

ANALYSIS OF MECHANICAL PROPERTIES AND FAILURE BEHAVIOUR OF RECLAIMED AND FRESH WOOD USING THREE POINT FLEXURE TEST

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ABSTRACT: The growing demand for sustainable construction has increased interest in reusing reclaimed wood collected from demolished buildings. To aid this, reclaimed wood needs to be investigated for its potential as a sustainable building material in line with circular economy principles. However, ageing has an impact on the mechanical performance of reclaimed wood which affects its performance; the extent of which is not known. Therefore, this study evaluates the mechanical properties and failure behavior of reclaimed wood in contrast to fresh wood via three-point flexure tests, strain evolution and scanning electron microscopy (SEM) analysis. The results show that reclaimed wood has a 35% decreased elasticity and strength likely as a result of hemicellulose degradation, lignin oxidation, and acquired building service-life defects. The prominent failure mechanism in reclaimed wood is brittle cross-growth ring fractures as opposed to fresh wood's ductile interlayer delamination-like failure. Findings of the SEM analysis correlates with these variations as it shows damaged cellulose microfibrils and eroded surfaces in the reclaimed wood samples. The results of this study show the importance of a thorough comprehensive of defect assessment in reclaimed wood, and the extent to which they affect the performance and structural integrity when reusing this material.

KEYWORDS: Reclaimed wood, Aging mechanisms, Stress, Strain, Failure mechanisms

1 – INTRODUCTION

The building sector is continuously searching for environmentally friendly ways to lessen its climate change impact and greenhouse gas emissions, using bio-based building materials. By encouraging resource efficiency and lowering dependency on fresh wood, recovering wood from demolition operations is consistent with the concepts of the circular economy [1]. However, wood is a natural and hygroscopic material that is continuously interacting with its environment; it goes through physical, mechanical and chemical changes throughout its years in service in a building's life, because of environmental factors, mechanical stresses, and biological factors, which ultimately affect the properties of reclaimed wood, its performance and reusability. Therefore, understanding the aging process and how it affects the molecular composition of wood is important for analysing the structural integrity of reclaimed wood and its potential for reuse [1]. A key factor that affects the ageing and degradation of wood in service with time is creep; a viscoelastic deformation that happens under

constant loading over prolonged periods of time. The magnitude of creep is contingent on temperature, moisture content, loading duration and levels, eventually leading to brittleness and different failure modes in old reclaimed wood compared to fresh wood [2]. Cyclic humidity and temperature changes cause alterations in wood's structural and chemical composition in various ways. Firstly, the deterioration of hemicelluloses over time makes wood more brittle because of a reduction in the elasticity of the cell wall polymers [3]. This brittleness can limit the ability of reclaimed wood to withstand dynamic loads or resist cracking during reuse. Hughes et al (2015) [4] reported that failure mechanism of wood is mainly affected by fibre structural organisation. The S1 layer aids the fibre while in compression while S2 layer controls the fibres while in tension. The above-mentioned factors together with geometry of the microfibrils affect fracture mechanism and crack propagation of wood. In comparison to the hemicellulose, lignin, which aids the rigidity of wood, has been found to go through oxidative degradation by several sources [5, 6]. Through scanning

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electron microscopy (SEM) and Fourier transform infrared analysis (FTIR), Mi et al [5] found that aged wood samples collected from historic wooden buildings showed evidence of lignin degradation as a result of oxidation reactions. Additionally, these aging mechanisms increases cellulose crystallinity and degradation of the amorphous regions in the cell wall [3, 5]. While this improves the stiffness of wood, it decreases its ductility thereby making wood more susceptible to brittle failure when under tension [7]. Another factor that influences the degradation and weathering of wood over time is fungal decay, generally occurring after exposure to damp conditions over long periods of time. There exists two main types of wood rotting fungi; brown-rot fungi which degrades cellulose and hemicellulose, causing a brittle lignin-rich structure with low strength; and white-rot fungi, which degrades both cellulose and lignin leaving behind a soft and spongy structure [8]. Wood in service for long periods of time can have severe fungal decay that makes wood susceptible to other defects such as cracking, splitting, insect damage and biological contamination. The combination of all the defects poses challenges to the efficient reuse of reclaimed wood by necessitating comprehensive grading procedures and repair prior to it being repurposed in new building projects. Without a proper insight into these aging mechanisms and their effect on wood's structural integrity, it a challenge to ensure the structural safety and reliability of reclaimed wood.

Therefore, this study aims to bridge this knowledge gap by analysing the mechanical properties, performance and failure behaviour of reclaimed wood in comparison to fresh wood using three-point flexure tests. By analysing stress-strain curves, strain evolution, and failure modes, the study presents valuable insights into the possibility of reusing reclaimed wood in new building and construction projects.

2 - OBJECTIVES

The objectives of this research are:

1. To assess and compare the strength and strain evolution of reclaimed wood in relation to fresh wood using three-point flexure tests.
2. To evaluate stress-strain curves for insights into the variations in elasticity and plasticity among reclaimed and fresh wood.
3. To identify and understand failure mechanisms noted in reclaimed and fresh wood samples under bending loads.

3 - EXPERIMENTAL SETUP

A Zwick universal testing machine (Zwick MTS 1475) was used to conduct 3-point flexure tests to examine the orthotropic nature of fresh and demolished wood. The reclaimed wood samples, collected from a building demolition site in Espoo, Finland, were carefully cleaned to remove debris, nails, or other contaminants that could interfere with the laboratory test.

Rectangular cross section wood specimens 200 mm in length, 10 mm in width, and 10 mm in thickness were cut using a circular saw then planned to smooth the surfaces and attain precise dimensions. The samples were cut to align the growth rings with the surfaces. A total number of 20 specimens were prepared per sample group as recommended by the ASTM D198 standard. The samples were conditioned at a temperature of 20°C and relative humidity of 65% ± 5%, until they reached constant mass and moisture equilibrium, before being tested. The small-size clear size wood samples were then each placed on two round supports at a set span of 160 mm. A rounded loading nose was positioned in the middle of the length, thus forming a three-point bending configuration. Following that, the Zwick machine was set up to apply force at a constant loading rate of 0.5 mm/min rate until sample fracture.

4 - RESULTS

4.1 THREE POINT FLEXURE ANALYSIS

Figure 1 shows the stress-strain graphs of reclaimed wood versus fresh wood. Two upper and lower bound median samples are shown per sample group. Fresh wood samples show plastic deformation behaviour before failure, displaying ductility of the material. These results are attributed to fresh wood having preserved hemicelluloses and lignin content, which aid wood with fibre reorientation and energy absorption during and after loading [9]. In contrast reclaimed wood shows reduced ductility, suggesting a brittle failure mode. This corresponds with the studies of Mi et al (2023) [5] and Szwajca et al (2024) [10] who found evidence of chemical degradation of hemicelluloses that helps with elasticity of wood and lignin oxidation over extended periods of time, which increases the stiffness of wood, thereby decreasing plastic deformation before fracture [11]. Additionally, old, reclaimed wood samples show a lower maximum stress (strength) of 85 MPa in comparison to fresh wood with an average value of 110 MPa, indicating aggregate damage from changes in the structural cell wall polymers.

This is consistent with Ottenhaus et al (2023) who stated that challenges with the reuse of wood is that accumulated damage from defects combined with extended loading that exceeded the elastic limit may alter the displacement capacity of wood [12]. Furthermore, defects that alter the physical structure of wood behave as stress concentrators, disrupting wood's continuous fibres ultimately causing failure even at lower loads [13].

The differing strain values of fresh wood, 0.25 versus reclaimed wood at 0.15, supports the notion of aging as

Fresh wood's greater strain capacity (0.25% versus 0.15% in reclaimed wood) can be attributed to greater plastic deformation prior to failure. Furthermore, fresh wood's ductile behaviour influenced crack propagation along paths of minimal resistance, in particular weak interlayer bonds [14]. This behaviour was shown by peeling-like fracture in fresh wood as seen in figure 2b, where failures occur along growth ring layers on the tangential plane of the wooden sample. Franke et al (2015) observed the same phenomenon in their old timber samples and characterised it as interlayer shear

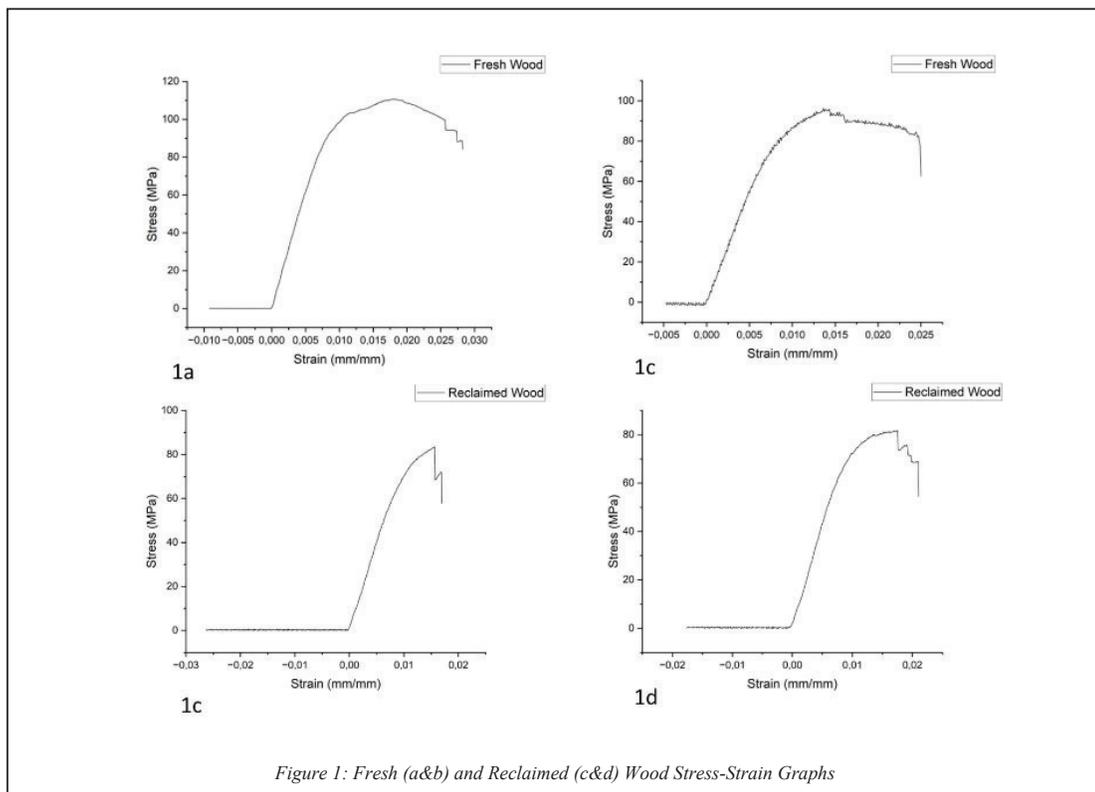


Figure 1: Fresh (a&b) and Reclaimed (c&d) Wood Stress-Strain Graphs

an important catalyst in degradation and the mechanical performance of wood. The statistical analysis shows that data from reclaimed wood samples have a greater standard deviation than fresh wood, which indicates that the multifaceted and varying effects of decay and defects on the properties of reclaimed wood complicate reuse initiatives.

4.2 FAILURE MECHANISM

When looking at the failure modes of fresh wood specimens, the ductility noted in the stress-strain graphs is also depicted in figure 2a. Fresh wood samples bent under loading with minimal fracture as shown in figure 2a, whereas reclaimed wood samples were observed to experience instantaneous crack propagation perpendicular to the plane of loading as shown in figure 2c.

failure along natural weak planes [14]. The response is characteristic of fresh wood's anisotropic structure because fresh wood still has its cell wall composition intact, with cellulose and hemicellulose components that bind fibres in growth rings whilst forming weaker interfaces in the middle of earlywood and latewood layers [15, 16]. Similar results were found by Hu et al (2024) whereby stress concentrated at these weak interfaces in fresh wood samples compared to their aged wood counterpart, causing delamination that looks like veneers separating [17]. Alternatively, the failure mechanism of reclaimed wood samples, manifested as cracks that traversed growth rings. In fresh wood, cracks normally transmit along growth ring boundaries as seen in figure 2b, however the opposite happening for old wood suggests degradation of hemicellulose, thereby decreasing stiffness between earlywood and latewood.

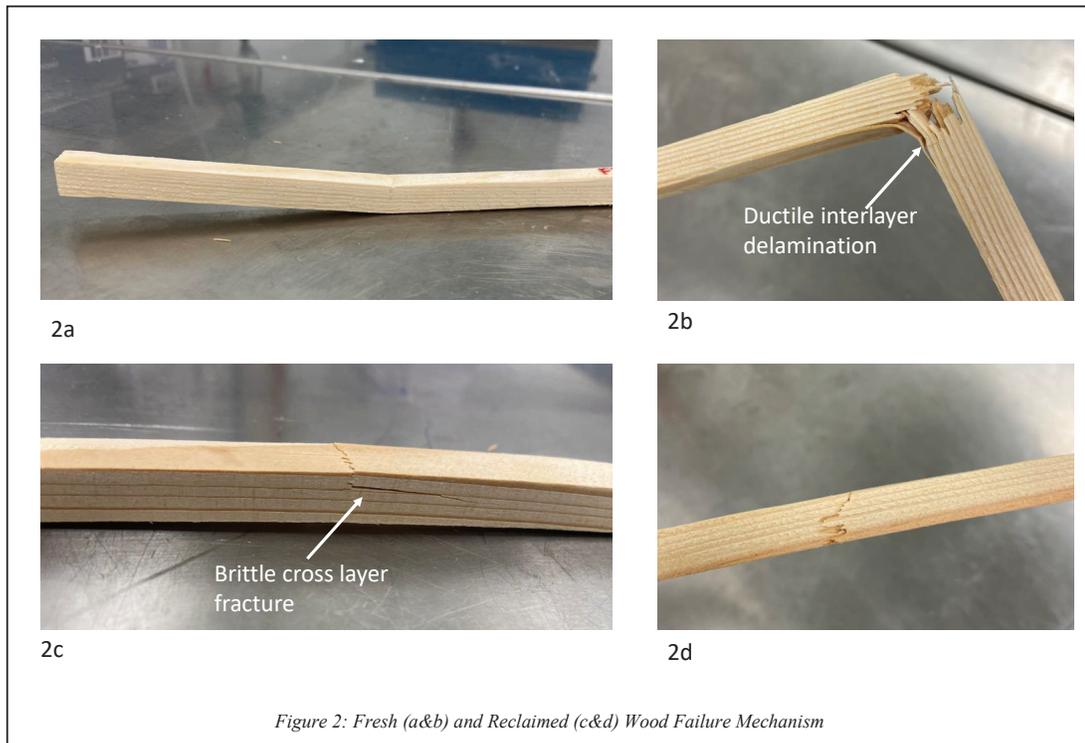


Figure 2: Fresh (a&b) and Reclaimed (c&d) Wood Failure Mechanism

A similar phenomenon was observed by Nairn (2019) and was attributed to degradation of hemicellulose, cellulose crystallinity and lignin oxidation which, in aggregate, lower interlayer cohesion, and in doing so homogenizing mechanical properties transversely across the layers [18]. As a result, the growth ring interface is weakened, making crack formation and propagation across cell walls likely, rather than along the cell walls [18]. Additionally, as mentioned before, aging of wood might form areas of stress concentration which further fuel the formation of fractures perpendicular to growth rings [16].

4.3 SCANNING ELECTRON MICROSCOPE ANALYSIS

The SEM images of fresh wood in figure 3a depict a smooth surface with intact and continuous cellulose microfibrils which may indicate interlayer cohesion that was attributed to the failure mode of fresh samples in section 4.2.

The microstructure also shows uniform orientation of the microfibrils, enabling ductile deformation through microfibrils, and a few defects such as resin pockets and pits on the surface. Reclaimed wood SEM images in figure 3b on the other hand display evidence of erosion and weathering on the surface possibly due to the cyclic humidity and temperature changes while in service. The microfibrils are torn apart which corresponds to the

brittle behaviour observed in the stress-strain graphs because of lignin and hemicellulose deterioration with uneven microfibril orientation. Increased voids and pits are also observed on the surfaces of reclaimed wood. This observation is consistent with van Niekerk (2021)'s study which reported changes in the cell wall structure from prolonged exposure that forming voids thus compromising the structural integrity of wood by reducing cellulose crystallinity [19].

The SEM analysis confirms that aging fundamentally alters wood's microstructure, transitioning it from a ductile material with well-defined weak planes to a brittle material with unpredictable crack paths. This study aligns with findings from previous studies on aging of wood and how it affects structure and properties: Menkis et al. (2022) [20] identified hemicellulose degradation as a main cause of reduced elasticity in reclaimed wood. Gibson (2012) [21] modelled cellulose crystallinity modifications under constant loading, which corroborates with buckled the buckled microfibrils observed in SEM findings of this study.

5 CONCLUSION

The experimental data and analysis collectively show that that aging and long-term service loads such as compression in wall structural beams essentially modifies wood's microstructure, mechanical properties and failure mechanisms.

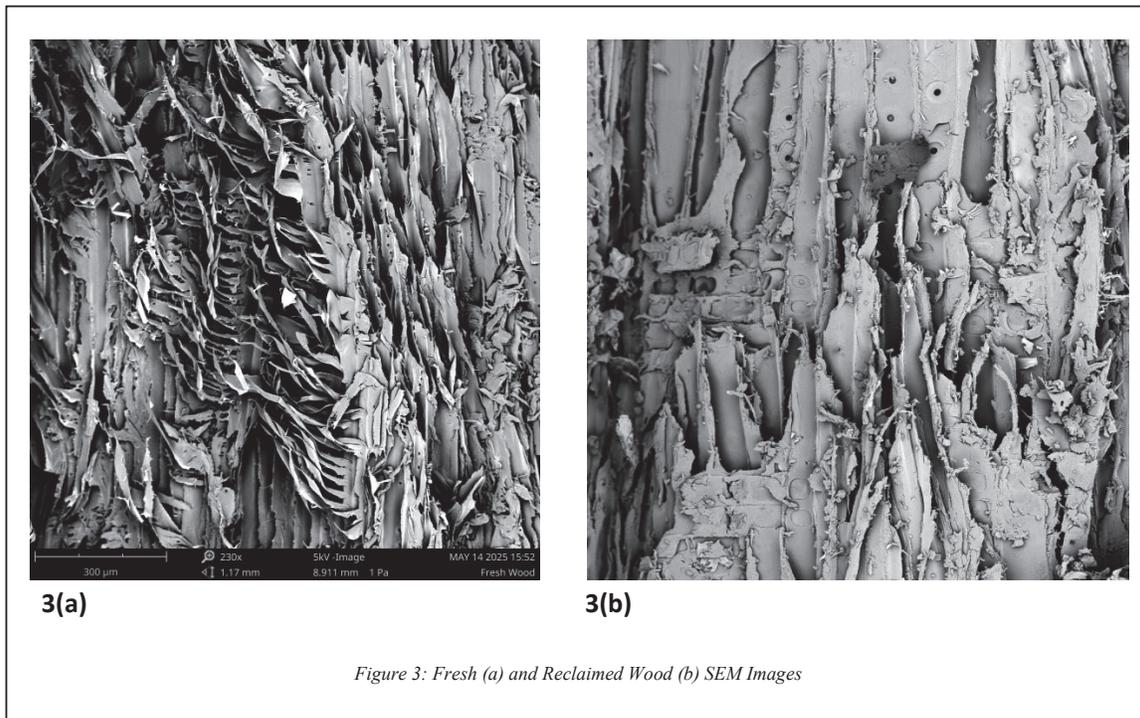


Figure 3: Fresh (a) and Reclaimed Wood (b) SEM Images

The conclusions of the study are as follows:

1. The stress-strain curves show that on average fresh wood has a higher strain capacity (0.25% in comparison to 0.15% for reclaimed wood) and increased stress tolerance. This contrast is indicative of the ductility of fresh wood as opposed to the brittle nature of reclaimed wood, and as such can absorb energy prior to failure.
2. Fresh wood fractures through ductile interlayer delamination because of strong cellulose networks and well oriented microfibrils while reclaimed wood displayed brittle cross-layer failure during loading probably because of lignin oxidation, degradation of hemicellulose, and various defects that develop during service life.
3. SEM results revealed torn uneven microfibrils, increased voids, and surface erosion zones as main causes of reclaimed wood's weaker performance.
4. These findings emphasise the need for in depth defect research and assessment protocols that aims to provide guidelines for reusing reclaimed timber in construction and building projects. In addition, future research should investigate treatments that repair loss of ductility in reclaimed wood while simultaneously looking

into design approaches that incorporate reclaimed wood with its defects to ensure structural integrity.

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