The Impact of High-Frequency/Low-Energy Seismic Waves on Unreinforced Masonry

Patrik Meyer,a John Ochsendorf,b John Germaine,c and Eduardo Kausel,d M.EERI

Traditionally, the high-frequency components of earthquake loading are disregarded as a source of structural damage because their energy content is small and their frequency is too high to resonate with the natural frequencies of structures. We argue that higher-frequency waves traveling through stiff masonry structures can trigger two types of failure mechanisms that have not yet been taken into account. First, the high frequencies can cause small vertical interstone vibrations that result in irreversible relative displacements of the stones, which may ultimately lead to collapse. The energy needed to cause this deformation and failure comes largely from gravitational forces. Second, the partial fluidification and densification of the loose, granular inner core of some unreinforced masonry walls results in an increase of outward thrust. Preliminary results of a series of static and dynamic tests, as well as numerical models, demonstrate the potentially destructive effects of high-frequency/low-energy seismic waves on unreinforced masonry structures. Based on this new understanding, an improved construction method is suggested.

INTRODUCTION

In developing countries, more unreinforced masonry (URM) structures exist than any other type of structure (UN-Habitat 2005), and such structures are the least seismically safe (California Legislature 2004). Recent earthquakes, such as those in Pakistan (2005), Bam (2003), and Gujarat (2002), have raised awareness of the need for scientific methods to assess the structural integrity of unreinforced construction under seismic loading, and of methods to increase their performance. Years of earthquake research and laboratory testing have demonstrated that houses and buildings built with brittle materials are intrinsically unsafe under seismic loading and require remedial reinforcement to guarantee an acceptable degree of ductility. Despite this research, however, the actual failure mechanisms of brittle masonry construction remain obscure and poorly understood. Two of the most common failure mechanisms of URM during earthquakes are

a) Research Assistant, Massachusetts Institute of Technology, Cambridge, MA 02139; E-mail: e4tw@mit.edu
b) Assistant Professor, Massachusetts Institute of Technology, Cambridge, MA 02139; E-mail: jao@mit.edu
c) Principal Researcher, Massachusetts Institute of Technology, Cambridge, MA 02139; E-mail: jgermain@mit.edu
d) Professor, Massachusetts Institute of Technology, Cambridge, MA 02139; E-mail: kausel@mit.edu

wall delamination and crumbling, which have been extensively documented in earthquake reports, more recently in the reports of Kashmir (EERI 2005a); Tarapaca, Chile (EERI 2005b); Molise, Italy (Decanini et al. 2004); and in the World Housing Encyclopedia reports (Brezv et al. 2006, Sinha and Ambati 2006). Moreover, the problems of wall delamination and crumbling are addressed in almost every manual providing guidelines for the construction of improved URM. The methods used in developing countries for low-cost construction are highly variable and based on empirical rules rather than an understanding of structural behavior and performance. Because of the inherent complexity and variability in masonry materials and construction methods, such structures are difficult to model effectively with numerical methods. Current analytical methods are based on a number of major simplifications, such as the pure brittle behavior and isotropy of masonry. These simplifications lead to models that often are not representative of the actual structures, and it is difficult, if not impossible, to determine the many structural and constitutive parameters needed for such numerical models. This is especially true in seismic situations, which involve loading and unloading, fracture propagation, contact and slip, and other considerations.

From our observations in the field we have learned that the failure mechanisms often involve the aggregation of irreversible “stick-and-slip” processes between bricks or stones (Kolb et al. 1999). The stick-and-slip process results in a gradual release of gravitational energy and dislocation of structural elements from their stable positions in walls (Figure 1). Frequencies higher than 10 Hz can be at the source of these processes and may cause two failure mechanisms that have not yet been accounted for. By understanding these mechanisms, it is possible to propose retrofitting schemes as well as improvements for new construction.

The first failure mechanism affects dry-rubble stone-masonry structures and is triggered by high-frequency vibrations that excite interstone vibrations. Relative displace-
ment of the stones may accumulate from repeated stick-slip processes elicited by these vibrations, in part because the stones are frequently oblong or pyramidal, with their flat surfaces oriented toward the exposed part of the wall (Figure 2a). Their irregular shape facilitates the irreversible downward sliding of the stones, leading to a relative displacement of the masonry units (Figures 2b and 2c). As a consequence of this relative movement of the stones, the wall becomes deformed and unstable, leading to catastrophic collapse under its own weight.

The energy needed to cause this deformation and failure mechanism does not come predominantly from the earthquake waves, as is commonly assumed, but rather from the release of the potential energy stored in the structure. That is, the energy needed to cause the collapse of the structure comes from the structure itself. Hence small-energy, high-frequency seismic waves can trigger the collapse mechanism of poorly built walls. Furthermore, the damaging effects of higher frequencies are amplified by the fact that for frequencies higher than 10 Hz, the vertical accelerations are larger than the horizontal ones (Bozorgnia et al. 1995), a situation that further reduces the cohesion of the masonry.

A second unaccounted-for failure mechanism is associated with the increase in outward thrust from the densification and fluidification, or loss of shear strength, of the wall’s inner-core granular material (Huntley 1998). In dry-stacked masonry walls, the inner core is often made up of loose sand and gravel that tend to densify and fluidify when experiencing high-frequency vibrations, resulting in a significant increase of the lateral thrust (Svinkin 2005). This additional thrust will push the unstable masonry units outward, causing the deformation and possible collapse of the masonry skins. This failure mechanism will compound the effect of the previously described interstone displacement elicited by the high-frequency motion components, as depicted in Figure 2.

To study the failure mechanisms described above, a series of laboratory-scale dry-stacked brick walls were built and tested to identify the heights at which the walls were statically stable with different sized infill. Although mud mortar is frequently used to facilitate the construction process of low-cost housing, more often than not it worsens the structure’s performance under seismic loading and the NICCE manual (2004) rec-
ommends avoiding its use. Therefore, the dry-stacked brick and stone walls will provide a clearer understanding of the upper bound of seismic performance. Then a second series of similar brick walls, as well as a number of stone walls, were tested to observe their dynamic behavior. Finally, UDEC, a discrete element modeling software, was used to analyze the brick walls and compare the results with those obtained experimentally (Itasca 2006). The results obtained from this research validate the significance of the damaging effects of higher frequencies on the overall structural stability of unreinforced masonry.

This paper first presents the experimental methodology. Then it describes the behavior and failure mechanisms observed during the static and dynamic experimental tests, including the results of the numerical models. The results are discussed and a number of significant detrimental effects of the seismic high frequencies on unreinforced masonry are described. Finally, the effectiveness of a simple construction improvement using through-stones is illustrated and quantified.

### METHODOLOGY

#### PRELIMINARY EVALUATION

The model for retaining walls of narrow backfill width by Take and Valsangkar (2001) was used to calculate the pressures resulting from the granular fill’s acting on the interior of the two wythes of the walls. The vertical shear coefficient \( K_v = 0.1 \) acting on the interior of the wythes is based on values obtained from the U.S. Army Corps of Engineers (1994). The coefficient of horizontal earth pressure at rest \( K_o = 0.5 \) was obtained from the formula \( K_o = (1 - \sin \phi) \), where \( \phi = 31^\circ \) is the smallest friction angle of cohesionless soils used in the tests. Table 1 shows the physical properties of the materials used as infill in the brick walls. The coefficient of static friction for the brick-brick interface was experimentally found to be 0.65.

To predict the failure mechanism and critical failure height of the walls, the horizontal interbrick frictional forces (self-weight multiplied by coefficient of friction) and the lateral resultant forces, from the infill pressure on the wall versus increasing wall heights, are found and plotted in Figure 3a. From this plot it can be observed that the resultant force of the internal pressure (solid line) remains smaller than the resisting frictional forces (discontinuous line), and therefore, sliding failure will not occur. In Figure 3b, the overturning moments, caused by the pressure acting on the wall (solid line), and

### Table 1. Physical properties of the different granular materials used as infill for the brick walls

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain Size mm</th>
<th>Friction Angle ( \phi )</th>
<th>Angularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Sand</td>
<td>0.5</td>
<td>31</td>
<td>Rounded</td>
</tr>
<tr>
<td>Gravel</td>
<td>15</td>
<td>34</td>
<td>Subangular</td>
</tr>
<tr>
<td>Coarse Gravel</td>
<td>60</td>
<td>38</td>
<td>Angular</td>
</tr>
</tbody>
</table>

80 P. MEYER, J. OCHSENDORF, J. GERMAINE, AND E. KAUSEL
the resisting moment, resulting from the self-weight of the wythe (discontinuous line), are again plotted versus increasing wall heights. This plot shows that the critical wall height needed for the soil pressure to cause overturning failure is 60 cm. From these two plots it can be concluded that the static failure mode would be governed by overturning at a height of about 60 cm. This height was then used as a reference to build the first walls.

**STATIC TESTS: BRICK WALLS**

The purpose of the static tests was to find the heights of the walls at which failure occurs due only to the lateral pressure from infill materials with different friction angles. A standard wall base length of 38 cm and width of 27 cm were used, and the failure height varied depending on the infill friction angle. Cape Cod solid bricks (19.5 cm × 9 cm × 5.5 cm) were used to build the walls, with the ends of the gap between the two wythes made of cardboard or wood. The three types of granular infill had friction angles of 31°, 34°, and 38°. No tests were conducted to find the static failure height of the stone walls because of the greater static stability of the stone walls.

For the static tests, the walls were built row-by-row and simultaneously filled in until failure occurred. Numbering the bricks ensured consistency among the different walls. As anticipated by the preliminary calculations, the walls failed at heights that ranged from 48 cm to 58 cm depending on the infill friction angle. The fact that the experimental failure height was consistently lower than the predicted one can be attributed to the irregularities in the shape of the bricks, which lowered the overall stability of the walls. Furthermore, all the walls failed by overturning as expected.
DYNAMIC TESTS: BRICK AND STONE WALLS

The brick walls used in the dynamic tests were identical to the ones used in the static tests, except that the height of the wall was significantly reduced. The stone walls were built with irregularly shaped stones to a height of 45 cm. The individual stones were numbered to ensure wall consistency (Figure 4b). The dynamic testing program consisted of two distinct testing phases: vertical and horizontal vibrations.

The first phase consisted of testing the walls dynamically on a vertically vibrating table with a fixed frequency of 60 Hz and variable acceleration. This frequency is higher than the critical 15–25 Hz resonant frequencies for granular soils, which would result in the maximum infill lateral pressure (Massarsch 2005). However, by varying the vertical acceleration, we were able to investigate two significant dynamic behaviors of unreinforced brick and stone walls. First, we evaluated the effect of the increase of internal pressure on the two-wythe brick walls, resulting from infill densification and shear fluidification by vertical vibrations. The lateral forces resulting from internal pressures are particularly relevant in historical buildings where the wide two-wythe walls often have a rubble infill. Second, the effect of high-vibration frequencies on dry, undressed stone masonry, commonly used in low-cost housing, was investigated. The testing procedure on the vertical vibrating table consisted in gradually increasing the vibration magnitude (i.e., acceleration) until failure occurred. Video recording of all the tests allowed for time logging.

In the second phase, the dynamic tests were conducted on a shake table with one horizontal degree of freedom and a maximum vibration frequency up to 25 Hz. This frequency range allowed us to investigate the behavior of the specimens under a wide variety of significant frequencies. Huerta-Lopez et al. (2000) have demonstrated that the
seismic waves observed in earthquake records manifest clearly nonstationary characteristics, as well as wide frequency content. As seismic waves always have vertical and horizontal components, both brick and stone walls were tested under horizontal vibrations to complement the previously conducted vertical vibrations tests (Figures 4a and 4b). The walls were set up on the shake table in such a way that the motion would be applied along the plane of the walls. This setup was used to isolate the effect on the wythes of the shear fluidification and densification of the infill due to vibrations. If the vibrations had been induced perpendicular to the wall plane, two additional overturning forces would have resulted from the dynamic loading: the inertial forces of the wythes and the infill. The characteristics of the brick walls built on the shake table were kept the same as the ones tested statically, with only small variations in the brick size. This similarity allowed us to compare the static and dynamic failure mechanisms and properties.

Two testing procedures were used. The first consisted of inducing a sinusoidal vibration with variable frequency and a fixed maximum displacement. It was decided to use a sinusoidal instead of a time-history loading because this type of loading is extensively used in structural dynamics research and it ensures testing consistency across the different specimens and tests (Yegian and Kadakal 1998). The wall was vibrated for two minutes at a fixed frequency and the displacement was gradually increased to the desired maximum. Then the vibration frequency was increased and held again for two minutes, while the vibration displacement was gradually increased to the desired maximum. This stepwise increase of frequency was repeated until the wall failed, which allowed us to identify the frequency and acceleration at which the walls started to fail and fully failed. These frequencies were then used in the second testing procedure, where the acceleration was gradually increased while the frequency was kept constant. These tests allowed us to confirm that high-frequency/low-energy vibrations could induce failure.

ANALYTICAL MODELS

The discrete element program UDEC was used for the numerical modeling of granular materials (infill) and individual blocks (bricks) as a series of stacked rigid bodies. The discrete element method (DEM) was initially developed to model the behavior of granular materials in geotechnical engineering (Cundall and Strack 1979). The analysis considers masonry as an assemblage of rigid blocks with no-tension frictional joints and the solutions are based on time-stepping integration of the equations of motion of the individual blocks. The software is fully dynamic and can model the interaction between falling and sliding blocks. Some of the strongest capabilities of DEM are its suitability for modeling crack initiation and propagation, as well as capabilities for modeling large displacements between the different masonry units (Azevedo and Sincraian 2005). To model the walls examined in this paper, the material properties of the bricks and infill were the same as those used in the physical walls. Though UDEC is capable of modeling elastic and nonlinear materials behavior, the blocks were modeled as rigid due to the negligent role of elasticity in the phenomena investigated here. The infill material was modeled using UDEC’s “voronoi” command, which generates random joints with user-defined parameters in a voronoi pattern. The static analysis of the models consisted in increasing the model height until its failure occurred.
The analytical models used to investigate the phenomenon of wall delamination, and its mitigation, consisted in two parallel wythes of stones with granular material as infill (Figure 5a). The coefficient of friction of the bricks was 0.65 and coarse gravel-sized material (with $\phi=38^\circ$) was used as the basic infill for the model. The material properties and dimensions of all the models analyzed were consistent with the physical experiments. The only variation on the model was the insertion of two and four through-stones to investigate their effectiveness in preventing wall delamination (Figures 5b and 5c). The loading accelerations were increased until failure of the model occurred.

**DISCUSSION**

**STATIC TESTS: BRICK WALLS**

Results from the 11 static tests indicate that the static infill pressure on the two wythes is significant enough to contribute to the damage of a wall. Overturning was the common failure mechanism and the friction angle of the granular infill was the main factor that influenced the changes in failure height of the wall.

**INFLUENCE OF GRANULAR INFILL FRICTION ANGLE**

The infill column height (i.e., wall height) needed for overturning failure increased with the increasing infill material friction angle ($\phi$), which is consistent with the fact that larger friction angles cause a smaller lateral pressure. Figure 6 correlates the mate-
rial’s friction angles and the average wall failure height. The failure heights vary from 48 cm for \( \phi = 31° \) to 58 cm for \( \phi = 38° \), which represents a 20% increase in failure height.

**ANALYTICAL MODEL: STATIC TESTS OF BRICK WALLS**

The failure mechanism obtained using the analytical model was almost identical to the failure mechanism of the physical walls, with a failure onset quickly followed by the overturning of the wythes (Figure 7). The failure height of the UDEC model was consistently higher than the failure height of the physical models. This height difference can be explained by the fact that the bricks used in the experiments were not perfectly cubical, allowing for some initial out-of-plane movement of the wall wythes, and reducing the overall stability of the wall. These tests were used to confirm that the UDEC model could capture the failure modes of infilled masonry walls due to overturning of the exterior wythes.

**Figure 6.** Effect of friction angle on failure height: increasing friction angle results in an increase of the wall failure height.

**Figure 7.** The UDEC static model with coarse gravel-sized infill material: (a) initial state of the model just after applying the gravitational force to the model, (b) failure onset after two seconds, and (c) failed state after four seconds.
DYNAMIC TESTS: VERTICAL VIBRATIONS ON BRICK WALLS

The dynamic failure mechanism of the brick walls at vertical vibrations of 60 Hz and accelerations below 0.4 g was characterized, like in the static case, by the overturning of one of the wall wythes. However, the dynamic failure onset occurred at 20% lower heights than in the static case. The full dynamic failure (without refilling the core material) occurred at wall heights 10 to 15% lower than the static failure, depending on the magnitude of the induced maximum vertical acceleration. In addition, the walls’ failure process occurred more gradually, unlike the sudden static failure.

A comparison plot of the wall heights needed for static and dynamic wythe overturning given the three different friction angles is shown in Figure 8. The consistent reduction in the wall failure height for the dynamic tests results from the increased lateral pressure caused by the shear fluidification and densification of the infill material undergoing vibration. When excited dynamically, the lateral pressure exerted by granular soils on the two wythes can be twice as high as the static pressure (Ni 1997). In addition, the lateral pressure exerted by the infill will increase further as a result of the removal of the arching effect, typical of granular soils in static conditions (Cizeau 1998). Figure 8 shows that the dynamic failure height increases with increasing friction angle and that it is reduced by 20% from the static failure height.

In some cases, the wall did not fully collapse after the failure onset because the outward thrust was reduced due to the significant infill height reduction (Figures 9a and 9b). This height reduction was a result of the densification of the infill and the outward motion of the wall. In addition to the dominant overturning failure, it was observed that for the cases where the wall had vertical joints, the walls had a tendency to buckle outwards. This shows the importance of laying the masonry in a well-staggered manner and avoiding continuous vertical joints at the wall corners.

Figure 8. Friction angle versus static and dynamic failure heights for brick walls: increasing friction angle results in an increase of the wall failure height.
This series of dynamic tests reveals the two following trends. First, that the dynamic failure mechanism is characterized by overturning of one of the wythes, and second, that the dynamic failure height is reduced by about 20% from the static failure height. In addition, as shown in Figure 8, the magnitude of the vertical acceleration has a significant role in the failure of the wall, reducing both the time to failure and the failure height of the walls.

**DYNAMIC TESTS: HORIZONTAL VIBRATIONS**

**Brick Walls**

The brick dimensions used to build the walls on the shake table were different from the ones used in the vertical vibration tests. Therefore, a series of five static tests were conducted to find the average static failure height of 67 cm. Two different wall heights were tested dynamically and found to fail at 37 cm and 45 cm, respectively, which represents a 44% and 33% reduction from the average static failure height of 67 cm. The static safety factors, defined as the resisting moment divided by the overturning moment, for the dynamically tested walls were 1.4 and 1.3, respectively. The failure mechanism observed during the dynamic tests consisted of three distinct stages: infill densification, shear fluidification causing significant wall deformation, and wall failure. Table 2 shows

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Frequency (Hz)</th>
<th>Min. Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infill Densification</td>
<td>7</td>
<td>0.14</td>
</tr>
<tr>
<td>Shear Fluidification</td>
<td>9–20</td>
<td>0.2</td>
</tr>
<tr>
<td>Major Wall Deformation</td>
<td>9–20</td>
<td>0.3</td>
</tr>
</tbody>
</table>
a summary of the frequencies and minimum accelerations needed for these three stages to occur.

The failure mechanism was initiated at an approximate frequency of 7 Hz and accelerations of approximately 0.14 g. At these frequencies, the granular infill densified and the arching effect was lost, resulting in an increase of lateral pressure on the two wall wythes. This densification continued for a short period of time and then the infill stabilized (Figure 10a). Infill densification resulted in a reduction of infill height, which in turn reduced the overturning moment caused by the internal pressure, and a slight outwards motion of the wythes (failure onset). In the cases where the infill was replenished, the wall failed without having to increase either the vibration frequencies or the acceleration.

The second failure stage occurred at frequencies between 9 Hz and 20 Hz and accelerations not larger than 0.2 g. In this range of frequencies the granular infill underwent both densification and shear fluidification (Figure 10b). The shear fluidification of the infill sharply increased the lateral pressure on the two leaves, pushing them farther away.

The third failure stage occurred when frequencies between 9 Hz and 20 Hz were applied and the maximum acceleration was increased to about 0.3 g. Under these conditions, the wall failed in spite of a significant reduction of the infill height (reduction of the moment caused by the internal pressure), which in some cases became less than half of its initial height. In addition, the wall also showed significant lateral deformation (Figure 10c).

These three failure stages can be correlated to the failure accelerations and frequencies of the individual walls plotted in Figure 11. No failure occurred below 7 Hz or 0.14 g. The dynamic tests conducted under horizontal vibrations show that at vibration frequencies exceeding 10 Hz and accelerations of 0.14 g, the failure height is reduced by at least 35% from the static failure height. Furthermore, as Figure 11 indicates, the acceleration needed to cause failure increases with the vibration frequency.
The results of the dynamic tests show that the failure of the stone walls is dependent on vibration frequency, acceleration, and vibration time. In Table 3, a typical variable frequency testing procedure for stone wall #2 is shown. The first dynamic failure occurs at a vibration frequency of 11 Hz and an acceleration of 0.17 g, and the final failure occurs at 15 Hz and 0.28 g. The damage of the wall progressed with time.

The test results presented in Figure 12 for the stone walls indicate that a minimum horizontal vibration frequency of 11 Hz and horizontal acceleration of 0.18 g was needed to cause dislocation of the stones. The fact that one wall failed at the same frequency, but at the much higher acceleration of 0.46 g, can be attributed to the difference in construction quality. To test the walls’ response at high vibration frequencies, two

<table>
<thead>
<tr>
<th>Frequency Hz</th>
<th>Acceleration g</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.11</td>
<td>Stable</td>
</tr>
<tr>
<td>9</td>
<td>0.12</td>
<td>Stone dislocations</td>
</tr>
<tr>
<td>11</td>
<td>0.17</td>
<td>1st failure</td>
</tr>
<tr>
<td>13</td>
<td>0.12</td>
<td>Gravel flow</td>
</tr>
<tr>
<td>13</td>
<td>0.19</td>
<td>Gravel flow</td>
</tr>
<tr>
<td>15</td>
<td>0.28</td>
<td>2nd failure</td>
</tr>
<tr>
<td>17</td>
<td>0.29</td>
<td>Moving stones</td>
</tr>
<tr>
<td>19</td>
<td>0.38</td>
<td>Moving stones</td>
</tr>
</tbody>
</table>
walls were tested to failure at a constant frequency of 20 Hz. The walls failed at 0.25 g and 0.5 g. As in the case of the brick walls, the experimental evidence shows that the acceleration required to cause failure increases with increasing frequency. It was observed that the vibration time proved to significantly influence the failure when the minimum failure frequencies and acceleration of 11 Hz and 0.18 g were exceeded. As can be observed in the videos of the tests, the failure progressed with time, even when the frequency and acceleration were constant. Raw data, videos, loading parameters, details of the DEM models, and extensive comments of all the tests can be downloaded from the project web site: http://www.engineering4theworld.org.

The stone walls were modeled in UDEC to determine the acceleration and frequency required for collapse for a rigid block system subjected to sinusoidal excitation. The model with no through-stones (Figure 13a) failed by delamination at an acceleration of 0.19 g, which corresponds closely with the experimental failure at 0.17 g. To test the effectiveness of a potential construction improvement, the same model was re-analyzed with through-stones added in the wall. The other two models, which had two and four through-stones inserted (Figures 13b and 13c), failed at accelerations of 0.32 g and 0.45 g, respectively, greatly increasing the onset of the failure mechanisms described in this paper. As can be observed in Figure 13a, the failure of the model with no through-stones occurred at a significantly lower acceleration in a catastrophic manner, dissipating only limited energy during the failure process. The models with through-stones (Figures 13b and 13c) were able to deform substantially before fully failing. This demonstrates that the use of through-stones could provide greater resistance in seismic events to unreinforced stone masonry walls.

Figure 14 shows how the acceleration needed to cause the failure of the model increases with an increasing number of through-stones. These results clearly indicate that the use of through-stones in the construction of unreinforced stone masonry walls can significantly improve their dynamic performance.

Figure 12. Failure frequencies and accelerations for stone walls.
This preliminary research shows that in spite of having small energy content far from the natural frequencies of structures, the high-frequency components of earthquake vibrations can be the source of significant structural damage to unreinforced masonry. Moreover, our tests have proven that the higher-frequency waves traveling through stiff masonry structures can trigger two types of failure mechanisms that have not yet been taken into account.

The first failure mechanism is associated with the fact that high frequencies can cause small vertical interstone vibrations that result in irreversible relative displacements of the stones, causing the wall to deform and ultimately collapse. The energy needed to

**CONCLUSIONS AND FUTURE WORK**

The first failure mechanism is associated with the fact that high frequencies can cause small vertical interstone vibrations that result in irreversible relative displacements of the stones, causing the wall to deform and ultimately collapse. The energy needed to

**Figure 13.** (a) Failure at 0.19 g; (b) failure at 0.32 g; (c) failure at 0.45 g.

**Figure 14.** Plot of the acceleration needed to cause the failure of the models with different numbers of through-stones.
cause this deformation and failure of the walls originates from potential gravitational forces contained in the structure itself, and the high-frequency interstone vibrations trigger its release. The stone wall tests have shown that significant wall deformations and partial failure occur at frequencies and accelerations as low as 11 Hz and 0.14 g, respectively. Experimental evidence indicates that at higher frequencies, the failure occurs significantly faster. In addition, the combination of both the vertical and the horizontal accelerations, which occurs in actual earthquakes, is expected to be even more detrimental. The reduction of frictional forces between the masonry resulting from the vertical accelerations compounds the deformational effects of the horizontal acceleration.

The second failure mechanism is associated with the significant increase of outward thrust generated by the shear fluidification and densification of the granular material making up the inner core of the wall can contribute to the structural failure. A series of dynamic tests on two-wythe brick walls with granular infill have shown the following trends: when the walls were vibrated vertically, the failure onset by overturning occurred at heights 20%–30% lower than in the static failure height; a failure height reduction of 30%–40% was observed when the walls were vibrated horizontally. Two-wythe stone walls, found in domestic architecture and monumental structures, are most affected by this failure mechanism.

**FUTURE WORK AND REMEDIAL ACTIONS**

After establishing that higher frequencies can have a detrimental effect on unreinforced dry masonry, it is important to conduct additional research to better understand and quantify these two new failure mechanisms. Future work should consider the following:

- Damage progression with respect to time at a given fixed vibration frequency
- Influence of the wall width
- Test wall with top constraint and load
- Simultaneous horizontal and vertical accelerations

Furthermore, these two new failure mechanisms will need to be integrated with other known masonry failure mechanisms to improve the design of low-cost housing and retrofit schemes. A number of simple, low-cost remedial actions can be used to reduce the risk of wall delamination and crumbling, such as insertion of through-stones, use of cementitious mortars, and rendering of stone units. The UDEC numerical model demonstrated that dynamic failure by wythe delamination, typical of unreinforced stone masonry walls, can be significantly mitigated by the introduction of through-stones.

**ACKNOWLEDGMENTS**

The Hugh Hampton Young Memorial Fund Fellowship at MIT supports the first author, and NSF funds facilitated by the MIT-India program made it possible to conduct research at the Indian Institute of Technology, Bombay, over the summer of 2005. The authors are especially thankful for the support obtained from Nissar Khan and his helpful team during the testing period on the shake table of the IITB’s Laboratory of Heavy Structures. We also want to thank Tom Kachoris, Jr., president of Spaulding Brick Co.,
Inc., for generously donating the bricks to construct the walls built in the MIT laboratory. In addition, we appreciate the support of Howard Bourdelais from Modern Continental, who provided some of the construction materials needed to build some of the walls. Finally, we thank Thanh-Hue Huynh for helping with the construction and testing of a number of walls.

REFERENCES


(Received 1 December 2005; accepted 23 June 2006)