Structural Analysis and Conceptual Seismic Design of Large-span Korean Traditional Timber Structure

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Abstract In this research, a test-bed large-span Hanok which adopts new structural system compared to the traditional structural system has been introduced, and the structural analysis and seismic design for it have been performed to test possibility as a large-span Hanok. The test-bed Hanok is composed of two parts, that is, 1st story part and 2nd story part. The roof structure of 1st story part is similar to that of the traditional Hanok, but that of 2nd story part is new-styled and different from the traditional Hanok. The two parts are joined together side by side. The largest span of this test-bed Hanok is 14.4m in 1st story part and 10.8m in 2nd story part. The structural design was done to extract optimal member size for both raw wood and glued laminated wood with satisfying safety and serviceability conditions. The comparison of the sectional area between raw wood and glulam showed that glulam required less member size than raw wood. The area ratio of the glulam compared to the raw wood is from 0.60 to 0.92, and this shows that, glulam is more economical than raw wood in large-span Hanok from the viewpoint of the required volume of the timber which affects much in cost and construction. Conceptual seismic design methods for the test-bed large-span Hanok were proposed and the structural characteristics of each method were discussed. The proposed method is summarized as addition of shear wall, reinforcing existing shear wall and isolating the basement of the structure from the ground.

Keywords Korean Traditional Timber Structure, Large-span Hanok, Structural Analysis, Seismic Design

1. Introduction

The Korean traditional timber structure is called Hanok. It is generally said that Hanok has history of about 2,000 years. The main structural characteristic of Hanok is that it utilizes post and beam structural system. Generally, the gravity load is resisted by post and beam frame, and the

lateral load is resisted by walls. The wall used in Hanok is combined with wall-frame system, which is somewhat like infilled wall, where wall is infilled to the peripheral wood frame. Traditionally, the connection between post and beam was made by mortise and tenon joint of only wood. Nowadays, new-styled Hanok is appeared to accommodate modern life-style and here, the connection type between main structural members is made steel joints to accelerate the construction process. Fig. 1A shows example of a traditional style Hanok, and Fig. 1B shows example of a modernized new-styled Hanok.

(A). Traditional style Hanok

(B) Modernized new-styled Hanok

Figure 1. Korean traditional timber house, Hanok

To expand the supply of Hanok, the usage of it should be diversified. Hanok has been used mainly for residential purpose. The span between columns in residential house is generally 2.4m~4.2m. To utilize Hanok as a public usage, such as community center, school, police station, library, museum and so on, the span should be enlarged at least those of a reinforced concrete and a steel structure. When the span of Hanok is about 10m~20m, it is called large-span Hanok. Large-span Hanok cannot be acquired by just expanding the traditional Hanok with its structural system unchanged. New structural system and new material should be adopted to make large-span Hanok aesthetically acceptable, structurally safe and functionally feasible.

Various researches on timber structures have been carried out worldwide. In Korea, researches on Hanok were mainly carried out on the architectural style viewpoint, but recently researches on the structural viewpoint have been carried out briskly. To enhance life-cycle performance of timber structures, researches on moisture contents of Korean traditional timber houses have been carried out [1, 2]. Monitoring of structural deformation for both on Korean traditional timber house and western large-span timber structures have been carried out [3, 4].

For Korean timber structure, static and cyclic behavior with tenon joints under lateral load has been analyzed [5] and relationship between damping ratio and vibration amplitude has been extracted by shaking table test [6]. For ancient Chinese timber structure, dynamic characteristics have been extracted by shaking table test [7]. To aid structural analysis and design of Hanok, automated

structural design tools have been developed [8, 9]. For the seismic design of Hanok, evaluation scheme for the determination of torsional irregularity and conceptual seismic isolation method have been suggested [10, 11].

2. Introduction of the Test-bed Large-span Hanok

In this chapter, a test-bed example of 14.4m span Hanok is introduced, the usage of it is exhibition space and cultural center. This test-bed large-span Hanok is scheduled to be built in Yongin, Korea, 2021. The final architectural design has not confirmed yet, and can be changed. The structural analysis and seismic design for the test-bed large-span Hanok under consideration is performed to test its possibility as a large-span Hanok.

Fig. 2 shows floor plan and elevational-section of the test-bed large-span Hanok. The test-bed Hanok consists of two parts, that is, 1st story part and 2nd story part. The two parts are joined together side by side and to be used as a single building. The longitudinal width of the Hanok is 48m and transverse width is 14.4m. The span between columns is 4.8m in longitudinal direction, and 14.4m in transverse direction. The test-bed Hanok belongs to large-span because its transverse span is more than 10m. The height of the 1st story part is 9.6m, and that of 2nd story part is 15.4m. The roof structure of 1st story part is similar to that of the traditional Hanok, but the roof structure of the 2nd story part is new-styled and somewhat different from that of the traditional Hanok.

Figure 2. Floor plan and section of the test-bed large-span Hanok

3. Structural Analysis of the Test-bed Large-span Hanok

3.1. Analysis Modeling of the Test-bed Hanok

Fig. 3 shows analysis model of the test-bed Hanok. The structural analysis software is Midas Gen Ver.881. Fig. 3A shows three-dimensional analysis model, and Fig. 3B shows modeled elevational section of each 1st story and

2nd story parts. Table 1 shows material properties of the analysis model. To compare the section size of the main structural members, two types of wood are used and compared, that is, raw wood and glued laminated wood. The species of raw wood is larch and its grade is 1st and the type of glued laminated wood is 17S-49B. Gravity load is composed of roof load, self-weight, and snow load. Roof load including self-weight is 4.5kN/m^2 , snow load is 0.5kN/m^2 .

Figure 3. Structural analysis model of test-bed large-span Hanok

Table 1. Material Properties Used in Structural Analysis Model

Wood Type	Basic allowable stresses and modulus of elasticity (MPa)					
	Fb	Ft	Fc	Fc $\perp$	Fv	E
Raw wood Grade 1 Larch	8.0	5.5	9.0	3.5	1.25	12,200
Glulam 7S-49B	10.0	6.5	7.5	3.5	2.0	8,000

3.2. Target Members for the Structural Design

The target members for the structural design are main horizontal members of the test-bed Hanok. Fig. 4 shows these target members. Fig. 4A and Fig. 4B show target members of the 1st story part both in transverse(Y) and longitudinal(X) direction, respectively. There are three members for the structural design in 1st story part in Y direction, such as, main girder, middle girder and cellar girder, the span of which are 14.4m, 8.4m and 2.8m respectively. And there are four members for the structural design in 1st story part in X direction, such as, ridge, middle-upper purlin, middle-lower purlin and column purlin, the span of which are identical, that is, 4.8m.

Fig. 4C and Fig. 4D show target members of the 2nd story part both in transverse(Y) and longitudinal(X) direction, respectively. There are two members for the structural design in 2nd story part in Y direction, such as, main girder and cellar girder, the span of which are 10.8m and 3.6m respectively. And there are four members for the structural design in 2nd story part in X direction, such as, ridge, middle purlin, column-inner purlin and column-outer purlin, the span of which are identical, that is, 4.8m. The largest member span of the 1st story part is 14.4m and that of the 2nd story part is 10.8m, both lay in Y direction.

(A) Main horizontal members in Y direction of 1st story part

(B) Main horizontal members in X direction of 1st story part

(C) Main horizontal members in Y direction of 2nd story part

(D) Main horizontal members in X direction of 2nd story part

Figure 4. The target members for the structural design

3.3. Results of the Structural Analysis

Static analysis under gravity load was performed for the test-bed large span Hanok. Fig. 5 shows deformed shape of the analysis model. Fig. 5A shows deformed shape from the isometric view, and Fig. 5B shows deformed shape from the top view. The maximum deformation is appeared in the cantilevered corner of the roof.

Fig. 6 shows member force diagrams of the elevational section of the 1st story part and 2nd story part. Here, bending moment diagram and shear force diagram are shown. As expected the maximum bending moment of the horizontal member appears at the center of the member, and that of the shear force appears at the extreme ends of the member.

(A) Deformed shape under gravity load from isometric view

(B) Deformed shape under gravity load from top view

Figure 5. Deformed shape of test-bed large-span Hanok

(A) Bending moment diagram of 1st story part

(B) Shear force diagram of 1st story part

(C) Bending moment diagram of 2nd story part (D) Shear force diagram of 2nd story part**Figure 6.** Member forces of test-bed large-span Hanok

4. Structural Design of the Test-bed Large-span Hanok

From Table 2 to Table 4, results of the structural design for the target members are shown. Table 2 and Table 3 show the structural design of main members of 1st story part both in Y and X direction, respectively. Table 4 and Table 5 show the structural design of main members of 2nd story part both in Y and X direction, respectively. The structural design was done for both raw wood and glulam. The target of the structural design is to extract optimal section size, that is, minimum width and depth of each member under condition of satisfying safety and

serviceability conditions. The shape of the section is assumed rectangular. Safety condition is to satisfy both flexural and shear stress requirements, and serviceability condition is to satisfy deflection requirement. The comparison of the sectional area between raw wood and glulam shows that glulam requires less sectional area than raw wood. The area ratio of the glulam compared to the raw wood is from 0.60 to 0.92 in this test-bed Hanok. This result shows that, for the case of large-span Hanok it is more economical to use glulam than raw wood just from the viewpoint of the required volume size of the timber which affects much in cost and construction.

Table 2. Structural Design of Main Members of 1st Story Part in Y direction

Wood type	Member	Section (width x depth)	Flexural stress ratio	Shear stress ratio	Deflection ratio	Area ratio (Glulam / Raw wood)
Raw wood Grade 1 Larch	Main girder	510 x 810	93.3%	38.2%	67.1%	-
	Middle girder	420 x 660	99.0%	23.6%	36.1%	-
	Collar girder	210 x 360	87.1%	34.0%	19.4%	-
Glulam 17S-49B	Main girder	480 x 720	59.6%	28.7%	95.3%	0.84
	Middle girder	330 x 540	89.4%	23.0%	78.7%	0.84
	Collar girder	180 x 270	85.7%	33.0%	50.3%	0.64

Table 3. Structural Design of Main Members of 1st Story Part in X direction

Wood type	Member	Section (width x depth)	Flexural stress ratio	Shear stress ratio	Deflection ratio	Area ratio (Glulam / Raw wood)
Raw wood Grade 1 Larch	Ridge	210 x 330	88.8%	36.8%	46.3%	-
	Middle-upper purlin	210 x 360	95.1%	43.1%	45.4%	-
	Middle-lower purlin	210 x 360	96.8%	43.8%	46.3%	-
	Column purlin	270 x 420	89.2%	47.2%	36.6%	-
Glulam 17S-49B	Ridge	180 x 270	73.5%	33.0%	85.9%	0.91
	Middle-upper purlin	180 x 300	75.9%	37.8%	79.8%	0.71
	Middle-lower purlin	180 x 300	77.3%	38.7%	81.3%	0.79
	Column purlin	210 x 330	88.3%	48.7%	84.4%	0.61

Table 4. Structural Design of Main Members of 2nd Story Part in Y direction

Wood type	Member	Section (width x depth)	Flexural stress ratio	Shear stress ratio	Deflection ratio	Area ratio (Glulam / Raw wood)
Raw wood Grade 1 Larch	Main girder	510 x 810	99.5%	34.0%	48.6%	-
	Collar girder	270 x 450	90.3%	34.0%	20.7%	-
Glulam 17S-49B	Main girder	420 x 690	79.2%	30.4%	89.6%	0.70
	Collar girder	210 x 360	86.2%	34.4%	48.8%	0.62

Table 5. Structural Design of Main Members of 2nd Story Part in X direction

Wood type	Member	Section (width x depth)	Flexural stress ratio	Shear stress ratio	Deflection ratio	Area ratio (Glulam / Raw wood)
Raw wood Grade 1 Larch	Ridge	210 x 330	88.8%	36.8%	46.3%	-
	Middle purlin	210 x 360	95.1%	43.1%	45.4%	-
	Column inner purlin	240 x 390	96.5%	47.2%	42.5%	-
	Column outer purlin	300 x 480	91.0%	54.9%	32.6%	-
Glulam 17S-49B	Ridge	210 x 300	82.7%	41.3%	87.0%	0.91
	Middle purlin	210 x 330	81.2%	44.8%	77.6%	0.92
	Inner purlin	210 x 300	88.5%	44.4%	93.0%	0.70
	Outer purlin	240 x 360	96.0%	57.4%	84.1%	0.60

5. Conceptual Seismic Design of the Test-bed Large-span Hanok

In this section, conceptual seismic design of the test-bed Hanok is discussed. Three methods are proposed, that is, addition of shear wall, reinforcing existing shear wall and applying seismic isolation technique. Fig. 7A and Fig. 7B show addition of shear wall to reinforce lateral resistance. Shear walls should be placed both in X and Y directions and as symmetrically as possible. Fig. 7C shows reinforcing existing shear wall by adding partial bracing which can help to increase ductility of the wall and hence to increase the overall seismic resistance capacity of the structure. Fig. 7D shows base isolation device installed between the base of the Hanok and the ground. By installing base isolation device, the transfer of the vibration of the ground to the structure can be mitigated and hence to reduce the seismic force transferred to the structure.

(A) Addition of shear wall in plan view

(B) Addition of shear wall in elevation view

Figure 7. Recommendation of seismic design for large-span Hanok

6. Conclusions

In this study, a test-bed large-span Hanok has been introduced, and the structural analysis and seismic design for it has been performed to test possibility as a large-span Hanok. The test-bed Hanok consists of two parts, that is, 1st story part and 2nd story part. The two parts are joined together side by side. The largest span of this structure is 14.4m. The structural design was done to extract optimal section size for both raw wood and glulam under condition of satisfying safety and serviceability conditions. The comparison of the sectional area between raw wood and glulam showed that glulam required less sectional area than raw wood. The area ratio of the glulam compared to the raw wood is from 0.60 to 0.92. This result shows that, it is more economical to use glulam than raw wood in large-span Hanok just from the viewpoint of the required volume size of the timber which affects much in cost and construction. In addition, seismic design concept for the test-bed large-span Hanok was proposed, that is, in addition to shear wall, reinforcing existing shear wall and introducing seismic isolation technique and the structural characteristics were discussed.

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