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A Study on Predictability for the Bending Characteristics of Korean Traditional Joints using the Finite Element Method

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In most countries, the post–beam wooden building construction method is the oldest architectural style, similar to the Korean traditional building (*Hanok*). In this study, numerical analysis was performed to evaluate the bending performance of the *Joomeokjang* joint (*J*–joint) and the *Nabijang* joint (*N*–joint), which are the most widely used in traditional Korean wooden frame constructions.

To examine whether it is possible to grasp the bending properties of wooden structural components, a structural sized specimen without joints was investigated first. To ensure accurate application of the numerical analysis method, the 3–D orthotropic elements were evaluated and the results confirmed the viability of the method. Subsequently, we confirmed the applicability of the numerical analysis by comparing the results of the actual bending performance test and the finite element analysis results for the *J*–joint and *N*–joint. Stress concentration and deformation similar to the actual fractured specimen were observed with finite element analysis. As a result, by applying FEM without destruction of the joint, which is uneconomical and inefficient, we will be able to ascertain the strength of various types of joints in the future.

Key words: 3–D orthotropic element, *J*–joint, Korean traditional building, numerical analysis method, *N*–joint

INTRODUCTION

In most developed countries including South Korea, the post–beam wooden building construction method is the oldest architectural style, similar to the Korean traditional building (*Hanok*). Only a slight difference is present in the arrangement of the cross–section and the structure of the roof. The basic structure of the post & beam is similar to that of the load–bearing body. However, in some structures, such as the roof structure and the wall, differences are present in accordance with the natural environment and culture of each region. Recently, logging has become more difficult due to the shortage of structure sized trees and environmental protection. As a result, the light frame construction method that uses wood with small dimensions has become the most common. Wooden architecture involving the post & beam method that use structural sized logs is no longer used.

In Japan, a wooden architectural style using a factory–type post & beam method with a much smaller size than the *Hanok* is still used. In the United States, Australia and Canada, more than 90 percent of single–family homes use the light frame construction method. Even in South Korea, most of the wooden architectural style that has been recently constructed employs the light frame construction method.

However, looking at the results of a poll at the Korean NFPI (National Forest Research Institute), the preferred method is the wooden architecture of the post & beam method represented by the *Hanok*. These results are ironic. (Kim *et al*., 2010a; Kim *et al*., 2010c;Kim *et al*, 2011b;Kim *et al*., 2013) Therefore, there is a need to study the *Hanok* which uses traditional joints.

Due to the potential health benefits, compliance with public demands and active support of the government, the supply and demand of traditional *Hanoks* as well as new style *Hanoks* are rapidly increasing in Korea.

However, in the *Hanok* industry, robust construction personnel are lacking. In addition, the field of *Hanok* is pouring method of apprentice–type in terms of the technology taught to the reverse. Hence, the systematic and scientific techniques employed are difficult. In particular, scientific analysis to improve the mechanical performance of the joints, which is the most difficult part of *Hanok* construction, is necessary to reduce the high cost of traditional *Hanok* buildings. Once this is achieved, a new economical style of *Hanok* will be adopted.

Therefore, in this study, numerical analysis was performed to evaluate the bending performance of the *Joomeokjang* joint (*J*–joint) and the *Nabijang* joint (*N*–joint), which are the most widely used in traditional Korean wooden frame constructions. By applying the finite element method, the study attempts to develop a new type of traditional joint with superior performance. (Kim *et al*., 2011b; Kim *et al*., 2011c; Kim *et al*., 2011d; Kim *et al*, 2013)

MATERIALS AND METHODS

Bending performance analysis and finite element model for the structural sized specimen.

In this study, we attempted to determine the bend-

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ing characteristics of traditional joints by applying the finite element method. First, 35 Douglas–fir, 2”×6”, span 2.4 m specimens were subjected to a bending test to verify the validity of the finite element method (FEM) in order to grasp the bending characteristics of structural sized components. The loading rate was 10 mm/min (KS F2208). Three–dimensional numerical analysis was carried out with ANSYS, which is a general–purpose finite element analysis program. Numerical analysis was conducted with orthotropic material using three–dimensional element SOLID64, a unique element suitable for anisotropic material, as shown in Fig. 1. Input variables for finite element analysis of the Douglas fir are shown in Table 1. To improve the accuracy of numerical analysis, the test piece without knot modeling was used as the control. A detailed view of the knot modeling is shown in Fig. 2.

Bending performance analysis and finite element model of the traditional joints.

The solid models of the traditional joints are shown in Fig. 3, and the FEM models are shown in Fig. 4. Due to the difficulty of production for the full–scale traditional joints as well as the fact that the main purpose of the present study is the comprehension of bending characteristics for the traditional joints using the numerical method, small sized specimens were manufactured. This will be followed by production and FEM analysis of large–scale traditional joints in the near future.

The shapes of the *J*–joint and the *N*–joint are shown in Fig. 3. Japanese Larch, which is widely used in Korean construction, was chosen for this study. For the sake of convenience during the experiment, the dimensions were 80 × 80 × 600 mm and the bending performance experiments were repeated 5 times for each type of joint. (Kim *et al.*, 2011e)

3–D numerical structural analysis using ANSYS, which is a general–purpose finite element program, was carried out. The orthotropic characteristic, which is a structural property of the timber, was evaluated and non–linear numerical analysis was conducted. A SOLID64 element, which is suitable for anisotropic material analysis, was utilized. The element was the same as that used for finite element analysis of the structural sized specimens. For the joint characteristics, special contact–target analysis was performed, rather than simple joint analysis, to reflect the difference between the mortise and tenon. The coefficient of friction between the components was fixed at 0.5. Both the target element and contact element were assumed to be flexible. Initial penetration was considered in analysis to prevent abrupt breakaway between members. Also, an unsymmetrical stiffness matrix was used. The normal penalty stiffness was 0.1 for both traditional joints. For the nonlinear analysis, a large–displacement–static option was used. Further selected options were: time at the end of load step=100, automatic time stepping=off, number of sub steps=1. (Kim *et al.*, 2013) The input variables required for finite element analysis are shown in Table 2.

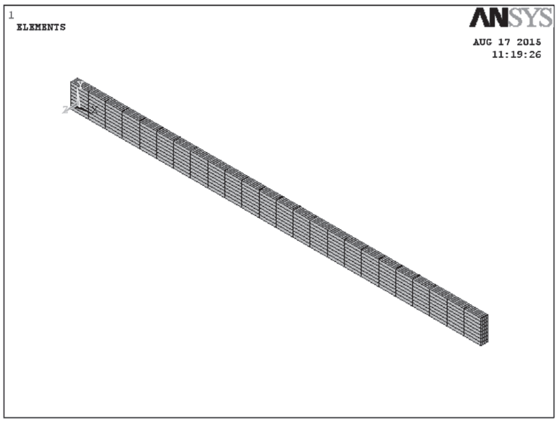


Fig. 1. Finite element model of the structural size specimen.

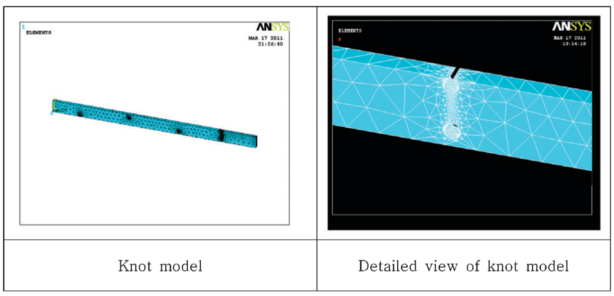


Fig. 2. Knot model of the structural size specimen.

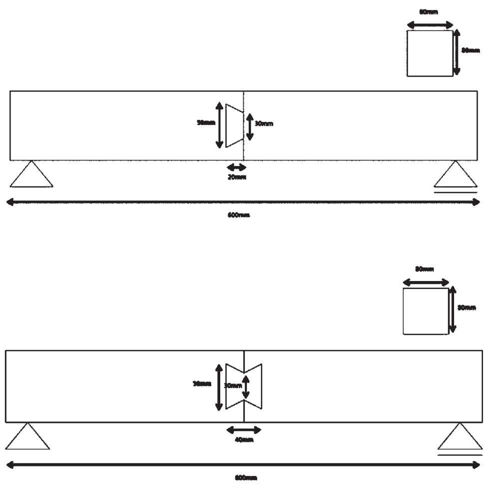


Fig. 3. The dimensions of the Korean traditional joint specimens (top: *J*–joint, bottom: *N*–joint)

Table 1. Ansys modeling specification of Douglas–fir

EX(MPa)	EY(MPa)	EZ(MPa)	PRXY	PRYZ	PRXZ	GXY(MPa)	GYZ(MPa)	GXZ(MPa)
13000	13000*0.068	13000*0.005	0.292	0.390	0.449	13000*0.064	13000*0.007	13000*0.078

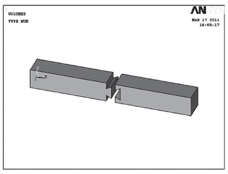
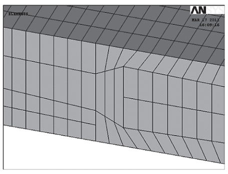
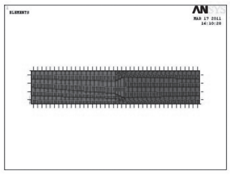
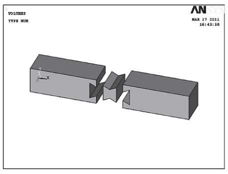
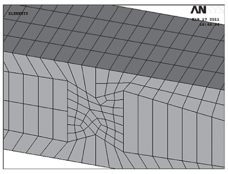
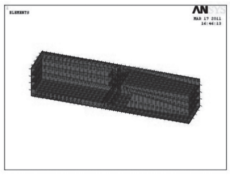
		
Solid model of *J*–joint	Detailed view of numerical model for the *J*–joint	contact–target element(*J*–joint)
		
Solid model of *N*–joint	Detailed view of numerical model for the *N*–joint	contact–target element(*N*–joint)

Fig. 4. The dimensions of the Korean traditional joint specimens (top: *J*–joint, bottom: *N*–joint)

Table 2. Ansys modeling specification of Japanese Larch

EX(MPa)	EY(MPa)	EZ(MPa)	PRXY	PRYZ	PRXZ	GXY(MPa)	GYZ(MPa)	GXZ(MPa)
12900	12900*0.065	12900*0.079	0.276	0.352	0.355	12900*0.069	12900*0.007	12900*0.063

RESULTS AND DISCUSSION

Evaluating the feasibility of the numerical analysis method (for structural sized specimen)

For the ultimate load capacity of the structural size specimen

Mean values of ultimate load and the maximum deformation for 35 specimens were 8616 N and 48 mm, respectively. (Kim *et al*., 2011c; Kim *et al*., 2011d) In contrast, the ultimate load determined by the numerical analysis method was 9034 N, and the amount of deformation was 37 mm. The estimated ultimate load was greater than the actual experimental values whereas the deformation amount was under–estimated. However, the variations in the ultimate load for the actual experimental samples ranged from 4883~11738 N, while the deformation exhibited a range of 26~68 mm. Considering the above results, it may be that the results of numerical analysis were fairly accurate.

Table 3. The experimental value and numerical value for the control specimen

Experimental value	Numerical value
8616 N	9034 N
48 mm	37 mm

Comparison of experimental results and numerical results for the structural sized specimen

The actual flexural failure types for the structural sized specimens are shown in the following Table 4. (Kim *et al*., 2011c; Kim *et al*., 2011d) Simple tension was the most common type of failure in the 35 specimens. For example, experimental sample No. 13 showed a simple tension type of failure. Looking at the numerical analysis results for the knots on the FEM model of the test specimen (Fig. 5), it can be observed that they fairly match the actual failure type. According to the results of numerical analysis, stress was concentrated in the vicinity of the destroyed area for the test specimen. In addition, excessive deformation occurred compared to the amount of deformation in other parts of the body.

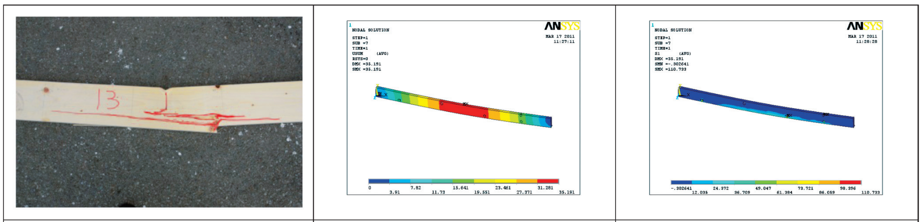
For the load–deformation relationship of the structural sized specimen

Fig. 6. contains the load–deformation curves from the results of numerical analysis taking into consideration

Table 4. Failure types for the structural sized specimens

No.	Failure type	No.	Failure type	No.	Failure type	No.	Failure type
1	ST	11	ST&SPT	21	ST&CGT	31	ST
2	ST&CGT	12	ST	22	ST&BT	32	ST
3	ST	13	ST	23	ST&SPT	33	ST
4	ST&BT	14	ST&CGT	24	ST&BT	34	ST&CGT
5	ST	15	ST	25	ST	35	ST&SPT
6	CGT	16	ST	26	ST		
7	ST	17	ST	27	ST&CGT		
8	CGT	18	ST	28	ST		
9	ST	19	CGT	29	CGT		
10	ST	20	CGT	30	ST		

*: Simple tension: ST, cross–grain tension: CGT, splintering tension: SPT, brash tension: BT, compression: C, horizontal shear: HS



No. 13 specimen	Deformation	1st principal stress

Fig. 5. The numerical analysis results for knots on FEM model of structural sized specimen.

only the mechanical properties of the 35 structural sized specimens. The numerical analysis was carried out with only the mechanical properties of Douglas–fir (elastic modulus, Poisson's ratio, shear modulus) without reflecting the shape or the number and position of knots on each test piece. Orthotropic characteristics, which are the most important structural properties of the wood, were reflected. Our method involved nonlinear analysis, not linear analysis. Numerical analysis was then carried out on the assumption that the ultimate load would range from 2000 N to 12,000 N. According to the results of comparison between numerical analysis and the real flexural test value obtained by performing the experiment until fracture, there were no significant differences. The numerical analysis model obtained in this study is applicable to all species, and it is possible to obtain a considerable level of accuracy for the prediction of the bending performance with only the basic mechanical properties of each species.

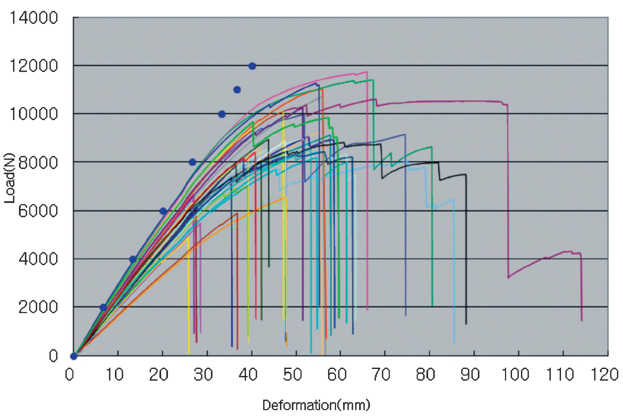


Fig. 6. The load–deformation curve for the structural sized specimens.

Applicability of the traditional joints

Traditional joints are mostly manufactured manually. Thus, the anchor between components is insufficient, and close contact gaps between components are lacking due to swelling and shrinkage. This leads to poor performance with traditional joints. Consequently, there is less accuracy in the numerical results for traditional joints compared to the numerical results for structural sized specimens without joints. Therefore, it may be necessary to select the optimum joint forms and readjust the specific sizes through actual comparative analysis between the experimental results and the numerical results for the traditional joints.

J–joint

The results of numerical analysis for actual J–joints with an ultimate load of 3000 N in a previous study are shown in Fig. 7. (Kim *et al.*, 2011b)

The deformation results and the distribution of principal stress in Fig. 7 are similar to the failure pattern of

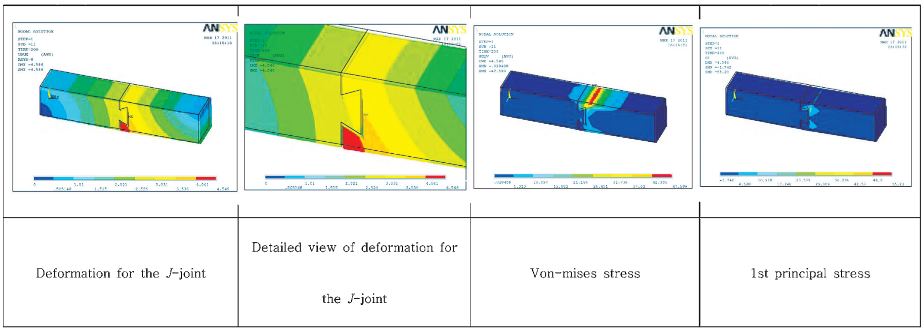


Fig. 7. The results for the numerical analysis of *J*–joint loaded, 3000N.

the actual specimen (Fig. 8). In other words, the deformation in the bottom of the specimen is excessive, and stress is concentrated in that spot.

Some differences between the actual experimental results and the numerical analysis of the *J*–joints are shown in Fig. 9. However, as the joint was fabricated manually, it may be possible to analyze the joint performance by utilizing the results of numerical analysis with a considerable degree of accuracy.

N–joint

The results of numerical analysis of actual N–joints with an ultimate load of 2500N in a previous study are shown in Fig. 11. (Kim *et al.*, 2011b)

The results of numerical analysis show that the failure pattern for the *N*–joint is similar to the failure type of the actual test piece (Fig. 12), similar to the *J*–joint.

Fig. 8. The real failure type for the traditional *J*–joint.

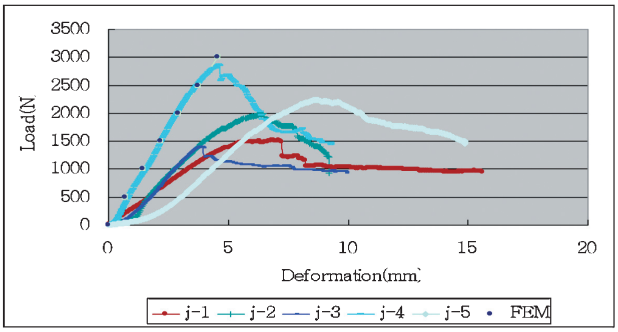


Fig. 9. Load–deformation curves for the *J*–joint specimen between experimental results and FEM result.

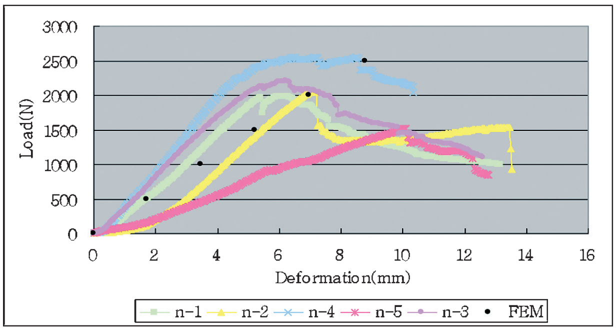


Fig. 10. Load–deformation curves for the *N*–joint specimen between experimental results and FEM result.

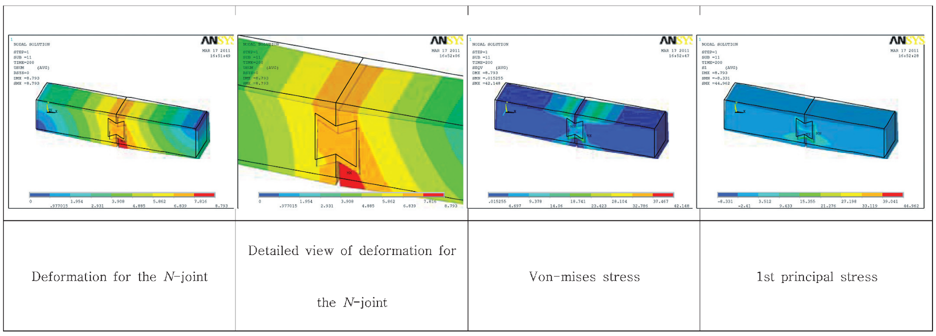


Fig. 11. The results for the numerical analysis of *N*–joint loaded 2500N.

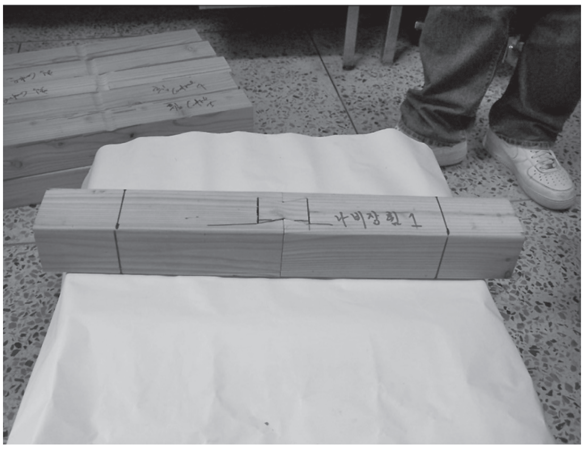


Fig.12. The real failure type for the traditional *N*–joint.

In other words, an excessive amount of deformation and stress concentration in the lower part of the joint were observed.

Fig. 10 shows the experimental results alongside the results of numerical analysis for the actual *N*–joint. The numerical results for the *N*–joint show a slightly higher degree of accuracy in comparison with the *J*–joint. However, the difference is small. As previously mentioned, since the traditional joints were fabricated manually rather than mechanically such as with a pre–cut machine, the traditional joints can be properly designed and analyzed utilizing the numerical model developed in this study.

CONCLUSION

Due to the potential health benefits, compliance with consumer demands and active support of the government, the supply and demand of traditional *Hanoks* and new style *Hanoks* are rapidly increasing in Korea.

In this study, numerical analysis was performed to evaluate the actual bending performance of the *J*–joint and the *N*–joint, which are the most widely used joints in traditional Korean wooden frame constructions. The study applies the finite element method in an attempt to develop a new type of traditional joint with superior performance.

To examine whether it is possible to grasp the bending properties of wooden structural components, a structural sized specimen without joints was investigated first. To ensure accurate application of the numerical analysis method, the 3–D orthotropic elements were evaluated and the results confirmed the viability of the method. Subsequently, we confirmed the applicability of the numerical analysis by comparing the results of the actual bending performance test and the finite element analysis results for the *J*–joint and *N*–joint. Stress concentration and deformation similar to the actual fractured specimen were observed with finite element analysis. As a result, by applying FEM without destruction of the joint, which is uneconomical and inefficient, we will be able to ascertain the strength of various types of joints in the future. On this basis, we conclude that it is possible to optimize various types of joints.

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