Validation Report for Pagoda Temple Modeling: Comparison of FEM and AEM Analysis Results

Rajendra Soti, Linh Abdulrahman,
Andre R. Barbosa, Richard L. Wood, Michael J. Olsen

April, 2019; Corvallis, Oregon State University

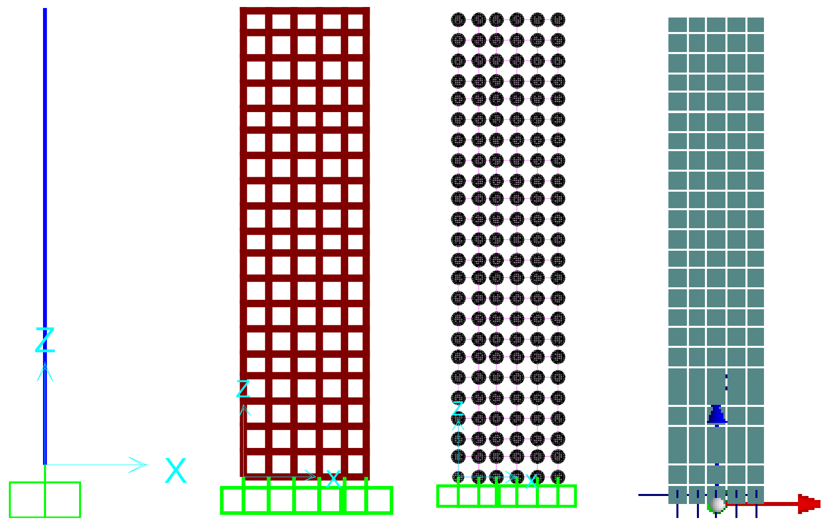
1 Overview

This report provides some basic examples to validate AEM model results with FEM model results for two fundamental examples that are dominated by flexural deformations.

1.1 Example 1 - Cantilever beam

In the first example, a vertical cantilever beam (12 m tall, 0.1m thick and 1m deep) was used to determine the deflection of the tip to the action of a 0.098 kN horizontal load applied at the tip. In the FEM models, the beam was discretized using three element types: (1) frame elements, (2) shell elements, and (3) solid (brick) elements, while in the AEM model developed, rigid brick elements were used. Except for the case in which the FEM model was discretized using frame elements, both FEM and AEM models were discretized into 60 elements along the height, 5 elements along the depth, and one element along the width of the beam; thus, for these cases, the elements have a size of 0.20 m by 0.20 m, with a thickness of 0.10 m. These are illustrated in Figs. 1(a) through 1(d).

Table 1 lists the results obtained for the displacement at the tip of the cantilever beam. The numerical tests revealed that the results from the AEM models correlate well with the FEM models as well as the theoretical results. It can be seen that the FEM model with brick elements was stiffer than the AEM model, but also stiffer than the FEM discretizations with shell and frame elements. Similarly to the FEM models, the refinement of the solutions using AEM models can be achieved by increasing the number of elements, but improved refinement can also be achieved by increasing the number of element-to-element contact springs Tagel-Din (1998). Thus, for the same number of elements, the AEM results are sensitive to the number of springs used, where a larger number of springs improves the accuracy of the results. Results are shown in the table are shown for three levels of number of springs (5x5, 10x10, and 40x40), and it can be seen that the convergence of the displacements are reached for the case in which 10 x 10 springs are used. However, it is worth noting that for the same



(a) (b) (c) (d)

Figure 1: Analysis of a cantilever column with a horizontal load. Discretizations in the: (a) FEM model using frame elements, (b) FEM model using shell elements, (c) FEM model using solid (bricks) elements, and (d) AEM model.

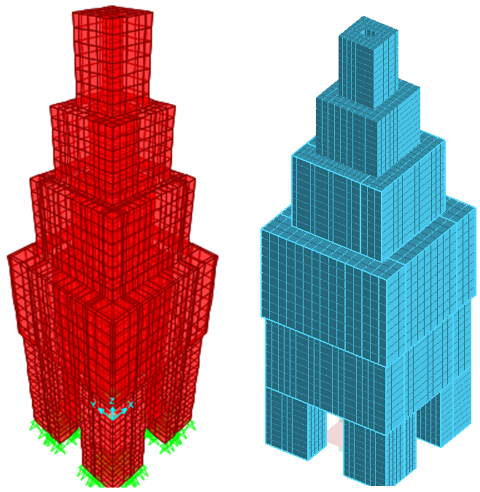
number of elements used in the FEM model, the tip displacement obtained for the AEM model is 4.7% higher than that of the FEM counterpart.

1.2 Example 2 - Simplified temple model

In the second example, FEM models are developed using only the three-dimensional solid (brick) elements and the three-dimensional elements used for the AEM model. These are used to develop simplified temple model by omitting the timber frames that surrounds the core masonry wall at the ground floor, and the outer walls just above the columns at second floor as shown in Figs. 2(a) and 2(b), because the objective is to provide a validation of the three-dimensional AEM model for complex geometries. Additional information on the material models assigned are described in Soti et al. (2019) and the models are available for download on design-safe Wood et al. (2019).

The deflection at the top of the temple was computed due to the action of a 9.8 kN horizontal load. In addition, the fundamental frequencies were obtained for both models.

Results indicate that, similarly to example 1, the FEM model revealed a higher stiffness compared to the AEM model ($u = 12.8\,\mathrm{mm}$ at FEM, versus $u = 13.3\,\mathrm{mm}$ at AEM). Table 2 reports the results obtained for the frequencies from a modal analysis performed using the FEM and AEM models. It can be seen that the difference between frequencies in the bending mode is about 1% whereas the difference between frequencies in the torsional mode is about 0.1%.



(a) (b)

Figure 2: Simplified temple models: (a) FEM model, and (b) AEM model.

Table 1: Deflection at the top of cantilever column using AEM, three FEM discretizations, and theoretical calculations based on flexural deformations only.

Analysis method	AEM	FEM with beam elements	FEM with shell elements	FEM with solid elements	Theoretical displacement without considering shear deformation
Displacement at the tip of cantilever beam (mm),(Fig. 1)	0.309$*$ 0.308$**$ 0.308$***$	0.325	0.324	0.294	0.322

AEM springs per element-to-element contact face: $*$5 x 5 ; $**$10 x 10; $***$40 x 40.

Table 2: Comparison of responses from AEM and FEM simplified models (Figs. 2(a) and 2(b))

Analysis method	AEM with 10x10 springs	FEM with brick elements
Fundamental frequencies, for the first three modes(Hz) (f_3 is a rotational mode)	f_1 = 1.607, f_2 = 1.607, and f_3=4.076	f_1 = 1.623, f_2 = 1.623 and f_3 = 4.081

1.3 Convergence study of simplified temple model in AEM

A sensitivity analysis is performed to investigate the minimum number of masonry elements sufficient for convergence of results in terms of displacement and acceleration in the simplified model (Fig. 2(b)). Three different discretization schemes (75000 elements, 15000 elements, and 26000 elements) along with their displacement and acceleration values at the roof of the AEM model are summarized in Table 3. It is found that a discretization with 15000 elements is sufficient to get convergence for the values of deformations and absolute acceleration (0.75% of the results obtained with the 26000 elements). In addition, the finer mesh with 26198 number of elements needed a significantly larger computational time compared to that of 15000 element model (9.5 hours versus 5 hours). These analyses were performed in a desktop computer with the following characteristics: Intel E3-1231 v3 CPU @3.4 Hz with 32 GB RAM and a 10k RPM hard drive.

Table 3: Convergence study of simplified AEM models (Fig. 2(b)).

Number of elements	Computational time	Roof displacement (mm)	Roof Acceleration (m/s^2)
7456	2 Hr 30 min	47.19	3.8719
15000	5 Hr 4 min	47.56	3.8160
26198	9 Hr 30 min.	47.91	3.8228

References

Soti, R., Abdulrahman, L., Barbosa, A. R., Wood, R. L., Olsen, M. J., 2019. Post-Earthquake Model Updating of a Heritage Pagoda Masonry Temple using AEM and FEM. Engineering Structures - Submitted for publication.

Tagel-Din, H., 1998. A New Efficient Method for Nonlinear, Large Deformation and Collapse Analysis of Structures. Ph.D. thesis, The University of Tokyo.

Wood, R., Barbosa, A. R., Soti, R., Abdulrahman, L., Olsen, M., Mohammad, E., 2019. 2015 Nepal Earthquake Data Archive: Nyatapola Temple. https://doi.org/10.17603/DS2DT3B.