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LOAD-TRANSFER MECHANISMS IN TIMBER CONNECTIONS USING DENSIFIED WOOD AND STEEL DOWELS: AN EXPERIMENTAL AND NUMERICAL STUDY

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Abstract: This study presents an experimental and numerical investigation of the mechanical behavior of L-shaped timber connections assembled using densified wood dowels and steel dowels under ambient mechanical loading conditions. Mechanical tests were con-ducted on a multilayer timber beam–column connection to determine the load–displacement response of the joint system. In parallel, a three-dimensional finite element model was developed in Abaqus to simulate the structural behavior and to investigate the load-transfer mechanisms within the connection region. The numerical results show good agreement with the experimental response, demonstrating the capability of the model to accurately reproduce the global behavior of the connection. Although the two types of dowels exhibit relatively similar overall stiffness, the stress distribution along the grain (S11) and the stress fields within the joint reveal fundamentally different load-transfer mechanisms. Steel dowels provide a more uniform stress distribution and more efficient force transfer, whereas densified wood dowels exhibit more localized stress concentrations and a more compliant mechanical response. Nevertheless, the use of densified wood dowels may offer advantages in terms of material compatibility and potential thermal performance under elevated temperatures. The findings contribute to a better understanding of the mechanical behavior of timber connections using different dowel types and provide a reference basis for future thermo-mechanical investigations of timber structures exposed to fire.

Keywords: Timber connections, densified wood dowels, steel dowels, mechanical behavior, load-transfer mechanism, finite element modelling

МЕХАНИЗМЫ СОПРОТИВЛЕНИЯ СОЕДИНЕНИЙ ДЕРЕВЯННЫХ КОНСТРУКЦИЙ С НАГЕЛЯМИ ИЗ ПРЕССОВАННОЙ ДРЕВЕСИНЫ И СТАЛЬНЫХ: ЭКСПЕРИМЕНТАЛЬНЫЕ И ЧИСЛЕННЫЕ ИССЛЕДОВАНИЯ

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Аннотация: Представлены экспериментальные и численные исследования сопротивления Г-образных деревянных соединений, собранных с использованием нагелей из прессованной древесины и стальных нагелей, при обычных механических нагрузках. Проведены механические испытания многослойного узла сопряжения балки с колонной для определения несущей способности и деформативности. Параллельно разработана трёхмерная конечно-элементная модель в программном комплексе Abaqus для моделирования сопротивления и изучения механизмов передачи усилий в зоне соединения. Численные результаты хорошо согласуются с экспериментальными данными, что подтверждает способность модели точно воспроизводить общее поведение соединения. Хотя оба типа нагелей демонстрируют относительно схожую общую жёсткость, распределение напряжений вдоль волокон (S11) и поля напряжений в узле выявляют принципиально различные механизмы передачи усилий. Стальные нагели обеспечивают более равномерное распределение напряжений и более эффективную передачу усилий, тогда как нагели из прессованной древесины характеризуются более локализованными концентрациями напряжений и более податливым механическим откликом. Тем не менее, применение нагелей из прессованной древесины может давать преимущества с точки зрения совместимости материалов и

потенциальных теплотехнических характеристик при повышенных температурах. Полученные результаты способствуют более глубокому пониманию сопротивления деревянных соединений с различными типами нагелей и служат основой для будущих термомеханических исследований деревянных конструкций, подвергающихся воздействию огня.

Ключевые слова: деревянные соединения, нагели из прессованной древесины, стальные нагели, сопротивление, механизм передачи усилий, конечно-элементное моделирование

1. INTRODUCTION

In recent years, timber structures have attracted increasing attention in the construction field due to their low density, high strength-to-weight ratio, recyclability, and environmental advantages compared with conventional materials such as steel and concrete [1]. Along with the development of engineered wood products (EWPs), various modern timber structural and connection systems have been investigated to improve load-bearing efficiency and expand the application of timber in large-scale structures [2]. However, many current connection systems still rely on steel mechanical fasteners or synthetic structural adhesives, which may reduce material homogeneity, recyclability, and the environmental benefits of timber structural systems [1].

In this context, densified wood, also referred to as compressed wood, has been considered a promising material for partially replacing metallic fasteners in timber structures. Densified wood is produced through thermo-mechanical compression, which reduces the internal porosity of the wood cellular structure and thereby significantly increases its density and mechanical properties [1,2]. Previous studies have shown that densification can markedly im-prove the elastic modulus, flexural strength, tensile strength, and shear strength of wood, allowing low-density softwood species to be used in structural applications requiring higher load-bearing capacity [2,3]. In addition, densified wood offers advantages such as material compatibility with timber components, recyclability, and the ability to create tight connections through moisture-dependent swelling [2].

Based on these advantages, several studies have proposed the use of densified wood dowels as an alternative to conventional steel dowels in timber connections. Jung et al. [4,5] developed connection systems using compressed wood dowels and plates for column–beam and column–base joints, showing that these systems can provide satisfactory load-bearing and rotational performance. In another study, Jung et al. [6] demonstrated that compressed wood dowels can be effectively used in glued-in-rod connections, achieving load-bearing capacity comparable to or higher than that of some traditional hardwood dowels. O'Loinsigh et al. [7] developed timber-to-timber composite beams using welded-through wood dowels to generate composite action between timber layers without the use of adhesives or metallic fasteners. These studies demonstrate the considerable potential of wood-based dowels for developing environmentally friendly timber connection systems and reducing dependence on metallic materials.

Alongside experimental investigations, the finite element method (FEM) has been increasingly used in timber engineering research to simulate stress distributions, load-transfer mechanisms, and the mechanical behaviour of timber connection systems. Xu et al. [8] developed a three-dimensional finite element model for dowel-type timber joints subjected to loading parallel to the grain, while Feio et al. [9] showed that FEM can reasonably repro-duce stiffness and stress distributions in traditional timber joints. More recently, Ar-ciszewska-Kędzior et al. [10] and Tran and Dao [11] combined experimental and numerical modelling to evaluate the mechanical behavior of timber joints using wooden dowels, demonstrating that FEM is an effective tool for analyzing load-transfer mechanisms and stress fields in connection regions.

In addition, numerical studies on multilayer timber beams have shown that the degree of interaction between timber layers strongly affects the load-transfer mechanism, global stiffness, and stress distribution of the structural system [12]. These findings confirm the potential of FEM for investigating the mechanical behavior of complex timber connections and structural systems.

Besides studies on mechanical behavior under ambient conditions, the fire performance of densified timber and timber connections using densified wood dowels has also been investigated in recent studies. Tran et al. [13] experimentally characterized the thermal behavior and degradation of thermo-mechanically compressed spruce timber and developed a three-step multi-reaction pyrolysis finite element model for predicting temperature profiles, mass loss, and charring depth under fire exposure. For timber connections, Khelifa et al. [14] developed a thermal modelling framework for connections assembled with densified wood dowels under fire, showing that pyrolysis-based modelling can reproduce temperature dis-tribution and char layer formation.

In addition, Tran et al. [15] experimentally investigated the thermo-mechanical performance of L-shaped timber connections assembled with densified wood dowels and steel dowels under fire exposure, demonstrating that densified wood dowels can reduce heat transfer, lower charring depth, and limit thermally induced deformation compared with steel dowels. Tran's doctoral thesis [16] further synthesized the thermal and thermo-mechanical modelling framework for timber structural systems assembled with densified wood dowels under fire conditions. However, although these thermal and thermo-mechanical studies provide important insight into fire-exposed behavior, the baseline mechanical behavior of L-shaped timber connections using densified wood dowels under ambient mechanical loading has not yet been fully clarified, particularly in terms of load-transfer mechanisms and stress distributions within the connection region.

Therefore, this study presents an experimental and numerical investigation of the mechanical behavior of L-shaped timber connections using densified wood dowels and steel dowels under ambient loading conditions. Mechanical tests were conducted to determine the load–displacement response of the connection system, while a three-dimensional finite element model was developed in Abaqus to analyze the load-transfer mechanism and stress distribution in the dowel region. The focus of this study is not only to compare the global stiffness of the two connection types, but also to clarify the differences in load-transfer mechanisms and stress fields between densified wood dowels and steel dowels. The results are expected to provide a mechanical baseline for further studies on the thermo-mechanical behavior of timber connections under fire conditions.

2. EXPERIMENTAL PROGRAM

2.1 Connection configuration and specimen

Experiments were conducted on L-shaped timber connections to evaluate the mechanical behavior of connection systems using densified wood dowels and steel dowels under ambient loading conditions. The connection consisted of a beam and a column assembled using four dowels with a diameter of 16 mm. Two connection configurations were investigated, namely connections using densified wood dowels and connections using steel dowels, in order to evaluate the influence of dowel material on the load-transfer mechanism and stress distribution within the connection region.

Details of the experimental specimen and the connection region are presented in Figure 1. Four dowels were arranged in a clustered configuration at the beam–column intersection to ensure effective load transfer between the two structural members.

The beam and column members were manufactured from three-layer oak timber. Each timber layer had a thickness of 32 mm, resulting in an overall cross-section of 190 × 48 mm. The lengths of both the beam and the column were 1180 mm. The average moisture content of the

timber during the experimental tests was approximately 10%. The overall geometry and dimensions of the L-shaped connection are shown in Figure 2. A symmetric configuration was adopted to facilitate the development of the numerical model presented in the following sections.

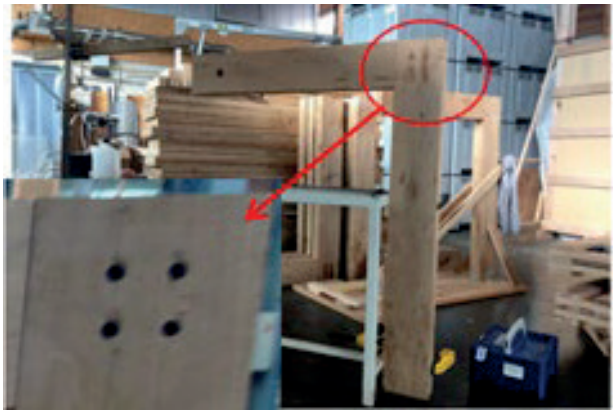


Figure 1. L-shaped timber connection specimen and dowel arrangement details

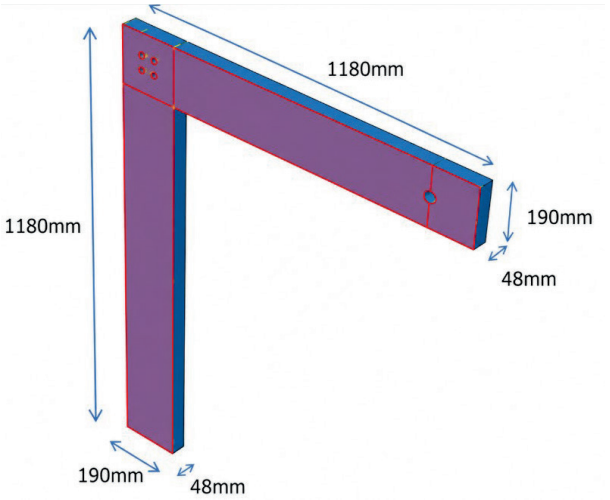


Figure 2. Geometry and dimensions of the L-shaped timber connection

2.2 Experimental and loading procedure

The experimental setup is illustrated in Figure 3. The connection specimen was installed in a testing frame with the column base fixed, while the load was applied at the free end of the beam to generate a bending moment in the connection region. The applied load correspond-ed to a concentrated mass of 51 kg (~ 510 N).

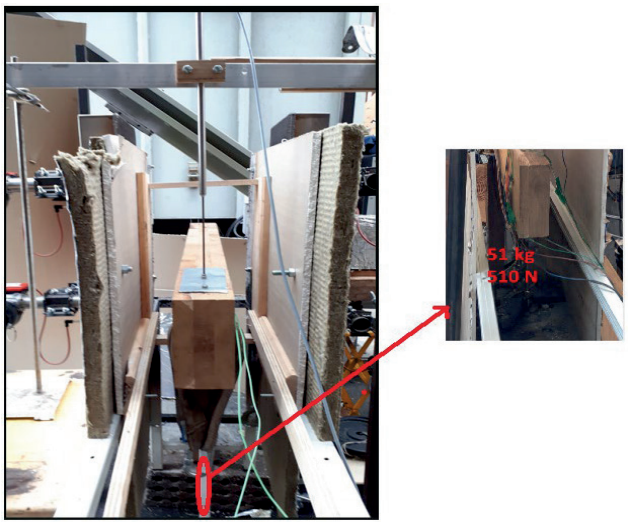


Figure 3. Experimental setup of the L-shaped timber connection under mechanical loading

3. FINITE ELEMENT MODEL

3.1. Numerical model configuration

A three-dimensional finite element model of the L-shaped timber connection was developed using Abaqus software [17] to simulate the mechanical behavior of connection systems using densified wood dowels and steel dowels under ambient mechanical loading conditions. The model was constructed based on the experimental configuration presented in Section 2 in order to analyze the load-transfer mechanism and stress distribution within the connection region.

Due to the symmetric geometry and loading configuration, only half of the model was considered in the numerical simulation in order to reduce computational time and modelling cost while maintaining mesh continuity and structural consistency. The boundary conditions were defined to correspond to the experimental setup, in which the column base was fully fixed and the load was applied vertically at the free end of the beam.

The finite element model and corresponding boundary conditions are illustrated in Figure 4; and details of the finite element mesh in the L-shaped connection are shown in Figure 5.

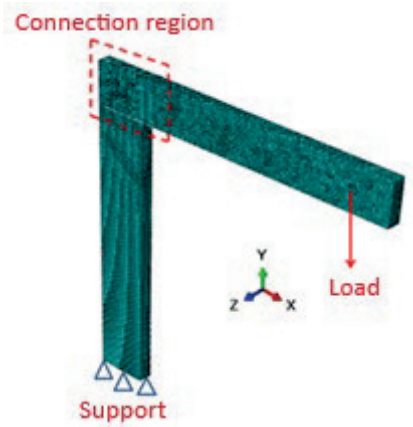


Figure 4. Finite element model of the L-shaped timber connection in Abaqus

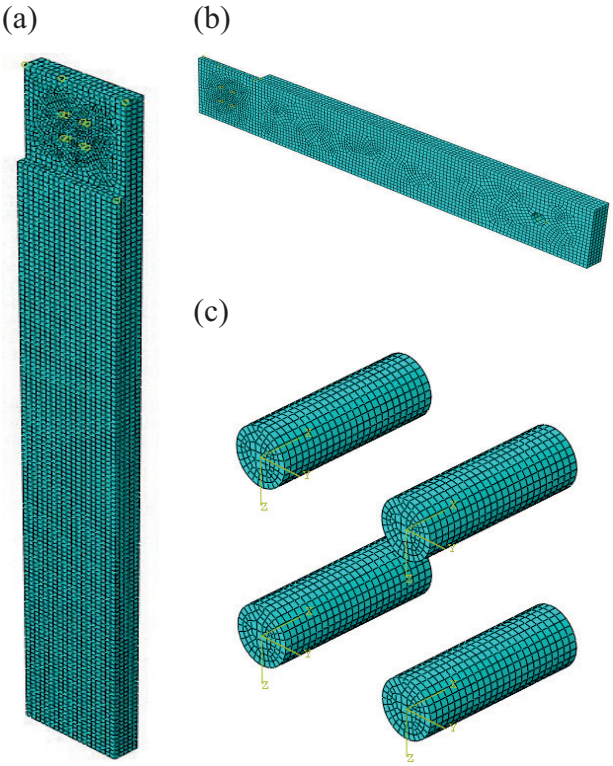


Figure 5. C3D8 finite element mesh in the L-shaped connection (a) Column; (b) Beam; (c) Dowels

The structural components in the model, including the beam, column, and dowels, were discretized using eight-node three-dimensional solid elements of type C3D8. Since this study focused only on the mechanical behavior under ambient conditions, coupled thermo-mechanical elements were not considered. The mesh was locally refined in the dowel region to improve the accuracy of stress distribution and load-transfer analysis within the connection area.

3.2. Material modelling

In this study, the oak timber used for the beam and column members was modelled as an orthotropic elastic material. The mechanical properties of the timber were determined based on average values obtained from experimental measurements and previous studies. The material properties of oak timber at ambient temperature are summarized in Table 1; while the material properties of the densified spruce dowels are presented in Table 2, was modelled using an orthotropic elastic formulation.

Table 1. Mechanical properties of oak wood at 20°C [16]

Property	Symbol	Value (MPa)
Longitudinal modulus	E_1 (E_L)	11380
Radial modulus	E_2 (E_R)	370
Tangential modulus	E_3 (E_T)	370
Poisson's ratio	ν_{12}	0.41
Poisson's ratio	ν_{13}	0.41
Poisson's ratio	ν_{23}	0.3
Shear modulus	G_{12}	690
Shear modulus	G_{13}	690
Shear modulus	G_{23}	50

Table 2. Mechanical properties of densified spruce wood at 20°C[16]

Property	Symbol	Value (MPa)
Longitudinal modulus	E_1 (E_L)	25500
Radial modulus	E_2 (E_R)	2050
Tangential modulus	E_3 (E_T)	2050
Poisson's ratio	ν_{12}	0.408
Poisson's ratio	ν_{13}	0.408
Poisson's ratio	ν_{23}	0.03
Shear modulus	G_{12}	1890
Shear modulus	G_{13}	1890
Shear modulus	G_{23}	137

Note: L, R, and T denote the longitudinal (grain), radial, and tangential directions of wood, respectively.

For the connections using steel dowels, the steel material was modelled as an isotropic elastic material with a Young's modulus of 210,000 MPa and a Poisson's ratio of 0.3 according to Eurocode 3 [18].

3.3. Contact Interaction

The contact interaction between the dowels and the timber members was defined using a surface-to-surface contact formulation. In the normal direction, a "hard contact" condition was adopted to prevent penetration between the interacting surfaces during loading.

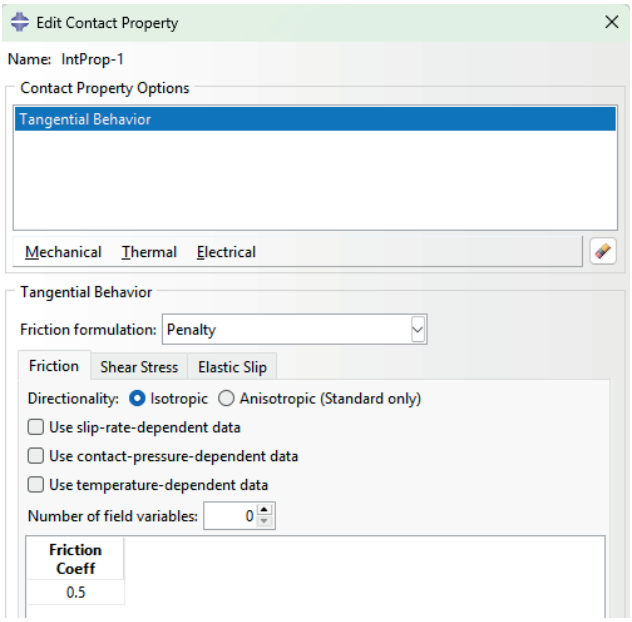


Figure 6. Friction contact definition between interacting surfaces in Abaqus

In the tangential direction, a Coulomb friction model was employed with a friction coefficient of $\mu = 0.5$ for both the densified wood dowels and the steel dowels. This value was selected to represent the frictional load-transfer capacity between the dowels and the timber layers within the connection region. The friction contact definition implemented in Abaqus is illustrated in Figure 6.

4. RESULTS AND DISCUSSION

4.1. Load–displacement response and model validation

The load–displacement relationships of the L-shaped timber connections using densified wood dowels and steel dowels obtained from the experimental tests and numerical simulations are presented in Figure 7. The results indicate that the finite element model is capable of reasonably reproducing the global mechanical behavior of the connection system under ambient mechanical loading conditions.

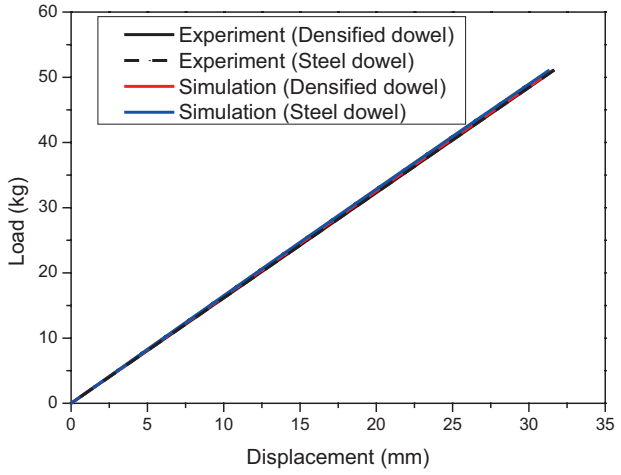


Figure 7. Comparison between experimental and numerical load–displacement responses of the L-shaped timber connections using densified wood dowels and steel dowels

It can be observed that the numerical load–displacement curves are in good agreement with the experimental results throughout the investigated loading range. Both connection configurations exhibit an approximately linear response, indicating that the connections mainly operate within the elastic regime under the applied loading conditions.

For the connection using densified wood dowels, the numerical model predicts the global stiffness and displacement evolution with satisfactory agreement compared with the experimental response. The discrepancy between the experimental and numerical curves remains relatively small over the entire loading

range, suggesting that the developed finite element model can adequately represent the load-transfer mechanism between the densified wood dowels and the timber layers within the connection region.

Similarly, for the connection using steel dowels, the finite element simulation also shows good agreement with the experimental results. The numerical response tends to exhibit a slightly higher stiffness at higher loading levels; however, the overall deviation remains limited.

In addition, the results show that the two connection systems exhibit relatively similar global stiffness within the investigated loading range. This indicates that densified wood dowels can provide an effective load-transfer mechanism in L-shaped timber connections under ambient mechanical loading conditions. Nevertheless, although the global load–displacement responses of the two configurations are relatively similar, the differences in stress distribution and load-transfer mechanisms within the connection region will be dis-cussed in the following sections.

4.2. Stress distribution in beam and column members

The longitudinal stress distribution (S11) within the beam–column connection region for the two connection configurations using densified wood dowels and steel dowels is presented in Figure 8. Figure 8a corresponds to the connection using densified wood dowels, while Figure 8b illustrates the connection using steel dowels.

The numerical results show that the stress is mainly concentrated in the vicinity of the beam–column intersection, particularly around the dowel region. This indicates that the externally applied load at the free end of the beam is primarily transferred to the column through the contact interaction and load-transfer mechanism between the dowels and the timber layers within the connection region.

For the connection using densified wood dowels (Figure 8a), the stress distribution tends to be more localized around the dowel region. Localized tensile and compressive stress zones can be observed near the contact interfaces between the dowels and the timber members, suggesting that the load transfer mainly occurs in the immediate vicinity of the dowels. In addition, the stress magnitude along the beam decreases relatively rapidly with increasing distance from the connection region, reflecting the comparatively more compliant behavior of the connection system using densified wood dowels.

In contrast, for the connection using steel dowels (Figure 8b), the stress field in both the beam and the column appears to be distributed more uniformly along the connection region. Tensile and compressive stresses are transferred over a broader area of the structural members, particularly near the beam–column interface. This suggests that the steel dowels pro-vide a stiffer and more efficient load-transfer mechanism compared with the densified wood dowels.

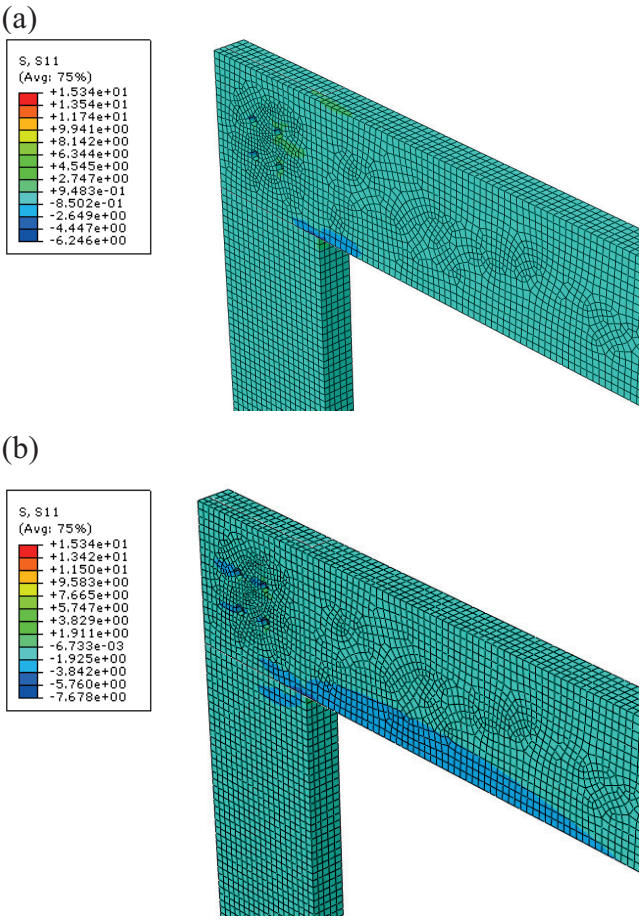


Figure 8. Longitudinal stress distribution (S11) in the beam–column connection region: (a) densified wood dowels; (b) steel dowels

Moreover, a larger compressive stress zone can be observed at the lower surface of the beam near the connection region in the case of steel dowels. This behavior indicates a more effective transfer of bending moment and shear force within the connection system, resulting in an increase in the local stiffness of the joint region.

Although the two connection configurations exhibit relatively similar global load–displacement responses, as discussed in Section 4.1, the stress distribution results reveal significantly different internal load-transfer mechanisms. The connection using densified wood dowels exhibits a more compliant behavior with localized stress concentrations around the dowel region, whereas the connection using steel dowels generates a broader and more uniformly distributed stress field within the connection region.

In contrast, the steel dowels (Figure 9b) exhibit a more uniformly distributed stress field over the entire dowel surface. The stress concentrations are less localized compared with the densified wood dowels, indicating a stiffer interaction between the steel dowels and the timber members. Due to the significantly higher stiffness of steel, the load is transferred more directly through the dowels, leading to a more efficient stress redistribution within the connection region.

In addition, the stress magnitude observed in the steel dowels is generally higher and more continuous along the dowel length, reflecting the stronger confinement and load-transfer capacity of the steel connection system. Meanwhile, the densified wood dowels exhibit a more gradual stress transition, which may contribute to reducing local stress peaks within the timber members.

These results further confirm that, although the two connection systems exhibit relatively similar global stiffness under the investigated loading conditions, the internal load-transfer mechanisms are substantially different. The densified wood dowels tend to provide a more compliant and localized interaction with the surrounding timber, whereas the steel dowels create a stiffer and more uniformly distributed load-transfer mechanism within the joint region.

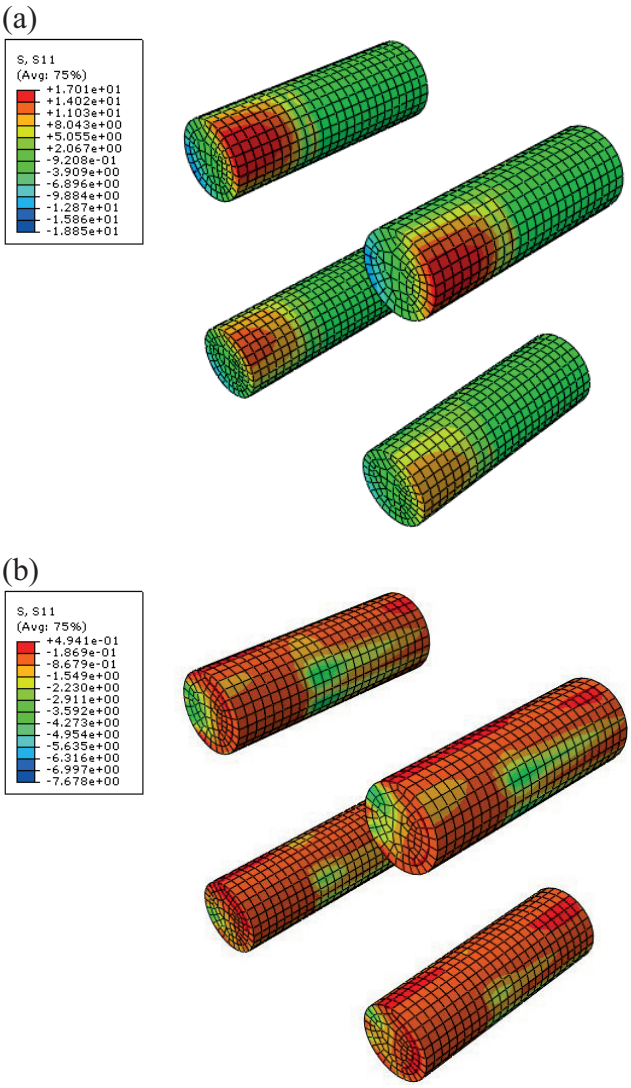


Figure 9. Longitudinal stress distribution (S11) in the beam–column connection region: (a) densified wood dowels; (b) steel dowels

4.3. Discussion

The numerical and experimental results show that although the two connection configurations using densified wood dowels and steel dowels exhibit relatively similar global load–displacement responses within the investigated loading range, their internal load-transfer mechanisms are significantly different.

For the connections using steel dowels, the high stiffness of the steel material results in a more

direct and efficient transfer of load between the beam and the column. This behavior is reflected by the relatively uniform stress distribution observed within both the connection region and the steel dowels. The stress field is distributed over a broader area along the beam–column interface, indicating that the steel dowels provide a more effective redistribution of internal forces and generate a higher local stiffness within the joint region. In contrast, the connections using densified wood dowels tend to exhibit a more compliant load-transfer mechanism due to the material compatibility between the dowels and the sur-rounding timber layers. The stress distribution results show more localized stress concentrations around the dowel region, while the stress magnitude along the beam decreases more rapidly with increasing distance from the connection area. This behavior indicates that the load is mainly transferred through the local contact interaction between the dowels and the adjacent timber layers, rather than being broadly redistributed throughout the entire connection region as observed in the case of steel dowels. Despite the comparatively more compliant behavior of the densified wood dowels, the load–displacement results demonstrate that the connection system is still capable of maintaining a global stiffness relatively close to that of the steel dowel connection within the investigated loading range. This suggests that densified wood dowels can provide an effective load-transfer mechanism for L-shaped timber connections under ambient mechanical loading conditions.

In addition, the differences observed in the load-transfer mechanisms of the two connection systems may also indicate different structural responses under elevated temperature or fire exposure. Connections using steel dowels may generate stronger localized heat-transfer zones due to the high thermal conductivity of steel, whereas densified wood dowels provide better material compatibility with the surrounding timber members. This difference may significantly influence temperature evolution, heat-field distribution, and the thermo-mechanical behavior of the connection region under fire conditions.

Therefore, the results obtained in this study provide an important mechanical basis for future investigations on the thermo-mechanical behavior of timber connections using densified wood dowels and steel dowels under elevated temperature and fire conditions.

5. CONCLUSION

This study presented an experimental and numerical investigation of L-shaped timber connections using densified wood dowels and steel dowels under ambient mechanical loading conditions. A three-dimensional finite element model was developed in Abaqus to simulate the load–displacement response and stress distribution within the connection region. Based on the obtained results, the following conclusions can be drawn:

1. The developed finite element model was capable of reasonably reproducing the global mechanical behavior of the L-shaped timber connections. The numerical load–displacement responses showed good agreement with the experimental results for both the densified wood dowel and steel dowel configurations.
2. Both connection systems exhibited an approximately linear response within the investigated loading range, indicating that the connections mainly operated within the elastic regime under the applied loading conditions.
3. The stress distribution results revealed significantly different load-transfer mechanisms for the two connection configurations, despite their relatively similar global stiffness. The connections using steel dowels generated a broader and more uniformly distributed stress field within the connection region, reflecting a more direct and efficient load-transfer mechanism.
4. For the connections using densified wood dowels, the stress tended to be more locally concentrated around the dowel region and decreased more rapidly with increasing distance

from the connection area. This behavior indicates a more compliant load-transfer mechanism due to the material compatibility between the densified wood dowels and the surrounding timber layers.

5. Although the load-transfer mechanism of the densified wood dowels was more com-pliant than that of the steel dowels, the results demonstrated that densified wood dowels were still capable of providing effective load transfer in L-shaped timber connections under ambient mechanical loading conditions.

6. The results obtained in this study provide an important mechanical basis for future investigations on the thermo-mechanical behavior of timber connections using densified wood dowels and steel dowels under elevated temperature and fire conditions.

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