

# Experiments and Analysis of the Traditional Wood Structural Frame Y.W. Lee<sup>1</sup>, S.G. Hong<sup>2</sup>, B.S. Bae<sup>3</sup>, J.K Hwang<sup>4</sup>, N.H. Kim<sup>5</sup> and S.J. Jung<sup>6</sup>

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## **ABSTRACT :**

To find the behavior of a wooden frame of a traditional structure system, experimental researches are performed. A temple(Deawoong-Jeon) of Bongjeong-sa built in the early stage of the tenth century is considered as a typical model. The interior frame of the temple has two exterior short columns and one inside high column called as Goju(high column) in crossbeam direction. At the top of the exterior column, Gongpo(Corbel bracket) is located to transfer the beam loads into columns. Subassembly of 1/2 scaled Gongpo and Goju frame is constructed and tested to find the force-displacement characteristics. Also a 1/2 scaled structural frame is constructed and tested for the comparison with analysis. From subassemblies of Gongpo and Goju frame, analytical models are proposed with shear and rotational spring, of which coefficients are obtained from the experiments. The envelope curve of each spring is presented by bilinear model. With the proposed model, a push-over analysis is performed and compared with the experimental results of the full interior frame. The force-displacement of the analysis of proposed model shows a good correspondence with that of the experiment within 2% story drift.

**KEYWORDS:** Experiment, Pushover Analysis, Traditional wood frame, Corbel bracket(Gongpo)

## **1. INTROCUCTION**

The main building Deawoong-jeon of Bongjeong-sa(temple) located in the Andong-city in Korea was originally built in the early stage of the tenth century. It was rebuilt several times from first construction to now. In 1809, it was reconstructed on a large scale and a large part of the present appearance(Fig. 1) is the result of that reconstruction. Until several years ago, the partial repair had been advancing for roof, decorative painting and wooden floor. The latest total repair was performed in 2000 and it was classified as the national treasure of Korea.

Deawoong-jeon has front exterior frames which have 3 spans and are perpendicular to a large crossbeam direction, as shown in Fig. 1 and 2. In the direction of large crossbeam, it has two side and two internal frames. In all frames, the column is just placed on a foundation stone without mechanical fasteners. The frame is composed by columns and connecting beams. The connecting beams are connected by rake joints located over the columns, taking advantages of the reinforcement provided by the surrounding slot (Fig.3). The architraves which are placed bracket sets are located on column-connecting beam joints. All bracket sets, composed of soro (blocks) and cheomcha (arms), are located on architraves (Fig. 4), of which the main role is to transfer the roof dead load to the foundation stone.

Its basic structural system consists of a column and lintel beam connected by friction joints and Gongpo(bracket set). The Gongpo system is a unique system of brackets placed on top of columns to provide additional support to beams or overhanging eaves. Some static and dynamic experiments (Hwang, 2008) are executed to find the characteristics of the system. In this paper the experiments of the internal frame in direction of main cross beam are introduced.

In the internal frame(Fig. 12) in the direction of main crossbeam, Gongpo(Fig. 6) is located at the top of an exterior column and a special joint at Goju(high column) shown in Fig. 7, which is connected by sanji(wood nail) with beams. These joints cause complex structural behaviors because forces are transmitted through contact areas and slips are occurred between the elements.



A numerical analysis with FEM is not easy to model including these joints and not practical because it requires much time. Macroscopic spring models are efficient for structural analysis for complex joints (Fang, 2001). In this paper, a simple macroscopic model with rotation and shear springs will be proposed, based on the experiments of sub-assembled frames and verified by the comparison with the full frame experiments (Fig. 12)



Figure 1 Exterior front view



Figure 3 Connecting beam & slot



Figure 2 Base floor plan



Figure 4 Soro(block) and cheomcha(arm)



## 2. Experiments

Experiments of a full frame (Fig. 12) and two subassemblies (Fig. 6 and 9) are executed in different laboratories. Through two subassembly experiments of Gongpo and Goju, joint behaviors are studied and analytical models and its spring coefficients are proposed for a numerical analysis, as shown if the flowchart in Fig. 5. Pushover analysis is carried out for the frame and compared with the experimental results for the verification. In this chapter the experiment and results of subassemblies and the full frame are described. All experimental models are constructed in half scale with Korean red pine wood. Gravity loads are applied in Gongpo subassembly and the interior frame experiments. Though all columns are elected upon a stone base, a hinge is used at the bottom of a column to avoid uncertainty of boundary condition in experiments.



#### 2.1 Subassembly experiments

#### 2.1.1 Gongpo subassembly

In the interior frame (Fig.12) there are 3 columns and Gongpo is located on two external columns and one internal column called Goju is higher than external columns. The location of a main crossbeam is 1.512m above the base hinge and span length is 2.0m. Constructed modes does not include roof which produces heavy dead loads, coming from thick soils, layered woods and roof tiles. To consider roof dead loads, steel blocks are applied at purlins same as in Fig.13. Applied dead loads are the same as in Table 2.1 at points (1), (2), (3) in Fig 12.



Figure 6 Experimental model of Gongpo subassembly



Figure 7 Force-displacement of Gongpo subassembly.

Figure 8 Macro model of Gongpo subassembly

Lateral forces are applied at the center of main crossbeam with displacement control unto 4% story drift. Loading is composed of total 8 steps which have 3 cycles per each step. 1st and 2nd step has equally 0.5% story drift and 0.5% story drift is increasing from 3rd to 7th steps. At the last 8th step 4% story drift is applied.



Lateral displacements are measured at each layer of Gongpo as can be seen in Fig.6. Also vertical displacements are measured to calculate the rotation of components of Gongpo and relative displacements are measured for slip. For positive loading in Fig.7 maximum resisting force is 953N at 1.6% story drift and for negative maximum is 680N at 1.1%. Fig 7 shows the force and displacement relationship which is nearly bilinear behavior until 1% story drift. After reaching the maximum force it shows strength degradation. As can be seen at 4% story drift in Fig. 7, it has a good hysteresis to dissipate energy though the resisting force is small.

#### 2.1.2 Goju subassembly

Fig.9 describes the test setup of Goju subassembly in which the height of main crossbeam is 1.512m like Gongpo subassembly. But this setup does not include dead loads. Lateral force is applied at the center of main crossbeam with displacement control. Loading is composed of total 11 steps which have 3 cycles per each step. 4th step is 0.81% story drift and 6th steps 1.52%, 8th step 2.38%, 10th step 3.79% story drift and the last 11th step is 5.41%(Fig. 10)



Figure 9 Experimental model of Goju subassembly



Figure 10 Force-displacement of Goju subassembly.

Figure 11 Macro model of Goju subassembly

Lateral displacements of the crossbeam and the column are measured as can be seen in Fig.9 and vertical displacements of crossbeam are measured to calculate the rotation. For positive loadings of Fig. 10, the resisting force linearly increases before to reach the maximum value 3,880N at 5.2% story drift. Positive resistance is greater than negative values because of the effect of Boaji (inserted symmetric haunch in Fig. 9).



Also negative force-displacement relationship shows linear. Hysteretic loop (Fig.10) shows pinching effect because of the gap between the column and the main crossbeam.

#### 2.2 Frame experiment

The setup of internal frame experiment is shown in Fig.12; the location of crossbeam center is 2.49m above the base hinge, which is different from that of subassemblies. The span length of the left beam is 1.494m and right span is 3.494m. For in-plane behavior of specimen, 3 rollers are used at main crossbeam perpendicular to the loading direction.

Because this model does not include the roof, steel blocks are applied at purlin to simulate the dead load of roof (Fig.13) like Gongpo subassembly. Applied steel block loads are listed in Table 2.1, which is calculated based on influenced loading areas. The load at the exterior roof purlin is the greatest because the eave that is cantilevered from a external column is longer than that of an ordinary building as can be seen in Fig. 1.



Figure 12 Test model - 1/2 scaled interior frame



Figure 13 Applied vertical loading block

Table 2.1 Applied dead loads at puttins											
	Location Number	(1) Exterior roof purlin	(2) Roof Purlin on column	(3) Interior roof purlin	(4) Roof purlin	(5) Ridge purlin	(6) Roof purlin.	(7) Interior roof purlin	(8) Roof Purlin on column	(9) Exterior roof purlin	
	Load(N)	13,450	232	4,671	7,902	4,620	7,902	4,671	232	13,450	

Table 2.1 Applied dead loads at purlins

Lateral load is applied at Goju, 1.898m above the base hinge (Fig. 12). Total 8 steps like Fig. 14 loads are applied from 0.5% to 4% story drift with 0.5% increment and each step is composed of static 4 cycles. Among 4 cycles, the amplitude of first cycle is half of the last cycle of the previous step.

Force and displacement relationship is not symmetric as in Fig. 15; positive maximum resistance is 2 kN and negative value is 2.3 kN. For positive loading, yielding occurs at 1% story drift but for negative loading yielding occurs after 2% story drift and pinching can be seen after 5th step. Though the resisting force is small, the efficiency of dissipating energy is high. For each step, there is no stiffness and strength degrading after 3 cycles of loading reversals. In positive loading direction, some spikes occurred, which mean some frictions are acting during loadings. In negative loading direction, pinching phenomenon can be seen after 5th step because of gaps between the column and the crossbeam.



Figure 14 Applied displacement-control load



Figure 15 Force-displacement of interior frame

## 3. Numerical Model

For the numerical analysis, the model of Gongpo is proposed as in Fig.8, which consists of 3 springs, a rotational spring at the capital of a column and a shear spring for the shear deformation of Gongpo and a rotational spring between the crossbeam and Gongpo. Spring coefficients are composed of 3 points; yielding, ultimate and ending points, to describe strength degrading like Fig.18. Strength degradation is calculated based on the ductility as Fig.17. All coefficients of Gongpo springs are listed in Table 3.1

For Gongpo spring, a numerical model is proposed like Fig.11, in which the column and the crossbeam behave as a rigid beam and a rotational spring is used between the column and the crossbeam. Rotational spring coefficients are calculated and listed in Table 3.2. For positive loading, Gap element is used to describe the gap between the crossbeam and the column as in Fig.19.

	rotation spring - Gongpo				rotation spring - crossbeam				shear spring - Gongpo			
	(+) direction		(-) direction		(+) direction		(-) direction		(+) direction		(-) direction	
	rot.	mom.	rot.	mom.	rot.	mom.	rot.	mom.	disp.	force	disp.	force
	(rad)	(N-m)	(rad)	(N-m)	(rad)	(N-m)	(rad)	(N-m)	(mm)	(N)	(mm)	(N)
Yielding (Dy,Fy)	0.56%	850	-0.82%	-583	0.13%	572	-0.30%	-1,220	2.45	760	-0.64	-560
Ultimate (Du,Fu)	1.28%	890	-1.80%	-599	0.67%	1,076	-0.53%	-1,430	5.3	876	-2.2	-590
Ending (De,Fe)	2.25%	725	-4.00%	-300	0.72%	1,076	-0.57%	-1,403	7.6	710	-5.79	-305
Ki (N-m/rad)	1.53×10 <sup>5</sup>		7.11×10 <sup>4</sup>		4.40×10 <sup>5</sup>		4.07×10 <sup>5</sup>		3.10×10 <sup>2</sup>		8.75×10 <sup>2</sup>	
Kh (N-m/rad)	5.53×10 <sup>3</sup>		1.63×10 <sup>3</sup>		9.33×10 <sup>4</sup>		9.13×10 <sup>4</sup>		40.7		19.2	
Hardening ratio	3.63%		2.30%		21.21%		22.45%		13.12%		2.20%	
Duct1*	2.3		2.2		5.2		1.8		2.2		3.4	
Rduct*	0.2		0.2		0.2		0.2		0.2		0.2	
Kd (N-m/rad)	1.70×10 <sup>4</sup>		1.36×10 <sup>4</sup>		0		6.75×10 <sup>4</sup>		72.2		79.4	
Duct2*	9.5		6.4		-		6.6		5.6		12.3	

Table 3.1 Spring Coefficients of Gongpo spring

\* Refer to Fig. 16







Figure 16 Strength degrading Model



Figure 17 Moment – rotation of spring r1



Figure 18 Moment – rotation of Goju spring







	(+) dir	rection	(-) direction		
	rot.	mom.	rot.	mom.	
	(rad)	(N-m)	(rad)	(N-m)	
Initial (Di,Fi)	0.71%	0	0.00%	0	
Yielding (Dy,Fy)	2.07%	2170	-1.50%	-555	
Ultimate (Du,Fu)	3.20%	3270	-3.11%	-1,059	
Ki (N-m/rad)	1.052	$\times 10^{5}$	$3.70 \times 10^4$		
Kh (N-m/rad)	9.732	$\times 10^4$	$3.13 \times 10^4$		
Hardening ratio, r	92.8	86%	84.61%		
Gap(rad)	0.1	71	0.0		



Figure 20 Yielding point in Pushover analysis

# 4. Analysis and comparison

Using the proposed numerical model of Gongpo and Goju joint in chapter 3, the experimental frame of section 2.2 is modeled with springs like Fig.19. Gongpo spring is located at the external column and rotational spring is inserted between crossbeam and center column. Same as the experiment, the external load is applied at center column above 1.894m from the base hinge. Because the strength of column and crossbeam is higher than that of the spring of Gongpo, first yielding occurred at rotational spring of capital of the exterior column as shown in



#### Fig.20.

Pushover analysis is executed with RUAUMOKO and compared with the experimental results in Fig.21. In case of positive loading with strength degrading model, a plastic hinge occurred firstly at the left rotational spring of Gongpo and secondly at right the rotational spring of Gongpo and the analysis is stopped at 1.3% story drift because stiffness approaches zero. For negative loading, program stopped before 1% story drift. But in case of positive loading with bilinear modeling, the resistance is greater than the result of the experiment

after 1% story drift. For negative loading, yielding occurred earlier than experiment and the resistance is less than the experimental value within 2.5% story drift. The analytical results show good agreements with the experiment within 2% story drift.



Figure 21 Force and displacement relation of analysis

## 5. Conclusion

To study the behaviors of a wooden structure, experiments and analysis are performed for a temple (Deawoong-Jeon) of Bongjeong-sa built in the early stage of the tenth century. Firstly, 1/2 scaled subassembly of Gongpo and Goju frame are tested to find the force-displacement characteristics of joints. From the results analytical models are proposed and spring coefficients for numerical analysis are derived. With these results pushover analysis is performed and compared with the experimental results of 1/2 scaled full frame. The force-displacement relationship of the analysis has a good correspondence with that of experiment within 2% story drift incase of using bilinear model. But the force-displacement relationship of the experiment is closer to that of the strength degradation model than that of bilinear model but the analysis of strength degradation model stops earlier because of stiffness approaches zero

Even though the proposed macro model for a traditional wooden frame is compared with only one experiment of interior frame, it could give an possibility to analyze traditional wooden frames more efficiently than using general FEM. More researches are needed to find the stiffness and strength based on and material strength and microscopic behaviors such as frictions, gaps and etc.

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