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DAMAGE INVESTIGATION: INFILL CONCRETE FRAMES

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ABSTRACT

Concrete masonry units provide an excellent infill material for reinforced concrete frames in earthquake and hurricane regions. The book entitled "Masonry Structures Behaviour and Design" by Drysdale and Hamid, 2008 Edition [1], Chapter 11, provides excellent reading on this lateral force resisting system. Historically the emphasis was on strength or life safety laboratory testing (Observation) and computer modelling (Simulation). This focus on the Life Safety Limit State has been expanded with the movement toward performance based design which focuses on other limit states. This paper focuses on the very important topic of damage investigation of the infill frames after an earthquake or hurricane. In many cases the infill frame has been displaced to drift levels considerably less than life safety drift amplitudes and limit states other than life safety. This paper also focuses on these limit states and particularly the very important insurance topic of the return of the infill frame to its pre-earthquake or hurricane condition.

KEYWORDS: concrete masonry, infill frames, earthquake, hurricane, insurance.

INTRODUCTION

What more is there to say about investigation of Infill Concrete Frames? Perhaps the main thing to say is that it is a great time to investigate infill frames because of the tremendous advances made in the science of structural engineering by persons past and persons in attendance at this symposium. The senior author had the honour at the start of his career of being part of a University of California and University of Chile joint team that investigated infill concrete frame damage that resulted from the 1968 Chilean earthquake. Later in his career, he also had the honour of being a keynote speaker at a previous Canadian Masonry Symposium. Today he has the privilege of working with the co-authors of this paper to investigate earthquake and hurricane damage to infill frames using the scientific contributions made by many of the attendees of this symposium. This paper attempts to share with the reader what has been learned and what has been applied with great success in the damage investigation of infill concrete frames.

Sometimes our past lessons learned can help us do a better job of our current work tasks. The following is an illustration of this.

The senior author recalls an experience that is perhaps relevant to this paper. In the early 1970's when he was a young, bushy haired professor at UCLA he had a consulting job for NASA with two great structural engineers- Jon Collins and Tim Hasselman. NASA believed that in order to have confidence in the Saturn Rocket launch they must have BOTH a laboratory full scale test program and a detailed structural analysis of the rocket program. The knowledgeable reader can probably guess what happened. The results for the natural frequencies of vibration and mode shapes were different for the laboratory tests and structural analysis. Now we enter our consulting job (Hart, Collins and Hasselman) for NASA, perhaps one of the first publications on System Identification and a resulting NASA Certification of Merit. Fundamentally what we contributed is a mathematical way of recognizing reality because BOTH the results of what we would now call Observation Work – testing in laboratory and these professionals and their experience – must be considered and also what we would now call Simulation Work – structural analysis and professional experience – must be considered. Both have uncertainties associated with their work and results! Our work recognized and rationally considered both in developing expected natural frequently used mode shapes.

Today we have the same problem when we do a damage investigation of an infill frame after a hurricane or earthquake and recommend a repair to bring the infill frame back to its pre-event condition. Fortunately over the last 30 years we, and many others, have advanced the science we use and increase the benefits, and confidence in our recommendations, from our observations and simulations.

STEP ONE: ACCEPTING REALITY AND QUANTIFYING CONFIDENCE

Imagine that a hurricane or an earthquake has occurred and your assignment, either for a public adjuster/owner or for an insurance company, is to recommend what rehabilitation, if any, is needed to bring the infill frame in the building back to it pre-event condition. To make this recommendation, it is essential to do observation and simulation work. Unfortunately the post hurricane or earthquake approach used today by many, many, many forensic engineers employed by insurance companies, public adjusters or lawyers fail to recognize the need for a state of the practice investigation method that recognizes uncertainty in stating their opinion. Instead they use the "I have gray hair, I have considerable experience, I have all of these credentials and besides I am smarter than you" approach. Sometimes this approach is used by engineers with no gray hair or no hair at all. It is our hope that this paper will reduce the number of such studies in the future.

The proposed method for recognizing the real world and facing uncertainty head on is not a new concept. In the 1960's the field of Structural Reliability and Bayesian Decision Making was ushered into structural engineering by several professors. Even today many structural engineers, some very powerful and influential, object to the use of these two areas of structural engineering because they require a scientific quantification of confidence. However, such a position shows a behind the time mentality and also perhaps more importantly a lack of understanding of the history of their own profession. One example of a historic decision made in structural engineering that recognized these two parts of structural engineering is the definition of the design basis earthquake, first published in the ATC 3-06 [2] document in 1978. The definition focused on answering the question: What is the maximum earthquake ground motion that can occur at a specific building site, assuming that the building being designed will be exposed to future earthquakes for 50 years? No single number can be used to answer this question because the answer is a random variable. However, using the science of probability theory and Bayesian Decision Making the design basis earthquake was defined to be an earthquake ground motion that has a 90% probability of not being exceeded in the 50-year design life of the building. (The 50-year design life was used based on the expectation that the building would likely be replaced in approximately 50 years.) Therefore, using Table 1 shown below, this means that the authors of ATC 3-06 were *Almost Certain* that the maximum earthquake ground motion in the 50-year design life of a typical building would not exceed the design basis earthquake defined in the document.

Table 1: Verbal to Numerical Transformation of Confidence.*

Expression	Single-Numbered (median) Probability Equivalent (%)	Range (%)
Almost Certain	90	90-99.5
Very Likely	85	75-90
Likely	70	65-75
Even Chance	50	45-65

**Reagan,R., Mosteller, F, and Youtz, C. "Quantitative meanings of Verbal Probability Expressions" Journal of Applied Psychology, 1989* [3]

The mathematical aspect of quantifying confidence has been presented in a previous paper [8}. The method presented in that document evaluates the confidence associated with different tasks performed in the two branches, or components, of an infill concrete frame damage investigation: Observation and Simulation. The variation of scope within each branch is very important in the real world because it offers a spectrum of tasks that can be performed to meet the required service for the project under consideration often at a significant variation in cost. It is possible to obtain a professional estimate of damage using information from any one, or a few, of these information sources, but the confidence the structural engineer has in an opinion rises with an increase in cost and scope of services. It is self evident that the confidence is associated with both the qualifications of the person doing the task and the sophistication of the task. An example of great sophistication is the structural engineering analysis we performed on the 9/11 Collapse of the NYC World Trade Center. An example of a much less sophisticated structural engineering analysis is a one day analysis to determine the lateral displacement of a roof damaged in a hurricane or earthquake using a simple computer model of a building. Quantification in confidence in Observation and Simulation work propagates through the decision-making process to determine the confidence in the final opinion. The confidence in the opinion of the cause of the damage and the required repair is a function of the completeness and competence of the work in each of these two branches.

Perhaps stated more directly the proposed method provides for the uncertainty reduction with expanded scopes of work that could include (1) more field evaluation, (2) more advanced and expensive structural analysis models, and (3) more accurate estimation of site specific future loading, etc. The presented approach has the added benefit of encouraging constructive communication between experts employed by different parties. This is done by requiring the documentation of the assumptions, analysis performed, etc. that were part of the work, identifying common ground and differences, and then perhaps proposing to remove the differences.

The words are now Observation and Simulation. However, the approach is not new. When the senior author visited Chile after the 1968 Chilean Earthquake, as noted earlier, the National Science Foundation funded the members of the project team to not only observe and document damage but to also perform computer models of selected infill concrete buildings with damage.

STEP TWO: THE OBSERVATION PHASE

Observation involves reading the published literature and learning from laboratory tests conducted on infill frames. Books like "Masonry Structures Behaviour and Design" [1] provide very valuable insight to planning and studying the images from photographic documentation of an infill's observed damage. For example, Figures 1 and 2 show basic information about infill frames. Figure 1 shows the different failure modes that must be considered in the observation phase. Also, it illustrates the different cracking patterns that might appear in the field observation. Figure 2 shows the different hysteretic loops for different combination of infill and frame strength. Again it is important in the observation phase to gain as much information as possible to determine this relative strength. The observation phase has a goal of obtaining field information to better understand basic behaviour characteristic of the performance of the frame and the building.

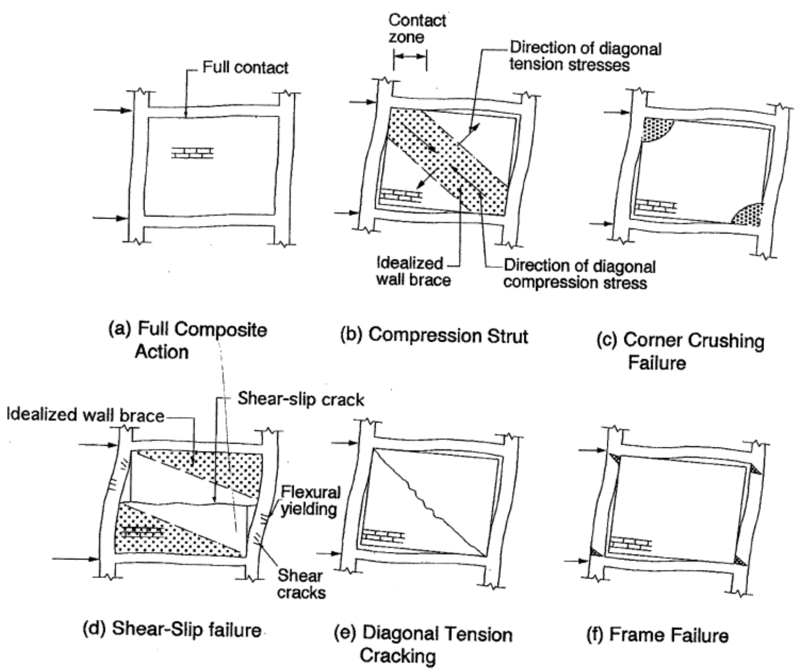

Figure 1: Infill Concrete Frame Failure Modes (Drysdale and Hamid, 2008)

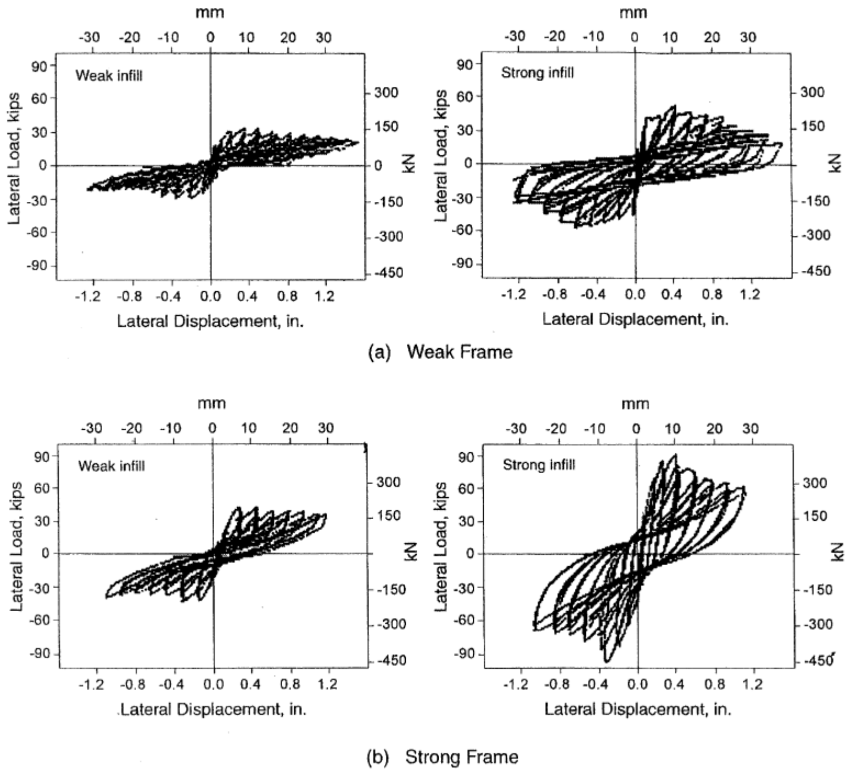

Figure 2: Performance Difference for Different Combinations of Infill and Frame Strength (Mehrabi, Shing and Noland, 1996) [4]

The observation of infill frames after they have either been tested in a laboratory or subjected to hurricane or earthquake loading always provides very valuable information to a structural engineer. A good laboratory test plan combines the professional experience of the test planners and structural engineering analyses of the expected performance of the test specimen. In the controlled environment of a laboratory, the loading that the infill wall is subjected to is usually well known. Therefore, the learning from the test is very important because it tells us how this infill wall is expected to perform in the future if it is subjected to the same loading as in the laboratory. It also provides a way on how we can perform reality checks on our structural engineering modelling.

Hurricanes and earthquakes both cause cyclic loading and a response of an infill concrete frame but the difference is significant. The wind response may be cyclic about a mean offset whereas the earthquake is cyclic about a zero datum, see Figure 3. As we obtain more full scale measurements of wind response of real buildings during severe winds, we may find that the wind has significant cyclic response about the zero datum and the similarity is more evident.

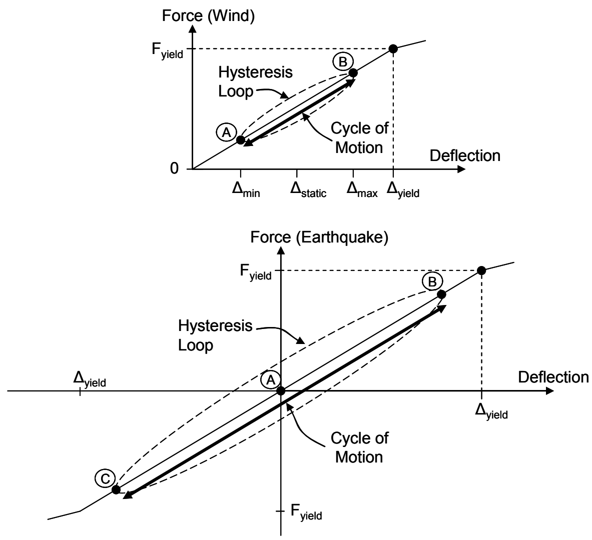

Figure 3: Cyclic Response for Wind and Earthquake

It is also extremely important to utilize appropriate investigation tools during the observation phase. For instance, one important question to answer in the investigation of masonry walls is whether the masonry cells are grouted or not. The spacing of grouted cells is also of interest to verify agreement of as-built condition with the construction documents. This is also valuable information for the simulation phase of the investigation to accurately model the structure. Infrared cameras are excellent tools to detect grouting of masonry walls. These cameras are heat sensitive devices that let you see and measure thermal energy emitted from an object. The products of investigation with an infrared camera are thermographic pictures that can accurately identify areas of solid grouting within a masonry wall, see Figure 4. Another question to answer is whether the masonry wall is reinforced. The authors have successfully used a Micro Covermeter, a metal detector type device designed to locate and determine the size of reinforcing bars, as well as concrete coverage.

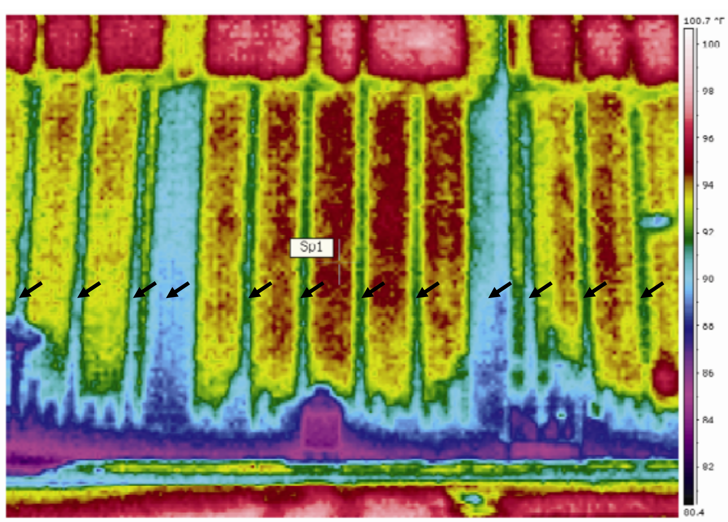

Figure 4: A Thermographic Photograph Taken by an Infrared Camera Shows Areas of Solid Grouting within a Masonry Wall, Note that Arrows Show Cells with Solid Grouting

STEP THREE: THE SIMULATION PHASE

It is essential that a structural analysis must be performed on the infill wall of the building under consideration to determine at a minimum the inter-story drifts during the hurricane or earthquake. This is called the Simulation Phase.

The ability to develop accurate structural engineering models of infill concrete frames has greatly advanced over the last few decades. The senior author recalls developing a structural engineering computer model of a Chilean building with the Chilean engineer Dr. Tomas Gundelman. He also recalls reading the PhD Dissertation of Richard Klingner at the University of California, Berkeley on infill concrete frames. Later on, the National Science Foundation funded the TCCMAR Program under the direction of Dr. James Noland and Dr. Jack Scalzi advancing and offering methods for modelling infill concrete frames. In today's literature of note is the work of Al-Chaar, Mehrabi and Manzouri [5] published in the July 2008 issue of the TMS Journal. It is possible for the structural engineer doing a damage investigation to select from a spectrum of structural engineering models to estimate structural response and performance to fit the clients' budget and required degree of confidence.

Of special note is this regard is the recent FEMA funded Applied Technology Council Project called ATC-63 [6]. The ATC-63 approach directly incorporates uncertainty into the evaluation process and therefore allows the direct use of limited information that comes from a limited budget for such assignments. It is now possible using today's available spectrum of structural engineering analysis (Simulation) options to define the prior condition of the building's infill concrete lateral force resisting system using Observation (laboratory) and Simulation (analytical) tools that have been developed in the last decade. It is also possible to evaluate the damaged building using the same methods. The performance of the damaged building can then be compared with the performance of the pre-event building to the same future events. If rehabilitation is needed then it can be proposed and evaluated until the building is returned at a minimum to its pre-event performance condition. Life safety protection may also require additional rehabilitation.

The Simulation part of the work can tell us many things that provide insight into the type and extent of repairs needed to return the building to its pre event condition. But what do we focus on when we recognize that a building and its infill concrete frame have many limit states?

To illustrate one of the many limit states consider Figure 5. A structural element loses its energy capacity after it experiences a first cycle of response. Therefore, a limit state may be the energy absorbing capacity of the infill wall as a component.

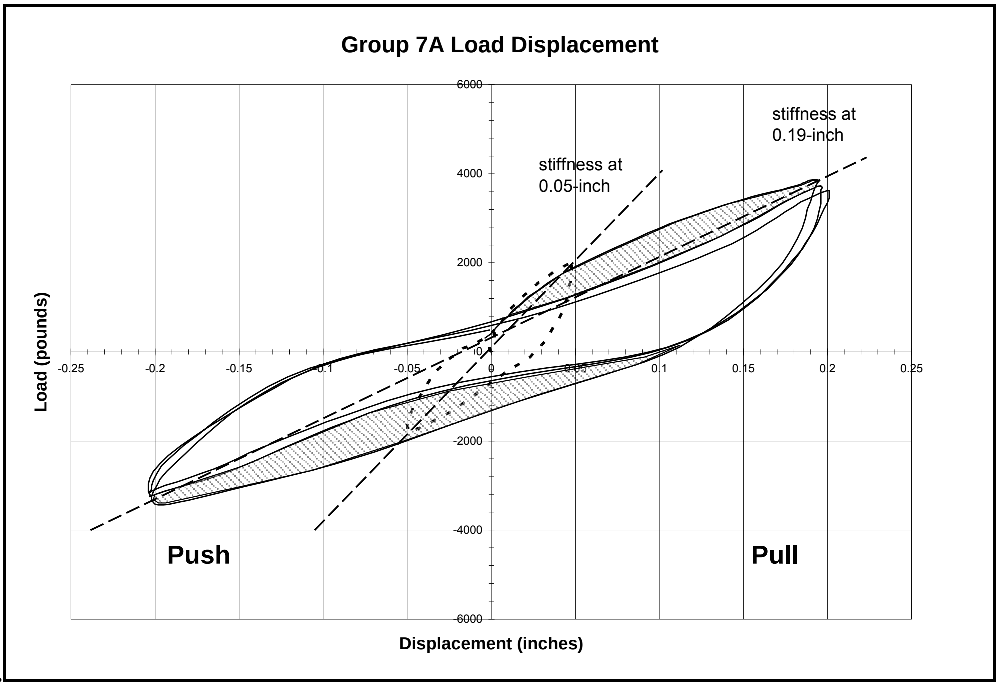

Figure 5: Loss of wall strength and energy capacity up to a defined level of displacement (1 in = 25.4 mm)

Or we can focus on what is commonly called a Fragility Curve, see Figure 6. It shows how the damage from the earthquake changes the fragility curve.

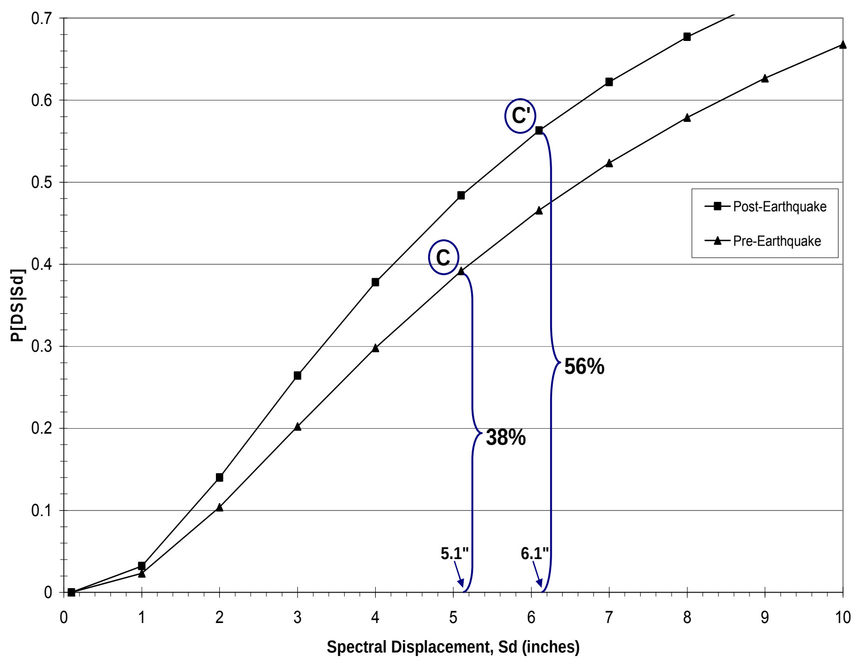

Figure 6: Consider Pre and Post Earthquake Fragility Curve (1 in = 25.4 mm)

Nonlinear computer analysis can be used in the simulation phase to accurately model masonry infilled frames. Such an approach is performed by detailed nonlinear computer modelling of masonry infilled panels (substructure modelling). The advantage of substructure modelling is to obtain an equivalent stiffness of the masonry blocks to use in the elastic global model of the structure. Nonlinear modelling estimates the contribution of masonry walls to the overall building deformation due to lateral loads such as winds and earthquakes.

An example of a nonlinear substructure simulation in a real case investigation is shown in Figure 7. This simulation was performed for a high-rise building with concrete frames infilled with masonry units in hurricane prone zone. The masonry infilled concrete frame panel was modelled using the FEM-I computer program [7]. Figure 7 represents force-displacement response of the panel subjected to monolithic horizontal displacement at the top of panel. The analysis was performed in two steps. First, the concrete frame was modelled without the presence of masonry units. Second, masonry units were added to the frame model and the response was calculated. The difference between response curves of the concrete frame and the combination of frame and masonry yields the force-displacement response of masonry units as shown in Figure 7. The initial slope of the masonry unit response curve was used as the stiffness of the infilled walls in the global computer model. It is clear from the response curves that the overall stiffness of the panel is mainly due to the stiffness of masonry units. Therefore, the stiffness property of the masonry units in the global computer model has a significant impact on the displacement of the computer model of the building. Using the described nonlinear model is a powerful tool in computer simulations for building investigation purposes.

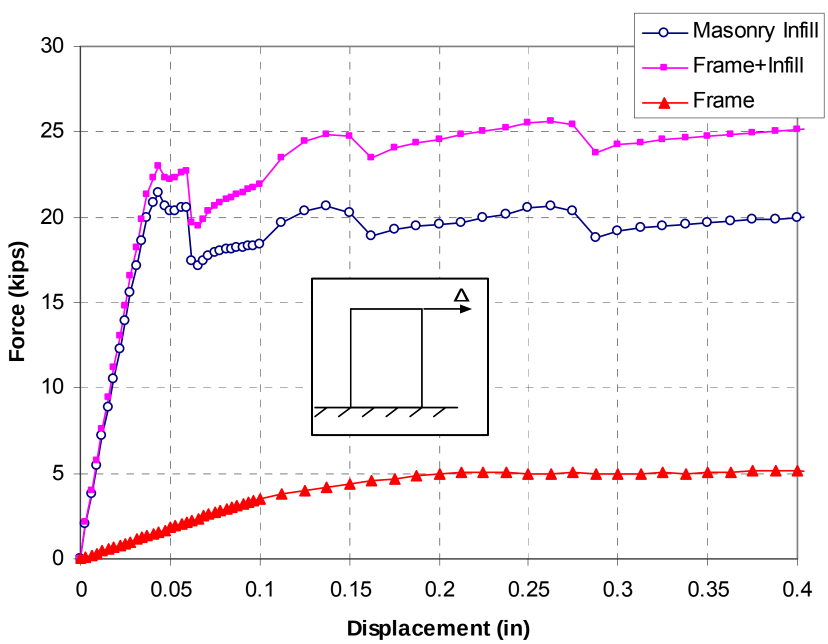

Figure 7: Force-displacement response of the wall panel due to Monotonic Horizontal Displacement at the top of Wall Panel (1 in = 25.4 mm)

STEP FOUR: CONCLUSIONS AND RECOMMENDATIONS
The only question that non-structural engineers typically care about after a building's infill concrete frame is damaged is HOW MUCH WILL IT COST? They want to know: Is the damage caused by the earthquake or hurricane, and how should the damage be repaired? This answer is best left for another paper.

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