



DEVELOPMENT OF GUIDELINES FOR ASSESSMENT AND REPAIR OF EARTHQUAKE DAMAGE IN WOODFRAME CONSTRUCTION

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SUMMARY

A major surprise of the January 17, 1994, Northridge Earthquake in California was that the insured losses to residential, woodframe construction eventually exceeded \$15 billion - about seven times initial state-of-the-art predictions. One of the reasons for the disparity between predictions and actual losses was the lack of generally accepted guidelines for the investigation, assessment, and repair of earthquake damage in residential woodframe construction, which resulted in great disparity in the adequacy of property inspections, accuracy of damage assessments, and the nature and scope of recommended repairs. 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.⁵ Research has focused on a) refining understanding of damage mechanisms in woodframe construction, b) establishing correlations between visible damage and structural response, and c) assessing the efficacy of repair techniques for common types of earthquake damage (e.g., stucco and drywall damage). Comprehensive guidelines are being developed for both engineers and non-engineers engaged in the evaluation of earthquake damage in woodframe construction. This paper provides an overview and summarizes the primary results of the research work to-date, the status of the *Guidelines*, and planned future work.

INTRODUCTION

As discussed by Osteraas et al [1], the January 17, 1994, Northridge Earthquake was the first earthquake in which a large numbers of engineers were engaged by insurance companies and property owners to

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⁵ The Earthquake Damage Assessment and Repair project is distinct from the CUREE-Caltech Woodframe project that has recently been completed. The CUREE-Caltech Woodframe project focused on structural performance and implications for design and retrofit, while the current project focuses on damage assessment and repair.

assist in the assessment and repair of damage to single-family woodframe dwellings. Following the 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 a hundred thousand woodframe buildings). Few involved in the process had the requisite education, training, or experience relevant to the task. Those who made the effort to look quickly discovered that there was very little helpful information in the technical literature. As a result, there was great disparity in the adequacy of inspections, accuracy of damage assessments, and the nature and scope of recommended repairs. Inexperience, poor communication, and the lack of consensus engineering guidelines for investigation, assessment, and repair of earthquake damage to wood-frame buildings led to inconsistent and sometimes incorrect engineering assessments, dubious repair recommendations, and widespread controversy. As discussed by Bonowitz et al [2] the insurance industry was likewise unprepared, lacking adjusters with experience in earthquake damage assessment, inspection protocols, and guidelines for working with engineering consultants.

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, the elected insurance commissioner was forced from office, and litigation over earthquake damage claims continues even today, over a decade following the earthquake. The State of California established the California Earthquake Authority (CEA) to fill the void in the residential earthquake insurance market.

PROJECT OVERVIEW

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. The plan is to approach that goal through research work, development of guidelines, and outreach. The 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. The development of guidelines will memorialize the best practices utilized for Northridge Earthquake damage assessment and incorporate the results of the research work. In addition to publication on the CUREE website,⁶ once the research and guidelines are reasonably complete, seminars will be offered to the engineering community in California and other interested groups to provide as broad dissemination of the information as possible.

While it is hoped that the direct effect of the project will be a more rapid economical recovery from future major earthquakes in California (with less controversy associated with engineering issues) there are potentially broader implications of the project. For the most part, the guidelines should be applicable throughout North America as well as in other countries that have adopted similar methods of construction. The most important long-term potential benefit of this project could however, be a reduction in earthquake insurance rates. Such a reduction could occur due to the following factors:

- A better 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,
- A better 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

⁶ <http://www.curee.org/projects/EDA/index.html>

- Better dissemination and acceptance of research results and evaluation standards leading to reduced need for costly litigation to address adjustment disputes.

There are currently two main thrusts of the project: focused research, and development of guidelines. The objectives of the research work are to improve understanding of earthquake damage mechanisms in residential woodframe construction, and to evaluate the efficacy of repair techniques for common types of earthquake damage. Specific research projects undertaken to-date, as well as future planned research are summarized in the following sections. The objective of the second thrust area is to develop and publish comprehensive guidelines for the assessment and repair of earthquake damage in residential woodframe construction. The guidelines will be published in two versions: a detailed engineering version directed towards engineers and architects, and a general version intended for a non-engineering audience (property owners, contractors, insurance adjusters). The status of the development of the guidelines is presented following the research summary.

Virtually all work on the project, including overall project management is performed by subcontractors to CUREE. A twenty-two member advisory group consisting of practicing engineers, engineering professors, architects, specialty contractors, a building official, and experts from various facets of the insurance industry provides guidance and review. In addition, an email list of interested individuals is maintained. Draft material is posted by the project manager for review by the advisory group and interested individuals; comments from the review process are addressed prior to public posting of documents on the CUREE website. Individuals interested in being included on the email list are encouraged to contact the first author of this paper.

Recognizing the necessity and importance of this work the California Earthquake Authority has provided major funding for the project to-date. While the CEA has provided major funding for the project, all work has been conducted by independent researchers working under subcontract to CUREE. The CEA did not direct the work and assumes no responsibility for the ensuing results or publications.

RESEARCH TO-DATE

Potential research topics were identified and prioritized by the advisory group at their first meeting in October 2000. Topics were prioritized based on issues or controversies that arose from adjustment of earthquake insurance claims following the January 17, 1994, Northridge Earthquake, and where there was little or nothing in the literature addressing the particular issue. At the top of the list were four issues:

- Damage assessment and repair of walls where shear resistance is provided only by stucco and drywall.
- Potential for earthquake-induced cracking of concrete slabs-on-grade and foundations at sites that are geotechnically stable (i.e., no ground failure or earthquake-induced permanent ground surface deformation).
- Efficacy of epoxy repair of cracks in concrete slabs-on-grade and foundations.
- Refined understanding of seismic compression of fills.

Results of research work to-date are summarized in the following subsections.

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 drywall finishes for their lateral support. Some of the buildings so constructed were severely damaged and at least one collapsed during the Northridge Earthquake. However, there were tens of thousands more that sustained lower levels of damage. How severe was that

damage and what were the appropriate repairs? The difference in repair cost associated with patch and paint, and removal and replacement of finishes (and associated activities and repairs) could be as high as \$100,000 for a typical dwelling. To compound matters, the City of Los Angeles adopted upgrade requirements based on percentage loss of strength in wall elements and more recently the Uniform Building Code has adopted upgrade requirements based on the cost of repair of structural damage as a percentage of replacement cost. The stakes were high and property owners and insurers turned to engineers for the answers. Unfortunately, in 1994, there was virtually nothing in the literature with respect to damage assessment and repair of earthquake damage in either drywall or stucco. Thus, for any given building, there were widely divergent opinions offered by engineers regarding the extent of damage and appropriate repairs.

To address these issues under this project, testing of wall panels sheathed only with stucco and drywall and with door and window openings was conducted by Arnold et al. [3]. The objectives of this test program were to:

- document damage patterns as a function of story drift
- develop correlations between visible indicators of damage and structural condition (strength, stiffness, deterioration)
- evaluate the efficacy of various repair methods

Testing was conducted on wall panels 8 feet tall by 16 feet long with openings comprising approximately half the length of the wall. All test specimens were cyclically loaded to failure under displacement control using the CUREE loading protocol for woodframe structures developed by Krawinkler [4]. For all but the first set of walls, the loading was conducted in four stages, three of which were repeated following repairs. Detailed reports on the two phases of this testing can be found at the CUREE website. The primary results are summarized as follows:

- The behavior of a stucco-clad wall is highly dependent upon the ratio of the net effective length of the wall to the length of wall attached to the sill plate. Studies by SEAOSC-UCI [5] on solid panels demonstrated that the behavior of the walls was governed by (i.e., the weak link in the system was) the fasteners between the stucco and the wood framing and damage to these fasteners occurred at relatively low load levels, with no visible distress in the stucco finish. In contrast, in Arnold's tests, where the effective shear length of the panel was approximately 50% of the length of the sill attachment, behavior of the walls through much of the loading history was controlled by cracking and deformation of the stucco rather than initial fastener failure, resulting in high ultimate strength (approaching 2000 pounds per foot of effective wall length). Stucco walls with openings behave as a single panel with openings rather than as isolated panels between openings (the common design assumption).
- The pattern of visible cracking is qualitatively correlated with the maximum imposed drift.
- Cracking and structural response of the wall is driven by the maximum imposed drift – smaller trailing cycles do not cause additional damage.
- For walls that have not developed cracks due to shrinkage and temperature fluctuations, fine cracks develop at the corners of openings under very small levels of drift – approximately 0.1%
- Wall behavior is essentially linear up to approximately 0.5% drift.
- Up to drift levels of approximately 0.7% finishes remained firmly attached to the framing and were repairable.
- Drift levels above approximately 1.0% resulted in significant strength deterioration and finish damage that was not economically repairable.
- There were no indications of potential framing damage until the connections between the stucco and the sill plate failed at a drift greater than 0.7%. At that point, shear loads were

- transferred through the studs to the sill plate, damaging the nailed connection between the studs and the sill plate.
- Racking distortions of the panel did not cause rupture or tearing of the building paper beneath the stucco. Building paper was torn when the lower portion of the stucco became detached from the framing at drifts above about 1.0%, allowing relative movement between the exposed furring nails and the building paper.
- 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. See Arnold [3] for more detail regarding repairs.

The first bullet item above represents perhaps the most significant result of the testing. The high strength observed (about eight times the current code allowable and approximately three times the strength based on eight foot square solid panels tested at UC Irvine [5] explains why so many older, non-engineered woodframe buildings with continuous connection at the sill plate and with many small window openings performed so well. From the perspective of damage assessment, the results indicate that there are two damage modes that must be considered: a) cracking of the stucco in those circumstances where the “weak link” is the stucco, and b) fastener failure or delamination in those circumstances where the wall behaves as a single panel without openings (and the effective wall length is small enough to result in the demand exceeding the capacity of the wall).

Testing to-date has addressed the most common wall configurations and boundary conditions. Much can be extrapolated from these results to other configurations. However, it is hoped that in the future additional funding will be available to test a larger matrix of wall configurations.

Transient Ground Surface Deformations Workshop

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 damaged (i.e., 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 universally 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.

In an effort to shed some light on the subject, a workshop was held in May 2003 in Oakland, California, USA, to review and summarize the state-of-science in the area of transient ground surface deformations and their effect on at-grade improvements; CUREE [6]. The primary objective of the workshop was to identify if, and under what conditions, transient ground surface deformations may have an adverse effect on at-grade improvements. Of special interest are the effects these surface deformations may have on residential slabs and foundations. The ultimate question to be addressed in this workshop was “Under what circumstances, if any, should transient ground surface deformations be considered as a potential cause of damage to at-grade improvements?” More specifically, the questions to be addressed during the workshop were:

- Can the magnitude of earthquake-induced transient ground surface strains at an arbitrary site be reasonably estimated given the current state-of-science?

- If so, what is necessary to develop an efficient methodology to relate common measures of ground motion to the magnitude of transient ground surface strains?
- If not, what research is needed to develop such a capability?
- What is the nature of earthquake-induced transient ground surface strains experienced at a given site with stable soil (i.e. no earthquake-induced ground failure)?
- What is the nature of demands (force and deformation) due to earthquake-induced transient ground surface strains on a concrete plate on the ground surface that is the size of a typical residential slab (less than 100 ft/30 m in any dimension)?
- Is it possible, given the current state-of-science, to identify any correlation between intensity of ground shaking (MMI or instrumental intensity) and potential for damaging earthquake-induced ground surface deformations?

Four distinguished panelists were invited to present and discuss the state-of-science addressing the foregoing questions. The panelists were Professor Bruce Bolt (University of California at Berkeley, Workshop Chair), Dr. Paul Somerville (URS Corporation), Dr. Norman Abrahamson (Pacific Gas & Electric Company), and Professor Aspasia Zerva (Drexel University).

The primary conclusions reached during the workshop include the following:

- The reported observations of visible waves on the ground surface during strong ground shaking cannot be explained from a seismological perspective, as fundamentally the wave speeds for both body and surface waves are too high for the waves to be visible to the human eye. Under special circumstances where the ground is extremely soft, it may be possible to observe the surface waves, however these waves would likely not be damaging to at-grade improvements, as the wavelength of these waves would be expected to be much larger than the dimensions of the at-grade improvements.
- Peak strains at the ground surface are caused by direct S-waves (shear waves) as opposed to surface waves.
- Conceptually, the general consensus was that the effect of surface strains on at-grade improvements would be inconsequential, except perhaps in the near fault region where large transient peak ground displacements (and consequently large surface strains) may occur.
- 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. Norman Abrahamson during the workshop.
- The discussion at the workshop focused on ground surface strains and stopped short of transferring ground surface strains into at-grade improvements. Determination of the force and deformation demands on at-grade improvements from the ground surface strains is a kinematic soil-structure interaction problem that requires further research.
- While suggestions were made regarding identifying correlations between intensity of ground shaking or peak ground accelerations and potential for damaging earthquake-induced ground surface deformations, it was felt that the transient peak ground displacement or velocity provide more appropriate and easily obtainable scientific measures that should be used to estimate the ground surface strains.

Based on the presentations and discussions certain topics were identified that require additional research and development efforts in order to better understand, implement, and disseminate the information related

to the effect of transient ground surface strains on at-grade improvements. The identified topics include the following:

- 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. The analysis could be extended to cover different site soil conditions depending on the nature and extent of data available.
- Translation of the ground surface strain estimates to force and deformation demands on at-grade improvements. This involves addressing the kinematic soil-structure interaction problem through numerical modeling.
- Development of a methodology and its implementation to produce transient peak ground displacement maps similar to the rapid post-event instrumental intensity, peak ground acceleration and velocity maps produced by the U.S. Geological Survey.
- A study to assess the damage potential of transient surface strains to at-grade improvements located at cut/fill intersections. Instrumentation of cut/fill intersections to assess the ground motion variability across these intersections.
- Instrumentation of typical at-grade improvements located over stable soil, which would provide a direct measure of the demands induced in these improvements during strong ground shaking.

Epoxy Repair of Concrete Slabs-on-Grade and Foundations

Injection of epoxy resins is a generally recognized and widely used method of 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 widely suggested by insurers for repair of cracks (virtually all of which were presumed to have been caused or exacerbated by the earthquake) in residential concrete elements.⁷ The use of epoxy injection for this application was challenged on various fronts and often derided as “glue” or a “band-aid.” 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 by some engineers. The cost difference between the two alternatives ranges from tens to hundreds of thousands of dollars.

The issue to be addressed with this research task is the efficacy of epoxy injection repair of cracks in unreinforced concrete under the circumstances frequently encountered in residential construction. The primary constraint in most residential applications is that access is limited to only one side of the element. In typical structural applications, all faces of the element are accessible and may be sealed.

For this study by the NAHB Research Center [7], a total of 18 stem wall and 18 slab test specimens were constructed, cracked in flexure in a universal testing machine, crack widths adjusted to a predefined value (hairline, 1/8 inch, 1/4 inch), placed outdoors on a sand bed (slabs) or backfilled with sand (stemwalls), repaired via epoxy injection, and retested to failure.

⁷ Crack control methodologies are not generally employed in the construction of residential foundations and floor slabs. Thus, observable cracking in stem walls and slab-on-grade floors is common and is primarily attributable to concrete shrinkage and differential settlement. Such cracks are typically ignored unless they lead to other problems. Obviously, it is desirable to repair cracks that compromise the structural performance of the foundation, although the circumstances under which that performance is compromised are not well defined. Sealing of cracks may also be desired to prevent moisture, pest, and/or potential radon infiltration into the residence.

The results of this testing demonstrated that when the cracks were completely filled with epoxy, both the flexural and shear capacities of the repaired specimens were comparable to those of original, uncracked specimens. The testing also demonstrated that cracks can be satisfactorily repaired when accessible from only one side. However, the testing also highlighted the importance of quality control and quality assurance to ensure that the cracks are completely filled. Accordingly, recommendations for Q/C and Q/A have been included in the *Guidelines*.

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 these areas were subjected to the long-term effects of expansive soils, slope creep, fill settlement, etc. During the earthquake some of these areas were subjected to landsliding, 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 fill settlement and seismic compression of fill.

Seismic compression is the accrual of contractive volumetric strains in unsaturated soil during strong shaking from earthquakes. As part of this project, Stewart et al [8] have developed a preliminary simplified procedure for estimating ground displacements from seismic compression in compacted fill. The procedure has three steps: (1) estimation of shear strain amplitude within the fill soil mass from the peak acceleration at the ground surface and other seismological and site parameters; (2) estimation of volumetric strains within the fill mass based on compaction conditions in the fill, the shear strain amplitude, and the equivalent number of uniform strain cycles; and (3) integration of volumetric strains across the fill section to estimate settlement. The framework of the present procedure is similar to that of Tokimatsu and Seed [9], which is strictly applicable only to clean sands. Stewart and Whang [10] updated that widely used procedure 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.

GUIDELINES STATUS

The ultimate goal of this project is the publication of *Guidelines for the Assessment and Repair of Earthquake Damage in Residential Woodframe Buildings*, herein referred to as *Guidelines*. It is intended that the *Guidelines* will cover all aspects of earthquake damage assessment and repair, including guidance on damage patterns and inspection procedures, structural versus non-structural damage, repair methodologies, and reporting of findings. The chapter outline of the *Guidelines* is as follows:

1. Introduction
2. Consultant Qualifications / Working with Engineers
3. Characterization of Ground Motion Damage Potential and Structural Vulnerabilities
4. Geotechnical Aspects
5. Foundations and Slabs-on-Grade
6. Wall Elements
7. Floors, Ceilings, and Roofs
8. Framing
9. Fireplaces and Chimneys
10. Mechanical Systems

11. Glossary

Two versions of the Guidelines will be published: *Engineering Guidelines* directed at engineering consultants and building officials and *General Guidelines* directed at a non-engineering audience (property owners, contractors, insurance adjusters). The *Engineering Guidelines* will provide detailed direction and background for engineering assessment and repair of structural and non-structural damage, along with references to relevant literature. The *General Guidelines* will provide direction for the assessment and repair of non-structural damage as well as guidelines for visual inspection and conditions that indicate potential structural damage and the need to contact an engineer for assistance.

As of this writing (February 2004) Sections 1, 2, 5, and 6 of the General Guidelines have been published on the CUREE [11] website.

FUTURE WORK

In addition to the accomplishments summarized above, the work to-date has most importantly established needs and priorities for research work as well as a framework for readily reducing research results to usable guidelines and making that information available to both the engineering community and the public at-large. There are three facets of future work: research/testing, guideline development, and education/dissemination of information.

Two areas of research and testing work are planned for the near future: ongoing research on seismic compression of fills, as described above to extend the results to a broader range of materials, and detailed study of the effects of transient ground surface strains to build upon the results of the workshop and develop guidelines regarding evaluation of the potential effects of transient ground surface strains on at-grade improvements. Longer-term, there is much work that could be done testing walls with openings sheathed with various combinations and variations of common construction materials.

In addition to the several chapters of the *General Guidelines* already published and the engineering guidelines for geotechnical aspects that were nearing completion as this paper went to press, development of engineering guidelines for foundations and wall elements is underway. Development of the remaining chapters must await future funding.

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. Longer-term, when the engineering guidelines are reasonably complete, seminars are contemplated to educate the engineering community. 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 made available to and understood by engineers, property owners, contractors, building officials, and insurance adjusters following the next major earthquake in the U.S. 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

engineers, owners, contractors, and insurances adjusters who will be called upon to respond to the inevitable, but infrequent future earthquakes.

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