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Resisting capacity of Korean traditional wooden structural systems subjected to static loading

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Abstract. This paper investigates the structural behavior of Korean traditional wooden structures on the basis of the structural analysis using the commercialized program, SAP 2000. All the structural systems were analyzed, and the rotational stiffness at each joint was inferred from the experimental result for a half scale model of Bongjeong-sa (a temple in South Korea). In addition, the artificial control of analysis parameters was prevented because the structural analysis was focused on the realization of the most exact structural behavior of real structures. The analysis was carried out for the horizontal and vertical static loads, and all the secondary members were excluded in the structural analysis. The obtained results show that the resisting capacity of the primary structural system is greater than that of the expanding structural system.

Keywords: traditional wooden structure; numerical modeling; structural analysis; lateral resisting capacity; moment distribution.

1. Introduction

Even though it seems to be difficult to quantitatively answer to the question “How significantly can the form of house affect the thinking and the behavior of humans?”, it is certain that there is a deep relationship between the two. Particularly because the form of a house is influenced and continuously changed by many factors such as climate, supply of construction material, the condition

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of human resources, and economic state, houses provide a great deal of information about a certain nation or region. However, inclusion of all the influencing factors into the form of a house requires a long socio-cultural transformation because a rapid socio-cultural transformation may cause the direct absorption of different traditions and culture without any consideration for sustaining the identity of one's own traditions and culture.

In the case of Korea, a rapid socio-cultural transformation also emerged in the 1900s during the process of modernization, and the field of architecture was no exception. Both positive and negative changes progressed, and one typical example of a negative change is the clear distinction between traditional wooden structure and new styles of structure because it caused a restriction on the research of the traditional wooden structures. In hindsight, the influence of this change was so significant in that it removed the possibility for the emergence of an architect with the ability to express the essence of Korean traditional architecture or a structural engineer with ability to take a scientific approach towards traditional wooden structure. Traditional wooden structure came to be considered as a relic even though it had been life itself in creating all Korean living spaces.

At present, South Korea holds 22 national treasure and 122 treasure wooden architectural structures. Nevertheless, very little research on the structural behavior of traditional wooden structure has been conducted, and the related research results are limited as well (Hwang *et al.* 2006, Hong *et al.* 2005, Lee *et al.* 2004). However, the need for the preservation of wooden cultural properties and the interest for the traditional wooden structures have increased with an increase in the gross national income, and it is time to conduct more research on traditional wooden structures. With the understanding of the current situation, accordingly, this research was conducted to analyze and compare the resisting capacity of Korean traditional wooden structures.

Korean traditional wooden structure is a prefabricated structure in which complete integration between structural members is not guaranteed. Because of the use of numerous structural members, the traditional wooden structure seems to be statically indeterminate structure with many degrees of indeterminacy, but actually it shows structural behavior similar to that of a statically determinate structure due to the insufficient rotational rigidity at each joint. To sustain such a structure for the long term, accordingly, a balance throughout the transfer of force process must be maintained. Korean traditional wooden structures exist in various forms, such as private houses, public schools of the Joseon Dynasty, Buddhist temples, and royal palaces, and their structural types have been changed according to the required size. However, the magnitude of loading applied to the structure also increased in proportion to an increase in house size, and finally the original structural system would have had a limitation in resisting all the loadings with merely an increase in its structural member size. This means that the need increased for more efficient structural systems and the improvement of conventional structural systems to effectively sustain the increased loadings. Many wooden structural systems that depend only on inherited experience without any verification of the efficiency of adopted structural system have existed and are still used today in the construction of wooden structures.

Accordingly, this paper focuses on the comparison of the efficiency of each structural system in the aspect of the moment resisting capacity in beams and the lateral resisting capacity in entire structural systems. The effect of partial rotational rigidity at each joint on the increase of the resisting capacity is reviewed on the basis of the obtained analytical results. To perform the analysis of each structural system, however, Korean traditional wooden structures must be classified, and many researchers usually use the number of purlines in the roof as the primary parameter and the number of columns and their heights as the secondary parameter for classification (Jang 1993). In

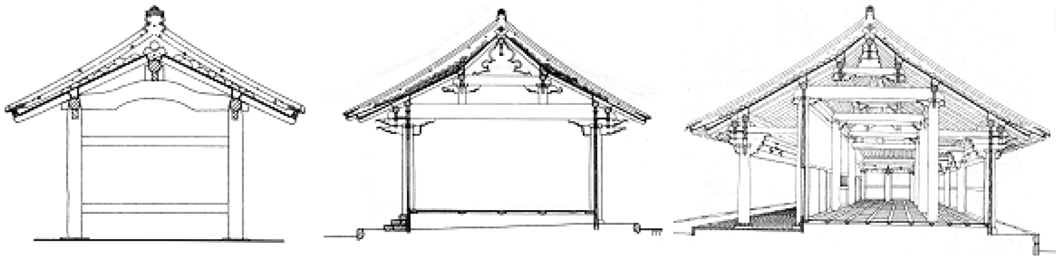


Fig. 1 The basic type of traditional wooden structure (3, 5, 7 roof-purlines)

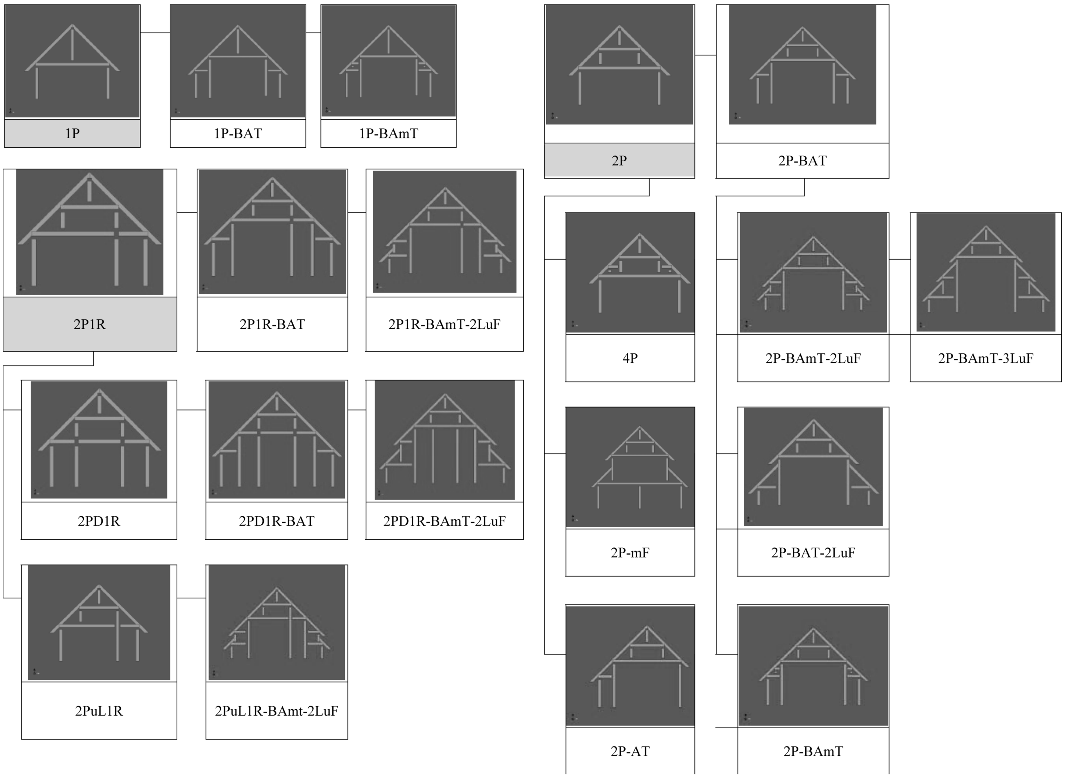
the case of a front-and-rear-symmetric structure, a ridge purline is located at the center so that the structure always has an odd number of purlines, and the structures are classified into four types, as shown in Fig. 1: three roof-purlines, five roof-purlines, seven roof-purlines, and nine roof-purlines. This classification method seems to be convenient and can effectively be used to estimate the size of the structure, but is still insufficient in delivering additional information required in the analysis of the structural system, such as the member size.

Therefore, an improved classification of the Korean traditional wooden structures is introduced in this paper. The classification is initiated first with the shape of moment envelop in a large crossbeam, and is then subdivided into extended structural systems considering the flow of force (Hwang *et al.* 2006). As shown in Fig. 2, the Korean traditional wooden structures are categorized into three basic structural systems: one-point loading type (1P in Fig. 2), two-point loading type (2P in Fig. 2), and Two-Point loading One Reaction type (2P1R in Fig. 2). In the case of the one-point loading type system, a concentrated point loading exerted by the king post is applied on a simple crossbeam, while developing the triangular moment distribution, which has the greatest moment value of the crossbeam at the loading point. On the other hand, the two-point loading type can be characterized by the applied two-point loads exerted by the posts on a simple crossbeam and is followed by the development of trapezoidal moment distribution, which has uniform moment value in the crossbeam between two posts. Finally, the Two-Point loading One Reaction type system is distinguished from the previous two systems by the installation of an additional column between two posts and represents a similar moment distribution to that of the one-point loading type.

Structural analyses were performed to obtain information related to the structural behavior of each structural system. SAP2000 was used for the structural analysis, and the research results from the previous experiment on the structural properties of a wooden national treasure (Hong *et al.* 2005) were applied in modeling the rotational stiffness at each joint of the wooden structure. The basic direction in modeling the structure was to simulate, as accurately as possible, the actual behavior by using the most reliable research results while minimizing artificial control of the analytical parameters. Finally, the analyses were conducted for the vertical and horizontal static loading cases.

2. Modeling of traditional wooden structure

The structural analyses focused on the static behavior of traditional wooden structure subjected to vertical and/or horizontal loadings, and, as was mentioned before, the main objective of this study is to analyze the efficiency of each structural system by comparing the lateral resisting capacity of each structural system and magnitude of moment acting on the crossbeam. Therefore, the



1P	: One-Point loading type
└ 1P-BAT	: One-Point loading Both Aisle exposed Tiebeam type
└ 1P-BAmT	: One-Point loading Both Aisle exposed multi-Tiebeam type
2P	: Two-Point loading type
└ 2P-BAT	: Two-Point loading Both Aisle exposed Tiebeam type
└ 2P-BAmT-2LuF	: Two-Point loading Both Aisle exposed multi-Tiebeam Two Layer uni-Floor type
└ 2P-BAmT-3LuF	: Two-Point loading Both Aisle exposed multi-Tiebeam Three Layer uni-Floor type
└ 2P-BAT-2LuF	: Two-Point loading Both Aisle exposed Tiebeam Two Layer uni-Floor type
└ 2P-BAmT	: Two-Point loading Both Aisle exposed multi-Tiebeam type
└ 4P	: Four-Point loading type
└ 2P-mF	: Two-Point loading multi-Floor type
└ 2P-AT	: Two-Point loading Aisle exposed Tiebeam type
2P1R	: Two-Point loading One Reaction type
└ 2P1R-BAT	: Two-Point loading One Reaction Both Aisle exposed Tiebeam type
└ 2P1R-BAmT-2LuF	: Two-Point loading One Reaction Both Aisle exposed multi-Tiebeam Two Layer uni-Floor type
└ 2PD1R	: Two-Point loading Drift One Reaction type
└ 2PD1R-BAT	: Two-Point loading Drift One Reaction Both Aisle exposed Tiebeam type
└ 2PD1R-BAmT-2LuF	: Two-Point loading Drift One Reaction Both Aisle exposed multi-Tiebeam Two Layer uni-Floor type
└ 2PuL1R	: Two-Point loading uni-Line One Reaction type
└ 2PuL1R-BAmT-2LuF	: Two-Point loading uni-Line One Reaction Both Aisle exposed multi-Tiebeam Two Layer uni-Floor type

Fig. 2 The basic and extended structural types of traditional wooden structure

consistency through all the structural systems in comparing the results is more important than the accurate consideration of the structural configuration, including relatively different member size and the slope of the roof. Accordingly, overall design conditions, such as the space between columns, member sizes of beams and columns, and roof slopes in the three basic structural systems in Fig. 2

(One-Point loading type, Two-Point loading type, and Two-Point loading One Reaction type) are unified with constant values, respectively. The same rule is also taken into account for the extended structural systems in Fig. 2 to maintain consistency.

The rotational stiffness at each joint will be one of the most important factors which governs the structural behavior, but only one related experiment was performed in the case of Korean traditional wooden structures (Hwang *et al.* 2006). Since experimentation usually provides a firm basis for the structural behavior and also supplies the exact information for the rotational stiffness at each joint, it is essential to determine unknown parameters through experimentation in the case of a new structural system. Unfortunately, however, the experiment for a Korean traditional wooden structure was conducted with a half scale model, and only the localized rotational stiffnesses, in which the vertical force effect and the member size cannot be taken into account, were introduced. This is why the numerical model used in this paper is based on an identical scale to that used in the experiment.

2.1 Determination of a basic numerical model

A basic structural system of the Two-Point loading One Reaction type system in Fig. 3, 2P1R is selected as the reference system for the structural analysis of structural systems to maintain the consistency with the experimental model. This model was scaled down to half of the main building at Bongjeong-sa (temple), and typical names for the composed members are be shown in Fig. 4. Fig. 5 shows the corresponding numerical model, and the comparison of both figures represents that (1) in the numerical model, all the secondary members with the exception of the primary members of columns, crossbeams, posts, and rafters are disregarded; (2) both columns are assumed to be identical with a length of 2295 mm, and a post is assumed to be located at the quarter point of the bay between both exterior columns; (3) the shape of the roof is a basic triangular form with a base of 1154 mm and a height of 600 mm, which is made by a rafter, crossbeam, and post; (4) the end of eave rafter maintains an inclined angle of 30° from the center line of the exterior column; and (5) the numerical models for the other structural systems can also be constructed according to the same rule.

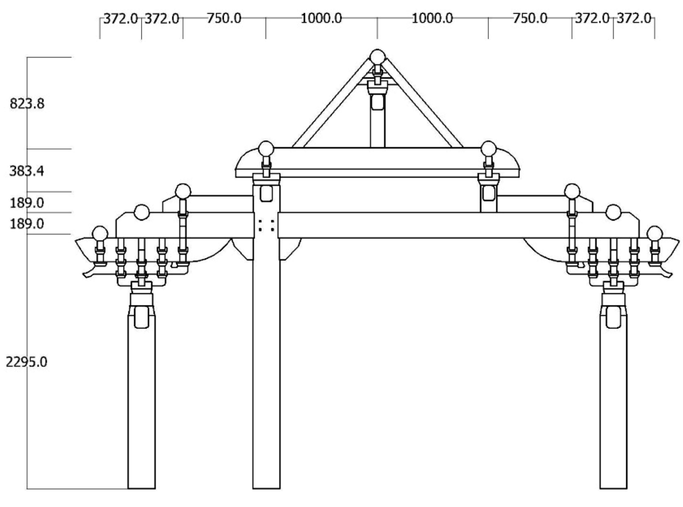


Fig. 3 Prototype model for numerical analysis model (unit: mm)

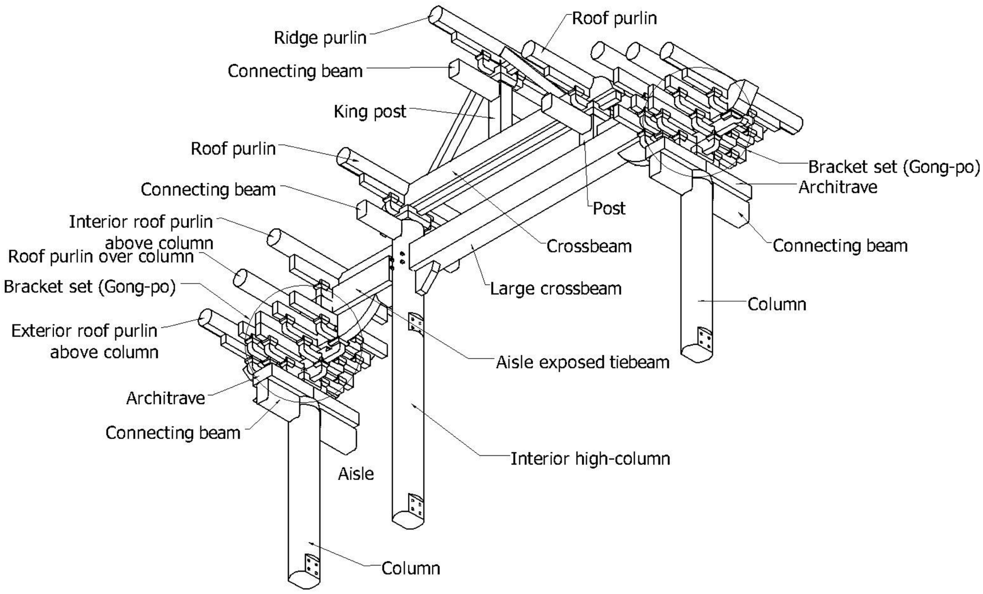


Fig. 4 Element name of Korean traditional wooden structure

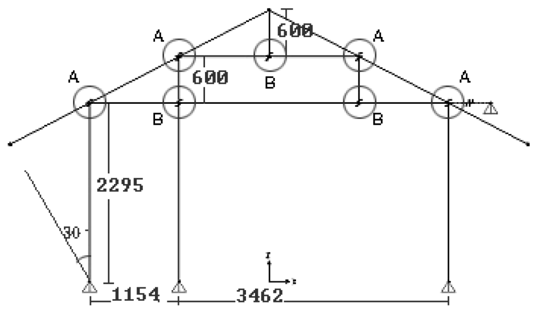


Fig. 5 SAP2000 Numerical analysis Model for Prototype (unit: mm)

2.2 Implementation of analytical conditions

In structural analyses, wood is considered as an isotropic material. The direction of wood's texture is taken as the main axis, and the elastic modulus of wood is assumed to be 6.87×10^9 N/m^2. On the other hand, the analysis of traditional wooden structures composed of a lot of line elements usually accompanies the numerical error induced from the limitation in modeling the structural system with only the complete truss shape. Because the triangle created by the rafter, king post, and small crossbeam represents a perfect truss, the force will be delivered through the truss mechanism, which will cause the king post to carry a smaller axial force than the actual value and finally a wrong result as if no moment occurring at the small crossbeam can be made. To correct such error, accordingly, the stiffness of the rafter was reduced in the structural analysis. Through parametric studies with the changes in the stiffness ratio of the rafter from 1/10 to 1/1,000,000, a contraction rate of 1/1,000, at which the constant axial force is maintained at the king post, was selected, as shown in Fig. 6.

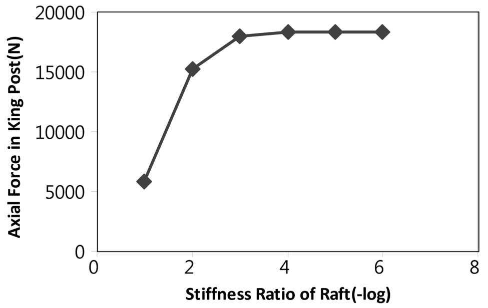


Fig. 6 The ratio of the rafter's stiffness and the axial force of the post

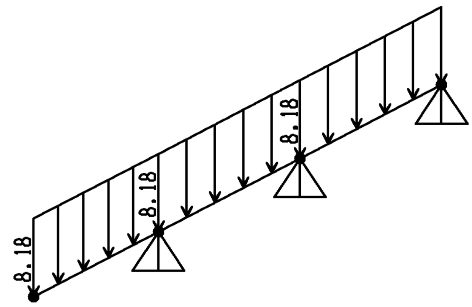


Fig. 7 Uniformly distributed vertical load on the rafter

As shown in Fig. 7, on the basis of the research on the structural properties of wooden structure (Hwang *et al.* 2006), the inclined uniformly distributed vertical load of 8.18 N/mm is assumed to be applied to the rafter and is considered as the equivalent concentrated nodal force in the numerical analyses (see Fig. 8). The structure is also assumed to be subjected to the uniformly distributed horizontal force of 100 kgf/m^2. Since one of the main objectives in this study is to compare the relative resisting capacity of structural systems to the applied horizontal forces, the magnitude of horizontal force is arbitrarily selected without consideration of the seismic or wind load, and Fig. 9 represents the constructed horizontal force distribution.

As was mentioned previously, the exactness of the obtained results highly depends on the modeling of the rotational rigidity. Accordingly, based on the experimental results for the structural properties of a wooden national treasure (Lee *et al.* 2006), the different rotational stiffnesses at the column-crossbeam joint (A in Fig. 5) and the interior high column-crossbeam joint (B in Fig. 5) are adopted. The obtained relations between the magnitude of the moment and the corresponding rotational angle for both joints are shown in Figs. 10 and 11, respectively, and represent non-linear behaviors with an increase in the rotational angle. The % unit along horizontal axes in Figs. 10 and 11 was used and it was the ratio of column height and lateral displacement at the height of crossbeam. In this paper, the initial rotational stiffnesses for the column-crossbeam joint and the interior high column-crossbeam joint are selected as 1.53×10^5 N·m/rad and 1.05×10^5 N·m/rad, respectively.

Furthermore, traditional wooden structure does not have any resisting capacity for tension at each

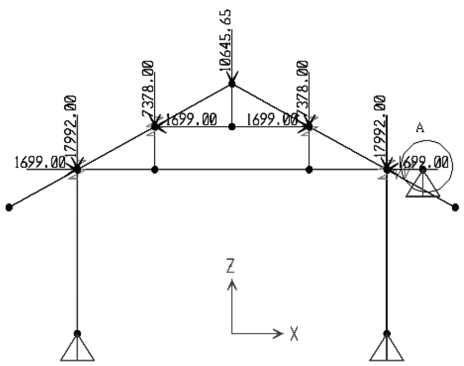


Fig. 8 Equivalent concentrated nodal forces

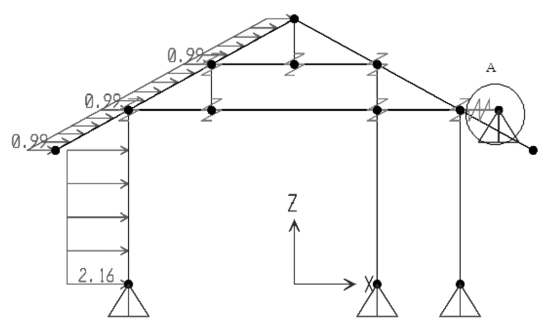


Fig. 9 Horizontal load

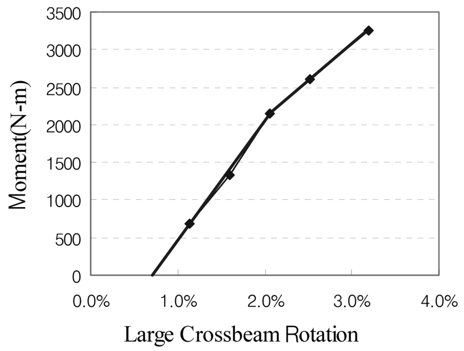


Fig. 10 Rotational stiffness between the interior high-column and a large crossbeam

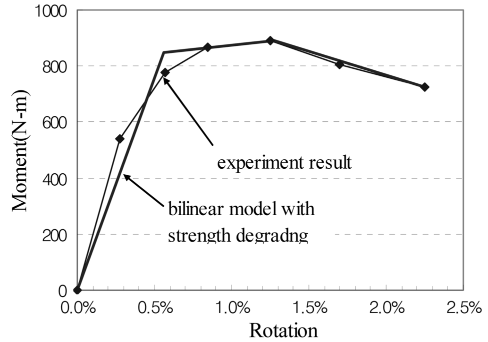


Fig. 11 Rotational stiffness between a column and a large crossbeam

joint because of its special construction method. It means that no tension can be resisted by structural members in traditional wooden structures. Differently from the real situation, however, the tensile force may be developed at a post when the numerical modeling for each joint is insufficient. If the length of a cantilever eave rafter is so long as to develop the negative reaction at the interior support where a post is connected, the tensile force will be accompanied with the lifting of the post. Accordingly, to remove this kind of discrepancy between structural analysis and real situations, the joint stiffness for the tensile force at point B in Fig. 5 is assumed to be zero and the use of contact elements makes this possible.

In fact, the bottom face of each column may preserve a small amount of rotational stiffness induced from the restoring moment, whose magnitude is determined by the three parameters of the column size, magnitude of axis force, and inclined angle of the column axis. Nevertheless, the hinge boundary condition is adopted for this part because there has been no related research to this rotational stiffness, and the main objective of this research is to compare the relative resisting capacities of structural systems. When the structural system or the applied load is not symmetric, traditional wooden structures tend to incline to a particular direction. Accordingly, to evaluate the relative stability of a structural system to horizontal sway, a dummy node is added to the upper end of an exterior column in the analysis model (as in Figs. 8 and 9). Because this dummy node prevents the horizontal sway while developing the horizontal reaction, the magnitude of the reaction can be used as an index to the stability of the structural system. The spring constant for the dummy node is assumed to be 100 N/mm.

2.3 Verification for the accuracy of the analytical model

The accuracy of the constructed numerical models is verified through the review of the obtained results with the following principles: (1) the total reaction forces in structural systems with identical rafter lengths must be the same because the vertical force applied to the roof is the same; (2) the rotational stiffness at each joint is so small that the moment redistribution through each joint cannot be expected; (3) when no load is applied to the crossbeam, its developed moment must be small; (4) since no joint can resist to the tension, all the structural members except the rafter cannot carry the tensile force; (5) in the case of an asymmetric structure, the reaction force developed at the dummy node must be remarkably larger than that of the symmetric structure.

3. Numerical analyses of wooden structures

3.1 Vertical loading case

As mentioned before, traditional wooden structures are classified into the three basic structural systems of the One-Point loading type, Two-Point loading type, and Two-Point loading One Reaction type, and a comparison of the obtained member forces was conducted for these three structural systems. First, the maximum bending moments in the large crossbeam and the horizontal reactions at the dummy node were compared, and the same comparison also proceeds to the extended structural systems. A few typical results for the bending moments and axial forces of the One-Point loading type structures are shown in Figs. 12 to 15 and summarized in Table 1. As shown in these results, one-point loading type structure represents an increase in the axial force in the king post together with an increase in the bending moment in the large crossbeam as the aisles are attached in the front and rear. This result can be explained by the structural response in which the applied loading on the cantilever eave rafter reduces the load delivered to the king post, and this effect is reduced with the attachment of the aisles. The symmetric configuration of the structural system develops negligibly small horizontal drift as can be inferred from the horizontal reactions at the dummy nodes in Table 1.

Moreover, the bending moments and axis forces of Two-Point loading type structures are shown in Figs. 16 to 21 and summarized in Table 2. Comparison of these figures represents that the axial forces in the post and the bending moments in the large crossbeam are increased as the aisles are attached to one side or to the back and front, and the reason for this result seems to be the same as that in one-point loading type structure. Besides, the magnitude of axis force and bending moment are smaller than those of 2P type structure in the case of 4P type structure with an added small post.

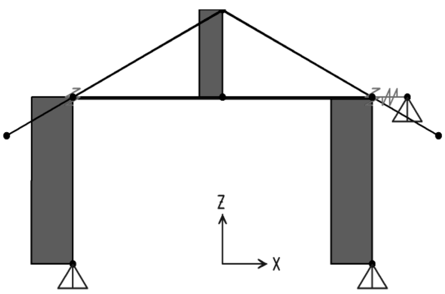


Fig. 12 Axial force diagram in 1P type

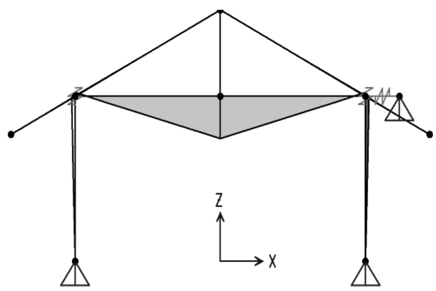


Fig. 13 Bending moment diagram in 1P type

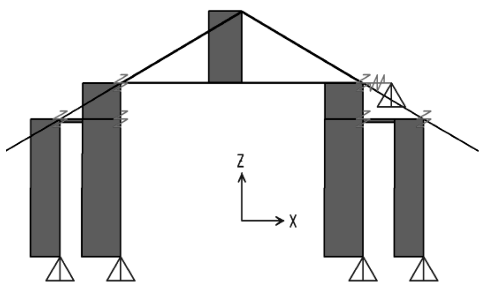


Fig. 14 Axial force diagram in 1P-BAT type

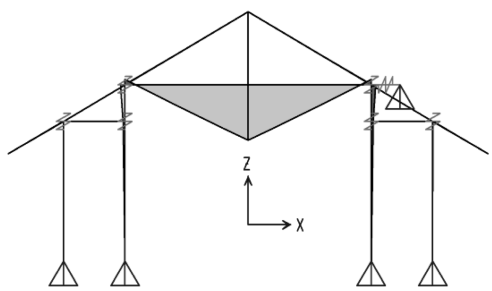


Fig. 15 Bending moment diagram in 1P-BAT type

Table 1 Member Forces in One-Point loading type

Structural Types		Max. Moment in Large Crossbeam (N·m)	Axial Force in King Post (N)
Basic Type	1P	19,536	17,989
Extended Type	1P-BAT	22,572	21,040
	1P-BAmT	22,608	21,056

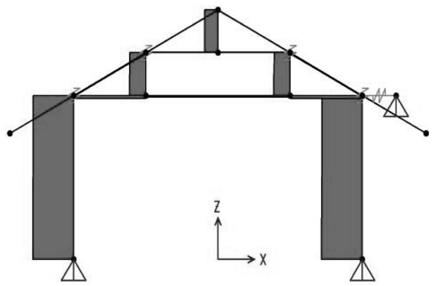


Fig. 16 Axial Force Diagram in 2P Type

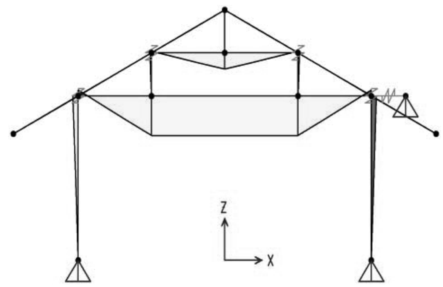


Fig. 17 Bending Moment Diagram in 2P Type

The horizontal drift will also be so small for the symmetric structures, as was reviewed in the one-point loading type structure, but the asymmetric attachment of aisles may cause relatively large horizontal reactions at the dummy nodes with an increased tendency toward horizontal drift.

Figs. 22 to 30 and Table 3 show typical results for Two-Point loading One Reaction type structure, and the structural behaviors according to an increase of the aisles are identical to those mentioned in the previous two structural systems. Particularly in the case of 2PD1R type structure, the positions of posts are coincident with the reaction points of the large crossbeam, and this leads to the occurrence of small shear force and bending moment along the large crossbeam. On the other hand, as shown in Table 3, relatively large horizontal reaction forces in the 2P1R type, 2P1R-BAT type, and 2PuL1R type mean that the possibility for lateral drift is larger than the other extended structural systems in the Two-Point loading One Reaction type structures, and it seems to be induce by the result of the inclination of structural stiffness center by the asymmetric addition of an internal column.

Comparing the magnitude of bending moments in a crossbeam, Two-Point loading type structures have smaller bending moments than those of One-Point loading type structures. This indicates that the Two-Point loading type structure is more effective to resist vertical loading if the surface area of the structure is identical. Moreover, it can be inferred that Two-Point loading One Reaction type

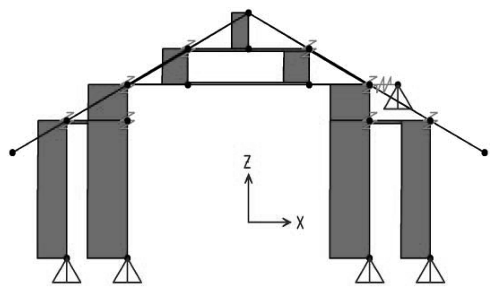


Fig. 18 Axial Force Diagram in 2P-BAT Type

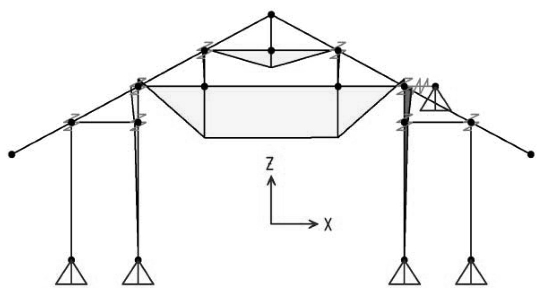


Fig. 19 Bending Moment Diagram in 2P-BAT Type

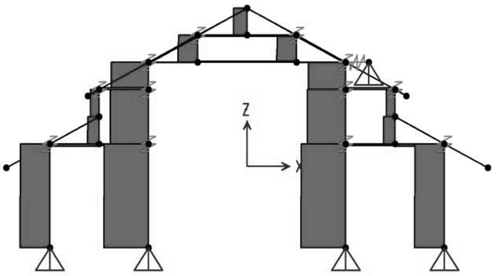


Fig. 20 Axial Force Diagram in 2P-BAmT-2LuF Type

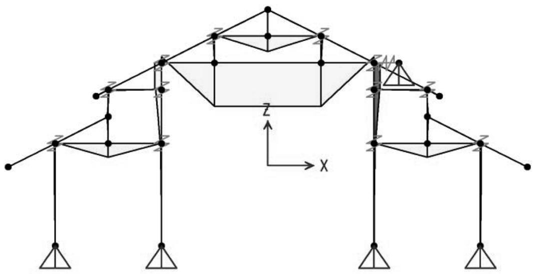


Fig. 21 Bending Moment Diagram in 2P-BAmT-2LuF Type

Table 2 Member Forces in Two-Point loading type

Structural Types				Max. Moment in Large Crossbeam (N·m)	Axial Force in the Bottom of Post (N)
Basic Type	2P			13,959	13,363
Extended Type	4P			10,420	12,158
	2P-AT			16,012	16,231
	2P-BAT			17,180	16,570
	Extended	2P-BAmT		17,015	16,570
		2P-BAmT-2LuF		16,297	15,595
		Extended	2P-BAmT-3LuF	17,123	16,347
		2P-BAT-2LuF		17,017	16,325

structure, which shows the smallest bending moment in the crossbeam is the most effective from the perspective of crossbeam size.

3.2 Horizontal loading case

To calculate the horizontal resisting capacity of each structural system, the same structures are analyzed for the uniformly distributed horizontal force without consideration for the vertical loads. Since each joint in a structure has no resistance to the tension, the traditional wooden structure does

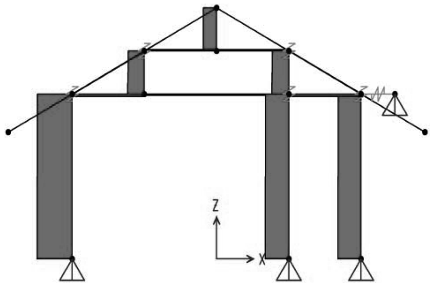


Fig. 22 Axial Force in 2P1R Type

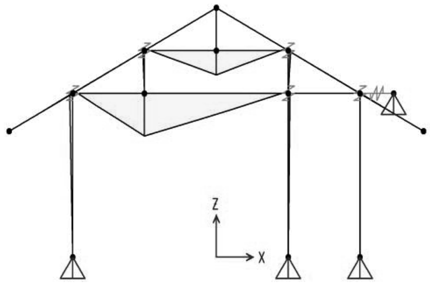


Fig. 23 Bending Moment in 2P1R Type

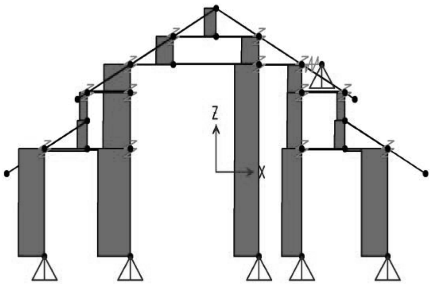


Fig. 24 Axial Force in 2P1R-BAmT-2LuF Type

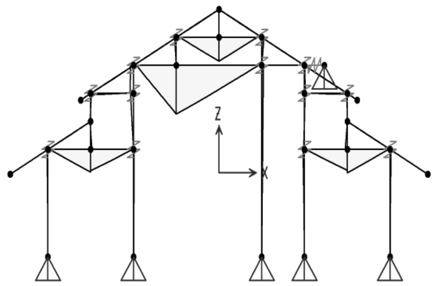


Fig. 25 Bending Moment in 2P1R-BAmT-2LuF Type

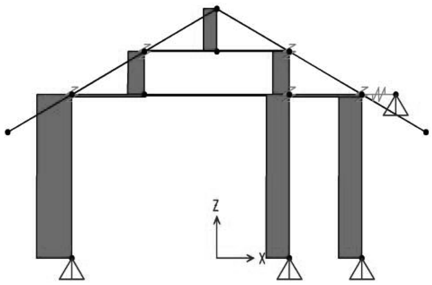


Fig. 26 Axial Force in 2PuL1R Type

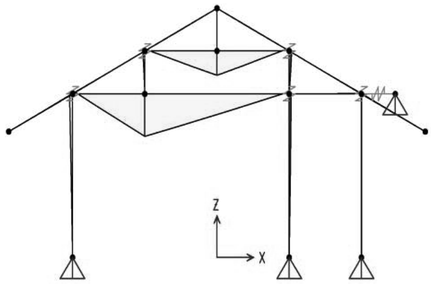


Fig. 27 Bending Moment in 2PuL1R Type

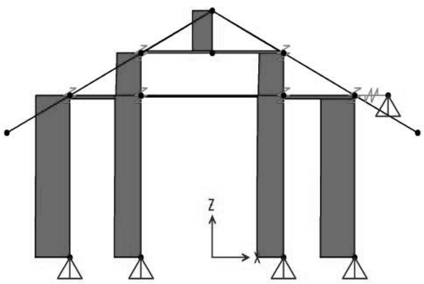


Fig. 28 Axial Force in 2PD1R Type

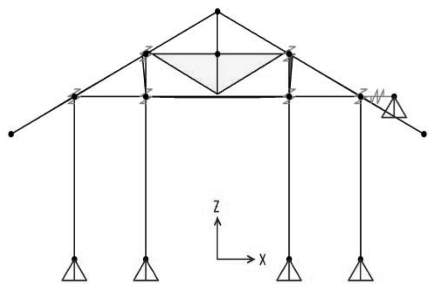


Fig. 29 Bending Moment in 2PD1R Type

not represent a complete truss mechanism in spite of the triangular composition of structural members. It means that the structural members in the roof cannot act efficiently as a truss for the applied horizontal forces and most applied forces will be resisted by the rotational stiffness at each joint. Nevertheless, as mentioned above, the value of rotational stiffness is so small that the developed bending moments in the structural members will also be small, and the comparison of the bending moment is not very revealing in the case of horizontal loading. On the other hand, the magnitude of horizontal reactions at the dummy node and the moment pattern at joints, which are changed with the structural system, become more significant (see Figs. 31, 32, and 33).

The bending moment diagrams of One-Point loading type structures subjected to the horizontal loading are shown in Figs. 34 to 36, and the corresponding horizontal reactions at the dummy node are summarized in Table 4. The total magnitude of horizontal loading in the extended structural system is larger than that in the basic structural system because the attachment of aisles increases the total height of the structure. Nevertheless, as shown in Table 4, the horizontal reactions in the

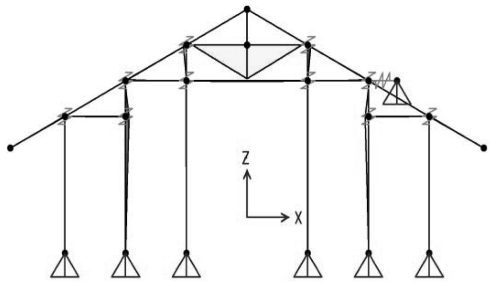


Fig. 30 Bending Moment in 2PD1R-BAT Type

Table 3 Member Forces in Two-Point loading One Reaction type

Structural Types				Max. Moment in Large Crossbeam (N·m)	Axial Force in the Bottom of Post (N)
Basic	2P1R			9,929	13,406
Extended	2P1R-BAT			12,284	16,627
	Extended	2P1R-BAmT-2LuF		11,557	15,646
	2PuL1R			9,931	13,408
	Extended	2PuL1R-BAmT-2LuF		11,559	15,649
	2PD1R			139	13,629
	Extended	2PD1R-BAT		158	16,889
		Extended	2PD1R-BAmT-2LuF	5,548	15,904

extended structural systems are decreased, which means that the extended structural system is more effective to resist the horizontal forces and has greater horizontal resisting capacity. The aisle contributes appropriately to an increase in the horizontal resisting capacity. Even a small post placed over the aisle increases the horizontal resisting capacity of the structure (see 1P-BAmT type in Table 4).

Figs. 37 to 44 and Table 5 show the bending moment diagrams and the horizontal reactions at the dummy node for Two-Point loading type structures, respectively. The horizontal resisting capacities of structures are usually increased in proportion to the attachment of the aisle, except 2P-AT type, in which aisles are attached on one side. In particular, 2P-BAmT type, which includes a small post on the ‘aisle exposed tiebeam’ shows the smallest horizontal reaction among Two-Point loading type structures, even though it is subjected to larger horizontal loading than the basic structural system.

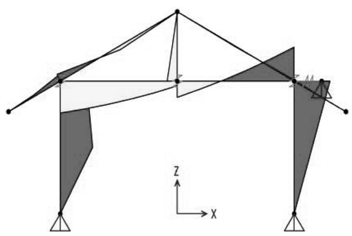


Fig. 31 Bending Moment Diagram in 1P by Horizontal Load

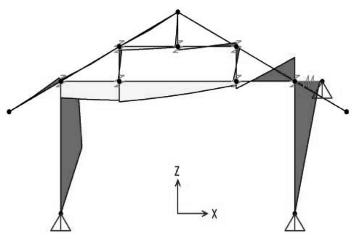


Fig. 32 Bending Moment Diagram in 2P by Horizontal Load

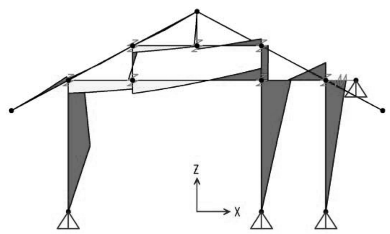


Fig. 33 Bending Moment Diagram in 2P1R by Horizontal Load

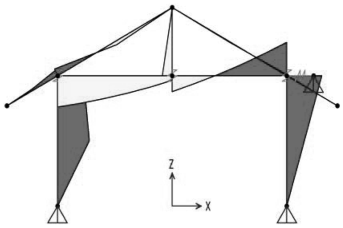


Fig. 34 Bending Moment Diagram in 1P by Horizontal Load

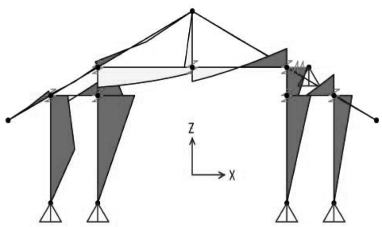


Fig. 35 Bending Moment Diagram in 1P-BAT by Horizontal Load

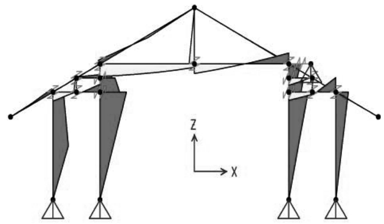


Fig. 36 Bending Moment Diagram in 1P-BAmT by Horizontal Load

Table 4 Horizontal Reaction at dummy node in One-Point loading type

Structural Types		Horizontal Reaction (N)
Basic	1P	-3,412
Extended	1P-BAT	-3,100
	1P-BAmT	-2,838

Accordingly, it can be concluded that 2P-BAmT type has the largest horizontal resisting capacity among the Two-Point loading type structures.

Typical results for Two-Point loading One Reaction type structures are also shown in Figs. 45 to 52 and Table 6. The size of this structural system is identical to that of Two-Point loading type structure, but generally smaller horizontal reactions are developed in the case of the same structural system (see Tables 5 and 6). This means that Two-Point loading One Reaction type structure relatively the greatest horizontal resisting capacity among the three structural systems.

4. Suggestion for improvement of resisting capacity

The fundamental factor which makes it difficult to improve the resisting capacities of traditional wooden structural systems is because of the fact that the structural member does not carry any tensile force because no tension can be resisted by the joints in all structural systems. Furthermore, the improvement of a structural system by impairing the essence of traditional structure has no meaning. Accordingly, this paper attempts find an alternative which yield remarkable improvement in resisting capacities of structural systems with the minimum modification on the basis of various numerical analyses, and the possibility for

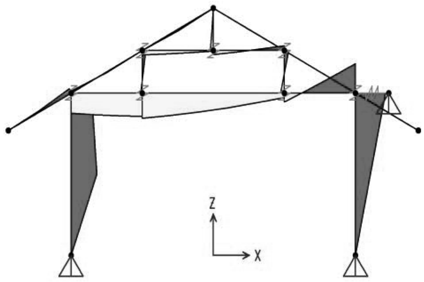


Fig. 37 Bending Moment Diagram in 2P Type

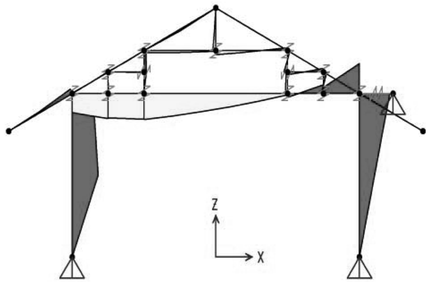


Fig. 38 Bending Moment Diagram in 4P Type

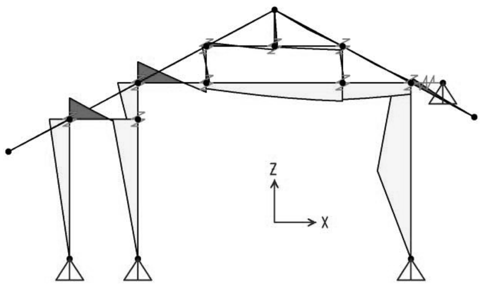


Fig. 39 Bending Moment Diagram in 2P-AT Type

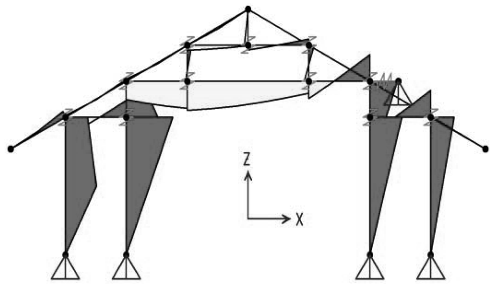


Fig. 40 Bending Moment Diagram in 2P-BAT Type

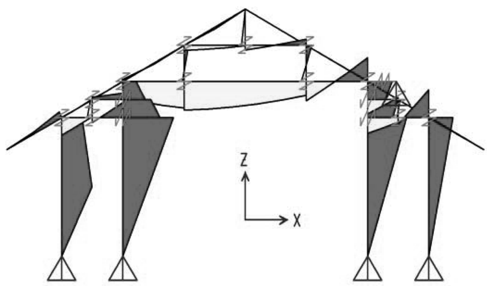


Fig. 41 Bending Moment Diagram in 2P-BAmT Type

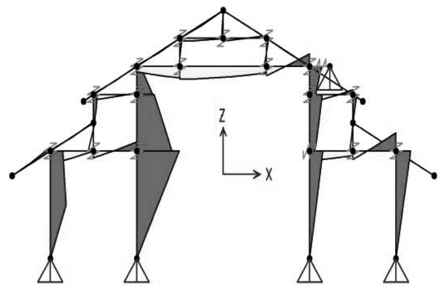


Fig. 42 Bending Moment Diagram in 2P-BAmT-2LuF Type

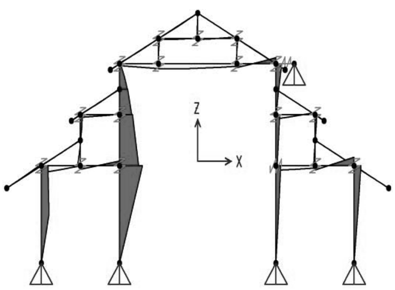


Fig. 43 Bending Moment Diagram in 2P-BAmT-3LuF Type

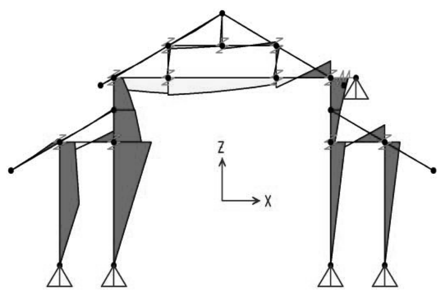


Fig. 44 Bending Moment Diagram in 2P-BAT-2LuF Type

the improvement of structural systems was found from the analyses for the Four-Point loading type structure which is an extended structural system of Two-Point loading type structure.

This structural system has the structural characteristic of dispersing the roof loading by erecting a small post when the distance between a column and a post is relatively large (see Fig. 53). However, in the case of the original Four-Point loading type structure, the roof loading is not effectively delivered on the post because the cantilever eave rafter is somewhat lifted and the negative reaction will develop at the post. As shown in Table 2, the maximum bending moment of crossbeam in this structural system is not much different from that in the basic Two-Point loading type structure because the roof loading originally delivered to the post does not flow as much as expected to the newly erected small post. To improve this phenomenon, a diagonal member is added between the post and the newly erected small post, as shown in Fig. 54. The improved structural system in Fig. 54 was analyzed, and the obtained results were compared in Figs. 53 and 54. As shown in these figures, the maximum bending moment of crossbeam in the improved

Table 5 Horizontal Reaction at dummy node in Two-Point loading type

Structural Types				Horizontal Reaction (N)
Basic	2P			−3,404
Extended	4P			−3,407
	2P-AT			3,630
	2P-BAT			−3,093
	Extended	2P-BAmT		−2,835
		2P-BAmT-2LuF		−4,261
		extended	2P-BAmT-3LuF	−5,071
		2P-BAT-2LuF		−3,998

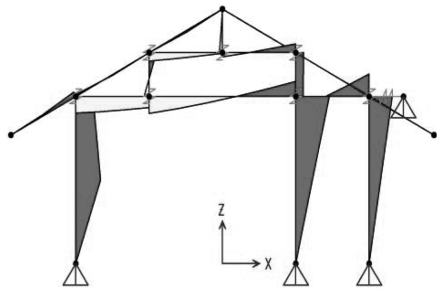


Fig. 45 Bending Moment Diagram in 2P1R Type

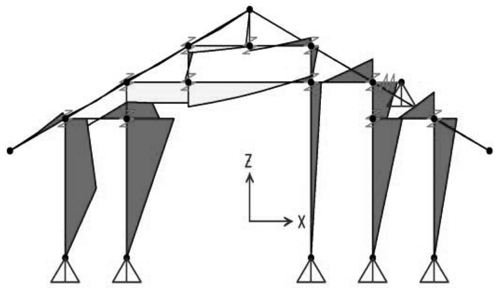


Fig. 46 Bending Moment Diagram in 2P1R-BAT Type

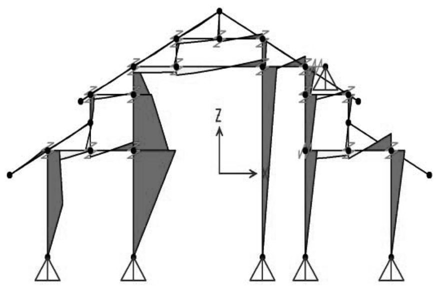


Fig. 47 Bending Moment Diagram in 2P1R-BAmT-2LuF Type

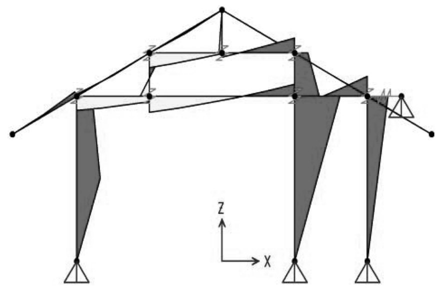


Fig. 48 Bending Moment Diagram in 2PuL1R

structural system represents 5,926 Nm corresponding to 43% reduction. This shows that a very significant improvement in the resisting capacity of traditional wooden structural system can be achieved through the addition of a small secondary structural member.

Increasing the horizontal resisting capacity of a structural system can also be considered as an alternative to improve the stability of traditional wooden structure. However, the use of artificial devices such as mechanical fasteners to lead all the connections to the rigid-joint condition is not a proper approach because to preserve a prototype of traditional wooden structure in which no mechanical fastener is used may be more important than to reinforce the structure, and social and/or cultural consensus must also be taken into consideration before engineering decisions. Accordingly, this research focused on parametric studies to find out the method which can increase the horizontal

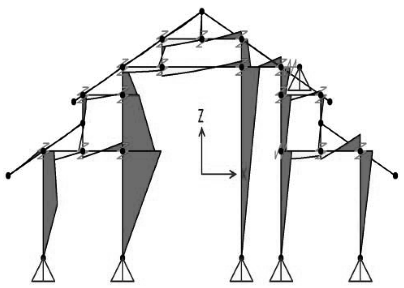


Fig. 49 Bending Moment Diagram in 2PuL1R-BAmT-2LuF Type

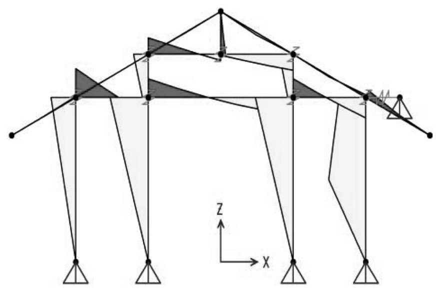


Fig. 50 Bending Moment Diagram in 2PD1R

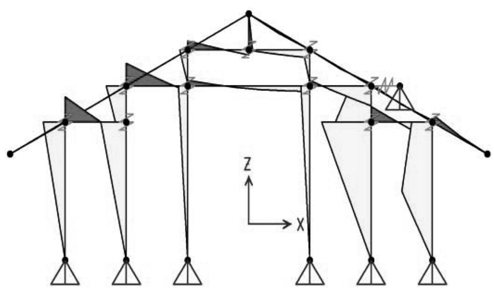


Fig. 51 Bending Moment Diagram in 2PD1R-BAT Type

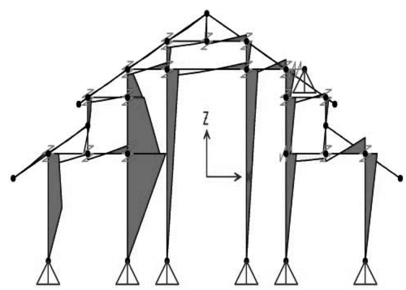


Fig. 52 Bending Moment Diagram in 2PD1R-BAmT-2LuF Type

Table 6 Horizontal Reaction at dummy node in Two-Point loading One Reaction type

Structural Types				Horizontal Reaction (N)
Basic	2P1R			–2,662
Extended	2P1R-BAT			–2,989
	Extended	2P1R-BAmT-2LuF		–3,983
	2PuL1R			–2,385
	Extended	2PuL1R-BAmT-2LuF		–3,879
	2PD1R			2,250
	Extended	2PD1R-BAT		2,883
		Extended	2PD1R-BAmT-2LuF	–3,766

resisting capacity with only minimal reinforcement while preserving the basic concept of traditional wooden structure. The obtained alternative is as follows: a wooden floor is usually installed in the aisle whenever it is attached and is formed by fixing plates on floor purlins uniformly placed between columns. Therefore, it will be possible to fix the floor-purlin to the column joint with the rigid connection. In this aspect, two identical structures with and without fixed floor-purlin fixed to the column joint were analyzed, and the horizontal repulsive forces developed at the dummy node were compared for all the structural systems with aisles (see Fig. 55 and Table 7). As shown in Table 7, the rigid connection of floor-purlin to column decreases the magnitude of horizontal repulsive force acting on dummy node by 48%~75%, which means that this slight modification can lead to a remarkable increase of the horizontal resisting capacity in traditional wooden structure.

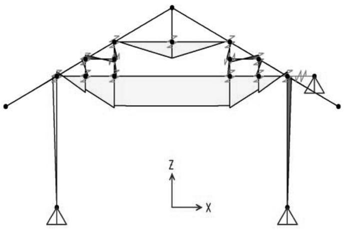


Fig. 53 Bending Moment Diagram in 4P

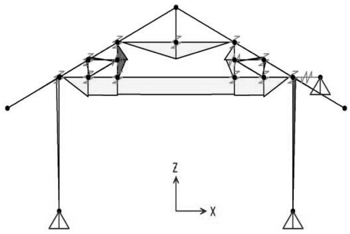


Fig. 54 Bending Moment Diagram in 4P which is reinforced

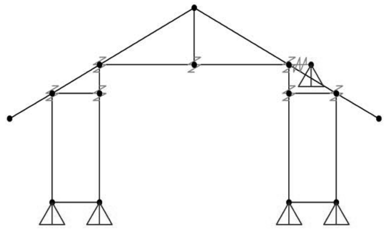


Fig. 55 The location of Floor Purlin in 1P-BAT

Table 7 Horizontal Reaction at dummy node

Structural Types	Horizontal Reaction (N)		Reduction Ratio (%)
	Not Floor Purlin	Floor Purlin	
1P-BAT	−3067.38	−767.08	74.99
1P-BAmT	−2838.71	−687.88	75.77
2P-BAT	−3093.09	−765.43	75.25
2P-BAmT-2LuF	−4261.22	−1645.15	61.39
2P-BAmT-3LuF	−5071.51	−2289.54	54.85
2P-BAT-2LuF	−3998.25	−1267.33	68.30
2P-BAmT	−2835.50	−686.72	75.78
2P1R-BAT	−2989.32	−763.80	74.45
2P1R-BAmT-2LuF	−3083.32	−1602.71	48.02
2PD1R-BAT	2883.07	756.79	73.75
2PD1R-BAmT-2LuF	−3766.50	−1562.25	58.52
2PuL1R-BAmT-2LuF	−3879.40	−1598.31	58.80

5. Classification of structural systems

The wooden architectural structures, which are a measure drawing, in Korea beyond treasure level are categorized into three basic structural systems and their extended structural systems, and Table 8 shows the statistics for the adopted structural systems. In particular, the extended structural systems in this table include the structural systems re-extended from the extended structural systems. As shown in this table, the frequencies for each structural type represent 17.0% for One-Point loading type, 50.8% for Two-Point loading type, and 32.2% for Two-Point loading One Reaction type, respectively. The following points can be deduced: (1) in spite of the variety in the Korean traditional wooden structural system, all the structures can be classified into one of the structural systems described in Fig. 2 on the basis of three basic structural systems and the method of aisle attachment; (2) the wooden structural system has been changed from One-Point loading type to Two-Point loading type as the size of structures has increased so that, accordingly, the Two-Point loading type was more frequently adopted in the Korean traditional wooden structures on a treasure level because of their large scale, and it can be inferred that the magnitude of moment developed in the crossbeam was one of the significant variables in determining the structural type; (3) the symmetric structural systems are usually preferred; (4) regardless of the efficiency in the structural system, the basic structural systems which have relatively simple structural configurations are

Table 8 Frequency Ratio for Structural Types

	Structural Types and Frequency			Frequency Ratio (%)
One-Point loading type	Basic	1P	3	2.54
	Extended	1P-BAT	15	12.71
		1P-BAmT	2	1.69
Two-Point loading type	Basic	2P	31	26.27
	Extended	4P	1	0.85
		2P-mF	1	0.85
		2P-BAT	25	21.19
		2P-AT	2	1.69
Two-Point loading One Reaction type	Basic	2P1R	15	12.71
	Extended	2P1R-BAT	5	4.24
		2PD1R	3	2.54
		2PuL1R	15	12.71

popularly adopted, and this result seems to be induced from the construction of wooden structures with experience rather than theoretical analyses on the structural systems; (5) nevertheless, frequently used structural systems still insure relatively strong resisting capacities of structures; and (6) to achieve more efficient construction of traditional Korean wooden structures, additional theoretical approaches are desirable.

6. Conclusions

This paper introduced an improved classification of Korean traditional wooden structures, and this was followed by structural analyses for all the classified structural systems to compare the relative efficiency of structural systems. Static vertical and horizontal forces were taken into account and the following conclusions were drawn on the basis of the calculated numerical results: (1) the bending moments developed at large crossbeams are increased with an increase of axial forces at king posts or posts as the aisles are attached in front and rear because the roof loading applied on the cantilevered eave rafter reduces the load delivered to the king post, and this effect is reduced with the attachment of the aisles in front and rear; (2) in the case of Four-Point loading type structure, which is an extended structural system of Two-Point loading type structures, the bending moment in a large crossbeam can effectively be reduced by dispersing the vertical force acting on the crossbeam. However, the possibility for the inclination of structure still exists when the aisles are attached on only one side; (3) generally, Two-Point loading type structures are more efficient than One-Point loading type structures in resisting the applied loadings; (4) extended structural systems have greater horizontal resisting capacities than basic structural systems for both loading cases, and the fore- and rear-side aisle showed that the multi-tie beam module is an efficient structural system in resisting the horizontal loading (in fact, additional improvement can be expected with a slight modification to the structural system); and (5) the numerical results show that very significant improvements in the resisting capacity of traditional wooden structural systems can be achieved through the addition of a small secondary structural member only or a slight modification of the structural system. Finally, even though it is much too difficult to obtain final conclusions for the structural behavior of wooden structures with these limited numerical analyses, this study will serve as an initial step to review and improve the Korean traditional wooden structural system.

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