On the application of quasi-static nonlinear explicit FE formulation to the evaluation of the lateral capacity of masonry structures

Renato Perucchio*, Selman Tezcan, Jiacheng Sun

University of Rochester
Department of Mechanical Engineering
Rochester, NY 14627, USA
rlp@me.rochester.edu, stezcan@UR.Rochester.edu, jsun29@u.Rochester.edu

ABSTRACT

As part of an ongoing research on the seismic assessment of heritage monumental architecture, our study has focused on the numerical evaluation of the lateral capacity of complex masonry structures by means of pushover analysis based on nonlinear FE explicit formulation. The concrete damaged plasticity formulation is adopted to represent quasi-brittle materials with nonlinear tensile and compressive behavior based on the Lourenço model. 2- and 3-D FE models are analyzed in Abaqus/CAE Explicit under gravitational loading and monotonically increasing lateral accelerations, applied over long time intervals to simulate quasi-static conditions. Local and global collapse conditions due to increasing lateral accelerations are identified from energy and reactions curves. The application of this procedures is illustrated on case studies including the adobe triumphal arch of the early Spanish Church of Andahuaylillas, Peru and the opus caementicium vault of the Frigidarium of the Baths of Diocletian in Rome.

Pushover analysis is a well-established approach for assessing the overall behavior of a structure due to seismic activity that uses an incremental-iterative solution based on static equilibrium to determine the response of the structure under monotonically growing lateral load patterns. In our approach, after gravitation loading, a uniform monotonically increasing horizontal acceleration is applied to the entire model using the Explicit FE formulation available in Abaqus. The desired quasi-static condition is enforced by adopting long time intervals for the application of both gravitation and lateral accelerations (typically, three seconds for gravitation to increase linearly from 0 to 1g followed by seven seconds for lateral acceleration to go from 0 to 0.6g.) Under these conditions, results indicate that no kinematic energy develops in the model until structural failure is achieved. The time-evolution of strain, kinetic, and dissipative energy (due to plastic deformations simulating internal fractures) is used to identify the development of local damage conditions up to final structural collapse. As long as structural integrity is maintained under increasing lateral acceleration, kinetic energy must remain negligible during the evolution of quasi-static structural response. Thus, structural failure is associated with the sudden transition from quasi-static to a fully dynamic state and can be detected by the accompanying asymptotic growth of kinetic energy. Plastic dissipative energy follows an identical asymptotic growth pattern, while strain energy immediately decreases after having reached a pick at failure. As a result of the inertial forces caused by the applied lateral acceleration, an equilibrating horizontal reaction force (basal shear) develops at the supporting boundary. The gradual application of lateral acceleration produces a monotonic increase in the basal shear versus time. At failure, this curve shows a sudden decrease indicating that the structure has lost the capability of resisting lateral loads.

The explicit (dynamic) nonlinear FE formulation is preferred over the implicit one because of its capability to sustain the large deformations and attendant local material failures, and to capture unequivocally the collapse condition due to lateral accelerations. In fact, in most of the cases of the present study, it may not be possible to detect the actual failure condition using an implicit nonlinear FE formulation because the analysis terminates due to numerical error (e.g., the stiffness matrix becomes singular) before the actual structural failure occurs. On the negative side, dynamic explicit models are computationally costly. In order to insure algorithmic convergences, Abaqus Explicit requires time increments of the order of 10-6 second for both gravitation and lateral acceleration.