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FATIGUE OF TIMBER CONNECTIONS: A REVIEW OF FAILURE MECHANISMS AND DESIGN LIMITATIONS

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ABSTRACT: Fatigue is a critical factor affecting the long-term structural integrity of buildings and structures, particularly those with, particularly in load-bearing components subjected to frequent cyclic loading. As the use of engineered wood products (EWPs) expands in high-rise structures, bridges, and other infrastructure, understanding fatigue performance is important for ensuring structural reliability and safety. Despite its significance, fatigue remains an under-investigated issue in timber construction, with no standardized design guidelines available. Timber connections are key to overall fatigue performance, with their behavior influenced by geometric design, material composition, anisotropy, natural defects, moisture variation, and creep—all contributing to complex damage accumulation. This paper presents a comprehensive review of fatigue mechanisms in timber structures, focusing on fatigue strength and fatigue-induced damage mechanisms of different kinds of timber connections, highlighting knowledge on fatigue performance for timber structures. The findings of this review help bridge the knowledge gap, promoting the necessity of developing guideline for fatigue-resistant connections in timber to improve long-term performance of timber structures.

KEYWORDS: Timber connections, High Cycle Fatigue, Fatigue life prediction, High-rise buildings

1 – INTRODUCTION

Timber has been a widely used building material for centuries due to its renewability and availability, high strength-to-weight ratio, and ease of fabrication. Advances in EWPs have expanded its applications beyond traditional low-rise structures, enabling its use in modern construction for long-span bridges, wind turbine towers, and high-rise buildings. However, as timber structures increase in height and span, they exhibit lower fundamental frequencies, making them more susceptible to dynamic loads such as wind forces, seismic actions, and pedestrian-, traffic-, or machine-induced loads. This growing exposure to cyclic loading conditions highlights the critical need for research into the fatigue performance of timber structures, particularly their connections.

In structural design, timber members and their connections are subjected to permanent (G) loads such as self-weight, which cause long-term deformations like (e.g. creep) and duration of load effects, and variable (Q) loads, which can lead to fatigue damage over time. In the fatigue of structures, a distinction is usually made between low-cycle fatigue (LCF) and high-cycle fatigue (HCF). LCF, driven by high stress ranges and fewer cycles, normally occurs in seismic events or extreme weather, while HCF, caused by low stress cycles with a large number of repetitions, arises from wind-induced oscillations, pedestrian movements, and traffic or machine loads. Currently, fatigue research in timber engineering is largely concentrated on LCF in low- to mid-rise buildings applications, primarily because these structures typically do not experience high cyclic loading conditions [1]. Conversely, HCF, which normally happens in structures due to prolonged exposure to wind-induced oscillations and traffic-induced loads, is insufficiently studied. The absence of standardized fatigue design guidelines [2], combined with limited experimental data and analytical models, presents a significant challenge in accurately assessing fatigue performance of timber structures under real-world conditions. As a result, engineers often rely on

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conservative design approaches that may limit the full potential of timber as a viable alternative to steel and concrete in high-rise construction.

This paper provides a comprehensive review of fatigue in timber connections, emphasizing failure mechanisms and design constraints. By integrating recent findings, it aims to identify existing limitations in design practices and propose research pathways to enhance the safety and efficiency of timber structures subjected to HCF.

2 – FATIGUE BEHAVIORS OF TIMBER CONNECTIONS

When a structure is situated in cyclic loading conditions, fatigue-induced failures are often initiated at points of stress concentration in connections. The fatigue behaviour of timber connections depend on the connection type and configuration, and environmental influences, making the understanding the failure of these connections essential for ensuring the long-term durability of timber structures.

2.1 DOWEL-TYPE CONNECTIONS (NAILS, DOWELS, BOLTS, SCREWS)

Timber connections with dowel-type timber fasteners such as nails, dowels, bolts, or screws are widely used in structural applications due to their standardized behaviour and efficient load transfer. Understanding their fatigue performance is therefore critical for ensuring the long-term reliability of new and existing timber structures, while research on fatigue behaviour in these connections remains limited. To address this gap, Niebuhar et al [3, 4, 5] performed a comprehensive experimental programme to investigate the fatigue performance of dowel-type screw connections under different loading conditions. In the shear direction [3], specimens were tested using a sinusoidal non-reversed load (R = 0.1) at a frequency of 5 Hz. The S-N curve derived from the test results exhibits a nonlinear trend, similar to that observed in metals, which may be attributed to the fact that most specimens failed due to screw tear-off, with only minor accumulated timber deformation (Fig. 1a). It was also found that, the failure location varied across different stress levels. At lower stress levels, higher embedment stiffness relative to the fastener's constant bending stiffness shifts the maximum bending moment closer to the shear plane. Moreover, at lower stress levels, failure locations were more variable, suggesting that material defects in both steel and timber play a more significant role in fatigue performance under reduced loading conditions [3].

In the axial loading direction, Niebuhr et al [4] conducted 27 constant-amplitude fatigue tests to examine the withdrawal behaviour of self-tapping timber screws under with two different penetration lengths, with at a fastener-grain angle of 45°. The results indicate that, with increased embedment length, the connection exhibits a faster rate of fatigue damage accumulation under cyclic loading, and fails at lower fatigue stress level (Fig. 1b). The connections specimens in this programme mainly failed in withdrawal failure with distinct failure of the wood fibres, leading to substantial scatter in the S-N curve. This scatter can be expected in wood failure due to its natural variability and anisotropic properties.

Compared to earlier fatigue tests of this team on the same type of screws, where focus was on steel tensile failure (50% failure in the threaded area and 50% screw head tear-off) [5], withdrawal failure associated with timber failure was found to be significant governing only at higher stress levels, while metal failure was predominant at lower stress levels. This may be attributed to the fact that, in steel, the governing fatigue parameter is the stress range rather than the maximum stress—though this should be confirmed through more in-depth research. These findings indicate that fatigue in dowel-type connections is governed by a complex interaction of stresses in the timber (embedment and withdrawal), accumulated deformation, and inherent material defects.

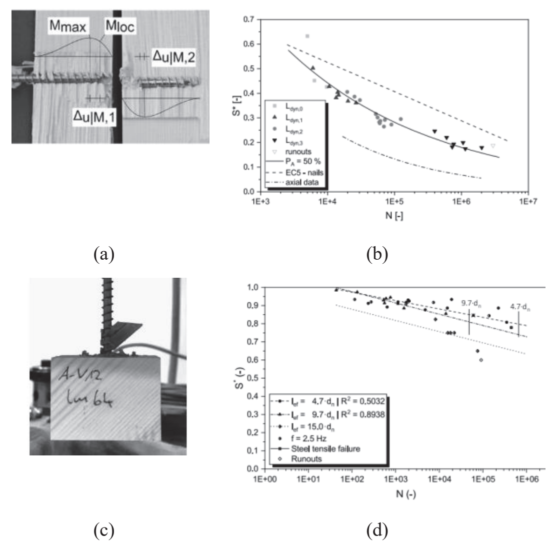

Figure 1. Fatigue testing on screws in shear and tensile directions [3][4]

2.2 TIMBER CONCRETE COMPOSITE (TTC) CONNECTIONS

TCCs are widely used in bridges and flooring systems due to their ability to combine the lightweight, flexibility, and sustainability of timber with the mass, high stiffness, and durability of concrete. Due to their frequent exposure to cyclic loading from traffic in bridges, wind, and vibrations in floors, the HCF behaviour of TCC systems has been studied more extensively than other timber connections. Research on TCC fatigue performance has mainly focused on connector behaviour, stiffness degradation, and failure mechanisms under repeated loading. Weaver et al. [6] conducted cyclic load tests on two 10.7 m glulam girders reinforced with fibre-reinforced polymer (FRP) on the tension face and composite concrete decks with dowel-type TCC specimens. Their findings showed that while the load-bearing capacity and ductility remained intact, stiffness degradation and midspan deflection both increased as the number of applied cycles increased,

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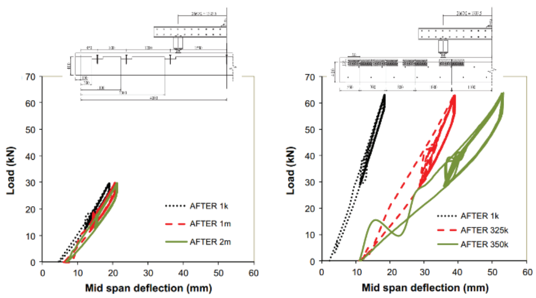
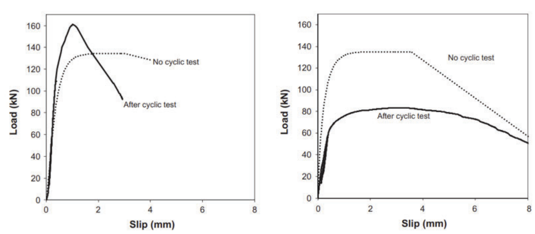
particularly within the first hundred thousand cycles. Despite this, the specimens sustained two million load cycles without significant failure before being subjected to quasi-static failure testing. Yeoh et al. [7] later compared the fatigue performance of two different TCC connection types—rectangular notch connections and metal plate connections (Figure 2a) —under cyclic loading conditions (R = 2, 4 4 Hz). The metal plate connection exhibited continuous slip and progressive stiffness degradation over increasing cycles, likely due to accumulated damage at the interface. In contrast, the rectangular notch connection demonstrated better resistance to slip, strength loss, and stiffness reduction, indicating superior fatigue performance (Figure 2a). After two million load cycles, static testing revealed a noticeable decline in capacity for both connection types, but the rectangular notch connection maintained its structural integrity better than the metal plate connection. Interestingly, Yeoh et al. [7] also observed increased stiffness in some TCC specimens after fatigue testing, which was concluded to the hardening of concrete over time (Figure 2b). This finding was consistent with measurements from a two-year on-site monitoring project on the Lynches Woods Park bridge [8], where continuously increased natural frequency was detected due to the improved composite action from concrete stiffening.



(a)



(b)

Figure 2. Comparative study on fatigue behaviour of rectangular notch floor beam (left) and metal plate floor beam (right): (a)stiffness reduction during fatigue testing; (b) post fatigue behaviour.

2.3 ADHESIVE TIMBER CONNECTIONS

Adhesive connections are gaining growing attention in high-rise timber structures due to their high stiffness and strength. The two main types, glued-in plate (GiP) connections and glued-in rod (GiR) connections, are increasingly used in lateral reinforcing bracing systems for wooden residential buildings and wind turbine towers. As their applications of these timber connections expands to high performance structures in extreme conditions, understanding their fatigue performance becomes crucial for ensuring long-term structural reliability.

Glue-in plate (GiP) connections

GiP connections involve adhesively bonding metal plates (perforated or smooth) into timber elements offering high load-bearing capacity and stiffness in axial direction. In a research conducted by Bathon et al. [9], GiP system were subjected to long-term fatigue testing at frequencies between 3 and 10 Hz and load ratios of R = -0.5 and 0.1, for validating their feasibility in in wooden wind turbine towers. The specimens were tested up to 10 million load cycles, demonstrating that well-designed adhesive connections can endure extended dynamic loading without catastrophic failure.

Jockwer et al. [10] later performed a more comprehensive testing on fatigue performance of the similar GiP system under different frequencies (5, 6, 8, and 10 Hz) and load ratios (R = -1, 0.1, 0.5). Various failure modes were observed in the tests, including glue dowel breakage (100%), adhesive debonding (60-80%), and timber surface peeling (20-30%) (Figure 3). The combination of these failure modes highlights the complexity of systematically classifying connection fatigue behaviour, making it challenging to analyze crack initiation and propagation effectively. The S-N curve reveals that, R=-1 is the most worst scenarios for loading conditions. These two studies in GiP connection fatigue performance observed consistent failure patterns, including glue breakage, timber surface peeling, and steel link breakage. These studies highlight the capacity of GiP connections under repetitive loading and revealed the complex material interactions in their long-term performance.

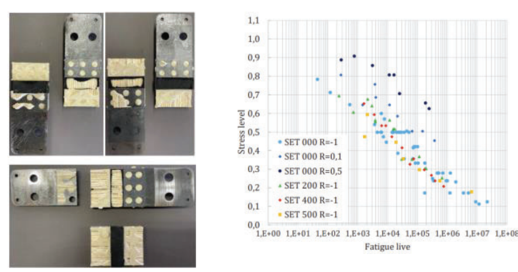


Figure 3. Fatigue testing on Gip connection [10]

Glue-in rod (GiR) connections

Compared to glue-in plate (GiP) connections, glue-in rod (GiR) connections are a more standardized and widely used adhesive timber structural solution. GiR consists of a solid metal rod adhesively bonded into timber, allowing for efficient load transfer and high strength. A three-year European project 'GIRODF-Glued In Rods For Timber Structures' between Sweden, Germany and UK extensively studied the behaviour of this connection, including its long-term fatigue behaviour [11]. In the fatigue testing performed in this project, specimens were tested with varied adhesives, timber types, and steel grades, revealing potential fatigue failure modes in different material (Figure 4). These included wood substrate failure, rod failure, adhesive failure, adhesive/timber interface failure, and adhesive/rod interface failure. In timber-related failures, the failure mechanism involved the pull-out of a plug of wood surrounding an intact bond and test rod. When failure happened in the steel bar, the steel bar broke near the surface of the bonded-unbonded line. Adhesive line failure often involves a combination of adhesive fracture and timber fibre tear-out. Visually identifying the initiation point is challenging due to its subjective and imprecise nature.

Madhoushi et al. [12] further investigated the influence of timber material and adhesive type on GiR fatigue behaviour, testing specimens at frequencies between 0.1–3.2 Hz and a load ratio of R = 0.1. Their results showed that laminated veneer lumber (LVL), due to its thin-layered structure, effectively slows down crack propagation, thereby enhancing the fatigue resistance. In contrast, glulam exhibited fractures originating at its weak points (eg. natural defects), making it more prone to fatigue failure due to size effect. Additionally, adhesive thickness was found to significantly affect fatigue performance. Connection specimens with a 4mm glue line thickness failed instantly during the first cycle at 80%, 75%, and 50% of their static shear strength. This indicates that while thicker adhesive layers improve static strength, they are highly vulnerable to tension–tension fatigue loading and should be avoided in fatigue-critical applications. Tannert et al. [13] performed 50 fatigue tests on timber joints with glued-in GFRP rods to examine the effect of anchorage length. Results showed that fatigue life increased with decreasing load amplitude and aligned well with existing Wöhler curves for wood under pulsating tensile shear stress. Failure mode in this programme typically happened at the adhesive-timber interface at approximately 65% of the static capacity after about 11,000 load cycles. In addition, joint strength increased with anchorage length up to a critical depth of approximately 250 mm, beyond which no significant gain was observed.

When analyzing the S-N curves with regards to different failure modes in GiR connections, a clear linear trend was observed in cases where failure occurred in the adhesive or timber. In contrast, when failure occurred in the metal rod, the S-N curve exhibited a nonlinear trend, indicating the potential existence of a fatigue limit (Figure 4). Furthermore, when metal failure was the dominant deformation mode, the connections retained significant post-failure capacity, allowing them to sustain some load even after initial failure. Therefore, it was concluded in most studies on adhesive timber connections that yielding failure in metal components is generally preferred, as it allows for gradual deformation rather than sudden brittle failure [10].

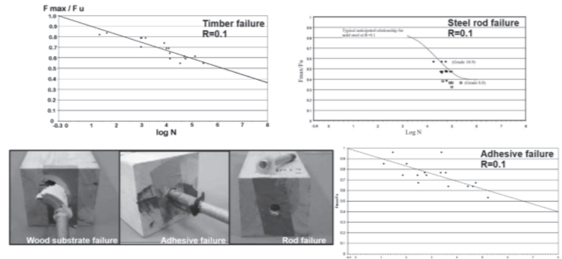


Figure 4. Fatigue behaviour of GiR and the associated S-N curve when designed for different kinds of failure [11]

Another experimental program placed special emphasis on the setup for fatigue testing of GiR [14], highlighting the need for a standardized testing methodology to ensure reliable results. It was observed that loading frequencies exceeding 5 Hz caused the bond line temperature to rise above 45°C (Figure 5), which was deemed unfavourable as it led to irreversible displacements, likely due to changes in the adhesive properties at elevated temperatures. Therefore, loading frequency of 5Hz was recommended to maintain bond line temperatures below 45°C to prevent adverse effects on adhesive performance.

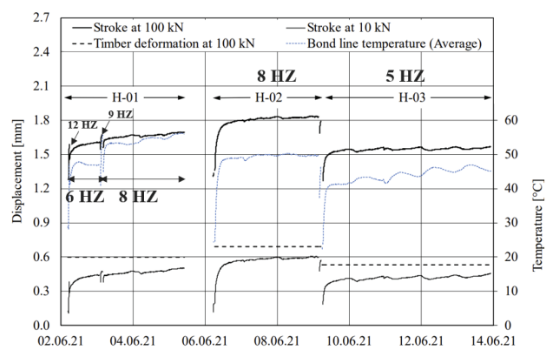


Figure 5. Temperatures in the bond lines as a function of time [14]

Another factor that may influence fatigue performance is moisture content. Molina et al. [15] conducted withdrawal tests on glued-in steel rods inserted at a 45° angle to the grain in glulam elements under three different moisture contents. The results showed that GiR connections exhibited less reduction in capacity at lower moisture contents. Additionally, different adhesives - specifically Sikadur 32 and Compound Adhesive - responded differently to changes in moisture content.

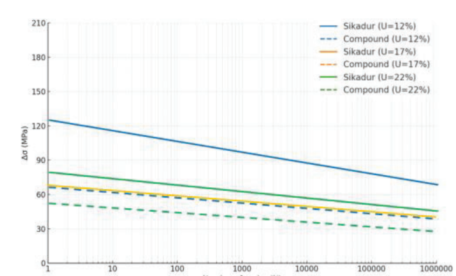


Figure 6. Fatigue performance of GiR under different moisture content (plotted according to [15]

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3 – FATIGUE DESIGN GUIDLINE

Fatigue is often overlooked in timber structural design. EN 1995-2 [16] provides a simplified verification method, requiring that structures subjected to 'frequent stress variations from traffic or wind loading' ensure 'no failure or damage due to fatigue'. This method is primarily applied to timber components in bridges. Fatigue assessment in timber structures is expressed using the dimensionless stress ratio (κ), which normalizes the stress range relative to the characteristic strength of the material:

$$\kappa = \frac{|\sigma_{d,max} - \sigma_{d,min}|}{f_k/\gamma_{M,fat}} \tag{1}$$

Where $\sigma_{d,max}$ and $\sigma_{d,min}$ are the numerically maximum and minimum design stresses respectively, f_k is the corresponding characteristic quasi-static strength and $\gamma_{M,fat}$ is the material partial factor for fatigue loading. If the κ value does not exceed the number specified in Table 1 for different timber structures, a fatigue verification is not required.

In fatigue verification, the design fatigue strength ($f_{fat,d}$) is calculated based on the characteristic strength for static loading (f_k), the partial factor for fatigue strength ($\gamma_{M,fat}$), and the strength degradation reduction factor (k_{fat}).

$$f_{fat,d} = k_{fat} \cdot f_k/\gamma_{M,fat} \tag{2}$$

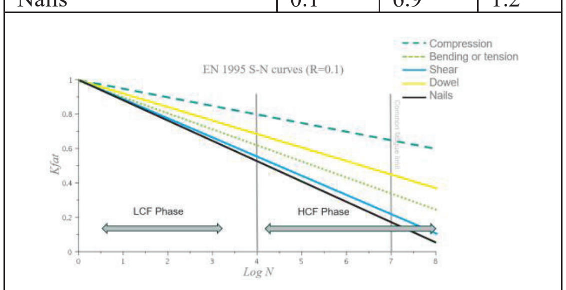
The reduction factor k_{fat} is defined as:

$$k_{fat} = 1 - \frac{1-R}{a(b-R)} \log(\beta N_{obs} t_L) \tag{3}$$

This equation considers the impact of both loading conditions (R ratio, N_{obs}-Number of constant amplitude stress cycles per year, t_L-Design service life in years) and structural characteristics (a, b-Coefficients representing fatigue action type, β-Damage consequence factor) to fatigue degradation.

Table 1: Key parameters in timber structure fatigue design

Structure type	κ	a_{fat}	b_{fat}
Compression parallel or perpendicular to grain	0.6	2.0	9.0
Bending or tension	0.2	9.5	1.1
Shear	0.15	6.7	1.3
Dowels with d≤12mm	0.4	6.0	2.0
Nails	0.1	6.9	1.2



For LCF phase (log n <4), fatigue-induced strength reduction is not considered in design, and the full static strength of the material is assumed (k_{fat}=1.0). However, for the HCF phase (log n>4), k_{fat} decreases with the increasing number of load cycles (Table.1), reflecting fatigue-induced damage as repeated loading leads to microstructural degradation, progressively reducing the material's effective strength. Current fatigue provisions typically limit the maximum number of load cycles to approximately $5 \cdot 10^7$ [10], though a clear fatigue cutoff limit has not yet been established in EN 1995-2. In addition, existing tests on timber joints are generally conducted below this maximum threshold, so the fatigue behaviour beyond this limit remains unclear [10]. However, unlike steel, this does not guarantee infinite fatigue life, as timber may still experience continued degradation beyond this threshold. Therefore, in fatigue-resistant design, stress levels should remain below this threshold to minimize progressive damage and ensure structural longevity under cyclic loading.

Moreover, Eurocode 5 primarily considers fatigue failure in wood or some basic metal elements like dowels and nails, without accounting for complex fatigue interactions in composite connections. By applying the fatigue strength reduction factor equations for both wood and steel (Figure 7), it becomes evident that at higher applied stress and lower cycle number, pull-out failure normally occurs due to adhesive and timber failure, whereas at lower applied stress and higher cycle counts, fatigue fracture develops in the threaded steel rod, consistent with experimental observations [4, 12, 14]. This behaviour can be attributed to the brittle failure mechanisms of timber and adhesives, which cause them to fail when stress exceeds a critical limit, rather than through progressive fatigue damage. At lower stress levels, metal element sustaining most of the cyclic loading, so insufficient load transfer to the adhesive and timber, leading to fatigue crack initiation and propagation in the steel rather than immediate adhesive or timber failure.

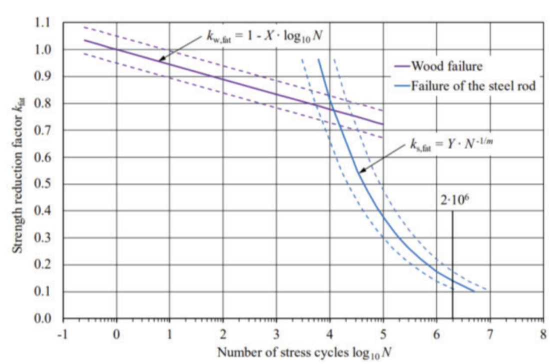


Figure 7. Fatigue strength reduction factor k_{fat} considering wood and steel failure [14]

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Several studies [17, 11, 18] have recognized that the fatigue prediction models in Eurocode 5 appear to be overly conservative (Figure 8) especially for cycles in the range above 10^6, as the predicted capacity reduction can be more significant to the actual reduction. This can potentially limit the financial efficiency of timber structures when fatigue design is considered, which suggests that existing design guidelines may require refinement to better reflect the actual fatigue performance of timber connections [19].

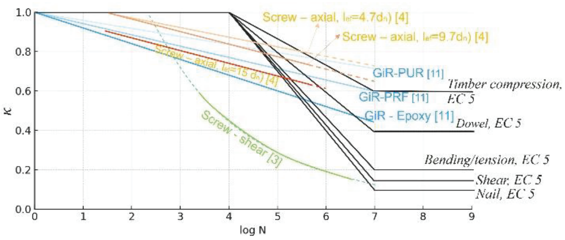

Figure 8. Comparison between testing results of different connections and provisions in EC5 at R=0.1

6 – CONCLUSION AND FUTURE RECOMMENDATION

Existing fatigue research in timber connections has primarily focused on those situations used in infrastructure such as bridges and wind turbine towers, while investigations into fatigue behaviour in building connections remain limited. In these structures, steel and concrete are commonly integrated in connections for improved mechanical performance. However, as confirmed by experimental research, the combinations of material properties and interfacial behaviour has led to more complex fatigue behaviours.

When the dominant failure component in connections changes, different S-N curves patterns can be observed in the test. For instance, in doweled and adhesive connections, when metal elements govern deformation, a nonlinear S-N curve with rapid strength reduction emerges, suggesting a well-defined endurance limit. Conversely, when timber is the component subject to failure in these connections, a linear trend can be observed in S-N curves, indicating the absence of a clear endurance limit. Additionally, when concrete is involved, its hardening effect can improve fatigue performance by enhancing stiffness over time.

Current knowledge on timber connection fatigue is largely derived from experimental testing at various scales, particularly S-N curve assessments, as existing design guidelines lack comprehensive fatigue provisions. In addition, knowledge and specification of design approaches of the fatigue behaviour of timber and timber connections is mostly based on coarse description of the material behaviour and traditional connections. A more detailed analysis of the impact of anisotropy of the material, its fibre structure and the related strength properties and failure behaviour has not been performed so far. Especially the complex stress situation and failure behaviour at modern, high-performance connections, where multiple failure modes may occur and which are often characterised by composite behaviour, require more detailed consideration. To gain a deeper understanding of these influences on connection fatigue behaviour, further experimental studies are needed. These should be carried out systematically to generate reliable data that can support broader applications in structural design. This effort will require the development of comprehensive guidelines covering testing procedures, including specimen layout (e.g., minimum spacing and edge distances), quality control measures (e.g., accounting for natural defects in timber and bondline curing quality), and standardised loading scenarios (e.g., loading frequency) and testing environments (e.g., temperature and moisture content) [20].

Most fatigue research has focused on constant-amplitude loading, particularly at common stress ratios (R = 0.1, variable tension cycles) or extreme conditions (R = -1, fully reversed loading). While these tests provide valuable insights into long-term cyclic behaviour, they may not fully capture real-world structural performance. To advance fatigue-resistant design, further research should focus on large-scale fatigue testing, incorporating realistic loading conditions, environmental influences, and multi-axial stresses. Investigations should include a broader range of stress ratios and loading scenarios to better reflect service conditions. Developing a comprehensive fatigue database and predictive numerical models that integrate stiffness degradation, creep effects, and fatigue-induced material weakening will enhance design accuracy.

7 – REFERENCES

[1] J. C. M. Schoenmakers. "Fracture and failure mechanisms in timber loaded perpendicular to the grain by mechanical connections." In: Research at Eindhoven University of Technology, 2010.

[2] J. Yi, Y. Chen, J. Liu, J. Yin, J. Wang, "Study on variable amplitude fatigue performance of glued laminated timber beam." In: Structures, Volume 71, 2025, pp. 107947.

[3] P. Niebuhr, M. Sieder. "High-cycle fatigue behaviour of a timber-to-timber connection with self-tapping screws under lateral loading." In: European Journal of Wood and Wood Products 79.4 (2021), pp. 785–796.

[4] P. L. Niebuhr, M. Sieder. "Estimation of the high-cycle fatigue behaviour of timber connections with inclined screws under tension." In: European Journal of Wood and Wood Products 83.2 (2025).

[5] P. Niebuhr, M. Sieder. "High-cycle fatigue behavior of a self-tapping timber screw under axial tensile loading." In: Journal of Failure Analysis and Prevention 20 (2020), pp. 580–589.

https://doi.org/10.52202/080513-0419

[6] C. A. Weaver, W. G. Davids, H. J. Dagher. “Testing and analysis of partially composite fiber-reinforced polymer-glulam-concrete bridge girders.” In: Journal of Bridge Engineering 9.4 (2004), pp. 316–325.

[7] D. Yeoh, M. Fragiacomo, D. Carradine. “Fatigue behavior of timber–concrete composite connections and floor beams.” In: Engineering Structures (2013). vol. 56, pp. 2240–48.

[8] J. P. Wacker, M. A. Ritter, D. Conger. “Field performance of timber bridges: 8. Lynches Woods Park stress-laminated deck bridge.” In: United States Department of Agriculture, Forest Service, Forest Products Laboratory (1996).

[9] L. Bathon, O. Bletz-Mühldorfer, J. Schmidt, F. Diehl. “Fatigue performance of adhesive connections for wooden wind towers.” In: Materials and Joints in Timber Structures. Ed. by S. Aicher, H.-W. Reinhardt, and H. Garrecht. RILEM Bookseries, Vol. 9 (2014), pp. 375–380.

[10] R. Jockwer, P. Landel, V. Norbäck, R. Ziethén, E. Dölerud, L. A. Naveda, C. J.Åkerström “Fatigue resistance of adhesive bonded connections with and without internal steel plates in large timber structures.” In: Proceedings of the World Conference on Timber Engineering (WCTE), Oslo (2023).

[11] R. Bainbridge, C. Mettem, K. Harvey, M. Ansell, “Bonded-in rod connections for timber structures – Development of design methods and test observations.” In: International Journal of Adhesion and Adhesives 22.1 (2002), pp. 47–59.

[12] M. Madhoushi, M. P. Ansell. “Experimental study of static and fatigue strengths of pultruded GFRP rods bonded into LVL and glulam.” In: International Journal of Adhesion and Adhesives 24.4 (2004), pp. 319–325.

[13] T. Tannert, H. Zhu, S. Myslicki, F. Walther, T. Vallée. “Tensile and fatigue investigations of timber joints with glued-in FRP rods.” In: The Journal of Adhesion 93.11 (2016), pp. 926–942.

[14] B. Maurer, E. Gehri, T. Strahm, R. Steiger, C. Affolter. “Fatigue strength of axially loaded steel rods bonded in European ash glulam.” In: Conference Proceedings of the 4th ICTB. Biel/Bienne, Switzerland, 9–12 May 2022.

[15] J. C. Molina, C. Calil Junior, M. R. Carreira. “Pullout strength of axially loaded steel rods bonded in glulam at a 45º angle to the grain.” In: Materials Research 12(4) (2009), pp. 427–432.

[16] European Committee for Standardization (CEN). EN 1995-2: Eurocode 5 – Design of timber structures – Part 2: Bridges. Brussels, Belgium: CEN, 2004.

[17] H. Stamatopoulos, K. Malo. “Fatigue strength of axially loaded threaded rods embedded in glulam at 45º to the grain.” In: Conference Proceedings, ICTB 2017, 3rd International Conference on Timber Bridges. Skellefteå (2017).

[18] C. Schröder. “Wooden and wood hybrid towers for wind turbines in the multi-megawatt class.” In: 21st International Timber Construction Forum (IHF 2015). Hannover, Germany (2015).

[19] P. Niebuhr, M. Sieder. “High-cycle fatigue behaviour of a timber-to-timber connection with self-tapping screws under lateral loading.” In: European Journal of Wood and Wood Products 79 (2021), pp. 785–796.

[20] R. Jockwer, P. Palma, A. S. Rebouças, A. Salenikovich. “Development of comprehensive testing procedures for high-performance bonded-in rods.” In: World Conference on Timber Engineering (WCTE), Oslo, Norway (2023).