean ultimate capacity of 29.1 kN and 26.8 kN, respectively. The test panels subjected to the simulated flood achieved a slightly higher ultimate capacity of 30.6 kN; however, the authors noted a moderate loss of initial stiffness (i.e., 696 N/mm for the flooded test panels compared to 954 N/mm for the cyclic control group).

Nakajima and Okabe [14] tested 204 nailed sheathing-to-timber connections in 4 different configurations, with 2 types of sheathing (i.e., plywood and OSB with thickness unspecified) fixed to unspecified timber using "common nails 50 mm in length (CN50)", under 3 different climate conditions: (1) conditioned at 20 °C and 65% relative humidity (RH) for one week, (2) as per (1) plus conditioned at 20 °C and 90% RH for three weeks, and (3) as per (2) plus conditioned at 20 °C and 65% RH for three weeks. The results showed that plywood specimens lost approximately 12% strength when tested following high-humidity conditioning but regained that capacity after the additional three weeks of conditioning in low humidity. The capacity of OSB specimens was unaffected by humidity conditioning but failure modes of all specimens were significantly affected by climate conditioning, with a marked increase in the number of pull-through failures in the high-humidity specimens.

Beall et al. [15] built an unspecified number of small 1.2 × 1.2 m shear walls with two types of sheathing (i.e., 12 mm Structural-1 Douglas fir plywood and 12 mm Exposure-1 OSB) fixed to 2″ × 4″ kiln-dried (KD) Douglas fir with 8d nails in various configurations under three different climate conditions: (1) standard "dry" condition, (2) conditioned at 85% RH for six weeks, and (3) wetting of the bottom plate to simulate green timber. The results showed moisture conditioning had minimal effect on the structural performance of small-scale shear walls.

King et al. [16] built 112 small 610 × 610 mm shear wall test panels with 11 mm Exposure-1 OSB fixed to 38 × 89 mm KD Douglas fir with 2.9 (ϕ) × 60 mm (l) gun-driven Senco nails and tested under dry and wet conditions. Half the specimens were given fungal inoculations to promote decay. A cyclic wetting regime was implemented and 16 specimens were tested after 32, 112, 177, 234, 258, and 402 days of wetting. Their study showed that the strength of wetted specimens was 14% to 34% higher than dry specimens. The result was statistically significant with $p < 0.001$. The authors speculated that the higher capacity of the wetted specimens was due to corrosion of the connectors, which created more friction in the connection. As an aside, this hypothesis has been tested in nail withdrawal studies by Yermán et al. [19], who conducted 240 nail withdrawal tests under several different scenarios and confirmed that corrosion of fasteners does, in most cases, increase nail withdrawal capacity after several cycles of wetting and drying (also correlating with increased corrosion); however, the capacity then declines with additional cycles of wetting and drying, while corrosion of the fasteners remained relatively constant.

Bradley et al. [17] made some improvements to the methodology of [13] and constructed nine 2.4 (w) × 1.8 m (h) timber-framed shear walls which were then tested with a monotonic loading protocol under three different scenarios ($n = 3$): (1) dry, (2) wetted for five days in 1m of water, and (3) as per (2) plus dried at 38 °C and 40% RH. Test panel framing comprised 38 × 140 mm Douglas fir top and bottom plate and studs at 600 mm spacings. Test panel sheathing was 9 mm "Norboard" OSB/3 panels fixed to the framing, with 3.1 (ϕ) × 90 mm (l) gun-driven nails at 150 mm spacing around the perimeter of the OSB sheets and 300 mm spacing along internal studs. Test panels under the three scenarios achieved a mean ultimate load of 18.2 kN (dry), 14.7 kN (wet), and 13.8 kN (restored), respectively. These results differ remarkably from those of [13], with the loss of ultimate capacity between the control group and the other two groups being statistically significant with $p < 0.005$. The authors also noted a statistically significant loss of approximately 20% initial stiffness and a slight reduction in the ductility (not statistically significant) of the wet and restored groups compared to the control group. The authors note that their result is consistent with other studies on weathering of sheathing materials but not STCs (not reviewed here), which show that flooding has a negative effect on building materials, whereas Leichti et al. [13] reached a different conclusion on the effect of flooding on the ultimate capacity of shear walls.

Maqsood et al. [18] constructed twenty 1.8 (w) × 2.4 m (h) timber-framed shear walls using two different sheathing types, described simply as OSB and high-density fibreboard (HDF), which were then tested with a cyclic loading protocol under two different scenarios ($n = 5$): (1) dry and (2) immersed in 600 mm of water for four days and allowed to air dry for six weeks. Timber framing was described as MGP10 with studs at 450 mm spacings; however, the sheathing thickness and timber framing sizes were not provided. Sheathing was fixed to the framing with 2.5 (ϕ) × 32 mm (l) nails. OSB test panels had nails at 80 mm spacing along the top and bottom plates, 150 mm spacing along the vertical edges of the sheets, and 300 mm spacing along internal studs. HDF test panels had nails at 100 mm spacing on all studs and plates. OSB test panels achieved a mean ultimate capacity of 5.35 kN for the dry group and 5.47 kN for the wet-then-dry group. HDF test panels achieved a mean ultimate capacity of 6.77 kN for the dry group and 5.60 kN for the wet-then-dry group. The difference in ultimate capacity was statistically significant for the HDF test panels, with $p = 0.016$ on a one-sided rank-sum test; however, there was no significant difference between the two groups of OSB test panels.

Way et al. [11] tested the lateral nail resistance of 240 sheathing specimens (i.e., not connected to a timber substrate) with nails driven near the edge using 2 different sheathing types, 11.1 mm thick aspen OSB and 18.25 mm thick Douglas fir plywood, of 3 different sheathing widths (76, 152, and 305 mm) under 4 different scenarios ($n = 10$): a control group tested dry and 3 different methods of accelerated weathering. Nails of 3.32 (ϕ) × 75 mm (l) were driven into the sheathing and tested in lateral shear. The results showed no statistically significant difference in capacity between the control group and weathered specimens.

Poletti et al. [5] tested the performance of nine traditional half-lap joints using 120 × 80 mm *Pinus pinaster* timber connected in three different configurations ($n = 3$): (1) unreinforced, (2) reinforced with four screws, and (3) strengthened with steel plates. One specimen in each group was subject to wet/dry cycles for 27 days and one specimen in each group was subject to the same wet/dry cycling for 54 days. The last specimen in each group was subject to the same wet/dry cycling for 4 days followed by submersion in water for 7 days. All specimens were allowed to dry for 7 days prior to testing. The results were compared to previous testing of sound connections [20] showing that all groups experienced a decrease in capacity of 11% to 31% due to weathering.

Way et al. [4] built 12 2.44 × 2.44 m timber-framed shear walls using 2 different sheathing types, 11.1 mm thick Exposure 1 OSB and 18.25 mm thick Exposure 1 plywood, and tested using a monotonic loading protocol under 2 different scenarios ($n = 3$): (1) dry and (2) with sheathing which had been subjected to accelerated weathering over a 28-day period followed by undercover storage for 21 days prior to assembly. Test panel framing comprised 38 × 89 mm KD Douglas fir double top and bottom plates, studs at 610 mm spacings, and double studs at the ends of the test panel. Test panel sheathing was fixed to the framing with 3.33 (ϕ) × 64 mm (l) 8d nails at 102 mm spacing around the perimeter and 305 mm spacing along intermediate studs. The results showed that test panels constructed with weathered OSB lost 20.4% ultimate capacity and 35.7% in energy dissipation (statistically significant with $p < 0.05$), whereas those constructed with weathered plywood experienced a small, but statistically insignificant, gain in ultimate capacity of 3.4% and loss in energy dissipation of 6.7%. Curiously, test panels with weathered sheathing had higher initial stiffness, although this result was not statistically significant.

To summarise the literature on weathering of STCs, some studies show that weathering can lead to a loss of up to 31% in the structural performance of traditional joints and timber-framed shear walls [5,17]; others show that weathering/flooding can improve the structural performance of STCs and timber-framed shear walls by as much as 34% [13,16]; most studies show that weathering/moisture conditioning has no significant effect on the structural performance of STCs and sheathing [11,14,15]; one study showed that flooding had no effect on the structural performance of timber-framed shear walls with OSB sheathing, but did have a 17% lower capacity on walls with HDF sheathing [18]; and one study showed that weathering did not affect the structural performance of timber-framed shear walls with plywood sheathing, but did have a 20% lower capacity on walls with OSB sheathing [4]. Importantly, all these studies used artificial weathering techniques. None of the studies in this review adopted a natural weathering methodology.

2.3. Test Methods for Sheathing-to-Timber Connections

Published capacities for individual connectors can be found in various standards and in technical guidance from industry associations and manufacturers of proprietary products. While this information is useful for design purposes, engineers would like more detailed information on the structural performance characteristics of sheathing-to-timber connections that are commonly used in timber-framed shear wall construction. Simple pullout tests of individual connectors may not adequately capture the behaviour of interest. On the other hand, full-scale testing of shear walls is time-consuming and expensive. To conduct testing on large sample sizes, it is more feasible to use small-scale specimens.

Sartori and Tomasi [10] devised small-scale specimens comprising two sheets of 320 × 600 mm sheathing glued to a horizontal 80 × 160 mm timber sill beam at the base and connected with nails or staples to a vertical stick of 60 × 160 mm timber. The sill beam was secured to the reaction frame, while the hydraulic actuator was connected to the vertical stick of timber. There was a gap between the two sticks of timber to allow deformation during the test.

Germano et al. [21] created small-scale specimens with two sheets of 600 × 621 mm particleboard sheathing nailed or stapled to two vertically oriented sticks of 100 × 160 mm GL24h glulam timber separated by a gap to allow deformation during the test. While some researchers use rollers to restrict out-of-plane effects, Germano et al. [21] chose to use "transverse connecting rods" to restrain the lateral buckling of sheathing. They used three pairs of 3 mm (ϕ) connecting rods to prevent detachment of the sheathing from the timber. The current study will adopt this design for STC specimens.

The choice of loading protocol can have a significant influence on the structural performance characteristics of timber-framed shear walls [8,12]. For this reason, the current study will use both a monotonic (EN 594) [22] and a cyclic (ISO 16670) [23] loading protocol.

3. Materials and Methods

In total, 117 small-scale specimens were assembled as shown in Figure 1 below. Each specimen comprises two sheets of 300 × 450 mm sheathing nailed to two 250 mm long sticks of 90 × 35 mm timber, with 16/2.8 (ϕ) × 30 mm (l) galvanised clouts hammered in by hand at 45 mm spacings and with six 3 mm (ϕ) booker rods as spacers, each with four nuts tightened by hand, on the vertical edges of the sheathing to restrain out-of-plane buckling and better replicate how the sheathing panels behave in a real-world application where the sheathing is continuous spanning between studs.

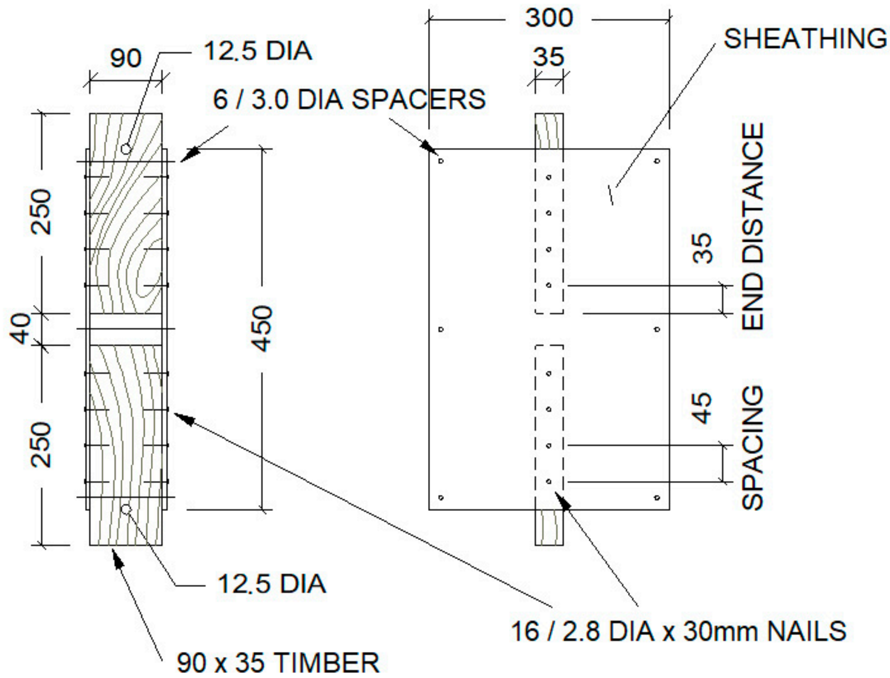

Figure 1. Typical small-scale test specimen (dimensions in mm).

The solid timber in this study came from two sources: (1) the Southern Queensland pine (SQP) resource, which includes *pinus elliottii* var. *elliottii*, *pinus caribaea* var. *hondurensis*, or a hybrid of the two species, and (2) spruce/pine/fir (SPF) imported from Europe and visually identified as a species of spruce. Both the SQP and SPF timber were graded MGP10 (i.e., machine-graded pine with a characteristic average modulus of elasticity of 10 GPa).

Five types of sheathing were tested in this study: (1) 7 mm thick F8 plywood consisting of three veneers of *pinus radiata* with a D-grade face and back glued together with a phenolic A bond resin; (2) 4 mm thick F22 plywood consisting of three veneers of mixed tropical hardwood species with a D-grade face and back glued together with a phenolic A bond resin; (3) 6 mm thick OSB made by two different European manufacturers, although only one product is currently available in the Australian market; (4) 5.5 mm thick general purpose (GP) hardboard available in the Australian market as a flooring underlay; and (5) 5 mm thick particleboard (PB) developed as part of a separate industry project. The F-grade on structural plywood in Australia relates to a set of characteristic design properties defined in AS 1720.1 [24], with the quality of the visible veneer (front and back) visually graded in accordance with s.2 of AS/NZS 2269.0 [25]. The GP hardboard and PB sheathing products are not currently sold as structural bracing materials in Australia and have been included in this study to better understand their suitability. It should be noted that the GP hardboard and PB sheathing products in this study do not have a "moisture resistant" rating.

The test matrix for the current study is shown in Table 1.

Table 1. Test matrix.

Group	Sheathing Type	Timber	Weathered?	Sample Size †
SP	7 mm F8 plywood	SQP	No	3M, 5C
WSP		SQP	Yes	3M, 5C
ESP		SPF	No	3M, 5C
WESP		SPF	Yes	3M, 4C
HP	4 mm F22 plywood	SQP	No	3M, 5C
WHP			Yes	3M, 4C
OS	6 mm OSB	SQP	No	6M, 10C *
WOS		SQP	Yes	3M, 5C
EOS		SPF	No	3M, 5C
WEOS		SPF	Yes	3M, 5C
WU	5.5 mm hardboard	SQP	No	3M, 5C
WWU			Yes	3M, 4C
PB	5 mm PB	SQP	No	3M, 5C
WPB			Yes	3M, 5C

† Number denotes sample size and letter denotes loading protocol: M, monotonic and C, cyclic. * The OS group is a combination of materials from two European manufacturers.

Conditioning of the 64 unweathered specimens aligned closely with s.8 of AS/NZS 4357.2 [26], with the specimens being stored undercover for a minimum of two weeks and then moved to an air-conditioned room for at least two days before being tested. The 53 weathered specimens were placed outside in an exposed location in Brisbane, Australia, for 3 months over the summer of 2020/2021 (Figure 2). The weathered specimens were then covered with a tarpaulin and left outdoors for a further 3 months over the autumn of 2021. The specimens were exposed to 311 mm of rain in the first 3 months. Over the 6 months of full exposure and being covered under a tarpaulin, the specimens were exposed to a minimum temperature of 12.4 °C, a maximum temperature of 33.2 °C, and a mean temperature range of 19.9–27.9 °C. The specimens were also exposed to a minimum relative humidity of 16%, a maximum RH of 100%, and a mean relative humidity of 64.0% [27]. The weathered specimens were then conditioned in the same way as the unweathered specimens; that is, stored undercover for a minimum of two weeks and finally moved to an air-conditioned room for at least two days before being tested.

Figure 2. Exposure of weathered specimens.

Testing was conducted using a 300 kN Instron testing machine with custom steel brackets for holding the specimens. The specimens were loaded into the brackets and fixed with two M12 bolts which were tightened with a ratchet spanner and Allen key (Figure 3). Observations were taken prior, during, and upon the conclusion of each test. A preload of 200 N was chosen and the monotonic specimens were tested using a simple monotonically increasing load under displacement control of 3 mm/min, as per the loading protocol from EN 594 [22]. Cyclic tests followed the same setup procedure as the monotonic tests. The ISO 16670 [23] cyclic loading protocol was used with a displacement-controlled rate based on the mean ultimate displacement (Δ_m) of the monotonic tests for each sample group (Table 2). Load and displacement data were obtained directly from the Instron (i.e., crosshead displacement). Laser displacement transducers were trialled early in the test program (see Figure 3) to obtain more accurate measurements but lacked sufficient precision and were subsequently discarded.

Figure 3. Test setup with unweathered OSB specimen (photo taken during test).

Table 2. Loading rate for cyclic tests by group.

Group	SP	WSP	ESP	WESP	HP	WHP	OS	WOS	EOS	WEOS	WU	WWU	PB	WPB
Δ_m(mm)	16	18	21	23	16	18	17	20	23	23	14	14	14	18
Loading Rate (mm/min)	20	22	26	28	20	22	21	25	28	28	17	17	17	22

Testing of the unweathered specimens occurred at various times between November 2019 and January 2020 and in October 2020, while testing of the weathered specimens occurred in April 2021.

4. Results

4.1. Determining Structural Performance Characteristics

For ease of comparison with similar studies of STCs (e.g., [10,21]), the structural performance characteristics will be calculated according to the methodology outlined in EN 12512 [28] and EN 26891 [29]. Since this study of small-scale specimens is relevant to full-scale shear walls, structural performance characteristics will also be calculated in accordance with the American standard test method for shear walls ASTM E2126 [30].

An averaged compression and tension envelope curve, often called a backbone curve, is derived from the hysteresis curve of the cyclic tests to determine the yield load (F_y) and yield slip (v_y) (Figure 4). The load–slip curve from monotonic tests can be used directly. The maximum load (F_{max}) is the absolute maximum load taken from the envelope curve. The yield load (F_y) and yield slip (v_y) are identified by finding the intersection of two lines: (1) a line through the $0.1{\cdot}F_{max}$ and $0.4{\cdot}F_{max}$ intersection points on the envelope curve, and (2) a tangent line with a gradient one-sixth of the first line just touching the envelope curve. In this study, due to the choice of loading protocols (i.e., EN 594 [22] and ISO 16670 [23] instead of EN 26891 [29] and EN 12512 [28]), the estimated maximum load (F_{est}) was not used in determining stiffness. The stiffness, or slip modulus (k_s), can be found by using a modified initial slip ($v_{i,mod}$), with F_{max} being used instead of F_{est}:

$$v_{i,mod} = \frac{4}{3}(v_{04} - v_{01}) \quad (1)$$

$$k_s = 0.4{\cdot}\frac{F_{max}}{v_{i,mod}} \quad (2)$$

where v_{01} is the slip at $0.1{\cdot}F_{max}$ and v_{04} is the slip at $0.4{\cdot}F_{max}$.

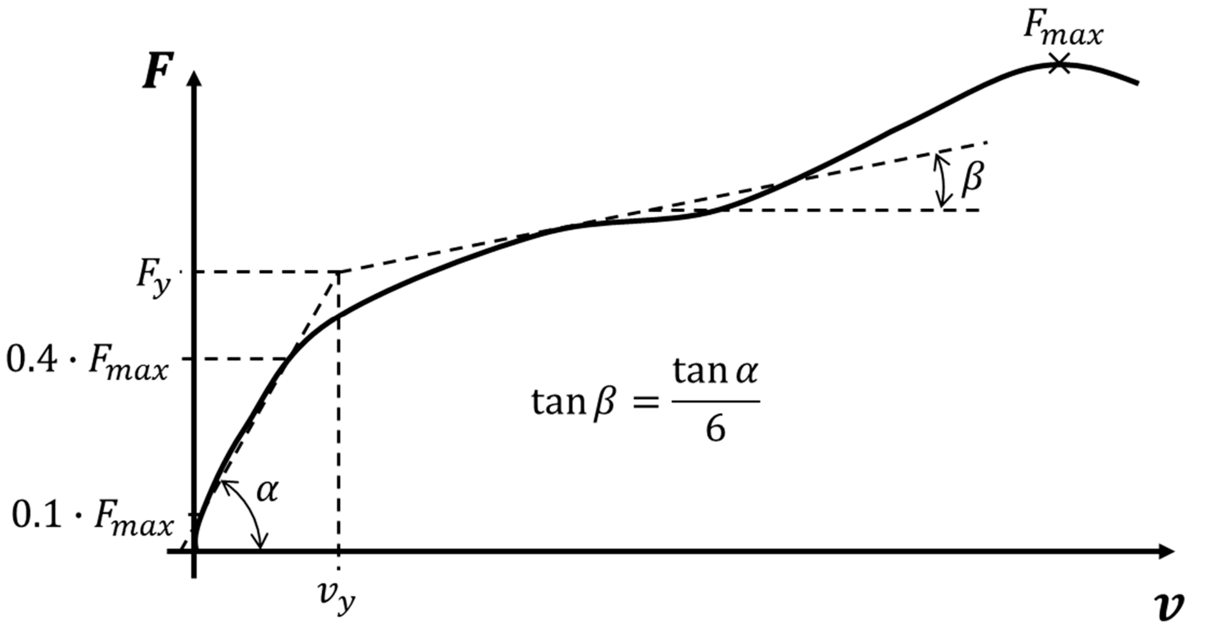

Figure 4. Definition of yield values for load–slip curve (reproduced from [28]).

Ductility (D) is the ratio of ultimate (v_u) and yield displacement (v_y), where v_u is the minimum of: (1) at the point of failure, (2) when the load drops below $0.8{\cdot}F_{max}$, or (3) when displacement reaches 30 mm.

Structural performance characteristics are determined differently in the American standard ASTM E2126 [30], where an equivalent energy elastic–plastic (EEEP) curve is used to find the yield load (F_y):

$$F_y = \left(v_u - \sqrt{v_u^2 - \frac{2A}{k_e}} \right) k_e \tag{3}$$

where A is the area under the envelope (cyclic) or load–displacement (monotonic) curve, v_u is the minimum of: (1) slip at the point of failure or (2) slip when the load drops below $0.8{\cdot}F_{max}$, and k_e is the elastic shear stiffness equal to $(0.4{\cdot}F_{max})/v_{04}$. Ductility ($D$) is the ratio of ultimate (v_u) and yield displacement (v_y), where $v_y = F_y/k_e$.

4.2. Load–Displacement Curves

Examples of load–displacement curves can be seen in Figure 5 (specimen HP2, tested under a monotonic loading protocol) and Figure 6 (specimen WSP6, tested under a cyclic loading protocol). The backbone curve in Figure 6 is the average of the tension and compression envelope curves using only the data from the first cycle at each displacement increment.

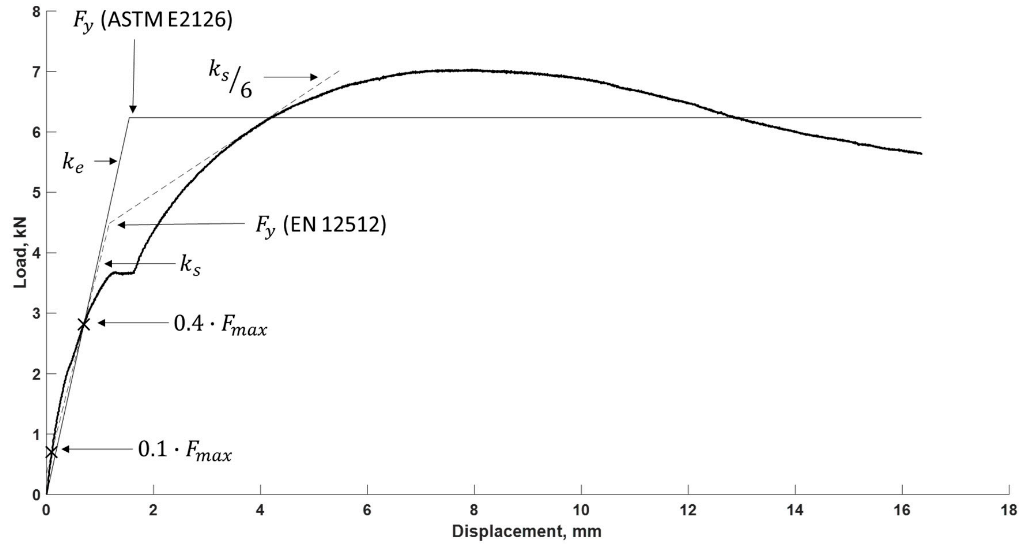

Figure 5. Load–displacement plot of specimen HP2 annotated to show stiffness and yield loads.

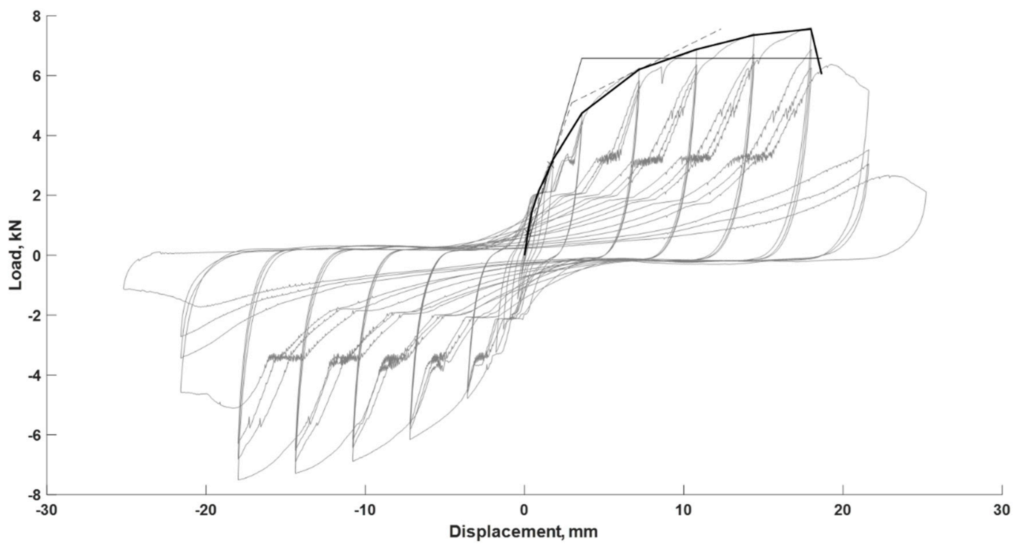

Figure 6. Load–displacement plot of specimen WSP6 including backbone curve.

The load–displacement curves of each group, tested under a monotonic loading protocol, have been averaged and plotted for comparison in Figure 7. The envelope curves of each group, tested under a cyclic loading protocol, have been averaged and plotted for comparison in Figure 8. In both figures, the solid lines represent unweathered groups and the dashed lines represent weathered groups.

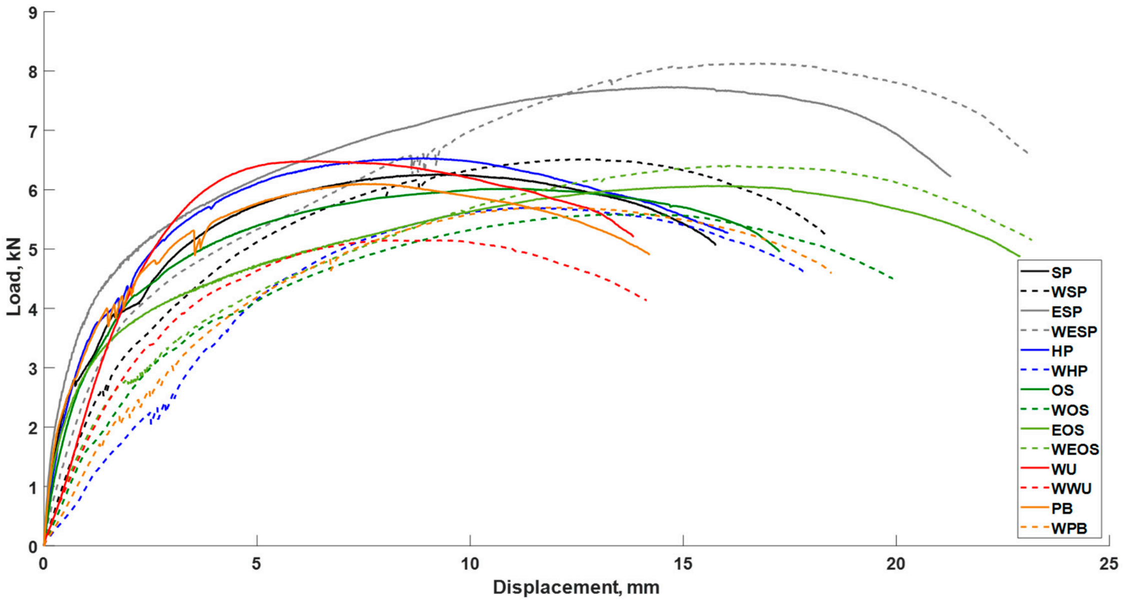

Figure 7. Averaged load–displacement plots by group tested under monotonic loading protocol.

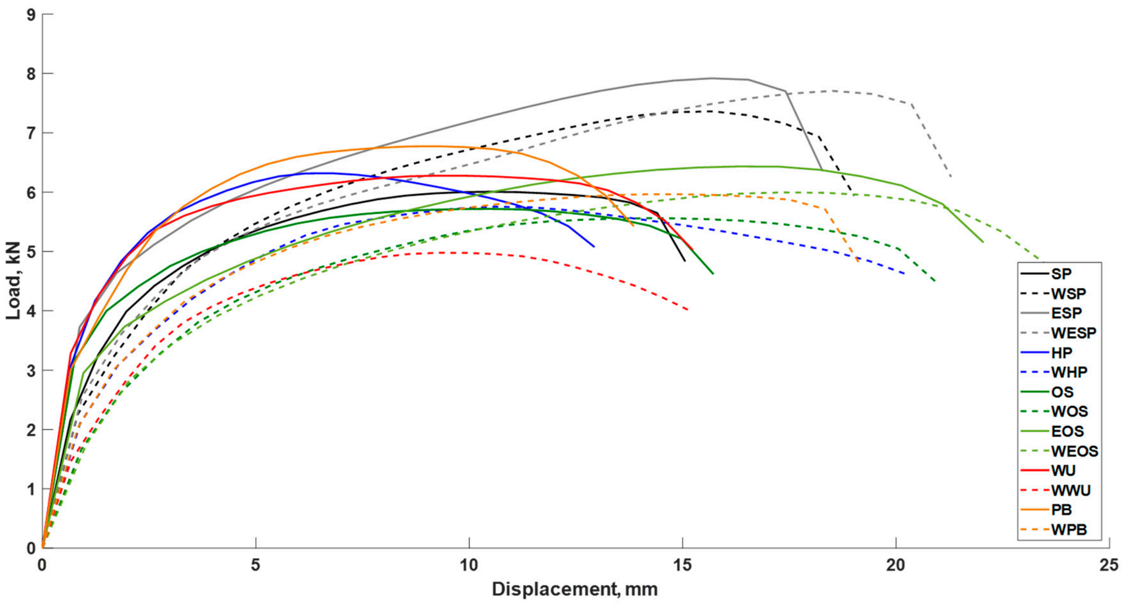

Figure 8. Averaged backbone plots by group tested under cyclic loading protocol.

Several features of the load–displacement plots in Figures 7 and 8 are worth noting. Most apparent is the lower stiffness of weathered groups (dashed lines) compared to unweathered groups (solid lines). In general, unweathered groups achieve higher peak loads than weathered groups; however, there are exceptions, for example, with the highest average peak load being observed in the WESP group tested under monotonic load in Figure 7 (i.e., weathered with SPF timber and 7 mm F8 plywood sheathing). Notably, groups with SPF timber (light grey and light green lines) have higher ultimate displacements compared to groups with SQP timber.

4.3. Results

Mean values for peak load (F_{max}), yield load (F_y), stiffness (k_s and k_e), and ductility (D), organised by group and loading protocol, are summarised in Table 3 below, with standard deviations *italicised* in parentheses.

Table 3. Structural performance characteristics of STCs by group and loading protocol.

Group	Sample Size and Loading Protocol ‡	F_{max} (kN)	F_y (kN) EN *	F_y (kN) ASTM †	k_s (kN/mm) EN *	k_e (kN/mm) ASTM †	D EN *	D ASTM †
SP	3M	6.28 (*0.70*)	3.53 (*0.94*)	5.63 (*0.69*)	3.96 (*0.60*)	4.49 (*0.59*)	20.41 (*7.50*)	12.65 (*2.63*)
	5C	6.04 (*0.62*)	3.87 (*0.18*)	5.47 (*0.59*)	2.78 (0.72)	3.19 (0.79)	11.84 (*4.10*)	8.69 (*2.24*)
WSP	3M	6.54 (*0.51*)	4.49 (*0.68*)	5.88 (*0.45*)	1.86 (*0.77*)	1.98 (*0.81*)	7.98 (*3.53*)	6.01 (*2.09*)
	5C	7.42 (*0.73*)	4.73 (*0.72*)	6.50 (*0.58*)	1.92 (*0.45*)	2.16 (*0.41*)	8.73 (*3.46*)	6.44 (*1.84*)
ESP	3M	7.76 (*1.15*)	4.08 (*0.46*)	6.88 (*0.89*)	4.41 (*0.68*)	5.25 (*0.78*)	25.97 (*3.00*)	16.15 (*2.05*)
	5C	7.94 (*0.34*)	3.94 (*0.28*)	6.77 (*0.32*)	4.61 (*0.84*)	5.12 (0.83)	23.23 (*3.77*)	13.75 (*1.94*)
WESP	3M	**8.20 (*0.25*)**	4.38 (*0.16*)	**6.99 (*0.24*)**	2.06 (*0.06*)	2.29 (*0.19*)	11.75 (*1.51*)	7.57 (*1.04*)
	4C	7.82 (*1.68*)	4.25 (*0.69*)	6.55 (*1.13*)	2.24 (*0.36*)	2.48 (*0.35*)	12.95 (*6.32*)	8.69 (*4.36*)
HP	3M	6.57 (*0.53*)	4.19 (*0.25*)	5.92 (*0.39*)	3.86 (*1.44*)	4.24 (*1.58*)	15.52 (*5.20*)	11.28 (*3.16*)
	5C	6.34 (*0.47*)	4.08 (*0.24*)	5.74 (*0.35*)	4.79 (*0.62*)	5.19 (*0.56*)	16.05 (*3.12*)	11.76 (*2.41*)
WHP	3M	5.73 (*0.22*)	5.04 (*0.30*)	5.39 (*0.25*)	**0.89 (*0.22*)**	**0.88 (*0.25*)**	**3.18 (*1.07*)**	**2.95 (*0.91*)**
	4C	5.76 (*0.40*)	3.64 (*0.10*)	5.13 (*0.37*)	2.14 (*0.30*)	2.29 (*0.32*)	12.42 (*1.75*)	9.02 (*1.04*)
OS	6M	6.06 (*0.40*)	3.81 (*0.52*)	5.53 (*0.33*)	3.40 (*1.03*)	3.71 (*1.27*)	17.77 (*9.71*)	12.04 (*5.73*)
	10C	5.77 (*0.35*)	3.32 (*0.20*)	5.24 (*0.31*)	5.00 (*0.75*)	5.37 (*0.76*)	24.91 (*4.30*)	16.10 (*2.48*)
WOS	3M	5.63 (*0.45*)	3.89 (*0.20*)	5.01 (*0.34*)	1.31 (*0.28*)	1.37 (*0.27*)	7.03 (*2.15*)	5.47 (*1.11*)
	5C	5.58 (*0.28*)	3.73 (*0.31*)	5.01 (*0.23*)	1.48 (*0.32*)	1.62 (*0.29*)	8.89 (*2.64*)	6.77 (*1.40*)
EOS	3M	6.08 (*0.16*)	**3.20 (*0.05*)**	5.37 (*0.17*)	3.15 (*0.86*)	3.77 (*1.00*)	25.54 (*5.83*)	15.92 (*3.43*)
	5C	6.44 (*0.24*)	3.23 (*0.19*)	5.63 (*0.25*)	3.17 (*0.19*)	3.57 (*0.19*)	23.94 (*4.75*)	14.04 (*2.51*)
WEOS	3M	6.42 (*0.12*)	3.90 (*0.43*)	5.58 (*0.11*)	1.47 (*0.17*)	1.59 (*0.14*)	9.37 (*2.17*)	6.63 (*0.93*)
	5C	6.01 (*0.38*)	3.70 (*0.21*)	5.27 (*0.36*)	1.41 (*0.19*)	1.52 (*0.18*)	9.36 (*1.18*)	6.74 (*0.74*)
WU	3M	6.50 (*0.46*)	**5.44 (0.23)**	6.05 (*0.36*)	2.46 (*0.28*)	2.34 (*0.22*)	6.08 (*1.04*)	5.34 (*0.95*)
	5C	6.28 (*0.36*)	3.42 (*0.33*)	5.76 (*0.30*)	**6.54 (0.58)**	**7.04 (0.56)**	**31.06 (5.17)**	**18.67 (2.33)**
WWU	3M	5.16 (*0.33*)	4.00 (*0.58*)	4.72 (*0.33*)	1.63 (*0.39*)	1.73 (*0.37*)	6.04 (*1.67*)	5.17 (*1.06*)
	4C	**4.99 (*0.36*)**	3.60 (*0.25*)	**4.49 (*0.28*)**	1.61 (*0.15*)	1.76 (*0.15*)	7.23 (*2.08*)	5.96 (*1.10*)
PB	3M	6.12 (*0.14*)	3.82 (*0.66*)	5.51 (*0.23*)	4.22 (*1.61*)	4.79 (*1.65*)	17.10 (*7.11*)	11.92 (*3.36*)
	5C	6.78 (*0.36*)	4.22 (*0.83*)	6.16 (*0.37*)	4.52 (*1.86*)	5.03 (*1.87*)	16.55 (*7.97*)	11.03 (*3.70*)
WPB	3M	5.74 (*0.70*)	4.54 (*0.36*)	5.22 (*0.59*)	1.08 (*0.26*)	1.11 (*0.21*)	4.69 (*2.34*)	3.97 (*1.35*)
	5C	5.97 (*0.25*)	3.60 (*0.16*)	5.35 (*0.18*)	2.18 (*0.18*)	2.29 (*0.17*)	12.01 (*1.08*)	8.20 (*0.67*)

NOTE: Results presented as the mean followed by standard deviation *italicised* in parentheses. Maximum and minimum values in each column are shown in **bold**. ‡ Number denotes sample size and letter denotes loading protocol: M, monotonic and C, cyclic. * As defined in EN 12512 [28]. † As defined in ASTM E2126 [30].

4.4. Influence of Weathering

To study the influence of weathering on the structural performance characteristics of STCs, and control for variables such as sheathing type, loading protocol, and timber species, the data are normalised and centred on the mean:

$$x_{i_{rescaled}} = (x_i - \mu_k) \cdot \frac{\mu_U}{\mu_k} + \mu_U \tag{4}$$

$$x_{j_{rescaled}} = (x_j - \mu_l) \cdot \frac{\mu_W}{\mu_l} + \mu_W \tag{5}$$

where μ_U and μ_W are the means for all unweathered and weathered STCs, and μ_k and μ_l are the means of unweathered and weathered groups, respectively, such as, for example, group SP tested under a cyclic loading protocol which has a sample size of five, and i and j are indices. Thus, x_i is the performance characteristic of the ith unweathered STC specimen and x_j is the performance characteristic of the jth weathered STC specimen. The normalised (i.e., rescaled) data are then used to study the influence of weathering.

The influence of weathering by group is shown in Table 4 below. The percentage difference between the unweathered condition and the weathered condition is shown alongside a p-value (*italicised* in parentheses), which is taken from a double-sided Wilcoxon rank-sum statistical analysis of the normalised data. This analysis shows that weathering of sheathing-to-timber connections is correlated with a substantial, and statistically significant, reduction in stiffness (41% to 68%) and ductility (38% to 69%). The influence of weathering on the ultimate and yield strength of STCs is less clear, with p-values mostly above 0.01. Weathering has increased the peak load of specimens using 7 mm F8 plywood sheathing (WSP compared to SP) by as much as 16%. In general, however, weathering has reduced the peak load of STCs as seen, for example, with 5.5 mm hardboard specimens (WWU compared to WU) which lost 20% ultimate capacity due to weathering. Of interest, the European and American methods of calculating yield load produce very different results. According to this analysis, weathering of STCs generally improves yield capacity as calculated in EN 12512 [28] (by as much as 24%, with WSP compared to SP) but reduces yield capacity when calculated according to ASTM E2126 [30] (by as much as 22%, with WWU compared to WU).

Table 4. Mean difference, as a percentage, between unweathered and weathered STCs by group.

Groups	F_{max} (kN)	F_y (kN)		k_s (kN/mm)	k_e	D	
		EN *	ASTM †	EN *	ASTM †	EN *	ASTM †
SP, WSP	15.7% (*0.010*)	23.8% (*0.010*)	13.3% (*0.015*)	−41.2% (*0.002*)	**−43.2% (*0.001*)**	−43.9% (*0.021*)	−38.3% (*0.005*)
ESP, WESP	1.4% (*0.336*)	7.8% (*0.121*)	−1.1% (*0.779*)	**−52.3% (<*0.001*)**	**−53.5% (<*0.001*)**	**−48.7% (*0.001*)**	−44.0% (*0.004*)
HP, WHP	−10.6% (*0.014*)	2.9% (*0.463*)	−9.8% (*0.009*)	**−63.9% (<*0.001*)**	**−65.1% (<*0.001*)**	**−46.6% (*0.001*)**	**−44.6% (<*0.001*)**
OS, WOS	−4.8% (*0.081*)	8.2% (*0.035*)	−6.3% (*0.022*)	**−67.8% (<*0.001*)**	**−67.8% (<*0.001*)**	**−63.1% (<*0.001*)**	**−56.9% (<*0.001*)**
EOS, WEOS	−2.2% (*0.065*)	**17.2% (<*0.001*)**	−2.6% (*0.013*)	**−54.6% (<*0.001*)**	**−57.5% (<*0.001*)**	**−61.8% (<*0.001*)**	**−54.6% (<*0.001*)**
WU, WWU	**−20.4% (<*0.001*)**	−9.8% (*0.094*)	**−21.9% (<*0.001*)**	**−67.7% (<*0.001*)**	**−66.9% (<*0.001*)**	**−69.0% (<*0.001*)**	**−58.9% (<*0.001*)**
PB, WPB	−10.0% (*0.002*)	−2.9% (*0.645*)	−10.4% (*0.002*)	**−59.8% (<*0.001*)**	**−62.6% (<*0.001*)**	−44.7% (*0.105*)	−41.8% (*0.002*)

NOTE: The p-value from a Wilcoxon rank-sum test is shown *italicised* in parentheses. Results with $p <= 0.001$ are shown in **bold**. * As defined in EN 12512 [28]. † As defined in ASTM E2126 [30].

The difference between the European and American methods of calculating yield load deserves some commentary. The European method for determining F_y is based on k_s. The initial stiffness of unweathered STCs is higher than the stiffness of weathered STCs, which means that the angle of the β line for unweathered STCs is steeper than that of the weathered STCs. The intersection point of the k_s and β lines (Figure 4) is, therefore, comparatively lower for unweathered STCs than weathered STCs. That is, when stiffness is reduced but ultimate capacity is not, the yield capacity will increase when using EN 12512 [28]. On the other hand, the American method for determining F_y is based more heavily on the energy dissipated during the test (i.e., the area under the load–displacement curve) and, when the shape of individual load–displacement curves are similar to each other, regardless of weathering, then ultimate and yield capacity, as defined in ASTM E2126 [30], will follow a similar pattern.

The overall influence of weathering on structural performance characteristics, as determined in ASTM E2126 [30], is shown in the following boxplots (Figure 9). The sample sizes in this analysis are 64 unweathered specimens and 53 weathered specimens. The difference between mean normalised values ($\mu_U - \mu_W$) is shown alongside a dashed line through the means. The results show that weathering correlates with reductions in peak load of 3.2%, $p = 0.0253$; yield load of 4.6%, $p = 0.0004$; stiffness of 60.5%, $p < 0.0001$; and ductility of 50.0%, $p < 0.0001$.

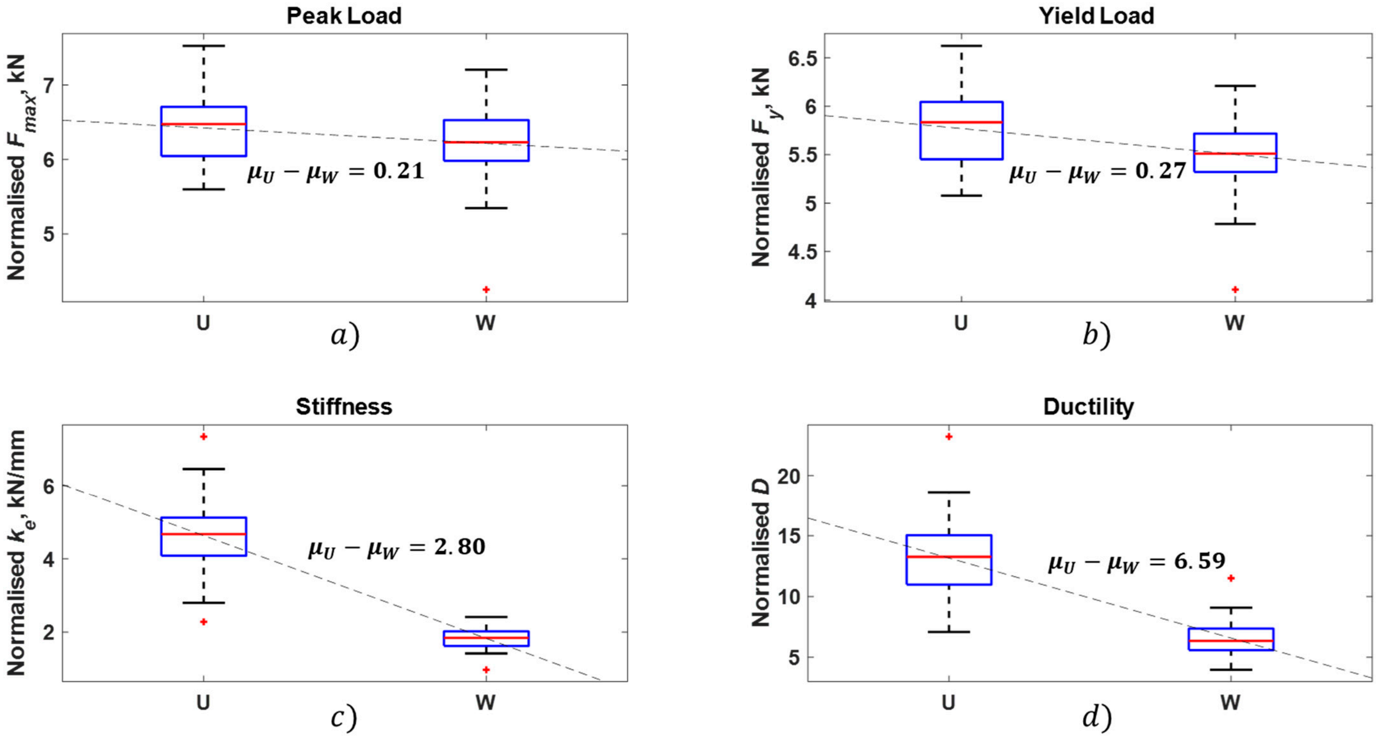

Figure 9. Boxplot comparisons of unweathered (U) and weathered (W) STC specimens by normalised (**a**) peak load, (**b**) yield load, (**c**) stiffness, and (**d**) ductility.

The above analysis is repeated on specimens with sheathing materials which are only available commercially as bracing materials (Figure 10); that is, by removing hardboard (WU and WWU) and particleboard (PB and WPB) from the analysis. This leaves a sample size of 48 unweathered specimens and 38 weathered specimens. The results of the analysis on this reduced dataset show that weathering has a negligible effect on ultimate and yield strength (i.e., an increase in peak load of 1.3%, $p = 0.3110$, and a reduction in yield load of 0.3%, $p = 0.9965$) but correlates with reduced stiffness of 58.8%, $p < 0.0001$, and ductility of 49.6%, $p < 0.0001$.

Light corrosion of the nails was observed on some of the weathered specimens.

4.5. Influence of Loading Protocol

To study the influence of loading protocol on the structural performance characteristics of STCs, and control for variables such as sheathing type, weathering, and timber species, the data are normalised, as outlined in Section 4.4 above, by monotonic (M) and cyclic (C) loading protocols instead of unweathered and weathered groups. The sample sizes in this analysis are 45 specimens tested under the EN 594 monotonic loading protocol [22] and 72 specimens tested under the ISO 16670 cyclic loading protocol [23]. The results, presented in boxplots in Figure 11 below, show that the loading protocol has a negligible effect on ultimate or yield strength (i.e., no change in peak load, $p = 0.7473$, and a small change in yield load of 0.1%, $p = 0.5772$). However, testing under a cyclic loading protocol instead of a monotonic loading protocol correlates with an increase in stiffness of 27.0%, $p < 0.0001$, and ductility of 21.2%, $p < 0.0001$.

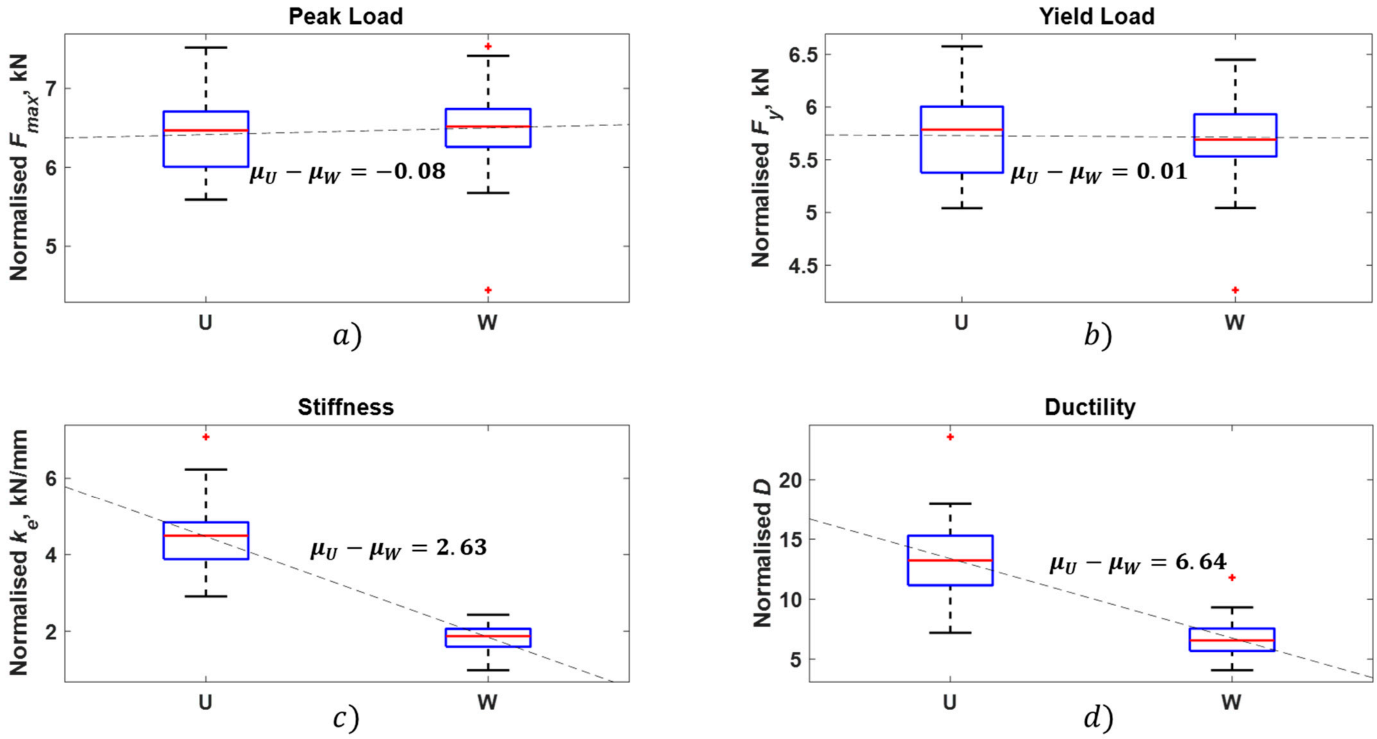

Figure 10. Boxplot comparisons of unweathered (U) and weathered (W) STC specimens (plywood and OSB sheathing only) by normalised (**a**) peak load, (**b**) yield load, (**c**) stiffness, and (**d**) ductility.

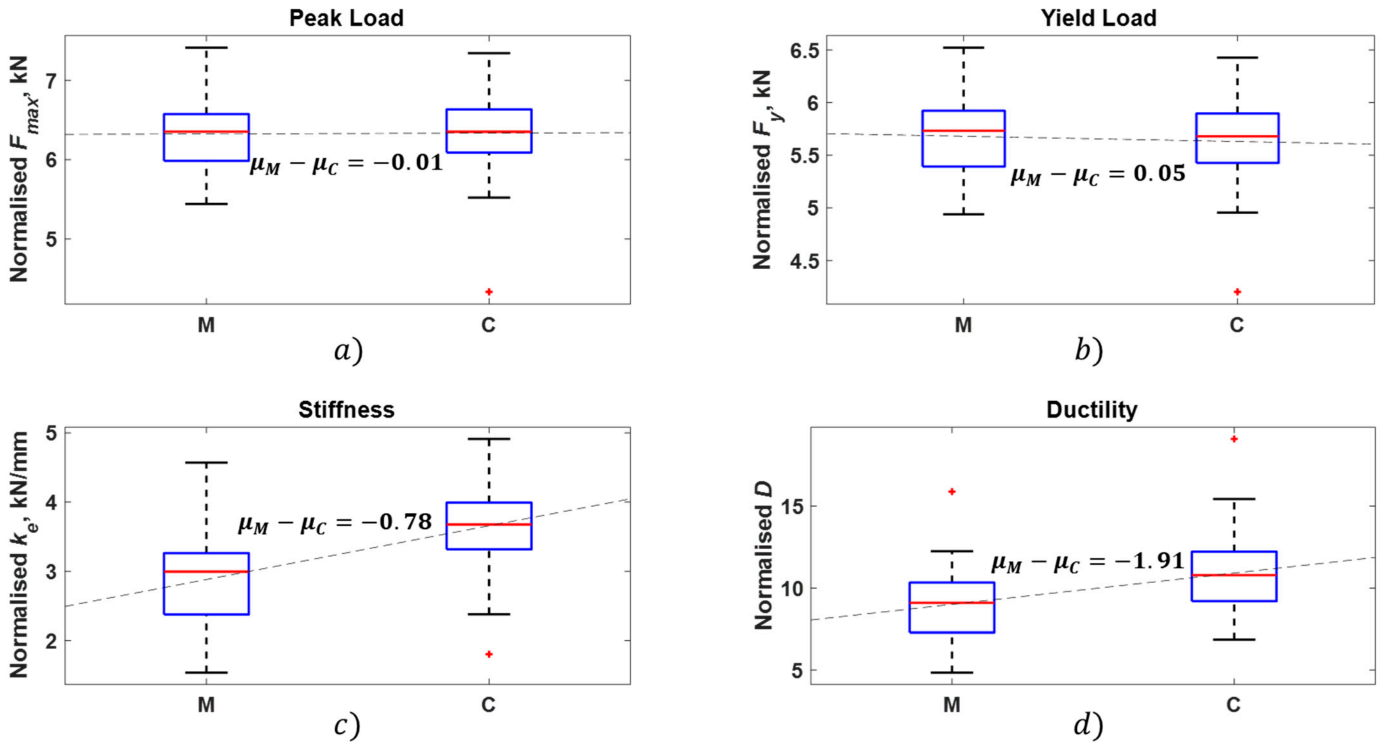

Figure 11. Boxplot comparisons of STC specimens tested under a monotonic (M) and cyclic (C) loading protocol by normalised (**a**) peak load, (**b**) yield load, (**c**) stiffness, and (**d**) ductility.

4.6. Influence of Timber Species

To study the influence of timber species on the structural performance characteristics of STCs, and control for variables such as sheathing type, weathering, and loading protocol, the data are normalised, as outlined in Section 4.4 above, by Southern Queensland pine (SQP) and spruce/pine/fir (SPF) timber species instead of unweathered and weathered groups. The sample sizes in this analysis are 40 SQP specimens and 31 SPF specimens. The results, presented in boxplots in Figure 12 below, show that SPF timber correlates with increases in peak load of 15.3%, $p < 0.0001$; yield load of 10.8%, $p < 0.0001$; and ductility of 7.6%, $p = 0.1921$, compared to SQP timber. On the other hand, SPF timber correlates with a reduction in stiffness of 4.3%, $p = 0.2888$, compared to SQP timber.

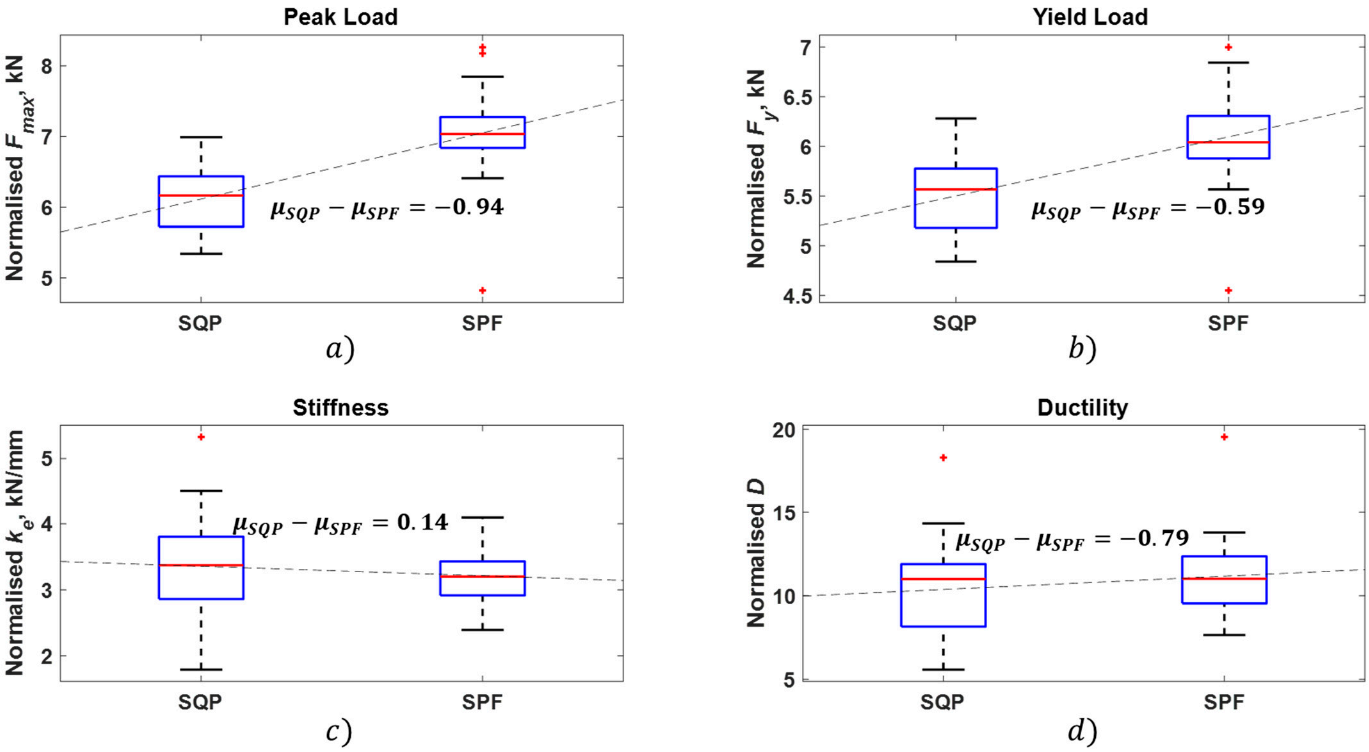

Figure 12. Boxplot comparisons of Southern Queensland pine (SQP) and spruce/pine/fir (SPF) STC specimens by normalised (**a**) peak load, (**b**) yield load, (**c**) stiffness, and (**d**) ductility.

4.7. Failure Modes

In this study, failures were localised to the connection between the sheathing and timber. During a typical test, nails were gradually pulled out of the timber and some crushing of the sheathing was observed near the head of the nail (see, for example, the top of specimen HP6 in Figure 13). Failures were typically isolated to part of the specimen only, such as, for example, the top half or the lower front portion of the specimen. During cyclic testing, some nails walked out of the specimen completely and fell to the floor. Pull-through failures, where the sheathing pops off the nail, were less common, except for the HP group which had a thinner sheathing material. Curiously, pull-through failures were not observed in the WHP group, even though it used the same thin 4 mm plywood as the HP group. Nail fractures were only observed during cyclic testing because the nails were repeatedly bent back and forth, leading to fatigue in the metal.

Buckling of the 4 mm plywood sheathing was observed during the compression cycles under the cyclic loading protocol, which may have contributed to pull-through failures of the nails due to prying action (e.g., see Figure 13). Buckling was not observed in any other groups in this study.

The failure modes of the STCs in this study have been summarised in Table 5 below. Almost half of all connections did not fail or showed signs of minor movement only. Most failures (i.e., approximately 40%) occurred by gradual pullout of the nail, which is the preferred failure mechanism. Nail fractures accounted for just over 15% of STC failure modes when tested under a cyclic loading protocol. Nail fractures did not occur when the specimens were tested under a monotonic loading protocol. Pull-through failures accounted for less than 5% of STC failure modes where plywood and OSB sheathing were used. Pull-through failures did not occur on hardboard or particleboard specimens.

Figure 13. Specimen HP6 buckling under compression load (notice the sheathing damage).

Table 5. Percentage (%) of connector failures by failure mode and group.

←Failure Modes.	Group→	SP		WSP		ESP		WESP		HP		WHP		OS		WOS		EOS		WEOS		WU		WWU		PB		WPB	
	Loading Protocol→	M	C	M	C	M	C	M	C	M	C	M *	C	M	C	M	C	M	C	M	C	M	C	M	C	M	C	M	C
Pullout		44	43	33	55	50	49	33	73	19	14	27	41	38	30	52	39	50	31	58	36	50	13	50	53	42	14	33	29
Pull-through		4	0	0	0	0	0	0	0	33	14	0	0	12	6	0	2	0	1	0	13	0	0	0	0	0	0	0	0
Fracture		0	30	0	1	0	1	0	0	0	32	0	17	0	26	0	14	0	4	0	6	0	26	0	0	0	36	0	34
Not Failed		52	27	67	44	50	50	67	27	48	40	73	42	50	38	48	45	50	64	42	45	50	61	50	47	58	50	67	37

* Based on data from two specimens out of three due to missing notes.

Examples of failures can be seen in Figure 14 below. The photo of OS8 (Figure 14a) shows two nails that have pulled through the OSB sheathing (top) and two nails that have fractured with the nail heads remaining in the sheathing (bottom). The photo of HP6 (Figure 14b) shows moderate crushing damage to the plywood where four nails have fractured and fallen out of the specimen (Figure 14c includes an additional three nails that have fallen out from the reverse side of HP6). The photo of WSP5 (Figure 14d) shows minimal crushing damage to the plywood and five nails that have pulled out completely from the specimen. The photo of WWU7 (Figure 14e) shows moderate crushing damage to the hardboard sheathing and four nails that have pulled out of the specimen. The photo of WPB5 (Figure 14f) shows minimal crushing damage to the particleboard sheathing, one nail that has not failed (top), one nail that has pulled out (second from top), and two nails that have fractured with the nail heads remaining in the sheathing (bottom).

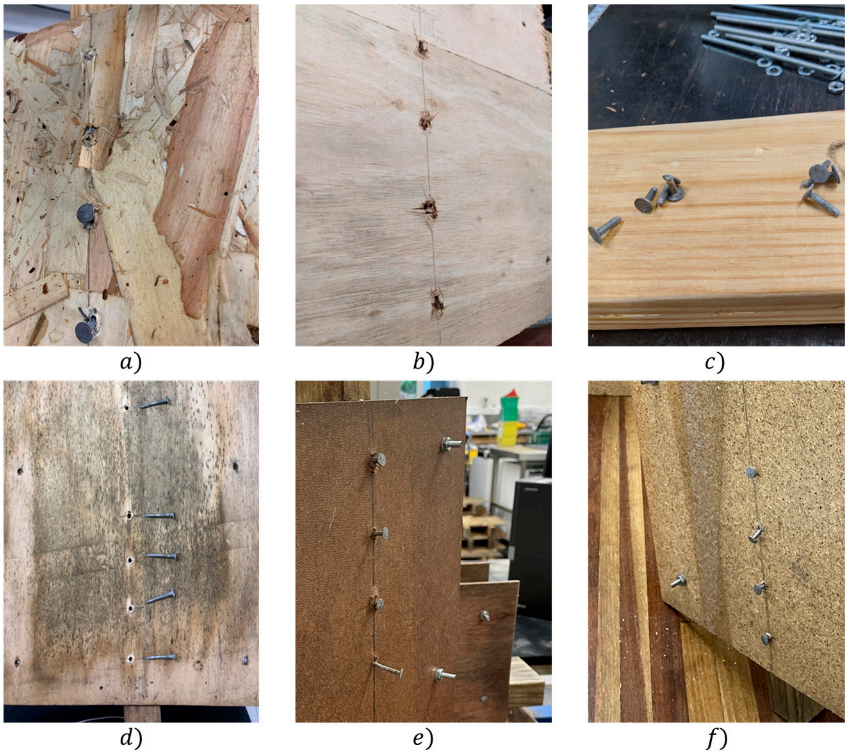

Figure 14. Photos of STC failures on (**a**) OS8, (**b**) & (**c**) HP6, (**d**) WSP5, (**e**) WWU7, and (**f**) WPB5.

5. Discussion

5.1. Influence of Weathering on Ultimate and Yield Capacity

Overall, the influence of weathering on the ultimate and yield capacity of STCs is not conclusive. Both ultimate and yield capacity were up to 16% and 24% higher, respectively, after weathering specimens with 7 mm F8 plywood sheathing and Southern Queensland pine timber (i.e., WSP compared to SP), a statistically significant result with $p = 0.01$. However, when the test was repeated with European spruce/pine/fir timber (i.e., WESP compared to ESP), there was little difference in the results. The effect of weathering on thin plywood and oriented strand board STCs is not statistically significant, with a minor reduction in ultimate capacity (2% to 11%) and conflicting results for yield capacity depending on the method of calculation used. Weathering appears to have reduced the ultimate and yield capacity of STCs with hardboard (i.e., WWU compared to WU) (20% and up to 22% lower, respectively) and particleboard (i.e., WPB compared to PB) (10% and up to 10% lower, respectively). This result is statistically significant with $p < 0.001$ for hardboard specimens and $p = 0.002$ for particleboard specimens (using the ASTM E2126 [30] method to calculate yield load). It should be noted that the hardboard and particleboard sheathing used in this study are not commercially sold as bracing materials and do not have a "moisture resistant" rating.

Previous studies have found that artificial weathering/flooding can increase the ultimate strength of shear walls and sheathing-to-timber connections [13,16], which aligns with the results in this study for STCs with 7 mm F8 plywood sheathing and Southern Queensland pine timber. Other studies have found that artificial weathering/flooding can reduce the ultimate strength of traditional joints and timber-framed shear walls [5,17], which aligns with the results in this study for STCs with hardboard and particleboard sheathing. Most studies have found that artificial weathering/moisture conditioning has no significant effect on the ultimate strength of STCs, sheathing, and small-scale shear panels [11,14,15], which aligns with the results in this study for STCs with 7 mm F8 plywood sheathing and SPF timber, 4 mm F22 plywood sheathing, and OSB sheathing. One study found that simulated flooding did not affect the ultimate capacity of timber-framed shear walls with OSB sheathing but did lead to a 17% reduction in the ultimate capacity of shear walls with HDF sheathing [18], which aligns with the results in this study (i.e., no significant effect of weathering on STCs with OSB sheathing and a reduction of 20% in ultimate capacity of STCs with hardboard sheathing). One study found that artificial weathering of plywood sheathing, which was then used in timber-framed shear walls, had no significant effect on ultimate strength [4], which aligns with the results in this study for STCs with 7 mm F8 plywood sheathing and SPF timber and 4 mm F22 plywood sheathing; however, their study also found that artificial weathering of OSB sheathing, which was then used in timber-framed shear walls, led to a reduction of 20% in ultimate strength, which does not align with the results of this study.

That weathering led to an increase in ultimate and yield capacity, for plywood and OSB specimens in this study, is an interesting result that demands an explanation. King et al. [16] noticed that the wetting of specimens led to corrosion of the connectors, which they speculated created more friction at the interface between the connectors and the timber. This hypothesis was studied in detail and confirmed in an excellent study by Yermán et al. [19] on the influence of repeated wetting and drying on nail withdrawal capacity. Alternatively, as suggested by Leichti et al. [13] and Way et al. [4], residual swelling of sheathing panels (that is, after the excess moisture had been removed) may lead to "a tighter fit of the sheathing panel to the framing" ([13], p.7). In this study, slight nail corrosion was observed with some weathered specimens but not with any of the unweathered specimens. Increased friction of the STC, due to corrosion of the nails and residual swelling of the sheathing, are plausible explanations for the increase in ultimate and yield capacity observed with some groups in this study.

If we accept the above explanations for an increase in ultimate and yield capacity for some groups, we must then seek to explain why weathering led to a decrease in ultimate and yield capacity for hardboard and PB specimens. Feist, writing several decades ago, noted that the particleboard of the time was highly susceptible to deterioration due to moisture cycling [7]. He described how the weathering process loosens the outer layers and exposes inner layers to shrinking and swelling due to changes in moisture. Since the particle sizes in hardboard and particleboard are much smaller than plywood and OSB, there is a relatively greater exposed area for the uptake of moisture. If shrinking and swelling, due to movement of moisture, is more pronounced in hardboard and particleboard than it is in OSB and plywood, this could explain the decrease in ultimate and yield capacity. It is worth noting again that the GP hardboard and PB products in this study do not have a "moisture resistant" rating, which may be relevant to the discussion here. Finally, even though the particleboard specimens lost some strength due to weathering (WPB), they compared favourably to weathered 4 mm F22 plywood specimens (WHP) and weathered OSB specimens (WOS).

5.2. Influence of Weathering on Stiffness and Ductility

In this study, we have shown that, in all cases, the stiffness and ductility of sheathing-to-timber connections are negatively affected by weathering. Both stiffness and ductility are reduced by 40%–70% in weathered specimens compared to unweathered specimens. This result is statistically significant for all groups in this study with $p < 0.001$ for stiffness and $p < 0.005$ for ductility (using the ASTM E2126 method [30]).

Most previous studies have found that artificial weathering/flooding/moisture conditioning of traditional joints, STCs, sheathing, and full-scale shear walls leads to a reduction in stiffness [5,11,13,14,17], which aligns with the results of this study. One study found that moisture conditioning of small-scale shear panels with plywood sheathing led to a reduction in stiffness [15], which aligns with the results in this study; however, their study found that, when OSB sheathing was used instead of plywood, moisture conditioning had the effect of increasing stiffness, which does not align with the results of this study. One study found that simulated flooding did not affect the stiffness of timber-framed shear walls with OSB and HDF sheathing [18], which does not align with the findings of this study. Curiously, one study found that artificial weathering of plywood and OSB sheathing, which was then assembled into full-scale shear walls, led to an increase in stiffness (not statistically significant) [4], which does not align with the findings of this study. Stiffness was not discussed by King et al. [16].

Ductility is not usually discussed in the literature (e.g., [4,5,11,13–16,18]). Only Bradley et al. [17] provide details on ductility where they note that simulated flooding had the effect of reducing the ductility of full-sized shear walls by between 22% and 25%, which aligns partially with the findings of this study where a reduction of 40% to 70% in ductility was identified.

Initial stiffness is a result of measurements taken in the early stages of a test. At this stage of the test, the STC connections are still holding firm. As such, any differences in stiffness between unweathered and weathered specimens must necessarily be due to differences in the stiffness of the sheathing and/or the timber. Since the timber is much thicker than the sheathing, it is likely that the differences in stiffness between unweathered and weathered specimens are predominantly due to softening of sheathing caused by weathering.

Ductility is a function of yield slip, which is itself a function of stiffness. The reduction in ductility due to weathering is, therefore, a proxy for the reduction in stiffness.

5.3. Influence of Weathering on Failure Modes

The failure modes in this study do not appear to have been affected by weathering. There is one unexpected result worth noting. Our review of the literature identified that pull-through failures were likely to increase because of weathering (e.g., [13,16,17]). Instead, we found that pull-through failures were more common in unweathered STC specimens which had thin 4 mm F22 plywood sheathing (HP) compared to weathered specimens (WHP).

Failure modes are not always detailed in the literature (e.g., [11,15]) or else are reported with insufficient detail to draw meaningful comparisons (e.g., [18]). Some studies found that accelerated weathering/moisture conditioning had no effect on the failure modes of traditional joints, STCs, and small-scale shear panels [4,5,14], which aligns with the findings of this study. Other studies found that simulated flooding/artificial weathering led to an increase in the number of pull-through failures in small-scale shear panels and full-scale shear walls [13,16,17], which does not align with the findings of this study.

5.4. Influence of Loading Protocol

The choice of loading protocol is known to influence structural performance characteristics (see, for example, [8,12]). In this study, we found that the choice of loading protocol did not influence peak load or yield load. The specimens tested under the cyclic loading protocol had 27% higher stiffness, $p < 0.0001$, and 21% higher ductility, $p < 0.0001$, compared to those tested under the monotonic loading protocol. Failure modes also differed between the specimens tested under different loading protocols, with nail fracture accounting for 15% of failures in specimens tested under a cyclic loading protocol compared to zero failures by nail fracture in specimens tested under a monotonic loading protocol.

Gatto and Uang [12] found that timber-framed shear walls tested under the ISO 16670 cyclic loading protocol [23] had lower strength than those tested under an unspecified monotonic loading protocol (6% lower for walls with OSB sheathing and 16% lower for walls with plywood sheathing). They found that stiffness was 2% higher for walls with OSB sheathing tested under the cyclic loading protocol compared to those tested under the monotonic protocol; however, stiffness was 11% lower for walls with plywood sheathing tested under the cyclic loading protocol compared to those tested under the monotonic protocol. The sample sizes in [12] were too small to test the statistical significance of these results. Gatto and Uang [12] do not report any notable differences in failure modes and do not present ductility results.

Cowled et al. [8] found that timber-framed shear walls tested under the ISO 16670 cyclic loading protocol [23] had 6% higher strength than those tested under the EN 594 monotonic loading protocol [22]; however, this result was not statistically significant. They found that internal shear modulus was 25% lower and ductility was 29% lower for walls tested under the cyclic loading protocol compared to those tested under the monotonic protocol, where shear modulus was calculated in accordance with the method outlined in ASTM E2126 [30]. There were some differences in failure modes noted in [8], with two nail fractures observed in one of the cyclic test panels and tearing of the plywood sheathing near the corners in two of the cyclic test panels. The primary failure mode for test panels in [8] was nail pullout.

Our findings in this study of sheathing-to-timber connections cannot be harmonised fully with the findings of [8,12].

Peak and yield load results in the full-scale shear wall studies of [8,12] are equivocal and not statistically significant, which aligns well with our finding that loading protocol did not influence peak and yield load.

Our results for stiffness and ductility contradict those of [8,12]. It should be noted that the sample sizes in this study are much larger than those of [8,12] which gives greater confidence in the results presented here. The test specimens in [8,12] are physically larger, with more parts (i.e., anchors, tiedowns, foundation beams, and multiple panels of sheathing) and very different test setups (i.e., racking test method instead of simple tension–compression test method) than the specimens in this study. It is possible that the larger, more complicated systems with very different test setups [8,12] introduce factors that influence the results differently at the larger scale.

The increase in the frequency of nail fractures identified in the specimens tested under a cyclic loading protocol in this study aligns well with the findings of Cowled et al. [8].

5.5. Influence of Timber Species

We found that there was a statistically significant ($p < 0.0001$) improvement in the peak (15%) and yield loads (11%) of specimens with spruce/pine/fir timber compared to Southern Queensland pine. There was, however, no statistically significant effect on stiffness or ductility. Failure modes were similar in specimens with both species.

All the studies reviewed in this paper focused on one timber species only: Douglas fir in [4,13,15–17], *Pinus pinaster* in [5], or described only as lumber in [14] or MGP10 in [18]. Since the literature review of sheathing-to-timber connections does not include any comparisons with different timber species, the following analysis will focus on a code-based analysis.

Australian Standard 1720.1 [24] provides characteristic capacities for nails laterally loaded in single shear in the side grain of timber based on the joint group. According to Table H2.4, the joint group for SPF is JD5 and the joint group for a common species of pine from the Southern Queensland resource, *Pinus elliottii* (also known as slash pine), is JD3. Alternative guidance in Table G1 of AS 1684.2 [31] indicates that all three Australian species (i.e., slash, radiata, and caribaea) should be nominally joint group JD5 or JD4 if the timber does not contain heart-in material, whereas the joint group for SPF is JD6 and European spruce is JD5. In the following example, JD5 will be assumed for all species of timber.

According to Table 4.1(B) of AS 1720.1 [24], the characteristic capacity, Q_k, for a single 2.8 mm (ϕ) nail laterally loaded in single shear in the side grain of seasoned timber is 545 N for JD5 timber. The unfactored design capacity for the type of joint in this study, which includes eight nails resisting the applied loads, is based on Equation 4.2(2) of AS1720.1 [24]:

$$\frac{N_{d,j}}{\phi} = k_1 k_{13} k_{14} k_{16} k_{17} n Q_k \tag{6}$$

where the load duration factor, k_1, is taken as 1.0 due to the short duration of the test, k_{13} is 1.0 for nails in side grain, k_{14} is 1.0 for nails in single shear, k_{16} is 1.1 for nails driven through plywood gussets (a reasonable assumption even when other wood-based sheathing products are substituted), k_{17} is 1.0 because there are four rows of nails resisting the applied load, and $n = 8$. Thus, the unfactored design capacity for JD5 specimens in this study is:

$$\frac{N_{d,j}}{\phi} = 1 \times 1 \times 1 \times 1.1 \times 1 \times 8 \times 545 = 4.80 \text{ kN} \quad (7)$$

The unfactored design capacity must be reduced according to cl.C2.2.2 of AS1720.1 [24], which accounts for the embedment length of the nail and thickness of plywood. The results of this calculation are shown in Table 6 and compared to the lowest yield load in each group, as determined by the ASTM E2126 method [30]. The only case where the lowest yield value for a group was lower than the design value was the weathered hardboard specimen WWU5, which was 3% below the unfactored design capacity; however, since the capacity reduction factor ϕ is between 0.75 and 0.85 (see Table 2.6 in AS1720.1 [24]), this result is still acceptable.

Table 6. Unfactored design capacity and minimum yield load per group.

Group	Loading Protocol	Timber Species	Sheathing Thickness t_o	Penetration of Nail in Timber, t_p	Unfactored Design Capacity, $\frac{N_{d,j}}{\phi}$	Minimum F_y as per ASTM E2126 [30]	Specimen ID of Minimum Value for F_y
			(mm)	(mm)	(kN)	(kN)	
SP	M	SQP	7	23	3.94	5.21	SP1
	C					4.81	SP5
WSP	M					5.39	WSP2
	C					5.74	WSP5
ESP	M	SPF	7	23	3.94	6.28	ESP2
	C					6.35	ESP7
WESP	M					6.79	WESP2
	C					4.89	WESP7
HP	M	SQP	4	26	4.24	5.48	HP3
	C					5.13	HP7
WHP	M					5.21	WHP2
	C					4.65	WHP4
OS	M	SQP	6	24	4.11	4.97	OE2
	C					4.76	OS5
WOS	M					4.62	WOS3
	C					4.76	WOS6
EOS	M	SPF	6	24	4.11	5.18	EOS3
	C					5.28	EOS7
WEOS	M					5.51	WEOS2
	C					5.08	WEOS5
WU	M	SQP	5.5	24.5	4.20	5.65	WU1
	C					5.36	WU7
WWU	M					4.44	WWU1
	C					***4.09***	WWU5
PB	M	SQP	5	25	4.28	5.24	PB2
	C					5.66	PB8
WPB	M					4.54	WPB3
	C					5.08	WPB8

NOTE: Results for minimum F_y that are lower than $\frac{N_{d,j}}{\phi}$ are shown in ***bold italics***.

The minimum yield loads for groups with SPF timber (nominally taken as JD5 according to AS 1720.1 [24] and JD6 according to AS 1684.2 [31]) all exceed the unfactored design capacity for JD4 timber (i.e., WESP7 has a yield load of 4.89 kN compared to the unfactored design capacity of 4.81 kN for JD4 timber, and WEOS5 has a yield load of 5.08 kN compared to the unfactored design capacity of 5.02 kN for JD4 timber). This data support the view that the SPF timber used in this study is better than JD5. There is also minor support for the view that some of the SQP timber in this study may be better than JD5 (see, for example, specimen SP5, which has a yield load of 4.81 kN compared to the unfactored design capacity of 4.81 kN for JD4 timber).

5.6. Relevance to Industry

The influence of weathering on the structural performance of timber and engineered wood products is an important area of study because it is not practical to protect these products from the weather during construction, and yet technical data are typically collected in a laboratory using materials and assemblies that have been protected from the weather. This brings into question the relevance of laboratory test results, using unweathered materials, to real-world conditions where weathering can negatively affect structural performance characteristics. Construction materials are commonly exposed to the weather for weeks or months before cladding is installed to provide protection from the weather. The industry needs to know whether the weather will have an impact on the structural performance of timber-framed shear walls.

This study found that weathering has no significant influence on the strength of sheathing-to-timber connections when commercially available bracing materials, such as plywood and OSB, are used. In some cases, weathering even seems to have improved the strength of STCs.

The adverse finding in this study is that weathering causes a reduction in the stiffness and ductility of STCs. The reduction in stiffness, however, may not be a critical issue because architectural cladding, such as plasterboard, can improve the stiffness of timber-framed shear walls. As an example, Patton-Mallory et al. [32] showed that the stiffness of a shear wall with plywood on one side and gypsum board on the other side was the sum of the stiffnesses of a wall with plywood only and a wall with gypsum board only. Satheeskumar et al. [33] conducted racking tests on a full-scale house structure with and without wall linings and cornices and found that the demand on the structural components of the building reduced by 40% when architectural finishes were added. Curiously, in a separate study of full-scale timber-framed shear walls [34], the authors found that the addition of plasterboard to timber-framed shear walls improved ultimate racking strength but did not affect stiffness.

The findings of this study relating to sheathing materials that do not have a "moisture resistant" rating and are not commercially available as bracing materials (i.e., the hardboard and particleboard groups) highlight the opportunity for these types of products to perform and the need for further product development, including the detailing of methods for protection and installation.

6. Conclusions

In this paper, the authors have presented some of the findings from an experimental study comparing the structural performance characteristics of sheathing-to-timber connections ($n = 117$) in both unweathered and weathered conditions, using both monotonic and cyclic loading protocols, comparing several different sheathing materials (i.e., 7 mm F8 plywood, 4 mm F22 plywood, 6 mm oriented strand board, 5.5 mm hardboard, and 5 mm particleboard), and comparing Southern Queensland pine timber to European spruce/pine/fir. The specimens comprised two sheets of 300×450 mm sheathing nailed to two 250 mm long sticks of 90×35 mm timber, with 16/2.8 (ϕ) $\times$ 30 mm (l) galvanised clouts hammered in by hand at 45 mm spacings.

We found that weathering does not affect the ultimate and yield capacity of sheathing-to-timber connections when commercially available bracing materials, such as plywood and OSB, are used. Weathering reduces the stiffness and ductility of all STCs by a statistically significant 40% to 70%. Weathering has the effect of reducing the ultimate capacity of STCs with hardboard and PB sheathing (both of which are not commercially available as bracing materials and are not rated as "moisture resistant") by 20% and 10%, respectively. Weathering does not affect the failure modes of STCs.

Similarly, we found that the choice of loading protocol has no effect on the ultimate or yield capacity of STCs, but it does have a statistically significant effect on stiffness and ductility, with an increase in stiffness of 27% and an increase in ductility of 21% when the ISO 16670 [23] cyclic loading protocol is used instead of the EN 594 [22] monotonic loading protocol. Nail fractures are also observed in the specimens tested under the cyclic loading protocol (15%) compared to zero nail fractures in the specimens tested under the monotonic loading protocol.

We found a statistically significant difference in the ultimate and yield capacity of the specimens, with European spruce/pine/fir timber achieving 15% and 11% better results, respectively, compared to specimens with Southern Queensland pine. There was, however, no significant difference in stiffness, ductility, or failure modes between SPF and SQP specimens.

The findings of our study provide technical data to support the continued use of commercially available bracing materials in construction without having to protect the materials from the weather.

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