Design for adaptability, disassembly and reuse – A review of reversible timber connection systems

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Review

Design for adaptability, disassembly and reuse – A review of reversible timber connection systems

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ABSTRACT

The building and construction (B&C) industry remains one of the highest greenhouse gas emitting and resource intensive sectors globally. Despite the recent trend to use renewable carbon sequestering building materials, such as timber, a paradigm shift is needed to transition the B&C industry towards an 'absolute zero' circular economy. Design for adaptability (DfA) allows buildings and their components to remain in use for longer by responding to changing environmental conditions and occupant needs. This paper provides a review of design principles to enable adaptability for timber buildings through design for disassembly (DfD) and reuse, as well as a systematic review of reversible timber connection systems that enable DfA and DfD.

1. Introduction

The building and construction industry remains one of the highest greenhouse gas emitting sectors globally; despite the imperative to decarbonise the sector by 2050 to meet the Paris Agreement targets [1], it still contributes about 40% of global energy-related CO2 emissions [2]. Yet, in most developed countries, the construction industry still operates on an obsolete, 'take-make-dispose' linear model [3], where natural resources are unproductively used and disposed. As a result, 60% of 3 billion tons of global construction and demolition waste is currently disposed in landfills [4].

The environmental impact of different construction materials ranges considerably; while steel and reinforced concrete, which dominate the mid- and high-rise building sector, are the most emissions and energy intensive [5,6], in the last two decades, more and taller timber buildings have been constructed [7–9] that sequester carbon dioxide in durable wood products [10–12], drastically reducing their environmental footprint when compared with current concrete and steel construction [9,10,13,14].

However, advances in construction materials alone are not sufficient to offset the environmental effects of a 'linear' design and construction process. The circular economy (CE) offers an opportunity for decarbonising the built environment: extending the life span of material resources in the value chain, and turning demolition costs into a positive business case [15–17]. Leising et al. [18] define the CE for buildings as a "lifecycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank."

Traditionally, CE concepts distinguish between the biosphere, where resources, or matter, are cascaded, and the technosphere, where materials and products, or their components, are 'looped' in the smallest possible cycle to achieve the least quality loss and retain value, labour and embodied environmental impact (emissions, energy, etc.) [19].

Timber buildings present a unique opportunity as they can maximise circularity at the interface of the technosphere and biosphere, as shown in Fig. 1.

Value retention in the technosphere is maximised through maintenance and repair, where design for durability and robustness are of relevance, and through reuse and refurbishment. The idea of 'buildings as material banks' [18,22] is realised through disassembly and reuse of modules, structural assemblies, components, and materials. Only once technosphere loops are exhausted, timber materials cross over into the biosphere, where they are 'cascaded', by manufacturing of engineered wood products from solid wood or wood veneers, recycling particles and fibres in boards (chipboard, fibre boards), and even further, by deriving chemical products [23,24]. Once cascading is no longer feasible, energy can be recovered through incineration in waste-to-energy plants, which, however, releases the stored carbon. If waste-to-energy is not possible, landfilling is considered as the least desirable option.

Nevertheless, one of the most effective ways to optimise construction material usage and maximise carbon storage in timber products [25,26], is to keep entire buildings in use for longer time [16,22,27,28]. Beside design principles for durability and robustness, Design for Adaptability (DfA) has become a growing area of research in the transition of the construction industry to a CE [22,29]. Operating on the smallest loops of the technosphere, adaptable buildings can respond to the changing needs of their occupants and varying environmental and contextual conditions [15,27–30] hence increasing the service life of a building. Schmidt and Austin [31] analysed how buildings can be adapted to change, defining six levels of adaptability: adjustable, versatile, refitable, convertible, scalable and movable. These categories define increasing changes to the building, from flexible buildings that can be modified by occupants themselves, to adaptable buildings, that can change size or be relocated [32]. Spatial adaptability thus requires a differed design approach, where future change scenarios are considered in the initial design [31,33–35]. Apart from the adaptability of the building as a whole, and its parts (structure, envelope, etc.), also a building's repairability should be considered as a way to extend its service life.

Fig. 2 illustrates how modular timber buildings can be designed for circularity by incorporating DfA principles, where entire buildings can be reused as they are repurposed and reconfigured (refitted, converted, scaled [31]), or relocated (moved). All the other circularity principles also apply to adaptable buildings, including disassembly and reuse (salvaging [36]), cascading in the biosphere (recycling), and energy recovery.

DfA enables not only the concept of technical material 'looping', with undeniable environmental advantages, but it also unleashes multiple social benefits, for example those associated with housing. Home ownership remains a prevalent form of social insurance in many countries [38]; however, housing affordability is a critical issue in many cities around the world [39], effectively excluding households with limited saving ability from the property market. DfA may enable changes of building size according to household needs and savings [40]. Benefits of incremental housing for young families are well documented [40,41], and downsizing, or 'rightsizing', offers equally significant opportunities for older households [42], allowing them to grow or age in place for longer, with proven benefits for their physical and psychological well-being [43].

While DfA theory has been studied in architecture [29,30,32,44], few structural systems exist that allow for multiple adaptation and reuse cycles, or internal adaptability (flexibility) of buildings [45,46]. This paper explores how DfA can be achieved for timber buildings from a structural engineering perspective. First, design principles for structural adaptability are discussed. Then, existing reversible timber joints are
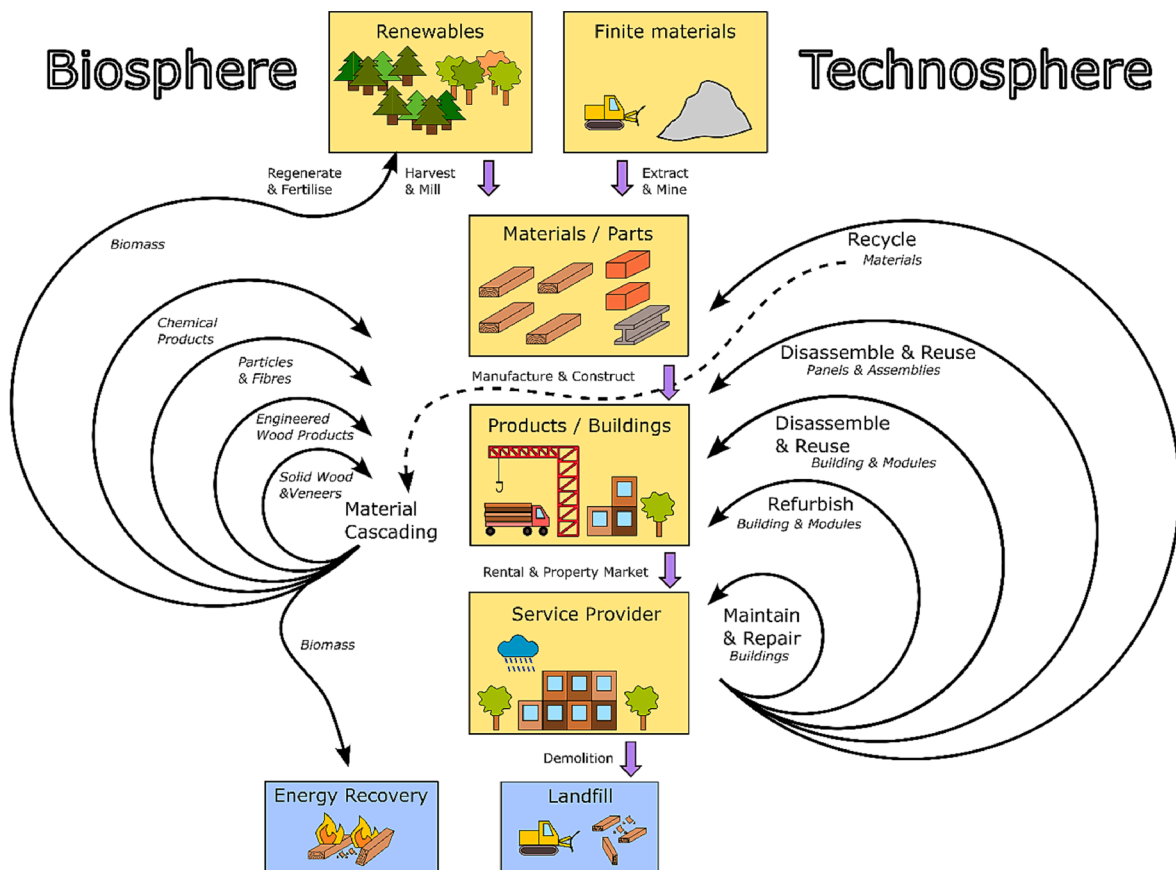

Fig. 1. Butterfly diagram of circular timber buildings [20]. Based on the idea from Ellen MacArthur Foundation's "Butterfly Diagram" [21].
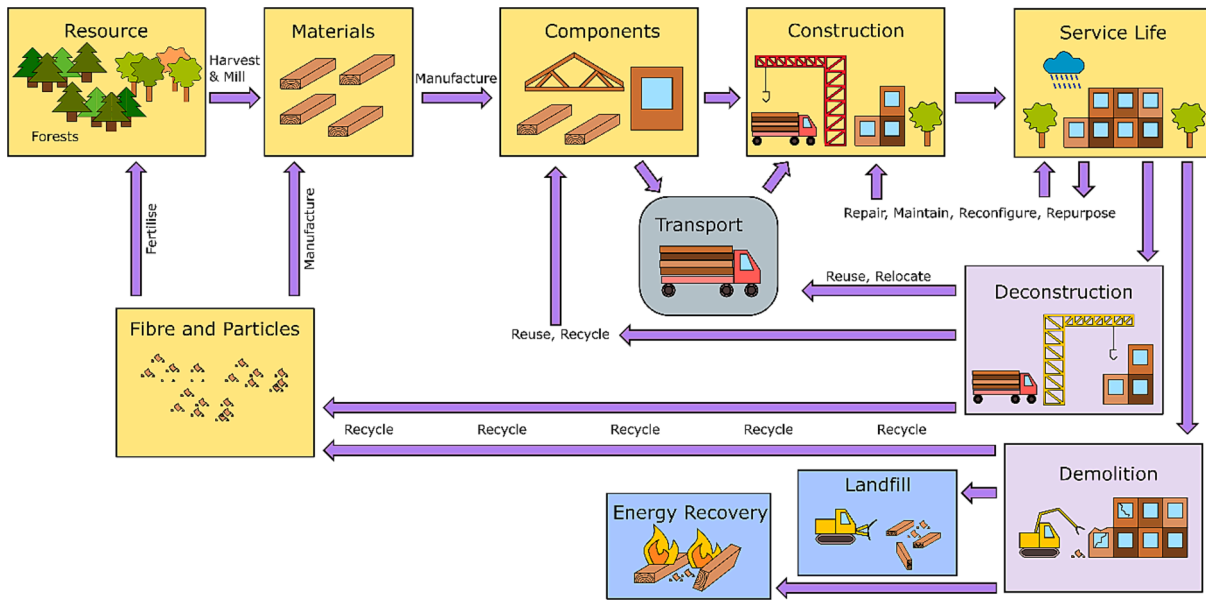
Fig. 2. Circular solutions for timber buildings in the technosphere [37]. DfA principles address the top right corner regarding repair, maintain, reconfigure, repurpose, reuse, and relocate.

reviewed that allow for repeated disassembly and reassembly. Finally, examples of reversible assemblies are presented.

2. Design principles for structural adaptability

This section discusses design principles for structural adaptability, i. e., designing in (shearing) layers, design for disassembly / deconstruction (DfD), and design for reuse. While all these concepts are generally material independent, additional considerations for timber buildings are highlighted where applicable. Furthermore, it should be noted that, in building construction literature, both terms 'Design for Deconstruction' and 'Design for Disassembly' are used interchangeably, collectively abbreviated as DfD in this paper.

2.1. Designing in (shearing) layers

Critical to enabling DfA is Brand's concept of a building as 'shearing layers of change', illustrated in Fig. 3, which acknowledges different lifespans of building components [47]. Designing a building in layers

enables modification and adaptation of its individual parts to new functions and requirements, thus avoiding or minimising material waste associated with conventional construction processes [48,49]. Physical adaptations can be efficiently achieved by using modular, standardised components with reversible connections, which allow building components to be added and reconfigured [29,50]. Prefabrication has the highest potential to integrate DfA due to the upfront design process, off-site manufacture, and rapid and waste-free on-site assembly [50–54].

From a structural design perspective, separation within and in-between shearing layers depends on reversible connections. In the context of this paper, reversibility of connections is defined as the combination of ease of disassembly and reuse potential of the connections themselves, as well as the components they attach to [36,52]. This includes disassembly and reassembly in the context of maintenance and repair, as well as reuse in a new context, due to relocation of the buildings or its modification - so that components may be reused in other parts of the same building or in other buildings. While in this paper the focus is on reversible connections for structural systems, assemblies, and components, many design principles for disassembly, reuse,
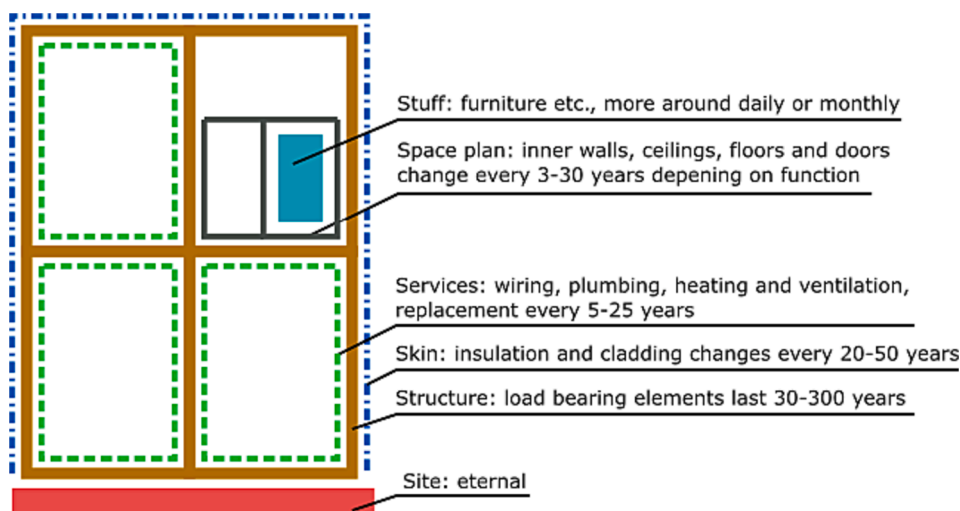

Fig. 3. Shearing layers concept [55] based on Brand [47] and Nordby [36].

adaptability, maintenance, and repair can equally be applied to the building enclosure (skin), building services, and other non-structural elements [56–59].

2.2. Design for disassembly

DfD is at the core of many circularity concepts, including maintenance and repair, adaptation, relocation, reconfiguration, 'building as material banks', and reuse. In buildings, DfD is generally enabled by reversible connections [36,48,50,60–63].

DfD is not a new concept. It has been used in many industries to facilitate maintenance and repair of products [64–70]. Bogue [70] defines DfD rules for product structure (modularity, standardisation, minimised components or variants), materials (mono materials, recyclability), connections (minimised number of connection points, increased accessibility and visibility of joints, easy to disassemble, use of fasteners instead of adhesives), component characteristics (lightweight, robust, durable, non-hazardous), and disassembly conditions (potential automation, no specialised procedures or tools). Smith et al. [64] provide further design rules for 'green products' that allow for disassembly of selective components for repair, reuse, recycling, or remanufacturing in the field of mechanical engineering. Many of these rules can be extended to buildings.

DfD can be seen as an evolution of 'Design for Manufacture and Assembly' (DfMA), a well-known concept in offsite construction, which uses standardised components or modules and plug-and-play connections [50,52,67,71]. Crowther [72] notes that DfMA and DfD have been used throughout history, e.g., in the design of settler homes of British colonies, or in the Swiss low-cost housing solutions "Volkshäuschen", "Globi-Heimeli", or the Uninorm houses in the period between the World Wars [73]. Crowther also makes recommendations for a multitude of circular design strategies that are enabled by DfD, such as materials recycling (use fewer materials, avoid hazardous and toxic materials, only use mono materials in inseparable sub-assemblies, avoid finishes and coatings, permanent material identification), component reprocessing and reuse (minimise the number of components and wearing parts, use mechanical connections, open buildings, building in layers, ease of access, tolerances, standardised connectors, permanent component identification), and building relocation (standardisation, regular grid, lightweight material and components). While Crowther [72] sees DfD as an implicit enabler of material, component and building reuse, Nordby [36] uses the term 'salvaging' to describe DfD with the purpose of reuse, and synthesises DfD literature to derive salvageability design criteria, including the need for accessible information (nowadays known as 'materials passports' [74] or digital twins [75]). Sanchez et al. [76,77] provide a method to plan partial disassembly of buildings with specific component retrieval, which makes it an attractive planning tool for maintenance and repair.

In conclusion, DfD has been embraced as a key design strategy to enable circularity in the built environment [22,50,52,67,78–81]; however, Akinade et al. [71] highlight that non-technical factors, such as policy and legislation, and a change in design thinking need to be addressed to enable DfD.

2.3. Design for reuse

DfD does not automatically imply reuse. Crowther [72] and Nordby [36] stipulate additional design criteria to increase reuse potential, many of which apply to timber buildings. Regardless of the construction materials used, design for reuse requires careful consideration at early design and planning stages to enable multiple reuse cycles [32,82].

Reuse of building components (such as beams and columns) or sub-assemblies (such as wall panels) is only possible if they are intact, including parts of joints that are permanently attached [83]. The amount of possible damage or loss of performance should be quantifiable or predictable.

Alternatively, components or sub-assemblies should have only sustained an acceptable (repairable) amount of damage, unless they can be reused in a way where the damage does not limit the functionality of the structural system [84]. Nijgh and Veljkovic [83] suggest 'buildings as functionality banks', where functionality of assemblies and components is retained rather than 'buildings as material banks', which focuses on reuse potential of materials and components [85]. An example of reuse with similar functionality is a temporary structure, such as a gazebo, podium or site office. Whereas an example of reuse with lower functionality would be a roof truss where all members have the same cross section but different degrees of utilisation, which allows for reuse of salvaged members in less critical locations. An example of reuse after acceptable damage would be structural members with sacrificial joints (fuses); these can be replaced while the member itself remains functionally intact, which is common practice in low damage seismic design [86–88].

To ensure safe and reliable use of reclaimed materials, building elements might need to be regraded or reclassified [89–92]. While this is especially important for materials salvaged from older buildings, where information about their original grade or quality is often missing [82], it can be also beneficial for contemporary buildings, where updated information about materials can be utilised to assess the suitability of building parts and component for reuse. Reclaimed timber materials may also suffer from biological degradation (insects or decay) or environmental degradation (sunlight, weathering and dimensional moisture effects) [93–96]. The latter might have changed the material either superficially (e.g., surface corrosion of metal components) or even deeper [97–99]. There might also be some mechanical damage from the time in service (wear and tear), accidental damage during erection and/or dismantling, but also fastener holes, slots from fittings, etc. from joining members together [49,100]. A challenge towards assessment and updating of material properties is presented by pigmented paint or superficial treatments that hinder visual assessment of structural integrity. In those cases, other non-destructive methods may need to be applied to assess salvageability [101,102]. It should be noted that the use of non-destructive methods for the assessment of timber structures is related to uncertainties [103,104]. Furthermore, as degradation and long-term load effects affect strength and elastic properties differently [105] relationships between indicating parameters determined by NDT, such as density, knottiness and eigenfrequency, and mechanical (especially strength) properties, which are well-established for new timber, need to be adapted.

Biological materials such as timber are well-known for their damage accumulation, which results in decreasing strength properties as consequence of long-term loading in addition to other forms of degradation and decay that are more related to the state of conservation [106–108], like previous exposure to moisture. Such effects need to be adequately addressed in any reclassification process of building materials, to ensure these are equally reliable as new materials [107]; this will be discussed in more detail in Section 2.4.

Finally, some reuse scenarios may require a structure to retain its performance across frequent assembly and disassembly cycles. Examples are temporary structures such as scaffolding, temporary stadium seating, and temporary buildings such as emergency housing or pavilions. For timber structures, it is crucial that joints retain their stiffness and tolerances, i.e., limit embedment deformation that creates slip [109], as will be elaborated in Section 2.4.

2.4. Reversible connectors

DfA, DfD and building in layers are enabled by reversible connections (some of which were reviewed by Pozzi [45]), joining members or building components that can then be reused in their entirety [36,61,62]. It is possible to design reversible systems or (sub-)assemblies by combining a reversible fuse-type joint with capacity protected reversible connections. The 'fuse', or potential ductile element (PDE),

dissipates energy in case of overloading while all other elements and joints remain elastic, in accordance with the basic principle of capacity design [110–113]. The key to achieving reversibility is that the fuse can be easily replaced – such as in low-damage seismic systems, which can be used for inspiration. Examples of such assemblies are given further below.

Reversibility presents some challenges for timber buildings due to the inherent nature of timber and timber connections; timber itself is a quasi-brittle, natural, highly hierarchically structured fibre composite, which means that loads exceeding the elastic limit lead to quasi-brittle failure in shear, bending, and tension, and to non-reversible deformation in compression (both parallel and perpendicular to the grain). As a result, contemporary timber buildings often employ connections with slender metal dowel-type fasteners, whose repeated plastic deformations provide ductility and energy dissipation, ultimately enabling robustness through alternative load paths [113,114]. The following sections focus further timber specific issues.

2.4.1. Challenges associated with disassembly

Non-reversible deformations present a challenge for disassembly of timber structures. Permanent deformations often occur in joints which provide ductility only or primarily during the first loading cycle (obvious in quasi-static monotonic tests) to an extend not repeatable in subsequent load cycles; either due to crushing of timber fibres and/or the visco-elastic nature of timber. Non-reversible deformations in joints present a particular challenge for reverse cyclic loading, such as wind, seismic, or other types of vibrational loading; the hysteresis curves of many common timber joints exhibit severe pinching [113] (i.e., a significant successive loss of dissipated energy from cycle to cycle) [113] due to elongation of fastener holes and timber densification, resulting in extensive initial slip. Common examples are carpentry joints that were developed for predominant unidirectional loading, including carpentry joints which rely on bearing (compression or shear) but also engineered joints with dowel-type fasteners loaded in shear (with ductile response that can be described by the European Yield Model [113]).

Apart from plastic or visco-elastic deformation, other durability issues, such as corrosion of metal fasteners, pose challenges for disassembly of timber joints, e.g., bolts with nuts that are hard to remove due to corrosion (rust) or increased friction of corroded galvanised dowels. Furthermore, screws produce sufficient heat during insertion to lead to a softening of wood components such as lignin and resin, causing some adhesion on the metal fasteners after cooling. In addition, the sliding coating on the thread surface, applied to ease screw insertion, gets abraded too.

2.4.2. Challenges associated with reuse

There are several aspects that affect the reuse potential of timber connections, even if disassembly is possible. 1) Non-reversible deformations of a fastener hole affect the performance of a connection in subsequent use cycles; pinched hysteresis provides a different load-bearing behaviour than that observed from quasi-static monotonic tests, which limits the amount of ductility and energy dissipation achieved in subsequent load cycles. In addition, it has an impact on the load distribution and redistribution in the re-used connection in the elastic state. However, timber embedment is not the only source of non-reversible deformation; the same phenomenon occurs for steel plates featuring beat out holes (sloppy connection, strain hardening). While fastener hole deformations may not necessarily affect the ease of reassembly of structures, elongated holes may exceed the permissible tolerances prescribed in regulations.

2) A load history that has resulted in some yielding (thus exceeded the elastic limit) of slender metal fasteners such as dowels, nails, and screws, not only prevents easy dismantling and re-assembly, but also presents a significant challenge for reuse. Firstly, damage may have accumulated, and the remaining fastener capacity is unknown, and secondly, previous loading beyond the elastic limit can cause a reduction

of displacement capacity, and a different load–displacement behaviour altogether.

In summary, characteristics of recycled joints can differ vastly from those determined from common short-term quasi-static tests. Since only limited test data is available for reused timber joints, the remaining performance and service life of a joint that has experienced some plastic deformation is usually unknown; hence, a safe reusability cannot be assured.

2.4.3. Duration of load effects

As discussed previously, the load history does not only affect timber joints and connections, but also the properties of timber members themselves. As a result of damage accumulation, the strength properties of reclaimed timber elements are generally lower than those of new timber elements. The Australian industry interim standard for recycled timber [115] provides some guidance on grading of recycled hardwood timber, and some rules for the design and applicable characteristic strength and elastic properties. According to this standard, the elastic properties are unaffected by past long-term loading and general service life, whereas for the strength properties a reduction from 50 to 65% of the properties for new timber components is recommended. This severe reduction in ultimate limit state (ULS) performance is counteracted by higher modification factors, to account for long-term loading effects for the next service life (k_1 factor in AS1720.1 [116]), which means: no reduction for short-term loads (<five days) instead of 6% reduction, 2% reduction for service loads up to five months instead of 20% reduction, and 10% reduction for permanent loads with a duration of more than five months instead of 43% reduction, respectively. As the strength properties of fasteners in timber (i.e., embedment, head-pull through and withdrawal strength), are commonly based to the timber density, which remains unaffected by long-term loading effects, only a strength reduction of 20% is suggested in [115] for long-term loading.

In reference to Falk et al. [91,92,117], similar rules might be applicable for softwood components. A summary on duration of load effect in conjunction with reusing structural timber components was recently published by Brandner & Ottenhaus [105]. Generally, however, little is known about reuse of more complex components or assemblies. While capacity design can overcome some of the challenges regarding ease of disassembly and reusability, it is not immune to time dependent and environmental effects, such as duration of load and moisture effects, and other durability issues (e.g., decay or corrosion). Furthermore, although the literature on duration of load effects is already comprehensive and a large number of engineering as well as physically-based models are available (reviews are provided e.g. by [118–124]) knowledge about this phenomenon and potential influencing factors, such as climate conditions (with focus on the moisture content & variation) as well as type and direction of loading, is still insufficient. It should also be noted that, because of the large natural variability in mechanical properties [123,125] this effect varies between members even within the same structural system.

2.5. Discussion

Several concepts exist that focus on aspects such as waste reduction, resource efficiency and circularity of materials and structures. DfD and DfA are paving the path to reuse of building components, assemblies, and entire structures. The implementation of these concepts in design of timber structures is progressing but still requires major development. Several challenges, especially regarding connection technology and material flow and reuse remain to be solved.

3. Review of reversible timber joints

This section discusses categories of reversible timber joints and connections. Although these two terms are often used interchangeably in literature, more elaborate joints involving several members are often

referred to as 'connections'. In this section, the joint types are grouped and described as follows:

- Carpentry joints (generally timber-to-timber, relying on bearing and friction).
- Joints made with simple fasteners, i.e., dowel-type fasteners loaded laterally or axially, used in timber-to-timber or steel-to-timber joints.
- Connectors using (proprietary) brackets and fixings that serve the purpose of connecting two or more timber elements.
- Connection systems for specific applications.

All joints and connectors are qualitatively assessed for reversibility in the elastic range. Brackets, fixings and connection systems for specific applications are evaluated assuming that some part of the joint stays permanently attached to a timber member.

While it is possible to assign a performance score by weighing different criteria (see e.g. Pozzi [45]) this is not done here, since performance is highly dependent on the use-case and function of a connector in a system. Instead, connectors suited as PDEs are highlighted.

Connectors can be categorised by their direction of load transfer, as shown in Fig. 4. Examples are brackets in panelised construction transferring out-of-plane shear (y-direction), in-plane shear (x-direction), and in-plane axial loading (z-direction). In post and beam structures, connectors can transfer loading in the direction of the member (z-direction), vertically in the connector installation line (x-direction), or horizontally out-of-plane (y-direction).

It should be noted that fasteners in joints can be loaded axially (withdrawal), laterally (shear), or in a combination of both. This is independent of the load to grain direction, and load directions indicated in Fig. 4.

3.1. Carpentry joints

Carpentry joints are the oldest timber joints and rely mostly on bearing but also friction, achieved both by gravity loads and tight fits. The latter poses an inherent challenge to reversibility of carpentry joints. Sophisticated detailing solutions have been developed over time and there are many historic examples of buildings that have been partly or entirely disassembled and reassembled [126]. Simple examples of reversible carpentry joints can be found in many block houses, whereas more sophisticated solutions can be found in Asian temples. In fact, many ancient Asian temples and pagodas, still intact today, rely on the replacement of sacrificial timber components that sustain damage due to environmental exposure, wear and tear, or seismic actions [127,128]. In those cases, the respective carpentry joints were designed as fully reversible, to allow disassembly, for repair or replacement of building components that experienced decay, deformation, or damage of the timber member itself [129]. Famous examples of historic carpentry joints still relevant today are traditional Chinese and Japanese timber connections, such as Dou-Gong brackets, [127,130], as well as European examples such as dovetail joints [131], step and lap joints [132,133], as well mortise-tenon joints [134–136], with some examples shown in
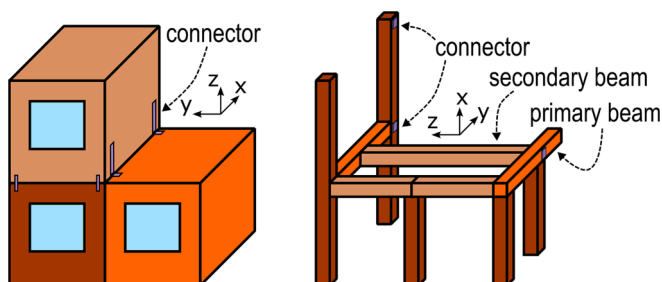
Fig. 5. In most cases, the timber elements are directly connected through the carpentry joints; however, in some cases additional wooden connector elements, such as dowels or wedges, are used in addition. Many of these joints have a tradition not only in building construction but also in furniture making [137].

The Dou-Gong bracket is a synthesis of mortise and tenon joints, which has more than 3000 years history. It can be divided into three main components: Dou (bearing blocks), Gong (a double bow-shaped beam), and Xiao (wooden dowels that act as shear keys) [138]. There are usually around 500 sets of Dou-Gong brackets in one pagoda [127], and they typically play a role in extending the spans, connecting the beams with corner columns, supporting upper levels and distributing the loads [139].

This type of timber connection has good seismic performance without any metal fasteners or bracings. Traditional Chinese carpentry joints were designed to be reversible and repairable; combining reversibility and high structural performance, traditional Chinese carpentry uses natural fish glue to reinforce joints, which can be easily steamed, thus loosening the adhesive, and allowing the carpenter to repair and replace parts as needed.

Prior to mass production of metal fasteners, timber-only carpentry joints were popular around the world and repairs were common. However, the structural performance of an entire structure depends on the stiffness, ductility, and intactness of the joint [140,141]. This can create conflicts with the requirements for reversibility, repairs, and disassembly, which often become labour intensive [45,142]. Pozzi [45] provides a review of some popular carpentry joints (mortise and tenon, box joint, halved joint, tongue and groove, column splice) based on several criteria, such as ease of assembly and disassembly, reusability, and strength. However, the visco-elastic nature of timber may affect reversibility of both traditional and modern carpentry joints; shrinkage, swelling, permanent deformation, and creep may affect disassembly, especially with increasing geometric complexity. In some of the traditional carpentry connections, these challenges are addressed using wedges, that can be readjusted.

Furthermore, traditional carpentry joints often work by utilising stresses perpendicular to the grain, which presents great challenges in terms of reinforcement, maintenance, and replacement due to the low stiffness and strength [128,143,144]. The load-carrying capacity of a timber member varies depending on the load direction relative to the fibre orientation. Being an orthotropic material, the maximum load-carrying capacity that can be achieved parallel to the grain is usually a magnitude higher than that perpendicular to the grain. Thus, in carpentry construction, the stiffness of the whole structure is essentially dependent on the stiffness and ductility of joint elements loaded perpendicular to the grain, such as tenon tongues [128,145], with risk of splitting due to tension perpendicular to the grain posing a further challenge for notched joints.

Nevertheless, CNC technology has recently initiated a renaissance of carpentry joints [146–148], allowing precise large-scale carpentry timber construction, as displayed in the Tamedia building Zurich [149] or the castellated joints used in Dalston Lane [150], which have also been studied in literature [151]. Performance of traditional carpentry joints can be further improved with reinforcement [152–154].

In summary, although many carpentry joints are reversible in principle, the stiffness, ductility, and strength of these kinds of joints do not usually satisfy the serviceability and strength requirements of contemporary timber structures, and reversibility is affected by time- and moisture-dependent dimensional changes.

3.2. Joints made with simple fasteners

'Simple fasteners' are those included in most timber design standards, including dowel-type fasteners (staples, nails, screws, dowels, bolts, rivets, nail plates), split ring and shear plate connectors, and glued-in rods.
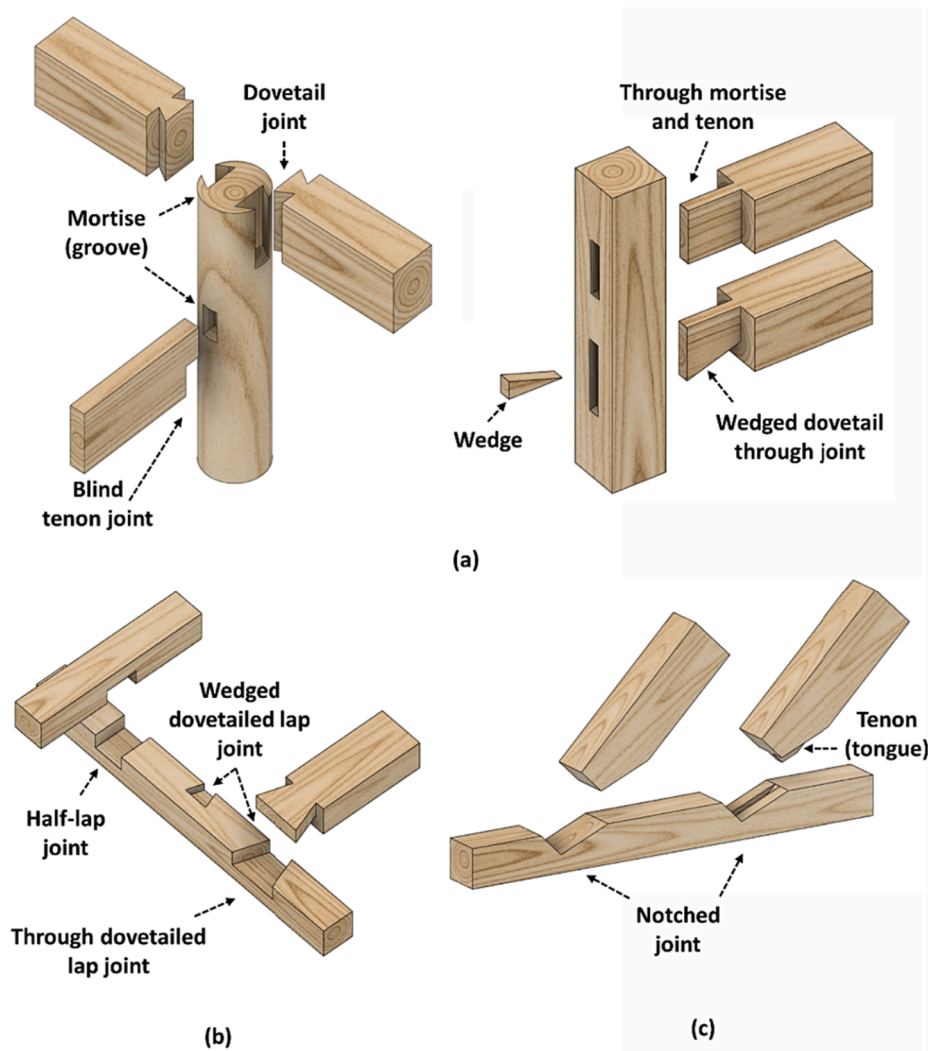

Fig. 4. Connector loading directions in timber buildings.

Fig. 5. Common carpentry joints: a) dovetail beam-column joints, b) mortise and tenon beam-column joints, c) beam half-lap and dovetail joints, c) roof truss step joints [155].

It is worth distinguishing the loading direction of the fastener (axially and laterally). Staples, (profiled) nails, rivets, and nail plates act typically predominantly in lateral loading. Screws, bolts, and glued-in rods can be loaded either axially or laterally, or in a combination of both. Dowels are designed to be loaded laterally only. Split ring or shear plate connectors carry only shear forces and require additional fasteners (screws or bolts) to carry the tension forces between the shear planes.

3.2.1. Axially loaded fasteners

Axially loaded bolts or threaded rods with washers and nuts are in principle steel joints and therefore, fully reversible in the elastic range, i. e., disassembly and reassembly are possible without any loss of performance in capacity, ductility, and stiffness. Bolts are typically inserted in predrilled, slightly oversized holes, which simplifies the dis- and reassembly.

Glued-in rods with metal connector elements can also be fully reversible in the elastic range, assuming the rod stays undamaged and attached to the members [156].

Axial loading of bolts, glued-in rods, and threaded rods provides high stiffness and high capacity, and the target ductility in case of overloading can be achieved by selecting a suitable steel grade in relation to other failure modes. When designing PDEs, it may be favourable to use threaded rods made of mild steel instead of bolts to achieve a targeted yield strength, or by physically reducing part of a fastener's cross-section

[157]. Regardless, when loaded in compression, care must be taken to prevent crushing of timber surrounding the fastener, e.g., by providing a larger bearing area for the washers or plates.

Modern self-tapping screws are typically designed for single-use installation. Theoretically, it is possible to remove axially loaded screws after service life; however, the friction and possible fusion between the screw thread and timber, as well as maximum allowable torque to be applied to the screw (head), as regulated in the corresponding technical assessments, often prevent disassembly of screwed joints after a longer period in use, especially for long, slender screws. Latest screw developments focusing on self-tapping insertion in hardwood and high-density products are advantageous in that respect, as such screws feature a thicker core and thus allow for a significantly higher maximum torque together with a similar withdrawal performance even in softwood [158]. Reinstallation of screws in the same hole can be difficult and generally leads to reduced performance. This can be overcome by installing larger diameter screws, to achieve similar anchoring capacity, or by staggering the screws (new insertion location). It should be noted, however, that the performance of a larger diameter screw might differ in many ways, including stiffness and strength, with effects on overstrength and capacity hierarchy, as well as required end and edge distances.

The use of traditional coach screws that are installed in pre-drilled, under-sized holes may be more advantageous regarding dis- and

reassembly, however, their threads still cut the timber which limits the number of possible reuse cycles.

3.2.2. Laterally loaded fasteners

Bolted connections and glued-in rod to steel connections can be fully reversible in the elastic range, whereas nailed (or nail plate, rivet), screwed (including coach screws) and, to some extent, dowelled connections (including self-drilling dowels) cannot be disassembled and reassembled multiple times while maintaining the same performance. Since dowels require a tight fit, disassembly often results in some localised damage and subsequent reassembly causes larger tolerances and loss of stiffness and performance. Hence, the only feasible options for the reuse of timber elements in combination with these fasteners are to install new fasteners in new locations, or to stagger fasteners leaving some holes or designated fastener locations unused in initial use. Similar to coach screws, this limits the number of possible reuse cycles.

3.2.3. Challenges

Load duration effects (creep), moisture fluctuation (shrinkage and swelling), or exposure to high stress levels (embedment crushing, yielding of fasteners, and beat out holes in metal plates) affect all connections that purely rely on dowel-type fasteners. Although disassembly may be possible in some cases, once significant plastic deformation has occurred, reuse of laterally or axially loaded fasteners is generally no longer practicable nor safe.

3.3. Brackets and fixings

This section discusses established proprietary system connectors (i. e., available for purchase from manufacturer, often with European Technical Assessment - ETA) and presents a systematic review - but a non-exhaustive overview. Most of the connectors discussed here rely on a metal-to-metal joint connected to timber elements using screws, which means they are generally only reversible in the elastic range, unless a fuse can be installed (discussed further below). The connectors are grouped by design application type, i.e., the typical application intended by the producer, however, connectors may also be well suited for other individual applications. The reuse potential is assessed for reuse in the same configuration where the connector stays connected to the initial element.

3.3.1. Sliding bracket connectors

Several similar beam-column and beam-beam bracket connectors exist, with loading directions according to the coordinates shown in Fig. 6. The capacities of connectors are then defined in the connection line, i.e., the contact surface between two joined timber members, with x-direction in the main direction (direction of the connection line), y-direction transverse and z-direction orthogonal to the connection line. The connectors can either be slid together (which requires access in the respective direction) or be clamped together by additional brackets.

While many are also suited for beam-wall connections, all systems with lock screws or threaded rods rely on access from the top of the beam in x-direction.

The **Sherpa connector series XS** to **XXL** is a metal dovetail sliding bracket with screws (long penetration depth), intended for beam-beam joints in sawn timber, glulam, LVL, LSL, CLT, but also connectable to steel and reinforced concrete [159–161]. The characteristic capacities and average slip moduli in C24 are $F_{x,k}$ = 5–247 ($-4 - -41$) kN, $F_{y,k}$ = 3–75 kN, $F_{z,k}$ = 4–60 kN and $K_{ser,x,mean}$ = 5–82 kN/mm, $K_{ser,y,mean}$ = 3–15 kN/mm, $K_{ser,z,mean}$ = 5–24 kN/mm. Since installation tolerances are small, ease of disassembly and reuse are somewhat limited.

The **Rothoblaas UV-T** and **UV-C** connectors are made of a metal dovetail sliding bracket with screws. The UV-T is a timber-timber connector (sawn timber, CLT, glulam, LVL), whereas the UV-C is used to connect secondary timber beams to concrete and steel supports. The UV-T is marketed for temporary structures, but also often applied for plug-and-play assembly in mass timber construction [162]. The characteristic capacity ranges for the UV-T are $F_{x,k}$ = 6.8–62.8 kN (main direction), 1.1–7.9 kN (secondary direction), $F_{y,k}$ = 1.5–3.7 kN and $F_{z,k}$ = 1.5–4.2 kN. Since installation tolerances are small, ease of disassembly and reuse are somewhat limited.

The **Sihga HobaFix** connector is a metal sliding bracket with screws (medium penetration depth) intended as a beam hanger for timber-to-timber connections in solid softwood timber ($\geq$C24) [163,164]. The characteristic capacity ranges are $F_{x,k}$ = 6.8–48.3 kN and $F_{y,k}$ = 4.4–23.8 kN. Installation tolerances are more forgiving than that of dovetail connectors due to a different geometry, which makes disassembly and reuse easier.

The **Rothoblaas Lock-T** and **Lock-C** connectors consist of a metal sliding bracket with screws (short penetration depth), intended as a beam-beam and beam-column connector. The Lock-T is used in sawn timber, glulam, CLT, LVL, whereas the Lock-C is connectable to steel and reinforced concrete. The characteristic capacity ranges from $F_{z,k}$ = 38–121 kN for the Lock-T and up to $F_{z,k}$ = 65 kN for the Lock-C [165–168]. Tolerances are somewhat higher due to the detachable wing design, allowing theoretically for easier dis- and reassembly in the z-direction.

The **Knapp Ricon** and **Gigant** connectors are metal sliding bracket beam hangers for timber frames, for connecting main and secondary beams but also beams to wall or diaphragm elements, e.g., made of CLT. While the Ricon brackets sit flat against each other and slide onto a collar bolt that is part of the connector, the Gigant features an s-shaped clip lock and slides onto screws installed into the respective timber members [169]. The brackets are fastened with screws (short penetration depth) to timber members. The connectors are intended for timber-to-timber, timber-to-concrete, and timber-to-steel joints. For timber applications, both end-grain to side-grain connections, end-grain to end-grain and side-grain to side-grain connections are possible in sawn timber, glulam, CLT, LVL, etc., allowing for three- and four-sided concealed connections. The Ricon characteristic capacities and average slip
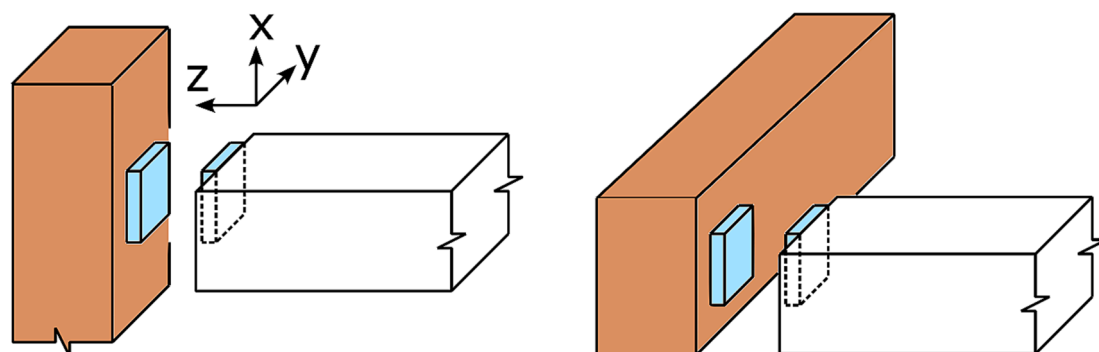

Fig. 6. Beam-column (left) and beam-beam (right) sliding connector loading directions.

moduli are $F_{x,k} = 3.7$–180 kN, $F_{y,k} = 1.8$–50.0 kN, $F_{z,k} = 2.6$–9.0 kN, and $K_{ser,x,mean} = 0.25$–4.0 kN/mm, $K_{ser,y,mean} = 0.25$–4.0 kN/mm, $K_{ser,z,mean} = 5$–25 kN/mm. The Gigant characteristic capacities and average slip moduli are $F_{x,k} = 12$–33 kN, $F_{y,k} = 12$–20 kN, $F_{z,k} = 6.2$ kN, and $K_{ser,x,mean} = 1.0$ kN/mm, $K_{ser,y,mean} = 1.0$ kN/mm, $K_{ser,z,mean} = 8.0$ kN/mm. The geometry is more forgiving, allowing for higher tolerances than dovetail shaped sliding brackets. Furthermore, the slot is much shorter.

The **Knapp Megant** connector consists of heavy-duty metal brackets, screws (short penetration depth), and threaded rods that lock the connector in z-direction [170]. The intended use is a beam hanger for timber-to-timber, timber-concrete, and timber-steel joints, with end-grain to side-grain, end-grain to end-grain and side-grain to side-grain connections in sawn timber, glulam, CLT, LVL, etc. The advantage of this type of connector is that it utilises additional brackets for the connection of the metal connectors and does not require the sliding together of the connector plates, which can create challenges depending on the dimensions and boundary conditions. The characteristic capacities and average slip moduli are $F_{x,k} = 27.6$–100.0 kN, $F_{y,k} = 32.0$–128.2 kN, $F_{z,k} = 18.9$–39.8 kN, and $K_{ser,x,mean} = 30.3$–67.5 kN/mm, $K_{ser,y,mean} = 6.1$–12.1 kN/mm, $K_{ser,z,mean} = 6.7$–19.5 kN/mm.

The **Simpson StrongTie CBH** connector consists of two metal sliding brackets with collar bolts and screws, designed to be installed as glulam beam hangers [171]. It is designed for the North American market and capacity values for load and resistance factor design are not provided by the manufacturer.

The **Pitzl HPV** connectors consist of a sliding tongue and groove and are made for applications in sawn timber or glulam [172]. The dimensions range from small connectors with 3 screws of diameter 4.5 mm per connector part up to heavy-duty, double row connectors with 46 screws of diameter 8 mm per connector part. Accordingly, the characteristic capacities range from $F_{x,k} = 2.39$–622.1 kN, $F_{y,k} = 3.94$–155.7 kN, and $F_{z,k} = 6.49$–96.8 kN in glulam GL24h. The connectors provide a moment capacity against torsion around the secondary beam axis with characteristic capacities of $M_{tor,k} = 34.1$–13,694 Nm.

The **GH TOP UV** connectors for timber-to-timber applications feature a sliding tongue and groove and are fixed primarily through perpendicular screws into the main member and inclined screws to the secondary member [173]. A corresponding product line for timber-to-concrete applications exists. The characteristic capacities range from $F_{x,k} = 12.2$–71.9 kN, $F_{y,k} = 5.49$–11.3 kN, and $F_{z,k} = 1.45$–4.16 kN.

The **Eurotec Magnus XS – L** connectors consist of a sliding tongue and groove plate and are fixed primarily through inclined screws to the main and secondary members (except for the XS-connector) [174]. The characteristic capacities range from $F_{x,k} = 1.57$–126.35 kN, $F_{y,k} = 1.19$–43.29 kN, and $F_{z,k} = 1.2$–9.29 kN.

It should be noted that several other sliding plate connectors are currently being developed, such as the interlocking connection system for volumetric CLT offsite construction by Li and Tsavdaridis [175].

In summary, most metal sliding connectors have been developed as beam-beam or beam-column connectors for plug-and-play assembly. Reversibility is possible in the elastic range, however, friction, shrinkage, swelling and creep may hinder disassembly after a certain period of use. Accidental damage of softer connector plates (e.g., those made of aluminium alloys), and possible corrosion of metal brackets present further challenges for disassembly and reuse. Finally, the required tight fit and low tolerances create challenges for use outside of the originally intended application [61].

3.3.2. Panel connectors

The **Rothoblaas X-RAD** and **X-Mini** are connectors installed in panel corners using self-tapping screws. While the X-RAD is designed for CLT modules, wall-wall and wall-foundation connections [176–178], the X-Mini was designed to be used in hybrid walls (TRE3 research project) [179,180]. The X-RAD characteristic capacities and average slip moduli are as follows: $F_{x,k} = -170/+110$ kN, $K_{ser,x,mean} = 15$–17 kN/mm and $F_{z,k} = -165/+110$ kN, $K_{ser,z,mean} = 15$–17 kN/mm. The system is designed

to be fully reversible and can be employed as a PDE by selecting mild steel bolts as fuses. However, it should be noted that the geometry of the system creates a cavity in the timber panel and a substantial thermal bridge if not properly isolated.

The **Sherpa CLT connector** is a coupling device screwed to CLT panels. While the connector itself is reusable, it requires removal of the screws. Given the high reuse value of CLT panels, the connector is considered in this review. The connector consists of a metal coupling piece and screws and is designed for insertion in timber side faces for longitudinal, corner and T-joints as well as step joints [181,182]. It can be installed in sawn timber, CLT and glulam. The characteristic capacities are $F_{x,k} = 10.0$ kN, $F_{y,k} = 5.3$–16.5 kN, $F_{z,k} = 18.8$ kN and the average slip moduli are $K_{ser,x,mean} = 3.3$ kN/mm, $K_{ser,y,mean} = 0.9$–3.6 kN/mm, $K_{ser,z,mean} = 9.8$ kN/mm.

3.3.3. Nut- and anchor-type connectors

While some of the nut- and anchor-type connectors are not yet developed for higher capacity structural applications, their working mechanisms lend themselves to DfD.

T-nuts are a common example of fully reversible connectors for low-capacity applications. They are pre-drilled and pressed into the back of plywood or OSB panels and commonly used to install climbing holds, which are frequently removed and re-installed.

The **Knapp Zipbolt** is a wedge-shaped nut with a threaded rod and an anchoring plate or internally threaded screw. The system is completely reversible and used for very low-capacity applications (up to 0.6 kN in axial loading of the rod), such as furniture and benchtop joints [183].

The **Steel-tube** connector [184,185] consists of a circular hollow section with a welded-on nut that is inserted in CLT panels. A threaded rod is then connected to the tube. Numerical optimisation resulted in a characteristic yield capacity of $F_{z,k} = 85$ kN and ultimate characteristic capacity of $F_{z,k} = 98$ kN [186].

The **Timberlinx** connector is designed for post-and-beam construction, consisting of a steel tube and expansion anchors (similar to an anchor plug) that are pushed apart by turning a nut [187]. Therefore, the system is in theory, fully reversible and can be re-tightened. The capacities relative to the tube loading the grain are $F_{t,par,k} = 12$ kN and $F_{t,perp,k} = 11.2$ kN for tension parallel and perpendicular to the grain, respectively. The system is primarily marketed in North America.

The **Sihga IdeFix** connector is a screwed-in nut designed to fit a bolt or threaded rod that can be removed repeatedly, being, therefore, fully reversible. The IdeFix is designed as a beam-beam, beam-column, or panel-panel connector in sawn timber, glulam, and CLT [188]. It can be combined with any other connection system that uses threaded rods. The characteristic capacities for a reference characteristic density of $\rho_k = 350$ kg/m^3 are $F_{x,k} = F_{y,k} = 10$–20.5 kN and $F_{z,k} = 17$–56 kN (axial loading). The average slip moduli are $K_{ser,x,mean} = K_{ser,y,mean} = 7.6$–12.6 kN/mm and $K_{ser,z,mean} = 31$–49 kN/mm.

Potential ductile elements in axial loading direction can be created by inserting a fuse-type threaded rod made of mild steel with grooves or shaped like a dog bone [157]. This allows for controlled yielding of the rod which can then be replaced after overloading events have occurred (see also Sections 3.4 and 4.3).

3.4. Connection systems for specific applications

In the last couple of decades, research has been carried out to develop reversible connection systems with specific applications, e.g., post-tensioning systems with dissipators or dampers for applications in seismic regions, and plug-and-play connections for hybrid elements, such as timber concrete composites (TCC) floor systems. It should be noted that some of these systems are still under development and are not yet fully commercialised.

3.4.1. Post-tensioning-type systems

The **Simpson StrongTie** anchor tiedown system uses threaded rods and coupler nuts to join adjacent rods [189]. While not initially designed for timber, it has been successfully employed in combination with CLT shear walls [190]. The nature of the system makes it fully reversible.

The **Pres-Lam** system was developed at the University of Canterbury as a post-tensioning system for LVL and glulam beams, and CLT walls [191–195]. Pres-Lam and other post-tensioned timber systems work, in principle, like post-tensioned concrete structures and the nature of the system makes it fully reversible. The self-centring nature results in low-damage design, which makes it especially attractive for DfD and reuse. Indeed, many post-tensioned timber buildings around the world have performed exceptionally well during seismic events [193,196–202], resulting only in replacement of fuses or non-structural parts, thereby providing a robust reversible timber construction system.

The **EXPAN QuickConnect** system was developed as part of the STIC (Structural Timber Innovation Company) project [203–207]. It was intended as a knee-joint for portal frames, which consists of timber channels that are nailed or screwed to a timber beam or column, a threaded rod and steel end plates with nuts. The system is fully reversible and can be adapted for other hold-down type applications.

3.4.2. Dissipators and dampers

Dissipators and dampers are intended as replaceable 'fuses' (PDEs) that work in combination with a post-tensioned system or shear wall.

The **resilient slip friction** (RSF) joint is a sliding steel plate dissipator developed at the University of Auckland and commercialised by Tectonus. It consists of profiled sliding steel plates that act as a friction dissipater and are prestressed by bolts with springs [208–210]. This allows to achieve high initial stiffness and a perfect hysteresis. The performance of the joint can be scaled to the demand through the number of bolts. The capacity ranges from around $F_{z,k} = 50$–5000 kN [211]. As a steel joint, the RSF can easily be dis- and re-assembled, as long as the anchorage of the joint in the timber remains in the elastic range.

Different types of **fuse-type threaded rods** were explored at the University of Canterbury [157] and installed in the Trimble Navigations Building in Christchurch, Aotearoa New Zealand, as shown in Fig. 7.

Hyper-elastic dissipative hold-downs for CLT shear walls have been developed at the University of Northern British Columbia [212,213]. They consist of a rubber damper and steel plate that is connected to a threaded rod. By concentrating the deformation on the elastic rubber, this connection can be designed basically damage-free while at the same time providing dissipation and ductility.

U-shaped flexural plates (UFPs) [200,214,215] made of mild steel provide a means to dissipate energy and couple adjacent shear walls. However, their disassembly and replacement may be more challenging due to their location, unless access is considered in the design.

3.4.3. Timber concrete composite connectors

Hybrid systems have become popular in recent years. An example is timber-concrete-composite (TCC) construction, where the advantages of both materials can be utilised. To achieve full composite action, a rigid connection between the materials is essential, which is typically permanent. Since timber components can be of high reuse value, this part of the review focuses on DfD without reuse of the concrete slab. The majority of TCC connectors with the potential for deconstruction are designed as a dry-dry system, where a prefabricated concrete slab is attached to the timber element on-site. Typically, steel or plastic tubes are placed in the formwork in order to create cavities in the concrete that can be used to connect the concrete slab to the timber elements using self-tapping screws [216,217]; alternatively, blocks might be used [218]. Deconstructable shear connections are often characterised by a lower composite action compared to permanent connections, mainly due to the gap around the screw. An alternative approach was presented by Derikvand and Fink [219,220], where the self-tapping screw is encased with a thin protective layer in the upper section and a lid to ensure screw access for disassembly. The thin rubber layer ensures a tight fit, resulting in a composite action similar to permanent connectors. For a comprehensive overview of DfD of TCC connections, refer to Derikvand and Fink [220].

3.5. Discussion

Dis- and re-assembly of connections require the limitation of damage and deformation in the connected members. This can be achieved either
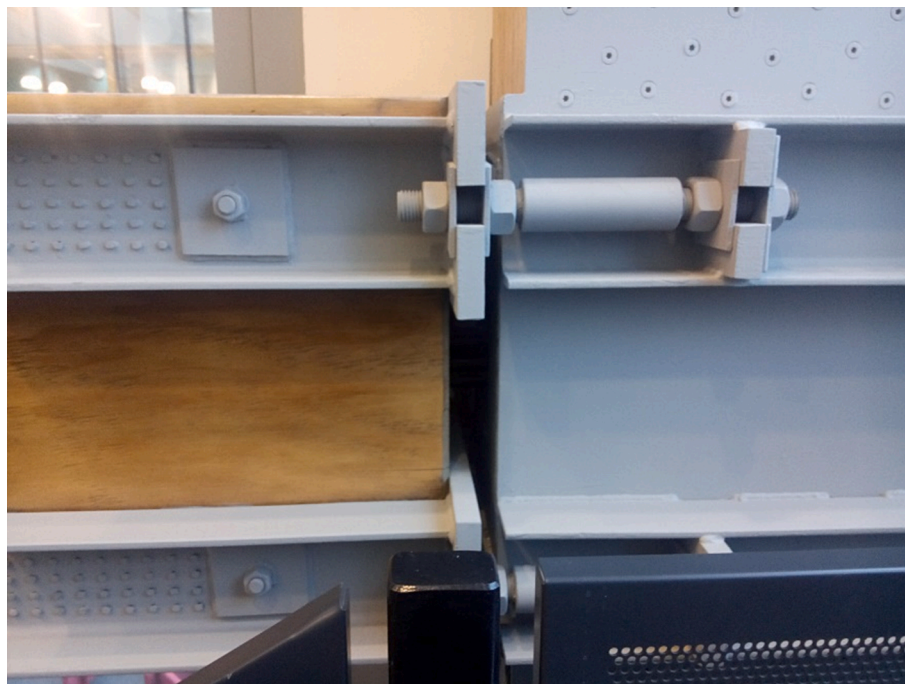

Fig. 7. Threaded rod fuses in the Trimble Navigations building, Ōtautahi Christchurch, Aotearoa New Zealand.

by pure elastic design, where deformations are limited, or capacity design, where deformation is concentrated in specialised fuse or hyper-elastic elements (PDEs). While the former may be required for simple carpentry connections or connections with metal connectors, ductility can be achieved by adding fuse elements that yield within the elastic range of non-deformable joints. Depending on the connection configuration, regular replacement of these fuse elements or retightening might be necessary. Typical fasteners such as nails, dowels, or screws show only a limited potential for DfD, while proprietary brackets can potentially achieve reversibility for their intended application. Further research should investigate reversibility of proprietary connectors and other connection systems under different (re-)loading scenarios.

4. Examples of reversible assemblies

At the core of reversibility are connections that can be reused, i.e., damage is limited. Low-damage seismic systems can serve as inspiration when designing such systems. Although low-damage seismic systems found in literature may not always be designed to be disassembled, they usually contain a replaceable energy dissipater or another type of fuse or damper. Capacity design can be extended to reversible assemblies, where PDEs are designed to dissipate energy in case of overloading. Overstrength needs to be considered such that all other joints remain elastic and have sufficient tolerance so that they can be disassembled. Several examples of reversible assemblies are described Sections 4.1 and 4.2.

4.1. Post-tensioning

Explicit examples of resilient or low-damage seismic design are post-tensioned self-centring timber elements with dissipators that are replaced after overloading, or systems that can be re-centred without residual deformation, e.g., RSF joints. Both systems are reversible.

An example of assemblies that combine several reversible elements are post-tensioned CLT shear walls with castellated inter-storey shear joints studied by Brown et al. [152,200–202], which are usually combined with dissipative PDE hold-downs (e.g., threaded-rod type dissipators, RSF hold-downs, or hyper elastic rubber dampers). Another example are post-tensioned timber frames, which were used in the ETH House of Natural Resources [221]. The rigid moment connection is created by contact in the butt joint between beams and columns, where contact pressure and friction are activated by a post-tensioning cable positioned centrally in the beams. Compression perpendicular to the grain stresses in the columns are addressed by using hardwood in these areas. Without dampers, the system is suitable for low and medium seismic regions and allows for easy and full dis- and re-assembly as well as re-stressing. The design is based on the Pres-Lam system, which was developed for high-seismicity regions and utilises dampers as external fuse elements. Post-tensioned timber elements have extensively been used across Aotearoa New Zealand, with examples being the Trimble Navigations Building in Christchurch (post-tensioned LVL frames and walls), Nelson Marlborough Institute of Technology, and Whare Puka-puka (Kaikōura District Library). A more detailed review is provided by Granello et al. [222].

4.2. Elastic assemblies

Many hold-downs are, in principle, fully reversible, if installed with a threaded rod/through-bolt to the underside of a floor panel (see Fig. 8 left) or anchored in the foundation. For a concealed connection, the rod or bolt can be fastened to a prefabricated system (e.g., Sihga IdeFix, Fig. 8 right), or a glued-in rod may be used (Fig. 8, centre). Similar assemblies for beam-beam, column-column and portal frame knee joints can be achieved with the EXPAN/Quick Connect system [203–206]. PDEs can be created by using a fuse-type rod in axial loading (hold-downs) [157].
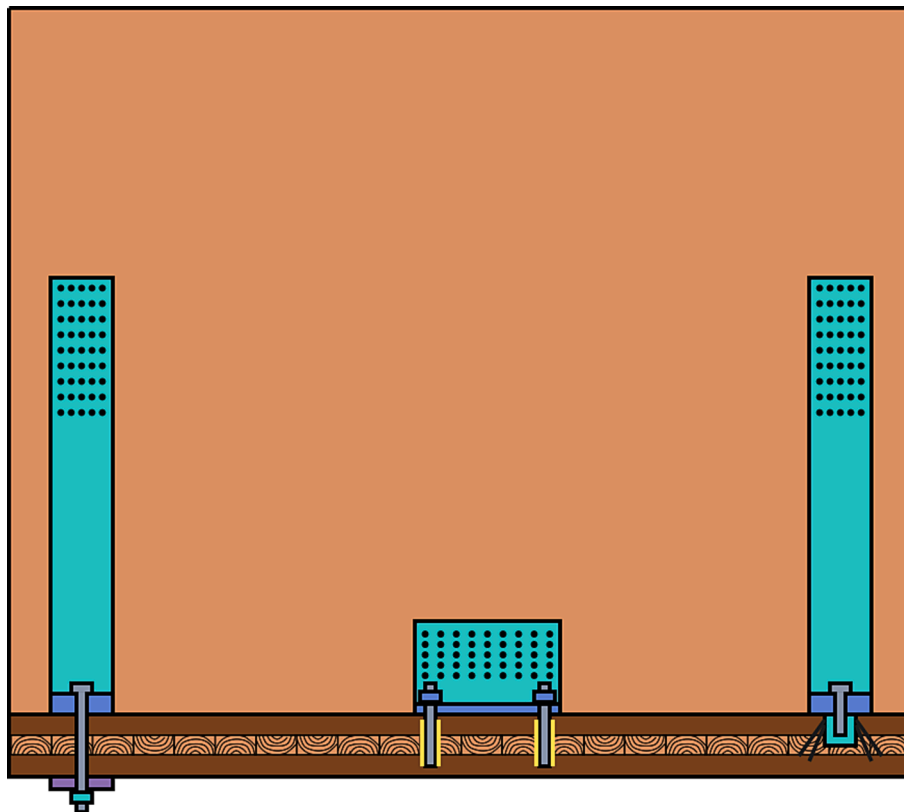

Fig. 8. Examples of reversible hold-down and angle bracket assembly options. Through-bolt to the underside of a floor panel (left) glued-in rod (centre) rod fastened to a connection system (right, e.g. Sihga IdeFix).

There are several examples of timber structures that have either been deconstructed or designed with DfD in mind [49,148,223–232]. A notable example is The Cradle Building in Düsseldorf, Germany, which is designed with a cradle-to-cradle approach [233]. All connections are made by carpentry joints or screw connections. In the main façade, carpentry joints with hardwood inlays are used in the columns, while steel fittings are used to transfer loads between the floors. The timber manufacturer guarantees taking back all timber members after service life with a prospect for reuse.

Finally, many temporary steel structures, such as scaffolding or gazebos, include reversible joints; however, lack of capacity design may result in permanent damage that prevents reuse. Nevertheless, many of these systems lend themselves to minor modifications that result in reversibility through capacity or low-damage design.

4.3. Other examples of reversible assemblies

An example of a fully reversible connection based on glued-in rods is provided by the **GSA system** by the company Neue Holzbau AG [234,235]. Specialised steel connectors are anchored through glued-in rods into each timber member. The gluing is done in a factory environment and accompanied by factory production control for quality assurance. These prefabricated timber members with their attached connectors are then assembled on-site by joining the steel connectors together with simple bolts or pins.

The system solutions range includes GSA-AL with attached steel plates for articulated connections or fixed supports, GSA-G as fully hinged joints with a single bolt connection, GSA-R with multiple bolts as a rigid connection, GSA-H knots for rigid skeleton and frame constructions, and GSA-L and GSA-LMV as a rigid pin and socket connector for axial, shear and moment actions between members or in portal frames.

The special glued-in rods feature a reduced cross-section, which allows to calibrate their capacity for the ductile failure of the steel rod. An unbonded length of the glued-in rod towards the end grain of the timber member reduces the risk of splitting in the timber member and allows to achieve a closer spacing between the individual rods. This close spacing together with the design for ductile failure of the steel rod enable high performance connections of the steel connectors to the timber members. As long as the glued-in rods provide sufficient overcapacity compared to the connection between the steel connectors, this system provides a low damage solution that guarantees easy assembly, disassembly, and reuse.

In principle, similar connections can also be realised by using glued-in perforated metal plates (e.g. HSK-system [236,237]) or perforated or profiled glued-in steel tubes [238–240].

4.4. Discussion

While several examples of reversible timber assemblies have been already built, more established building concepts with standardised timber components are necessary in order to benefit from the full potential of dis-assembly and reuse. Depending on the demands on the structures, the type of elements and structures, different connection solutions with different level of deformation capacity may be chosen. It should be noted that reversibility in the elastic range can increase cost, and lifecycle costing or other cost benefit analyses can help decide whether reversibility is required or whether repair or reuse of members and components is possible by other means.

5. Conclusions

This paper reviewed and discussed design principles to achieve structural adaptability of timber structures, such as design in shearing layers, design for disassembly, and design for reuse. The importance of reversible connections was highlighted, and a systematic overview of reversible timber joints and connectors was provided. Examples of reversible timber assemblies were presented, and challenges to achieve reversibility and reuse were highlighted.

The following recommendations with respect to reversible timber joints and assemblies are made:

- Reversible connections should generally remain in the elastic domain, i.e., undergo no or very low damage.
- Capacity design should be used with identified Potential Ductile Elements that provide ductility, dissipate energy, and are designed to be replaced (fuses).
- Additionally, dissipators such as hyper elastic rubber hold-downs, UFPs, or resilient slip friction joints may be employed.
- Permanent deformations affect joint performance as well as allowable tolerances. In general, deformations should be concentrated in replaceable steel elements rather than timber elements.
- Friction, creep, and durability issues such as corrosion can affect disassembly and need to be considered in the initial design for disassembly.

Several challenges were identified that should be addressed in further research:

- Reverse-cyclic, repeated, and alternating loading can affect reversibility and their effect should be studied for reversible connectors designed for static / monotonic loading.
- Reversibility of many connectors and connection systems relies on simple load paths. Combined loading and its effect on reversibility should be further investigated.
- Moisture effects on reversibility and reuse should be studied, since these can lead to creep, shrinkage and swelling, and potentially corrosion.
- Performance after repeated dis- and re-assembly should be studied in conjunction with required and permissible tolerances.
- Residual capacity of reclaimed timber elements needs to be further investigated.

CRediT authorship contribution statement

Lisa-Mareike Ottenhaus: Conceptualization, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Zidi Yan:** Conceptualization, Writing – original draft, Visualization. **Reinhard Brandner:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Paola Leardini:** Conceptualization, Writing – original draft, Writing – review & editing. **Gerhard Fink:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Robert Jockwer:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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