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Knowledge gaps and fire behavior of deadwood

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Abstract

The reuse of salvaged and deadwood timber represents a promising yet challenging opportunity within a circular construction framework. Deadwood is an abundant resource whose mechanical and thermal responses are significantly affected by ageing, environmental degradation, and prior exposure conditions. These factors may alter density, moisture transport, and chemical composition, leading to fire behavior that differs markedly from that of new timber. Moreover, reclaimed wood is frequently subjected to conditioning or stabilization treatments, such as drying, hydrothermal vaporization, or saline impregnation, whose implications for fire resistance are still poorly understood. This paper reviews the current state of knowledge on the thermo-mechanical behavior of aged and treated wood under fire exposure, with a particular focus on the mechanisms governing ignition, charring, and post-fire strength degradation. The work highlights the scientific and technological gaps that must be addressed to ensure safe and reliable reuse of salvaged timber in structural applications. By mapping available data and identifying research priorities, this study aims to establish a foundation for future experimental and modelling investigations supporting the sustainable valorization of deadwood in a sustainable built environment.

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1. Introduction

The construction sector is under increasing pressure to reduce greenhouse-gas emissions, limit virgin resource consumption, and promote circular material flows across the built environment. Within this context, timber plays a strategic role because it is renewable, stores biogenic carbon, and can substitute more emission-intensive structural materials; however, the availability of high-quality new timber remains constrained by long biological growth cycles, land-use pressures, and increasing demand from both construction and bio-based industries (GlobalABC, 2022; Orenge Panizza and Nik-Bakht, 2024). In parallel, growing attention is being directed towards secondary wood resources that can be reintroduced into structural applications, thereby extending service life, reducing waste generation, and improving resource efficiency within circular construction strategies (Bergsagel et al., 2022; Pitti et al., 2019; Ranttila et al., 2025). Among these resources, deadwood represents a particularly relevant but still insufficiently characterized feedstock, since it is potentially abundant after storms, windthrow, drought, lightning, pest outbreaks, or natural forest decline, yet its structural reliability and fire performance remain poorly documented.

Unlike newly harvested timber, deadwood is affected by a pre-recovery history that may include prolonged environmental exposure, repeated wetting (drying cycles, incipient biological degradation, checking, extractive redistribution, and local density changes). These ageing and exposure related processes can alter both mechanical and thermo-physical behavior, making direct equivalence with new structural timber scientifically unjustified without dedicated assessment (Cavalli et al., 2016; Zachar et al., 2017; Dúbravská et al., 2024). From a structural fire-engineering perspective, this issue is particularly important because timber performance in fire depends on a coupled set of variables including density, moisture content, permeability, anatomical orientation, crack distribution, heat flux, and chemical composition, all of which influence ignition, pyrolysis, charring, and the residual load-bearing section (Lowden and Hull, 2013; Dietenberger and Hasburgh, 2016; Mensah et al., 2023). Although the fire behavior of new timber is relatively well understood and forms the basis of current structural design approaches, equivalent knowledge for deadwood is still fragmentary. Recent studies on aged or reclaimed timber suggest that chronological age alone is not a reliable predictor of charring performance, whereas variability in density, annual-ring orientation, and pre-existing fissures may become dominant factors controlling fire response (Liblik et al., 2025; Zachar et al., 2021). An additional source of uncertainty arises from the fact that recovered wood is often subjected to conditioning or stabilization treatments before reuse. Drying, hydrothermal treatments, and saline impregnation may be applied to improve moisture stability, dimensional behavior, biological durability, or handling properties; however, these treatments also modify the same material parameters that govern thermal degradation and fire behavior, including equilibrium moisture content, permeability, acidity, extractive mobility, and char-forming tendency (LeVan and Winandy, 1990; Ali et al., 2021; Popescu and Pfriem, 2019). Their effects may therefore be beneficial, neutral, or detrimental depending on species, dosage, treatment severity, and the pre-existing condition of the wood substrate (Gündüz and Aydemir, 2009; Shen et al., 2023; Bonfatti Júnior et al., 2024). The current state of knowledge thus reveals a double gap. First, fire-oriented studies on wood recovered from dead trees are very limited compared with the broader literature on new timber, engineered wood products, or reclaimed timber from buildings. Second, even where data on aged wood exist, the combined effects of natural ageing, treatment history, and thermo-mechanical response under fire remain insufficiently resolved for structural application. These limitations hinder the safe valorization of deadwood in construction, because the absence of reliable evidence makes it difficult to justify design assumptions regarding ignition resistance, charring rate, and residual post-fire capacity (Cavalli et al., 2016; Uldry et al., 2024; Liblik et al., 2025). Against this background, a critical review of the available literature is needed to clarify what is currently known, what remains uncertain, and which variables should be prioritized in future experimental and modelling work. This review addresses the fire behavior of deadwood with specific emphasis on the mechanisms and descriptors most relevant to structural reuse, namely ignition susceptibility, charring kinetics, thermo-chemical transformation, and residual mechanical integrity after heating. Particular attention is given to the role of conditioning treatments and to the current lack of evidence for deadwood. By consolidating the available findings and identifying the principal scientific gaps, the review establishes a technical basis for subsequent thermo-mechanical testing and for the development of performance-based criteria supporting the safe structural reuse of deadwood within circular construction frameworks.

2. Fire behavior of aged and deadwood timber

The fire behavior of timber is governed by a coupled thermo-chemical and transport process in which external heat flux first causes drying and internal moisture migration, then progressive pyrolysis of the main wood constituents, volatile release, ignition, char formation, and finally reduction of the effective load-bearing section (Dietenberger and Hasburgh, 2016; Lowden and Hull, 2013; Mensah et al., 2023). In structural fire conditions, the main engineering descriptors are ignition susceptibility, heat release, charring rate, and the temperature-dependent degradation of mechanical properties ahead of the char line, because these parameters control both fire growth and residual structural capacity (Dietenberger and Hasburgh, 2016; Janssens, 2004). Charring is commonly associated with the 300 °C isotherm, while the thermal decomposition process extends over a broader temperature range and involves dehydration, hemicellulose degradation, cellulose depolymerization, lignin transformation, and secondary reactions within the porous char layer (Dietenberger and Hasburgh, 2016; Dúbravská et al., 2024). The protective function of char is well established, but its effectiveness depends on continuity, crack development, permeability, density, anatomical orientation, and local oxygen transport, all of which may vary more strongly in aged material than in new timber (Bartlett et al., 2019; Liblik et al., 2025). For aged timber and deadwood, the direct transfer of contemporary fire-performance assumptions is not straightforward, because ageing modifies both physical integrity and chemical composition. Long-term natural exposure can increase checking, porosity, permeability heterogeneity, and defect populations, while repeated moisture cycling and environmental degradation may alter extractives distribution, dehydration behavior, and local thermal transport (Dúbravská et al., 2024; Špilák and Majlingová, 2026). At the same time, the evidence currently available does not support a simple monotonic relation between age and fire resistance. In cone-heater tests on reclaimed timber from Estonia and Norway, Liblik et al. (2025) found no clear correlation between timber age and charring rate, whereas significantly greater variability was observed within aged batches than in new timber. Their results indicate that density, annual-ring orientation relative to heat exposure, and the presence of cracks or local visual heterogeneity can be at least as influential as age itself in determining charring performance (Liblik et al., 2025). This is consistent with the broader fire literature, where burning behavior is known to be strongly controlled by species, density, moisture content, grain direction, specimen geometry, and exposure configuration, making inter-study comparison difficult unless these variables are tightly controlled (Bartlett et al., 2019; Lowden and Hull, 2013). Recent work on historical wood confirms that ageing effects are real but often act through mechanisms more specific than age alone. Dúbravská et al. (2024), studying historical pine under a 50 kW · m⁻² radiant panel, reported faster charring during the early stage of exposure, with values at 10 mm depth ranging from 1.28 to 3.16 mm · min⁻¹, while at 30 mm depth the charring rate approached about 1 mm · min⁻¹. The same study identified distinct degradation zones and showed that thermal loading changes the relative proportions of extractives, holocellulose, and lignin, with decreasing extractives and holocellulose and increasing relative lignin content as temperature rises (Dúbravská et al., 2024). These chemical shifts are relevant because extractives and lignin-rich residues influence calorific value, volatile evolution, and char-forming tendency, so naturally aged wood may follow decomposition pathways that differ from those of freshly harvested material even when the species is the same (Dúbravská et al., 2024; Mensah et al., 2023). Zachar et al. (2021), working on naturally aged oak, likewise concluded that the effect of age on fire resistance cannot be interpreted independently of compositional changes and material condition, reinforcing the view that “aged timber” should not be treated as a homogeneous category. A further nuance emerges from the comparison between fresh and aged larch reported by Špilák and Majlingová (2026). In medium-scale radiant-panel tests, fresh and aged beams exhibited highly comparable internal temperature histories, with average charring rates of 0.65 and 0.63 mm · min⁻¹, respectively, suggesting that natural ageing did not substantially impair fire-relevant thermal performance in that specific material set. However, the same study showed earlier and narrower free-water phase-change intervals in aged wood and documented local acceleration of heat penetration when cracks developed during heating, indicating that ageing may influence fire behaviour through altered moisture transport and localized defect-driven heat transfer rather than through a uniform reduction in charring resistance (Špilák and Majlingová, 2026). Wang et al. (2022) reported that ancient timber from traditional Chinese buildings generally exhibited higher basic charring rates than modern wood of the same species, with ancient larch reaching 0.8559 mm · min⁻¹, about 15.66% higher than modern larch, indicating that long-term natural ageing may increase charring susceptibility under fire exposure (Wang, 2022). Taken together, the available literature suggests that deadwood and aged timber should be expected to display higher scatter, stronger dependence on local material

features, and potentially altered thermo-chemical response, while not necessarily exhibiting systematically higher charring rates than new timber. The present knowledge base therefore supports a performance-based approach in which density, moisture state, anatomical orientation, cracking, and chemical condition are treated as primary explanatory variables, and chronological age is treated as a secondary descriptor unless accompanied by well-characterized degradation history (Liblik et al., 2025; Dúbravská et al., 2024; Špilák and Majlingová, 2026).

3. Influence of conditioning treatments on fire performance

Conditioning treatments can substantially modify the fire response of wood because they act on the same material parameters that govern ignition, pyrolysis, charring, and the residual mechanical capacity of the heated section, namely moisture content, permeability, density, acidity, mineral content, and the chemical stability of the cell-wall polymers (Lowden and Hull, 2013; Dietenberger and Hasburgh, 2016; Mensah et al., 2023). For reference, standard fire exposure in structural fire engineering is commonly represented by the ISO 834 temperature–time curve shown in Fig. 1. In general, the fire behavior of timber is not controlled by a single treatment effect, but by the balance between competing mechanisms: moisture reduction tends to accelerate heating and facilitate ignition, chemical dehydration pathways may promote earlier char formation and lower heat release, while excessive chemical or thermal severity may damage holocellulose and reduce the strength retained in the heated zone (LeVan and Winandy, 1990; Popescu and Pfriem, 2019; Hasburgh et al., 2024). For deadwood, this issue is even more critical because the substrate is already heterogeneous due to prior weathering, checking, and ageing-related changes in moisture transport and extractive distribution; therefore, the same treatment may produce more scattered fire-performance outcomes than in newly harvested timber (Liblik et al., 2025; Dúbravská et al., 2024). Drying and heat-based conditioning primarily affect fire performance through moisture removal and thermochemical modification. The reduction in moisture content generally lowers the energy required to bring the surface to ignition-relevant temperatures, because less heat is consumed by water evaporation; accordingly, lower moisture contents are commonly associated with shorter ignition times and, under many exposure conditions, with increased flammability of the surface layer (Lowden and Hull, 2013; Dietenberger and Hasburgh, 2016). At the same time, moderate drying can improve dimensional stability and reduce moisture-related variability, which may be beneficial from an experimental and structural standpoint. When the conditioning severity increases into the range of thermal modification, however, additional chemical effects appear. Hemicelluloses are the least thermally stable wood constituents and degrade first, while lignin undergoes condensation and cross-linking reactions and cellulose may show changes in crystallinity; these changes reduce hygroscopicity and swelling, but they also alter pyrolysis pathways and may reduce mechanical properties, especially bending strength, depending on temperature and duration (Esteves and Pereira, 2009; Hill et al., 2021; Peng et al., 2022). Since these same chemical changes influence volatile release and char yield, heat-based conditioning cannot be interpreted as purely beneficial or purely detrimental in fire: lower moisture tends to favor earlier ignition, whereas greater relative lignin content and dehydration reactions may favor char formation and reduce some flaming characteristics. The net result is species- and process-dependent, and direct evidence for structurally relevant deadwood remains scarce. Dúbravská et al. (2024) showed that under thermal loading the relative content of holocellulose and extractives decreases while lignin becomes proportionally enriched in the heated layers, and that combustion heat correlates negatively with holocellulose and positively with lignin, confirming that even modest chemical shifts can affect fire-relevant behavior. Hydrothermal vaporization occupies an intermediate position between drying and thermal modification, because it combines heat and moisture under controlled conditions. Hydrothermal treatment is widely reported to reduce hygroscopicity, modify permeability, improve dimensional stability, and alter extractive mobility, while also inducing partial hydrolysis of hemicelluloses and changes in lignin chemistry as treatment severity increases (Ali et al., 2021). These changes are directly relevant to fire performance. Lower equilibrium moisture content and facilitated internal transport may accelerate early heating, whereas the chemical rearrangement of cell-wall polymers may shift decomposition toward greater char formation or lower volatile production in some cases. However, the same treatment may also reduce mechanical strength if the degradation of hemicelluloses becomes excessive, which is particularly important in structural fire design because the heated layer behind the char line already experiences severe strength loss with temperature (Ali et al., 2021; Dietenberger and Hasburgh, 2016). Available evidence therefore supports a cautious interpretation: hydrothermal vaporization is mechanistically relevant to fire performance, but its net effect cannot be assumed without direct testing on the treated

material. Saline impregnation and mineral-based flame-retardant treatments have the clearest direct link to fire performance, because many of these systems are designed specifically to delay ignition, reduce heat release, suppress flame spread, and increase char residue. The dominant mechanism is usually condensed-phase action: the chemicals catalyze dehydration and favor formation of non-combustible gases and carbonaceous char at lower temperatures, thereby reducing the fraction of combustible volatiles released to the flame zone (Lowden and Hull, 2013; Diitenberger and Hasburgh, 2016). Water-soluble inorganic salts such as phosphates, sulphates, borates, and related systems are well documented in this regard, and Diitenberger and Hasburgh (2016) note that such treatments typically delay ignition and reduce heat release and flame spread. However, these advantages are coupled with well-known drawbacks. Flame-retardant salts may increase hygroscopicity, promote corrosion issues, and reduce mechanical properties; in particular, acid-catalyzed systems can accelerate holocellulose degradation and embrittlement, whereas buffered borate systems are generally less damaging to strength than more acidic formulations (LeVan and Winandy, 1990; Diitenberger and Hasburgh, 2016; Hasburgh et al., 2024). For this reason, improved reaction-to-fire behavior does not automatically translate into improved structural fire resistance, especially where the treated wood must retain adequate mechanical integrity under elevated temperature. The problem is even more open in the case of non-standard saline impregnation routes, such as simple NaCl-based treatments, because they may modify hygroscopic behavior and moisture redistribution without delivering the same fire-retardant efficiency as purpose-designed phosphate or borate systems. Ageing can increase crack density, modify permeability pathways, and alter moisture transport, all of which can affect how deeply a treatment penetrates and how uniformly it is retained. Liblik et al. (2025) showed that factors such as annual-ring orientation, cracks, and local heterogeneity can be at least as influential as age in determining charring behavior, while Dúbravská et al. (2024) showed that thermally loaded historical wood develops chemically distinct layers with different combustion characteristics. The available literature thus supports three conclusions: drying and hydrothermal conditioning are fire-relevant because they alter moisture and decomposition chemistry; mineral or salt-based impregnation can improve reaction-to-fire but may compromise strength and hygroscopic stability; and none of these effects can yet be transferred with confidence to structural deadwood without dedicated testing on the target species and treatment protocol. Table 1 shows the tests set up and the conditions of the samples, Table 2 summarizes the main charring-rate values available in the literature together with the corresponding test setups. Although the reported values are not fully harmonized, the comparison shows that ageing alone does not explain fire behavior consistently, while density, cracking, anatomical orientation, and exposure configuration appear to play a stronger role.

4. Knowledge gaps and research needs

Despite growing interest in circular timber construction, the current evidence base remains insufficient to support reliable fire-oriented assessment of deadwood for structural reuse. The first and most fundamental gap concerns the limited number of fire studies explicitly addressing aged, recovered, or deadwood-derived timber. Most available knowledge on timber in fire has been developed for newly harvested solid timber or engineered wood products, whereas studies on aged or reclaimed material remain scarce and fragmented (Lowden and Hull, 2013; Diitenberger and Hasburgh, 2016; Liblik et al., 2025). As a result, the applicability of conventional assumptions derived from new timber to deadwood remains largely unverified. A second major gap concerns the lack of separation between chronological age, degradation history, and current material condition. Existing studies indicate that age alone is not a robust predictor of charring behaviour or ignition response, while density, moisture content, annual-ring orientation, crack distribution, permeability, and service-related or environmental degradation may exert stronger control on fire performance (Zachar et al., 2021; Dúbravská et al., 2024; Liblik et al., 2025). However, these variables are not consistently quantified across studies, and their interactions are rarely isolated experimentally. This prevents the development of predictive relationships capable of distinguishing between harmless ageing, severe degradation, and merely increased variability. A third gap lies in the insufficient coupling between fire behaviour and mechanical residual capacity. Much of the available literature focuses on ignition, mass loss, thermal decomposition, or charring, whereas fewer studies address the residual structural performance of aged wood after heating or fire exposure (Cavalli et al., 2016; Uldry et al., 2024).

Table 1. Comparative summary of fire-relevant parameters reported for fresh, aged, reclaimed, and historical timber in selected studies.

Study	Species	Timber condition	Estimated age / service life	Test setup	Specimen size	Density (kg/m ³)	Initial moisture content (%)	Visible cracks / heterogeneity
Liblik et al. (2025)	Norway spruce and other recovered species	Fresh and aged reclaimed timber	0, 10, 30, 100, 120 years	Cone heater / cone calorimeter-based exposure	Typically about 45 × 100 × 100 mm	Fresh timber: 506; aged groups: 436–464	Average about 9	Yes; variability in annual-ring orientation, glued layers
Dúbravská et al. (2024) – sample 50S/140H	Historical pine	Historical wood	Historic material	Medium-scale radiant panel, 50 kW·m ⁻² , 60 min	Medium-scale specimen	n.r.	n.r.	Historical heterogeneity
Dúbravská et al. (2024) – sample 20S/170H	Historical pine	Historical wood	Historic material	Medium-scale radiant panel, 50 kW·m ⁻² , 60 min	Medium-scale specimen	n.r.	n.r.	Historical heterogeneity
Špilák and Majlingová (2026) – fresh larch	Larix decidua	Fresh timber	New timber	Medium-scale radiant panel	Beam specimens	489.9	10.0 ± 0.1	None before testing
Špilák and Majlingová (2026) – aged larch	Larix decidua	Naturally aged timber	120–150 years	Medium-scale radiant panel	Beam specimens	494.7	9.7 ± 0.3	Present before testing due to natural ageing

Table 2. Summary of charring-rate values reported in selected studies on fresh, aged, reclaimed, and historical timber, together with the main test setup characteristics.

Study	Species	Exposure conditions	Charring-rate metric reported	Reported value(s)
Liblik et al. (2025)	Norway spruce and other recovered species	Heat-flux-based exposure; specimens conditioned to about 9% moisture content	Comparative charring performance	No single universal charring-rate value proposed; values showed broad scatter, with new timber in 15 min tests around 1.0 mm·min ⁻¹ and literature references around 0.8–1.3 mm·min ⁻¹
Dúbravská et al. (2024) – sample 50S/140H	Historical pine	50 kW·m ⁻² , 60 min	Charring rate at fixed depths	10 mm: 1.29 ± 0.15 mm·min ⁻¹ ; 20 mm: 1.14 ± 0.09 mm·min ⁻¹ ; 30 mm: 0.99 ± 0.05 mm·min ⁻¹
Dúbravská et al. (2024) – sample 20S/170H	Historical pine	50 kW·m ⁻² , 60 min	Charring rate at fixed depths	10 mm: 3.16 ± 0.30 mm·min ⁻¹ ; 20 mm: 1.90 ± 0.18 mm·min ⁻¹ ; 30 mm: 1.08 ± 0.06 mm·min ⁻¹
Špilák and Majlingová (2026) – fresh larch	Larix decidua	Radiant heat source	Charring rate by depth interval	0–1 cm: 0.79 mm·min ⁻¹ ; 1–2 cm: 0.52 mm·min ⁻¹ ; mean 0–2 cm: 0.65 mm·min ⁻¹
Špilák and Majlingová (2026) – aged larch	Larix decidua	Radiant heat source	Charring rate by depth interval	0–1 cm: 0.69 mm·min ⁻¹ ; 1–2 cm: 0.57 mm·min ⁻¹ ; mean 0–2 cm: 0.63 mm·min ⁻¹

Yet for structural reuse, the critical engineering issue is not only whether deadwood chars differently, but also whether the remaining heated section can sustain load with sufficient reliability. This is particularly important because ageing-related checks, extractive redistribution, and treatment-induced chemistry may alter both the progression of

thermal damage and the strength retained behind the char front. A fourth unresolved issue concerns the effect of conditioning treatments on fire performance, especially when treatments are applied to heterogeneous aged substrates rather than to new timber. Drying, hydrothermal treatment, and saline or mineral impregnation are known to modify moisture sorption, permeability, chemical composition, and char-forming tendency, all of which are directly relevant to ignition and charring (LeVan and Winandy, 1990; Ali et al., 2021; Popescu and Pfriem, 2019). However, the available evidence is largely indirect, species-dependent, and generally derived from studies on new wood or on treatments optimized for purposes other than structural fire resistance. The extent to which these treatment effects remain valid for deadwood, where uptake and retention may be strongly influenced by cracks, anisotropy, and prior degradation, is still unknown. A fifth gap is the absence of species-specific evidence for chestnut deadwood. Chestnut is of particular interest because of its tannin-rich chemistry and its relevance in regional construction traditions, yet the literature does not provide a systematic fire-performance database for structurally graded chestnut recovered from dead trees. Available studies on chestnut mainly address thermal modification, pyrolysis of chestnut by-products, or broader material characterization, rather than structural fire behaviour under controlled loading and heating conditions (Gündüz and Aydemir, 2009; Shen et al., 2023). This absence of species-specific data is significant, because extractives content and decomposition chemistry may influence ignition, volatile evolution, and char stability. A sixth gap concerns testing methodology and comparability. Current studies employ different heat fluxes, specimen sizes, orientations, conditioning procedures, and output variables, making direct comparison difficult even within the limited body of literature on aged wood (Bartlett et al., 2019; Liblik et al., 2025). Standardized procedures for assessing the fire performance of reused or deadwood-derived structural timber are not yet established, and existing structural fire design provisions do not explicitly address such material classes. Without harmonized methodologies, the generation of transferable design data remains difficult. These gaps define several immediate research needs. First, systematic comparative testing is needed between new timber and deadwood of the same species, with careful control of density, moisture content, anatomical orientation, and defect population. Second, conditioning treatments should be evaluated as part of the fire problem, not only as preprocessing operations, by quantifying their effect on ignition delay, charring rate, char morphology, and residual mechanical properties. Third, thermo-chemical characterization should be coupled with structural response, so that changes in extractives, holocellulose, lignin, and permeability can be related directly to fire-relevant engineering parameters. Fourth, a species-specific evidence base for chestnut is required, especially for material recovered under real environmental exposure histories. Finally, the field would benefit from performance-oriented testing frameworks capable of linking laboratory-scale fire indicators to structural design variables relevant to reuse decisions. Until such evidence is available, the fire assessment of deadwood for structural applications will remain conservative, case-specific, and weakly supported by codified knowledge.

5. Conclusions

Deadwood is a promising secondary resource for circular construction, but its structural reuse still lacks a sufficiently robust fire-performance evidence base. The available literature indicates that its behaviour under fire cannot be inferred directly from new timber, since ageing and environmental exposure may modify density, cracking, moisture transport, and decomposition chemistry. Current evidence also suggests that age alone is not the governing parameter. Fire response appears to depend more strongly on local material characteristics such as density, anatomical orientation, defect distribution, and chemical condition. As a result, deadwood should be treated as a distinct material class rather than as a simple variant of new timber. Conditioning treatments further increase this complexity. Drying, hydrothermal vaporization, and saline impregnation may all influence ignition, charring, and residual strength, but their combined effects on aged wood remain insufficiently understood.

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References

- Ali, M.R., Lin, L., Huang, Y., 2021. Hydrothermal modification of wood: A review. *Polymers* 13(18), 3071. <https://doi.org/10.3390/polym13183071>.
- Bartlett, A.I., Hadden, R.M., Bisby, L.A., 2019. A review of factors affecting the burning behaviour of wood for application to tall timber construction. *Fire Technology* 55, 1–49. <https://doi.org/10.1007/s10694-018-0787-y>.
- Bergsagel, D., Isaac, P., Koeck, A., 2022. Reusing Timber in Construction – Feasibility Study Exploring Turning Reclaimed Timber into Structural Glulam. CIRCuiT Project, MS8. <https://doi.org/10.13140/RG.2.2.22225.54888>.
- Bonfatti Júnior, E.A., de Barros, J.M.R., Silva, G.F., Lengowski, E.C., 2024. A comparative analysis of tannin and commercial fire retardants in wood fire protection. *Forests* 15(6), 951. <https://doi.org/10.3390/f15060951>.
- Cavalli, A., Cibecchini, D., Togni, M., Sousa, H.S., 2016. A review on the mechanical properties of aged wood and salvaged timber. *Construction and Building Materials* 114, 681–687. <https://doi.org/10.1016/j.conbuildmat.2016.04.001>.
- Dieterberger, M., Hasburgh, L., 2016. Wood products thermal degradation and fire. In: Reference Module in Materials Science and Materials Engineering. Elsevier. <https://research.fs.usda.gov/treearch/50041>.
- Dúbravská, K., Kučerová, V., Štefková, J., Mišíková, O., 2024. Charring of and chemical changes in historical wood under thermal loading. *Forests* 15(7), 1189. <https://doi.org/10.3390/f15071189>.
- Esteves, B.M., Pereira, H.M., 2009. Wood modification by heat treatment: A review. *BioResources* 4(1), 370–404.
- Global Alliance for Buildings and Construction (GlobalABC), 2022. Buildings and Climate Global Status Report 2022. United Nations Environment Programme. <https://globalabc.org/buildingmaterialsandclimate/executive-summary.html>.
- Gündüz, G., Aydemir, D., 2009. The effects of heat treatment on physical and mechanical properties of wild pear (*Pyrus elaeagnifolia* Pall.) and chestnut (*Castanea sativa* Mill.) woods. *Wood Research* 54(2), 33–42.
- Hasburgh, L.E., Zelinka, S.L., White, R.H., 2024. Flame-retardant treatments and protection. In: *Wood Handbook: Wood as an Engineering Material*, Centennial Edition. USDA Forest Products Laboratory.
- Hill, C.A.S., Altgen, M., Rautkari, L., 2021. Thermal modification of wood - a review: chemical changes and hygroscopicity. *Journal of Materials Science* 56, 6581–6614. <https://doi.org/10.1007/s10853-020-05312-5>.
- Janssens, M., 2004. Modeling of the thermal degradation of structural wood members exposed to fire. *Fire and Materials* 28(2–4), 199–207.
- LeVan, S.L., Winandy, J.E., 1990. Effects of fire retardant treatments on wood strength: A review. *Wood and Fiber Science* 22(1), 113–131.
- Liblik, J., Pernits, M., Just, A., Konist, A., 2025. Structural fire design with aged reclaimed timber: Small-scale charring performance assessment. In: *Proceedings of the 14th World Conference on Timber Engineering*, 1776–1785. <https://doi.org/10.52202/080513-0217>.
- Lowden, L.A., Hull, T.R., 2013. Flammability behaviour of wood and a review of the methods for its reduction. *Fire Science Reviews* 2, 4. <https://doi.org/10.1186/2193-0414-2-4>.
- Mensah, R.A., Harun, J., Jawaid, M., Abdul Khalil, H.P.S., Ghani, M.H., 2023. Characterisation of the fire behaviour of wood: From pyrolysis to fire-retardant mechanisms. *Journal of Thermal Analysis and Calorimetry* 148, 1407–1422. <https://doi.org/10.1007/s10973-021-10663-8>.
- Orenga Panizza, R., Nik-Bakht, M., 2024. Building stock as a future supply of second-use material – A review of urban mining methods. *Waste Management Bulletin* 2(2), 19–31. <https://doi.org/10.1016/j.wmb.2024.03.001>.
- Peng, Q., Ormondroyd, G., Spear, M., Chang, W.S., 2022. The effect of the changes in chemical composition due to thermal treatment on the mechanical properties of *Pinus densiflora*. *Construction and Building Materials* 358, 129303. <https://doi.org/10.1016/j.conbuildmat.2022.129303>.
- Pitti, A.R., Espinoza, O., Smith, R., 2019. The case for urban and reclaimed wood in the circular economy. *BioResources* 14(4), 6900–6922. <https://bioresources.cnr.ncsu.edu/resources/the-case-for-urban-and-reclaimed-wood-in-the-circular-economy/>.
- Popescu, C.-M., Pfriem, A., 2020. Treatments and modification to improve the reaction to fire of wood and wood-based products—An overview. *Fire and Materials* 44(1), 100–111. <https://doi.org/10.1002/fam.2779>.
- Ranttilä, H., Fink, G., Brandner, R., Ridley-Ellis, D., 2025. Circulating structural timber and engineered wood products – challenges and potentials towards reliable evaluation of mechanical properties. *Wood Material Science & Engineering* 20(4), 910–925. <https://doi.org/10.1080/17480272.2025.2517186>.
- Shen, Y., et al., 2023. Comprehensive study on the pyrolysis process of chestnut processing waste (chestnut shells): kinetic triplet, thermodynamic, in-situ monitoring of evolved gasses and analysis biochar. *Fuel* 331, 125944. <https://doi.org/10.1016/j.fuel.2022.125944>.
- Špilák, D., Majlingová, A., 2026. Comparison of temperature profiles of aged and fresh larch timber beams exposed to radiant heat source. *Buildings* 16(2), 306. <https://doi.org/10.3390/buildings16020306>.
- Uldry, A., Husted, B.P., Pope, I., Ottosen, L.M., 2024. A review of the applicability of non-destructive testing for the determination of the fire performance of reused structural timber. *Journal of Nondestructive Evaluation* 43, 106. <https://doi.org/10.1007/s10921-024-01120-6>.
- Wang, Y., Wang, W., Zhou, H., Qi, F., 2022. Burning characteristics of ancient wood from traditional buildings in Shanxi Province, China. *Forests* 13(2), 190. <https://doi.org/10.3390/f13020190>.
- Zachar, M., Majlingová, A., Mitterová, I., Čabalová, I., 2017. Influence of an age and damage of the oak wood on its fire risk. *Wood Research* 62(3), 495–504. <https://www.woodresearch.sk/wr/201703/14.pdf>.
- Zachar, M., Čabalová, I., Kačíková, D., Tribulová Jurczyk, T., 2021. Effect of natural aging on oak wood fire resistance. *Polymers* 13(13), 2059. <https://doi.org/10.3390/polym13132059>.