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ORDER OUT OF CHAOS: APPLICATION OF EARTHQUAKE DAMAGE ASSESSMENT AND REPAIR GUIDELINES

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ABSTRACT

Assessment and repair of earthquake damage in buildings has, in the past, been fraught with a very high degree of variability primarily because of lack of appropriate guidelines that could consistently be applied by engineers, adjusters, and property owners. This variability was readily apparent in the aftermath of the Northridge Earthquake wherein similar adjacent woodframe buildings had claimed damage and associated repair costs ranging from a few percent to 100 percent of the replacement value of the building. In response to the lack of clear appropriate guidelines, since the Northridge Earthquake guidelines have been developed for post-earthquake damage assessment of steel moment frame connections, masonry and concrete shearwalls, and residential woodframe buildings. While the specific intent of guidelines developed to date has been to improve the practice of post-earthquake damage assessment, the ultimate effect of the proper application of these guidelines could be much broader: a better and more consistent estimation of actual incurred earthquake losses and consequently improved earthquake loss estimation models that rely on loss data from earthquake events. This paper briefly summarizes results of the CUREE Earthquake Damage Assessment project and illustrates the improvement that application of these guidelines could bring to the loss estimation process.

KEYWORDS Structures, Woodframe, Earthquake, Performance, Damage

1. INTRODUCTION

A major surprise of the January 17, 1994, Northridge Earthquake in California was that insured losses to residential, woodframe construction eventually exceeded $15 billion – about seven times initial predictions based on then state-of-the-art portfolio modeling tools. As discussed by Osteraas et al, one of the reasons for the disparity between predictions and actual losses was a disconnect between the damage and loss assumptions implicit in the fragility relationships implemented in the models and the damage assessment and loss adjustment practices that developed in the field. At the time, some of those fragility relationships were likely based on consensus opinion of leading earthquake engineering experts regarding the nature and extent of expected damage and the cost of repair of that damage, similar to the ATC-13 formulation [ATC]. Following the Northridge Earthquake, engineers, contractors, building officials, insurance adjusters, and residential property owners were challenged with the assessment and repair of earthquake damage for a large population of woodframe buildings (on the order of 100,000 buildings). Few involved in the process had the education, training, experience, and understanding of earthquake damage patterns of the group of experts involved in the development of the fragility relationships. Furthermore, those who made the effort to look quickly discovered that there was very little helpful information in the technical literature. Inexperience, poor communication, and the lack of consensus engineering guidelines for investigation, assessment, and repair of earthquake damage to woodframe buildings led to inconsistent and sometimes grossly incorrect engineering assessments, dubious repair recommendations, widespread controversy, and paid losses far in excess of predictions.

For California, the consequences of the poor response to the earthquake were perhaps more disruptive than the earthquake itself; major insurance carriers pulled out of the residential earthquake insurance market, and the State of California had to establish the California Earthquake Authority (CEA) to fill the void in the residential earthquake insurance market. Some portfolio loss modelers adjusted their fragility functions for woodframe buildings to varying degrees based on Northridge Earthquake loss data resulting in higher loss estimates and correspondingly higher earthquake insurance premiums for residential property owners in California.

2. CUREE EARTHQUAKE DAMAGE ASSESSMENT PROJECT

In an effort to substantially improve the response to the next major earthquake in California, the multi-year Earthquake Damage Assessment and Repair project was initiated under the auspices of the Consortium of Universities for Research in Earthquake Engineering (CUREE) to conduct research and develop guidelines for the assessment and repair of earthquake damage in woodframe construction. The ultimate goal of the Earthquake Damage Assessment and Repair project is to improve objectivity and consistency in the infrequent but essential task of post-earthquake damage assessment and repair in woodframe construction. That goal is approached through research work, development of guidelines, and outreach. Research work will lead to better understanding of damage patterns, provide analytical tools for the assessment of damage, and establish the efficacy (or inadequacy) of common repair methods. Development of guidelines will memorialize the best practices utilized for Northridge Earthquake damage assessment and incorporate the results of the research work. Outreach will disseminate knowledge of best practices to those likely to be involved in woodframe damage assessment following future earthquakes.

2.1. Research to Date

The objectives of the project research work were to improve understanding of earthquake damage mechanisms in residential woodframe construction, establish correlations between visible damage and structural response, and to evaluate the efficacy of repair techniques for common types of earthquake damage. Specific research completed to-date is summarized below.

2.1.1. Transient Ground Surface Deformations

One of the more controversial issues that arose from the Northridge Earthquake was the extent to which shallow residential building foundations and at-grade improvements (concrete floor slabs, driveways, sidewalks, patios, pool decks) could be cracked by earthquake ground motions. There are a number of recognized mechanisms that can cause such damage: earthquake-induced ground failure, pre-existing soil conditions that have undermined or stressed improvements, inertial forces generated by the superstructure, and various combinations of these factors. Following the Northridge Earthquake, in the course of scrutinizing property for earthquake damage, cracking of pavement and foundations at sites with stable soil (and often little damage to the superstructure) was widely observed and commonly attributed to ground surface deformation during the earthquake. While there is a widespread belief amongst the general public that earthquakes generate large, damaging waves on the ground surface, there is significant doubt in the earthquake engineering community about this damage mechanism.

To shed some light on the subject, two lines of inquiry were pursued: a workshop to review and summarize the state-of-science in the area of transient ground surface deformations and their effect on at-grade improvements and, based on the guidance of the workshop, development of a methodology to estimate transient ground surface strains.

The ultimate question addressed by the workshop panel was “under what circumstances, if any, should transient ground surface deformations be considered as a potential cause of damage to at-grade improvements?” The general consensus of the workshop panel was that the magnitude of earthquake-induced transient ground surface strains at an arbitrary site can be reasonably estimated given the current state-of-science. Surface strains result from wave passage effects, spatial incoherency of ground motion, and variation of site amplification of the ground motion. An empirical formulation that relates the transient peak ground displacement at a site to the magnitude of transient ground surface strains at the site was proposed by Dr. Norm Abrahamson. The effect of those surface strains on at-grade improvements was expected to be inconsequential, except perhaps in the near fault region where large transient peak ground displacements (and consequently large surface strains) may occur [Gupta et al].

Based on the results of the workshop, work is underway to develop a methodology to quantify the conceptual formulation proposed at the workshop. That work includes analysis of recorded peak ground displacement data from seismic arrays to estimate the ground surface strains (horizontal and vertical), thereby assessing and improving the accuracy of the formulation proposed during the workshop and development of closed form equations to estimate peak transient ground surface strain based on peak ground velocity. That work also includes a limited analytical study of the kinematic soil-structure interaction problem to estimate the levels of strain induce in at-grade improvements, given a peak ground surface strain.

2.1.2. Seismic Compression of Fills

Many of the residential structures affected by the Northridge Earthquake were located in areas of less than ideal soil conditions. Prior to the earthquake, many of those areas were subjected to the long-term effects of expansive soils, slope creep, fill settlement, etc. During the earthquake some of those areas were subjected to landslides, liquefaction, lateral spreading, lurching, and seismic compression of fills. Following the earthquake, engineers were asked to distinguish between the long-term non-earthquake soil effects and damage caused by the earthquake. A particularly challenging problem was distinguishing between long-term settlement and seismic compression (accrual of contractive volumetric strains in unsaturated soil during strong shaking from earthquakes) of fill.

As part of this project, Stewart et al have updated the widely used procedure of Tokimatsu and Seed to incorporate the results of a large number of recent laboratory tests on clean sands, non-plastic silty sands, and low-to medium-plasticity clays. The procedure has been validated relative to three field case history sites with measured settlements and was found to generally provide reasonable, first-order estimates of ground settlements given the simplifying assumptions associated with this approximate method of analysis.

2.1.3. Epoxy Repair of Concrete Slabs-on-Grade and Foundation

Injection of epoxy resins is a generally recognized and widely used method for structural repair of cracks in reinforced concrete structural elements. Based largely on issues of cost and the general absence of any real structural safety (or even serviceability) concerns, epoxy injection has not been widely used for the repair of cracks in unreinforced or lightly reinforced residential concrete. Following the Northridge Earthquake, epoxy injection was commonly suggested for repair of cracks in residential concrete elements that were presumed to have been caused or exacerbated by the earthquake. The use of epoxy injection for this application was challenged primarily on the lack of any testing demonstrating the efficacy of epoxy injection in elements where only one face is accessible. Rather than repair with epoxy, removal of the cracked concrete slabs and foundations in their entirety and replacement with monolithic, “crack free” concrete was recommended in many cases. The cost difference between the two alternatives can be on the order of many tens to hundreds of thousands of dollars.

As part of this project, testing was conducted by the NAHB Research Center on specimens of slabs and stem walls that were repaired under typical field conditions where the crack was accessible from one face only. That testing demonstrated that with appropriate procedures, both the flexural and shear capacities of the repaired specimens reached a level comparable to those of original specimens for cracks ranging in width from hairline to 1/4-inch. That testing also highlighted the importance of quality control and quality assurance to ensure that the cracks are completely filled.

2.1.4. Damage Patterns and Repair of Walls with Openings

Many residential woodframe buildings in California rely, either entirely or in part, upon exterior Portland cement plaster (stucco) and interior gypsum wallboard (drywall) finishes for their lateral support. Thus damage to these elements can have structural as well as cosmetic aspects. Post-Northridge damage assessment of wall elements was chaotic due to lack of good data on the relationship between visible cracking and deterioration of the shear capacity of the stucco and drywall. As a result, complete removal and replacement of stucco was recommended for even minor degrees of cracking. To address those issues, testing of wall panels sheathed only with stucco and drywall and with door and window openings was conducted by Arnold et al.

For the most common wall configurations and boundary conditions, the testing documented damage patterns as a function of story drift; developed correlations between visible indicators of damage and structural condition (strength, stiffness, deterioration); and evaluated the efficacy of various repair methods. It was found that up to story drift ratios of approximately 0.007 finishes remained firmly attached to the framing and were repairable while drift levels above approximately 1.0% resulted in significant strength deterioration and finish damage that was not economically repairable. Commonly used repairs, with minor modifications or more attention to detail were found to be effective: performance of the repaired walls was comparable to that of the undamaged walls.

2.2. Damage Assessment Guidelines

Comprehensive guidelines were developed for the assessment and repair of earthquake damage in residential woodframe construction. The objective of those guidelines is to assist in more accurate, consistent, and objective damage assessment in the aftermath of future earthquakes. The *General Guidelines for the Assessment and Repair of Earthquake Damage in Residential Woodframe Buildings* [CUREE] are intended for a non-engineering audience (property owners, contractors, insurance adjusters) but also provide a good introduction to the topic for engineers without prior experience in the area. A more detailed and technical version directed towards engineers and architects is in progress.

The *Guidelines* cover all aspects of earthquake damage assessment and repair for residential woodframe buildings, including guidance on damage patterns and inspection procedures, structural versus nonstructural damage, repair methodologies, and reporting of findings, as well as guidelines for identification of conditions that indicate potential structural damage and the need to contact an engineer for assistance. The chapters of the *Guidelines* are as follows:

- Introduction
- Characterization of Ground Motion Damage Potential and Structural Vulnerabilities
- Geotechnical Aspects
- Foundations and Slabs-on-Grade
- Wall Elements
- Floors, Ceilings, and Roofs
- Fireplaces and Chimneys
- Mechanical Systems
- Consultant Qualifications / Working with Engineers
- Glossary

The *Guidelines* are available at no cost <http://www.curee.org/projects/woodframe/>

3. FUTURE WORK

The most significant future challenge will be information dissemination and education, of which there are two aspects: awareness and implementation. This paper is part of the effort to address the first aspect: alerting the earthquake engineering community to the existence of this project and the resources available on the CUREE website. In addition, there is much work to be done to make the insurance industry, as well as the various public agencies (California Office of Emergency Services, Federal Emergency Management Agency, Small Business Administration) involved in earthquake disaster response aware of this effort and the resources available. The *Guidelines* can also provide the technical content for earthquake damage assessment training of insurance adjusters (as now required by California law).

Ultimately, given the infrequent nature of earthquakes the biggest challenge will be to see that the results of this work are understood, accepted, and aplied by engineers, property owners, contractors, building officials, and insurance adjusters prior to the next major earthquake in the United States. Perhaps the most significant long-term value of the *Guidelines* is for the collection and codification of relevant research work and lessons learned from each earthquake into a readily accessible source of information for those who will be called upon to respond to the inevitable future earthquakes.

4. APPLICATION TO LOSS MODELING

While it is hoped that the direct effect of the project will be a more rapid and efficient recovery from future major earthquakes in California (with less controversy associated with engineering issues), there are potentially broader implications of the project. The most important long-term potential benefit of this project could be a reduction in earthquake insurance rates. Such a reduction could occur due to the following factors:

1. An improved correlation between earthquake ground motion parameters and structural performance, damage expectations, and repair costs, leading to more accurate modeling and probabilistic assessments of potential insured earthquake losses that typically form the basis of rate making processes;

2. An improved characterization of damage states (e.g., distinction between serious damage requiring engineered repairs versus minor damage requiring cosmetic repairs) leading to a more efficient and consistent distribution of insurance payments; and

3. An improved dissemination and acceptance of research results and evaluation standards leading to reduced need for costly litigation to address adjustment disputes.

As discussed in prior sections of this paper, research completed as part of the CUREE Earthquake Damage Assessment project has clarified the most significant areas of post-Northridge technical controversy for residential woodframe buildings. Translation of those results into practice can have a substantial impact on insured losses in future events. Ultimately, to overcome the significant influence of the Northridge loss data on catastrophe modeling, the benefits of the *Guidelines* will have to be demonstrated in a future major event. A successful demonstration will require awareness and acceptance of the *Guidelines* by all involved in the damage assessment process.

As an example, consider the building shown in Figure 1; a one-story, duplex constructed in the 1970s in southern California. Exterior and interior finishes are stucco and gypsum wallboard, respectively. The sloped roof is weatherproofed with heavy clay tile, and the building is constructed with shallow footings and a slab-on-grade floor. The building is located on essentially flat, geotechnically stable lot and is free of design or construction defects that would significantly affect its seismic performance. In other words, it is a typical California residential woodframe building with no major seismic vulnerabilities. The building is located in an area that experienced an Instrumental Intensity of 7 and a peak ground acceleration of 0.3g during the 1994 Northridge Earthquake. Thus, given the construction features and moderate ground shaking the expectation of damage would, at worst, be nonstructural damage. Following the Northridge Earthquake the building was inspected by two different teams of engineers, contractors, and adjusters. One team found only non-structural damage with an estimated repair cost less than the deductible while the other team projected the cost of earthquake damage repair of the duplex at approximately $500,000.

Detailed inelastic time history analyses of the building structures were carried out, which indicated that the maximum story drift ratio was on the order of 0.0019 for the ground motions representative of the site for the Northridge Earthquake. In other words, the calculated transient drift was in line with expectations given the building construction and ground shaking intensity at the site. Furthermore, the analysis clearly indicated that the response of the building elements (stucco and gypsum sheathed walls) was essentially elastic. Expectations of wall finish performance at the calculated drift levels can be based on research, such as that referenced above, which indicates minor cosmetic cracking at corners of wall finishes (Figure 2). A typical damage observation, minor cracking in the stucco finish is as shown in Figure 3.

Figure 1. Subject building: typical 1970s construction in southern California

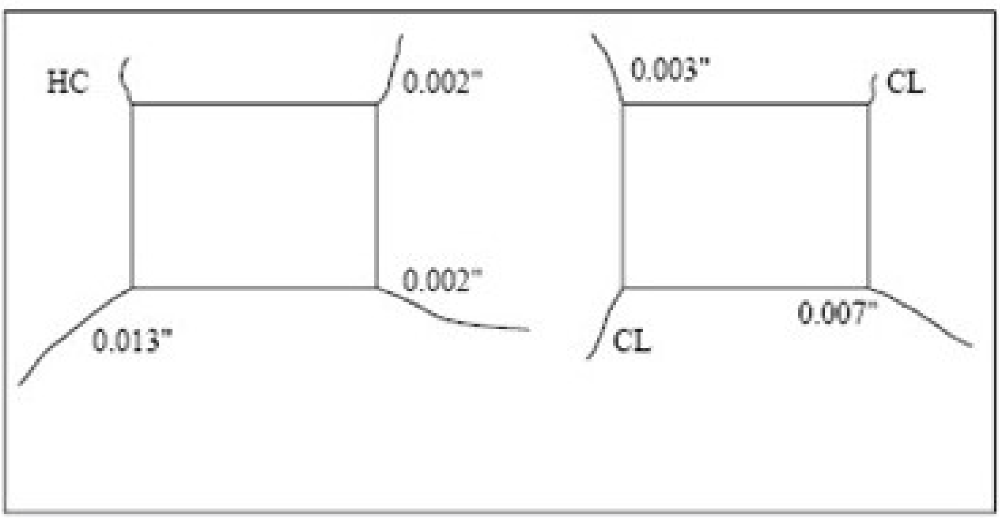

Figure 2. Expected stucco performance at the calculated drift levels.

Figure 3. A typical damage observation: minor cracking in the stucco finish.

Thus, a rational investigation of the performance of the building using elements of the developed *Guidelines* indicated a near elastic response of the building, with no structural damage and very minor nonstructural damage that could easily be addressed through cosmetic patching and painting. Costs associated with such repairs would be minimal as a percentage of the replacement value of the property. The particular property, however, was the subject of multiple investigations and litigation wherein the difference between actual repair costs (to address the nonstructural damage) and the eroneous hypothetical repair costs were on the order of the replacement values of the building and then some to account for engineering and litigation fees. A simple, rational application of the *Guidelines* in the first go around should have resulted in all interested parties arriving at the same result that the damage was minimal. Such information, which would be consistent with analytical expectations, could then easily form the basis of fragility functions that would be used to project future losses and rate setting. The understanding and acceptance of the *Guidelines* by the community holds the potential for improved damage assessment, repair development, loss mitigation, and loss assessment.

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