UDC 624.011.1:624.046.5

MECHANICAL CHARACTERISTICS AND FAILURE MECHANISMS OF TIMBER-CONCRETE COMPOSITE CONNECTIONS WITH INCLINED STEEL RODS

Wei You[1], *A. Ya. Naichuk*[2]

[1] *Graduate student, Brest State Technical University, Brest, Belarus, e-mail: 18206599529@163.com*
[2] *Doctor of Technical Sciences, Associate Professor, Professor of the Department of Building Structures, Brest State Technical University, Brest, Belarus, e-mail: atnya@yandex.ru*

Abstract

The application of Timber-Concrete Composite (TCC) structures in long-span floor systems is becoming increasingly widespread, and their collaborative efficiency highly depends on the shear stiffness and load-bearing capacity of the interface shear connectors. Although inclined self-tapping screws significantly improve connection stiffness by utilizing axial tensile force, the mechanism by which the mechanical behavior of large-diameter inclined connections with bolts steel rods, which have higher load-bearing capacity and require greater construction tolerance, is influenced by the constraints of hole clearance and concrete slab thickness remains unclear.

This paper proposes a comprehensive research scheme combining theoretical derivation, full-scale experiments, and high-fidelity numerical simulation for a TCC system composed of a 70 mm thin concrete slab and a 160 mm timber beam. The study aims to quantify the coupling effect of the diameter of the bolts steel rods (d = 6, 8, 12 mm) and inclination angle (α = 30°, 45°, 60°), focusing on solving two key problems: initial slippage caused by the clearance of the bolts steel rods and brittle punching out of thin slabs. In the numerical simulation stage, this study will use ANSYS finite element analysis software to establish a three-dimensional nonlinear solid model. ANSYS's powerful contact algorithms will be used to accurately simulate the closing process of the gap between the shank of the bolts steel rods and the hole wall. Combined with the concrete damage plasticity model (CDP) illustrated in Figure 2a, which can simultaneously, the evolution of failure modes under different working conditions will be predicted.

Expected results show:

1) ANSYS-based contact analysis will reveal that a 30° tilt angle can produce a significant geometric self-locking effect, effectively suppressing the initial stiffness loss caused by pre-drilled hole gaps;

2) in a 70 mm thin plate, 12 mm diameter bolts steel rods easily induce concrete cone failure, and numerical simulation will provide the critical parameter boundary to avoid this brittle failure. The results of this paper will correct the existing European Yield Model (EYM), providing a design basis based on high-precision simulation for the reinforcement and renovation of thin-plate concrete structures in existing timber floor slabs.

Keywords: timber-concrete composite structure, inclined bolted connection, ANSYS finite element analysis, slip modulus, bolt clearance, European yield model.

МЕХАНИЧЕСКИЕ ХАРАКТЕРИСТИКИ И МЕХАНИЗМЫ РАЗРУШЕНИЯ КЛЕЕНЫХ ДЕРЕВЯННО-БЕТОННЫХ СОЕДИНЕНИЙ С НАКЛОННЫМИ СТАЛЬНЫМИ СТЕРЖНЯМИ

Вей Юй, А. Я. Найчук

Реферат

Применение деревобетонных композитных (ДБК) конструкций в системах монолитных перекрытий с большими пролетами становится все более распространенным, и их совместная эффективность в значительной степени зависит от сдвиговой жесткости и несущей способности соединительных элементов. Хотя наклонные самонарезающие винты значительно повышают жесткость соединения за счет осевой растягивающей силы, механизм влияния ограничений зазора отверстия и толщины бетонной плиты на механическое поведение крупногабаритных наклонных соединений с болтовыми стальными стержнями, которые обладают более высокой несущей способностью и требуют большего строительного допуска, остается неясным.

В этой статье предлагается всеобъемлющая исследовательская схема, сочетающая теоретическое произведение, полномасштабные эксперименты и высокоточное цифровое моделирование для системы TCC, состоящей из тонкой бетонной плиты 70 мм и деревянной балки 160 мм. Исследование направлено на количественное измерение эффекта соединения диаметра стальных прутиков болтов (d = 6, 8, 12 мм) и угла наклона (α = 30). Исследование направлено на решение двух ключевых проблем: первоначальное скольжение, вызванное расщеплением стальных прутиков болтов и хрупкое пробивание тонких плит. На этапе цифрового моделирования в этом исследовании будет использовано программное обеспечение для анализа конечных элементов ANSYS для создания трехмерной нелинейной твердой модели. Мощные алгоритмы контакта ANSYS будут использоваться для точного имитации процесса закрытия разрыва между стволом стальных штанг, болтов и стеной отверстия. В сочетании с моделью пластичности повреждения бетона (CDP), иллюстрированной на рисунке 2а, которая может одновременно предсказать эволюцию режимов сбоя при различных условиях работы.

Ожидаемые результаты показывают:

1) анализ контакта на основе ANSYS покажет, что угол наклона 30° может создать значительный геометрический эффект самоблокировки, эффективно подавляя первоначальную потерю жесткости, вызванную предварительно пробуренными пробелами в отверстии;

2) в тонкой пластине 70 мм, 12 мм диаметра болтов стальные пруты легко вызывают сбой бетонного конуса, и цифровое моделирование обеспечит границу критического параметра, чтобы избежать этого хрупкого сбоя. Результаты этой работы будут корректировать существующую Европейскую модель урожайности (EYM), обеспечивая основу проектирования на основе высокоточного моделирования для армирования и ремонта тонкоплиточных бетонных конструкций в существующих деревянных половых плитах.

Ключевые слова: деревобетонная композитная конструкция, наклонное болтовое соединение, анализ конечных элементов ANSYS, модуль скольжения, клиренс болта, Европейский режим урожайности.

Introduction

Against the backdrop of the continuous advancement of green transformation and carbon reduction goals in the global construction field, Timber-Concrete Composite (TCC) is becoming a hot topic in academic research and engineering applications due to its complementary materials and high system efficiency. This system typically connects concrete slabs with excellent compressive performance and timber beams or planks with excellent tensile performance through shear connectors, so that the two materials have clear division of labor and complementary advantages in the same stress system, thereby significantly improving the overall stiffness and load-bearing capacity of the components, and showing better sound insulation and vibration comfort in terms of floor performance [1]. For the reinforcement and renovation of existing timber structures, TCC can improve structural safety reserves and service performance without significantly increasing structural complexity; and in modern multi-story timber structures, TCC floor slabs are also considered a powerful technical path that takes into account structural efficiency and sustainability, thus showing broad potential for promotion [2]. At the same time, the requirements for space utilization and floor height control in architectural design are constantly increasing, making the development trend of "thinner and lighter" floor systems more and more obvious. Driven by this, thin-plate wood-concrete composite structures have gradually entered the research field. For example, the construction form with a concrete slab thickness of only about 70 mm is attractive in practice, but it also brings more stringent connection performance requirements [1]. Under thin-plate conditions, traditional vertical shear connectors often cannot provide sufficient connection stiffness, and interface slip is more likely to accumulate, resulting in limited composite action; at the same time, the reduction in concrete slab thickness directly compresses the anchorage space of the connectors, making the risk of brittle failure such as local crushing, splitting or pull-out of concrete more prominent, which may control the structural bearing capacity and ductility level in advance. Based on the above engineering pain points, the inclined bolts Steel rods as a shear connector is considered to have strong application prospects in thin-plate TCC systems [3]. Based on a systematic review of relevant research, this paper discusses the mechanical performance of inclined connections with bolts steel rods in thin-plate TCC, focusing on its stiffness prediction method, failure mechanism and the influence of factors such as pore defects and long-term load on connection and overall performance, aiming to provide more targeted theoretical basis for the optimization design and safety assessment of this type of structure.

To provide a unified reference for the subsequent discussion, the push-out specimen configuration, inclination-angle cases, and the key geometric details (slab/beam thicknesses, hole clearance, and embedment length) are summarized in Figure 1.

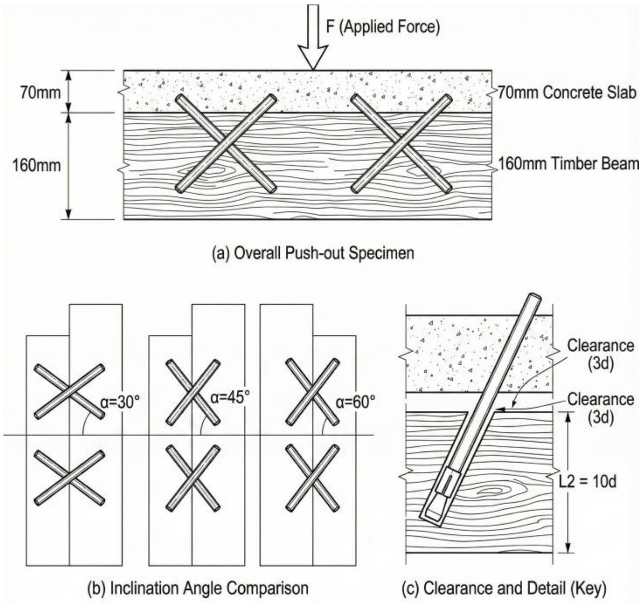


Figure 1 – Specimen geometry and key details

As shown in Figure 1a, the TCC push-out specimen consists of a 70 mm concrete slab and a 160 mm timber member connected by an X-shaped pair of inclined bolts Steel rods. Figure 1b compares the three inclination angles (α = 30°, 45°, and 60°) considered in this study, while Figure 1c defines the bolt-hole clearance and the embedment length in timber (L2 = 10 d), which are critical to the initial slip response and the potential brittle failure of the thin slab.

The Development of Timber-Concrete Composite Structures and the Advantages of Inclined Connectors

Whether a wood-concrete composite structure can achieve efficient collaboration depends on the reliable transmission of interface shear force, and the interface force transmission capacity is directly controlled by the stiffness and strength level of the connectors. Early TCC systems generally used traditional fasteners such as nails, vertical bolts Steel rods or pins. Although these connection forms are convenient to construct and have mature structures, they often have a low slip modulus. Interface slip is more significant under load, making it difficult to fully form the composite section. The structure is closer to "partial composite action" than the ideal full composite action [3]. With the increasing requirements for structural bearing capacity, stiffness and service performance, research has gradually shifted to more efficient connection strategies. Among them, inclined screw or bolts Steel rods connections have received widespread attention due to their unique force path and stronger stiffness potential.

Unlike vertically inserted fasteners that mainly rely on pin groove bearing (Embedment) and fastener bending deformation (Bending) to transmit shear force, inclined connections can more fully mobilize the axial stiffness of the fasteners to participate in interface shear resistance, thereby achieving higher connection efficiency under the same material and construction conditions [1]. When fasteners are arranged at a certain angle along the direction of force (usually about 45° in engineering), the interfacial shear force will decompose inside the fastener and induce significant axial tensile or compressive components, so that the connection no longer relies solely on local bearing and bending energy dissipation, but forms a force transmission characteristic closer to a "tension-compression rod system". Especially for inclined bolts Steel rods on the tension side, their working mechanism can be compared with the tie rod members in the truss system. By leveraging the excellent tensile strength of steel to bear the main internal force, and generating a "rope effect" during deformation, additional normal pressure is introduced at the wood-concrete interface. This normal pressure not only helps to suppress interface opening and relative slippage, but may also further stimulate the contribution of interface friction, so that the shear bearing capacity and stiffness level of the connection are improved simultaneously [4].

Experimental studies have shown that compared with traditional vertical connectors, the use of inclined screws or bolts Steel rods arranged at 45° (X-type) can significantly improve the connection stiffness, with an increase of up to 66 % or even more than 100 %, thereby more effectively restraining interface slippage and significantly enhancing the combined action level [3]. This advantage is even more decisive in thin plate TCC systems, because when the thickness of the concrete slab is reduced to the order of 70 mm, the contribution of the thin plate itself to the bending stiffness is limited, and the overall performance of the structure depends more on efficient interface force transfer to form the effective stiffness of the composite section EI_{eff} [5]. However, it should be emphasized that thin plate construction will also amplify several special challenges of inclined bolts Steel rods connections: the reduction of concrete slab thickness will limit the effective anchorage depth of the bolts Steel rods, thereby weakening the bearing margin of the concrete ends and local areas, and causing the potential failure mode to gradually shift from wood bearing or fastener yielding to concrete local failure or pull-out failure control. Since this type of concrete failure often has more obvious brittle characteristics and is not conducive to structural ductility and safety reserve, in thin plate TCC design, how to avoid or delay brittle concrete failure through structural refinement and parameter optimization often becomes one of the controlling factors affecting the reliability of the system [6].

Mechanical Mechanism and Stiffness Model of Inclined connection with bolts (steel rods)

To reliably assess the working mechanism of inclined connection with bolts (steel rods) in thin-plate wood-concrete composite structures, it is insufficient to rely solely on empirical descriptions. A unified explanatory framework must be established from three dimensions: force balance, deformation compatibility, and material constitutive model. This is because inclined bolts Steel rods, under interfacial shear, often simultaneously bear lateral compression and bending effects, and under certain geometric conditions, significantly induce axial tensile and compressive effects. Therefore, the stiffness and load-bearing capacity of the connection are the result of multiple contributing mechanisms. Simultaneously, wood exhibits significant anisotropy and nonlinear embedding characteristics, while concrete displays strong brittleness and size effects in local compression and cracking. When these two factors are coupled with the elastoplastic behavior of the steel bolts Steel rods, the load transfer path, local stress concentration, and potential failure modes of the connection significantly change with factors such as angle, anchorage length, porosity, friction, and long-term effects. Based on this understanding, the core objective of establishing a stiffness prediction model for engineering design is not to pursue formal complexity, but rather to incorporate decisive factors into a clear parameter form under computable conditions. This provides a traceable theoretical basis for SLS deflection and vibration control, as well as the optimization of connection details.

2.1 Stiffness Analytical Model and Component Superposition Method

In serviceability limit state design, the slip modulus K_{ser} of the inclined bolts Steel rods is often considered one of the most critical connection parameters because it directly controls the amplitude of interface slip, which in turn determines whether the composite section can maintain high cooperative efficiency within a small deformation range. When K_{ser} is low, more significant relative slip occurs between the concrete slab and the timber beam, weakening the composite effect, leading to a decrease in effective moment of inertia, and further amplifying deflection and vibration response. When K_{ser} is sufficiently high, relative interface slip is effectively suppressed, the composite section is closer to the ideal cooperative state, and the overall stiffness and service performance are significantly improved. Based on the research of Tomasi et al. and combined with the theoretical treatment of inclined fasteners in the European Timber Structure Design Code (Eurocode 5), the equivalent stiffness of inclined bolts Steel rods can be understood as the result of the synthesis of the axial stiffness component and the lateral pin stiffness component in the shear direction [7]. The key to this idea is that the inclined arrangement changes the way forces are decomposed, so that the connection, which was originally mainly controlled by lateral bearing and bending, can make more use of the axial stiffness of the bolts Steel rods at a certain angle. If the angle between the bolts (steel rods) axis and the normal to the shear plane is α, then the total stiffness K_{total} can be approximately written as

$$\mathrm{K_{total}} = \mathrm{K_{ax}} \cdot \sin^2(\alpha) + \mathrm{K_{lat}} \cdot \cos^2(\alpha). \quad (1)$$

In this expression, K_{ax} represents the axial stiffness of the fastener. Its physical source includes not only the axial tensile stiffness EA/L of the bolts Steel rods itself, but also the anchorage and interface interaction of the bolts Steel rods on both sides of the wood and concrete. For the wood side, the pull-out resistance and local indentation deformation around the thread or the shank will change the equivalent length and equivalent stiffness of the axial deformation. For the concrete side, the anchorage length, local crushing, and the tendency of possible splitting or tapered pull-out failure will also limit the extent to which the axial stiffness is exerted. Correspondingly, K_{lat} represents the lateral stiffness component, that is, the traditional pin stiffness, which is mainly controlled by the bearing stiffness of the wood and concrete hole wall, the evolution of local damage to the hole wall, and the bending stiffness of the bolts Steel rods [7]. In the thin plate TCC scenario, due to the small thickness of the concrete plate, the local deformation and cracking on the concrete side are more likely to occur earlier. This will cause the "effective value" of K_{lat} to enter the degradation stage more quickly, which also means that the model parameters need to be reasonably selected in combination with the structure and material state. This component superposition formula further reveals the mechanical nature and angular sensitivity of the inclined arrangement. When α approaches 0°, the $\sin^2(\alpha)$ term is almost zero, and the overall stiffness of the connection is basically controlled by K_{lat}. The lateral pin mechanism typically corresponds to larger borehole wall bearing deformation and more significant slip accumulation, thus the equivalent stiffness is often low. When α increases and approaches 45°, the weight of the axial component increases significantly, and the high axial stiffness K_{ax} is more fully incorporated into the shear deformation, resulting in a significant increase in K_{total}. It is worth noting that this increase is not unlimited, because whether the axial stiffness can be fully utilized is also constrained by anchorage conditions and local material failure. Especially in thin concrete slabs, insufficient anchorage may cause concrete splitting or prying before the axial force is fully established, thus prematurely "cutting off" the theoretical contribution of axial stiffness.

In order to describe the coupling deformation of fasteners in the two media more precisely in theory, Symons et al. further introduced the Beam on Elastic Foundation (BOEF) theory, which regards bolts Steel rods as beams embedded in two elastic media, wood and concrete. By establishing and solving the corresponding differential equations, analytical solutions are obtained, so as to more clearly consider the difference in stiffness of wood along the grain and across the grain, as well as the influence of local compression deformation of concrete and constraint conditions on the distribution of lateral reaction force in the calculation [8]. Compared with the simple superposition method, the BOEF frame can provide a more reasonable description of the internal force and displacement distribution, and is also more conducive to explaining why, at the same angle, changes in material anisotropy, contact length and boundary conditions lead to significant differences in stiffness and damage mode. For TCC structures characterized by thin plates, such more refined analytical models can also help identify the balance point between "stiffness improvement" and "brittle failure risk", thus providing a more targeted basis for structural design and parameter optimization.

2.2 Contribution of the Rope Effect

The outstanding advantage of inclined bolts Steel rods, especially tension-type inclined bolts Steel rods, in terms of connection bearing capacity is often attributed to the additional shear contribution brought about by the rope effect. The basic mechanism is that when shear slip occurs at the interface and causes deformation of the connector, the inclined arrangement makes the bolts Steel rods more prone to axial elongation, thus generating axial tensile force F_{ax}. This axial tensile force directly participates in resisting interface shear through its horizontal component, thereby supplementing the traditional pin bending and hole wall bearing mechanism in the force path; on the other hand, the vertical component of F_{ax} introduces additional compressive stress at the wood-concrete interface, increasing the interface normal pressure, thereby activating and enhancing the Coulomb friction contribution [4, 9]. In this process, the shear capacity of the connection is no longer entirely determined by fastener yield and hole wall bearing, but exhibits a composite mechanism of "axial tensile force and friction synergy", which is one of the key reasons why inclined connections often achieve higher bearing capacity under the same diameter and spacing conditions.

To theoretically incorporate the rope effect into shear capacity calculations, the Extended Kinematic Approach (EKA) is often used to modify Johansen's Yield Theory. Traditional Johansen's theory primarily focuses on the yielding mechanism of fasteners forming plastic hinges under shear stress and the bearing failure mechanism of wood hole walls, combining these mechanisms into expressions for shear capacity corresponding to different yield modes. However, this framework has limited consideration of axial forces. EKA, by introducing the work done on axial tensile forces and the mechanical equilibrium condition, allows the rope effect to be superimposed on the traditional yield capacity as an additional term, thus yielding a modified expression for shear capacity

$$F_{v,Rk} = F_{Johansen} + \Delta F_{rope}. \quad (2)$$

Wherein, ΔF_{rope} represents the gain of the rope effect on the bearing capacity. It should be emphasized that the rope effect is usually more likely to develop significantly under large deformation conditions. Over-reliance on this effect may lead to unfavorable tendencies in design in terms of ductility and safety margin. Therefore, research and code recommendations usually set an upper limit on the value of ΔF_{rope} to ensure that the bearing capacity assessment is not based on excessive slip or unacceptable local damage. According to the latest research conclusions and code recommendations, the contribution of the rope effect is usually limited to 25 % to 100 % of the Johansen yield bearing capacity. The specific upper limit is closely related to the fastener type, whether it is threaded, and the anchorage conditions and pull-out control mechanism on both sides [9]. In the thin plate TCC system, the assessment of the rope effect must be more cautious because the thickness of the thin concrete plate limits the anchorage length and the development space of the concrete side bearing zone. The concrete is more likely to experience failure modes such as splitting, local prying out or conical pull-out before the axial tensile force is fully established. Once brittle failure occurs on the concrete side first, the axial tensile force of the bolts Steel rods is difficult to increase continuously, the normal pressure at the interface cannot be maintained stably, and the friction contribution decreases accordingly, making it difficult to achieve the theoretically expected ΔF_{rope} [10]. Therefore, in thin plate structures, the rope effect should be regarded as a "possible gain term" rather than a "necessary dominant term", and its potential needs to be evaluated in a consistent manner with the thickness of the concrete slab, the edge distance, the reinforcement or local reinforcement measures, and the initial defects caused by construction errors.

2.3 Interface slip and nonlinear behavior

Although linearized models have the advantages of simple calculation and clear parameters in engineering design, a large number of experimental and numerical studies have shown that the real load slip relationship of TCC connection usually exhibits obvious nonlinear characteristics, and this nonlinearity often begins to appear in the early stage. Typical load slip curves can be summarized as the initial approximately linear elastic stage, the subsequent elastoplastic development stage, and the final softening and failure stage [11]. In the initial stage, the connection response is mainly controlled by the elastic modulus of the material, the contact stiffness and the interface friction condition. At this time, the hole wall bearing pressure has not yet caused significant plastic damage, and the bolts Steel rods are mostly in the state of elastic bending or small axial deformation. Therefore, the stiffness is high and the curve slope is relatively stable. As the load continues to increase, the wood hole wall will gradually show local indentation and plastic extrusion. The hole wall damage causes the stiffness of the contact area to decrease. At the same time, the bolts Steel rods gradually enter yielding and form plastic hinges under the combined action of shear and bending. The overall stiffness of the connection begins to continuously degrade, and the curve slope decreases significantly. After entering the later stage, if local damage expands or cracks and spalling occur on the concrete side, the connection may soften after peak or even suddenly become unstable. This stage is highly sensitive to failure mode and structural details, and it best reflects the control role of brittle risk in thin plate structures.

The influence of clearance on nonlinear response is particularly noteworthy. If there is a significant gap between the bolts Steel rods hole and the bolts Steel rods diameter, the connection may mainly rely on frictional force transmission under small loads, and the bearing pressure of the hole wall has not yet formed an effective contact. Once the load exceeds the friction threshold, the bolts Steel rods will move relatively freely in the hole until it contacts the hole wall and re-establishes the bearing pressure transmission path. At this time, the load slip curve often shows a significant slip plateau or a near-zero stiffness section. This phenomenon will not only significantly reduce the initial stiffness and the equivalent value of K_{ser}, but will also amplify the slip accumulation under dynamic action or repeated loads, making vibration comfort and fatigue performance face more unfavorable responses [12]. For thin plate TCC, since the overall system stiffness relies more on the connection stiffness to maintain the combined effect, the initial low stiffness section caused by pores may have a more direct impact on SLS deflection and vibration control. Therefore, at the design and construction level, it is usually necessary to reduce the adverse effects of pores by means of pore precision control, grouting or local reinforcement, and to reasonably characterize the initial slip section in the analysis model in order to avoid systematic misjudgment of the structural performance.

Special Failure Mechanisms in Thin-Plate Structures

When the thickness of the concrete slab is reduced to approximately 70 mm, the failure control logic of thin-plate TCC systems often undergoes a fundamental change. Traditional design and research of thick-plate TCCs typically assume that the concrete slab has sufficient local load-bearing and anchorage reserves. Therefore, failure in the connection zone is more likely to be dominated by ductile mechanisms such as bearing development through the wood hole walls, bending yielding of fasteners, or tensile yielding of steel. The structure often undergoes sufficient plastic development and deformation redistribution before reaching its ultimate state. However, the geometric constraints of thin plates significantly weaken the anchorage space and crack propagation path on the concrete side, making the connection zone more susceptible to brittle phenomena such as local crushing, splitting, and spalling. Especially in inclined connection with bolts (steel rods), the axial component and leverage effect amplify local stress concentration near the concrete cover and anchorage zone, making brittle failure modes on the concrete side more likely to occur earlier and become the controlling factor. Existing studies have shown that, under thin plate conditions, two types of failure modes characterized by brittle cracking and spalling of concrete, namely concrete cone failure and pry-out failure, often occur before the bolts Steel rods have fully yielded, thereby altering the ductility level of the connection and the available load-bearing capacity [6]. Therefore, for thin plate TCC, identifying and constraining the triggering conditions of brittle fracture of the concrete side is usually more critical than simply pursuing higher connection stiffness or greater steel strength.

3.1 Concrete Pry-out Failure

Pry-out failure is generally considered to be a typical failure mode that is more likely to occur in short-anchored, relatively "short and thick" shear connections under shear loads. In thin plate structures, this mode often has stronger suddenness and destructiveness. When the inclined bolts Steel rods deforms under the action of interface shear force, if its anchorage depth is shallow and the bending stiffness of the connector is relatively large, the bolts Steel rods tends to exhibit a combination of rotation and small translation of an approximately rigid body, rather than forming a long bending deformation zone in the anchorage area. At this time, the rotation of the bolts Steel rods will form an obvious lever effect on the force path, resulting in a strong local action of compression and tension on the concrete side. More specifically, the bolts Steel rods tail area often applies a relatively concentrated compressive stress to the concrete, and the local concrete may first be crushed and crushed; at the same time, in the deep part on one side of the force direction, the bolts Steel rods shank will have a prying effect on the concrete, causing the back concrete to be lifted along the potential crack surface and form a cone or wedge, and finally be "pried out" in the form of overall peeling [6]. Since this process is mainly characterized by concrete cracking and local spalling, the failure often lacks obvious yield warning, and the bearing capacity may drop rapidly after the load reaches its peak, thus significantly weakening the structural ductility and safety redundancy. From a design calculation perspective, the Concrete Capacity Design (CCD) method in ACI 318 or Eurocode 2 provides a commonly used mechanical framework for assessing pry-out failure. This framework typically correlates the shear capacity V_{cp} of pry-out failure with the tensile cone failure capacity N_{cb} of concrete, commonly expressed as

$$V_{cp} = k_{cp} \cdot N_{cb.} \quad (3)$$

Where k_{cp} is the pry-out coefficient, typically used to reflect empirical corrections when the anchorage zone transitions from a tensile cone mechanism to a pry-out mechanism under shear conditions. For connections with shallow anchorage depths and greater susceptibility to rigid body rotation, k_{cp} is often taken on the order of 1,0 or 2,0. N_{cb} is strongly correlated with the effective anchorage depth h_{ef} and is often considered to be proportional to $h_{ef}^{1.5}$. The key problem of thin plate construction is that the 70 mm plate thickness will significantly limit the achievable h_{ef}, which will cause the calculated value of N_{cb} to drop sharply, thus theoretically putting the load reserve for pry-out failure at an unfavorable level. In engineering, it is even more troublesome that dense steel mesh is often configured in thin plates to control cracks and improve the overall integrity, but when the protective layer is too thin or the steel reinforcement arrangement near the anchorage zone does not match the cracking path, the steel mesh may act more as "post-crack constraint" rather than "pre-crack enhancement", and may induce the protective layer to peel off or local cracking concentration, resulting in earlier or more sudden pry-out failure [13]. Therefore, in the detailed design of TCC connections in thin plates, pry-out failure is usually considered as one of the control modes to be checked first, and it needs to be specifically suppressed by means of anchorage length, edge distance, local reinforcement or structural thickening.

3.2 Concrete Cone Failure and Edge Effect

Besides pry-out failure, the axial component introduced by inclined bolts Steel rods under shear conditions can also trigger direct pull-out brittle failure on the concrete side, i. e., concrete cone failure. This failure mode is usually characterized by a crack initiation area near the tension end of the fastener, forming a failure cone surface extending from the concrete interior to the free surface. The angle between the cone surface and the concrete surface is often empirically taken as about 35°, eventually leading to the overall detachment of the concrete cone or wedge within a certain range [14]. In thin plate TCC, cone failure is more alarming because, on the one hand, the thickness of the thin plate limits the complete development of the cone failure surface, making it easier for the failure surface to be "cut off" by the free surface in advance, thus forming a smaller effective resistance volume; on the other hand, thin plates are usually accompanied by smaller edge distances and more compact connector arrangements, which makes it easier for the cone failure surface to intersect with the plate edge or overlap with the failure surface of adjacent connectors, resulting in a further reduction in bearing capacity relative to the single-unit condition. Considering that TCC floor slabs usually function as composite beams in structural systems, connectors are often arranged in rows along the beam length, and the group anchoring effect is particularly significant under thin plate conditions. If the spacing between connectors is insufficient, multiple cone failure surfaces will overlap, reducing the effective concrete resistance volume that each connector can "allocate", and the individual bearing capacity cannot be simply linearly superimposed. Accordingly, engineering design usually needs to introduce a reduction factor or use the group anchoring check method to correct the bearing capacity of a single connector in order to reflect the mutual influence and edge cutoff effect [15]. Furthermore, since the force direction of inclined bolts Steel rods is not purely tensile or purely shear, cone failure and pry-out failure may exhibit a competitive or coupled relationship under certain structural and load conditions, which means that independent verification of a single mode may not be sufficient to cover the actual control situation. For thin plate TCC, a more reasonable approach is to understand the potential failure of the concrete side as a brittle failure family "with anchorage depth and geometric boundaries as the core constraints", and to prioritize ensuring sufficient edge distance, reasonable connector spacing and local reinforcement scheme that matches the potential crack path in the structural design, so as to improve the resistance of the connection area to brittle failure and the predictability of failure.

3.3 Failure Modes on the Timber Side

Unlike concrete, which is mainly controlled by brittle cracking and spalling, the failure modes on the timber side are more often manifested as a progressive damage process of anisotropic materials under local pressure and crack propagation. For inclined connection with bolts (steel rods), typical failures that may occur on the timber side include dowel bearing failure, splitting along the grain, and block shear failure when multiple connectors are arranged in a row [16]. In the dowel bearing mechanism, the bolts Steel rods generates local compressive stress on the hole wall, and the timber undergoes indentation and plastic deformation under the constraint of the fiber structure. The bearing area gradually expands and is accompanied by local fiber buckling and crushing. This mechanism has ductile characteristics to a certain extent, but its development speed and ultimate bearing capacity depend significantly on the grain direction and moisture content.

The stress on timber by inclined bolts Steel rods is more complex because after the decomposition of the axial force and shear force of the bolts (steel rods), the timber will simultaneously bear stress components perpendicular to the grain and parallel to the grain. In order to deal with this complex stress state at the engineering level, the Hankinson formula is often used to estimate the equivalent bearing capacity of timber under different grain direction combinations. However, for connections with large tilt angles or significant axial components, stress concentration caused by wood anisotropy may lead to early microcracks at the hole edge. These microcracks may gradually penetrate and evolve into splitting failure along the grain under repeated loading, humidity changes, or stress redistribution. Such splitting failure often exhibits more obvious brittle characteristics and is highly sensitive to edge distance, end distance, pre-drilling quality, and wood moisture content changes. Therefore, it needs to be regarded as an important design control in the actual construction of thin-plate TCC [2]. In addition, when the connectors are arranged in rows along the beam length, hole edge cracks and shear cracks may be interconnected and form a block shear failure path, causing shear plug failure to occur at a small slip level. This will reduce the connection ductility and weaken the overall assembly efficiency [16]. Therefore, in the thin-plate TCC system, the wood side is not necessarily a "controllable ductile end". Its failure mode may also turn to brittle or quasi-brittle failure in advance due to geometric constraints, environmental effects, and arrangement density. This, together with the brittle mechanism of the concrete side, determines the controllable failure mode and structural safety boundary of the connection area.

The Influence of the Clearance of Holes for Bolts (Steel Rods) on Installation Accuracy

In actual engineering construction, to reduce installation difficulty and improve assembly efficiency, the pre-drilled hole diameter in the concrete slab is often moderately enlarged relative to the bolts Steel rods diameter. Simultaneously, factors such as drilling deviation, formwork positioning error, and duct deformation during pouring can also lead to unavoidable geometric deviations. The combined effect of these factors results in varying degrees of porosity between the bolts Steel rods and the hole wall, i. e., hole diameter margin. The geometric definition of the holes for Bolts (Steel Rods) clearance adopted in this study is illustrated in Figure 1 c. Extensive testing and field experience show that this seemingly subtle geometric difference not only affects construction convenience but also alters the stress initiation mode of the connection during small deformation stages, causing the interface shear force to shift from continuous transmission to staged contact transmission. This, in turn, significantly impacts the initial stiffness, energy dissipation characteristics, and failure mode of the TCC connection. To facilitate establishing a direct correspondence between porosity levels and mechanical consequences at the engineering level, this paper summarizes the initial response characteristics, stiffness and bearing capacity variation trends, and typical failure characteristics of different porosity types, as presented in Table 1, serving as a reference framework for subsequent discussion and parameter selection. For 70 mm thin plate TCC, the concrete cover and effective anchorage depth are already limited. Contact impact and local stress concentration caused by pores are more likely to trigger crushing or spalling near the concrete opening, making the pore effect more sensitive in thin plate systems.

4.1 Effects on Stiffness and Slip

The most direct consequence of pores is that they alter the stress initiation process of the connection, significantly affecting initial stiffness and slip evolution. When the pores are small or even close to a tight fit, the bolts Steel rods can form stable contact with the hole wall in the early stages of loading, the shear force transmission path is relatively continuous, and the load-slip relationship usually exhibits a clear linear elastic characteristic, thus maintaining a high equivalent slip modulus K_{ser}. Conversely, when the pores increase, the connection often experiences a stage where contact is not fully established in the early stages of loading. At this time, the interface shear force is mainly borne by friction and local point contact, and the bolts Steel rods will experience a certain degree of free movement within the hole until they fully conform to the hole wall and enter the bearing deformation stage. Because the stiffness in this stage is significantly lower than in subsequent stages, the overall load-slip curve will exhibit slip lag or a slip plateau, thus systematically reducing the equivalent stiffness of the initial segment. The patterns summarized in Table 1 show that from tight fit to Small clearance and then to Large clearance, the initial response gradually transitions from approximately linear elasticity to a more pronounced slip plateau characteristic, with the corresponding equivalent initial stiffness showing a decreasing trend. This phenomenon is usually further amplified in thin-plate TCCs.

From a structural response perspective, the deflection and vibration control of thin-plate TCCs are highly dependent on the initial stiffness of the connections. This is because the system often has not yet entered a significant plastic development stage under service load levels, and whether the combined effect is fully formed is largely determined by early slip. When porosity leads to amplified initial slip, the effective stiffness of the combined section will decrease at lower load levels, thereby amplifying mid-span deflection and floor vibration response. It also increases the dispersion between different specimens or different construction batches, making it more difficult to interpret test results consistently with actual engineering performance. Based on the classification results shown in Table 1, when performing SLS calculations and connecting the model, a more reasonable approach is to include the initiation stage corresponding to the pores as a component of the model, rather than using only a single linear stiffness to cover the entire process. This avoids systematic misjudgments of slippage and stiffness during small load stages.

4.2 Impact Effects and Stress Concentration

Pores not only affect stiffness, but more importantly, they alter the continuity of the contact process, introducing adverse effects such as impact and local stress concentration. When pores exist, the bearing contact between the bolts Steel rods and the hole wall is often not smoothly established from the loading start point, but rather occurs in a relatively abrupt manner after free movement ends. At this time, the stress in the local contact area will rapidly increase over a very small bearing area, equivalent to a contact impact, and induce local crushing and microcrack propagation near the concrete hole opening. For 70 mm thin TCC plates, the concrete slab thickness and protective layer are relatively thin. Once cracks initiate in the hole opening area, they are more likely to penetrate to the free surface and form spalling or local breakage, leading to further degradation of the bearing capacity and stiffness of the connection area. The typical failure characteristics in Table 1 also reflect this trend: as the pore size increases, the failure manifestations tend to shift from localized crushing to more significant splitting, prying out, or the associated risk of brittle spalling.

Table 1 – Influence of holes for bolts (steel rods) clearance level on connection performance [17]

Clearance level	Initial behavioural characteristics	Effect on Rigidity	Impact on load-bearing capacity	Typical Failure Characteristics
Tight-fit	Linear elastic response	High	High	Bolt yielding/wood compression failure
Small clearance (0,5–1 mm)	Minor slip hysteresis	Medium	Slightly reduced	Localised concrete crushing
Large clearance (>2 mm)	Significant slip plateau	Low	Significantly reduced	Impact-induced splitting/prying out

Under long-term loads, repeated loads, or dynamic actions, the aforementioned impacts and stress concentrations exhibit stronger cumulative damage characteristics. The gradual propagation of pore wall crushing and microcracks continuously softens the contact surface, leading to sustained growth in slippage at the same load level. The equivalent stiffness and bearing capacity of the connection gradually decrease with the number of cycles. Especially when the pore size is large, the slippage platform is more pronounced, and repeated contact and release make localized damage more easily amplified, potentially resulting in a combined failure of splitting on the wood side and prying out or localized fragmentation on the concrete side. Consequently, the structural safety reserve is depleted more early. Given the correlation between porosity level and performance degradation summarized in Table 1, porosity should be considered as a key factor that changes the stress path of the connection in the structural design and construction control of thin plate TCC. Its adverse effects should be reduced by controlling the porosity accuracy, optimizing the installation process, and taking necessary local reinforcement and constraint measures. Sufficient attention should also be paid to the nonlinear starting behavior caused by porosity in the calculation model.

Finite Element Numerical Simulation and Parametric Analysis

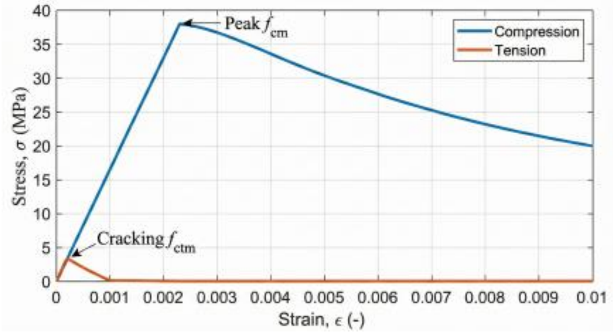
To overcome the limitations of experimental research in terms of cost, parameter coverage, and observability of internal responses, finite element analysis (FEA) has become an important tool for studying inclined connection with bolts (steel rods) in thin-plate TCC (Transient Cavity Cordless Concrete) systems. Unlike external characterizations that rely solely on bearing capacity or slip curves, numerical simulation can simultaneously track the evolution of the axial force and bending moment of the bolts (steel rods), stress concentration in the borehole bearing zone, the propagation of concrete cracks, and the formation of potential pry-out cones within a unified mechanical framework. This provides a more complete chain of evidence for identifying failure modes and sensitivity analysis of design parameters. Especially in cases where the concrete slab thickness is only about 70 mm, local failure often precedes overall yielding, and structural behavior is more dependent on subtle differences in detailed geometry and contact conditions. This makes it even more necessary to establish a high-precision model that reflects actual contact and damage evolution.

5.1 Material Constitutive and Contact Models

High-reliability FEA models are typically built upon the foundations of "interpretable material constitutive model" and "traceable contact definition". For wood, due to the significant differences in its mechanical properties along the grain, across the grain, and radial directions, and the obvious asymmetry in tensile and compressive strength and yield evolution, the orthogonal anisotropic elastoplastic model combined with the Hill yield criterion can more reasonably describe its strength envelope and yield initiation under multi-directional stress conditions [2]. In the borehole wall bearing problem of the connection zone, local indentation of wood is usually an important source of nonlinearity of the slip curve. Therefore, the constitutive model also needs to be able to reflect the gradual hardening or softening characteristics under compression, and to make the evolution of the borehole wall crushing zone consistent with the experimental phenomenon as shown in Figure 2c. If the model only uses linear elasticity or an oversimplified yield rule, it will often underestimate the initial stage of bearing deformation and overestimate the connection stiffness, thus affecting the reliability of subsequent parameterization conclusions.

The simulation of the concrete side is usually based on the concrete damage plasticity (CDP) model, because CDP can simultaneously characterize the stiffness degradation after tensile cracking and the hardening and softening process under compressive damage, and allows the influence of the crack propagation zone on the overall bearing capacity and stiffness to be characterized by damage variables [2]. For thin-plate TCC (Transformed Crush Capacitance), the key to the concrete side lies not in whether the overall compressive strength is sufficient, but in whether the model can stably capture local crushing, cracking cones, and pry-out wedges. Therefore, CDP (Contraction Power Determination) parameters typically need to be calibrated around the tensile softening segment, fracture energy, and the rationality of post-compression peak softening, ensuring that the crack morphology, crack propagation direction, and spalling tendency observed near the borehole in the model are consistent with thin-plate experimental observations. If tensile softening is ignored or an overly rigid post-compression peak behavior is used, the model may incorrectly transform the failure path, which should be controlled by brittle cracking, into ductile compressive yielding, thus masking the true controlling role of cone failure and pry-out failure.

The steel of the bolts (steel rods) typically employs an isotropic elastoplastic constitutive model with a bilinear response (Figure 2b), and the strain hardening, and the strain hardening process after yielding is described using the Von Mises yield criterion and strengthening laws. For inclined connections with bolts (steel rods), these bolts (steel rods) not only bear shear and bending but may also generate significant axial tensile force due to the rope effect. Therefore, the model needs to ensure consistency between the yield criterion and strengthening response of the steel under coupled axial tension and bending conditions. If the research objective involves the formation location of the yield hinge and the length of the plastic zone, a sufficiently fine mesh and a reasonable element type are usually required to avoid numerical sensitivity caused by plastic localization. The specific constitutive curves and stress responses defined for the three materials are summarized in Figure 2.



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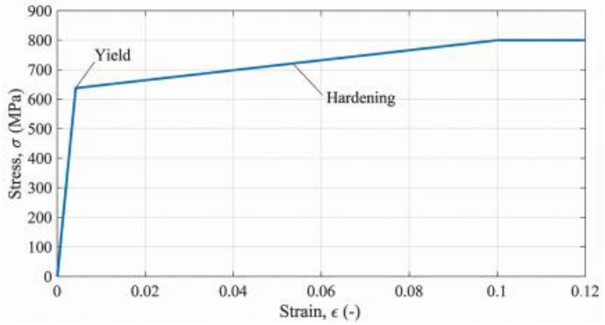

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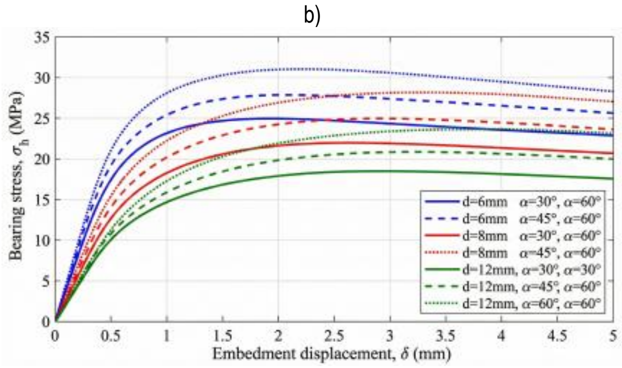


c)

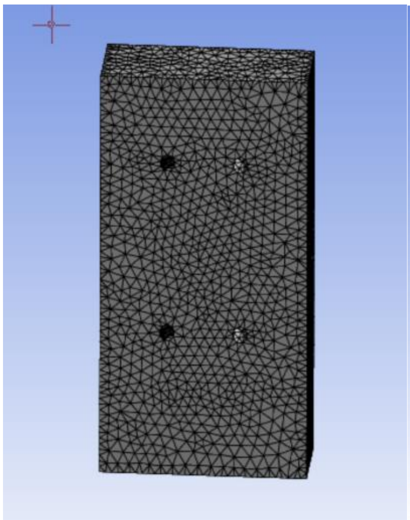
a) Concrete Damage Plasticity (CDP) model for compression and tension; b) Bilinear isotropic hardening model for bolt steel; c) Direction-dependent embedment stress-displacement curves for timber

Figure 2 – Material constitutive models and stress-strain relationships adopted in the FEA

Contact simulation is one of the core aspects of the reliability of this type of FEA. The contact between the bolts (steel rods) and the wood hole wall, and between the bolts (steel rods) and the concrete hole wall, is generally defined as surface-to-surface contact as shown in Figure 3b. Hard contact is used in the normal direction to avoid penetration and ensure a reasonable contact pressure distribution during pressing. In the tangential direction, a penalty function friction model is often used, with the friction coefficient μ typically ranging from 0,3 to 0,6 to cover different interface roughness and construction conditions [4]. In thin plates, friction not only affects the initial slip but also changes the local damage evolution by increasing the interface normal pressure. Therefore, the value of the friction coefficient usually needs to be combined with experimental curves or literature recommendations for sensitivity testing to avoid mistaking the friction contribution as the material strength contribution. Meanwhile, porosity and installation deviations can cause the contact to not be continuously established in the early stages of loading. The initial clearance (gap) to be closed during loading is defined according to the detail shown in Figure 1c. If the initial gap is ignored in the model, the initial stiffness is often significantly overestimated and the slip plate length is underestimated. This is particularly important to be aware of in the SLS analysis of thin plate TCC. To more accurately reproduce the formation mechanism of pry-out failure, it is usually necessary to establish a solid model that includes the geometric details of the head of the bolts (steel rods), washer, and thread, rather than simply using equivalent beam elements, because pry-out failure is essentially driven by the local compression of the head of the bolts (steel rods) and its neighborhood, contact eccentricity, and lever rotation [18]. When the thickness of the thin plate is limited, the size of the local bearing zone near the head of the bolts (steel rods) is on the same order of magnitude as the thickness of the concrete cover, and the geometric details have a direct impact on the peak contact pressure and the crack initiation location. Accordingly, the model usually needs to use locally refined meshes at the orifice and anchorage area (Figure 3a), and through reasonable boundary constraints, and through reasonable boundary constraints and loading methods, make the stress path of the connection area as consistent as possible with the loading fixture conditions in the experiment, thereby improving the interpretability and comparability of the simulation results.

5.2 Parametric Analysis Results

After completing the reasonable calibration of the material and contact model, parametric analysis can systematically reveal the influence of key design parameters on the performance of thin plate TCC inclined connections with bolts (steel rods) at a lower cost. Based on a combination of multiple numerical studies and comparative conclusions, a relatively consistent trend judgment can be obtained, which explains the mutual constraint relationship between "stiffness improvement" and "brittleness risk" under thin plate conditions.



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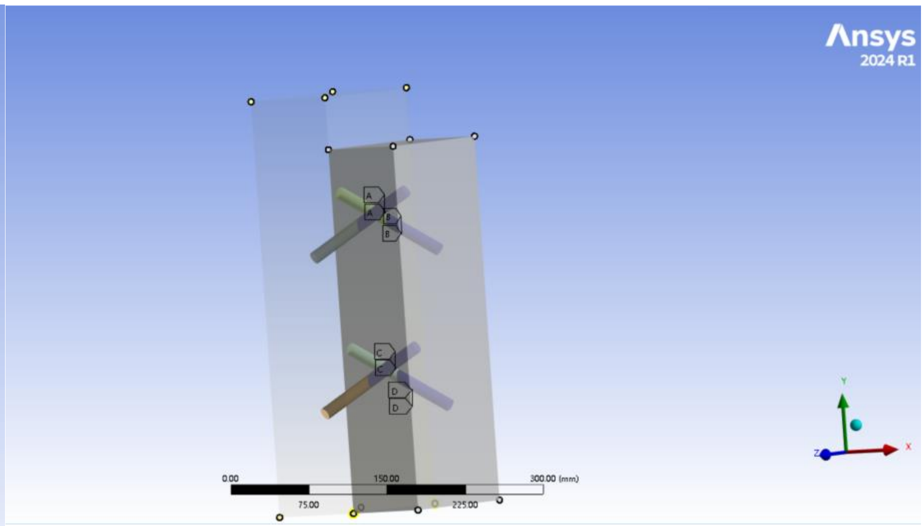
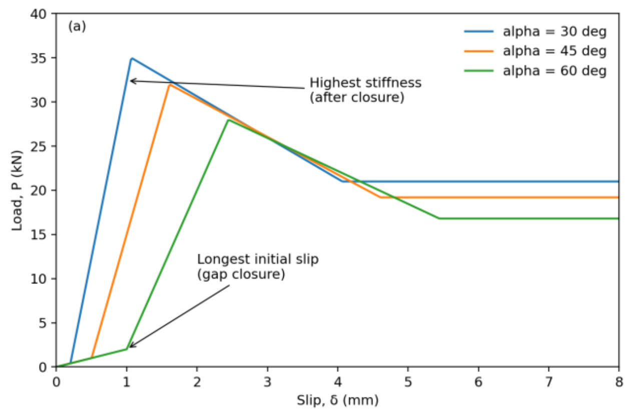


b)

a) Global mesh generation with local refinement; b) Definition of contact pairs at the head of the bolts (steel rods) interface

Figure 3 – Finite element model establishment details, developed by the author of the article



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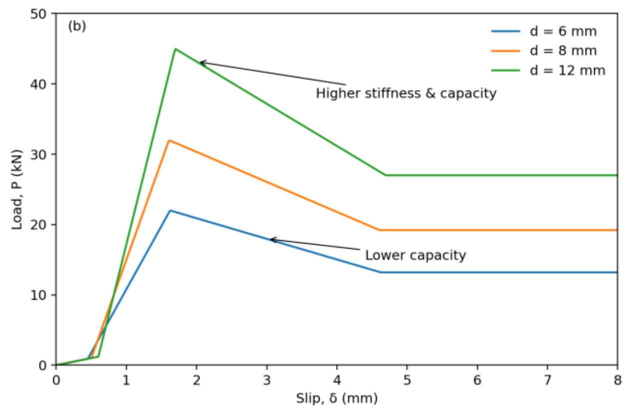


b)

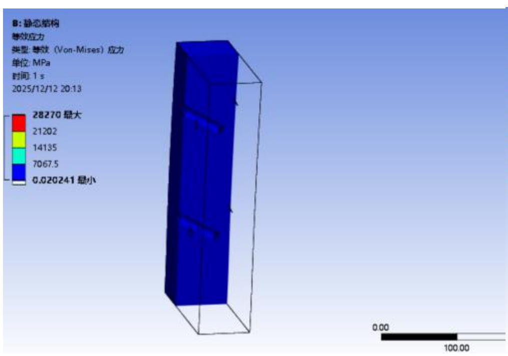
a) Effect of inclination angle (α) on initial stiffness and gap closure mechanism; b) Effect of the diameter (d) of the bolts (steel rods) on ultimate bearing capacity and stiffness

Figure 4 – Simulated load-slip response curves under different geometric parameters, received by the author of the article

The tilt angle α is often one of the most decisive geometric parameters. As α gradually decreases from a vertical arrangement of 90° to around 45°, the initial stiffness and ultimate bearing capacity of the connection usually increase synchronously (Figure 4a). This is because the axial force component is easier to establish, the axial stiffness of the bolts (steel rods) and the interface friction effect are more fully mobilized, and the interface slip is more strongly constrained [3]. As shown in Figure 4 a, the 30° case exhibits the highest stiffness and effectively suppresses the initial slip plateau compared to the 60° case. In most studies, 45° is often considered to achieve a better balance between mechanical efficiency and construction convenience, because this angle can provide a significant axial contribution and avoid the construction perforation difficulties and insufficient anchorage length caused by too small an angle. If the angle is further reduced to the order of 30°, the effective anchorage depth that can be provided in the thin plate will be significantly reduced, and the concrete side is more likely to split or pry out before the axial tensile force of the bolts (steel rods) is fully developed, thus reducing the bearing capacity and possibly showing a stronger tendency for brittle failure [3]. This phenomenon suggests that angle optimization in thin plate TCC is not a monotonic problem, and the anchorage space and potential concrete failure surface must be taken into account.

The role of concrete strength $f_c{}'$ in thin plate systems is often more prominent than in thick plates, especially when the control failure mode is close to prying or cone failure, concrete strength almost directly determines the upper limit of brittleness of the joint. Numerical studies usually show that increasing $f_c{}'$ can significantly delay crushing and crack initiation near the orifice, slow down the propagation rate of the cone failure surface, and give the bolts steel rods a greater chance to enter the steel yield stage before reaching the concrete control limit, thereby improving the ductility and energy dissipation capacity of the joint [19]. In thin plates, due to the limitation of h_{ef}, it is often unrealistic to obtain higher load-bearing capacity simply by geometric enlargement. Therefore, the strength improvement and local constraint enhancement at the material level are more efficient within a certain range. However, it should be noted that strength improvement is not necessarily equivalent to toughness improvement. If the CDP parameter or fracture energy value is unreasonable, the model may show a "strong but brittle" response. Therefore, in the parameter analysis with $f_c{}'$ as the variable, it is usually necessary to check the crack propagation morphology and the post-peak softening rate at the same time to avoid mistaking the increase in bearing capacity as the disappearance of the risk of failure.

The bolts steel rods diameter d has a direct impact on the bearing capacity, because the increase in cross-section can increase the axial and shear bearing capacity reserves, and at the same time change the bearing area of the hole wall and the distribution of contact pressure. Most simulation results summarized in Figure 4 b show that increasing d can significantly increase the shear bearing capacity of the single unit and reduce the slip level required for steel yielding to a certain extent, but this gain is often accompanied by stricter end distance and edge distance requirements. The more critical problem in thin plates is that larger holes will weaken the effective cross-section of concrete and aggravate the stress concentration in the hole area (as visualized in Figure 5a), making the concrete plate more prone to splitting or spalling, especially when the connectors are densely arranged or close to the edge of the plate, this adverse effect will be further amplified [3]. Therefore, there is usually a more sensitive "diameter-thickness matching range" in thin plate TCC. If the diameter is too small, the steel yielding and friction effect will be difficult to develop fully, while if the diameter is too large, the failure mode may be pushed to the brittle control of concrete, making it difficult to exert the ductile advantage. The value of parametric analysis lies in its ability to clarify, by comparing the crack initiation location, the time of prying out cone formation (Figure 5a), and the evolution of the plastic zone of the bolts steel rods (Figure 5b) under different d, that the "optimal" is not determined solely by the peak bearing capacity, that the "optimal" is not determined solely by the peak bearing capacity, but is constrained by both bearing capacity and ductility.



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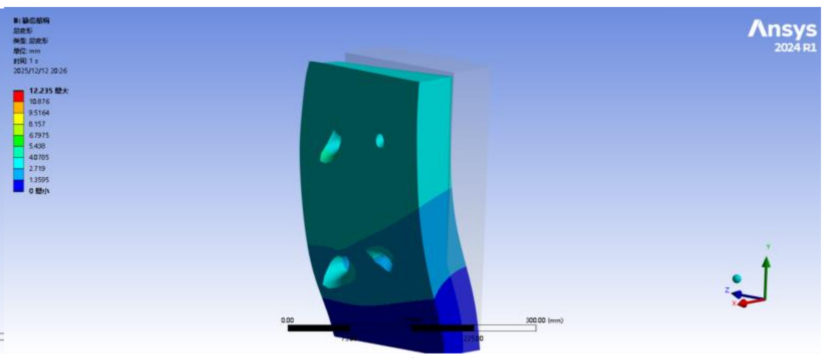

b)

a) Von Mises stress concentration indicating potential concrete pry-out failure ($d = 12$ mm); b) Large deformation and plastic hinge formation in the shank of the bolts steel rods ($d = 6$ mm)

Figure 5 – Comparison of simulated failure modes under different diameters of the bolts steel rods

The presence of an interlayer is a common structural condition in actual TCC engineering. For example, OSB permanent formwork or sound insulation layers introduce additional thickness between the concrete slab and the wooden beam. Numerical simulations generally show that the interlayer increases the shear arm and introduces additional bending moment, making the bolts steel rods more prone to rotation, and the bearing zone of the hole wall also exhibits a more uneven stress distribution. Its direct consequences are usually manifested as a decrease in connection stiffness and a reduction in bearing capacity, with the reduction reaching approximately 30 % to 50 % in many studies [1]. For thin-plate TCC, this reduction is even more noteworthy, because thin plates rely on connection efficiency to form effective combined stiffness, and the stiffness reduction caused by the interlayer will quickly manifest as increased deflection and decreased vibration comfort during the service stage. Meanwhile, the intermediate layer may also alter the normal pressure path formed by the axial component of the bolts (steel rods) at the interface, making the friction contribution more unstable and thus exacerbating the nonlinearity and dispersion of the load-slip curve. Based on these mechanisms, engineering design typically requires explicit reduction of the intermediate layer effect, rather than treating it as a negligible construction ancillary condition. The numerical results in Figure 4a confirm that smaller inclination angles effectively mitigate the stiffness loss caused by hole clearance.

Long-term performance and environmental factors

The long-term service performance of thin-plate TCC structures is largely determined by the time-varying properties of the materials and the effects of the environment. Both wood and concrete exhibit significant creep behavior, and under long-term loads, the slippage of the joints increases over time, making the long-term deflection of the composite beam significantly greater than the short-term deflection [20]. Due to its larger specific surface area, thin-plate concrete develops drying shrinkage faster, and early shrinkage may introduce additional tensile or shear stresses near the interface, thereby changing the microcrack state and friction conditions in the joint area. In addition, wood is highly sensitive to changes in temperature and humidity; moisture absorption expansion and desiccation shrinkage will induce continuous stress redistribution in the bearing area of the borehole wall, leading to cumulative degradation of the joint stiffness. More importantly, in a cyclic humidity environment, a mechanical sorptive effect often occurs under moisture-drying cycles. This effect causes wood to produce additional deformations exceeding conventional creep predictions under the combined action of load and humidity changes, resulting in a gradual increase in residual slip and weakening the recoverability of the joint [20]. The difference between indoor and outdoor environments is often reflected in the humidity fluctuation range and cycle frequency. Therefore, the long-term slip growth rate of the same connection type may be significantly different in different environments. Related studies have pointed out that the creep coefficient of connections with bolts steel rods in outdoor environments can reach about 2,5 times that in indoor environments [20]. This means that if indoor parameters are directly used for long-term prediction of outdoor thin plate TCC, the risk of deflection growth and stiffness degradation may be significantly underestimated. Based on engineering usability considerations, long-term performance prediction should not directly use short-term K_{ser}. A more reasonable approach is to reduce the short-term stiffness to long-term stiffness through the effective modulus method and introduce the creep coefficient ϕ to characterize the time-varying effect. Its expression can be written as [21]

$$K_{eff} = K_{ser}/(1+\phi). \quad (4)$$

In thin plate TCC, this reduction not only changes the deflection calculation results, but also affects the judgment of interface slip accumulation, because a lower K_{eff} means a greater long-term slip demand. Meanwhile, the self-balancing stress caused by shrinkage and moisture expansion may alter the normal pressure level in the connection zone, thereby changing the friction contribution and slip threshold, resulting in stronger nonlinearity and path dependence in the long-term response of the connection. Therefore, in durability design, it is necessary to consider environmental level and humidity cycle characteristics as important bases for determining long-term stiffness values, and to verify the value of φ using experimental or long-term monitoring data to reduce systematic biases caused by environmental differences.

Conclusions and Outlook Research

Based on existing research, it can be concluded that inclined connections with bolts steel rods have clear mechanical advantages in thin-plate wood-concrete composite structures. In particular, the 45° cross arrangement can improve the initial stiffness and ultimate bearing capacity of the connection by introducing a stronger axial stiffness contribution and stimulating the rope effect, thus compensating to some extent for the insufficient flexural stiffness contribution of the thin concrete slab itself. At the same time, the geometric characteristics of the thin slab significantly compress the anchorage space and crack propagation path on the concrete side, making pry-out failure and cone failure more likely to become the controlling failure modes earlier, and triggering the upper limit of bearing capacity before the bolts steel rods have fully yielded. Given this paradoxical relationship, the key to thin-plate TCC (Transient Concrete Cavity Control) lies not in infinitely increasing the strength of the steel or the stiffness of the connection, but in ensuring that brittle fracture of the concrete side is not prematurely triggered while improving the efficiency of the combined action. To achieve this goal, the design phase needs to adopt stiffness models and load-bearing capacity assessment methods that better conform to the inclined connection mechanism, such as stiffness estimation based on the Tomasi model and explicit consideration of porosity effects. Simultaneously, the risk of brittle fracture of the concrete side should be reduced by reasonably controlling porosity, optimizing end and edge distances, and implementing necessary local structural reinforcement. Furthermore, the reduction in stiffness due to creep and humidity cycling effects should be incorporated into long-term predictions to make the performance assessment during service more closely reflect real-world service scenarios.

Looking to future research, several directions warrant further exploration. One direction is to develop more targeted structural details to address the anti-pry-out requirements under thin-plate conditions. For example, this could involve improving bolts Steel rods head and washer construction, introducing local reinforcing mesh or local thickening strips to reduce stress concentration at the orifice and delay the formation of cone and pry-out failures. Another direction is to establish a long-term slip prediction model that can reflect the coupling effect of humidity cycles, so that the damp-drying cycle and creep shrinkage can be consistently described within the same framework, thereby improving the prediction accuracy of long-term deflection and residual slip. Further research can be conducted on the applicability evaluation of new fasteners such as self-tapping screws in thinner concrete slabs, especially when the slab thickness is less than 50 mm. Anchoring mechanisms, crack propagation paths, and group anchoring effects may exhibit new controlling laws, requiring verification through both experiments and high-fidelity numerical simulations to promote the development of the TCC system towards lighter weight and higher efficiency.

References

1. Mechanical behavior of timber-concerte connections with inclined screws / B. Berardinucci, S. Di Nino, A. Gregori, M. Fragiacomo // International Journal of Computational Methods and Experimental Measurements. – 2017. – Vol. 5, No. 6. – P. 807–820. – DOI: 10.2495/CMEM-V5-N6-807-820.
2. Numerical Investigation of Connection Performance of Timber-Concrete Composite Slabs with Inclined Self-Tapping Screws under High Temperature / Z. Chen, Y. Bao, W. Lu [et al.] // Journal of Renewable Materials. – 2021. – Vol. 10, No. 1. – P. 89–104. – DOI: 10.32604/jrm.2021.015925.
3. Bedon, C. Vibration Analysis and Dynamic Characterization of Structural Glass Elements with Different Restraints Based on Operational Modal Analysis / C. Bedon, M. Fasan, C. Amadio // Buildings. – 2019. – Vol. 9, No. 1. – P. 13. – DOI: 10.3390/buildings9010013.
4. Seim, W. The European Yield Model (EYM) for laterally loaded timber connections with smooth nails / W. Seim, M. Schick, T. Waschkowitz // Wood Material Science and Engineering. – 2022. – Vol. 17, No. 6. – P. 965–978. – DOI: 10.1080/17480272.2021.1983870.

5. Kocetov, T. Modeling of composite timber-concrete system with inclined cross screws / T. Kocetov, D. Manojlović // iNDIS2015 : Planning, design, construction and renewal in the civil engineering : 13th International Scientific Conference, Novi Sad, November 2015 / Department of Civil Engineering and Geodesy – Faculty of Technical Sciences. – Novi Sad, 2015.
6. Anderson, N. S. Pryout Capacity of Cast-In Headed Stud Anchors / N. S. Anderson, D. F. Meinheit // PCI Journal. – 2005. – Vol. 50, No. 2. – P. 90–112. – DOI: 10.15554/pcij.03012005.90.112.
7. Girhammar, U. A. Stiffness model for inclined screws in shear-tension mode in timber-to-timber joints / U. A. Girhammar, N. Jacquier, B. Källsner // Engineering Structures. – 2017. – T. 136. – P. 580–595. – DOI: 10.1016/j.engstruct.2017.01.022.
8. Moshiri, F. The Predictive Model for Stiffness of Inclined Screws as Shear Connection in Timber-Concrete Composite Floor / F. Moshiri, R. Shrestha, K. Crews // RILEM Bookseries. – Vol. 9. – Springer, 2014. – P. 443–453. – DOI: 10.1007/978-94-007-7811-5_40.
9. Structural Timber Connections with Dowel-Type Fasteners and Nut-Washer Fixings : Mechanical Characterization and Contribution to the Rope Effect / M. Domínguez, J. G. Fueyo, A. Villarino, N. Anton // Materials. – 2022. – Vol. 15 (1). – P. 242. – DOI: 10.3390/ma15010242.
10. Seim, W. Nailed Connections for Engineered Timber Structures: Extended Kinematic Approach for Consideration of the Rope Effect / W. Seim, A. P. Ho, J. Küllmer // Journal of Structural Engineering. – 2025. – Vol. 151, No. 10. – Art. 14340131. – DOI: 10.1061/JSENDH.STENG-14340.
11. Simulation of Load–Slip Capacity of Timber–Concrete Connections with Dowel-Type Fasteners / D. Manojlović, A. Rašeta, V. Vukobratović [et al.] // Buildings. – 2023. – Vol. 13 (5), P. 1171. – DOI: 10.3390/buildings13051171.
12. Effect of Bolt-Hole Clearance on Bolted Connection Behavior for Pultruded Fiber-Reinforced Polymer Structural Plastic Members / S.-P. Woo, S.-H. Kim, S.-J. Yoon, W. Choi // International Journal of Polymer Science. – 2017. – Art. 8745405. – DOI: 10.1155/2017/8745405.
13. Mohyeddin, A. Failure modes and tensile strength of screw anchors in non-cracked concrete / A. Mohyeddin, E. F. Gad, J. Lee // Construction and Building Materials. – 2019. – Vol. 221. – P. 501–513. – DOI: 10.1016/j.conbuildmat.2019.06.096.
14. Santana, G. Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19) / G. Santana, ACI Committee. – Farmington Hills, MI : American Concrete Institute, 2019. – 624 p. – DOI: 10.14359/51716937.
15. Di Nunzio, G. A Literature Review about the head-size effect on the capacity of cast-in anchors / G. Di Nunzio // 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures : Proceedings. – 2019. – P. 1–12. – DOI: 10.21012/FC10.239783.
16. Esmaeildoust, S. Performance of Timber-Concrete Composite (TCC) Systems Connected with Inclined Screws: A Literature Review / S. Esmaeildoust, D. Tomlinson, Y. H. Chui // Journal of Composites Science. – 2025. – Vol. 9, No. 1. – P. 13. – DOI: 10.3390/jcs9010013.
17. Mccarthy, M. A. Finite element analysis of effects of clearance on single shear composite bolted joints / M. A. Mccarthy, C. T. Mccarthy // Plastics, Rubber and Composites. – 2003. – Vol. 32, No. 2. – P. 69–75. – DOI: 10.1179/146580103225001390.
18. Hadjioannou, M. Development and validation of bolted connection modeling in LS-DYNA® for large vehicle models / M. Hadjioannou, D. Stevens, M. Barsotti // 14th International LS-DYNA Users Conference : Proceedings. – 2016. – P. 1–12.
19. Shear behavior study on timber-concrete composite structures with bolts / G. He, L. Xie, X. A. Wang [et al.] // BioResources. – 2016. – Vol. 11, No. 4. – Art. 9205–9218. – DOI: 10.15376/biores.11.4.9205-9218.
20. Review of long-term performance of timber-concrete composite beams / P. Liu, H. Du, Z. Chen, X. Hu // BioResources. – 2025. – Vol. 20, No. 1. – Art. 2374–2390.
21. Long-Term Behavior of Timber–Concrete Composite Structures: A Literature Review on Experimental and Numerical Investigations / B. Shi, X. Zhou, H. Tao [et al.] // Buildings. – 2024. – Vol. 14, No. 6. – P. 1770. – DOI: 10.3390/buildings14061770.

Material received 17.12.2025, approved 21.12.2025, accepted for publication 06.01.2026