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Determination of moment carrying capacity of sagae connection using different methods

Gi Young Jeong*, Jin Hyuk Kong, So Sun Lee

Department of Wood Science and Engineering, Chonnam National University, 77 Yongbongro Bukgu, Gwangju 500-757, South Korea

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ABSTRACT

The goal of this study was to analyze the moment carrying capacity of sagae connections. Sagae connections have been used for connecting a column and two cross beams in timber frame buildings in South Korea. Reverse-cyclic loading was applied to measure the load and moment carrying capacities of the sagae connection. Yield load, yield moment, and ductility ratio of the sagae connections were evaluated using three methods. Stress distribution, failure behavior, and load carrying capacity of sagae connection were analyzed using finite element methods. The most critical failure behavior of sagae connection was found to be a split at the reentrant corner of the upper beam. Stress distributions from FEM showed the highest stress values of combination of longitudinal stress (σ_L) and shear stress (τ_{RT}) at the reentrant corner. The difference of load carrying capacity of sagae connection ranged from 1.68% to 20.54%. In general, initial stiffness, yield load, maximum load, yield moment, and maximum moment of sagae connection increased as the size increased. However, yield displacement, maximum displacement, and ductility ratio of sagae connection did not show a consistent trend with an increment of size.

1. Introduction

Wood to wood connections have been widely used in traditional timber constructions in South Korea. There were many different kinds of wood to wood connections found in the timber frame buildings (Fig. 1). The different connection styles were developed based on the culture of the local areas. Fig. 1a shows the sagae joints used in the traditional timber frame building called Mireukjeon located at Gimje province in South Korea. Fig. 1b shows the modernized sagae connection. Among the different style of wood connections, sagae joint was found to be one of the good performance connections which can carry higher moment resistance compared to the other wood to wood connections [7]. Also, the connections were strong enough to support many buildings for hundreds years. However, the mechanical behavior of the sagae connection made of different size and species was not evaluated.

Wood to wood connections used in Europe are used to connect beam to beam, column to column, and truss members. Therefore, most previous studies on wood to wood connection focused on load carrying capacity under tension and compression. Although the results from the studies could not be directly compared with the results from the current study, the approach used in the previous study could be adapted for the current study. Previous studies showed that finite element method (FEM) modeling for wood to wood connection was applied [6,9,11,12,14]. Due to the advantage of FEM for the complex geometry of wood to wood connection and the complex of geometric variables from tenon and mortise, and orthotropic properties of wood materials, many studies used FEM model to analyze the stress distribution, failure behavior, and strength.

However, there was no standard test method for evaluating moment carrying capacity of wood to wood connections such as sagae connection. Since the sagae connection was a part of post and beam frame, the structural behavior should follow the frame. In this logic, different test methods for timber frame wall including ASTM E 2126 [2], Yasumura and Kawai [13], and EN 12512 [5] were adapted for the determination of moment carrying capacity of sagae connection.

In seismic design, ductility ratio and yield load are important since these values indicate how the structural members could redistribute load so that all members could participate in carrying the load without failure. Although different seismic guidelines from Eurocode 8 [4], CSA 086-14 [3], KBC [10], NDS 2015 [1] have different ways to use ductility ratio, yield load, these values were one of the important factors in the determination of reduction factor and behavior factor. In performance seismic design, drift ratio of structure was also important factor indicating the status of structure. There was no research on the relation between drift ratio and damage in wood to wood connection.

The purpose of this study was to evaluate the moment carrying

* Corresponding author.
E-mail address: gjeong1@jnu.ac.kr (G.Y. Jeong).

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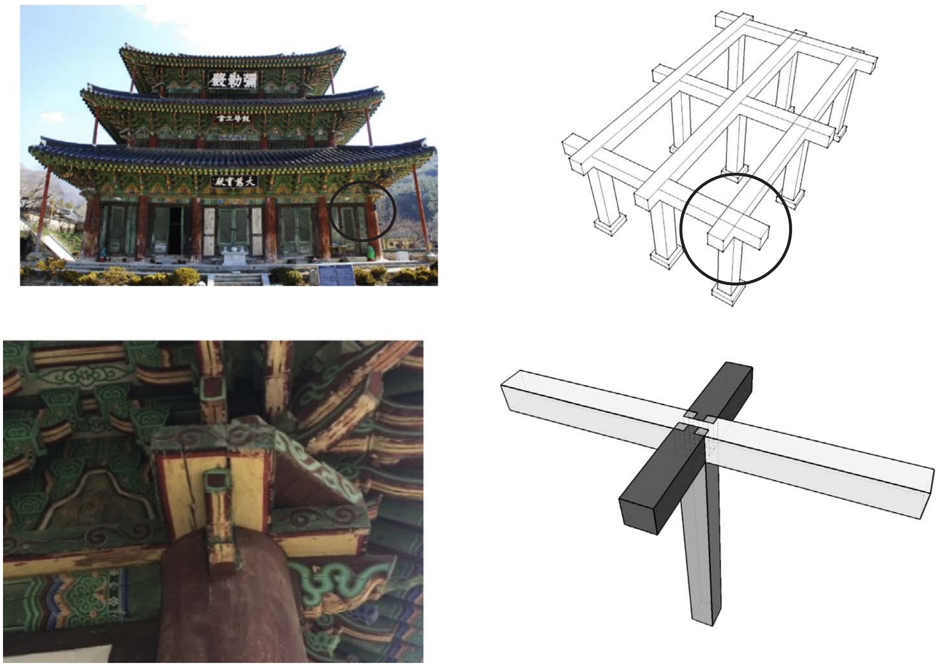

(a) (b)

Fig. 1. Sagae connection used in traditional timber frame building called Mireukjeon in South Korea (a) and modernized sagae connection used in this study (b).

capacity of sagae connection made from different species and sizes. Initial stiffness, yield load, yield moment, rotation, and ductility ratio of sagae connection were evaluated using ASTM E 2126 [2], Yasumura and Kawai [13], and EN 12512 [5]. Stress distributions and load carrying capacity of sagae connections were analyzed using FEM.

2. Materials and methods

2.1. Specimen preparation

Different sizes of glulam materials made from *larix kaempferi* and *pinus koraiensis* were used to test moment carrying capacity of sagae connections. Table 1 shows the test arrangement for sagae connection including nomenclature, species, size of the beam and column. The column size was 120 × 120, 180 × 180, 240 × 240 mm, and the lower and upper beam sizes were 120 × 120, 180 × 180, 180 × 240, 240 × 240 mm. The length of column was 2400 mm, upper beam length was 2000 mm, and lower beam length was 1100 mm. Three specimens for each condition were prepared. Total number of specimens was 24 for the evaluation of the moment carrying capacity of the sagae connection. To identify the species and size, nomenclature was used in Table 1. L stands for *larix kaempferi* and P stands for *pinus koraiensis*. The following number is the size of the beam used. The

Table 1
Nomenclatures for the sagae joints from different species and sizes used for column and beam including moisture content (MC) and specific gravity (SG).

Species	Specimen names	Sizes (mm × mm)		SG	MC
		Column	Beam		
Larix kaempferi	L 120 × 120	120 × 120	120 × 120	0.51	8.83
	L 180 × 180	180 × 180	180 × 180	(0.04)[a]	(0.03)
	L 180 × 240		180 × 240		
	L 240 × 240	240 × 240	240 × 240		
Pinus koraiensis	P 120 × 120	120 × 120	120 × 120	0.44	6.86
	P 180 × 180	180 × 180	180 × 180	(0.08)	(0.07)
	P 180 × 240		180 × 240		
	P 240 × 240	240 × 240	240 × 240		

[a] Coefficient of variation.

specific gravity (SG) of sagae connection made from *larix kaempferi* was 0.51 with a coefficient of variation (cov) of 0.04. The SG of sagae connection made from *pinus koraiensis* was 0.44 with a cov of 0.08. The moisture content (MC) of sagae connection made from *larix kaempferi* was 8.83% with a cov of 0.03 and the MC of sagae connection made from *pinus koraiensis* was 6.86% with a cov of 0.07.

Fig. 2 shows the shape of the column and beam used in the sagae connection and geometric factors in the column and beam. For the column, the width of the column, the width of the tenon, the length of the tenon were defined as a, b, and c, respectively. For the upper and lower beams, the width and depth of the beam, the width of tenon, the depth of the mortise, the length of tenon were defined as d, e, f, g, h, respectively. The geometric variables of column and beams that maximized moment carrying capacity of sagae connection were determined from the previous study using FEM and experimental test [7]. The dimensions of the geometric factors used in the different size of the sagae connection were provided in Table 2.

2.2. FEM development

3-dimensional finite element models for sagae connection were constructed using ANSYS v.15.0. Beams and columns were assumed as orthotropic materials. The orthotropic properties including elastic modulus and Poisson's ratio were used as an input values for the models from the previous study [8]. Table 3 shows the orthotropic properties used for the FEM model. To construct the sagae connection, solid 186 element was used for finite element models. For the contact area from two beams and a column, CONTA 176 elements were used for the surface to surface contact option with a friction coefficient of 0.6 applied. To apply different grain directions for the lower and upper beams and columns, the x axis in the model was parallel to the longitudinal direction of the lower beam. The y axis in the model was parallel to the longitudinal direction of column. The z axis in the model was parallel to the longitudinal direction of the upper beam. For the upper beam, the x and y direction is the perpendicular to the fiber direction. The x axis was assumed as the width diretion related to the tangential direction. The y axis was assumed as the depth direction related to the radial direction. For the lower beam, the y and z directions were perpendicular to the fiber diretion. The y direction was assumed as the depth of