Connections Design and Analysis: Numerical, Analytical and Code-Based Methods

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Abstract. The design and performance of structural connections in timber engineering plays a critical role in the safety and functionality of timber structures, especially in applications involving tall buildings. In this chapter, the design and modelling strategies of structural connections in timber engineering are examined. The study highlights the significance of key parameters, including stiffness, strength, and ductility, and explores how these factors influence the behaviour and performance of various connection types under different loading conditions. Analytical and numerical methods for assessing the mechanical properties of connections are presented, including those outlined in widely used standards like Eurocode 5. The discussion highlights the limitations of these guidelines, particularly their inability to fully address complex behaviours such as non-linear deformation and long-term effects. The importance of experimental validation is also emphasized, as a critical step in refining models and improving design practices.

Keywords: Connections · Load-transfer mechanisms · Mechanical parameters · Guidelines · Modelling strategies

1 Introduction

In tall buildings, connection deformation can potentially cause serviceability failures through deflection of the structure [1, 2], and in slender structures could also lead to ultimate limit state failure through second-order P-delta effects [3]. Connection deformation also affects both serviceability and ultimate-limit state behaviour of mechanically jointed composite beams and slabs, including timber-concrete composites (TCC) [4] and dowel-laminated timber (DLT) [5]. Moreover, the stiffness of connections is a key parameter in modelling for vibration and acoustic serviceability [6, 7], to ensure, for example, occupant comfort or usability of sensitive instruments. Seismic design also requires modelling of connection stiffness and ductility. An overview of most recent studies and issues on connections is summarized in the following sections.

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2 Fundamentals of Structural Connections

2.1 Types of Structural Connections

2.1.1 Mechanical Connections

Mechanical connections can be classified based on the type of fasteners in: (i) dowel-type connections and (ii) bearing connections. Fasteners, in turn, are divided into two groups depending on the force-transfer mechanism between the connected members. The main fastener group is represented by the dowel-type fastener (generally made of steel) including staples, nails, screws, bolts, dowels and threaded rods. Hardwood dowels [8] have been proposed as an alternative connector for DLT beams with the aim to reduce the use of adhesives in engineered wood products. The second group of fasteners is represented by the bearing-type or "surface-type" fasteners, such as toothed-plate connectors, punched metal plate connectors and split rings.

2.1.2 Bonded Connections

In this framework, just pure timber-timber joints are accounted as adhesive connections. Those connections are vital for the creation of laminated timber elements (i.e. glulam and LVL) and glued composed members [9] but are also used in structural joints between elements: end-joints for knee and reinforcements (i.e. scarf, lap or finger joints, knee and truss joints with gussets from plywood, LVL, etc.) [10].

2.1.3 Hybrid Connections

Hybrid connections are defined as joints combining two of the following jointing categories: carpentry joints, mechanical connections and bonded connections [11]. Bonded-in rods, often considered a subset of adhesive joints, represent a type of hybrid joint since they involve three materials (timber, rod-connector and adhesive bonding layer). Rods are usually made of steel, nevertheless, an alternative is represented by bonded-in fibre-reinforced polymer (FRP) rods, which use provide an improved resistance in corrosive environments, a lower weight and a reduced heat conduction into the joint in case of fire due to lower thermal conductivity. Another hybrid joint type entails the combination of adhesive bonding and steel plates. One option in this category is glued-in solid steel plates, and the epoxy-based adhesives seemed to be the most appropriate choice [12]. Another approach that conceptually eliminates the reliance on the adhesion between adhesive and steel is to use perforated steel plates [13]. To overcome adhesives 'short-coming related to limited gap-filling capabilities and strength-reducing effects in the bond-line during the initial hardening shrinkage, new hybrid connections using grouting technology with concrete-type adhesives (CTA) have been developed. Its application was proposed by [14] for hybrid steel-cross-laminated timber building systems consisting of threaded rods reinforced by a layer of epoxy grout encased into the CLT panel.

3 Key Parameters Influencing Connection Behaviour

3.1 Load-Transfer Mechanisms

3.1.1 Mechanical Connections

Connections with dowel-type fasteners transmit axial, shear, and even bending loads between structural members. They are categorised as shear connections since forces are mostly transferred between members via shear in the fasteners, but, to some extent, they also transmit forces through axial capacity of the fasteners [15]. Depending on the direction of the force relative to the fastener axis, dowel-type connectors can experience two types of loading: shear, when the force is applied perpendicular to the fastener axis, and withdrawal/pushing-in, when the force is applied along the fastener axis. Additionally, combined stresses may occur under certain conditions [9]. When subjected to lateral loads, dowels-type connectors may deform in bending, creating one or more plastic hinges within the fastener. In this situation, some parts of the load uptake also occur in tension. Depending on the surface and end anchorage of the fastener, the part carried in tension can be larger or smaller. Because of the loading, the dowel will press against the surrounding timber members, creating embedding pressure against the dowel.

Bearing-type connections transmit lateral loads only. The mechanism to transmit shear forces is through bearing on the connected materials. For double-sided connectors (e.g., split rings and double-sided toothed-plate connectors), forces are transferred through embedment stresses of the first member into the connector and then to the second member via the connector's shear resistance. Bolts manage any eccentricity to maintain joint stability. For single-sided connectors (e.g., shear plates and single-sided toothed-plate connectors), forces generate embedment stress between the connector and bolt. The bolt's shear resistance ensures force transfer, moving it to the second connector in timber-to-timber joints or directly to the steel member in steel-to-timber joints [9].

3.1.2 Glued Connections

The strength of glued joints is difficult to describe analytically. If the glue is ductile, (i.e. polyurethane) the shear strength describes its behaviour well. If it is brittle, the fracture energy, G_f, of the glue is the best descriptor. To characterize the brittleness, a brittleness ratio has been defined as $f_v{}^2/G_f$, [16]. One of the problems is that pure tension or shear is seldom present in a real joint, making it impossible to separate strength components even in testing. However, the resorcinol/phenol adhesives employed for the production of EWPs, are more brittle than wood itself, while polyurethane is less brittle than wood. Adhesive connections are generally considered to be rigid for practical engineering design purposes, but flexible adhesive joints have been proposed for structural joints in seismic regions [17, 18], and to increase the bending capacity of laminated timber [19, 20].

3.1.3 Hybrid Connections

The mechanical description of the load transfer in hybrid joints involving adhesives is additionally complicated by them is match of stiffness between the mechanical fasteners and the adhesive layer while these involving carpentry connections are affected by uncertainty related to friction and contact mechanisms. Taking as example the glued-in rods, which can be accounted as a mechanical joint or as combination of glued and mechanical connections. The force between the rod and the glue is generally seen as transferred either by compression or shear, however in some cases it is perceived as a combination of the two [21], depending on the combination of several influencing parameters (i.e. the ratio of the diameter of the hole to the diameter of the rod, the adhesive bond line thickness, the timber and rod surface features).

3.2 Stiffness, Strength, Ductility

The load carrying capacity of a dowel-type connection in shear is determined by three parameters: the embedding strength of the timber f_{h}, the dowel strength represented by its yield moment M_{y} and the anchorage capacity enabling tensile action in the dowel F_{ax}. The load carrying capacity of connections with dowel-type fasteners was first described by Johansen [22] which distinguished three different failure modes, depending on the relation between the embedding strength, the yield moment of the dowel and the thickness of the timber members. Nevertheless, this theory does not account for potential brittle failure modes. The other limitation of Johansen's formulation lies in the analysis method itself: the model can predict the ultimate failure load but cannot provide any indication of the deformability of the connection, nor, consequently, of its stiffness and ductility properties.

To properly account for the semi-rigidity of timber joints with mechanical fasteners it is necessary to evaluate its stiffness. It is possible by carrying out tests in accordance with some standardized procedures (i.e. EN 26891:1991 [23]), or alternatively by referring to different documents (i.e. the N.I.CO.LE document) [24] and Standards that provide simplified formulas for different types of connection, fastener diameter and timber density.

Connections are often intended to act as potential ductile elements contributing significantly to overall ductility and energy dissipation in case of overloading and allowing for safe load paths when construction tolerances are exceeded [25]. A ductile connection response is often associated with plastic fastener deformation, which allows for energy dissipation under reverse-cyclic loading and is crucial for seismic design [26], also known as "dynamic ductility".

Some authors have given empirical indications on the possible maximum and minimum values of ductility D [27]. Ductility is often defined as ratio the between the deformation corresponding to the maximum load (u_{u}) and the one at the elastic limit (u_{y}) and was correlated with the Johansen's failure modes; often the deformation at the point where the maximum load drops by 20% is considered. It can be experimentally estimated on mechanical fasteners by carrying out cyclic tests following EN 12512:2001/A1:2005 [28], by using the method proposed by Kobayashi and Yasumura [29] or the method presented in ASTM E2126–11 [30]. A novel method that resembles in some aspect the short procedure of EN 12512 [28] to determine the ductility class of dowel-type connections is the one proposed in the revised version of the standard EN 14592:2017 [31].

4 Design Standards and Guidelines

4.1 Codes

With changes and adaptations, the Johansen theory [22] is the basis for the so-called European Yield Model (EYM) which is used in the current generation of design codes EN 1995-1-1 [32]), National Design Specification for Wood Construction-NDS [33], Engineering Design in Wood-CSA O86 [34] and Standard for Design of Timber Structures-GB 50005 [35] for the estimation of the load-carrying capacity of connections in timber structures.

The EYM assumes simplified rigid-plastic material behaviour for the fastener when exposed to bending stresses and for the timber when exposed to embedment stresses [9] even though, various studies involving embedment tests on wood and tests on connections [36–38] revealed for both a highly non-linear behaviour. This can be attributed to the non-linear behaviour of steel dowels under bending and wood under embedment stress. EYM is also addressed as “local design criteria” since its applicable to the single connector and doesn’t account for brittle failure modes. The applicability of this model is guaranteed by the application of the so called “global design criteria” which consists of spacing and distance rules between the single connectors, which ensure the global capacity of the cross section to withstand the forces transferred by the connectors [39].

Empirical formulations for the estimation of in-service stiffness of all dowel-type connections, which is identified as slip modulus, K_{ser} are provided in Sect. 8 of EC5. Slip modulus is a measure of joint stiffness, i.e. resistance to displacement, hence it has unit N/mm. The slip modulus of a joint at the ultimate limit state K_{u} is determined as 2/3 of the K_{ser}.

4.1.1 Limitations of Existing Guidelines

Connection stiffness is a critical aspect of structural performance, yet current design approaches exhibit significant limitations: thickness is not factored into stiffness calculations, leading to unrealistic assumptions that slim and thick connections share the same stiffness [40, 41]. For the design of multi-dowel connections, only general design rules but no design equations are given in the standard. In general, the load levels of the individual dowels for a specific load case (including the load-to-grain direction at each dowel) needs to be calculated in order to be able to compare these values to the corresponding single-connector strength. The compatibility of deformations is requested but only strongly simplified stiffness values for single-dowels not compatible with limit loads are provided [42].

Experimental studies (e.g., Sandhaas et al. [43]) have demonstrated that the EN 1995-1-1 equation for serviceability stiffness, K_{ser}, often fails to accurately predict dowel stiffness, especially for connections with multiple dowels or dowels with unconventional features. This issue becomes even more pronounced in large-scale structures like multi-story timber buildings, where deformation effects due to scale become significant. The non-linear deformation behaviour of dowel-type connections is another key challenge. Current parameters, such as K_{ser} and K_{u} (the connection stiffness at the ultimate limit states), do not account for the real non-linear, behaviour of connections, limiting the ability to design for robustness and ductility. Non-linear behaviour affects load distribution among fasteners, especially when connections experience combined rotational and translational forces. Furthermore, the stiffness's influence on force distribution within a structure cannot be realistically assessed, and modern techniques like interlayers (e.g., acoustic layers) are not accommodated in current formulas.

To optimize design, more comprehensive data on non-linear connection behaviour will be achieved and provided, including upper and lower stiffness limits alongside mean values. The existing rigid-ideally plastic limit design and empirical elastic stiffness formulas used in EC5 fail to address uncertainties in stiffness and ductility, will be overcome by carrying out further research and development in this area.

5 Modelling Strategies for Connections

5.1 Analytical Approaches

5.1.1 Closed-Form Equations for Shear Behaviour

Analytical closed-form models based on mechanical approaches contribute to understanding the factors influencing connection behaviour and are useful for designers.

The most widespread closed-form solution that has gained increasing acceptance in recent years is the European Yield Method (EYM) since compared to the other analytical formulations, it entails closed-form and rather simple equations. Uibel and Blaß [36] validated and expanded this formulation to enable the design of dowel-type connections in CLT. Specifically, they modified the timber embedment strength equations by incorporating corrective factors into Johansen's formulas. Other analytical solutions for the prediction of the load-displacement relationship for timber joints with dowel-type fasteners subjected to lateral loading have been presented by several research works. They considered a joint as a two-dimensional arrangement in a plane and represent the connector by a one-dimensional beam on a Winkler or discontinuous foundation. For a Winkler type foundation, the force per unit length beneath the connector is taken to be directly proportional to the displacement at all points along the length of the connector. This method was proposed also in more recent works [44–46] aiming at investigating the mechanical behaviour of different dowel-type connections.

To develop an exact theoretical design method for connections with dowel-type fasteners, many researchers have proposed adopting the theory of beam on foundation (BOF) for predicting the load-deformation behaviour of the fasteners since 1950, and the relevant research works can be mainly divided as linear and non-linear. In this case, the fasteners are assumed as elastic or elastoplastic beams supported by the linear or non-linear foundation equivalent from timber. For the linear model, the target is to solve the exact fastener deformation expressions by using the general solutions of the beam on elastic foundation (BOEF) model. Kuenzi [47] first introduced the BOEF model into dowel timber-to-timber connections with the consideration of the timber embedment properties and the connection geometric conditions, proving that the load-slip relationship of timber connections could be predicted with high accuracy at the elastic stage. However, challenges remain, with particular reference to the non-linear behaviour of materials which can't be easily accounted in closed-form equations. Additionally, theoretical solutions based on the traditional BOEF model are overly complex for direct application in practical engineering.

5.1.2 The Component Method

Although almost all timber connections should be treated as semi-rigid, EN 1995-1-1:2004 does not provide any methods for determination of the rotational stiffness of the connection. In this framework, the component method, which is one of the most used methods for the determination of the moment resistance and rotational stiffness of the steel and steel-concrete composite connection, can be successfully employed to investigate the characteristic properties of semi-rigid timber-steel connection. The originality of the component method is that it considers any joint as a set of "individual basic components". Each component is represented by an extensional spring, which is independent and can be connected to other springs or to rigid elements. Once the individual constitutive components are identified and characterized, the overall behaviour of the connection can be modelled through the so-called assembly procedures [48]. By using the component method, [49, 50] carried out detail investigation on ductile moment-resistant timber connections with the combination of glued-in rods and steel connecting studs. It was discovered that the method could well predict the joint response in terms of failure mode, ultimate resistance, stiffness, and rotation capacity.

5.2 Numerical Modelling Techniques

In parallel with these analytical approaches, developments in computational mechanics made it possible to develop numerical methods [51, 52], which accounted even for non-linear phenomena. These approaches have remained unused in practical design due to their complex implementation and their high running time, at the time of their invention, while today's computational resources strongly reduced corresponding limitations.

A large number of researchers have then focused on the non-linear BOF model by using the numerical methods. Dowel-type fasteners are numerically modelled as elastoplastic beams on a nonlinear foundation in engineered in wood-based products [53, 54]. For example, Hirai [52] proposed a non-linear controlling differential function solved by using the stepwise numerical linear approximation method, by adopting the elastoplastic behaviour of the dowel and the foundation.

5.2.1 Finite Element Modelling (FEM) for Connections

The accurate mechanical analysis of connections is highly complicated and challenging, due to the large number and type of structural details and influencing parameters that should be taken into account. Firstly, nonlinearity of the material behaviours of steel and timber (and possible other materials) has to be properly considered. Secondly, for dowel-type connections, there is contact between the dowel and the surface of the hole in the timber element, where normal and tangential stresses are transferred and friction between steel and wood has to be accurately taken into account. In this case, the possible presence of gaps and production tolerances must be also carefully considered. Thirdly, the load distribution is highly non-uniform within the timber parts loaded in tension, where the primarily applied compressive stresses are transformed via shear stresses into tensile stresses. The combination of these mutually affected processes occurs simultaneously and within a small spatial region [55].As a consequence, in most cases, the use of refined 3D numerical models is necessary. The intrinsic limitations of spring-based models compared to full 3D models, for collapse simulations, have been for example discussed in [56], while a vibration sensitivity study on timber-timber floors has been successfully carried out in [57] with spring-based 2D models. Many authors carried out various 3D models for connections, by taking into account specific computational features and strategies. Since the nonlinear material model is crucial to the development of accurate load-slip behaviour for timber connections, many authors proposed the use of a plasticity-based constitutive material formulation to model wood as elasto-plastic orthotropic according to the Hill yield criterion [58–60]. The most important aspect is the definition of a realistic damage and failure criterion [56]. Moreover, it is worth noting that the Hill yield criterion is symmetric in tension and compression and should be thus used with attention. To overcome this possible limitation, more advanced subroutines have been implemented to overcome this limitation [61].

Finally, to accurately account for the failure modes that significantly impact the estimation of the mechanical parameters of connections, various theories have been proposed specifically for anisotropic materials like wood. The most widely used are the maximum stress criterion [62], the Tsai-Wu stress criterion [63] and the Hoffman stress criterion [64]. Since the interaction between connector and timber is essential in finite element modelling, several authors (i.e. [65, 66]) introduced a fictitious ‘soft layer’ with cohesive damage interactions, at the interface between the dowel-type connector and the surrounding timber components. Compared to other modelling approaches, the Cohesive Zone Modelling (CZM) method has well-known intrinsic advantages, since it does not need: (i) pre-existing definition of cracks, (ii) prior assumptions for onset and growth of damage, (iii) complex moving mesh techniques, and (iv) a very dense mesh definition close to the cracks (to ensure local occurrence of infinite stress and strain peaks). Moreover, the CZM strategy can be also adapted to many other connection typologies for timber structures, such as notched connections [67] or bonded-in-rod connections [68].

5.2.2 Spring Elements and Equivalent Beam/Shell Elements

Connections are often effectively modelled as spring elements in numerous studies that use 2D finite element methods to validate analytical models describing the behaviour of various Lateral Load Resisting Systems (LLRS). For platform-type CLT buildings, [60, 69, 70] developed 2D models in which shear-walls consist of two-dimensional (i.e. area) rigid elements and the connections (e.g., hold-down, angle brackets and connections between adjacent CLT panels) were modelled as nonlinear elastic spring (link) elements. The adopted models differ each other mainly in the assumptions related to the implementation of the non-linear behavioural characteristics assigned to the mechanical anchors, including uni- vs bi-directional behaviour and tri-linear vs multi-linear behaviour. In analogy with this approach, [71] conducted a parametrical study to investigate the interaction between the floor-to-wall connections and lintel elements on the mechanical behaviour of CLT shear-walls with cut-out openings. The same approach was employed to analytically model the log-house timber walls under in-plane lateral loads by Sciomenta et al. [72]. In this case the typical corner joint is considered to be an elastic extensional spring. At the same time, static friction contributions are evaluated by means of classical Coulomb law, while the presence of possible gaps is properly considered in the lateral displacement evaluation. It is worth stressing out the crucial role of experimental test for the assessment of mechanical properties of connections. In particular, the calibration of the springs in the aforementioned numerical models was achieved via experimental test. One of the most cited and useful work is the one from Gavric et al. [73] which summarize the outcomes from an extensive experimental program on typical cross-laminated timber (CLT) screwed connections including in-plane monotonic and cyclic shear and withdrawal tests were performed on screwed wall-to-wall, floor-to-floor and wall-to-floor CLT connections.

5.3 Some Specific Challenges in Timber Connections

5.3.1 Long-Term Effects

Timber members exhibit creep: time-dependent deformations. This phenomenon is related to the duration of the action, the state of stress and hygrometric variations. According to EN 1995-1-1:2004, the additional deformation of joints caused by creep shall be calculated as the short-term deformation multiplied by the deformation factor (k_{def}). The short-term deformation shall be determined based on the slip modulus of the joint (K_{ser}) [74]. Using connectors that resist creep, such as grouted bolts with washers or specialized engineered wood connectors (i.e. dog screws or coach screws for timber-to-steel connections), can mitigate these issues. Temperature and moisture fluctuations can pose an additional challenge to connection performance, particularly in tension or compression members. Thermic and moisture variations can cause shrinking and swelling in timber leading to connection loosening or member splitting. In climates with significant temperature swings, connections that allow some movement (e.g., bolted joints or Z-clips) may perform better by accommodating these fluctuations without compromising the joint. The effect of temperature and humidity is particularly significative in hybrid connections involving glues. Kemmsies and Streicher [12] analysed the performances of different adhesive types and gluing techniques for bonded-in steel plates under temperature and humidity variations. One key finding was that epoxy-based adhesives seemed to be the most appropriate choice.

5.3.2 Group Effect and Connection Stiffness

EN 1995-1-1:2004 bases the design of multiple-fasteners connections on the behaviour of single fasteners. The connection slip modulus is determined by multiplying the slip modulus per shear plane of a single fastener, with the total number of fasteners and the number of shear planes. Nevertheless, it has been proved [75] that the assumption of a linear combination of the individual behaviours of each fastener is inaccurate, since the material and geometrical properties of the timber members and the number of fasteners in steel-to-wood connections influence their overall response as well as the connection failure mode. Jorissen and Fragiacomo [26] observed reduced shear capacity with decreasing spacing due to premature splitting of the connection. It was demonstrated by Hochreiner et al. [76] that the failure mechanism in the timber matrix in a connection could be related to the non-linear global moment-relative rotation behaviour of dowel groups. Hochreiner et al. [76] also demonstrated the potential for strain fields in the timber surrounding the dowels to overlap and interact with each other, thus alluding to the possibility of a group effect on the stiffness and failure modes of the connections [77].

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