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A Study on the Compressive Strength Properties of Traditional Korean Joints

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To obtain the basic data for the mechanical properties of *Joomeokjang* and *Nabijang* joints, which are most widely used in *Hanok*, a comparative analysis for the compression test was carried out.

The compressive strengths of the *Nabijang* and *Joomeokjang* joints were 55% and 47%, respectively, compared to that of the non–jointed control specimen. An F–test and a t–test were carried out to understand the significant differences between the compressive performances of the *Nabijang* and *Joomeokjang* joints. There was no statistical significance between the distributions of both groups. Although the compressive strength of the *Nabijang* joint was higher than that of the *Joomeokjang* joint, the *Nabijang* joint showed a splitting failure, a complete scattering around the wedge of the joint. Splitting was also the main failure type for the *Joomeokjang* joint and the crushing failure was mixed.

It was understood that joints should be processed or constructed with the acknowledgment that longitudinal splitting in the vicinity of the mortise is the main failure place for both traditional joints. As manual work is still prevalent over automation in traditional Korean construction, the standardization through a precise machining process and the mechanization of the construction technique is urgently required.

Keywords: *Nabijang* joint, *Joomeokjang* joint, statistical significance, failure type, traditional Korean construction

INTRODUCTION

Each country has its own traditional construction methods. Korea's traditional building is called *Hanok*, which is a wooden framed house with a cultural heritage and an old history. Most wooden frame construction, which has recently been spreading rapidly through Korea, is made with a light–frame with load–bearing walls. However, traditional Korean wooden frame construction is made with heavy timber and has posts and beams. Materials for *Hanok* construction include stone, wood, and, yellow ocher for practical purposes.

As a rule, stone was used for the *kidan* (a kind of stylobate) and wood was used for the posts, rafters, doors, and *daecheongs* (the main hall of a wooden *maru*, where *maru* is a raised wooden floor). The walls of a *Hanok* consisted of yellow ocher mixed with straw, and *Hanji* (a traditional Korean paper) was applied to the windows. *Hanji* was also applied to the floor, after which bean oil was spread on it to make it water proof. *Hanok* is a natural construction method because it is made with natural recycled materials such as fuel, manure, etc. Thus, it is reasonable to conclude that *Hanok* is a circulating eco–building construction. Also, wood, straw, and yellow ocher are healthful and are able to naturally control moisture. Scientific research has revealed many healthful advantages of yellow ocher. Also, Korean ancestors utilized the materials in an eco–friendly manner by using not only straight but also curved pieces for the wooden frames. Wood pieces with their original curved shape can still be seen in old *Hanok* construction. Representative structures that used the *Hanok* method are temples, palaces (Fig. 1), and *Hyanggyos* (local schools annexed to the Confucian Shrine, Fig. 2). The oldest existing Korean wooden frame constructions are the *Geungnakjeon* Hall (the Hall of Paradise, Fig. 3) of the *Bongjeongsa* Temple and the *Muryangsujeon* Hall (the Hall of Eternal Life, Fig. 3) of the Buseoksa Temple. UiSang, the greatest Buddhist priest in history, built the *Geungnakjeon* Hall of the *Bongjeongsa* Temple in 672 AD and founded the *Muryangsujeon* Hall of the *Buseoksa* Temple in 676 AD. These two constructions have been well preserved and are still in use today, the wooden frame *Hanok* constructions have been preserved for over 1300 years. Histories and traces of Korean ancestors that cannot be found in modern steel–concrete buildings remain in *Hanok* constructions.

Hanok is an eco–building construction because it is in coexistence with nature. On the other hand, *Hanok* has some weak points. It is inconvenient to live in a *Hanok*, because all of the facilities in the building are separated from one other. As a modern viewpoint, there are many controversial points in its efficiency and convenience.

However, *Hanok* should be regarded not only as a

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traditional construction form but also a unique and spiritual property of Korea. Thus, *Hanok* construction urgently demands design, construction, preservation, and maintenance not by experience, but by systematical and scientific approaches. However, the knowledge of *Hanok* is retained by only a few craftsmen, and a new type of construction, reformism *Hanok*, has increased in popularity, at the expense of traditional *Hanok*. So, to overcome these critical situations, *Hanok*, which is the representative domestic construction, should be systematically and scientifically approached, analyzed, and consolidated.

To obtain the basic data for the scientific approach, a comparative analysis for the compressive properties of *Joomeokjang* and *Nabijang* joints, which are most widely used in *Hanok*, was carried out. Detailed research for joint patterns, which have fully engineered characteristics, may be essential because *Joomeokjang* and *Nabijang* joints are the most fundamental joint methods used in traditional Korean wooden frame constructions. Of course, the specific shapes and sizes of each joint can affect the mechanical properties of the *Joomeokjang* and *Nabijang* joints in complicated pattern. For example, in the case of the *Joomeokjang* joint, the stress of the joint is determined by the bearing strength of the head of the tenon and the grasping power of the mortise. Important factors in determining the mechanical properties of the joint are the fitness of both the tenon and the mortise.

To obtain the preliminary data and characterize the tendencies of the traditional joints, compressive strengths of *Joomeokjang* and *Nabijang* joints had been compared and the failure modes for each joint had been studied.

Fig. 1. The feature of palace in Korea.

Fig. 2. The feature of *Hyanggyo* in Korea.

Fig. 2. The features of temples in Korea.(left: *Bongjeongs*a temple, right: *Buseoksa* temple)

MATERIALS AND METHODS

Japanese larch, which is widely used in Korean construction, was used for this study. The dimensions of a traditional joint are 60×60 mm per section and 200 mm in length. *Joomeokjang* and *Nabijang* joints were selected as traditional joints, and the non–jointed control specimen was also prepared. A schematic diagram of the specimen is shown in Fig. 4. The compressive strength of the traditional joint was tested as in KSF 2206–2004–06. The loading speed was 10 mm/min and five replications per each joint were used in this research.

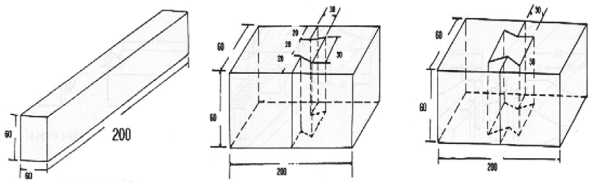

Fig. 4. The features of the traditional joint specimens (from left to right: control specimen, *Joomeokjang* joint, *Nabijang joint*).

RESULTS AND DISCUSSION

Compressive properties of the traditional joints

The compressive strengths and proportional limit stresses of the non–jointed control specimen, the *Nabijang* joint, and the *Joomeokjang* joint are shown in Table 1. The *Joomeokjang* and *Nabijang* joints showed about half compressive strengths contrary to the non–jointed control specimen. The compressive strengths of the *Nabijang* and *Joomeokjang* joints were 55% and 47%, respectively, compared to the non–jointed control group. As both the *Joomeokjang* and *Nabijang* joints had nearly half the compressive strength of the control group, both joints might be expected to show a considerable compressive performance if additional adhesive were applied. It was judged that additional research to improve the capacity of the joints will be essential. Also, optimum detail sizes of each joint should be calculated by evaluating the compressive strengths of various wedge sizes for the *Nabijang* joint. Optimum sizes for the *Joomeokjang* joint should also be calculated by evaluating the compressive strengths for various sizes of the mortise and tenon.

Representative load–deformation curves for the *Nabijang* and *Joomeokjang* joints are shown in Figs. 5 and 6. Ultimate loads for the *Nabijang* and *Joomeokjang* joints were attained in the vicinity of 6 mm and 5 mm of deformation, respectively. The patterns of the load–deformation curve for the *Nabijang* joint are similar to those for the *Joomeokjang* joint. Although the average compressive performance of the *Nabijang* joint was better than that of the *Joomeokjang* joint (see Table 1, Fig. 7, and Fig. 8), it was hard to conclude which joint was better when only considering the compressive strengths. Failure modes for each joint should also be considered. A further discussion was included in the later section.

A statistical significance test to analyze the performance difference of the traditional joints–A statistical significance test by the analysis of the variances of the compressive strengths of the non–jointed control specimen, the Joomeokjang joint, and the Nabijang joint

A statistical significance test by the analysis of the variances of the compressive strengths of the non–jointed control specimen, the *Joomeokjang* joint, and the *Nabijang* joint was conducted. Since the F–value was 165.9 (Appendix 3.2.1), which was much higher than the rejection limit of 3.7, and the significance probability was very low at 5.9E–11, it was concluded that there were significant differences among the compressive strengths of the three groups.

Next, an analysis of the variances to observe the differences of the proportional limit strengths among the three groups was conducted. Since the F–value of the proportional limit strength was 187.3 (Appendix 3.2.1),

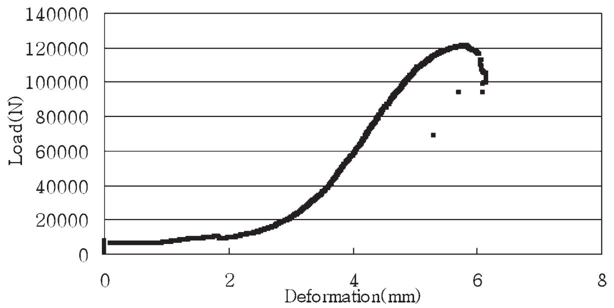

Fig. 5. The load–deformation curve for the *Nabijang* joint (Specimen No. 1).

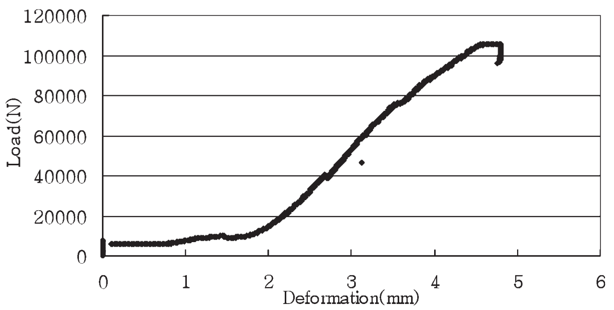

Fig. 6. The load–deformation curve for the *Joomeokjang* joint (Specimen No. 5).

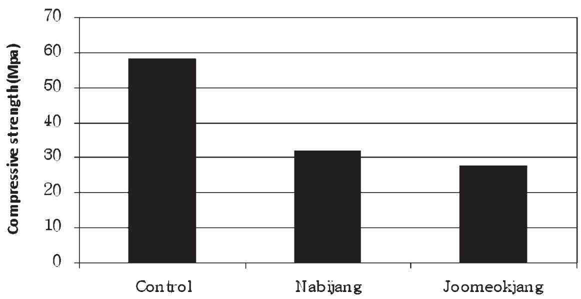

Fig. 7. Comparisons of the compressive strength between the traditional Korean joints.

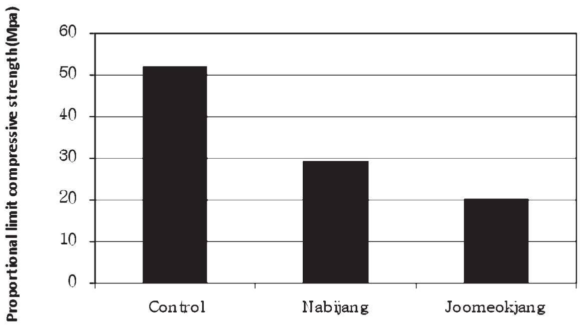

Fig. 8. Comparisons of the proportional limit compressive strength between the traditional Korean joints.

Table 1. Comparisons of the compressive capacity between the traditional Korean joints.(MPa)

	Control		*Nabijang*		*Joomeokjang*	
	Compressive strength	Proportional limit strength	Compressive strength	Proportional limit strength	Compressive strength	Proportional limit strength
No.1	59.54	55.69	33.61	30.69	25.88	20.15
No.2	61.00	53.61	34.51	32.04	28.14	19.45
No.3	58.87	50.02	26.09	22.33	32.92	22.68
No.4	54.31	47.72	34.58	33.47	21.48	18.14
No.5	57.43	53.46	31.56	28.92	29.43	21.45
Average	58.23	52.10	32.07	29.49	27.57	20.37

which was much higher than the rejection limit of 3.7, and the significance probability was 2.46E–11, it was also concluded that there were significant differences among the three groups.

–A statistical significance test to analyze the performance difference of the traditional joints–A statistical significance test between the compressive strengths of the Joomeokjang and Nabijang joints

The analysis of the variances showed that there were significant differences between the compressive properties among the non–jointed control specimen, the *Joomeokjang* joint, and the *Nabijang* joint. It is understandable that the jointed members would have a lower strength than the solid member, but the difference between the *Nabijang* and *Joomeokjang* joints should also be examined. Although there was a difference between the means of the two groups, a t–test was carried out to test the significant difference between the two joints after determining whether there was an equal or an unequal variance by performing an F–test for their compressive strengths.

The significance probability of the F–test for the compressive strengths was 0.369 (Appendix 3.2.2), which is higher than 0.05. Therefore, the t–test, which assumed an equal variance for the compressive strengths between the two groups, was carried out to clarify the significant difference. Since the significance probability of the F–test for the proportional limit strength was 0.053 (Appendix 3.2.2), which was also higher than 0.05, a t–test was conducted to determine the differences between the two groups with the assumption of equal variances. The results of the t–test for the compressive strength and the proportional limit strength are presented as follows:

Because the t–value from the t–test for the compressive strength was 1.82 (Appendix 3.2.2), which is lower than the rejection limit, and the significance probability was larger than 0.05, it was concluded that there was no statistically significant difference between the *Nabijang* and *Joomeokjang* joints.

It might be possible to conclude that the *Nabijang* joint was superior to the *Joomeokjang* joint because the compressive strength means of the *Nabijang* and *Joomeokjang* joints were 32 MPa and 27 MPa, respectively, but there were no statistically significant differences between them. Hence, because comparing them only to the representative value presented an issue, it was necessary to include an analysis of the failure modes to draw a complete conclusion.

Since the t–value from the t–test for the compressive proportional limit strength was 4.35 (Appendix 3.2.2), which is lower than the rejection limit, and the significance probability was smaller than 0.05, it was concluded that there were statistically significant differences between the *Nabijang* and *Joomeokjang* joints.

Analysis of the compressive failure types for the traditional Korean joints

As shown in Table 2, the complicated failure types of crushing and shearing were shown in the non–jointed control specimen, and the compressive strength of the *Nabijang* joint was higher than that of the *Joomeokjang* joint; however, it also showed splitting failure types that show a complete scattering around the wedge of the *Nabijang* joint. Splitting was also a main failure type for the *Joomeokjang* joint, but the crushing failure type was mixed. The main failure types for the traditional Korean Hanok are shown in Fig. 9, and the detailed failure types of the *Joomeokjang* and *Nabijang* joints are represented in Figs. 10 and 11.

Splitting was the main failure type for the *Joomeokjang* joint (see Fig. 10), which was different from that for the *Nabijang* joint (see Fig. 11). This joint showed longitudinal failure, not tenon failure, in the vicinity of the mortise. Because the lateral distance of the mortise was short, the local longitudinal failure in the vicinity of the mortise might progress. Therefore, a further study with many replications as a factor of lateral distances for the tenon and mortise are essential to deter-

Table 2. Failure types for the compression parallel to the grain of the traditional Korean joints

Specimen		Failure type
Control	1	crushing*/shearing**
	2	crushing
	3	crushing/shearing
	4	wedge split/shearing
	5	crushing
Specimen		**Failure type**
Nabijang	1	crushing/splitting***
	2	splitting
	3	splitting
	4	splitting
	5	splitting
Specimen		**Failure type**
Joomeokjang	1	splitting
	2	crushing/splitting
	3	splitting
	4	splitting
	5	crushing/splitting

(*This term shall be used when the plane of rupture is approximately horizontal. **This term shall be used when the plane of rupture makes an angle of more than 45 deg with the top of the specimen. ***This type of failure usually occurs in specimens having internal defects prior to testing and shall be the basis for culling the specimen.)

Fig. 9. Samples of each failure type of the traditional Korean joints (From left to right: splitting, crushing, and shearing).

mine the optimum performance. Prior to settling on the *Joomeokjang* joint, it was determined how the optimum performance was changed as the dimensions of the tenon were changed. It was assumed that performance would change as the dimensions of the protruded head of the tenon and the bottom base of the mortise changed. Standardization through the precise machining process and the mechanization of the technique might be required because the fitness of both the tenon and the mortise matters not only in the failure mode but also in the compressive performance. Many interests and researches are required to determine this information as manual labor based on experience is still prevalent over automation in traditional Korean construction.

An extreme failure along the length and around the top and bottom of the wedge of the mortise was the main failure of the *Nabijang* joint and is similar to that of the *Joomeokjang* joint. However, the extent of the failure of the *Nabijang* joint was more severe than that of the *Joomeokjang* joint. Representative value of the compressive strength was higher for the *Nabijang* joint, but the extent of its failure was also more severe. Thus, to select an adequate traditional joint, one must consider not only the simple representative value but also the analysis of the failure type or the variation of the mean. After determining the optimum performance for the *Nabijang* joint as the dimensions of the wedge and mortise changed, a performance comparison with the *Joomeokjang* joint should be conducted with priority. Based on the results of this study, while the compressive performance of the *Nabijang* joint was higher than that of the *Joomeokjang* joint, the *Nabijang* joint should be avoided in *Hanok* because the possibility of longitudinal failure is high. However, further study is needed.

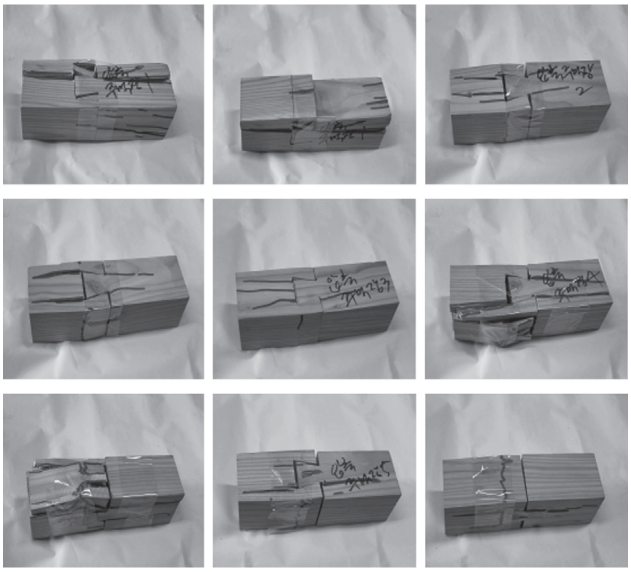

Fig. 10. Failure types of the *Joomeokjang* specimens.

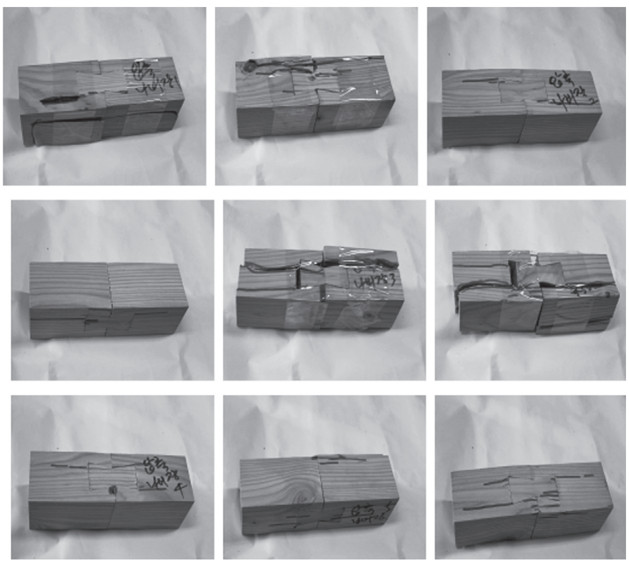

Fig. 11. Failure types of the *Nabijang* specimens.

CONCLUSION

The compressive strengths and failure types of the non–jointed control specimen, the *Joomeokjang* joint, and the *Nabijang* joint were studied to collect the basic information of the Korean traditional joints.

The compressive strengths of the *Nabijang* and *Joomeokjang* joints were 55% and 47%, respectively, compared to that of the non–jointed control specimen. An F–test and a t–test were carried out to understand the significant differences between the compressive performances of the *Nabijang* and *Joomeokjang* joints. The means of the *Nabijang* and *Joomeokjang* joints were 32 MPa and 27 MPa, respectively, so we concluded that the *Nabijang* joint was superior to the *Joomeokjang* joint. However, there was no statistical significance between the distributions of both groups. Because a simple comparison of the representative values presented a problem, it was understood that a total assessment of the performances including the analysis of failure types and the variance of data should be included.

Although the compressive strength of the *Nabijang* joint was higher than that of the *Joomeokjang* joint, the *Nabijang* joint displayed a splitting failure, which showed a complete scattering around the wedge of the joint. Splitting was also the main failure type for the *Joomeokjang* joint and the crushing failure was mixed.

It was understood that joints should be processed or constructed with the acknowledgment that longitudinal splitting in the vicinity of the mortise is the main failure type for both traditional joints.

Based on these results, that the compressive performance of the *Nabijang* joint was higher than that of the *Joomeokjang* joint, it might be concluded that the *Nabijang* joint should be avoided in *Hanok* because the possibility of longitudinal failure is high.

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APPENDIX

3.2.1

Anova(compressive strength)

Summary

Groups	Count	sum	mean	variance
Column 1	6	349.3913	58.23189	5.155077
Column 2	6	192.4357	32.07261	10.12683
Column 3	6	165.409	27.56817	14.47053

Anova

factor	SS	DF	MS	F	P–value	F–limit
teatment	3289.723	2	1644.862	165.8549	5.9E–11	3.68232
error	148.7622	15	9.917477			
total	3438.486	17				

Summary

Groups	Count	sum	mean	variance
Column 1	6	312.597	52.0995	8.103068
Column 2	6	176.9217	29.48694	15.07049
Column 3	6	122.2493	20.37489	2.470683

Anova

factor	SS	DF	MS	F	P–value	F–limit
treatment	3201.616	2	1600.808	187.2711	2.46E–11	3.68232
error	128.2212	15	8.548081			
total	3329.838	17				

3.2.2

F–test: two sample for variance (compressive strength)

	variable 1	variable 2
mean	32.07261	27.56817
variance	12.65853	18.08816
observations	5	5
DF	4	4
F	0.699824	
P(F<=f) one–sided test	0.368933	
F limit: one–sided test	0.156538	

F-test: two sample for variance(Proportional limit strength)

	variable 1	variable 2
mean	29.48694	20.37489
variance	18.83812	3.088353
observations	5	5
DF	4	4
F	6.099728	
P(F<=f) one-sided test	0.053928	
F limit: one-sided test	6.388233	

t-test: assuming equal variances(compressive strength)

	variable 1	variable 2
mean	32.07261	27.56817
variance	12.65853	18.08816
observations	5	5
pooled variance	15.37335	
Hypothesized Mean difference	0	
DF	8	
t value	1.816465	
P(T<=t) one-sided test	0.053414	
t-limit one-sided test	1.859548	
P(T<=t) two-sided test	0.106829	
t-limit two-sided test	2.306004	

t-test: assuming equal variances(proportional limit strength)

	variable 1	variable 2
mean	29.48694	20.37489
variance	18.83812	3.088353
observations	5	5
pooled variance	10.96323	
Hypothesized Mean difference	0	
DF	8	
t value	4.35128	
P(T<=t) one-sided test	0.001221	
t-limit one-sided test	1.859548	
P(T<=t) two-sided test	0.002441	
t-limit two-sided test	2.306004	