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Structural Evaluation of Mireuksaji Stone Pagoda

*Fahimeh Yavartanoo[1], Thomas Kang[2], Seokwon Jeon[3] and Sung-Gul Hong[4]

[1], [2], [4] Department of Architecture and Architectural Engineering, Seoul National University, Seoul 08826, Korea
[3] Department of Energy Resources Engineering Seoul National University, Seoul 08826, Korea
[2] tkang@snu.ac.kr

ABSTRACT

Mireuksaji stone pagoda has existed for nearly 1400 years. More than half of the Mireuksaji stone pagodas have collapsed. In 1915, Japanese people who lived in Korea at the time covered some collapsed parts of the pagoda with concrete and stone. Due to the historical, cultural and architectural value of the Mireuksaji stone pagoda, which reflects the style of wooden buildings of that era, it is necessary to evaluate and investigate the cause of collapse for reconstruction and restoration, i.e., keeping the structural stability of this cultural heritage for long term. First, material properties are investigated by taking samples from some of the collapsed constituent stones found near the pagoda. Next, by utilizing the material data, the structure under self-weight load has been simulated in finite element software, and a comparative analysis was performed to evaluate the structural behavior of the original and renovated pagodas and their stability.

1. INTRODUCTION

The Mireuksaji stone pagoda is the oldest and largest stone pagoda in Korea which was built in Baekje Muwangdae (660 ~ 640 years). It is an important cultural property showing the process of transition from wooden pagoda to the stone pagoda. However, the Mireuksaji stone pagoda largely collapsed before 1915, and Japanese preserved the collapsed part of the pagoda by using concrete and stone in an emergency repair. The structural safety check carried out in 1998 raised the risk of

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[1] Ph.D. Student
[2] Associate Professor
[3] Professor
[4] Professor

further collapse, and since 2001 it has been repaired in order to investigate the cause of the collapse and restore it.

In this study, material properties are investigated by taking samples from some of the constituent stones found near the pagoda. Further, by utilizing the material data, the structure under self-weight load has been simulated numerically, and a comparative analysis was performed to evaluate the structural behavior of the original and renovated pagodas and their stability.

2. MATERIAL TEST

In order to simulate the structural behavior of the pagoda, the material properties have been identified accurately to utilize in modeling and analysis. In this study, a couple of samples were taken from the collaped stones found near Mireuksaji stone pagoda, and physical properties were determined by performing standard tests, ASTM D 3967 (2005) and ASTM D 2938-95 (2002). It has been tried to get samples from different points of the structure to cover all ranges of its mechanical properties, and the results are reported in Table 1, where MI# represents the samples that are (believed to be) from #th floor of Mireuksaji stone pagoda.

Table 1 Characteristics of Mireuksaji stone pagoda materials

Sample	Density (tonne/m^3)	Compressive strength (MPa)	Modulus of elasticity (GPa)	Poisson ratio	Cohesion (MPa)	Friction angle (°)
MI1	2.51	39	7.5	0.32	7	57
MI2	2.52	44	9.4	0.34	12	58
MI3	2.56	85	19.8	0.31	-	-
MI4	2.58	74	17.1	0.30	-	-
MI5	2.55	62	10.7	0.28	-	-
MI6	2.51	54	15.8	0.33	-	-

In the material properties of Table 1, MI1 and MI2 were sampled from the parts with the most weathering for the safety analysis (with the average value of 41.5 MPa) and MI3 ~ 6 samples were taken from the other parts which are relatively sound (with the average value of 68.8 MPa).

3. NUMERICAL SIMULATION

Since the structure of the pagoda has been formed by individual stones, it is a kind of discontinuous medium and load transfer between the members depends strongly on contact surface properties. For this reason, 3DEC (Itasca consulting group, Inc., 2013) software was used for modeling which is based on Distinct Element Method (DEM). The method as described by Cundall (1971) is similar to Finite Element Method with some modification to be more efficient and compatible for discontinuous structures.

Individual stones were modeled as separate blocks with hexagonal 8-node 3D continuum solid elements using linear shape function. Mohr-Coulomb was used to define material properties of stones. Interface behavior between blocks was modeled by surface based-contact model with Coulomb-slip formulation. The material properties used in the model referred to the database provided by National Research Institute of Cultural Heritage (2005).

The minimum values from the test results were used for the material and the contact properties, as listed in Table 2 and Table 3.

Table 2 Material properties of stone

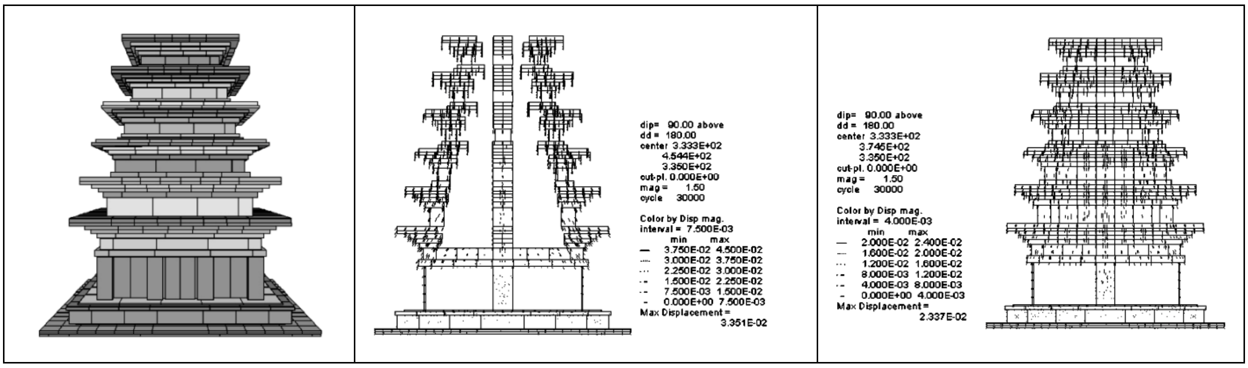
Application model	Density (tonne/m^3)	Modulus of elasticity (GPa)	Poisson ratio	Cohesion (MPa)	Friction angle (°)
Mohr-Coulomb model	2.51	7.5	0.32	7	57

Table 3 Material properties of stone contact surfaces

Application model	Cohesion (MPa)	Friction angle (°)	Normal stiffness (GPa)	Shear stiffness (GPa)	Note
Coulomb-slip Model	0.03	28.3	4.96	5.91	No tension capacity

4. SIMULATION RESULTS

Fig. 1(a) shows a 3D view of the analytical model, which was created with 6 stories based on the existing pagoda. Two cases were considered for the plan of each floor; the case where the whole floor is left empty and the case where it is filled with Jeokssim stone. Figs. 2(b) and 2(c) show the vertical displacement due to gravity load in the center section of two models. Based on the results, maximum displacement is 0.335 mm for the model not filled and 0.234 mm when it is filled with Jeokssim stone.



(a) Analytical model (3D view)

(b) Displacement distribution of non-filled case

(c) Displacement distribution of filled case

Fig. 1 Analytical models and displacement distribution results of Mireuksaji stone pagoda

In the original structure of the pagoda that is not filled with the Jeokssim stone, relatively large normal stresses are distributed in the walls. On the other hand, when it is filled, arching action is formed and the stress is distributed throughout the entire floor. The maximum normal stress occurred in the non-filled case is 1.11 MPa in the lower layer of the first floor and 0.98 MPa in the filled case on the same floor.

Maximum normal stresses in each floor for both cases are reported in Table 4. The values are smaller in the filled case with the Jeokssim stone, except in the lower part of first floor and sixth floor. In case of floors 2 to 5, the maximum normal stress is decreased by 30 to 50 percent. Considering the fact that the weight of the whole stone is greatly increased when it is filled with the Jeokssim stone, the rate of decrease in normal stress is larger.

Table 4 Comparison of maximum normal stress with and without Jeokssim stone

Division	Maximum normal stress (MPa)		Decrease rate (%)
	Without Jeokssim stone	With Jeokssim Stone	
1 floor	1.110	0.978	11.1
2 floor	0.536	0.348	35.0
3 floor	0.643	0.310	51.8
4 floor	0.556	0.345	38.0
5 floor	0.336	0.231	31.3
6 floor	0.209	0.212	-1.6

Considering the test results that the compressive strength of stone is 39-85 MPa in both cases, the normal stress caused by self-weight would not affect the safety of the pagoda. However, further studies are needed to check the stability under combined gravity and lateral loads.

6. CONCLUSION

To sum up, a wide range of samples were taken from Mireuksaji stone pagoda and the results show that the average compressive strength of stones is between about 40 to 85 MPa which is almost less than half of the average compressive for the fresh stone which is 160 MPa. The structure was simulated numerically by considering minimum value of the data, and its structural behavior was investigated under gravity load. The results show that the materials are safe even with considering weakest material condition. Moreover, by filling the structure with the Jeokssim stone, although the overall mass is increased, but the stress distribution would be more effective. However, further studies are needed to check the stability under combined gravity and lateral loads.

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