WHAT IS NEEDED FOR MASONRY TO BE SEISMICALLY BENIGN

D.P. Abrams[1]
[1] Willett Professor of Engineering, University of Illinois at Urbana-Champaign, USA, d-abrams@illinois.edu

ABSTRACT
As the oldest construction material, masonry has experienced more earthquakes than any other construction form. Yet, it is widely acknowledged in the seismic engineering community that masonry is a primary contributor to mortalities, injuries, damage and economic losses when earthquakes of moderate or strong intensities strike urban areas. Even some essential facilities such as firehouses and hospitals, or school buildings, are constructed of unreinforced masonry in seismic regions, and thus endanger public safety. However, with current technologies masonry construction can be made to perform well in earthquakes. This paper provides an overview of how this can be done from a long-range perspective, and what is needed to advance masonry as a competitive construction alternative in seismic regions.

As an introduction, earthquake risk and fragility are discussed, followed by examples of potential losses and how they can be estimated across a community. Mitigation action plans passed by the State of California to reduce risk attributable to collapse and damage of unreinforced masonry (URM) buildings are summarized as a model for other municipalities to follow. Useful tools for creating building inventories are presented as well as details for retrofitting seismic deficiencies in URM buildings. Performance-based seismic rehabilitation of existing masonry construction is addressed in terms of new standards. In particular, the use of displacement-based approaches for masonry is discussed.

Research needed to make masonry construction seismically benign is outlined. Views on what is necessary over the next several decades to mitigate the effects of disastrous earthquakes are given in terms of the cadre of masonry research talent, and current research capabilities. Estimates are given of the economic impact of future research expenditures on the reduction of earthquake loss. The primary conclusion is that the oldest construction material can be made seismically benign if the right steps are taken through a concerted program of long-range structural engineering research.

KEYWORDS: codes, damage, earthquake, loss, risk, seismic, unreinforced masonry

INTRODUCTION

Risks of suffering from polio, rheumatic fever or tuberculosis have reduced significantly as a result of former research to treat these diseases. Risks of experiencing a major flood are being reduced through the construction of seawalls or levees. Risk of serious injury or death in a vehicular accident has been decreased with safer design of automobiles and stricter driving laws. Similarly, earthquake risk can be decreased through wise assessment and retrofit of existing buildings and design of new construction. Such mitigation goals exist today but are not always adopted because of cost limitations, or preference of owners to allocate their resources to higher priorities. A long-range plan of research can possibly reverse this trend by reducing costs of enhanced seismic safety and demonstrating that the risk is indeed genuine.

The term "*benign*" is defined as "…not harmful to the environment such as an "ozone-benign refrigerant…" This definition carries over to medicine as "…not harmful in effect, in particular (of a tumour) not malignant…" The concept of an earthquake-benign form of building construction implies one that will not be harmful to mankind. This is a broad definition. Buildings are obviously harmful if they collapse and result in death or serious injuries. As depicted in Fig 1 mortalities can be in the hundreds of thousands for a single earthquake. Most of these deaths were attributable to the collapse of buildings. The official death toll from the January 12, 2010 Haitian earthquake, as given by the government one year later, was 316,000 – one of the largest ever for a magnitude 7 earthquake. In contrast, the death toll for the February 27, 2010 Chilean earthquake of magnitude 8.8 was 723. This comparison suggests the impact that good seismic design practices can have on reducing public harm. Following this trend, the concept of seismically benign buildings can someday be a reality if continued research and development are done.

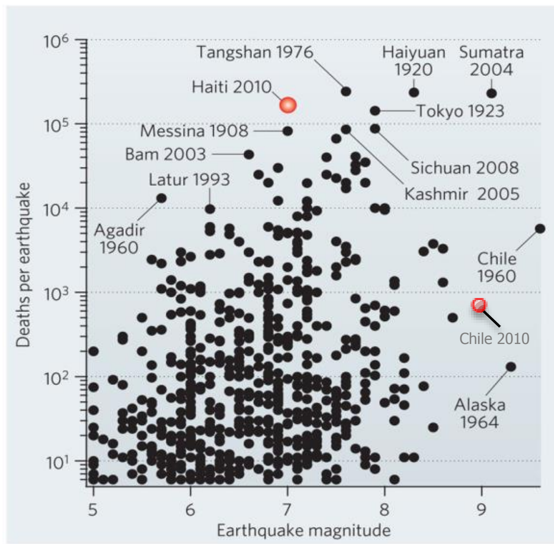


Figure 1: Deaths vs. Earthquake Magnitude from Bilham (2010)

Earthquake loss is just not physical, but also financial. Lesser forms of damage can result in significant losses to building owners, insurers, municipalities and other stakeholders as buildings damage and loose their function. Total economic losses from the 2011 Tokohu earthquake were estimated as high as $365 billion, the largest loss of any earthquake to date, and orders of magnitude larger than the loss due to building damage. Losses for the 2010 Chile and 2010-11 Christchurch earthquakes were estimated at $30 billion and $20 billion respectively. The anticipated loss for a re-occurrence of the 1811-12 New Madrid earthquakes has been postulated in excess of $200 billion. These earthquakes are far from being benign, indicating that much work needs to be done in setting mitigation action plans, improving engineering practice and doing research.

Unreinforced masonry buildings are notorious as “killer” buildings because of the thousands of examples cited where they collapse or endanger life safety. This connotation can change if appropriate actions are taken to rehabilitate them in an appropriate manner. Improvements in design and construction of new masonry buildings can also change this perception. Further research can help to reduce loss and damage by improving on construction technology, perhaps to the extent that masonry buildings will no longer be a threat, but actually a preferable and cost effective option for seismically resistant construction. To understand these issues in a more specific context, this paper explores how earthquake risk and loss potential can be quantified in a probabilistic context, what extents of damage are likely, and examples of how research can reduce future losses.

EARTHQUAKE RISK AND FRAGILITY

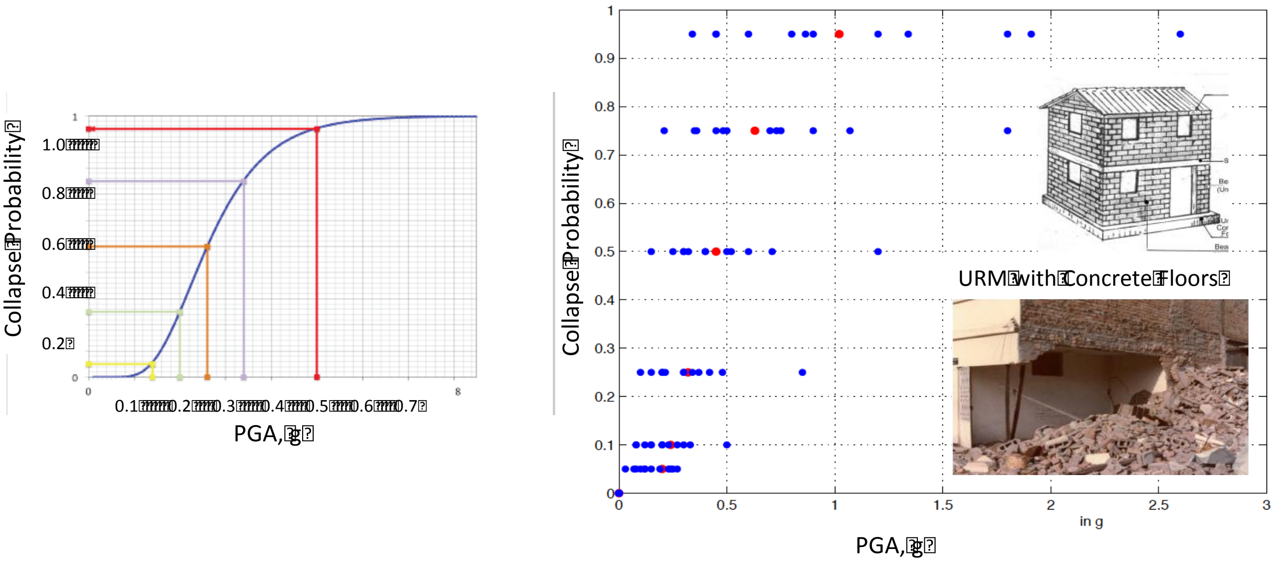
A simple definition of risk is the product of loss times the probability of having the loss. This is the same concept as risking $1.00 by placing a bet of $2.00 and having a 50-50 chance of winning. Thus, if the total loss of an earthquake is estimated at $200 billion and the probability of having such an event within a given time frame, say 50 years which is typically used, is 10%; then the risk is $20 billion. The annualized risk is this amount divided by the number of years, or $400 million per year. One cannot isolate the loss amount for an entire urban region into amounts attributable to a specific type of construction because of the interdependencies of indirect business losses, injuries and deaths, network losses and other factors. None-the-less, damage or collapse of unreinforced masonry buildings can result in an appreciable percentage of the total loss. Just to illustrate magnitude, if a conservative estimate of 20% is assumed, the seismic risk due to URM vulnerability is $4 billion. This is the same amount estimated to retrofit all of the deficient URM buildings in the state of California (CSSC, 2005). Because rehabilitation will result in loss reductions for more than a single future earthquake, this investment will reduce risk for many future generations to come.

Probabilities of occurrence for earthquakes are expressed in terms of the probability of exceeding a given intensity, p_t, within a specific time frame t. This is equivalent to expressing the probability in terms of the return period T. For the basis of design for new buildings, motions are considered that have a 10% probability of being exceeded in 50 years. This is equivalent to an occurrence interval of 475 years as given by Eq. 1. Extreme events are defined with a 2% probability of exceedance in 50 years, or an occurrence interval of 2475 years. Other indices of earthquake intensity are the peak ground acceleration and spectral acceleration for which there are national hazard maps in many countries.

$$p_t = 1 - \left(1 - {}^{1}\!/_{T}\right)^{t} \qquad (1)$$

The probability of damage or collapse of a specific form of construction is expressed using what is known as a fragility curve that plots the probability of getting a particular damage state versus some measure of seismic intensity (PGA is typically used). A sample fragility curve taken from Jaiswal (2012) is shown in Figure 2a for a typical mud-wall building. This shows an almost certain probability that all such structures should collapse for PGA’s greater than 0.5g, and smaller probabilities for getting collapse at smaller intensities.

Fragility curves represent uncertainty in construction quality as well variations in structural design. Ideally the curve would be a vertical line if all such buildings were designed and



(a) Mud-Wall Building **(b) URM Walls with Concrete Floors**

Figure 2: Fragility Curve Based on Expert Opinion

constructed exactly to the same demands, but since they are not some are more fragile than others.

Fragility curves are often developed based on computational simulations of nonlinear dynamic earthquake response of particular building types. Smoothing of curves is done using a log-normal distribution or other algorithm. Alternately, fragility curves are based on opinions of experts. Each of the arrays of points shown in Fig. 2b have been given by an individual expert based on judgement. These fragility curves are being developed for various masonry-building types contained in the World Housing Encyclopedia (http://www.world-housing.net) as part of a study done by the Global Earthquake Model (GEM) and USGS.

POTENTIAL LOSSES

A significant percentage (32.8% per French and Olshansky, 2000) of essential facilities in Mid-America are constructed of unreinforced masonry. These include firehouses, hospitals, police and school buildings within the seven-state region surrounding the New Madrid fault zone. Masonry damage can restrain or curtail emergency response operations. Buildings may burn to the ground if fire trucks are trapped under a collapsed firehouse. Hospitals may not function at capacity if masonry walls are cracked or rubble impedes egress. Similar delays can result from damage to masonry police stations and quick responder centres. Damage or collapse of school buildings (which comprise 57.8% of this data set) could result in death rates in the thousands. This is a similar threat to one identified in Iran where a national retrofit program underway exceeding $2 billion. Indirect business losses due to the shutdown of commercial or banking facilities can be as high as two or three times the direct economic loss due to building damage. For example, the loss of the Christchurch central business district was highly detrimental to the economic vitality of the city.

Stakeholders across the community need to commit to mitigation, in addition to owners of individual buildings. It is cost effective, on a community basis, to invest in seismic mitigation, particularly for obvious vulnerable buildings such as those constructed of unreinforced masonry.

Potential earthquake losses are estimated using a number of different methods. The most popular method in the USA is the HAZUS program developed by FEMA for projections of community loss. In addition, risk assessment professionals have developed proprietary methods for loss assessment used by the insurance industry. As a research tool, the Mid-America Earthquake Center developed a software package known as MAEviz that depicts earthquake risk with computer visualization tools that capture distributions of building inventories, critical lifeline systems, seismic hazards and maps of soil types.

Another regional loss estimation methodology, developed by Erbay (2004) specifically for URM construction, characterized the distribution of buildings across an urban area. He identified four critical parameters to depict damage to a typically configured masonry building: (i) number of stories, (ii) floor area, (iii) story height and (iv) wall-to-floor aspect ratio. Using inventory information on the variation of these parameters for different urban areas (Urbana, Carbondale, Memphis and San Francisco), idealized parametric distributions could be made. By modelling fragility of such building types and relating loss to hazard level, a simple method was developed for summing losses knowing the total building area in a community and the replacement or repair costs. The methodology was used to estimate losses for the small town of Puglia in Italy that was subjected to a magnitude 5.4 earthquake in October of 2002. Such tools may be used to estimate losses due to the collapse of masonry buildings, and thus provide an idea of risk and possible loss reductions resulting from refinements in mitigation methods.

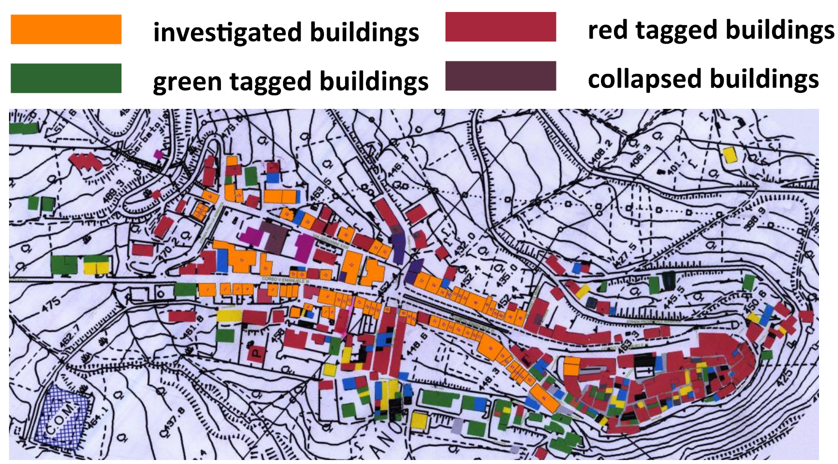


Figure 3: Building Inventory in Puglia from Erbay (2004)

WHAT IS NEEDED TO REDUCE LOSS

Actions to reduce earthquake loss can be placed in three categories: (i) demolition of existing deficient buildings, (ii) mitigation of risk for existing buildings through effective seismic rehabilitation, and (iii) construction of seismically resistant new buildings.

Building owners usually oppose actions in the first category. If they have little fear that an earthquake will occur, they will of course not demolish their buildings. There are few municipalities that mandate demolition of dangerous buildings, though this is reserved as an option if rehabilitation is not done. Only 14% of inventoried buildings in California (3,566) were demolished in response to local ordinances (CSSC, 2005). Demolition is a popular option after an earthquake to clear away damaged buildings, however in that context, it is of course not a risk reduction measure since the earthquake has already occurred.

Though somewhat reluctant to invest in mitigation options, particularly in regions of low-probability seismic regions, owners prefer the second category as opposed to demolition or reconstruction. Seismic rehabilitation may consist of minimal prescriptive measures, or a systematic re-engineering of the complete lateral-force resisting system. Losses can be reduced greatly when obvious deficiencies such as unbraced parapets or unanchored exterior masonry walls are remedied with simple prescriptive design rules. For larger, more complex buildings an engineering analysis may be done using methods recommended in ASCE 41-13 (2103), which is discussed later in this paper.

Rehabilitation of the existing infrastructure is the best option to circumvent earthquake losses. Newly constructed buildings should not incur significant damage, and should thus be seismically benign according to the definition given at the start of this paper. Modern strength design requirements for reinforced masonry wall structures are fairly well developed, though updates continue to be made with each code cycle. These requirements explicitly consider strength and displacement capacity through proper detailing of reinforcement. Large-scale experiments on shaking tables (Ahmadi, 2012) have demonstrated more than adequate strength and ductility of a properly detailed reinforced masonry structure.

Taking no action is also an option though costly and dangerous, but with time and a number of damaging earthquakes, hazardous buildings will either collapse, be so damaged that they must be demolished, or proved to be resilient. This is not a sensible strategy since it is a blueprint for disaster, though a popular one.

MITIGATION ACTION PLANS

Some local, state and federal governments have taken action to mitigate earthquake losses attributable to collapse and damage of unreinforced masonry buildings. In 1986, California enacted a law requiring local governments in high seismic zones to inventory their stock of URM buildings, to establish loss reduction programs, and report their progress. As of 2004, about 98% of the 25,400 URM buildings in the state were in loss-reduction programs with 69% of them being retrofitted, mostly as a result of mandatory regulations rather than incentives or voluntary action.

The California Seismic Safety Commission recommended to the state legislature to pass laws that would mandate strengthening of all URM bearing wall buildings and recommend that local governments provide incentives for seismic retrofit. The cost of retrofitting URM buildings per the California law was estimated at $4 billion when the law was enacted - a small percentage of the perceived loss of several hundred billion dollars in anticipated damage from a single major earthquake. A report prepared by the City of Seattle (2006) summarizes best practices for URM retrofit in California local jurisdictions including incentives, penalties and time lines for compliance. In 2004, California enacted a law mandating owners to post a warning placard on their URM buildings (Fig. 4). If owners retrofitted their buildings, they could replace the placard with one that states that the building was improved in accordance with seismic safety standards. Because this influenced property values, owners were motivated to invest in seismic retrofit.

Other mitigation action plans to retrofit URM buildings have taken place in Oregon, Seattle and Utah as summarized in FEMA P-774 (2009).

Whereas these mitigation plans are impressive in scope and implementation, further development of engineering aspects of rehabilitation methods can further reduce earthquake losses. For example, new performance-based rehabilitation methods, as described below, can result in less cost and improved seismic safety and function. These methods are far more descriptive than the simplified empirical methods described earlier, and represent the state-of-the-art in seismic engineering.

Figure 4: California Placard

Efforts to mitigate seismic risk on the west coast will have a significant effect in reducing losses for the next major earthquake and will help to approach the target for masonry to be seismically benign. However, the remainder of the United States, and other countries, remain vulnerable since no similar legislation has been past to date.

INVENTORIES OF VULNERABLE BUILDINGS

As noted in the California retrofit law, the first step of a mitigation action plan is to identify the percentage and number of deficient buildings. FEMA 154 provides a simple form for rapid visual screening of buildings where simple information such as the overall dimensions of the building in plan and elevation are recorded as well as occupancy type, soil type, and structural type. Each building is rated with regard to these parameters and given a composite score to determine if a more detailed evaluation is required. A simple smart-phone application is available for recording of such information, which can then go into larger databases to identify the landscape of buildings in an urban area. Research can be done to make this process more expedient by developing new technologies relying on aerial surveys.

REHABILITATION METHODS FOR URM BUILDINGS

Seismic rehabilitation methods for unreinforced masonry buildings range from fixing obvious flaws with prescriptive measures, to a systematic overhaul of the complete lateral-force resisting system by strengthening individual elements and/or constructing alternate systems. The standard for retrofit in the USA is the International Existing Building Code published by the International Code Council (2012). This code contains requirements intended to encourage the use and reuse of existing buildings. Topics include repair, alterations, addition and change of occupancy for existing and historic buildings. The focus is to enable users to achieve appropriate levels of safety without requiring full compliance with new construction requirements of other codes. Prior to this code, the model code most commonly used was the *Uniform Code for Building Conservation* (UCBC) Appendix Chapter 1, 1997 edition.

A summary of retrofit methods is given in FEMA 547 (2006) for several types of buildings, including masonry. These methods are generally strengthening schemes and are organized with respect to model building type. Addition of new elements is listed in table form to enhance particular deficiencies. As an example, to improve in-plane strength of URM walls, wood panels, reinforced concrete or masonry shear walls, steel braced frames or moment frames may be added. Methods of enhancing existing elements are also listed such as placement of concrete or fibre composites over existing URM walls, grouting or infilling openings. Other recommendations are given for improving strength of out-of-plane walls, parapets, chimneys and floor diaphragms. Several blueprint-quality details are given of retrofit measures.

Several resources are available to educate the public on simple prescriptive measures for strengthening masonry buildings. Simple prescriptive manuals on how to retrofit specific categories of URM buildings have proven practical for contractors. A good example of this is the Utah guide for seismic improvement of URM dwellings (http://ussc.utah.gov/utahseismic).

Using current documents produced by FEMA for collecting inventories, assessing seismic strength and prescribing retrofit strategies should result in masonry buildings that are close to seismically benign at a reasonable cost. However, these methods do not provide guidance on how to assess seismic demand forces from a structural analysis, nor how the global structural system may respond to ground shaking. Such aspects are described in the next section.

PERFORMANCE-BASED REHABILITATION OF EXISTING BUILDINGS

Starting in 1993 with FEMA support, the Applied Technology Council embarked on a multi-year activity to develop the first set of performance-based guidelines for seismic rehabilitation of buildings. The first resource document was FEMA 273, which was followed with a pre-standard known as FEM 356 that evolved to the current ASCE 41-06 and soon to be published ASCE 41-13. Separate chapters of these documents are devoted to different materials, including one on masonry. The term "systematic" rehabilitation is used to differentiate simple prescriptive measures from those based on engineering analyses which are intended for larger and taller structures. Rehabilitation strategies are based on meeting various performance objectives (immediate occupancy, life safety and collapse prevention) for various earthquake intensity measures (2% and 5% probability of exceedance in 50 years). Because rehabilitation is performance based, displacements are considered explicitly rather than the more common force-based approach of traditional building codes. Thus, this is the first displacement-based set of requirements for masonry structures. Additional description of these rehabilitation guidelines for masonry buildings is given by Abrams (2001).

Retrofit methods do not necessarily need to strengthen a building, but rather they can increase its displacement capacity. As a result, a new of thinking has emerged for unreinforced masonry structures where displacement-controlled actions like rocking and bed-joint sliding are preferred over force-controlled actions like toe compression or diagonal tension. Several new questions emerge from such a shift in engineering perspective. Can URM buildings really fit within a performance-based framework? If so, what analysis procedures are appropriate for them; linear or nonlinear, static or dynamic? Can a URM wall be characterized as displacement based if it is in line with other walls that are controlled by force-based actions? What are the best rehabilitation techniques to improve displacement capacity as opposed to traditional strengthening methods?

The development of displacement-based rehabilitation requires substantial research to help answer these and other questions. Such investment should result in safer and better performing buildings with perhaps lower rehabilitation costs. Large-scale experiments should be run on masonry walls or piers to identify their displacement capacity, and on complete building systems to verify how force-based and displacement-based components may act together. Little research has been done on URM building structures from this performance-based perspective despite the continued development of ASCE 41. Confidence is needed that this approach is applicable to URM buildings. Practitioners must develop an intuition for displacement-based design before the approach can be widely implemented. Furthermore, experiments on masonry piers and walls must be done from a perspective of identifying displacement capacity. Abrams (2005) summarizes some exploratory tests in this context, however a systematic, expanded series of experiments is warranted.

NEEDED RESEARCH

Despite the accomplishments and advances done on the state and federal levels regarding mitigation action plans, methods for building inventories, and techniques for seismic rehabilitation, earthquake engineering research on unreinforced masonry buildings has been done at a fairly slow rate in the United States. Since there have been no national coordinated research programs, research that has been done has usually been done on the level of individual projects, though some joint efforts have been done at the MAE Center and MCEER during the time of their NSF support. Funding of these individual efforts has been somewhat sporadic, meeting the needs of single academic activities rather than fitting within master research plans focused on widespread earthquake loss reduction. Many of the technical details in recommended retrofit guidelines mentioned earlier, have not been substantiated with research. Whereas they are sound based on substantial engineering experience, research is needed to confirm them or perhaps enhance them. The following list of research investigations would complement the framework of earthquake loss reduction measures already established for URM buildings. This list is by no means exhaustive. It is given to illustrate research needs and opportunities.

1. Technologies for rapid inventories of URM buildings could be developed. New imaging technologies such as light detection and ranging (LIDAR) can be exploited to make aerial surveys of building populations. Building heights, number of stories and plan dimensions can be measured with an aerial survey. Other newly developed image-based reconstruction methods can be used to generate a 3D point cloud model of buildings for automated stability analyses used for post-disaster assessments (Fig. 5).

Figure 5: 3D Point Cloud Model (from M. Golparvar-Fard)

2. Many of the rehabilitation details given in FEMA 547 could be tested. These include a large number of details for anchoring diaphragms to walls, parapets to roofs and connecting various masonry elements. The long list of recommended retrofit methods for improving in-plane and out-of-plane strength and behaviour of URM walls could serve as a basis for a coordinated research investigation.

3. Damage at the corners of URM buildings are commonly observed after earthquakes (Fig. 6), yet has not been researched in depth. Codes and retrofit guidelines are silent on how to detail or analyse corners. Such damage is a result of interaction of two orthogonal shear walls and twisting of floor diaphragms causing torsion on the corners. These are three-dimensional effects that are not captured with typical in-plane wall models.

Figure 6: Typical Corner Damage

4. Three-dimensional response of building systems has been studied with a few experimental studies, but could be studied further to improve code recommendations for assessing effects of: (i) in-plane damage on out-of-plane strength, and the reciprocal case; (ii) effective flange widths for L or T-shaped walls, (iii) dynamic interactions of flexible diaphragms and shear wall systems; (iv) the effect of vertical accelerations on systems which benefit from vertical axial forces such as rocking, net flexural tension or shear; and (v) response of buildings with irregular plan or elevation layouts. A long-range coordinated program of research addressing these needs using multi-degree-of-freedom shaking tables could easily include twenty or more full-scale test structures taking more than a decade.

5. The concept of displacement-based design for URM buildings needs to be explored further. FEMA 273/356 introduced this concept for unreinforced masonry because this design approach was being propositioned in the same document for steel and concrete structures for which much more research had been done on the topic. Rocking and bed-joint sliding of URM piers or walls were identified as displacement-based, which is justified based on their force-deflection behaviour, but work needs to be done to confirm how a building system comprised of these elements can work in parallel with components that are controlled by force-type actions such as diagonal shear stress or toe compressive stress. Testing and simulation of large-scale buildings on a shaking table should be done to investigate the use of displacement-based methods for URM buildings. Such research could answers questions posed earlier in this paper regarding performance-based rehabilitation.

6. Computational simulation of dynamic response for URM buildings has been attempted with success by researchers, yet engineering practice has generally not adopted them for seismic assessment of existing or retrofitted buildings. A finite-element model developed by T. Yi, et. al. (2006)

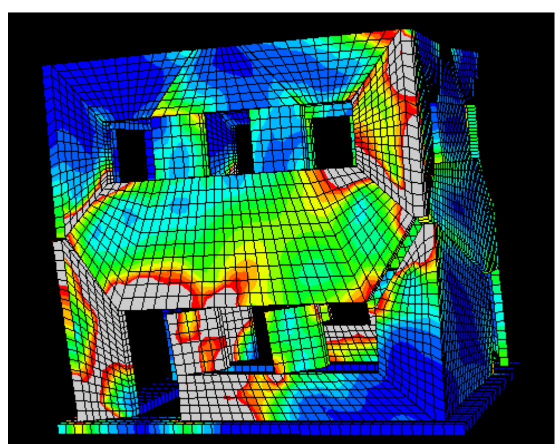


Figure 7: FEM Model of URM Test Structure from T. Yi, et. al. (2006)

as shown in Fig. 7 illustrates the complexity of such a model. More work needs to be done to develop sophisticated models simple enough for general use. As computational methods continue to become more versatile, user friendly and faster, future practitioners should be able to run nonlinear dynamic analyses of complete three-dimensional building systems. To meet this goal, research needs to be done to further develop computational simulation methods. With enhanced analysis ability, some URM buildings may be found to have sufficient earthquake resistance with much less retrofit than prescribed with current empirical methods. As a result, costs for more detailed analyses may be justified in terms of reduction in retrofit costs, and the historic fabric of a URM building might be more readily preserved. Advanced computational models could also be used to identify selective retrofit strategies where only those elements of the structure that are found to be deficient are strengthened.

7. Soil-foundation-structure interaction has not been studied extensively for URM buildings, nor is addressed in current codes or guidelines. Because masonry buildings are usually stiff and periods of vibration are short, foundation flexibility might be a concern. Also, more detailed studies are need to be done on the relationship between site effects and building response since again this form of construction is unique in terms of vibrational properties.

8. Unreinforced concrete masonry is many times used for partition walls in steel, concrete or masonry buildings. Though these elements are usually neglected for structural considerations, because of their large volume, they can play a significant role in resisting earthquake forces. In particular, partition walls could provide support of a damaged building thus preventing collapse. Research should be done to study the interaction of such non-structural elements with the structural system, and how they can be relied upon in this context.

ACCELERATION OF RESEARCH TO MEET IMMEDIATE NEEDS

Funding for seismic research has fluctuated as the memories of recent disasters have waned, or as economies of the industry have weakened. Available funds for research are many times focused towards innovation and new construction methods, rather than helping to mitigate hazards associated with construction of the past. Research funding can easily be deferred when resources must be allocated to more short-term needs. Research capacities in terms of people and facilities have also varied depending on the availability of funding. The past has shown that the pool of capable masonry researchers would no doubt increase, causing the pace of research to accelerate, if resources were increased. Funding of research has usually followed needs of the masonry industry to remain competitive. However, a broader societal view is needed to make masonry seismically benign. Concerted efforts at national and international levels over long periods of time are needed to meet this goal. The pace of research needs to be set so that seismic risk can be reduced for the next probable earthquake.

Research expenditures can be modest in terms of the reduction in economic loss attributable to the research. Economic losses for future earthquakes can be in the billions of dollars whereas research may cost in the millions of dollars. As an example to illustrate relative orders of magnitude, let’s assume that a full-time equivalent (FTE) researcher can reduce earthquake losses by 0.10% per year, and the cost per year of this FTE is $200,000 (including laboratory and indirect costs and working 12 months of the year). Loss reduction as calculated with Eqs. 2 and 3 can then be plotted vs. research expenditure and number of years of research as shown in Fig. 8. This is done for a sample loss of $50 billion.

$$\text{FTE} = \frac{\text{research expenditure/yr}}{\$200{,}000} \tag{2}$$

$$\text{Loss Reduction} = \text{FTE} * 0.10\%/\text{year} * \text{number of years} \tag{3}$$

Through this overly simple projection, one can easily see that if research funding is supported at high levels for short terms, or small levels for long terms, the loss reduction will be minimal. However, with consistent funding of say $5 million per year, losses could be cut by a quarter with ten years of research, or cut in half with twenty years of research. In either case, this would be a payoff of 250 times the investment. The question to address when setting funding rates is how many years do we have to solve the problem.

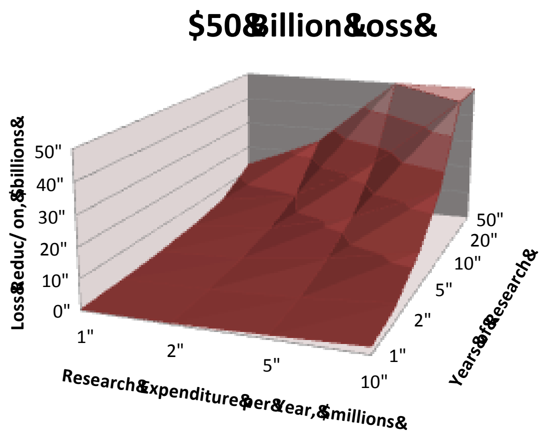


Figure 8: Loss Reduction vs. Research Allocation

Like investment in other futuristic-based endeavours such as the US social security system or state pension systems, deferment of payments for a latter time is not wise or prudent though decision makers may select that course of action to meet immediate financial demands. If masonry seismic research continues at a trickle as it has been, we should anticipate having similar levels of damage if a significant earthquake occurs in the future. This will happen and will re-happen with each successive earthquake until the problem is fixed, or until all the vulnerable buildings have collapsed or are demolished, provided that new ones are not constructed with deficiencies. In fact, with the same intensity of earthquake, the economic loss will be higher in the future because of society's increased dependence on infrastructure. Therefore, why not accelerate the research pace now so that the payoff can be appreciated within the likely time before an earthquake occurs (the first time) and thus the rewards can be appreciated for each successive seismic event as well. To re-iterate, current technology and the research talent base are not a limitation.

CONCLUDING REMARKS

To reflect on the title of this paper, what is needed to make masonry seismically benign? Community, government and industry must be committed to long-range mitigation action plans that will: (i) identify building inventories relative to spatial distribution of seismic hazards, (ii) estimate probabilistic losses, (iii) rehabilitate, or demolish and replace, vulnerable construction, and (iv) continue to construct new masonry buildings with well-proven seismic design practices. In concert with this action plan, research should be done at an accelerated rate over a long term and focused on reducing damage, particularly in terms of the four aspects of this implementation plan.

The possibility for masonry to be seismically benign is within the scope of our technical knowledge, engineering skills and research talent. All that is needed is coordination, cooperation and continued support. As a result, masonry buildings will become more competitive in regions of moderate or strong seismicity, communities will be more resilient, people will be safer and the quality of life will improve.

Whereas masonry can be made seismically benign using current design and construction practices, investing in accelerated and long-term research on improving methods for building inventories, loss estimation, rehabilitation, and new-age seismic design methods can result in a favourable return in terms of reducing losses for major earthquakes in the decades to come. Perhaps one day, the effects of earthquakes on the built environment will be as threatening as thunderstorms - fearful during their occurrence but forgotten the next day as businesses and lives resume their normal routines. In which case masonry can indeed be seismically benign.

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