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Challenges in High-rise Wooden Structures and the Seismic Design in Japan

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Abstract Research and development on high-rise or large-scale wooden buildings have been actively conducted both domestically and internationally. The trend of high-rise wooden buildings is driven by increasing awareness of environmental issues. To utilize wooden materials in buildings is believed to lead to the reduction of the environmental impact. On the other hand, Japan is one of the most earthquake-prone countries in the world, and many wooden detached houses have been damaged in past major earthquakes. This paper summarizes the issues that arise in the realization of medium- and high-rise wooden buildings in Japan, and introduces the initiatives that have been seen so far.

Keywords Cross laminated timber, Passive control structure, Hybrid structure

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1. Introduction

At the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, the Paris Agreement was adopted as a new international framework for greenhouse gas reduction. The Paris Agreement stipulates that all countries that have signed the agreement must implement effective measures to address the threat of climate change and contribute to building a global environmentally friendly society on a global scale.

In Japan, the establishment of a decarbonized society has been set as a policy goal, and the roadmap for achieving zero emissions by 2050 includes a 46% reduction in greenhouse gas emissions by 2030 (compared to 2013 levels). Through the use of wood in the construction sector, we have to contribute to the realization of a decarbonized society by strengthening the CO_2 absorption effect of forests.

In 2010, the Law for the Promotion of the Utilization of Wood in Public Buildings was enacted. This expanded the potential for wood use through technological innovations in seismic performance and fire resistance, as well as the rationalization of building standards. In 2021, the law was further amended to promote the use of wood in buildings in general, including private buildings. Further active use of wood is required.

On the other hand, Japan is one of the most earthquake-prone countries in the world, and many wooden detached houses have been damaged in past major earthquakes. However, each time Japan has experienced earthquake damage, laws have been revised and earthquake resistance standards have been gradually raised. Relatively new wooden construction methods, such as moment resisting glulam structures, have not collapsed in major earthquakes and are being actively evaluated through full-scale tests.

This paper summarizes the issues that arise in the realization of medium- and high-rise wooden buildings in Japan, and introduces the initiatives that have been seen so far.

2. Technical issues on high-rise wooden structures in japan

2.1 Seismic design

Table 1 summarizes the required structural calculation methods according to the building height and the structural type. The structural design of low-rise buildings is based on Route 1 and Route 2, which are so-called allowable stress designs. They assume strong earthquakes which could occur several times during the lifetime of the building, and demand enough high strength instead of not requiring deformation capacity.

On the other hand, the structural design of high-rise buildings requires Route 3 or more advanced calculations such as Calculation of Response and Limit Strength (CRLS) or time history analysis. Route 3 requires secondary seismic design in addition to allowable stress design. The

Table 1. Required structural calculation methods according to the building height and the structural type

Number of floor	Height	Wooden post and beam construction		CLT panel construction	Steel building	RC building
		Floor area ≦ 500m^2	Floor are > 500m^2			
	≦ 60 m >31 m	Route 3		Route 3	Route 3	Route 3
	>20 m >13 m	Route 2			Route 2	Route 2
3			Route 1	Route 1	Route 1	Route 1
2 1		Specification code				

Table 2. Necessary fire resistance performance for each member

		Column	Beam	Floor	Shear wall		Stairs	Roof
					Exterior	Partition		
1st to 4th floor from the top	1	1 hour					30 min	
	2							
	3							
	4							
5th to 14th floor from the top	5	2 hours						
	6							
	7							
	8							
	9							
	10							
	11							
	12							
	13							
	14							
15th or more floor from the top	15	3 hours		2 hours				
	16							

secondary seismic design assumes extraordinary earthquakes which could occur once in the lifetime of the building. The intensity of seismic force is described by standard base shear coefficient C_0, and it must be larger than 1.0. The required base shear coefficient can be reduced according to the plastic deformation capacity represented by D_s factor (structural characteristic value). Building Standard Law (BSL) provides D_s factor for every structural type, and the values are 0.25 to 0.5 for wooden structures. Although structural designers have to decide appropriate D_s value, it is quite confusing because of the less information.

The Route 3, which was established in 1981, does not give earthquake response like maximum story drift angles originally. The idea of D_s factor is often explained using Energy Conservative Rule proposed by Newmark and Hall (1974) as shown in Figure 1. It indicates that the structure must permit a certain level of deformation and the corresponding damages after a major earthquake. Although the design criteria of maximum story drift angle for wooden structures is generally less than 1/30rad, it is unlikely to be adequate to use the same criteria for high-rise buildings.

2.2 Fire design

Table 2 summarizes the required fire resistance performance for each member. 1-hour fire resistance performance is required for the main structural members such as columns, beams, floors and walls in the upper four floors. 2-hour fire resistance performance is required in 5th to 14th floors from the top except for some cases. In order to provide wooden buildings with 2-hour fire resistance performance, the structural members have to meet specifications that have obtained ministerial certification. Designers can refer to manuals released by some industry groups and meet the specifications. Basically, wooden members have to be covered by gypsum boards with enough thickness, and it increases the building weight. Therefore, mixed

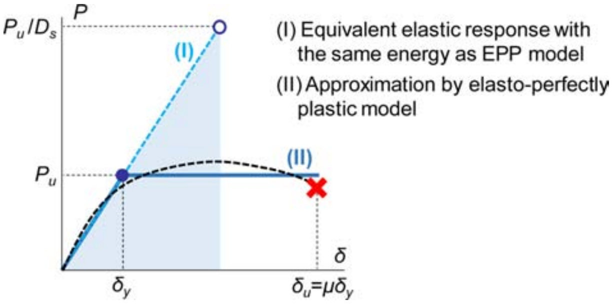


Figure 1. Energy Conservative Rule proposed by Newmark and Hall (1974) and the relation to D_s factor.

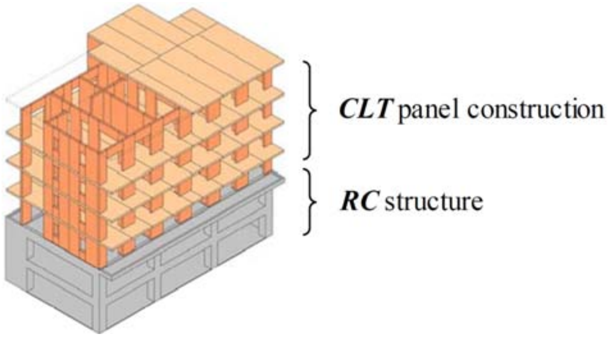


Figure 2. An example of a mixed structure along the building height. (involving RC structure in the lower stories)

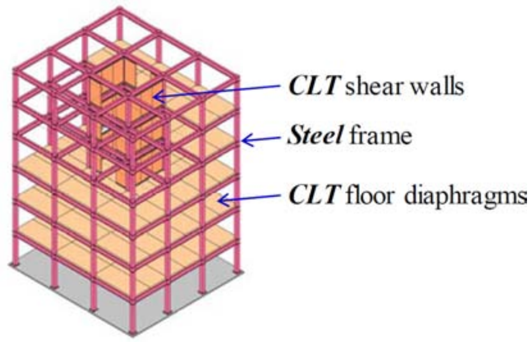


Figure 4. An example of a hybrid structure utilizing CLT panels as shear walls or floor diaphragms.

structures involving reinforced concrete structures in the lower stories to minimize the number of stories in wooden parts less than five are sometimes adopted as shown in Figure 2.

Although wood has relatively high strength despite its low weight, higher wooden buildings are likely to be heavy because of the fire proof specification. Table 2 shows the comparison of typical building weight. Low-rise wooden detached houses are about 2 kN/m^2 of weight per floor area in every story. However, high-rise wooden buildings are about 6 kN/m^2, which is similar to that of steel buildings.

3. Recent trend of middle- to high-rise wooden structures in Japan

Research and development on high-rise or large-scale wooden buildings have been actively conducted both domestically and internationally. As for high-rise wooden buildings, progressive examples can be seen in foreign countries. 24-story wooden building was built in Vienna, and 18-story wooden and concrete building was built in Vancouver.

On the other hand, 7-story wooden building was built in Sendai, Japan. 11-story wooden building which is a

Table 3. Comparison of typical building weight

	Weight per floor area in every story (kN/m^2)	Reference
Low-rise wooden detached houses	2	JBDPA, 2012
Ten-story wooden office building with 1-hour fire resistance	5	Akiyama, 2021
Ten-story wooden office building with 2-hour fire resistance	6	Akiyama, 2021
Steel office building	6	Akiyama, 2021
RC building	12	JSCA, 2019

Figure 3. Cross laminated timber (CLT) and the maximum size of CLT panel fabricated in Japan. (3 m × 12 m)

Figure 5. Full-scale shaking table test on 7-story wooden building at E-defense in 2009. (First story is steel structure)

base-isolated structure was also completed this year.

The trend of high-rise wooden buildings is driven by increasing awareness of environmental issues. To utilize wooden materials in buildings is believed to lead to the reduction of the environmental impact. Recently, software to calculate the environmental impacts of a building were developed, and the life cycle assessment has become available (ex) https://www.oneclicklca.com/). Cost efficiency is unlikely to be so emphasized. Total cost of a wooden building tends to be higher than the one of a steel or concrete building. However, wooden buildings are likely to be constructed more quickly rather than concrete buildings because the curing time of concrete is not required.

Cross laminated timber (CLT) is a relatively new material, and they are utilized in mid- to high-rise buildings (Figure 3). In Japan, a technical standard regarding CLT construction was established in 2016. The number of CLT constructions including partial use will reach one thousand this year. CLT panel construction not including mixed structures has a track record of building structures of up to five stories. Generally, CLT is characterized by its orthogonal layers, which mitigate anisotropy, suppress splitting failure, and enable the production of large-size panels. On the other hand, the orthogonal layers reduce the cross-sectional strength in bending, compression, and tension to about half that of glued laminated timber (glulam). This is the reason why CLT is often used in mixed structures as shown in Figure 4.

The highest wooden building in Japan so far is 11-story, which is a base isolated structure. For each project, new techniques such as wooden joints are often developed, tested, and modeled for structural analysis. It is always a difficult challenge to increase the strength capacity while ensuring plastic deformation capacity. Therefore, a base isolated structure is likely to be a suitable solution since only an elastic design is required.

Full scale shaking table tests have been conducted on mid- to high-rise wooden structures at E-Defense (5-story of CLT panel construction in 2014 and 7-story light-frame wood construction in 2009 Japan-U.S. joint experiment shown in Figure 5), which has demonstrated that it is possible to build a safe wooden structure against major earthquakes. However, it is necessary to develop versatile design methods and joint details.

In such a situation, a trial design example of a 10-story wooden building was presented at 2021 Architectural Institute of Japan (AIJ) annual meeting (Akiyama, 2021). Figure 6 shows the joint details and the building elevation. Drift pinned joints with insert-steel plate, which do not

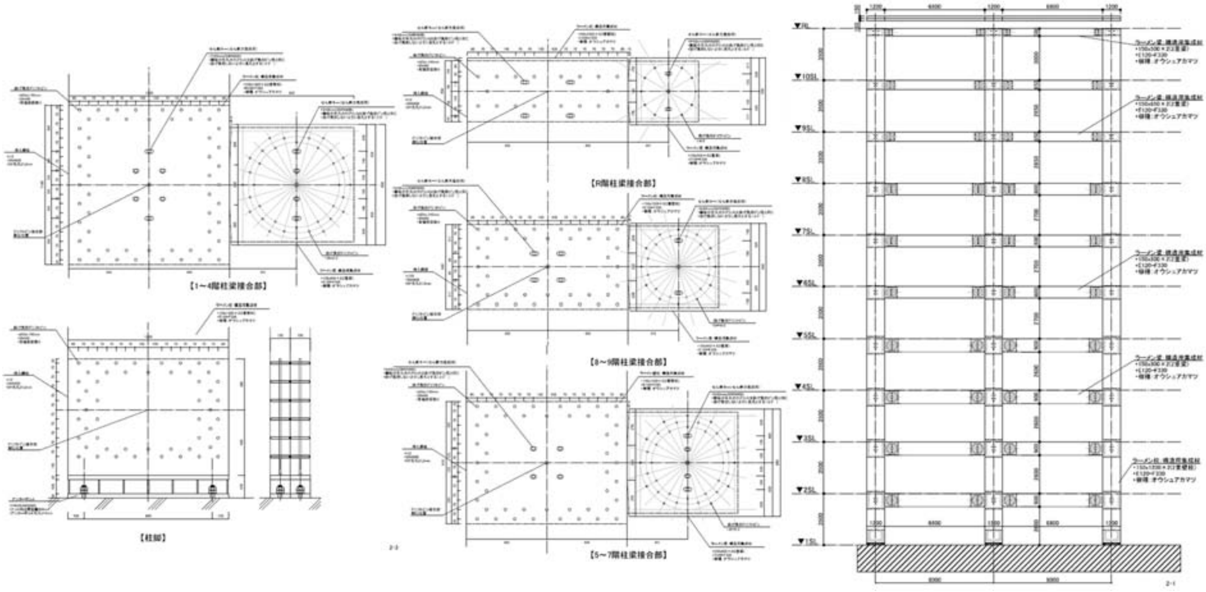


Figure 6. Trial design of 10-story wooden building presented in 2021 AIJ. (Akiyama, 2021)

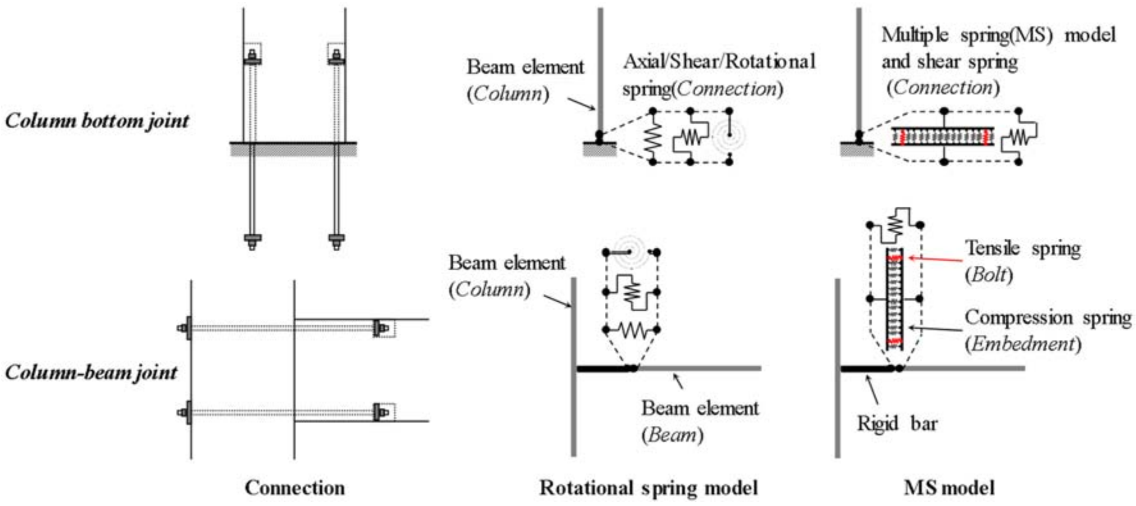


Figure 7. Framing models of wooden connections. (An example of tensile-bolted joint)

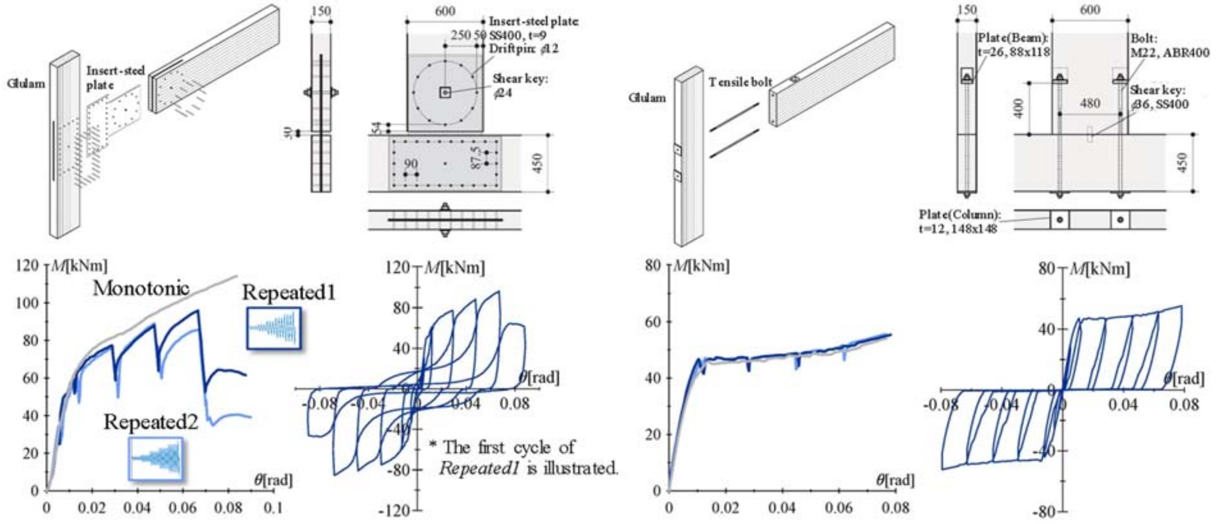


Figure 8. Typical moment resisting joints and the moment M-rotation θ relations. (Left: Drift pined joint with insert-steel plate, Right: Tensile-bolted joint)

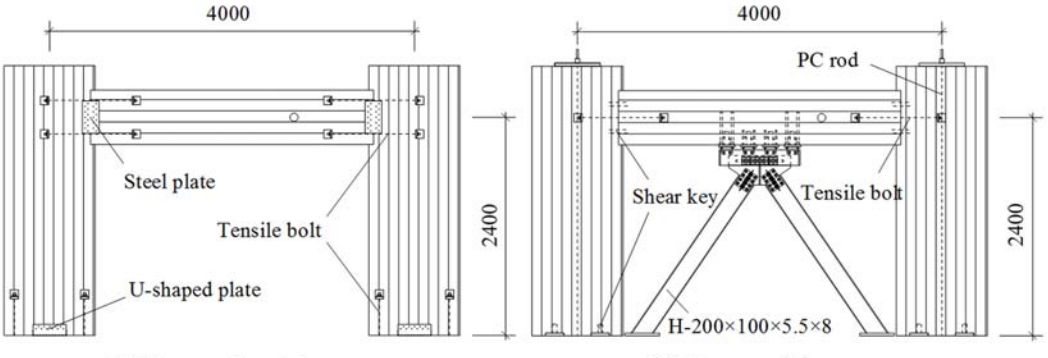
require special connectors and are one of the common joint methods, are applied. The cross section of columns is 300 mm × 1200 mm, and their spans are 3.0 m and 8.0 m in each direction.

4. Introduction of recent technique enhancing seismic performance to high-rise wooden structures

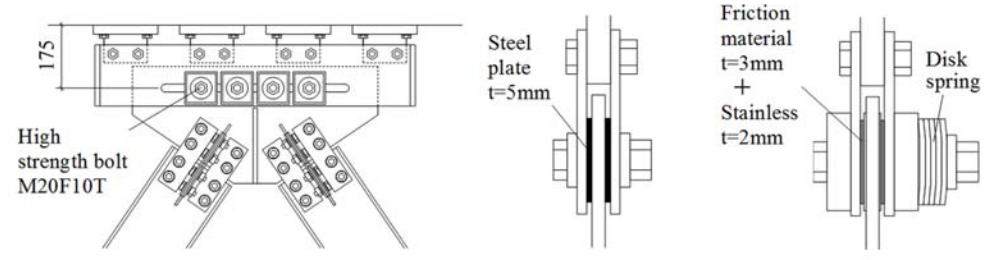
4.1 Characteristics of wooden structures

Most of the small-scale wooden buildings in Japan have so far been wall-type structures. Moment resisting frames are also applied, but since the joints are semi-rigid, a framing model with rotational springs modeling the joints is necessary for the structural analysis (Figure 7). Some guidelines give methods for determining the characteristics of the rotational spring, but if not available, experiments should be conducted. Generally, about half of the horizontal stiffness of a structure is derived from the joints. Shear walls may be used in combination with moment resisting frame.

Multiple-spring model is also applied for the joint where axial force and bending moment are coupled such as column base (Figure 7: right). Since wood itself has almost no plastic deformation capacity (except in compression) and many high-strength connectors such as Lagscrew bolts (LSB) or Glued-in rods (GIR) also have no plastic deformation capacity, most of the design examples are based on a concept that allows anchor bolts to yield in advance. However, assurance design on the wooden side is difficult. To supply additional damping equipment or core structure having high lateral stiffness is one of the expected solutions to enhance the seismic performance.

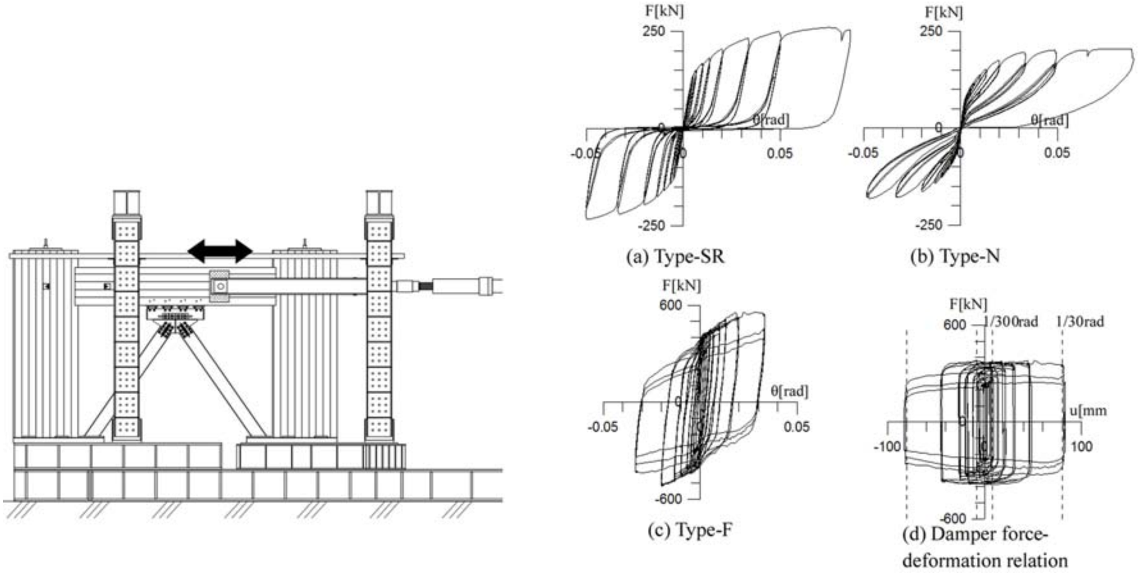


(a) Conventional frame (b) Proposed frame



(c) Front view (d) Type-R (e) Type-F

Figure 9. Conventional CLT frame(a), post-tensioned CLT rocking wall with/without brace-type friction damper(b) and the details of damper((c)-(e)). (Matsuda et al., 2017)



(a) Type-SR (b) Type-N (c) Type-F (d) Damper force-deformation relation

Figure 10. Force F- story drift angle θ relation of conventional frame((a) Type-SR), post-tensioned CLT rocking wall without damper((b) Type-N) with damper((c) Type-F) and damper hysteresis(d) (Matsuda et al., 2017).

These examples will be presented in section 4.2-4.4.

4.2 Passive control structure

Wooden structures typically have slip-type hysteresis characteristics and absorb little energy in a deformation cycle. For example, a drift pined joint with insert-steel plate in which the steel pins repeatedly yield in bending, has some energy absorption while a tensile-bolted joint has quite low energy absorption as shown in Figure 8 (Yamazaki et al. 2022).

CLT panel construction is increasing in Japan, and there are examples of improved energy absorption performance by installing dampers (Matsuda et al., 2017). Figure 9 illustrates post-tensioned CLT rocking wall with brace-type friction damper and the details, and Figure 10 shows force- story drift angle relation of conventional frame((a)

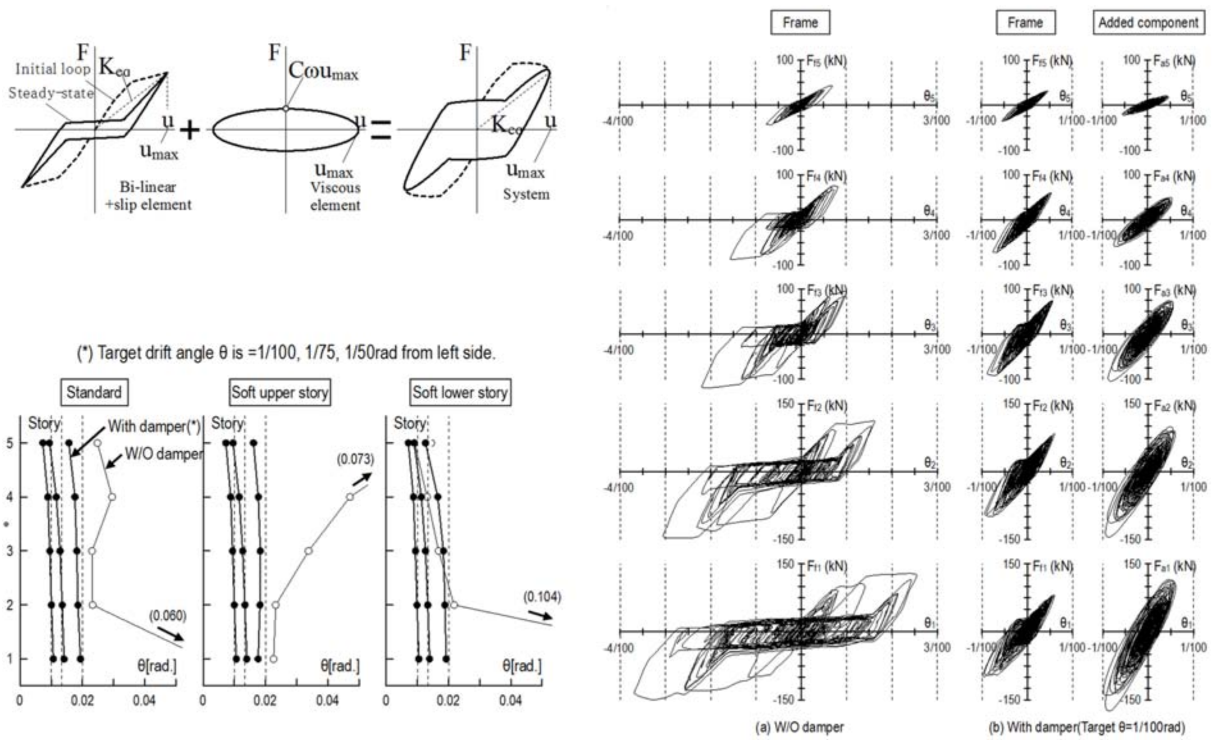


Figure 11. Passive control design for wooden frame using visco-elastic dampers. (Matsuda et al., 2015)

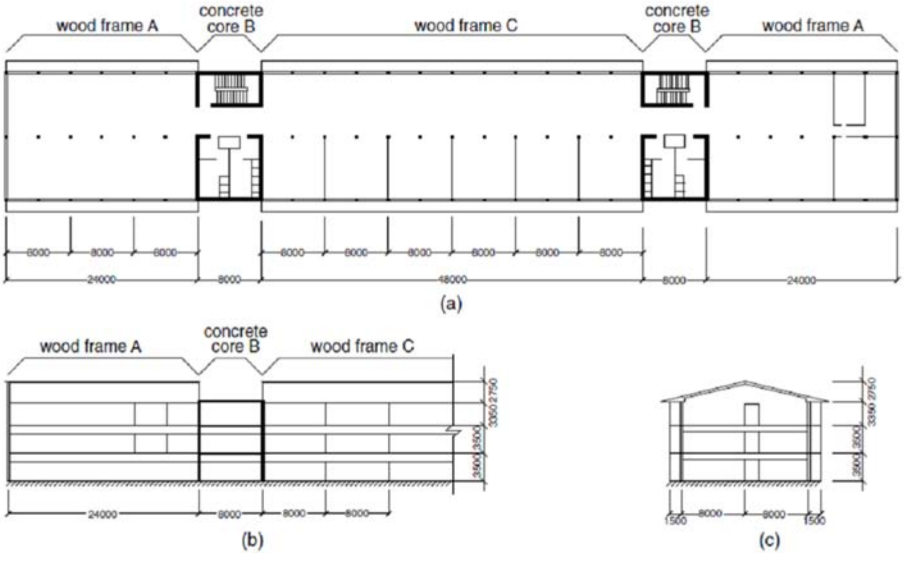


Figure 12. Prototype school building presented in 2012 AIJ. ((a) plan, (b) elevation, (c) side view, Wu et al., 2018)

Type-SR), post-tensioned CLT rocking wall without damper ((b) Type-N), with damper((c) Type-F) and the damper hysteresis(d), respectively. It is found that Type-N is provided with self-centering performance while Type-F shows good energy absorption performance.

In Japan, a design manual for passive control structure, which mainly targets medium- to high-rise steel buildings, has been published by The Japan Society of Seismic Isolation (JSSI), and it helps better understanding of passive control structures for designers. There is a case study of the application of this concept to wooden structures (Matsuda et al., 2015). A design method is proposed in which the slip-type hysteresis characteristics are improved with dampers while the inter-story drift angle of each story is made uniform. Figure 11 shows the results of time history analyses of 5-story wooden structures with/without dampers. By properly adding dampers in each story, equal distribution of story drift angles is achieved.

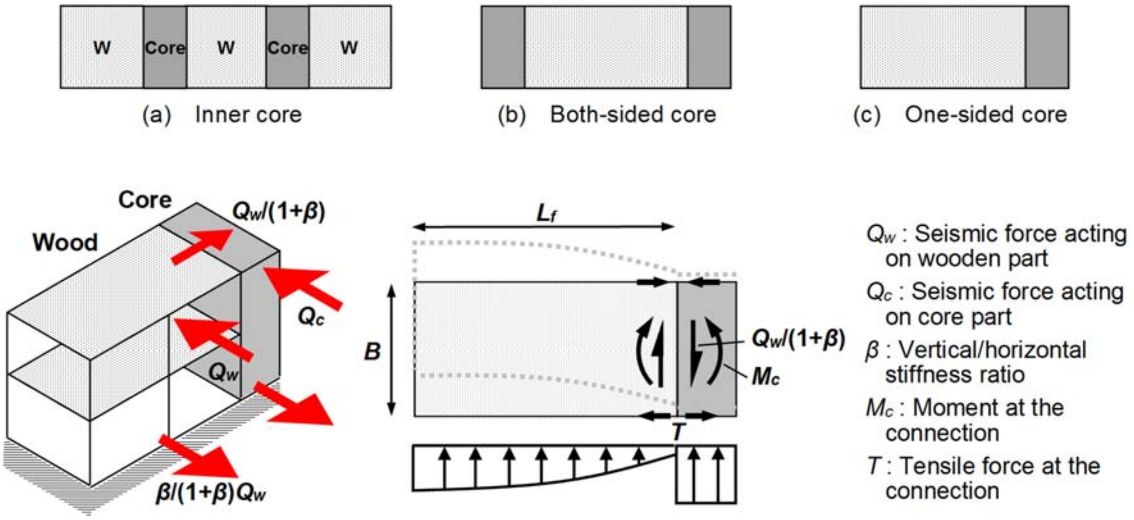
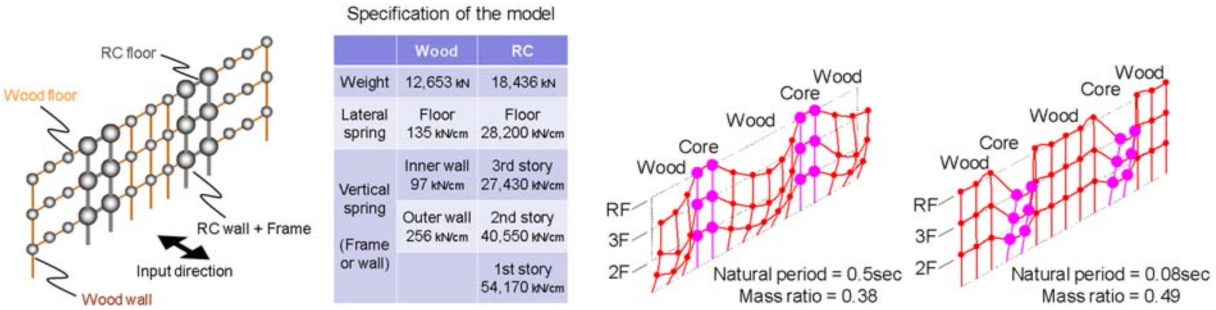


Figure 13. Configuration of cores and the Force balance.



Specification of the model

	Wood	RC
Weight	12,653 kN	18,436 kN
Lateral spring	Floor 135 kN/cm	Floor 28,200 kN/cm
Vertical spring (Frame or wall)	Inner wall 97 kN/cm	3rd story 27,430 kN/cm
	Outer wall 256 kN/cm	2nd story 40,550 kN/cm
		1st story 54,170 kN/cm

Figure 14. Fundamental vibration modes of horizontal hybrid structure. (Yamazaki et al., 2016)

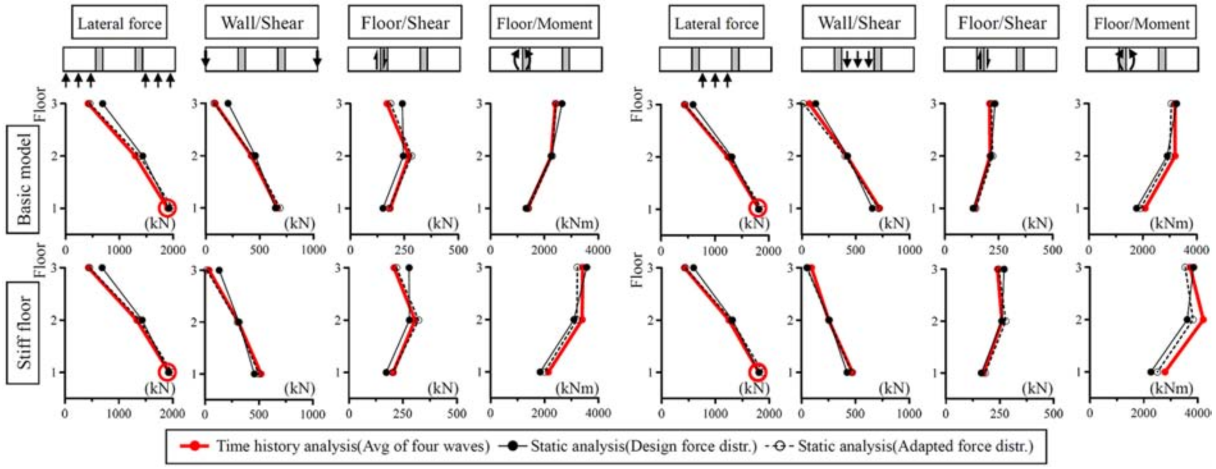


Figure 15. Simulation of earthquake response by static analysis. (Yamazaki et al., 2014)

4.3 Horizontal hybrid structure

There is a concept of a horizontally mixed-plan structure with rigid RC cores while the wooden structure parts are open plan. As mentioned in section 2.2, fire resistant structure is required depending on the height or the floor area of the building, but the wooden parts do not need to be fire-resistant even if the area of each section is limited by fire-resistant walls and other partitions.

In Japan, there are several examples of such mixed-plan structures in low-rise school buildings. The use of RC cores for stairwells has advantages in terms of both seismic and fire resistance. Figure 12 shows a prototype

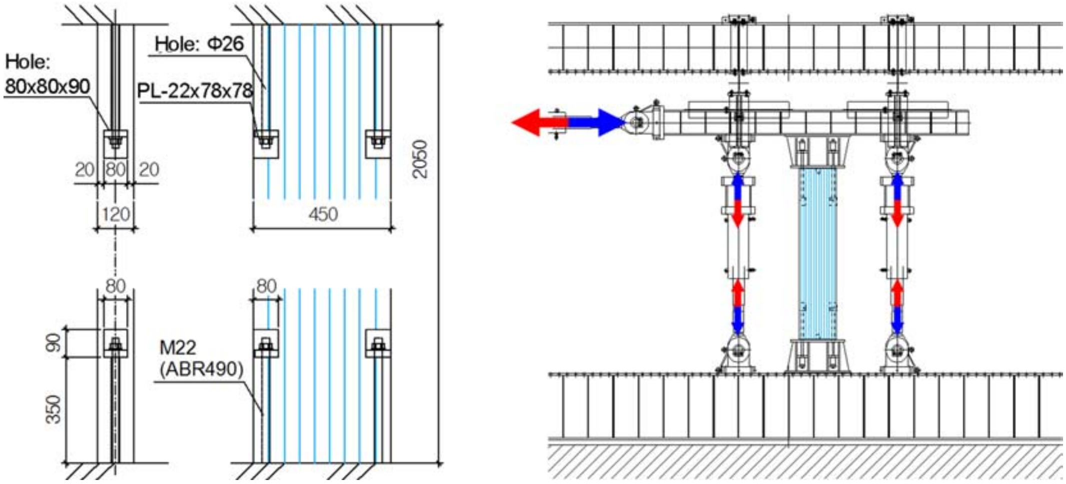


Figure 16. Experiments of tensile bolted-glulam column bottom joints subjected to moment and axial force. (Mizoguchi et al., 2022)

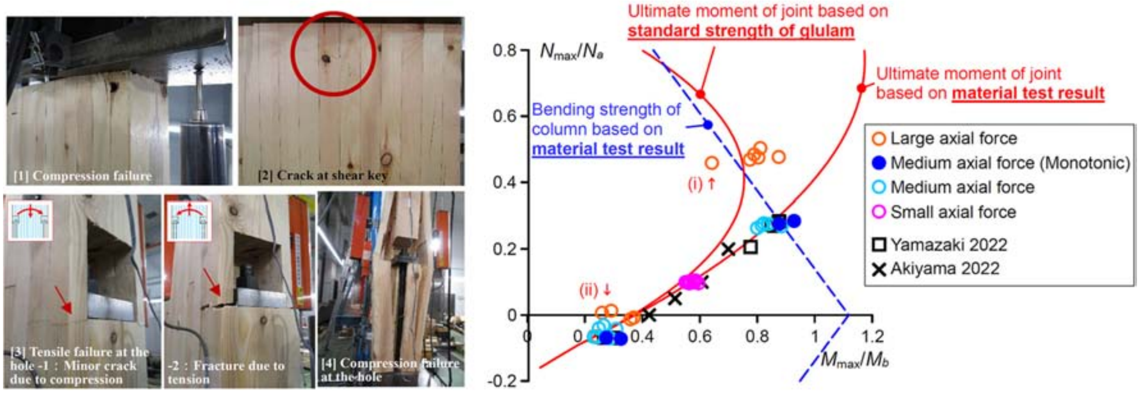


Figure 17. Moment *M*-axial force *N* interaction relation. (Mizoguchi et al., 2022)

of such school building presented in 2012 AIJ (Inayama et al., 2012, Wu et al., 2018).

Since the seismic force acting on the wooden parts is transmitted to the core parts, the design of the horizontal diaphragms and their joints are quite important as shown in Figure 13. It is also known that the structure shows characteristic vibration modes, and since the wooden parts and the core parts vibrate separately in different modes, the equivalent mass ratio is not concentrated in a certain mode, which is generally the first mode, and the total base shear force is not very large for the weight (Figure 14, Yamazaki et al., 2016). In addition, the seismic force distribution is also characteristic. The lateral force is not very large in the upper stories of the wooden parts because it is connected to the stiff cores. As long as the seismic force distribution is properly determined, the stresses can be obtained with enough accuracy by static analysis (Figure 15, Yamazaki et al., 2014).

4.4 Effect of repeated and combined stress

Wood itself breaks brittlely except when compressed, and the failure should be avoided. Because of the variability of strength, the standard strength of wood determined in BSL is specified at the lower 5% limit of the 75% confidence level. The short-term allowable stress is two-thirds of that value. For strong earthquakes, the response stress should be kept within the short-term allowable stress, and for extraordinary earthquakes, the response stress should be kept within the standard strength. Since a safety margin is assumed for the standard strength, the experimental values may be higher than the design values based on the standard strength. Figure 16 shows experiments of tensile-bolted glulam column bottom joints subjected to moment and axial force (Yamazaki et al., 2022), and Figure 17 shows the observed failure modes and the *M*-*N* interaction relation. It is found that the actual strength capacity is higher than the design value especially in high axial force range.

On the other hand, the behavior subjected to cyclic stress is still not understood well. For example, once a wood experiences a level of stress close to the material strength in compression, minor cracks may occur, although there is no stress reduction, and this may lead to a strength reduction in tension (Figure 17: Left [3]-1 and -

2). The plots illustrated with (i) and (ii) in Figure 17 (Right) show specimens fractured by cyclic stress, and their strengths do not reach calculated values. Therefore, in areas subjected to repeated stresses in compression and tension, it may be advisable to secure even safer than the standard strength.

5. Conclusions

Because of the strict earthquake and fire resistance standards for high-rise buildings, Japan lags behind other countries in the realization of high-rise wooden buildings. However, we have been actively developing technologies to improve the earthquake resistance of high-rise wooden buildings by utilizing the seismic isolation, passive control, and mixed structural technologies that have been cultivated over the years.

On the other hand, since new medium- and high-rise wooden buildings in Japan have yet to experience a major earthquake, wooden buildings need to be carefully promoted while also taking advantage of the knowledge obtained from other structures.

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