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Stiffness of timber connections with dowel-type fasteners under lateral load

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ABSTRACT: When designing structural timber systems, serviceability limit states (SLS) can govern the final design solutions. Deformations in mechanical timber connections play a key role in controlling common SLS, such as vibration and deflection, which are dependent on the stiffness of the connections. It is also required for ultimate limit states (ULS) design. For instance, in statically indeterminate structures where the applied design load is resisted simultaneously by more than one component, and the load distribution is governed by stiffness properties of these components. Therefore, accurate models predicting the deformation or stiffness of timber connections are required for design purposes. Early timber connection models were largely based on the theory of beam on elastic foundation (Winkler foundation). Winkler foundation model works reasonably well for strength prediction but not stiffness. This is because the Winkler theory tends to lead to an over-estimation of the deformation due to the assumption of decoupling of the foundation springs. An improved approach is necessary for connection stiffness prediction. This paper investigates the use of Multi-spring foundation and Half-space foundation theories to address the limitations of Winkler foundation model. Finite element models based on the three different foundation theories were developed and the predicted results are compared. It was found that the Multi-spring foundation and Half-space foundation theories provide more accurate predictions of connection stiffness for dowel-type fasteners compared to the Winkler foundation theory. However, further experimental studies are required to determine the specific application ranges of these models.

KEYWORDS: deformation in connection, connection stiffness, Multi-spring foundation, Half-space foundation

1 – INTRODUCTION

In timber structural systems with mechanical connections, the mechanical characteristics of the connections play a key role in dictating the overall system performance. Knowledge of timber connection stiffness is required for designing timber structures to satisfy serviceability requirements such as floor vibration, floor deflection and lateral drift of lateral-force-resisting systems. It is also required for ultimate limit states (ULS) design, e.g. analysis of statically indeterminate structures and load distributions in situations where the applied design load is resisted simultaneously by more than one component. Despite the importance of connection stiffness in dictating behaviour of structural timber systems, there is a lack of complete design specifications for timber connection stiffness in most timber design standards around the world (e.g. CSA O86 [1] and Eurocode 5 [2]). Only a few design equations for selected fasteners are presented in design standards to predict lateral slip or stiffness of timber connections. These equations are largely empirical in nature and have limited scope. As such, they generally lead to conservative results. Generalized mechanics-based models that cover a broader range of parameters are desirable. The development of such models would not only enhance the accuracy of structural analysis but also enable more efficient and sustainable timber designs by reducing material overuse and optimizing load distribution.

1.1 INFLUENCING FACTORS

Connection stiffness is influenced by numerous factors, and Ehlbeck [3] provided a comprehensive summary of the key parameters affecting stiffness. Since connections consist of fasteners and fastened members, the properties of these components—such as size, modulus, and material characteristics—significantly influence the connection performance. This paper focuses specifically on the effect of dowel-type fasteners on stiffness, with nails, bolts, and screws being three common types that have been extensively studied in the literature. Numerous studies have evaluated the influence of fastener diameter and penetration length [4–8], consistently demonstrating a positive correlation between these parameters and connection stiffness. In addition to fasteners, the materials

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used in conjunction with timber also play a critical role, as steel and concrete are widely incorporated into timber structures. Steel plates are commonly used as side and knife plates [9], while concrete is often integrated into floor systems to enhance acoustic separation and mechanical performance compared to pure timber floors [10,11]. The characteristics of wood itself, such as density and moisture content, also significantly affect connection stiffness, with density being included as a key parameter in many empirical models [2,12]. The influence of density on stiffness is well-documented; for instance, Dorn et al. [13] observed that specimens with higher density exhibit greater stiffness during initial loading, while stiffness during unloading remains relatively consistent across different densities. Similar findings have been reported in [12,14], further underscoring the importance of density as a critical factor in connection performance. In addition to density, moisture content plays a significant role in determining the stiffness of timber connections [15,16]. For example, experimental studies by [17] demonstrated that post-fabrication wetting of timber leads to a notable reduction in the stiffness of the joints.

Loading conditions and the configuration of fasteners and fastened members also significantly influence connection performance, with factors such as screw angle and loading rate playing critical roles. The effect of the angle of inclination on the stiffness of timber connections is particularly pronounced. Inclined self-tapping screws facilitate axial load transfer, resulting in substantially higher connection stiffness compared to connections with screws inserted normal to the shear plane [18] [19]. In contrast, the influence of the screw's thread and diameter is less apparent relative to the effect of the angle [18]. In addition to geometric configuration, loading conditions—such as cyclic loading, long-term loading, and loading rate—have been studied to understand their impact on timber connection properties. Compared to static loading, cyclic loading has been observed to cause a considerable increase in connection stiffness, which may be attributed to the associated increase in loading rate [20]. The effect of loading rate on joint stiffness has been further confirmed by Chui and Ni [21]. However, under successive loading cycles, the connection stiffness tends to degrade with increasing displacements due to hysteretic pinching [22]. After approximately 200,000 to 300,000 cycles, the stiffness decline becomes negligible and stabilizes, indicating a transition to a steady-state behavior. These findings underscore the importance of considering both configuration and loading conditions in the design and analysis of timber connections to ensure accurate predictions of performance.

1.2 WOOD CONNECTION DESIGN PHILOSOPHY

In the previous century, the focus of stiffness calculations was primarily on bolts and nails, which were typically utilized perpendicularly to the applied forces. Contemporary methodologies for calculating the stiffness of timber connections can be broadly classified into two main categories: mechanical and empirical formulas. The mechanical approach, exemplified by models such as the Kuenzi model [23], is predominantly based on the beam on elastic foundation theory, which assumes that the force at a given point is proportional to the displacement. On the other hand, empirical formulas, including various standard formulas and those proposed in [1,2], have been developed based on extensive accumulated data and experimental observations. While mechanical models provide a theoretical foundation for understanding connection behaviour, empirical formulas offer practical approximations derived from real-world testing, highlighting the complementary nature of these two approaches.

Beam on Elastic Foundation Models

Kuenzi [23] derived connection stiffness formulas for bolts and nails under both single and double shear conditions, modelling wood as a Winkler foundation. In this approach, the nail or bolt is treated as a beam resting on an elastic foundation, where deflection is resisted by a pressure proportional to the deflection at any given point, acting in both upward and downward directions. These formulas incorporate the bending stiffness of the fasteners as well as the embedment stiffness of the wood, with Hetenyi's solution for beams of finite length [24] being employed during the derivation. Wang et al. [25] expanded this work by summarizing three Pre-Yield modes based on the deformation mechanisms of bolted connections and proposing a simplified equation for Kuenzi's model corresponding to these modes. Pre-Yield I describes pure translation of a rigid bolt, Pre-Yield II describes pure rotation of a rigid bolt, and Pre-Yield III applies to relatively slender bolts. Similarly, Tao et al. [26] utilized an analogous method to derive equations for dowel/bolted timber connections with slotted-in steel plates. Additionally, based on the exact equations, simplified numerical regression equations were proposed to facilitate practical applications, making these models more accessible for engineering design and analysis.

Empirical Models

The existing equations provided in design standards, such as Eurocode 5 [2] and CSA O86 [1], are primarily empirical models. In Eurocode 5 [2], the connection

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stiffness (Equations 1a and 1b) is calculated based on two key parameters: wood density and fastener diameter. While this approach offers simplicity, it does not account for other potentially influential factors. In contrast, CSA O86 [1] does not provide a direct equation for calculating connection stiffness; instead, it includes an equation (Equation 1c) to estimate the lateral deformation of wood-to-wood connections using nails, spikes, or wood screws. The CSA formula incorporates a service-creep factor K_m, which accounts for the effects of load duration and moisture condition. Beyond these standards, Rahim [12] proposed a more comprehensive equation for the stiffness of bolted connections using multiple linear regression (MLR). This model considers a wide range of variables, including bolt diameter, end distance, bolt spacing, row spacing, member thickness, and wood density.

Eurocode 5 $\quad K_{\text{ser}} = \rho_{mean}^{1.5} d^{0.8}/30$ (nails) (a)

$\quad K_{\text{ser}} = \rho_{mean}^{1.5} d/23$ (bolts, screws) (b) (1)

CSA O86 $\quad \Delta = 0.5 d K_m (\frac{P}{n_u})^{1.7}$ (c)

where K_{ser} = slip modulus, N/mm; ρ = mean density, kg/m³; Δ = lateral deformation, mm; d = nominal fastener diameter, mm; K_m = service-creep factor; P = specified load per fastener per shear plane, N; n_u = unit lateral strength resistance per shear plane, N.

2 – METHODOLOGY

Early models for predicting the stiffness of dowel-type timber connections were largely based on the theory of the Winkler foundation (Figure 1), which assumes that the reaction at any point on the foundation depends solely on the settlement at that specific point and is independent of the settlement of neighbouring points. This assumption leads to a discontinuity in the displacement of adjacent springs, which is a significant limitation of the Winkler approach. To address this limitation, alternative theories such as the Half-space foundation theory and the Multi-spring foundation theory have been developed. The Half-space foundation theory, also referred to as the semi-infinite elastic foundation theory, treats the foundation as a homogeneous, isotropic, semi-infinite elastic medium. The solution for a concentrated force acting on a Half-space foundation is presented in Equation 2 [27].

$$s = \frac{(1-\upsilon^2)P}{\pi E_0 r} \qquad (2)$$

where s is the displacement; P is the force; υ is the Poisson's ratio; E_0 is modulus of elasticity and r is the distance between force and calculation point.

On the other hand, the Multi-spring foundation theory introduces shear springs ($K_{D,i}$) between embedment springs (K_i) to account for coupling effects between springs, thereby addressing the discontinuity issue inherent in the Winkler model. Illustrations of the Winkler foundation and Multi-spring foundation models are provided in Figures 1 and 2, respectively. In this study, connection stiffness models based on both Half-space foundation and Multi-spring foundation theories have been developed, offering more accurate and comprehensive predictions of timber connection behaviour.

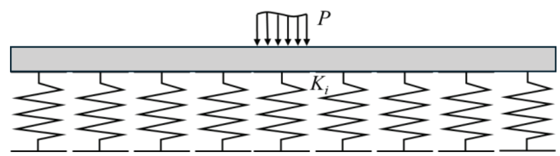

Figure 1: Winkler foundation

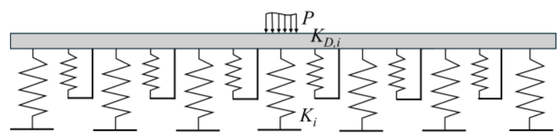

Figure 2: Multi-spring foundation

2.1 HALF-SPACE FOUNDATION

Due to the complexity of the governing equation (Equation 2), deriving a closed-form solution is impractical. However, a finite element model can be developed to obtain an approximate solution. The equilibrium equation (Equation 3) can be established from Figure 3. In this formulation, the foundation reaction, the nodal load on the beam, and the element nodal force are denoted as R, P, and F, respectively. The nodal loads are treated as known quantities, and the global nodal forces can be expressed by summing the element stiffness matrices.

The foundation reaction can be solved using the beam on an elastic foundation method, as shown in Equation 4. If the Winkler foundation model is applied, the foundation reaction force is equal to the embedment stiffness, K_i, multiplied by the point settlement, as expressed in Equation 4(a). In Equation 4(b), δ_{ij} represents the flexibility coefficient, which describes the settlement at point i when a unit force $R_j = 1$ is applied at point j. When the Half-space foundation theory is applied, δ_{ij} can be derived from Equation 2. However, when $i = j$, Equation 2 yields an infinite value, which is physically unrealistic. To address this issue, the exact value can be obtained by assuming that the unit force R_i is uniformly distributed over element i, thereby resolving the singularity and providing an accurate representation of the foundation behaviour.

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$$\{F\} = \{P\} - \{R\} \tag{3}$$

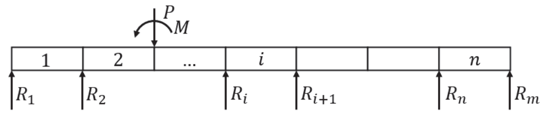

Figure 3: Beam on elastic foundation

$$\begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_i \\ \vdots \\ R_m \end{bmatrix} = \begin{bmatrix} K_1 & & & & & \\ & K_2 & & & & \\ & & \vdots & & & \\ & & & K_i & & \\ & & & & \vdots & \\ & & & & & K_m \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_i \\ \vdots \\ s_m \end{bmatrix}$$

(a) Winkler foundation

$$\begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_i \\ \vdots \\ s_m \end{bmatrix} = \begin{bmatrix} \delta_{11}\delta_{12} \cdots \delta_{1i} \cdots \delta_{1m} \\ \delta_{21}\delta_{22} \cdots \delta_{2i} \cdots \delta_{2m} \\ \vdots \\ \delta_{i1}\ \delta_{i2}\ \cdots \delta_{ii}\ \cdots \delta_{im} \\ \vdots \\ \delta_{m1}\delta_{m2} \cdots \delta_{mi} \cdots \delta_{mm} \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_i \\ \vdots \\ R_m \end{bmatrix}$$

(b) Half-space foundation

$$\begin{matrix} \mathrm{R}_1 \\ \mathrm{R}_{\mathrm{M}1} \\ \mathrm{R}_2 \\ \mathrm{R}_{\mathrm{M}2} \\ \vdots \\ \mathrm{R}_i \\ \mathrm{R}_{\mathrm{M}i} \\ \vdots \end{matrix} = \begin{matrix} K_i + K_{D,1} & 0 & -K_{D,1} & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ -K_{D,1} & 0 & K_2 + K_{D,1} + K_{D,2} & 0 & -K_{D,2} & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ & & & & \vdots & & & & \\ 0 & 0 & -K_{D,i} & 0 & K_{(i+1)} + K_{D,i} + K_{D,(i+1)} & 0 & -K_{D,i} & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\ & & & & \vdots & & & & \end{matrix} \begin{matrix} \mathrm{s}_1 \\ \varphi_1 \\ \mathrm{s}_2 \\ \varphi_2 \\ \vdots \\ \mathrm{s}_\mathrm{m} \\ \varphi_\mathrm{m} \\ \vdots \end{matrix} \tag{4}$$

(c) Multi-spring foundation

2.2 MULTI-SPRING FOUNDATION

The Multi-spring foundation model is a widely adopted approach in structural engineering to simulate the interaction between structural elements and their supporting foundation. It idealizes the foundation as a series of discrete springs, with adjacent springs modelling the coupling effect between the vertical embedment springs. This method improves the accuracy of load distribution analysis by accounting for both vertical and shear deformations, making it suitable for materials like timber, which can exhibit varying stiffness properties. By incorporating embedment springs (embedment stiffness) and shear springs (shear stiffness), the Multi-spring foundation model offers a flexible framework to capture complex interactions and localized behaviours in timber-based structural systems [28]. According to the definition of Multi-spring foundation, shear spring, K_D, are added into Equation 4a, shown in Equation 4c. And the value of K_D is shown in Equation 5.

$$K_{D,i} = \frac{GA}{L} \tag{5}$$

where $K_{D,i}$ is the stiffness of shear spring between embedment springs; G is shear modulus of the material; A is the shear-effective cross-sectional area and L is the element length.

2.3 MOMENT IN THE BEAM

In the previous analysis, the nodal load on the beam was assumed to be known. However, determining this load directly from force analysis can be challenging. Figure 4 illustrates a single-shear connection, where the force P can be easily calculated, as it is equivalent to the force P' acting on the connection. However, the moment M cannot be derived directly. To address this, an iterative method is employed to determine the moment M.

Initially, Member 1 and Member 2 are analysed separately, starting with an assumed moment $M = 0$. The slopes at points A and B are then calculated. If the slope at point A is greater than the slope at point B, the moment M is incrementally increased, and vice versa, until the slopes at points A and B are equal. The resulting moment and deformation are the desired outputs of this analysis. For double-shear connections, the methodology is similar, with the primary difference being that the applied force is half of the total load on the connection, and this load is distributed equally to each end of the middle member. This approach ensures an accurate determination of the moment and deformation for both single-shear and double-shear configurations.

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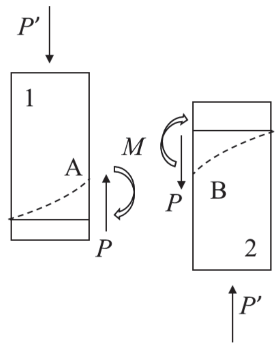

Figure 4: A single-shear connection

3 – VERIFICATION

Experimental data from prior studies [7,25,26,29–31] focusing on dowel-type fasteners, bolts, and self-tapping screws were collected to validate three finite element models based on the Winkler, Multi-spring, and Half-space foundation theories. The experimental data for dowels and bolts were sourced from two studies [25,26]. Specifically, [25] provides the connection stiffness for dowels in timber-to-timber connections, while [26] details the connection stiffness for dowels and bolts in timber-to-steel connections. The primary distinction between the models for bolts and dowels lies in the boundary conditions: for bolts, rotation at each end is fixed, whereas for dowels, it remains free.

The verification results for these models, as compared to the experimental data [25], are summarized in Table 1. The input properties for the finite element models, including fastener diameters, embedment stiffness, experimental data, and Eurocode 5 predicted results, were obtained directly from the original studies. The Poisson's ratio and shear modulus, which are critical for capturing shear effects in the Half-space and Multi-spring foundation models, were sourced from the Wood Handbook [32] for the corresponding wood species. For self-tapping screws, most existing studies focussed on inclined screw configurations, resulting in limited experimental data for screws perpendicular to the loading direction. The available test data for perpendicular screws were obtained from [29–31]. The sources of input properties for self-tapping screws were consistent with those used for bolts and dowels, except for the embedment stiffness. The embedment stiffness for self-tapping screws was derived from [4], with a value of 65.6 N/mm^3.

From Table 1, it is evident that the Eurocode 5 equation consistently overestimates the connection stiffness, with an average absolute difference of 61.5%. This indicates that the Eurocode 5 equation does not predict connection stiffness with sufficient accuracy. In contrast, the three finite element models based on Winkler, Multi-spring, and Half-space foundation theories demonstrate significantly better predictive performance, with average differences of approximately 20%. Among these, the multi-spring model exhibits the highest accuracy, with an average difference of 18.4%. The equation ($K_{w,e}$) proposed in the existing literature is still grounded in the Winkler foundation theory, which explains why its results align closely with the FEM predictions based on the Winkler foundation ($K_{w,f}$).

Figures 5(a) and 5(b) further validate the performance of the models for dowels and bolts, as reported in [25,26]. In Figure 5(a), the data can be divided into two distinct groups: data points below 20 kN/mm, sourced from [25], and data points above 20 kN/mm, sourced from [26]. A detailed analysis of the data below 20 kN/mm is provided in Table 1. For data above 20 kN/mm in Figures 5(a) and (b), the Winkler and Multi-spring models continue to demonstrate strong predictive accuracy. However, the Half-space model performs less effectively for data from [26] compared to [25], likely due to the small specimen dimensions in [26], which limits the applicability of Equation (3). This observation is further supported by the results for self-tapping screws (STS) (Figure 5(c)). The specimen dimensions for STS tests are consistently large, and in this case, the Half-space model outperforms the others, with average absolute differences of 11.8%, 6.2%, and 7.4% for the Winkler, Half-space, and Multi-spring models, respectively.

These findings suggest that the Half-space model is related to specimen dimensions, and additional experimental data are required to establish the appropriate range for its application. An additional noteworthy observation from Figure 5(a) is the contrasting behaviour of the Eurocode 5 predictions. For data points below 20 kN/mm, the Eurocode 5 equation consistently overestimates the connection stiffness. Conversely, for data points above 20 kN/mm, the Eurocode 5 equation tends to underestimate the stiffness. This dual behaviour highlights a significant limitation in the Eurocode 5 formulation, as it fails to provide consistent accuracy across the full range of connection stiffness values. This discrepancy further underscores the need for more refined predictive models, such as the finite element models evaluated in this study, to achieve reliable and consistent results across varying conditions.

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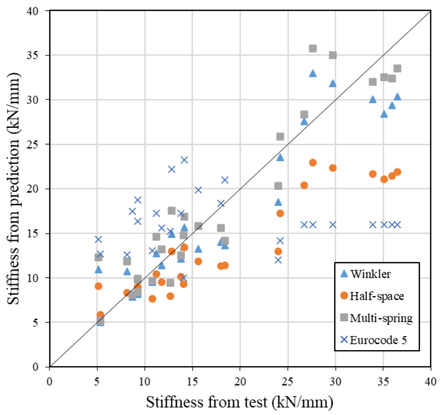
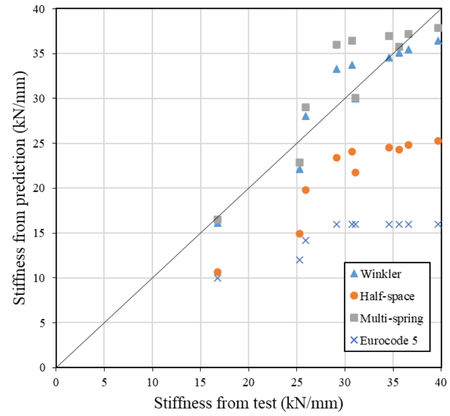
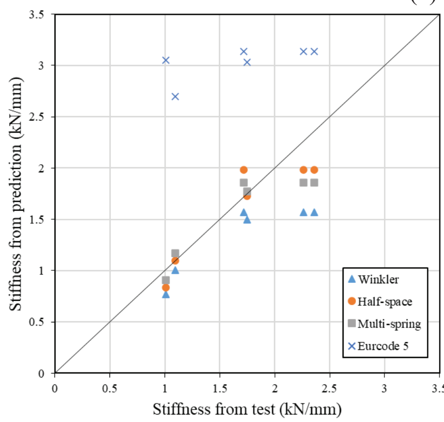


(a) Verification for dowels



(b) Verification for bolts



(c) Verification for screws

Figure 5: Verfication for 3 different foundation theories

Table 1 Comparison of predicted stiffness with experimental stiffness from [25]

Specimen	Elastic stiffness (kN/mm)									
	K_t	K_{EN}	D_{EN}	$K_{w,e}$	$K_{w,f}$	$D_{w,f}$	$K_{h,f}$	$D_{h,f}$	$K_{m,f}$	$D_{m,f}$
P40-P10	5.33	12.65	137%	5.19	5	-6%	5.89	10.5%	5.19	-3%
P40-P30	10.79	13.05	21%	9.52	9.53	-12%	7.65	-29.1%	9.71	-11%
P80-P40	5.16	14.32	178%	10.93	10.97	113%	9.07	75.8%	12.27	58%
P80-P80	8.13	12.58	55%	10.75	10.76	32%	8.35	2.7%	11.89	32%
P40-L10	8.72	17.46	100%	8.06	7.9	-9%	8.14	-6.7%	8.09	-8%
P40-L20	12.64	15.20	20%	9.37	9.42	-25%	7.94	-37.2%	9.48	-33%
P80-L40	11.77	15.61	33%	11.40	11.41	-3%	9.51	-19.2%	13.19	11%
P80-L60	11.23	17.22	53%	12.78	12.79	14%	10.44	-7.0%	14.6	23%
L40-L10	9.24	18.77	103%	8.40	8.2	-11%	8.98	-2.8%	8.44	-9%
L40-L30	18.40	20.98	14%	13.68	13.65	-26%	11.4	-38.0%	14.18	-30%
L80-L40	15.63	19.88	27%	13.25	13.26	-15%	11.83	-24.3%	15.8	1%
L80-L60	12.78	22.20	74%	14.92	14.92	17%	13	1.7%	17.54	27%
L40-P20	9.25	16.33	77%	9.77	9.83	6%	8.86	-4.2%	9.88	6%
L40-P30	13.79	17.23	25%	12.15	12.14	-12%	10.13	-26.5%	12.5	-10%
L60-P30	14.12	23.24	65%	15.74	15.71	11%	13.44	-4.8%	16.87	16%
L60-P80	17.96	18.34	2%	14.08	14.05	-22%	11.33	-36.9%	15.58	-15%
Average (Abs)			61.5%			20.9%		20.5%		18.4%

Note: K_t denotes the experimental connection stiffness; K_{EN} is the predicted stiffness following Eurocode 5; $K_{w,e}$ is the predicted stiffness with Kuenzi model; $K_{w,f}$, $K_{h,f}$, and $K_{m,f}$ are the predicted stiffness with finite element models based on Winkler, Half-space and Multi-spring foundation theories, respectively; D_{EN}, $D_{w,f}$, $D_{h,f}$, and $D_{m,f}$ are the relative differences between the predicted stiffness values and the experimental connection stiffness, calculated as the difference between predicted and experimental stiffness divided by the experimental stiffness.

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4 – CONCLUSIONS AND FUTURE WORK

This paper summarizes the primary influence factors, such as density and fastener diameter, that affect the stiffness of timber connections. While numerous studies have investigated the effects of density, diameter, and penetration length on the connection performance, other critical factors, such as number of fasteners and moisture content, remain underexplored. Traditional mechanical formulas for predicting connection stiffness often rely on the Winkler foundation theory, which does not account for the coupling effects between adjacent foundation springs. To address this limitation, new models based on the Half-space foundation theory and the Multi-spring foundation theory have been developed. Experimental data from existing studies on dowels, bolts, and screws were collected to validate the three finite element models.

The results demonstrate that the new models based on the Half-space and Multi-spring foundation theories provide more accurate predictions compared to the Winkler foundation model. However, the Half-space model is only suitable for large-size connections, and further experimental studies are required to determine the specific application ranges of these finite element models. Additionally, beam on elastic foundation models are highly sensitive to input properties, such as embedment stiffness. Existing studies utilizing beam on elastic foundation theory for connection stiffness analysis often rely on experimental data to obtain accurate values for embedment and withdrawal stiffness, highlighting the need for precise input parameters to ensure reliable predictions.

Future work will focus on developing advanced models for Cross-Laminated Timber (CLT) and timber connections with inclined fasteners, which are increasingly used in modern timber construction. Furthermore, comprehensive experimental studies considering factors such as group effects, moisture content, and size effects should be conducted to validate the proposed models and compare their performance with existing models. Additionally, the development of accurate predictive models for embedment and withdrawal stiffness is essential to enhance the accuracy and applicability of these analytical approaches in engineering practice.

5 – ACKNOWLEDGEMENT

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