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A Study on the Bending Properties of Traditional Korean Joints

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Since an apprentice system was prevalent in Korea instead of the transfer of systematical and scientific theories and techniques for traditional constructions. Therefore, few data have been accumulated for the mechanical and physical properties of traditional joints. The *Joomeokjang* and *Nabijang* joints are the most basic jointing method in Korea traditional building construction. In this study, the bending performances for four types of widely used Korean traditional joint, *Joomeokjang*, *Nabijang*, pair of double *Joomeokjang* and cross shaped joint, were evaluated.

The MOR of *Nabijang* was higher than that of *Joomeokjang*, and the MOE of *Joomeokjang* was higher than that of *Nabijang*; however, there were no significant differences between the two methods. Therefore, the performance of *Joomeokjang* and *Nabijang* could not be compared only with the mean values, and additional information such as failure type is necessary. The pair of double *Joomeokjang* was statistically superior to the cross shape joint in terms of both mean values and the statistical analysis for MOE and MOR. Needless to say, the failure types of *machoom* joints should be sufficiently considered such as *ieum* joints. The failure types of *Joomeokjang* and *Nabijang* mainly consisted of cross grain failure. Simple tension failure was developed in the pair of double *Joomeokjang* and cross shaped joints, which created a mixed failure of simple tension failure and cross grain failure.

Keywords: *ieum* joints, *machoom* joints, *Joomeokjang*, *Nabijang*, pair of double *Joomeokjang*, cross shape joint

INTRODUCTION

Hanok, a Korean traditional construction, is built by closely fitting the elements together with a *machoom* (a kind of joint with various angles) or *ieum* (a kind of longitudinal join) that is different from western construction using nails and adhesives. *Hanok* is well recognized as a solid and durable house. *Hanok* will never collapse even if one post is missed due to the inherent advantage of closely fitting the elements together with a *machoom* or *ieum* method. *Hanok* is an earthquake resistant building because of these aspects of its unique construction methods. *Hanok* is constructed with only *ieum* and *machoom* of tenon or mortise, with nails never being used in any joints beyond the roof assembly construction.

There is a proverb that states "without the error of single *Chi*" in Korea. *Chi* is a unit of length that corresponds to 3.303 cm. This expression stems from the fact that just one *Chi* of error is allowable to build a *Hanok*. An error of about 3 cm would not be permitted in modern constructions but is permissible in Korean traditional constructions and wood joint constructions. The shrinkage and twisting during drying that is a characteristic of wood has supported a stereotype of *Hanok* as a poor heating system. Outer wind can often enter through the cleavages that often develop due to shrinkage and twisting, leading to a cold house. Of course, modern techni

cal developments can prevent this problem. *Hanok* has been unstably constructed in which purlines were placed across an unsettled rectangular structure as part of the joint method for *ieum* and *machoom*. Due to the *machoom* of tenon and mortise, *Hanok* is very stable for swelling and twisting, and can support vertical loading. Frames of *Hanok* mainly consist of post, beam and purlines made of wood. The following house type was called wooden framed construction. To understand the structure of *Hanok*, an appreciation of post, beam and purline is necessary.

Although wood offers many advantages as structural members, its limited dimensions necessitated its use with joints for the sake of convenience. The term 'joint', which means the way in which one member is made with two or more members, can be classified into three categories in Korea: *jokmae* (a kind of parquet) means adding into sides of boards or panles, *machoom* means a joint of members in a T–shape or at a certain angle such as post and beam, purlin and post, or brace and post, post and foundation, and *ieum* means a joint of members along the members' direction such as post and post, or beam and beam. Ancient Koreans followed some principles in using *ieum* and *machoom*. For good jointing of wooden framed construction, as little cutting as possible is made, and jointed at a point subjected to only a small stress, and not crafted for decoration. The ending of joints should be fitted tightly to transfer stress equally, and the cross–section of the joints should be perpendicular to the stress direction.

In Korea, an apprentice system was prevalent instead of the transfer of systematic and scientific theories and techniques for traditional constructions. For this reason, mechanical and physical data for traditional joints do not

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exist in spite of the continued presence of many *Hanok*. To systematically and scientifically advance the *Hanok* which is not merely ancient structures but also the spirit and soul of Korea, some studies are necessary to understand the basic physical and mechanical properties of the principal traditional joints that are unique to *Hanok*.

Ieum and *machoom* of *Joomeokjang*, which have been used most widely in Korea, are not just a simple joint method but a well functioning joint method with proper mechanical performance. As the *Joomeokjang* and *Nabijang* joints were considered the most basic and important joint method in terms of mechanical performance, it is necessary to specifically investigate their joint patterns.

To appreciate the bending performance of the four types of traditional joints widely used in Korea, *Nabijang*, *Joomeokjang*, a pair of double *Joomeokjang*, and cross shaped joint were tested in this study. A control specimen with no joint was also examined for comparison.

MATERIALS AND METHODS

The bending test was conducted according to KSF 2150:2004. The span of the specimen should be more than 15 times its depth, and its total length should be its span plus two times its depth, as stated in KSF 2150, but these conditions could not be met due to the difficulties in preparing a full–scale traditional joint.

However, as the main study goal was to estimate the mechanical performance of the Korean traditional joint, a test was conducted to evaluate the bending strengths of Korean traditional joints in comparison to control specimens of the same dimensions. Also, a test was conducted to identify those joints with superior performance among the traditional joints.

The wood species of the specimens was Japanese larch. The loading speed for all specimens was 5 mm/min, according to KSF 2150. The cross section was 80×80 mm and the length was 600 mm for all joints. Only the cross

Fig. 1. The features of traditional joint specimen (From left top; Control, *Nabijang Joomeokjang*, Pair of double *Joomeokjang*, Cross shaped joint).

shaped joint was 400 mm long because of manufacturing difficulties. For the *Joomeokjang* joint, the width and height of the tenon's protrusion were 50 mm and 20 mm, respectively, and the width of the base was 30 mm. To compare the capacity for the *Joomeokjang*, the dimensions of the *Nabijang* joint were also the same as those of *Joomeokjang*. The span for all traditional joints was 400 mm, except for the cross shaped joint which had a span of 300 mm. As the main objective of this study was to compare the relative bending property among traditional Korean joints, each joint was only subjected to 5 test repetitions.

There is no special testing standard for evaluating the bending performance of traditional Korean joints. The position of traditional joints in *Hanok* should be placed in a post or other structural member. Therefore, the resistance of the jointed member to lateral loading might be more important than its bending performance to vertical loading on the jointed section. Therefore, the loading direction was applied as shown in Fig. 2.

Fig. 2. Loading configuration of Korean traditional joints (Left: Side view, Right: Upside view).

RESULTS AND DISCUSSION

The members for the main target of this study were *dori* (Korean term: a kind of purline), *changbang* (Korean term: a kind of connecting member between post and post by *Joomeokjang* joint), *booyeon* (Korean term: extended eaves), and *yeonmok* (Korean term: a kind of rafter). Those members were all affected by bending performance. As a rule, the parts that are important for the bending performance are also important for tensile performance rather than compressive performance.

Comparison of bending performances for Korean traditional joints

The load–deformation curve for the *Joomeokjang* and *Nabijang* joints are shown in Figs. 3 and 4, respectively. Rupture occurred when maximum deformation exceeded 15 mm through the ultimate load pass by the proportional limit point.

Typical load–deformation curves for the pair of double *Joomeokjang* and cross shaped joint are shown in Figs. 5 and 6. Both joints were ruptured immediately after reaching ultimate strength at around 6mm deformation.

The *Joomeokjang* and *Nabijang* joints are manufactured by *ieum*, and the pair of double *Joomeokjang* and cross shaped joints are produced by *machoom*. The longitudinally jointed *ieum* therefore showed more deformation than the vertically jointed *machoom* and failed.

The bending strength of *ieum*, which has only one direction joint, exhibited a ultimate strength ranged from 2000 N to 2500 N. However, *machoom*, which has both
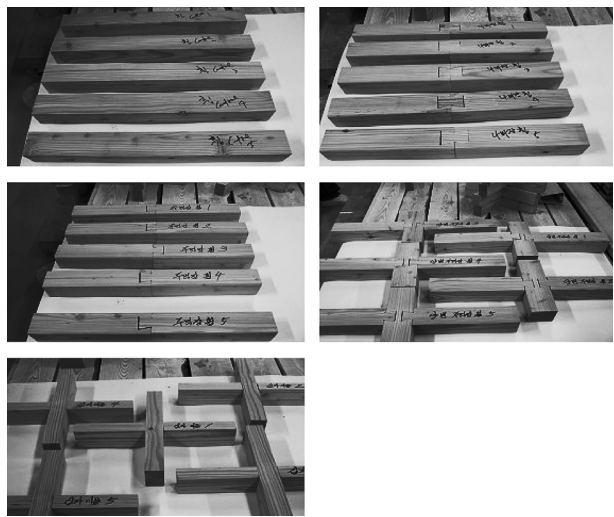
side joints, showed a ultimate strength ranging from 3000 N to 3500 N in the pair of double *Joomeokjang*, and showed a ultimate strength of 8500 N in the cross shaped joint. Accordingly, the bending strength of *machoom* was greater than that of *ieum*. The connections in *Hanok* are usually *machoom* joint, which has a sufficient bending performance. Moreover, since the connection of post and beam in *Hanok* is not a rigid joint but a hinge joint, so the stiffness of connections in *Hanok* is sufficient to resist an earthquake.

MOR and MOE values for the five groups, including the four types of traditional joint plus the control specimen, are presented in Tables 1 and 2. As mentioned previously, a sufficient span could not be attained according to KSF 2150:2004 for the bending test, so the bending strength of the control specimen was lower than the standard value. However, as the main goal of this study was to make a relative comparison of the bending performance among some Korean traditional joints, the same length and cross sections of each joint were only satisfied for the comparison (only the dimensions of the cross shaped joint were different from those of the other joints due to the manufacturing difficulty).

The MORs of the *Joomeokjang* and *Nabijang* joints were 2.35 MPa and 2.42 Mpa, respectively, corresponding to 5.88% and 6.05% of the 39.99 MPa value of the bending performance of the control specimen. The result was considerably low compared to the previous compression test where the *Joomeokjang* and *Nabijang* joints showed 47% and 55% of the performance of the control specimen (submitted to Wood & Fiber Science: A study on the compressive strength properties of traditional Korean joints).

Because no other treatment for increasing the joint performance except traditional *ieum* and *machoom* method was used in this study, the bending performance can be increased by using adhesive or supplementary wedge. However, the main study purpose was to evaluate the relative structural performance of Korean traditional joints and identify the best joint, in order to improve the jointing ability.

Methods to improve the jointing ability will be investigated in future study. The strength of the *Joomeokjang* and *Nabijang* joints was considerably reduced compared to the control specimen, and the bending performance of *Nabijang* was better that that of *Joomeokjang* when only their mean strength was compared. This result corresponded to a previous compression test showing that the compression performance of *Nabijang* was better than that of *Joomeokjang* (submitted to Wood & Fiber Science: A study on the compressive strength properties of traditional Korean joints).

In the compression test results, the mean strength of *Nabijang* was better than that of *Joomeokjang*, but the difference was not statistically significant. *Joomeokjang* was more efficient than *Nabijang* considering the failure types. Hence, statistical analysis and understanding of failure types for bending test were also added to this study.

The MOEs of the *Joomeokjang* and *Nabijang* joints

were 178.82 MPa and 151.19 MPa, respectively, which were 11.2% and 9.5% of the 1593.70 MPa value of the control specimen. Comparing only the mean values, the compressive strength and MOR of *Nabijang* were better than those of *Joomeokjang*, but one MOE result of *Joomeokjang* was higher than that of *Nabijang*. These
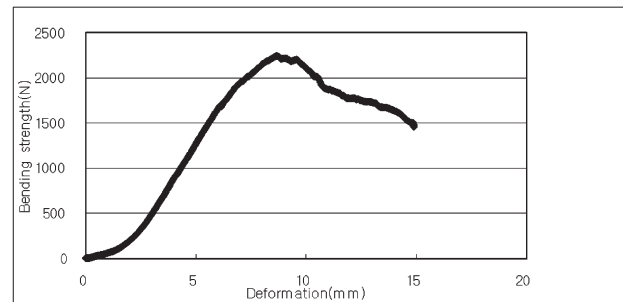

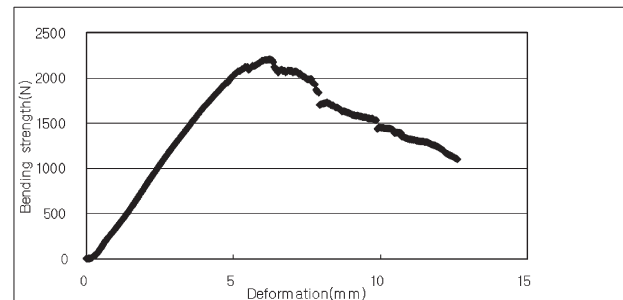**Fig. 3.** Load–deformation curve for the *Joomeokjang* joint (Specimen No. 5).

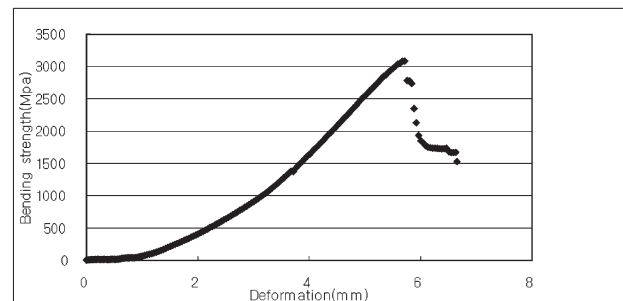**Fig. 4.** Load–deformation curve for the *Nabijang* joint (Specimen No. 3).

Fig. 5. Load–deformation curve for the Pair of double *Joomeokjang* joint (Specimen No. 5).
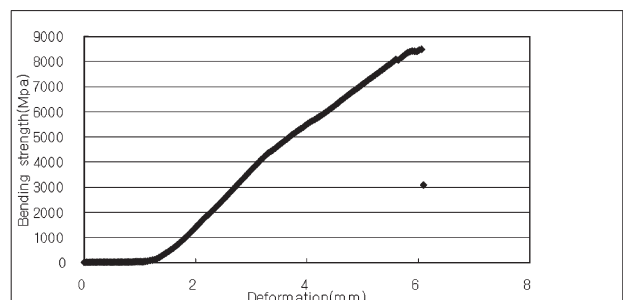

Fig. 6. Load–deformation curve for the Cross shaped joint (Specimen No. 1).

results suggested that the *Joomeokjang* joint is better than the *Nabijang* joint for *Hanok*, which comprises not rigid joints but hinge joints, because *Joomeokjang* had greater stiffness than *Nabijang*.

The MOR of the pair of double *Joomeokjang* and cross shaped joints where the members meet in the rectangular direction was lower than that of the control specimen, but higher than that of *ieum* where the members me*et al*ong the same direction. The performance of the pair of double *Joomeokjang* was 10.1% of that of the control specimen, and that of the cross shaped joint was 68.2% of that of the control specimen. The span used for the cross shaped joint was 300 mm, which was different from the 400 mm span of the other joints. Therefore, although it was impossible to compare the values directly, we assumed that the bending performance was considerably higher than that of the pair of double *Joomeokjang*.

The MOE of *machoom* was higher than that of *ieum*. The MOE of the cross shaped joint was especially higher than that of the control specimen. The MOE value of the pair of double *Joomeokjang* was 12.4% of that of control specimen, and the MOE value of the cross shaped joint was 135.3% of that of the control specimen.

The fitness of the contacting area between the members for cross shaped joint was considered superior to that of the *Joomeokjang* and *Nabijang* joints, and mutual compression occurred when the bending was loaded, thereby improving the stiffness. More accurate study is needed for more detailed results. However, based on these results the cross shaped joint is recommended as a good joint method in *Hanok* that features a hinge–type joint because the cross shaped joint has better stiffness than the other joint methods.

Table 1. Comparison of MOR for among the Korean traditional joints. (Unit: MPa)

	Control	*Joomeokjang*	*Nabijang*	Pair of double *Joomeokjang*	Cross shaped joint
	39.97	1.78	2.33	1.93	23.59
	42.06	2.33	2.42	2.92	2.95
	38.76	1.64	2.58	3.12	24.78
	43.21	3.36	2.99	3.80	15.36
	35.95	2.63	1.78	3.62	24.51
Avg.	39.99	2.35	2.42	3.07	18.24
St.de.	2.85	0.69	0.44	0.73	9.39

Table 2. Comparison of MOE for among the Korean traditional joints. (Unit: MPa)

	Control	*Joomeokjang*	*Nabijang*	Pair of double *Joomeokjang*	Cross shaped joint
	1501.69	114.94	209.77	132.03	3621.30
	1685.74	153.78	160.35	201.56	299.07
	1305.66	203.52	145.31	151.76	2638.58
	1923.18	286.46	167.66	316.41	1952.78
	1552.25	135.39	72.85	186.52	2270.99
Avg.	1593.70	178.82	151.19	197.66	2156.54
St.de.	229.22	68.54	49.89	71.86	1212.71

Statistical analysis of the bending performance differences of the traditional joint

Analysis of significant differences among traditional joints

The MORs and MOEs for traditional joints and the control specimen are shown in Fig. 7, respectively. As mentioned previously, the bending performance of *machoom* was better than that of *ieum* when only the mean values were considered. For the *machoom* joint, both MOR and MOE of the cross shaped joint were higher than those of the pair of double *Joomeokjang*. The MOR of *Nabijang* was higher than that of *Joomeokjang* but MOE exhibited the opposite tendency for the *ieum* joint. However, further statistical analysis of each group in comparison to a previous study of the compression test is required (submitted to Wood & Fiber Science: A study on the compressive strength properties of traditional Korean joints).

There was a low necessity for the cross shaped joint because it showed much better performance than the other joints, but *Joomeokjang*, *Nabijang* and the pair of double *Joomeokjang* cannot be confidently compared only on the basis of the mean values. Hence, analysis of variance statistical analysis was conducted for all groups.

From Table 3, the much higher F–value of 69.2 compared to the rejection limit of 2.87, and the very low level of significance at 2E–11, supported the possibility of significant differences among the groups. In other words, there were statistical differences of MOR between the four types of traditional joints and the control specimen.

According to Table 4, the analysis of variance for MOE showed that the F value of 14.8 was higher than the rejection limit of 2.87 and that the level of significance was very low, which was the same tendency as MOR. This result supported the possibility of a significant difference among the groups. Namely, the MOE of each traditional joint differed significantly. However, *Joomeokjang* and *Nabijang* in *ieum* have similar appearance and uses, and the pair of double *Joomeokjang* and cross shaped joints also have similar appearance and uses in *machoom*. Consequently, the *ieum* and *machoom* groups had to be separated for additional comparison and investigation of the bending performances among the groups.

Analysis of significant differences among the traditional ieum joints

The F–test should be conducted in advance to identify the significance of the difference between the two groups and then verify the equal variance or unequal variance of the groups. The significance between the two groups can be judged through the t–test based on that verification. The t–test for the MOR of *Joomeokjang* and *Nabijang* was conducted after the F–test and the results are shown in Table 5.

The level of significance of the F–test was 0.19, which was higher than 0.05. Therefore, the t–test, based on the assumption of equal variance for the bending performances between the two groups, was carried out to clarify the significant difference. The results are shown in Table 6. The level of significance exceeding 0.05
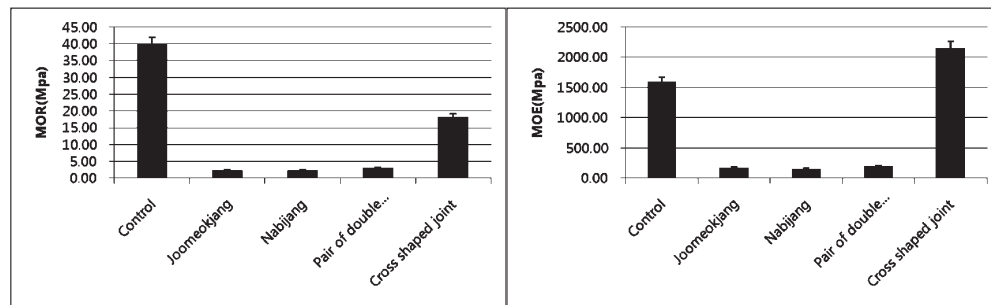
Fig. 7. Comparison of MOR and MOE among the Korean traditional joints.

Table 3. ANOVA table for MOR of the Korean traditional joints

Anova		(MOR)				
Summary						
Groups	Count	Sum	Mean	Variance		
Column 1	5	199.9441	39.98883	8.128411		
Column 2	5	11.74688	2.349375	0.479897		
Column 3	5	12.09961	2.419922	0.191451		
Column 4	5	15.37266	3.074531	0.538691		
Column 5	5	91.20278	18.24056	88.18839		
Anova						
Factor	SS	DF	MS	F	P–value	F–limit
Treatment	5397.594	4	1349.398	69.18087	2E–11	2.866081
Error	390.1074	20	19.50537			
Total	5787.701	24				

Table 4. ANOVA table for MOE of the Korean traditional joints

Anova		(MOE)				
Summary						
Groups	Count	Sum	Mean	Variance		
Column 1	5	7968.522	1593.704	52543.85		
Column 2	5	894.082	178.8164	4697.417		
Column 3	5	755.9375	151.1875	2489.408		
Column 4	5	988.2813	197.6563	5163.517		
Column 5	5	10782.72	2156.543	1470668		
Anova						
Factor	SS	DF	MS	F	P–value	F–limit
Treatment	18121872	4	4530468	14.75182	9.15E–06	2.866081
Error	6142248	20	307112.4			
Total	24264119	24				

revealed the absence of any statistically significant differences between the *Nabijang* and *Joomeokjang* joints.

There were no statistically significant differences between *Joomeokjang* and *Nabijang* through the t–test of MOE based on the assumption of equal variance because the level of significance exceeded 0.05, as shown in Table 8. As in the MOR results, there were no statistically significant differences between them. Therefore, the bending performance could not be compared between

*Joomeokjan*g and *Nabijang* only with the mean value, and additional information such as failure type should be included.

Analysis of significant differences among traditional machoom joints

As with the previous *ieum* joints, the F–test was conducted in advance to identify the level of significance between the two groups and then verify that the groups had equal variance or unequal variance for the pair of

Table 5. F–test result for MOR between the *Joomeokjang* joint and *Nabijang* joint

F–test: two sample for variance		
	Variable 1	Variable 2
mean	2.349375	2.419922
variance	0.479897	0.191451
observations	5	5
DF	4	4
F	2.506628	
P(F<=f) one–sided test	0.19759	
F limit: one–sided test	6.388233	

Table 6. t–test result for MOR between the *Joomeokjang* joint and *Nabijang* joint

t–test: assuming equal variance		
	Variable 1	Variable 2
mean	2.349375	2.419922
variance	0.479897	0.191451
observations	5	5
Pooled variance	0.335674	
Hypothesized mean difference	0	
DF	8	
t value	–0.19253	
P(F<=f) one–sided test	0.426064	
F limit: one–sided test	1.859548	
P(F<=f) two–sided test	0.852128	
F limit: two–sided test	2.306004	

Table 7. F–test result for MOE between the *Joomeokjang* joint and *Nabijang* joint

F–test: two sample for variance		
	Variable 1	Variable 2
mean	178.8164	151.1875
variance	4697.417	2489.408
observations	5	5
DF	4	4
F	1.886962	
P(F<=f) one–sided test	0.276827	
F limit: one–sided test	6.388233	

Table 8. t–test result for MOE between the *Joomeokjang* joint and *Nabijang* joint

t–test: assuming equal variance		
	Variable 1	Variable 2
mean	178.8164	151.1875
variance	4697.417	2489.408
observations	5	5
Pooled variance	3593.413	
Hypothesized mean difference	0	
DF	8	
t value	0.728753	
P(F<=f) one–sided test	0.243468	
F limit: one–sided test	1.859548	
P(F<=f) two–sided test	0.486936	
F limit: two–sided test	2.306004	

Table 9. F–test result for MOR between the Pair of double *Joomeokjang* joint and Cross shaped joint

F–test: two sample for variance		
	Variable 1	Variable 2
mean	3.074531	18.24056
variance	0.538691	88.18839
observations	5	5
DF	4	4
F	0.006108	
P(F<=f) one–sided test	0.00011	
F limit: one–sided test	0.156538	

Table 10. t–test result for MOR between the Pair of double *Joomeokjang* joint and Cross shaped joint

t–test: assuming unequal variancee		
	Variable 1	Variable 2
mean	3.074531	18.24056
variance	0.538691	88.18839
observations	5	5
Hypothesized mean difference	0	
DF	4	
t value	–3.60022	
P(F<=f) one–sided test	0.011377	
F limit: one–sided test	2.131847	
P(F<=f) two–sided test	0.022754	
F limit: two–sided test	2.776445	
F limit: two–sided test	2.306004	

Table 11. F–test result for MOE between the Pair of double *Joomeokjang* joint and Cross shaped joint

F–test: two sample for variance		
	Variable 1	Variable 2
mean	197.6563	2156.543
variance	5163.517	1470668
observations	5	5
DF	4	4
F	0.003511	
P(F<=f) one–sided test	3.66E–05	
F limit: one–sided test	0.156538	

Table 12. t–test result for MOE between the Pair of double *Joomeokjang* joint and Cross shaped joint

t–test: assuming unequal variance		
	Variable 1	Variable 2
mean	197.6563	2156.543
variance	5163.517	1470668
observations	5	5
Hypothesized mean difference	0	
DF	4	
t value	–3.60559	
P(F<=f) one–sided test	0.011323	
F limit: one–sided test	2.131847	
P(F<=f) two–sided test	0.022645	
F limit: two–sided test	2.776445	

double *Joomeokjang* and cross shaped joints. The t–test was conducted after completion of the F–test.

The t–test, assuming unequal variance, was conducted because the level of significance was less than 0.05. The previous conclusion of unequal variance for *machoom* but equal variance for *ieum* implied that a severe difference of characteristics for the pair of double *Joomeokjang* and cross shaped joints. The results of the t–test are shown in Table 10. The significant differences between two groups implied a considerably difference between the pair of double *Joomeokjang* and cross shaped joints for MOR.

The F–test results of MOE for the pair of double *Joomeokjang* and cross shaped joints are shown in Table 11. The t–test assuming unequal variance was conducted because the level of significance was less than 0.05.

The two groups exhibited a significant different with a level of significance of less than 0.05, according to the t–test results shown in Table 12.

The pair of double *Joomeokjang* and cross shaped joints differed not only in terms of the mean values but also in terms of the statistically significant difference. This confirmed the superiority of the cross shaped joint over the pair of double *Joomeokjang* joints for the *Hanok* construction. Naturally, the failure types must also be considered for the *machoom* joints such as the *ieum* joint.

Comparison of failure types for traditional joints

Although there were no specific failure types, a complex failure type comprising a mix of simple tension, horizontal shear and cross grain failure was developed in the control specimen. On the other hand, cross grain failure was dominant for the *Joomeokjang* and *Nabijang* joints. Simple tension failure was developed in all of the pair of double *Joomeokjang* while the cross shaped joint
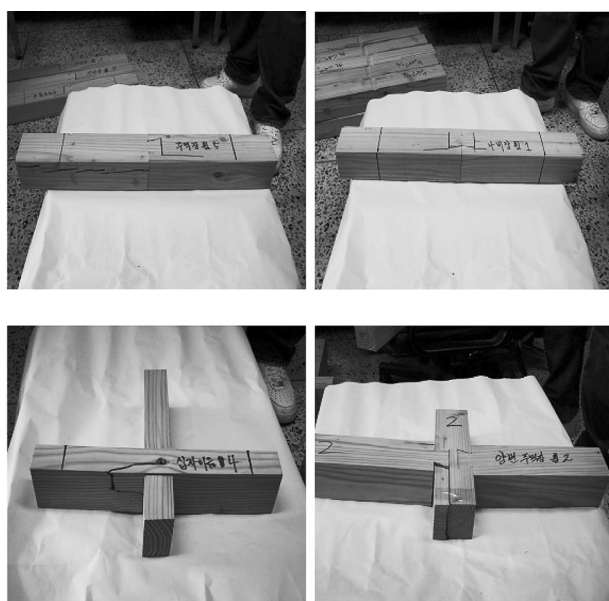

Fig. 8. Failure types for each Korean traditional joints. (*Joomeokjang* joint; *Nabijang* joint; Cross shaped joint; Pair of double *Joomeokjang* joint).

showed a mixture of simple tension failure and cross grain failure.

Some of the types of failure are presented in Fig. 8. According to these results, the *Joomeokjang* and *Nabijang* joints should not be used in the possible failure of cross grain, nor the pair of double *Joomeokjang* and cross shaped joints in the possible failure of simple tension failure.

CONCLUSION

Hanok, a Korean traditional house constructed without nails or adhesive, is durable due to its different construction techniques compared to the typical western house. However, an apprentice system was prevalent in Korea instead of the transfer of systematical and scientific theories and techniques for traditional constructions. Therefore, few data have been accumulated for the mechanical and physical properties of traditional joints.

Since the *Joomeokjang* and *Nabijang* joints are the most basic jointing method in Korea traditional building construction, their jointing pattern warrants further investigation. In this study, the bending performances for four types of widely used Korean traditional joint, *Joomeokjang*, *Nabijang*, pair of double *Joomeokjang* and cross shaped joint, were evaluated.

For *ieum* joints, the MOR of *Nabijang* was higher than that of *Joomeokjang*, and the MOE of *Joomeokjang* was higher than that of *Nabijang*; however, there were no significant differences between the two methods. Therefore, the performance of *Joomeokjang* and *Nabijang* could not be compared only with the mean values, and additional information such as failure type is necessary.

For *machoom* joints, the pair of double *Joomeokjang* was statistically superior to the cross shape joint in terms of both mean values and the statistical analysis for MOE and MOR. Needless to say, the failure types of *machoom* joints should be sufficiently considered such as *ieum* joints.

The failure types of *Joomeokjang* and *Nabijang* mainly consisted of cross grain failure. Simple tension failure was developed in the pair of double *Joomeokjang* and cross shaped joints, which created a mixed failure of simple tension failure and cross grain failure.

The dimensional variation of the *Joomeokjang* or *Nabijang* joints needs to be further evaluated in future study in order to determine the optimum performance. In other words, the performance of various tenon sizes for *Joomeokjang* and of various wedge sizes for *Nabijang* should be further investigated, as should the performance of various cross section sizes for the cross shaped joint.

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