Review on research progress of metal-plate-connected wood joints

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Abstract：The problem of metal-plate-connected wood joints is an important aspect of wood structure design and research. Metal-plate-connection (MPC), tenon-mortise connection and pin connection are the three most common connection forms in timber structures. The mechanical properties and safety of joint connections in wood structures are of great value to evaluate the performance of building components and structures. The wood is anisotropic and its mechanical properties are susceptible to external factors (e.g., moisture content, density, temperature and load condition). Based on summarizing these influences on the mechanical properties of metal-plate-connected wood joints, this paper further explores the simulation model and analysis software for predicting the performance of these joints, and it also involves aspects of conservatory and creep. Finally, the new development of MPCs is put forward.

Keywords：Metal-plate-connection; Wood joints; Mechanical properties; Performance simulation model; Creep.

1 Introduction

The connection types of wood joints are becoming more and more diverse. From tenon-mortise connections, to tooth connections, to pin connections, to key connections, to MPCs, to planting bar connections and so on, the performance of wood joints is gradually optimized and developed. One of the most widely used connection forms of wood structures are MPCs, which are widely used for connecting wood members and trusses as well as extending tension members.

This connection type was invented in the United States in 1952 by Carroll Sanford, Florida, through a series of tests on the mixed connection of plywood wedges, U-shaped nails, nails and bolts, and then applied to connect the wood truss, marking the beginning of the wood truss industry [1]. MPCs are widely used for wood structures because of their convenient construction, and it can quickly locate the chords in the truss [2]. More than 90% of residential, commercial, and agricultural buildings in the United States use MPC wood trusses. According to industry estimations, total sales of the nearly 2000 manufacturers of MPC wood trusses in the United States were $3.4 billion in 1996. This kind of structural system can bear and transmit large span loads, and has excellent thermal insulation and waterproofing, which is due to the fact that wood has better thermodynamic properties than materials such as steel and concrete. MPCs can also be prefabricated to allow the assembly of floors and roofs in a short construction period, saving materials and labor[3].

The plate is made of galvanized steel, which is cut out by a high-speed stamping machine and then cut into various specifications[4]. The steel plate is made with a thickness of 1~2 mm, with the teeth perpendicular to the steel plate. Depending on the stamping device, each hole can be punched into one or two teeth. The length of the tooth is generally between 8~15 mm, and the size of the plate is from 30cm^2~1m^2. Fig. 1 shows the schematic diagram of a metal plate, and Fig. 2 shows some types of metal plate.

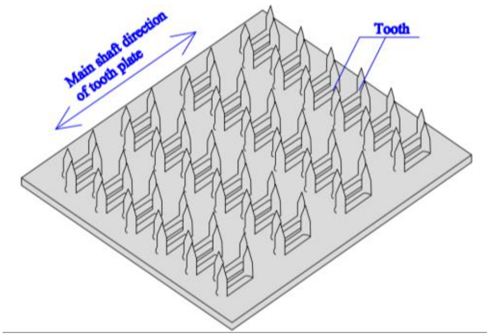


Fig. 1. Schematic diagram of a mate plate

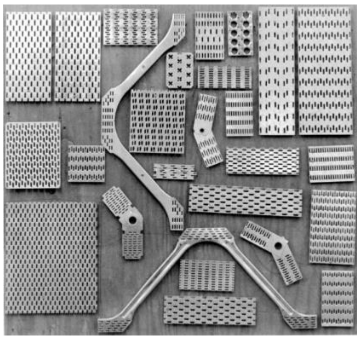


Fig. 2. Some types of metal plate [5]

Although MPCs in wooden trusses have many advantages, they have some shortcomings. For example, the material begins to rust easily when it is in a corrosive and wet environment. This reduces load-bearing capacity and can cause structural damage. In addition, the plate easily loses stability under compression, so it should not be used for the connection of elements subjected to compression.

Most of the early studies on MPCs focused on the testing and modeling of static connections to evaluate the strength, stiffness, load-slip characteristics and failure modes, as well as the effects of some variables on the behavior of the joints. The subsequent research aims at the mechanical properties of MPCs under different types of loading conditions (e.g., seismic load and wind load), and modeling new types of joints. Although MPC wood trusses have been widely used for more than 50 years, the performance of MPCs is not fully understood. So far, few papers have summarized the past literature and research on the connection behavior of MPCs in structural wood. The purpose of this paper is to review literature on metal-plate-connected joints and analyze the static and dynamic performance, aging and corrosion of MPCs from small (single joint) to large structures (wood truss). Finally, the results are summarized and an outlook is given for future research that will contribute to a better understanding of MPCs in wood structures.

2 Design specifications for MPCs

Choosing an appropriate specification can lay a good theoretical foundation before conducting the study. Table 1 summarizes the design specifications of MPCs, and analyzes their functions and scope of application, which is convenient for designers to find a suitable specification depending on the needs of the research and design.

3 The form of connection and loading

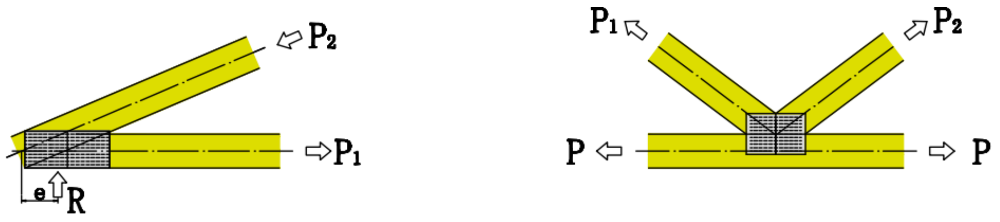
MPCs are widely used in the roof and floor systems of wood trusses. The connections can be divided into the following types: tension connection, heel connection, web connection, parallel chord connection, apex connection and so on. Fig. 3 shows different forms of these connections and their loads [5].

Table 1 Design specification of MPCs

Code	Loading condition	Joint type	Application	Reference
GB50005	Tension, shear and shear-tension compound force	Heel joints, chord joints	Determine the bearing capacity, design strength and test method of metal plate and teeth	[2]
JGJ-T265	Local compression, bending, pressure-moment composite force, Tension, shear and shear-tension compound force	Wood truss joints	Design, manufacture, installation and maintenance management of light wood truss and other related structural	[6]
EN 1995-1-1	Tension, compression and shear	Tension, compression and shear joints	Determine the strength and anchorage strength of the metal plate and the connection strength of the MPCs	[7]
EN 1075	Tension, compression and shear	Tension joints with different angle	Specifies the test methods for determining the strength capacity and stiffness of joints	[8]
EN 14545	—	—	Some regulations on metal plates and the determination of related bearing capacity	[9]
EN 13271	—	—	The carrying capacity and slip problem of MPCs are stipulated	[10]
CAS Standard S347	—	Wood truss joints	Provide methods and regulations for testing MPC wood trusses	[11]
ASTM D1761	—	Mechanical fasteners joints in wood	Stipulate the test method of MPCs in wood products	[12]

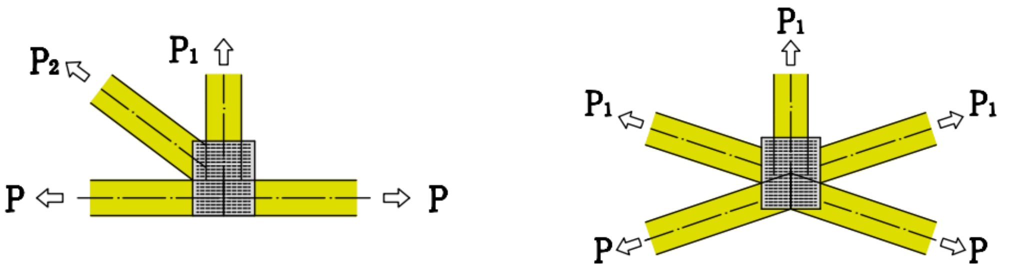
(a). Tensile joint under uniaxial tension

(b). Tensile joint under combined forces (tension and bending)



(c). Heel joint with moment (R • e)

(d). Web joint with combination of force



(e). Parallel-chord truss joint with combination of forces

(f). Scissors truss, bottom chord, peak joint with combination of forces

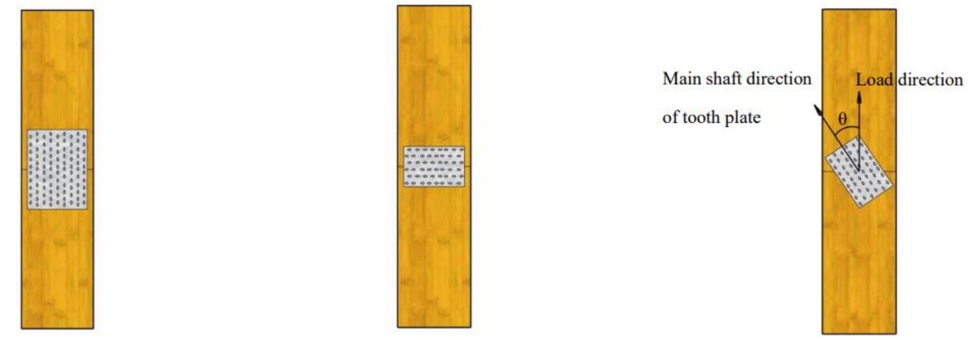
Fig. 3. Different MPC joints and loads. P = force, R = reaction, e = eccentricity [5]

4 Static behavior

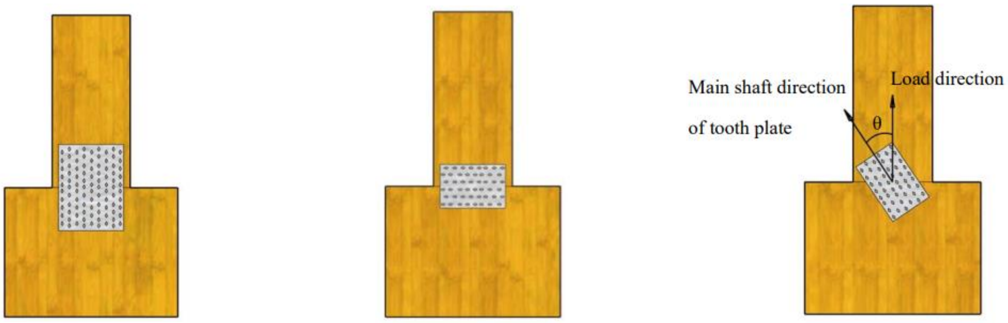
The mechanical behavior of MPCs is complex, and the evaluation of its bearing capacity is mainly considered from the aspects of tensile, shear, anti-slip and shear-tensile composite forces. Since the plate is a thin steel plate with a large opening rate, it is prone to buckling under compression, so it is not advisable to use MPCs for components which are mainly under compression.

4.1 Tensile properties

For tensile joints connected by metal plates, the connection types AA, AE, EA, EE and some special angles were mainly studied (Fig. 4). Some scholars have carried out studies on the properties of tensile joints with these connection modes [1, 13-16]. The parameters of the test materials and the results are shown in Fig. 5 and Table 2.



(a). AA (b). AE (c). A Special angle



(d). EA (e). EE (f). E Special angle

Fig. 4. Schematic diagram of tension joints at different angles

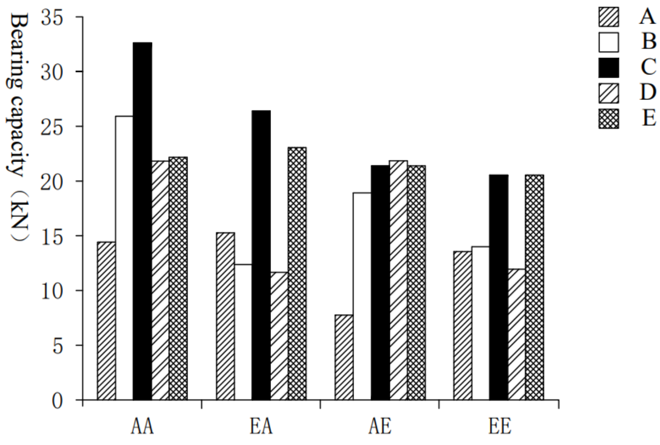


Fig. 5. Comparison of tensile bearing capacity of MPCs [1, 13-16]

Table 2 Material parameters of MPCs at different angles

Group	Wood species	Moisture content (%)	Plate size(mm^2)				Plate type	Wood size(mm^3)	Reference
			AA	EA	AE	EE			
A	Southern pine	—	75×125	75×125	75×125	75×125	—	—	[13]
B	Southern pine	12	75×125	75×125	75×125	75×125	—	50×100×1200	[14]
C	Chinese larch	12	75×125	75×125	75×125	75×100	GN20	38×89×300	[15]
D	Larch、Korean pine	12	75×100	75×100	63×100	50×100	M20	40×90×200 40×150×200	[1]
E	Larix dahurica	12	75×100	75×100	75×125	75×100	M20	40×90×300	[16]

Comparing the experimental results of various scholars, it can be observed that load bearing capacity decreases when the size of the metal plate is smaller. The load-bearing capacity of AA is larger than that of EA and AE, and the bearing capacity of EE is the smallest. Thus, in practical application, the loading of the joint should be parallel to the spindle state of the wood grain and the metal plate to maximize its load-bearing capacity.

Three basic failure modes of MPCs under AA and AE models are listed in Fig. 6: The first is anchorage failure when the tooth is pulled out of the wood. The second is tensile failure, when the net section of the metal plate breaks. The third is shear failure that occurs on the surface of the metal plate.


(a). Anchorage failure (b). Tensile failure

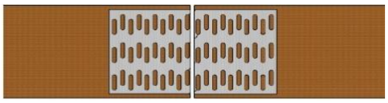

(c). Shear failure

Fig. 6. Basic failure modes of splice joints

The anchorage failure is brittle, while the fracture of the metal plate is a ductile failure mode. Compared with the former, there are obvious signs before the failure of the metal plate, and the failure process takes a long time. The seismic performance is also better than that of the joint in anchorage failure mode. Therefore, in the design of MPCs, anchorage failure should be avoided as much as possible. Table 3 summarizes the failure modes of some scholars who have studied tensile performance of MPCs.

Table 3 Failure modes of tensile joints

Type of joints	Force state	Variable	Failure mode	Reference
Tensile joints	Tension	Wood specific gravity (0.34~0.53) Plate type(S/L) Tooth row number (R, 2~8)	R<6, Tooth pull-out R=6, Transition R>6, Plate tensile failure	[17]
Web joints	Tension	—	Plate tensile failure, Tooth pull-out and Plate shear failure	[18]
AA、EE、AE、EA	Tension	Plate angle	Tooth pull-out, Plate broken and Wood cracking	[19]

Note: 1. R represents rows of teeth.

These tests showed the diversity failure modes of MPCs. Consistency means that a change in parameters, such as the size of the plate, the number of tooth rows, and the angle of the plate connection, results in different failure modes. However, the boundaries have yet to be determined.

Various factors lead to the emergence of these different phenomena. To explore the boundaries of these differences, some scholars have discussed them. Hussein [20] studied the factors influencing buckling failure of MPCs, and the results showed that the string shear led to and dominated the buckling, with the shear length having a greater influence than clearance. Larger gauges and smaller unbraced areas can improve buckling response. Lau [21] found out that the collapse of wood in the shear plane is the main reason for the decrease of the stiffness of shear joints. The yield failure of the short metal plate often occurs, and the anchorage failure of the long plate occurs more frequently. At the same time, by increasing the net cross-sectional area of the metal plate, the tearing of the steel plate can be avoided and the number of slots at the joint can be reduced to improve the strength of the steel plate. O'Regan et al. [22] thought that the strength of the metal plate has an important influence on the failure mode of MPCs, and they concluded that the length of the metal plate, which ensures that no anchorage failure of the metal plate occurs, should be greater than the width of the metal plate.

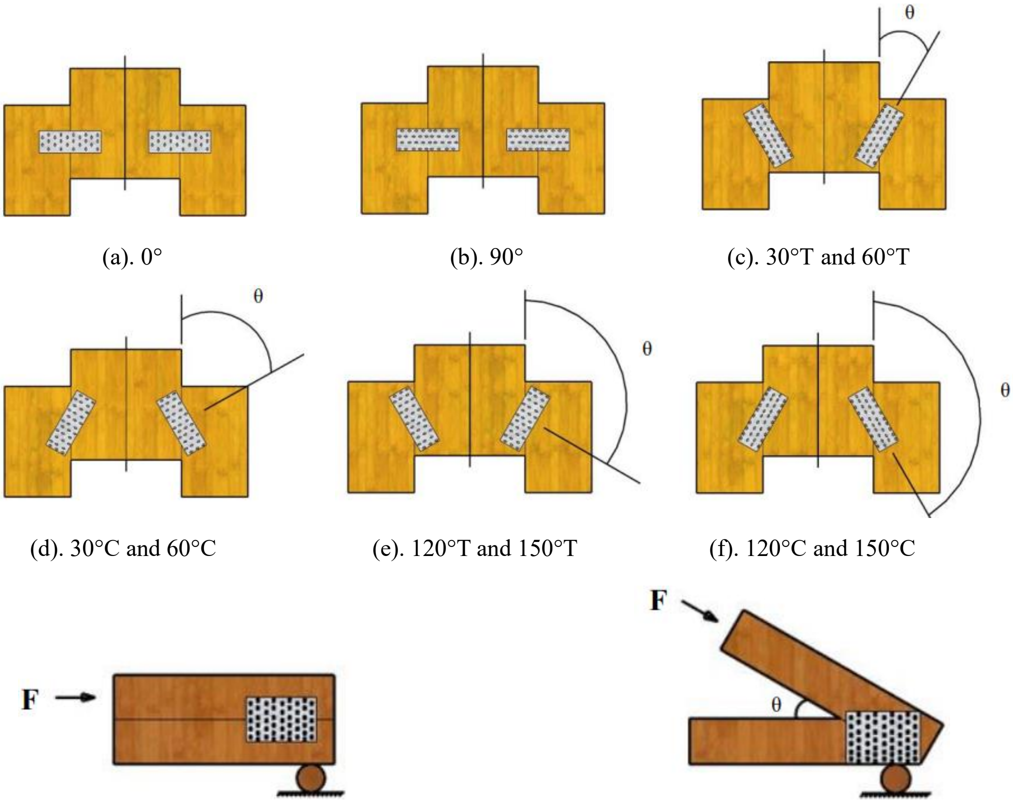
In summary, the length of the metal plate should be increased in relation to the wood when anchorage failure occurs, and the metal plate itself is prone to damage if the length is reduced. Appropriate measures should be taken, such as increasing the contact area between the metal plate and the wood, to enhance the load-bearing capacity of the metal plate, so that the connection strength between the metal plate and the wood is greater than the strength of the wood itself, and the wood failure occurs first.

In addition to the difference between the load and the direction of the main shaft of the wood and the metal plate, the effects of the wood species, density and moisture content on its tensile properties cannot be ignored. Via et al. [23] determined the relationship between the density of the standard material and the pull-out strength of the metal plate: the density is helpful to improve the ultimate pull-out strength of the tooth under AE or EE mode. Yeoh et al. [24] carried out tensile tests on different kinds of Malaysian wood MPCs, observed the maximum load, maximum displacement, and the failure mode of the specimens, and deduced the basic working load (BWL). The results showed that the orientation of the plate, wood species and density, and its moisture content all influenced the strength of MPCs, but the effects of gaps and different embedding levels are not yet clear. There are great differences in the tensile properties of wood along the grain, transverse the grain and in the twill direction.

4.2 Shear properties

According to JGJ/T 265-2012 [6], there are ten different connection modes for testing the shear performance of MPCs (Fig. 7 (a)~(f)). Wang [25] carried out an experiment on the shear capacity of standard MPCs according to JGJ/T 265-2012. However, Gebremedhin et al. [14] refer to the Canadian specification and used various angles between the two timber connectors (Fig. 7 (g), (h)). Their results were compared and analyzed in Table 4. The comparison shows that the 90° type in JGJ/T 265-2012 is the same as the 0° types in the Canadian code, and the classification of the other angles is also different, which is problematic for the evaluation. Compared with the test results, it can be seen that the different test methods also have a great impact on the test results.

Corinaldesi [26] studied the mechanical properties of MPCs under compression, tensile, shear and bending tests. The test results showed that due to the small cross-section of the metal plate compared to the wood cross-section, the metal plate failed. Therefore, by increasing the thickness of the metal plate or reducing the number and size of holes, the number and size of teeth in the plate are reduced, and the tensile, bending and shear properties of the connection can be improved.



(a). 0° (b). 90° (c). 30°T and 60°T

(d). 30°C and 60°C (e). 120°T and 150°T (f). 120°C and 150°C

(g). θ = 0° (h). θ = 30°/45°/60°/90°

Fig. 7. Canadian schematic diagram of shear joints [6, 14]

Table 4 Comparison of shearing test of MPCs

Wood species	Plate size (mm^2)	Angle	Ultimate load (kN)	Sheared length (mm)	Relative ultimate strength (N/ mm)	Reference
Southern Yellow Pine	76.2×127	0°	23.65	254.0	93.11	[6]
		30°	21.73	296.2	73.36	
		45°	26.49	215.6	122.87	
		60°	23.59	176.0	134.03	
		90°	15.31	152.4	100.46	
SPF Specification	50×170	0°	21.75	200.0	108.75	[25]
		30°C	19.17	230.9	83.02	
		60°C	22.33	400.0	55.83	
		120°T	38.40	400.0	96.00	
		150°T	26.93	230.9	116.63	
	50×180	90°	25.56	200.0	127.80	
		30°T	48.35	400.0	120.88	
		60°T	36.75	230.9	159.16	
		120°C	20.75	230.9	89.87	
		150°C	28.90	400.0	72.25	

Note: Relative ultimate strength is obtained by the ratio of Ultimate load to Shear length.

4.3 Bending properties

Timber trusses are generally similar to steel trusses. In the case of a nodal force, each member is only subjected to an axial force. However, the actual situation is more complex because the node may also be forced by bending, shear, or a combination of bending and shear. Noguchi [27] analyzed the pure bending situation of a splice joint by comparing the results calculated by different methods, and he pointed out that the plastic model had the best agreement in calculating the bending moment. Guntekin [28] studied the ultimate bending moment capacity of three different sizes of Korean metal-plate-connected wood truss joints. The research showed that both the plate size and the tooth direction had an impact on the bending capacity. As the plate size increased, the bending limit of the joint increased slightly. Kevarinmäki [29] studied the tooth extraction capacity of metal-plate-connected wood truss joints under a bending moment using elastic and plastic theoretical models. He proposed ten methods to determine the force and bending moment components acting on the truss plate of the joint, which were used to check the tooth extraction capacity of the joint under bending and tension (or compression).

At present, research on the bending performance of the metal plate remains to be further developed and explored. Due to the anisotropy of the special material wood, the type and size parameters of the wood and the performance of the tooth plate itself have a certain impact on the bending performance of the joint.

4.4 Slip properties

The slip phenomenon of MPCs is always accompanied by a variety of failures rather than a single slip. No matter what kind of force it is subjected to, the relative slip with increasing load always occurs at the connection between the plate tooth and the wood. Therefore, the evaluation of the anti-slip ability of the joints is an important factor to test whether the connection is strong. Güntekin [30] measured the ultimate strength, stiffness, and critical slip load values of the joints under four different conditions (AA, EA, AE, EE) using connections between the metal plate and Calabrian pine as the object. The experimental results showed that the loading mode and the size of the metal plate significantly affected the performance of the joint. The strength and the critical slip load in the AA direction were higher than in the EA direction. The average load range of the critical slip value of each tooth in the test is between 0.32 kN and 0.53 kN. Compared with the results of other researchers, it is found that the value is higher than that of the southern pine in Onat's [31] study and similar to laminated strand lumber (LSL).

4.5 Tension-bending combination property

In addition to the study of metal-plate-connected joints under a single force, scholars also carried out experimental analysis on the joints under a composite force. This situation corresponds more to the force situation of MPCs in engineering practice. Therefore, the study of MPCs under composite force mode is more practical. Table 5 summarizes the test data and results of some scholars on MPCs under combined tension-bending force.

O' Regan et al. [32] proposed a formula for the relationship between the joint gap and the ultimate bending moment (Eq. 1) and Wolfe [33] and Gupta [34] proposed the formula for the interaction between axial force and bending moment (Eq. 2, Eq. 3). The parameters a and b in the formula need to be obtained by testing each different metal plate (e.g., the types of teeth and the grade of steel). Wolfe determined that the value of index a is 1.28, and Gupta determined that the values of parameters a and b are 8.3011 and 0.6083, respectively.

The comparison and analysis of their test results showed that the greater the eccentricity of the specimen, the smaller the ultimate tensile force, the greater the ultimate bending moment and deformation, and the lower the tensile capacity of the joint under the combined tension-bending force.

Table 5 Tensile-bending test of MPCs

Loading Method	Failure Mode	Sample Type	Eccentricity (mm)	Tension Load (kN) (COV (%))	Moment (N·m) (COV (%))	Failure Deflection (COV (%))	Reference
Eccentric tension	Plate broken	24L20G	0	53.25(0.77)	—	—	[32]
			38.10	35.41(7.3)	765.14(14)	16.396 mm (14)	
			76.20	19.21(23)	961.37(7.4)	25.037mm (29)	
			114.30	13.31(1.9)	1201.85(5.3)	24.051mm (13)	
		26L20G	0	86.47(1.2)	—	—	
			38.10	58.14(2.7)	1682.14(3.3)	9.167 mm (7.3)	
			88.90	31.80(4.5)	2435.88(4.5)	12.283 mm (11)	
		26L16G	0	105.05(2.7)	—	—	
			38.10	69.35(4.4)	1780.93(2.7)	12.385 mm (8.9)	
			88.90	41.93(3.0)	2993.96(2.7)	17.480 mm (11)	
Eccentric loading of special device	Plate yielding 、 Tooth pulled out	oT	0	29.78(6)	—	—	[33, 35]
		lMhT	22.23	21.34(7)	375.97(9)	—	
		mMmT	66.68	11.25(5)	681.93(3)	—	
		hMlT	200.03	4.18(5)	802.74(5)	—	
		oM	∞	—	980.00(6)	—	
Axial force and bending moment applied by special device	Plate broken 、 Tooth pulled out 、 Wood cracking	oT’	0	28.03(10)	—	1.740 mm (17)	[34]
		E1	12.70	26.40(8)	335.32(8)	0.0078 rad (40)	
		E2	25.40	24.22(23)	615.21(23)	0.0131 rad (18)	
		E3	38.10	23.01(11)	876.58(11)	0.0227 rad (13)	
		E4	50.80	20.94(13)	1063.77(12)	0.0252 rad (7)	
		oM’	∞	—	1235.50	0.0476 rad (21)	

Note: 1. The specimen number 24 / 26L represents the type of wood, 20 / 16G represents the type of steel plate.

2. The number M represents bending moment, T represents tension, E represents eccentricity, l represents low, h represents high, m represents middle, o represents only, as oT represents that the specimen is subjected to tension, lMhT represents that the specimen is subjected to low bending moment and high tension.

$$m_{i,e} = \frac{M_{i,e} - \overline{M}_e}{s_e} \tag{1}$$

Where $m_{i,e}$ is the standardized moment for the i repeated test of 2 × 4 joints using 20-gauge plates and e-inch initial eccentricity; $M_{i,e}$ is the ultimate bending moment at the failure of the i repeated test; $\overline{M}_e$ is the average ultimate bending moment of 2 × 4 joints with 20-gauge plates and e-inch initial eccentricity; s_e is the standard deviation of the ultimate failure moment of 2 × 4 joints with 20-gauge plates and e-inch initial eccentricity.

$$\frac{t}{T} + \frac{m^a}{M} \le 1 \tag{2}$$

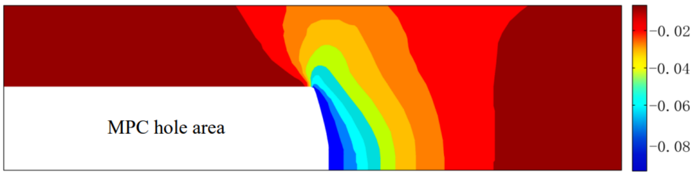
Where t is the axial tension; T is the axial tension capacity; m is the bending moment; M is the bending moment capacity; a is the index derived from the test results.

$$\left(\frac{t}{T}\right)^a + \left(\frac{m}{M}\right)^b \le 1 \tag{3}$$

Where t is the axial tension; T is the axial tension capacity; m is the bending moment; M is the bending moment capacity; a and b are the indexes derived from the test results.

4.6 Stress and strain

Due to the large number of holes in the cross-section of the metal plate, the stress distribution is not uniform and stress concentrations occur. Misra et al. [36] found that both the “difference equation” and the “principle of minimum complementary energy” can effectively predict the stress distribution of MPCs in the tensile process. They found that the distribution of stress elements on the metal plate is not uniform, and the stress value at the calculated maximum stress is about 2.4 times the average stress of each part of the plate. Samad et al. [37] analyzed the stress distribution in the three-point bending beam by Digital Image Correlation (DIC) technology and obtained the contour map of the stress σ_y in the vertical direction of vertical displacement (Fig. 8). According to Fig. 8. the stress distribution on the surface of the MPC is uneven, and the stress is concentrated in the cross-sectional area reduced by perforation. Beineke and Suddarth [38] compared five theories [39-43] by calculating the load distribution at different distances from the joint. The predicted stress distribution in the study was almost the same. Regardless of which hypothesis is taken into account, or whether discretion or continuity is considered, the stress distribution on the surface of the metal plate is non-uniform. They also show that the theory predicts high stresses at both ends and in the middle of the joint. Gebremedhin [44] found that the row of teeth close to the center line of the connection plate carried more load than the row of teeth farthest from the center line (the data are shown in Table 6), which is consistent with the results predicted by Beineke and Suddarth [38]. They also found that there was no apparent load redistribution when three teeth in each row of the connector were damaged.



Note: The same color represents the same stress in this area.

Fig. 8. Contour plot of the MPC wood veneer [37]

Table 6 Load distribution in metal plates at different locations [44]

Connection Type	Center line (%)	Number of teeth at central line	Edge line (%)	Number of teeth at edge line
A	11	6	8	6
B	12	5	18	10
C	23	12	18	12
D	23	12	18	12

In summary, the stress distribution on the metal plate is uneven and there is a stress concentration at the perforation and cross-sectional reduction. The stress near the central line of the connecting plate is higher than that at the distal end, which also makes the stress on the tooth near the midline higher than that on the edge tooth. However, in the test, the research on the stress of the tooth is still in the development stage, and only the average stress distribution of the tooth was studied, but the specific stress distribution on the tooth surface had not been involved.

The damage and failure behavior of wood under tension, compression or shear is an important factor to be considered in the design of wood structures. Therefore, damage analysis of wood under load, i.e., strain analysis, is particularly important. Some models can separate the factors affecting crack initiation and propagation and predict their cumulative effects on the mechanical properties of structural components. Alsheiab [45] used DIC technology to measure the full-field strain of MPCs, and the study showed that the strain on the plate fluctuates at low load and increases with increasing load. When the external load replaced the shearing force of the teeth, the strain distribution became organized and regular, and when the load was parallel to the wood grain, the plate showed higher strength and occlusal degree than when the load was perpendicular to the wood grain. Luong [46] first applied the non-destructive, non-contact and real-time detection technology of infrared temperature record to the study of MPCs and used a scatter plot to show the whole process of the force on the metal plate. He found that the load-bearing capacity of the metal plate obtained by this research is larger than that of the American scholar Soltis [47], and that the relative slip between the plate and the wood is also large. This is mainly due to the great differences in wood materials in different regions, its vulnerability to the influence of the external environment and the different processing methods of the specimen, which also have a great influence on the test results.

5 Dynamic behavior

5.1 Earthquake and cyclic load

At present, more studies focus on the static performance of MPCs, while research on the dynamic performance of MPCs is not yet as advanced as the former. The development of the research on dynamic performance of MPCs begins with the development of a “horizontal loading device” for the dynamic performance of MPCs, which was developed by Gupta and Gebremedhin [48] in 1990. The main body of this device is mainly composed of a trapezoidal detachable metal frame, and the internal structure can be changed flexibly according to the different forms of joints. Various joint testing devices can be formed by connecting the corresponding loading instruments and support bars. The appearance of this kind of device greatly simplifies the method of studying the dynamic performance of MPCs and solves the technical problems which are lacking in previous research in this field.

In 1994, Dolan [49, 50] conducted a preliminary study on the dynamic test of MPCs based on the quasi-static test of masonry shear walls and proposed a sequential phased displacement (SPD) loading method suitable for MPCs. Three years later, Kent [51] used this kind of loading method and two other dynamic loads to analyze the dynamic characteristics of tension joints and heel joints. The results showed that the strength of the joints was not reduced under seismic loads. The SPD loading mode does not affect the ultimate strength of tension splice joints, but reduces the ultimate strength of heel joints. The damping ratio and energy dissipation increased with increasing SPD loading, while cyclic stiffness decreased. Cyclic loading has a significant effect on the bearing strength of MPCs, and the effect is related to the amplitude.

In 2004, Gupta et al. [52] improved the “horizontal loading device” and studied the dynamic force of 110 specimens under cyclic loads of the fink and the heel joint. The results showed that the strength of the joint did not decrease under cyclic loading, but the stiffness decreased significantly. Prior to this, Emerson et al. [53] reached a similar conclusion that the metal-plate-connected joint maintained most of its static strength, but the static stiffness decreased slightly after bearing a dynamic load up to 60% of its maximum static strength.

De et al. [54] analyzed the influence of wood density on the mechanical behavior of MPCs under cyclic loading and obtained the following conclusions. The remaining damage energy depends on the number of cycles. Compared to low-density wood joints, high-density wood joints are more rigid, and high-density wood joints can withstand an average load of 30%. Apart from the magnitude of the initial load, wood density does not affect the mechanical properties of such joints. For any wood density, the horizontal displacement of the connector leads to a decrease in stiffness and strength and increases the vertical slip of the joint.

In summary, seismic and cyclic loading have little effect on the ultimate strength of MPCs, but have adverse effects on the stiffness of the joints. At the same time, changes in the moisture content and density of the wood itself also have a certain impact on the dynamic performance of the joints.

5.2 Wind and impact load

In addition to seismic and cyclic loads, wind and impact loads are also dynamic loads to which MPCs are subjected. Gupta [55] studied the performance of MPCs under wind and impact loading. Comparing the stiffness of the joints before and after dynamic loading, it is found that the average stiffness after hurricane loading increased by 300%, and the increase in stiffness after impact loading is similar to that after wind loading. The reason could be that the tooth is more tightly connected to the wood after loading. The strength of the joints does not decrease significantly after dynamic loading. For tensile joints, the results of accelerated loading are the same as those of static test loading for 1/10 of the time.

6 Moisture cycling and creep

6.1 Interaction process

Wood, a natural macromolecular biological material, has different shapes, different functions, and is arranged crosswise. There are pores in the cell cavity and the cell wall of mature wood, and there are gaps between microcrystals, microfibrils and filaments in the cell wall, which makes the wood become a capillary porous colloid with finite expansion. The form and amount of water in wood are closely related to the unique structure of wood cells. Water in wood can be generally divided into chemical water, free water and absorbed water. When the moisture content in wood is below the fiber saturation point, moisture absorption and desorption occur. When the moisture absorption rate and the desorption rate reach equilibrium, the moisture content of wood is in balance. The moisture content of wood in the roof of a wooden structure approaches the fiber saturation point due to the change of external climate, which changes its structural performance [56]. Under the action of the water cycle, the teeth surfaces produce corresponding stress due to the expansion and contraction of wood cells, so that the metal plate is removed from the wood (Fig. 9).

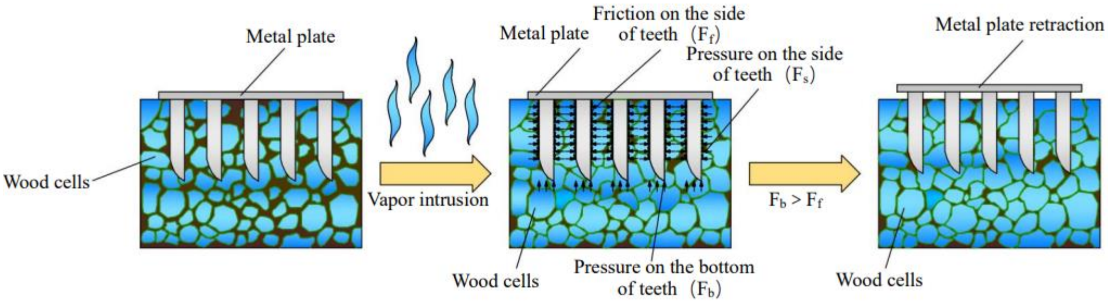


Fig. 9. The process of a water cycle acting on metal plate

The diagram shows the ideal situation where the effect on each tooth is the same, but in the actual situation, the force on each tooth is different due to the different degree of shrinkage and expansion of each cell, so the metal plate also bends and twists. Therefore, it is of great practical significance to study the effects of the water cycle on the fatigue and creep properties of MPCs.

6.2 Short-term effect

The change of moisture content in the environment causes repeated drying shrinkage and expansion of wood, which has an unfavorable effect on the mechanical properties of joints. Hayashi

[57], Senior [58], Mohammad [59] and Yeh [60] found this adverse effect in their tests, which is manifested in many aspects and is summarized in Table 7.

These adverse effects are mainly reflected in the fatigue and creep properties of joints, while static strength is less affected by moisture cycling. Mohammad [59] found that different moisture contents of wood had different effects on joint stiffness after moisture cycling. In contrast, the study of Yeh [60] showed that the temperature and humidity pretreatment had no significant effect on the short-term loading performance of composite materials, so the influence of moisture content change of wood itself on the short-term loading performance of MPCs could be excluded. It can be seen that warm and wet pretreatment of wood has a certain effect on improving the fatigue and creep properties of joints, but whether this method is economical remains to be verified.

Table 7 Adverse effects of water cycle on MPCs

Testing Method	Adverse Effects	Data Result	Reference
Rotating bending fatigue test	Fatigue strength decrease	The strength of the dry specimen and saturated water sample is 9% and 11% of the static strength respectively.	[57]
Comparing between finite element model and test	Plate retraction	The plate retracted 0.6 mm in 21 days.	[58]
5% / 12% water cyclic tensile test	Stiffness of dry wood joint reduces	The strength decreased by 20%~30%.	[59]
Bending creep test under cyclic humidity	Creep property decrease	—	[60]

6.3 Long-term effect

Except for the influence of short-term factors, the long-term moisture cycle has a slow and far-reaching impact on the performance of the joints. The long-term moisture change can increase the slip and tooth extraction of MPCs, but the short-term effect is not obvious, and the tooth extraction increases with the increase of the embedded depth of the plate and tooth [61]. In reality, the actual service life of the wood structure is certainly longer than that of the short-term tests. It is also of great significance to study the effect of the bond under long-term humidity cycles, which better corresponds to the actual situation and ensures the service life of wooden structures. With age, the creep and fatigue properties of MPCs also change. Table 8 shows the effect of long-term action with different duration on the mechanical properties of metal-plate-connected wood structure under the change of environmental humidity.

Table 8 Effect of long-term action with different durations on MPCs

Structural Style	Duration	Relative Cycle Humidity	Test Conclusion	Reference
MPC truss	One year	35%-90%	The rigidity of MPCs change under dynamic load.	[62]
Joints of MPC truss	Six weeks	45%-95%	Deflection increased 2.1~6.9 times Maximum tensile load loss 0%~23% Maximum bending load loss 0%~30%	[63]
4×2 Parallel chord MPC truss	Ten years	Ambient humidity	Deflection over L / 360 at second year There are seasonal variations in creep rate and amount.	[64, 65]
MPC Wood truss bridge	Three years	Ambient humidity	Rod force loss during drying Stabilization of rod force with increasing water content	[66, 67]

Although extensive research has been conducted on the influence of long-term loading, humidity changes and their bond effect on the connection performance, the influence of moisture cycle changes on stiffness and strength has not yet been quantified and the level of moisture cycle has not been defined. Groom [68] quantified the effects of moisture cycling on the mechanical properties of MPC truss joints and evaluated the possibility of applying adhesive to the tooth immediately before assembly to delay the degradation of moisture cycling. The results show that the strength and stiffness of the truss joints are reduced by about twice as much as under constant moisture conditions due to the relaxed moisture cycle, and increasing the speed of the moisture cycle accelerates this reduction, which is about three times as much as in the original.

6.4 Calculation of creep deflection

Creep is the deformation of structural members that changes with time under constant load. Creep of wood is affected by many factors, including the stress level, temperature and moisture content [69]. Donald et al. [70] reviewed and summarized the relevant standards and research on creep behavior of MPC wood trusses and proposed a reasonable calculation method for estimating the creep deflection of MPC wood trusses with parallel chords. According to this calculation method, the minimum creep coefficient of 1.5 required in the original standard may not be sufficient to control the long-term deflection in all cases, but should be adjusted according to the percentage of the permanent load in the total design load. McAlister [71] determined the influence parameters of three aging processes on the ultimate load and load/deflection (F/D) curve. The three parameters are initial slope (k), final slope (m_1) and intercept of final slope (m_0). These three values define the F/D curve through the following relationships (Eq. 4):

$$F=\left(m_0+m_1D\right)\left[1-e\left(-kD/m_0\right)\right] \tag{4}$$

The formula shows that aging reduces the maximum permitted load of wood, which is consistent with the previous test results.

7 MPC wood trusses

7.1 Types and features

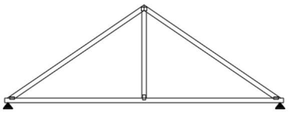
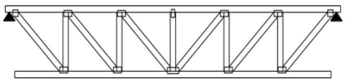
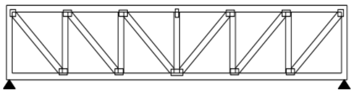
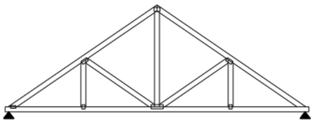
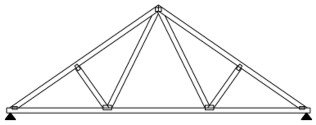
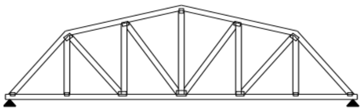
There are different types of connections of wooden trusses, such as MPC, nail connection, bolt connection and so on. The most effective and convenient connection type is MPC, and its biggest advantage is to ensure the integrity of the wood. MPC wood trusses are widely used in civil buildings as roof and floor systems. Depending on the geometric shape, trusses can be divided into triangular trusses, parallel chord trusses, or other complex geometric forms. The types and characteristics of commonly used triangular and parallel chord trusses are shown in Table 9. The application of wood trusses is very popular in North America. At present, about 95% of new built residential roofs in Canada are constructed with wood trusses.

7.2 Properties of MPCs in wood trusses

The mechanical properties of MPCs from the overall truss can be more targeted to analyze to solve such connection problems. The joint types of MPC wood trusses mainly include butt weld joints, heel joints, crown joints, web joints and ridge joints. Different trusses contain different types of joints, and the appellations are slightly different. Considering the force applied to different joints in wood trusses, destructive testing is generally carried out to test the mechanical performance, and the load-slip curve is obtained to determine the stiffness and strength. Fig. 10 shows a schematic diagram of the wood truss joints.

Vatovec and Gupta et al. [48, 72] analyzed the mechanical properties of different types of truss joints. The results are summarized in Table 10. It can be seen that the joint type affects the connection performance of MPCs. The bearing capacity of the heel joints was smaller than that of other types of joints, because the heel joints are located at the support position, and the force is more complex than that inside the truss.

Table 9 Common forms and characteristics of MPC wood truss

Structural Type	Schematic diagram	Features
King post truss		Simple; Mainly used in sheds or temporary buildings with span less than 6.1m; The load is generally small
Plank pose truss (Top chord support)		Can reduce the overlap area of truss and wall; Mainly applicable to the floor system
Plank pose truss (Bottom chord support)		Less member type; Unified node structure; Easy to manufacture; Can be used for floor and roof system
Howe truss		Span between 4.8m~12m, generally not more than 18m; The longer inclined rod is tensioned while the shorter vertical rod is compressed; The inclined rod must dip down to the middle of the span
Fink truss		Simple; The allowable load and deflection are large; Common span is generally between 4.8m~9m; The force of abdominal rod is reasonable
Double slope truss		The upper chord adopts fold line; More used for roof shape of buildings with special requirements or for agricultural buildings; The force is the most reasonable; The internal force of the chord is uniform; The internal force of the web member is small

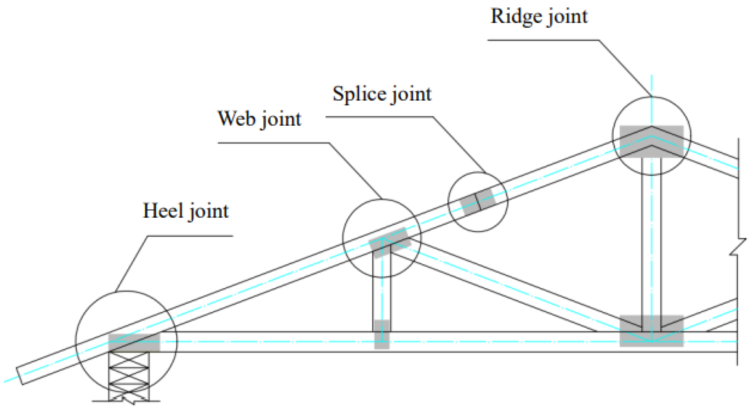


Fig. 10. Wood truss node

7.3 Properties of MPC wood trusses

In addition to the study on the mechanical properties of specific joints of different trusses, Song, Rittenburg, Sandanus, Gupta and Karacabeyli et al. [73-78] studied the mechanical properties of different forms of full-scale trusses, such as ultimate load, failure mode and location, critical buckling load, lateral support force and deformation. The research results are summarized in Table 11. It can be seen that many factors affect the mechanical properties of MPC wood trusses, such as the way of loading, the loading duration, etc. Increasing the lateral support force of the truss is beneficial to improve load-bearing capacity. The long-term loading is unfavorable for the truss and causes plastic deformation. The mechanical properties of the truss under dynamic loading are different from the static performance. The hypothetical model of semi-rigid joints can better predict the mechanical behavior of the truss, not only for wood truss joints, but also for traditional steel truss joints [79].

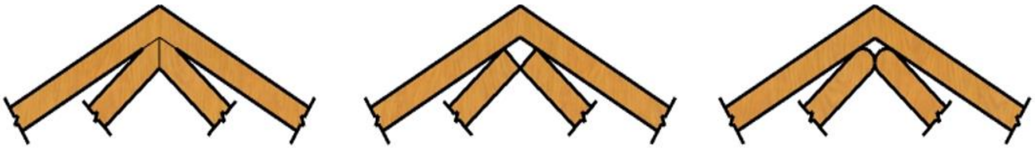
However, actual testing of trusses on a large scale is impractical, and the truss test model has a good performance compared to the actual truss test. Although the two structures seem to be similar, the behavior of them is diverse [80]. Therefore, Gupta et al. [81] tested the stiffness and strength of a small-scale truss at 1:3 and the actual size truss and found that except for the stiffness variability, the other mechanical properties were relatively close between these two scales of truss. For the TSJ joints of two truss types, the difference in stiffness values is not more than 1%, and the strength value of the truss with a small proportion is 7% lower than that of a large truss. For HJ joints, the stiffness and strength of the small truss are 22% and 17% lower than those of the large truss, respectively.

Table 10. Mechanical properties of different types of truss joints

Truss type	Node type	Failure mode	Stiffness (COV) (kN/mm、(%))	Ultimate bearing capacity(COV) (kN、(%))	Reference
Scissors truss	Bottom-chord splice joint (BSJ)	Metal plate cracked	61.7(65.2)	51.2(2.8)	[72]
	Heel joint (HJ)	Shear failure or top chord buckling	29.2(23.4)	49.8(6.0)	
	Crown joint (CJ)	Web rod pulled out	—	33.0(19.8)	
	Bottom-chord ridge joint (BRJ)	Cracking of metal plate at bottom chord	40.2(25.5)	52.3(4.1)	
	Test frame with top-chord splice join (TSJ)	Web rod pulled out	—	43.1(6.8)	
Fink truss	BSJ	Wood tearing and tooth extraction (brittleness)	52.8(18.3)	27.0(17.6)	[48]
	Bottom-chord web joint (BWJ)	Tooth failure at web rod (brittleness)	41.2(52.0)	16.7(17.1)	
	HJ	Tooth pullout at bottom chord (ductility)	3.8 (10.4)	22.7(6.7)	

7.4 MPC wood trusses with irregular end joints

Compared to the trusses of the same type with conventional joints, the mechanical properties of the special-shaped end joints (Fig. 11) may be worse than those of the conventional joints. However, for wood structures with low requirements, this connection method can be used to simplify the production and processing of the trusses and save materials and costs. Douglas et al. [82] studied the load-bearing capacity of the connection trusses with a square web and compared it with the conventional joint. The test results showed that the buckling load of the plate changed greatly compared to the ordinary pattern. The joint is very sensitive to initial defects, and the post-buckling compression capacity is greatly reduced. Dadhiala [83] carried out full-scale experiments on different round-end joints and compared them with ordinary joints. The experiment showed that the strength and stiffness of the top-tight joints were larger than those of the round-end joints, but the shearing force of the metal plate and the sliding amount of the tooth in the round-end joints were smaller than those in the top-tight joints.



(a). Ordinary joints (b). Square-end joints (c). Round-end joints

Fig. 11. Irregular-end joints [82, 83]

Table 11 Research results of different types of full-scale truss

Truss type	Load form	Failure feature	Parameter	Data	Reference
Fink truss	Uniform load of top chord	—	Max deflection	The predicted value of semi-rigid assumption is 34% smaller than the fixed value	[73]
			Max bending moment	The predicted value of semi-rigid assumption is 13% smaller than the fixed value	
Howe truss	Four Concentrated Loads on String	All the buckling failures occur at the W2 web, but the buckling failure directions of different trusses are different.	Critical buckling load (test)	36.7kN	[74]
			Critical buckling load (prediction)	34.3kN	
			Lateral support force (test)	0.33%	
			Lateral support force (regulation)	0.2%	
Attic truss	Cyclic loading	—	Short-term deflection	Maximum deflection reduction percentage between 5.8% and 19%	[75]
Plank pose truss	Long-time loading	Wood fracture, metal plate pull-out	Long-term deflection (max)	26.2mm The long-term deflection is about 2 times higher	[76]
Scissors truss	Simulation of complex real load	The metal plate of bottom chord joint was torn The compression joint fails with the web member tooth pulled out	Average strength (kN)	BSJ：51.2 HJ：49 8 CJ：33.0 BRJ：52.3 TSJ：43.1	[77]
			Average rotational stiffness (kN • mm/rad)	BSJ：245440 HJ：249600 BIL：103700 TSJ：33800	
Howe truss	Design load for western Canada	Failure of member or metal plate without shear or buckling failure of top chord	Max design load	4.9kN/m	[78]
			Max limit load	19.2kN/m	
			Max midspan deflection	29mm	
Parallel chord truss			Max design load	3.85kN/m	
			Max limit load	12.7kN/m	
			Max midspan deflection	32mm	

8 Performance simulation method

8.1 Material and connection properties hypothesis

The most effective method for determining the behavior of MPCs is to simulate the mechanical behavior of joints using analytical techniques based on known parameters, wood properties and loading conditions, and then verify and correct the model through experiments. This section summarizes the material and connection properties hypothesis and the commonly used analytical model for MPCs. The research on the materials and properties of MPCs mainly includes three aspects, namely metal plate, wood and wood-metal plate connections. In theoretical predictions and analysis of MPC performance, researchers usually consider the metal plate as a rigid or nonlinear isotropic material and also consider the tooth deformation as linear elastic. Furthermore, the tooth can be simplified into simple stress objects or models, such as “cantilever beam on elastic foundation”, “rigid-plastic beam”, “spring”, “linear elastic finite element”.

The anisotropy of wood makes the research and analysis of mechanical properties of metal-plate-connected wood joints complex. In order to simplify the problem and analyze the connection performance, many scholars regard wood as rigid-plastic, nonlinear-elastic or linear-elastic isotropic material. On this basis, the stress state of wood can be simulated by "spring elements" and "finite element units".

The connection between wood and metal plate can be considered as a nearly rigid body between a simple hinge and a rigid body, a semi-rigid node with statically indeterminate structure, or a nonlinear connection, and then the connection between wood and metal plate can be analyzed by "spring elements" or "nonlinear contact elements". Table 12 shows the assumptions of some scholars on these three aspects of the model they proposed.

Table 12 Material and connection property hypothesis of MPC analysis model

Model	Metal plate	Tooth	Wood	Wood-Metal plate connection	Simplified model	Reference
"Nonlinear finite element model"	Nonlinear isotropic	Linear elasticity	Nonlinear isotropic	Spring element	Rigid body connected by nonlinear springs	[84]
"2D nonlinear plane stress finite element model"	Nonlinear isotropic	—	Orthotropic Linear Elasticity	Nonlinear elastic spring element with two degrees of freedom	—	[85]
"3D nonlinear spring element model"	Elastic-plastic bilinearity	—	Isotropic linear elasticity	Three uniaxial springs acting along each spindle	—	[86, 87]
"Cantilever beam model of elastic foundation"	Linear elasticity	Linear elasticity	—	Spring element	Cantilever beam on elastic foundation	[88]
"2D finite element model of contact element"	Linear elasticity	Linear elasticity	Isotropic Linear Elasticity	nonlinear contact element	Spring element	[89]

8.2 Simulation analysis model

After accurately grasping the material properties of each part of MPCs, the selection of a suitable analytical model can effectively analyze and predict the physical and mechanical properties of the joints. Selecting and improving models and optimizing analysis methods has been the continuous development direction of simulation research on the performance of MPCs. Table 13 summarizes various types of analytical models proposed by previous researchers and analyzes the applicability of these models.

$$F=(m_0+m_1|\Delta|)\left[1-e^{-k|\Delta|/m_0}\right] \quad (5)$$

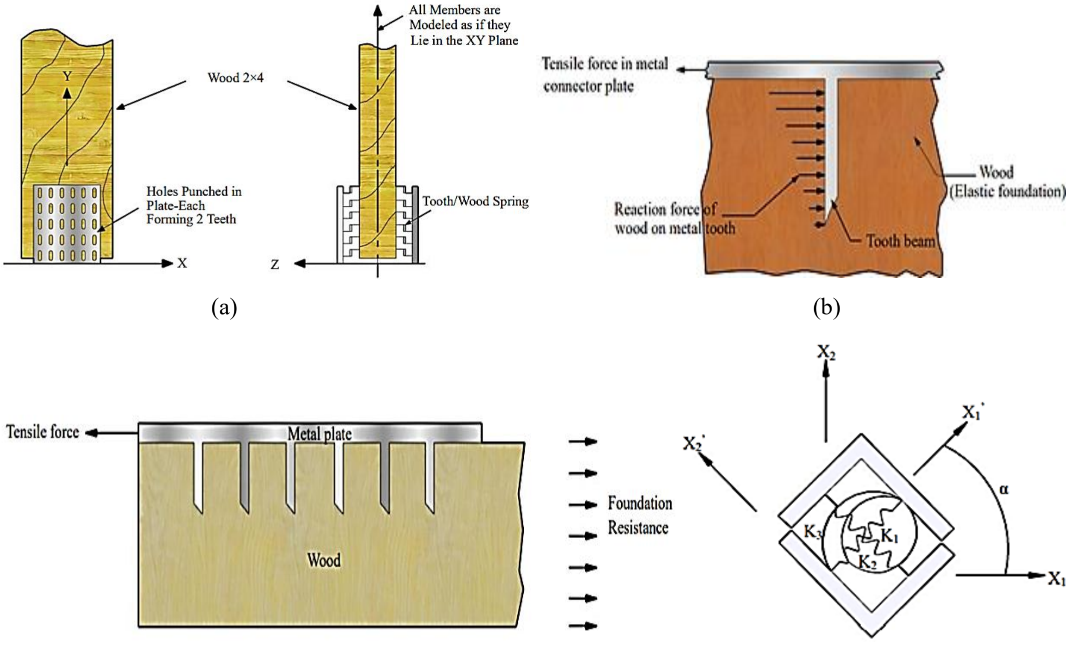
Where F is the force; Δ is the slip; K is the initial stiffness; m_0 is the ultimate load in the case of $m_1 = 0$; m_1 is the stiffness at large slips.

$$EI\frac{d^4y}{dx^4}=-ky \quad (6)$$

Where y is the longitudinal deflection of the beam, and assuming $y=e^{mx}$; E is the Measure of effectiveness (MOE) of the beams; I is the moment of inertia of the beam; k is the foundation modulus of wood around the beam.

Table 13 Analytical models and applicability

Method	Abbreviations of the model	Usage	Serviceability	Related formulas	Schematic diagram	Reference
Finite element method	Nonlinear finite element model	Determine the load-slip characteristics of the joint/Check the plate-tooth-wood interface element	Some parameters need to be determined by test	Eq. 5	—	[84, 90]
	2D nonlinear plane stress finite element model	Estimate the internal deformation, stress conditions and ultimate strength of tensile joints/ Predict the influence of the bending performance of gap	Not suitable for the situation of larger metal plate or excessive stress deflection in the plastic range	—	Fig. 12(a)	[85]
	A improved version of Foschi's model	The semi-rigid and non-linear assumptions of joints and the contact problem between wood components are considered	Not applicable to high level loads because the stiffness will be overestimated	—	—	[91]
	A finite element model	Predict the axial stiffness of tension splice joints and heel joints in wood trusses	Does not need empirical factors in predicting the axial stiffness	—	—	[92, 93]
Contact element analysis method	3D nonlinear spring element model	Analyze the joint force and the interaction between wood interfaces/ Forecast the axial load-displacement relationship of the joint	Lack the consideration of the interaction between the teeth	—	—	[86, 87]
	2D finite element model of contact element	Predict the axial stiffness of tensile joints	Does not require any other validation tests except for the basic properties of materials	—	—	[71]
Elastic foundation model	Cantilever beam model of elastic foundation	Analyze the axial and rotational stiffness of joints	Need to know the density and moisture content of wood, geometric parameters of metal plate and loading conditions		Fig. 12(b)	[88]
	—	Study the stiffness of MPCs and the mechanical properties of tensile joint	—	Eq. 6	Fig. 12(c)	[94]
	—	Predict the stress, ultimate load and failure mode of the tensioned joint	Consider less of the influence of density and moisture content of wood and concentrated load	—	—	[95]
Other models	3-spring model	Predict the axial stiffness, shear modulus and rotational stiffness characteristics of the joint	—			[96]
		Explain the eccentricity and the nonlinear semi-rigid properties of the joint/Calculate the geometric characteristics of each metal plate-wood contact surface	—			[97]
	—	Obtain the relationship between the connection stiffness of the metal plate and the contact area of the metal plate	—		Fig. 12(d)	[98]



(a) (b)

(c) (d)

Fig. 12. Schematic diagram of the analysis model

8.3 Simulation analysis software

The existing mature computer simulation software for trusses includes Structural Analysis of Truss (SAT) and Purdue Plane Structure Analyzer II (PPSA II).

SAT was developed based on Foschi's method for analyzing truss structures. The software can simulate the load-slip characteristics of an MPC under various loading conditions. In the simulation, the truss is regarded as a linear elastic frame structure and the MPC is regarded as a nonlinear connection. PPSA II obtains the stress and displacement of each component required for the truss design, assuming that the joints are fixed and the components have linear elastic properties. Wang et al. [99-101] developed a series of economical, efficient and reliable non-destructive testing (NDT) methods to measure the modulus of elasticity (MOE), shear modulus and Poisson's ratio of lumber. According to the actual experimental results, the elastic modulus of hypothetical components can be compared and corrected by PPSA II software.

In addition to the above-mentioned two software for truss research, the stiffness, stress and displacement distribution of joints can be predicted by Ansys, SAP2000, SAMPC and other software based on the geometric characteristics and material properties of MPCs. Some scholars [102-107] use these procedures to study MPCs, and Table 14 summarizes the advantages and disadvantages of these software. The development of simulation software greatly simplifies the complex process of structural calculations, which is the inevitable way for the development of modern structural design.

9 Conservatory measure

Wood is an inflammable and corrosive material. Anticorrosion and flame retardant measures of MPCs are beneficial to improve the performance of the joints. Perciva et al. [108] studied the effect of flame retardant measures on the stiffness and ultimate strength of MPCs. The test results showed that the ultimate strength of the connection decreased when the wood was treated with flame retardant. At a moisture content of 20%, the joints from flame retardant treated wood were slightly harder than those of the control group, but this difference would disappear as the wood dried. Laidlaw et al. [109] studied the influence of anti-corrosion treatment on joints. They assume that joints from wood treated with copper chromate arsenate (CCA) lose some strength after two or three years, while wood treated with organic preservatives barely lose strength after four years. Oliva et al. [110] carried out load tests on three types of joints (one from untreated wood and the other two from treated wood with creosote oil) to qualitatively determine if the treatment affects the strength or stiffness of the joints. Compared to untreated wood, the joint bearing capacity and stiffness of wood treated with creosote oil were improved. Li et al. [111] studied the system performance of MPC truss components with plywood sheaths. The results showed that the plywood sheathing not only helped to increase the stiffness of the chord members of the truss, but also played the role of a distribution beam that transfers the load from the loading or harder truss to the unloading or more flexible truss system model.

Table 14 MPC Performance analysis software

Type	Advantages	Disadvantages	Research content	Reference
SAP2000	Convenient spatial modeling and perfect function	Weak function in elastoplastic analysis	A semi-rigid nonlinear heel joint model is developed	[102]
			Model of heel joint is developed	[103]
			Accurate modeling of truss components	[104, 105]
SAMPC	Simulation details Better realistic joint configuration and joint behavior under load conditions	Small application scope and low popularity	Building MPC model The out-of-plane rotational stiffness modeling of MPC joint was studied for the first time.	[106]
ANSYS	More convenient and flexible application Nonlinear analysis available	Not accurate enough Long processing time for complex models	Optimized timber use in MPC timber truss	[107]

10 New developments of MPCs

The energy problem of modern buildings is quite serious [112], but engineered wood can alleviate this problem to a certain extent, and in this context MPCs have also been improved. Raw wood is formed into engineered wood after a series of chemical and physical processes, which have the advantages of environmental friendliness, high performance, and standardization [113-117] and it has been widely used in different types of timber buildings [118, 119]. MPCs are no longer just used for light wood trusses, but are also increasingly used in wood frame structures and wood shear wall structures. Table 15 summarizes various cases of MPCs made with modern engineered wood instead of raw wood and discusses their feasibility.

Table 15 MPCs made with modern engineered wood

Engineered wood	Feasibility	Reason	Reference
laminated veneer lumber (LVL)	Feasible	The strength of LVL has no negative effect compared with the equivalent sawn wood	[120]
laminated strand lumber (LSL)	Feasible	Performance of LSL joints is better than that of solid South pine joints under tensile (51%) and shear (10%) loads	[31]
Pine plywood	Feasible	MPCs have good performance in pine plywood	[121]

Emerson et al. [122] compared the bending stiffness and the strength performance of traditional nail-connected wood frames and MPC wood frames to determine if the traditional shear wall can be improved by using MPCs for frame connections. The results showed that MPCs were beneficial for the bare frame and sheath walls, and that connection stiffness and strength increased with the size of the plate. Compared with the retaining wall with MPCs, the end stud-connected retaining wall had lower stiffness and yields loads. This study verified the feasibility of improving the timber shear wall by MPCs.

Due to the superior performance of modern engineered wood, its application is becoming more and more widespread [123-126]. This new material combined with MPCs improves the mechanical properties of the joint and combines it aesthetics and environment-friendliness. Therefore, strengthening the research on this aspect is also the future trend of MPC research and application development. In addition, the growth cycle of bamboo is shorter than that of wood, and the resources are abundant. The mechanical properties of engineered bamboo are also better than those of engineered wood [127-129]. Therefore, exploring the combination of engineered bamboo and MPCs is an important direction for future development.

11 Conclusions and suggestions

According to the summary and analysis of the experimental research conducted by the above scholars, the following conclusions are mainly obtained：

(1). There are three main factors affecting the mechanical properties of MPCs: the various parameters of material, the different connection forms of MPCs, and the external environment. Choosing the appropriate size of metal plate (not the bigger the better) can not only save material and cost, but also improve the strength of the connection and prevent brittle failure. The bending moment and the tooth hole are averse to the properties of MPCs, and the hole induces the stress concentration. Dynamic load has little effect on ultimate strength of MPCs, but has an adverse effect on joint stiffness. Frequent weather changes will lead to an increased creep and a decreased performance of MPC wood trusses, so such regions are not suitable for MPCs.

(2). Metal-plate-connected joints are widely used in wood trusses. When the truss is subjected to force, the metal plate is often in the state of shear-tensile composite force. Due to the different modes, the control section and the type of control load, which makes the form of failure different. Wood trusses with special-shaped end joints can be used to shorten the construction period and save materials, but only in cases of low requirements for buildings.

(3). Since wood belongs to biomass materials, it is easy to be corroded, so it is very important to take good protective measures. Effective protective measures can not only improve the performance of MPCs to achieve the goal of service life requirements and improve the safety of the structure. Common protective measures include protective coating or jackets on the surface of components, etc.

(4). Most of the previous studies were based on the performance test of MPCs with timber. In recent years, some scholars have been actively exploring the feasibility of this combination of modern engineered wood material and MPCs. The application of MPCs is becoming more and more extensive, not only applied in wood trusses, but also in bridges, shear walls and other structures or components.

At the same time, there are many aspects that have not been improved in previous studies. In view of these aspects, some suggestions are put forward for future research directions:

(1). The metal plates used in this paper are regular rectangular metal plates. At present, scholars have studied the mechanical properties of metal plates with special shapes, such as pentagon plates, but they are not comprehensive. The research on the shape of the steel plate is helpful to find new connection forms of wood structures and improve the bearing performance of MPCs. Research on fire resistance of MPCs is also relatively new, which is a worthwhile research direction.

(2). At present, most studies on the mechanical properties of MPCs are tested by static loading.

However, there are few researches on fatigue and creep properties of joints under cyclic loading to determine the design load and predict service life of joints. Few research related to studying the seismic load, the wind load and other dynamic loads apply to MPCs, so the research in this field should be expanded.

(3). Although the feasibility of the combination of MPCs and modern engineered wood materials has been studied, there is still a lack of detailed research on the mechanical properties. Based on current research, it is possible to conduct more progressive research on it, and explore its tensile, shearing and other specific properties.

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Conflict of Interest

The authors declare no conflict of interest.

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