IN COLLABORATION

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NEW ZEALAND TIMBER DESIGN SOCIETY

Case-Hardened Steel Fasteners & Mass Timber Construction

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The use of large (8mm diameter and larger) fully threaded and partially threaded screws are critical to facilitate the design and construction of Mass Timber (MT) structures. This includes basic applications such as fixing Cross-Laminated Timber (CLT) panels to supporting glued-laminated beams, but also at critical gravity (i.e. beam-to-column) and seismic (timber lateral systems and/or steel collector plates to timber) connections.

In general, case-hardened steel timber screws (i.e. fasteners) have been used on thousands projects globally, with relatively few reported failures. That said, there are reports of screw failures in large numbers, on isolated projects in Europe, the USA and Canada, where project conditions (e.g. prolonged exposure to excessive moisture) have led to Environmental Hydrogen Embrittlement (EHE) in the fasteners. These have often occurred where thick steel plates are being fixed to timber. In New Zealand, some projects have observed similar failures as well. While the projects affected are small in number, the consequence to individual projects can be significant, and thus this issue deserves additional scrutiny for the betterment of the industry.

The following tech note will explain the conditions required for hydrogen embrittlement to occur, how to identify connections with a higher risk profile, along with recommendations on how to mitigate the risk.

Hydrogen Embrittlement in Case-Hardened Steel Fasteners

The screw fasteners typically used in MT construction are of case-hardened carbon steel (Fy > 1000 MPa) in order to achieve larger structural capacities and enable easier installation into timber, often without the requirement of pre-drilling. While this enables for faster and easier construction, critical to realising one of the benefits of MT, hardened carbon steel fasteners are potentially susceptible to both Internal Hydrogen Embrittlement (IHE), during the manufacturing process, and Environmental Hydrogen Embrittlement (EHE), post manufacturing. The core hardness threshold for which fasteners are considered susceptible to hydrogen embrittlement is typically cited as being 360 Vickers Hardness (HV) or above, noting that the fastener casing will be harder to facilitate installation. Between a core hardness level of 360 and 390 HV, the risk to hydrogen embrittlement is believed to be manageable, while the susceptibility of the fastener to hydrogen embrittlement increases sharply above a core hardness of 390 HV.

For fasteners with a core hardness above the susceptibility threshold (i.e. 360 HV), a sophisticated manufacturing and QAQC process is required to control the risk of IHE, often fine-tuned over time. This is particularly true during the application of protective coatings, where hydrogen can be trapped and introduced to the fastener core. Through post-production quality control validation testing, in accordance with ISO 15330, manufacturers can demonstrate fasteners do not have IHE at the time of packaging, even for core hardness well above 390 HV.

Environmental Hydrogen Embrittlement (EHE)

While the risk of IHE may be able to be controlled for fasteners with a core hardness above 390 HV, these same fasteners can still be prone to EHE, particularly under adverse storage, construction and/or permanent in-service conditions.

For EHE to occur during construction (or in-service), three items must be present in unison:

1. presence of a susceptible material in the fastener,
2. sustained tension on the fastener and
3. a source of atomic hydrogen into the fastener.

Reducing the Risk of EHE

If one of these three items can be precluded, the risk of EHE occurring is significantly reduced, if not practically eliminated. The risk of EHE can also be appropriately managed by a series of risk reduction measures for each of the three items required for EHE to occur.

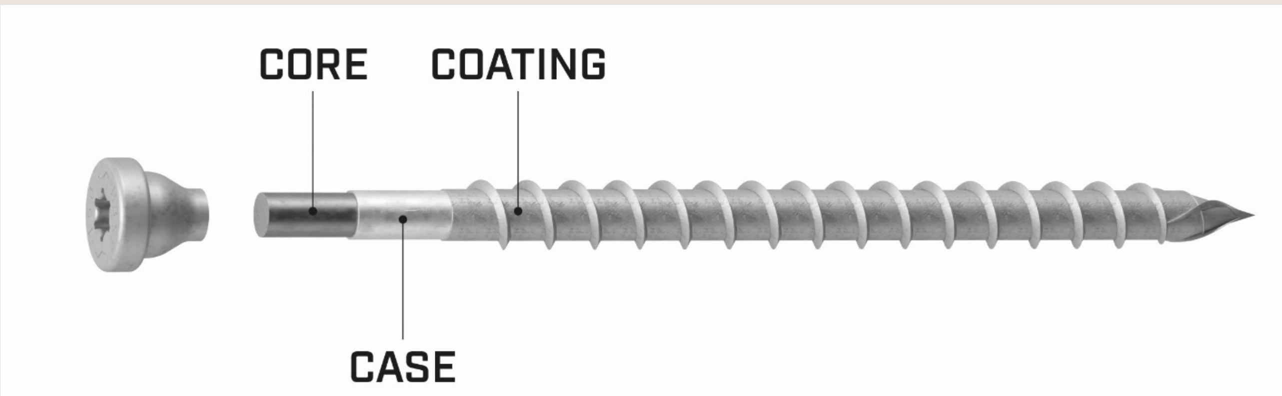

Figure 1 – Screw Anatomy[1]

Susceptibility to Sustained Tension

The extent of sustained tension required for EHE to occur, in the presence of the other two ingredients required, is up for debate, varying from any sustained tension, to 10–50% of the ultimate screw capacity. Whatever the threshold may be, the risk will be reduced if elevated sustained tension demands are avoided, recognising there can be project conditions where fasteners are required to resist permanent tension loads. In this case it is even more important to address the risk of the other two ingredients.

The susceptibility to unintended sustained tension during construction (i.e. in addition to design in-service tension) is greatest for steel-to-timber connections, and to a lesser degree timber-to-timber connections utilising a fastener with a washer head. This is because fasteners installed into steel plates are more likely to be over-torqued during installation and have a greater surface bearing area to accumulate pressure if the timber swells under excessive MC gain. The risk increases if thick steel plates are being used, as these have less ability to deform, and thus activate an even larger bearing area to resist the pressure from swelling timber. Typical timber-to-timber connections, particularly those without a washer head, are considered to be significantly less susceptible, as the fastener heads will be pulled into the timber if swelling occurs due to MC gain.

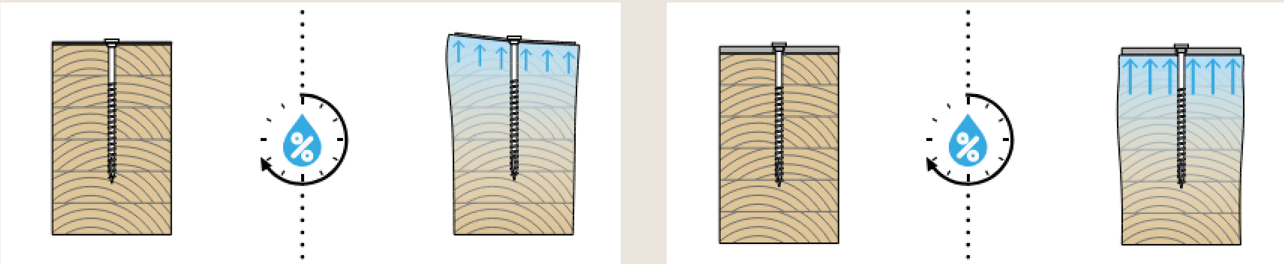

Figure 2 – Pressure under Thin & Thick Steel Plates[2]

To reduce the risk of unintended sustained tension loads, it is important to follow the fastener manufacturers recommendations. This includes using the correct tools, installation speed and limiting torque, all especially critical for steel-to-timber connections, where over-torquing the fastener is more common. Once the fasteners are installed, it is important to limit the MC gain of the timber (i.e. swelling), from time of installation to maximum MC. This can be achieved through a good moisture management plan and execution. For high-risk connections, such as steel-to-timber, consideration should be given to delaying the installation of the fasteners until after the building is enclosed, eliminating the role of timber swelling.

The designer also has a critical role to play in the design of connections to limit the risk of sustained tension. This can be achieved through thoughtful detailing to limit the susceptibility to unintended sustained tension, along with limiting project conditions where sustained tension is designed into connections. When a fastener is designed to resist tension in a connection, the designer also needs to consider the potential impact of swelling due to MC gain, along with a reasonable expectation on seating tension, when assessing the demand to capacity of the chosen fastener.

Figure 3 – Risk of Elevated Sustained Tension

Susceptibility to Atomic Hydrogen Exposure

The potential sources of atomic hydrogen are primarily free water and/or the reaction (i.e. corrosion) of a sacrificial metallic coating, such as zinc. The risk of excessive corrosion will depend on project conditions, including proper storage of the fasteners, MC of the timber (extent and duration), corrosivity of the timber / treatments and atmospheric conditions (i.e. vicinity to the ocean). Steel plate to timber connections require additional care as the coatings can be damaged during installation, facilitating a pathway for hydrogen into the fastener. Water can also become trapped under steel plates, increasing the local MC in the timber.

To reduce the risk of excessive corrosion, it is important to limit the maximum MC of the timber during construction along with the duration of any elevated levels. In particular, any standing water should be removed as soon as possible. The clearest limits on the acceptable exposure to moisture during construction are in EN 1995–1–1:2023 DRAFT: Eurocode 5 – Design of timber structures – Part 1–1: General rules and rules for buildings. The Service Classes noted in this draft standard define a yearly average and upper limit on MC. For Service Class 2, which covers most temporary construction conditions in ANZ and North America, this includes an upper limit MC of 20%, with a yearly average limit of 16%.

Service Class (SC) per EN 1995-1-1		1	2	3	4
Upper limits	MC of Timber (1)	12%	20%	24%	-
	Relative Humidity(3)	65%	85%	95%	Saturated
Yearly Average Limits	MC of Timber (2)	10%	16%	20%	-
	Relative Humidity(3)	50%	75%	85%	Saturated

(1) Corresponding MC
(2) Corresponding MC
(3) Relative humidity of surrounding air at a temperature of 20
(4) For additional notes, see EN1995-1-1 Table 4.2

Figure 4 – Thresholds as per EN1995–1–1 Table 4.2[3]

The upper limit of MC permitted in Service Class 2, aligns with the point at which the rate of corrosion spikes considerably.

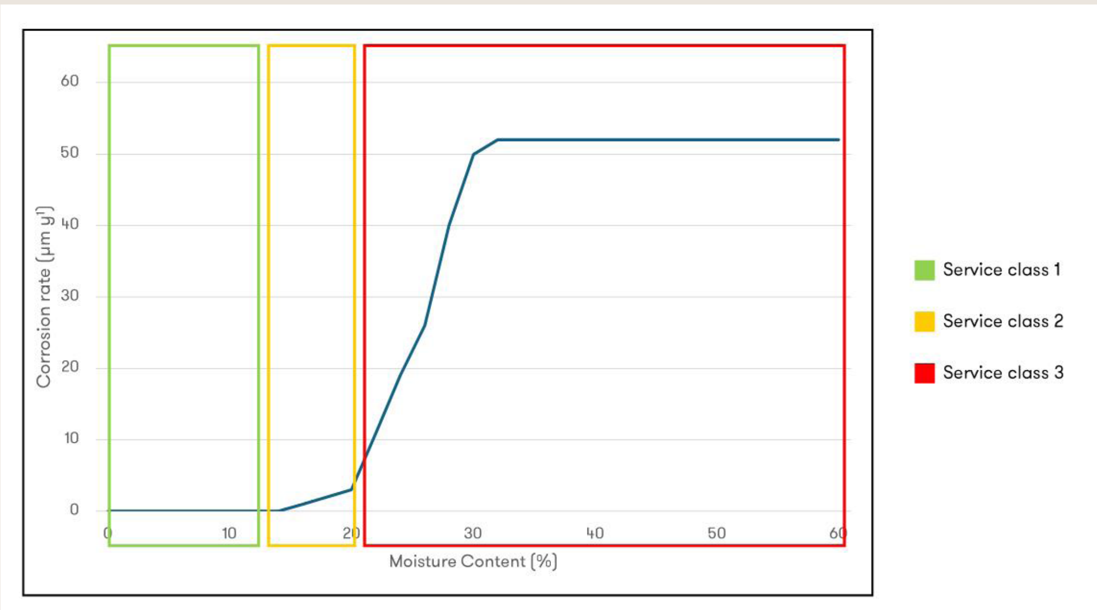

Figure 5 – Service Class vs Corrosion Models[4]

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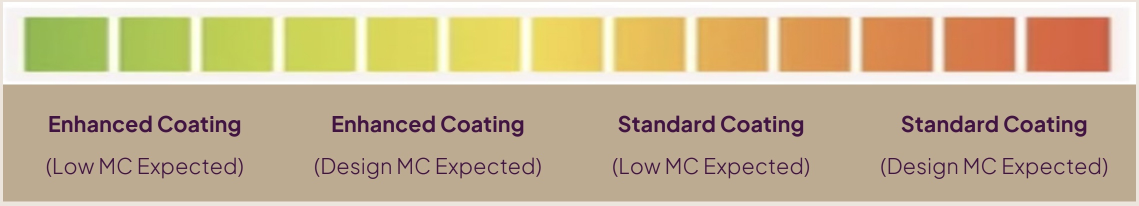

Figure 6 – Risk of Hydrogen Exposure to Fastener Core

Susceptibility of Fasteners:

The root susceptibility of hardened carbon steel fasteners to hydrogen embrittlement falls into three bands. These bands are recognised in standards such as ISO 4042:2022 Fasteners – Electroplating Systems, which applies varying requirements for electroplated coatings onto hardened carbon steel elements.

Low Risk – Core Hardness < 360 HV:

The primary way to reduce the susceptibility of the fastener itself, is to use a non-hardened carbon steel screw (e.g. stainless steel) or a hardened steel fastener with a core hardness below 360 HV, the lower bound threshold at which HE is typically believed to not be of concern. This is likely not practical in all situations based on the in-service structural performance requirements of timber fasteners and cost / availability but should be considered in high-risk applications. It should be noted however, that even with the use of fasteners with a core hardness below 360 HV, particularly those with a standard zinc coating, it is still very important to limit the fastener to excessive moisture (i.e. enhanced corrosion).

High Risk – Core Hardness > 390 HV:

Above a core hardness of 390 HV, the susceptibility of a fastener to hydrogen embrittlement is considered to increase significantly as noted in Technical Report ISO-TR-20491-2019 – Fasteners – Fundamentals of hydrogen embrittlement in steel fasteners. This is also the maximum hardness allowed if fasteners are fabricated in conformance with ISO 2702:2022 Fasteners – Heat treated tapping screws – Mechanical and physical properties.

Manageable Risk – Core Hardness between 360–390 HV:

Between a core hardness of 360–390 HV, the risk to hydrogen embrittlement is believed to be manageable with the appropriate precautions to limit the susceptibility of fasteners to unintended sustained tension and to excessive moisture, which could lead to the introduction of hydrogen into the fastener.

National Building Code of Canada – New Hydrogen Embrittlement Provisions:

To address the susceptibility of IHE and EHE to hardened carbon steel fasteners, the National Building Code of Canada created a task group to investigate the topic. The outcome of the task group was to introduce new limits on the maximum core hardness of case-hardened carbon steel timber screws, to reduce the susceptibility to hydrogen embrittlement, and to introduce language to ensure the screws are produced in compliance with the appropriate and consistent standards.

The baseline requirements for fasteners used in a 'dry-service' conditions, roughly equivalent to Eurocode Service Class 2, are now included in CSA O86:2024: Engineering Design in Wood, clause 17.6.4 Hydrogen Embrittlement. This includes fabrication of the base fastener to two acceptable standards, ASME B18.6.3 or ISO 2702, along with an upper core hardness limit of 390 HV (as required by these standards). It also includes quality control measures for fasteners with a core hardness between 360–390 HV, intended to limit the risk of IHE.

For 'wet-service' conditions (i.e. in-service MC > 19%), roughly equivalent to Eurocode Service Class 3, the allowable core hardness for carbon steel fasteners is limited to 360 HV, per Table 12.1 of CSA O86:2024, irrespective of the fastener coating. This is to reflect the fact that the fasters will have greater potential exposure to the hydrogen embrittlement triggers (i.e. source of hydrogen combined with sustained tension).

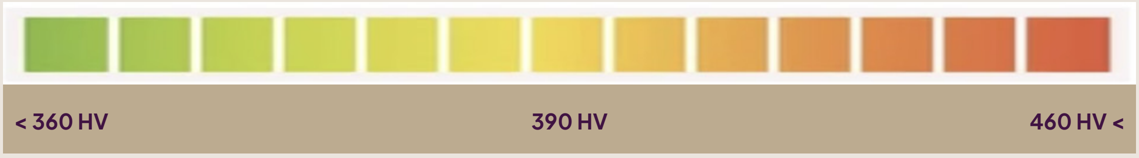

Figure 8 – Fastener Risk Profile vs Core Hardness

Summary and Recommendations

While the elimination of one of the three ingredients required for EHE to occur would eliminate the risk of hydrogen embrittlement, this is often not practical. Most large fully threaded and partially threaded screws on the market have a core hardness above the lower bound hardness threshold of 360 HV. A realistic allowance for exposure to moisture during construction is also required, which depending on the application, could simultaneously lead to the build-up of sustained tension and a source of hydrogen.

The new CSA O86:2024 core hardness limits are intended to reduce the susceptibility of the fastener to hydrogen embrittlement, thus providing a greater margin for error. Appropriate measures are still required to limit the exposure of the fasteners to sustained tension and a source of hydrogen. While many of the screw manufacturers on the market can produce screws in conformance with this new standard, many either have old stock on the market or are still producing fasteners with a core hardness above 390 HV. Note, since neither the European Assessment Document (EAD) 130118-01-0603 Screws and threaded rods for timber constructions or the ICC-ES Acceptance Criteria for Dowel-type Threaded Fasteners Used in Wood (AC233) currently address core hardness, the associated European Technical Assessments (ETA's) and Evaluation Services Reports (ESR's) cannot be relayed upon to assume conformance with CSA O86:2023.

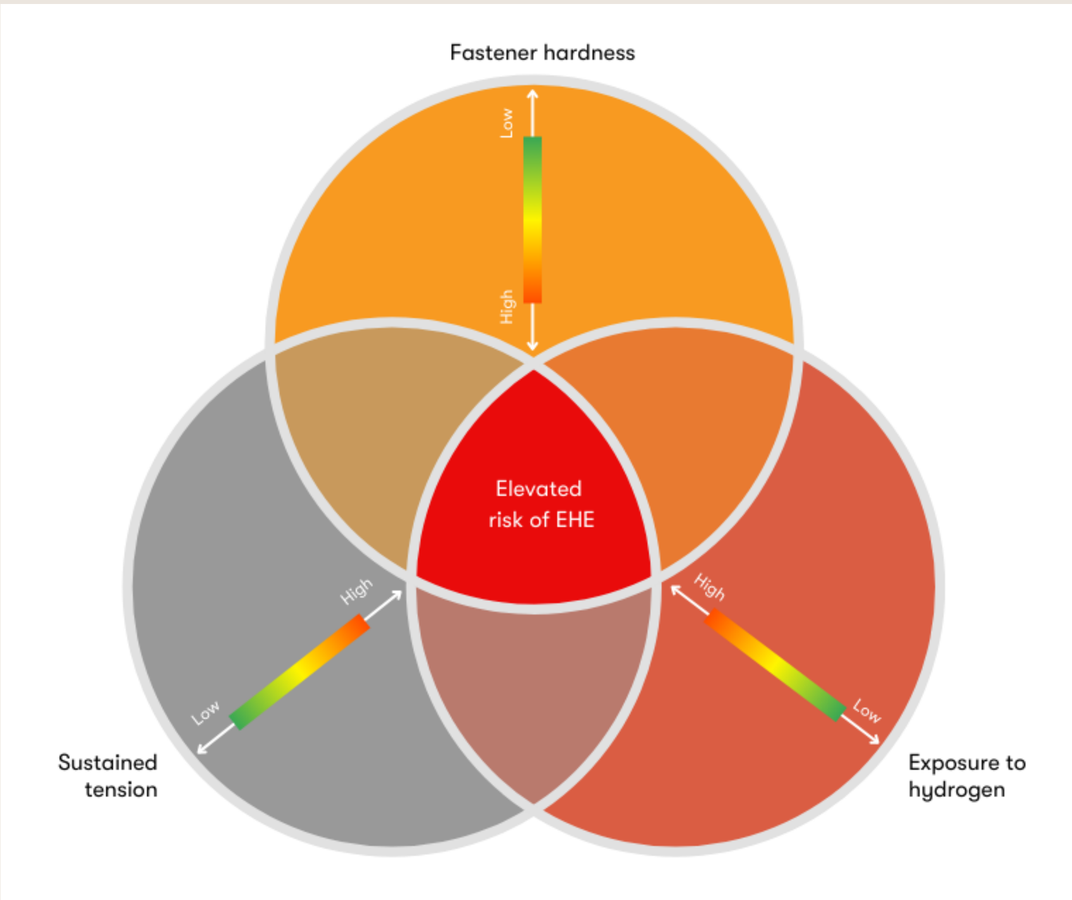

Figure 9 – Overall EHE Risk Profile

While these new requirements greatly reduce the risk of EHE, they should not preclude good design and detailing, along with a robust and comprehensive moisture management plan. This is true even for fasteners with a core hardness below 360 HV.

Recommendations for Consideration

1. Create a risk profile for each screw type and application. This will help guide any additional mitigation measures required, particularly at critical gravity and/or thick steel plate to timber connections.
2. For case-hardened carbon steel fasteners, limit the allowable core hardness of fasteners to less than 390 HV for Service Class 1 & 2, in conformance with the new CSA O86:2024 requirements. Note, this requirement could be relaxed, at the designer's careful discretion, if the risk profile of sustained tension and/or hydrogen exposure is low (i.e. if the fasteners were installed after the building is enclosed). For Service Class 3 and above, special consideration is required by the designer to account for seasonal changes in MC, along with coordination with the screw manufacture to ensure the appropriate fastener / coating is selected.
3. Ensure manufacture installation instructions are well communicated to the installer. This should include recommended tools, speed, torque limits, pre-drilling, angle of installation tolerance, etc.
4. Request limits from the screw manufacturer on the MC range of the timber at time of installation, during construction (extent and duration) and for the in-service condition.
5. Ensure the screw and coating specified is in alignment with manufacture limitations and realistic construction constraints. Adjust the screw or coating specification as required.
6. Develop a clear and achievable comprehensive moisture mitigation plan as a design and construction team. This is critical, even for fasteners with a core hardness below the lower bound threshold of 360 HV.
7. Exercise heightened caution at thick steel plate to timber connections, as the majority of the reported cases of EHE the authors are aware of have occurred at this condition. Provide specific attention to these conditions in the project moisture mitigation plan, potentially designing and detailing these connections per the requirements of Service Class 3 in lieu of Service Class 2.

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(3) Figure 4 is a partial reproduction of Zelinka, S.L., 2014, Corrosion of Metals in Wood Products, Table 4.2
(4) Figure 5 is a partial reproduction of ISO / TR 2049, Figure 4–2

Existing Enclosed Buildings

Once a mass timber structure is enclosed, the risk to EHE reduces significantly as potential sources of hydrogen are typically eliminated. The amount of tension on the fasteners will also typically be reduced, as the timber shrinks with a reduction in MC. Thus, there is not a significant concern for installed fasteners in existing enclosed buildings which do not meet the core hardness limits in now specified in CSA O86.

Special attention should still be given to any significant moisture ingress, particularly if it results in elevated timber MC for an extended period of time.

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