Structural Forensics

investigating structures and their components

Wall collapse during excavation/underpinning. Note lack of joist ties to masonry.

Cases of Failure of Unreinforced Brick Walls Due to Out-Of-Plane Loads

By Dan Eschenasy, P.E.

Dan Eschenasy, P.E. is the New York City Buildings Department Chief Structural Engineer. He is an Honorary Member of SEAoNY.

Over the past five years, the New York City Buildings Department investigated several serious unreinforced masonry wall failures. The investigation found that, in most if not all of the cases, the out-of-plane weakness of the masonry wall was exploited. There is vast technical literature describing out-of-plane failures of unreinforced masonry (URM) walls during earthquakes, but the study observations refer to failures that did not occur during extreme natural events. The failures were due to fires, owner neglect or abandonment (mortar and wood joist decay, un-repaired cracks), improper construction practice (alteration, demolition, and underpinning), etc. These observations are circumscribed to brick masonry structures built before the introduction of the 1938 NYC Building Code.

Awareness of some of these out-of-plane modes of failure should raise concerns and consequently improve the engineering practice. These types of structures are no longer being built, but a large stock of such buildings remains. Some engineering firms incorporate in their practice renovation of historic structures with experts on staff. However, most commonly, engineers practicing today did not study unreinforced brick masonry in college and have only sporadic professional involvement with such structures. Given the large number of pre-World War II masonry buildings in New York City, there is a significant chance that a new building will require the demolition of a masonry structure existing on a lot or adjoining a brick tenement or loft building. Code provisions trigger the need to evaluate the effects of construction activity on existing buildings.

Unreinforced Masonry Buildings in New York City

New York City has over 100,000 multi-family unreinforced brick masonry buildings. These 3 to 7 story, usually attached buildings were built over a period ranging from the mid 1800s to the 1930s. They are masonry bearing structures with widths ranging from 20 feet to 26 feet, and depths ranging from 40 feet to 80 feet. The floors consist of one span wood joists. Starting with the first Building Code in 1860, relatively detailed prescriptions regulated masonry construction. They covered height and thicknesses of walls, composition and manufacture of mortars, bonding of masonry, etc. The prescriptions (and evolution) of New York City building codes influenced building codes throughout the country, including the first national model code, the National Board of Underwriters' *Model Building Code* of 1901. The code requirements were the result of empirical observations following fires and construction accidents. They permitted construction with only minimal or no engineering intervention. Many of these prescriptive requirements still survive in the "empirical" design sections of masonry codes. *(It is worth mentioning that all old New York City building codes and ordinances are now available for consultation at free internet libraries.)*

The general stability of URM buildings has not been affected by the lack of explicit lateral load calculations. Although not yet part of the engineering conceptual thinking of the early 1900s, shear walls and diaphragms were present as a result of the empirical based requirements, providing lateral stability for these buildings. The tying of wood floors to walls, and walls to each other, created a stable structure that, by and large, meets today's stability and stress requirements for vertical loads and even wind loads. Probably as a result of the success of these structures,

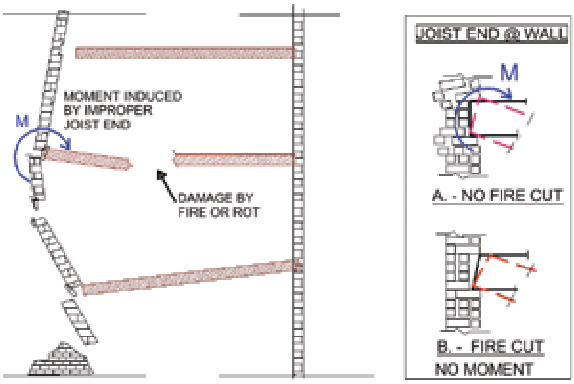

Figure 1: Out-of-plane moment due to collapsing floor.

only in the 1960s did wind design became compulsory for buildings under 100 feet in height. The stability and resistance to lateral forces were significantly enhanced by the practice of building attached houses. The widespread use of party wall construction made the city block an interlocked structure. The support provided by the abutting buildings hid, in some cases, the weakness to out-of-plane loads.

Fire concerns drove many code provisions. By the 1850s, regulations made compulsory the use of masonry for exterior walls to limit fire spread. Firemen noted the tendency of walls to overturn and promoted requirements that, although not explicit, were in recognition of the brick masonry's weakness to out-of-plane loads. Since 1860, the code has required a joist "fire cut". The fire cut allows a floor joist to collapse without generating an out-of-plane moment that could lead to the collapse of the bearing wall. To avoid such moment, metal joist ties, intended to transfer horizontal loads from the wall to the diaphragm, had to be placed at the bottom at the fire cut.

The wall thickness requirements were intended to avoid the collapse of the bearing wall that may have become too slender in the event of a wood floor collapse during fire. Limitations of the percentage of openings in the wall that were intended to avoid large concentrations of stresses, resulted in the presence of a substantial shear wall. All elements of the building were required to be tied (wall intersections were to be toothed and tied with metal anchors; floor joists had to be anchored to both the bearing and the side walls). The empirical practice of tying of the building elements together and the measures intended to avoid total wall collapse seemed to have been precursors to the modern building integrity design provisions preventing progressive collapse.

A recent post-fire collapse illustrated the wisdom of the historic code requirements (*Figure 1*). The total building collapse occurred about one hour after the fire was put out. The investigation revealed that this structure's lower floors dated from the federal era, that is prior to any regulation. Around 1900, two floors were added and an 8-inch party wall had a new 4-inch wythe added to satisfy the code existing at the time. As predicted, the severely burnt floors produced an out-of-plane wall collapse. A contributing factor was the lack of sufficient bond between the 1900 wythe to the old wall.

Engineering Assessment

The empirical provisions produced a structure with a factor of safety that could have exceeded 20.

Many present day engineers when commissioned to evaluate such "empirically designed" structures limit their examinations to observations of recent deterioration. They argue that since these buildings had never been the subject of engineering design, engineering calculations are not necessary or feasible and the very existence of the building over so many years is sufficient proof of its reliability.

The NYC Building Department investigation found that serious accidents occur when there is a confluence of deficiencies. The fact that failure did not occur in the presence of a certain defect allowed many builders and engineers to falsely conclude that such defect was not likely to seriously affect the wall's stability. Old cracks or building leans were qualified as "historic" and deemed not an immediate stability risk. Consequently, repairs were often delayed.

The various failures presented here are intended to illustrate the limitations of such arguments, and to advocate the use of analytical and computational tools for masonry assessments

Visual Inspection

Erosion of mortar joints, especially the decay of its lime component, is a common problem. When total loss of binder occurs, the masonry resistance to lateral forces is provided only by friction forces. Visual and simple scratching of the mortar is an adequate means to detect deterioration. To be fully effective, visual inspection needs to be performed on both faces of the masonry.

At parapets, as the joints are exposed to the weather at both faces, mortar deterioration is faster. Investigations prove that solutions that cover the roof side of the parapet with waterproof membranes may not be adequate, as they can allow water accumulation (and correlated mortar decay) on the inside face of the roofing. In effect, these membranes hide the fact that the mortar is reduced to sand. Collapse is likely, as there is minimal weight to induce friction.

In another case, an abandoned building had its windows and doors walled with blocks, preventing interior inspection. At the exterior face, a bearing wall was almost entirely covered with a sign. Following this wall's failure, it was established that the lack of joist fire cuts, combined with gross mortar and joist deterioration, were the main causes. For years, rainwater that had been allowed to penetrate through large roof holes had rotted the joists and eroded the mortar from inside the building. At some point in time, the moment induced by the sagging rotting floors overcame the out-of-plane resistance of the mortar-less walls, leading to a sudden collapse. The rotting of joists, albeit occurring at a slow rate, has the same effect as fire and can lead to wall collapses. As a consequence, the New York City Buildings Department considers buildings with open large holes in the roof as potentially compromised, and requires building owners to provide periodic engineering reports.

Out-of-Plane Loads Due to Construction Operations

Sometimes badly conceived construction operations result in applications of out-of-plane loads that cannot be resisted by the masonry. Several blowouts of masonry walls occurred when brick masonry walls were used to provide support for concrete formwork. The high pressure resulting from the rapid concrete pour punched the wall. To prevent similar accidents, the New York City Buildings Department has begun to require assessment of walls prior to using them as support for formwork.

Underpinning of foundations in New York City produced so many incidents that a Buildings Department specialized unit was created to gain control of the problem. The unit has noted local failures of rubble foundation walls as well overturning of entire assemblies of masonry walls and rubble foundations. The underpinning practice

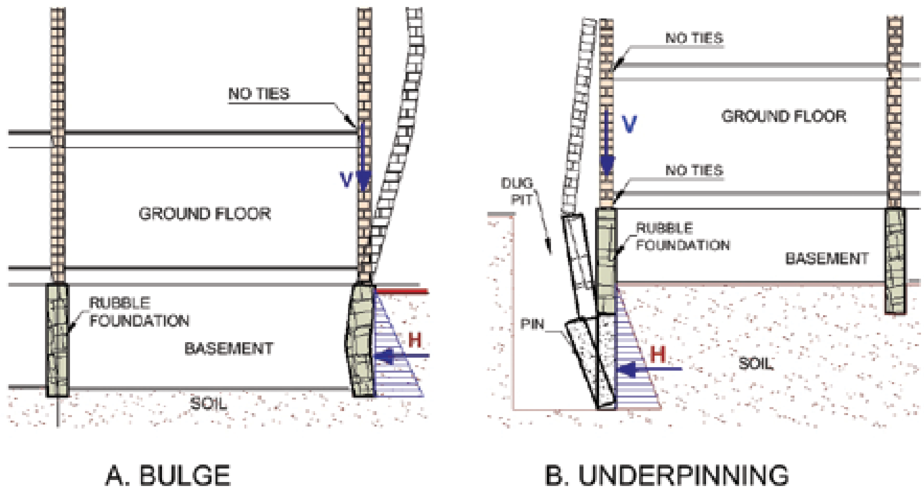

Figure 2: Out-of-plane loads on foundations. Higher vertical load has stabilizing effect at underpinning.

involves hand digging pits and placing concrete "pins" under existing continuous wall foundations. The process takes advantage of the arching properties of the masonry above as well as the stand-up time of typical soils in the city. The sequence assures that no more than a limited length of the foundation has soil removed from underneath. Failures are commonly blamed on the contractor not following proper procedures, allowing the underlying soil to "run out" with ensuing foundation settlement. Settlement or loss of soil can explain, in large part, masonry cracking, but not failures that involve wall overturning. In fact, as long as it is laterally supported, masonry can arch over significant spans without collapse. (This was proven by a recent incident where improper construction work collapsed a 15 foot section of a rubble foundation that supported a 100 year old masonry wall above. The wall arched over the collapsed section without even developing major new cracks.)

The most significant of the underpinning accidents that were investigated involved out-of-plane wall collapses that occurred after most of the pins had been placed. The analysis found that excavation in front of the foundation had transformed the existing foundation wall into a soil retaining system. The addition of the pins had increased the magnitude of the lateral load even more. In essence, the rubble foundation wall was subjected to loads for which it had not been originally designed. The deleterious result was magnified by an increase in the wall slenderness resulting from the added height of the underpin. As a result, the accident occurred as the application of these out-of-plane loads had not been analyzed and temporary shoring had not been installed. The overturning of the entire assembly – masonry walls, rubble foundation walls and concrete underpinning systems – occurred when the loads could not be effectively transferred to the floor diaphragms (*Figure 2*).

It is interesting to note that the severity of incidents was in direct correlation to the weight of the structure above, with the weight of the structure in fact improving the moment resistance and stability of the walls.

"Historic" Cracks and Load Paths

Some buildings exhibit cracks that remained unrepaired or were poorly stitched. It was theoretically proven that such cracks might not significantly diminish the capacity of the wall to sustain in plane or compression forces. In many cases, settlement cracks have ceased to be active after the supporting soil had stabilized. Many engineers argue that since the cause of the overstress was controlled, the walls will remain stable for many years. Such argument might not be adequate without evaluating the effect of cracks on load paths. When the load path is severed, relatively small additional out-of-plane loads (e.g. transient water pressure on foundations) or changes in the verticality of the wall (bulges) can lead to serious accidents.

During a recent building alteration, removal of several floors (horizontal supports) combined with existing vertical cracks created conditions for a wall collapse. The investigation revealed that old vertical cracks had in effect partitioned the bearing wall. The relatively small moment induced by an eccentric lintel support could no longer be resisted by the wall.

Analysis of another recent collapse found that it had occurred in a wall with a vertical crack at the corner that extended the entire building height. The wood floor framing system was comprised of wood joists; however, the wood planks had been removed (*Figure 3*). A relatively small local load created by a bulge at the basement could not be directly transferred to the shear walls because the diaphragm had been impaired and the direct corner connection was no longer present.

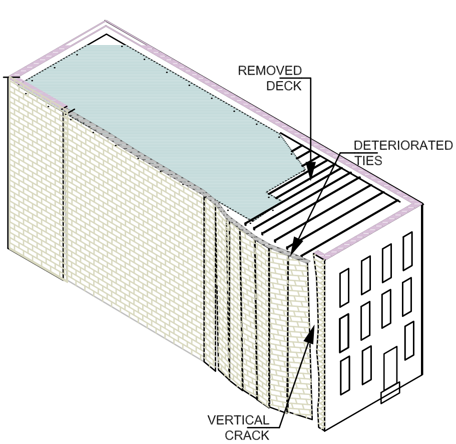

Figure 3: Lack of load path due to missing ties, vertical cracks or removal of flooring.

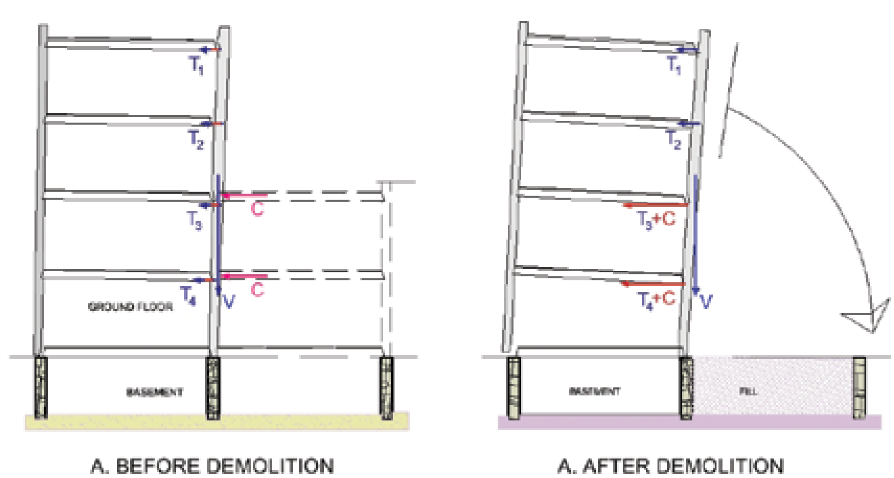

Figure 4: Out-of-plane moment produced by wall lean. Demolition of adjoining building increases demand on lateral supporting system.

Leaning Walls

Some abutting masonry buildings support each other. This is particularly the case when one of the buildings is leaning. The moment resulting from the lean, in fact an out-of-plane load, might overcome the capacity of the floor diaphragms or the shear walls. If the lean is stopped by the walls of the adjoining building, the condition might appear stable. Demolition operations need to be designed to take into consideration the possible destabilizing effect on the adjoining building (*Figure 4*).

In a recent case, the demolition exposed a bearing wall that was leaning. The building also had a full height vertical corner crack that interrupted the transfer of the forces to the shear wall. Various shoring solutions were tried but did not stop the ever increasing lean. Public safety required demolition.

Whatever the cause of the lean – foundation rotation, settlement or original out of plumb construction – the condition needs to be evaluated using detailed engineering analysis. Even when the safety factors are found to be acceptable, periodic inspections must be performed as settlement and creep can further increase the out-of-plane moments.

Lesson Learned

The current engineering practice pays significant attention to mortar decay and development of new cracks in URM walls. Some engineers deem stable and relatively safe some conditions (cracks or wall leans) that have been in existence for long periods of time. The example presented here should help change these views.

Some cracks, especially vertical corner cracks, may interrupt the continuity of load paths. Cracks should not be allowed to become “historic”. Walls with such cracks can collapse when subjected to even minor new out-of-plane loads.

Building leans produce out of plane loads. The capacity of the building elements to resist the resulting stresses might be stretched to the limit. Removal of adjoining buildings or interior partitions that act as shear walls can be destabilizing.

Application of new out-of-plane loads (underpinning or concrete pours against walls) might produce local failures or system wide distress.

Such masonry or load conditions cannot be sufficiently understood using empirical tools. The building assessment should involve detailed engineering evaluations, probes and calculations, with special attention paid to the capacity of the URM to sustain and transfer out of plane loads.▪

Roof opening allowed rot of joists and decay of mortar in masonry.