Crack Mapping for the Analysis of Complex Shear Wall Systems

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Abstract

This project explores the creation of crack maps as a tool to analyze the damage mechanisms and characteristics of reinforced concrete shear walls. The objective is to use crack maps as an aid in the future development of performance-based design tools so that practicing structural engineers will have a model of wall response vs. load. The crack maps are created in conjunction with photogrammetric techniques and are made using a series of high-resolution images gathered from six cameras around the specimen. The final result of the crack-mapping process is a video that synchronously shows the loading protocol and the current deformed wall state.
Table of Contents

Abstract ........................................................................................................................................... 1
1. Introduction ................................................................................................................................. 3
  1.1. Background .......................................................................................................................... 3
  1.2. Research Objectives ............................................................................................................. 4
  1.3. Literature Review .................................................................................................................. 4
2. Methods ....................................................................................................................................... 6
  2.1. Photogrammetry .................................................................................................................... 6
  2.2. Image Manipulation ............................................................................................................. 8
3. Results ......................................................................................................................................... 10
  3.1. Final Crack Maps ............................................................................................................... 10
  3.2. Movie .................................................................................................................................... 11
4. Conclusion .................................................................................................................................... 12
5. References ................................................................................................................................. 13
6. Acknowledgements .................................................................................................................... 15
1. Introduction

1.1 Background

Shear walls are the most common form of lateral load resistance in new and retrofit reinforced concrete structures. Despite their prevalence in concrete construction (Figure 1), practicing engineers have very few tools available to them to simulate wall response under load. The NEES project, “Seismic Behavior, Analysis and Design of Complex Wall Systems”, seeks to create performance-based design tools through the experimental testing of 9 reinforced concrete shear walls. The walls are tested using hybrid simulation using the University of Illinois’ advanced MUST-SIM facility. Analyses will explore the impacts of soil-structure interaction, bi-directional loading, and complex geometries on wall damage mechanisms such as concrete cracking and spalling. One aspect of these analyses are detailed crack maps, which provide a qualitative illustration of wall damage in relation to time, and thus the engineering demands on the specimen. While seemingly very primitive, crack maps are not used all that often as a tool for observing the development of concrete damage and thus few refined methods exist for creating them. Despite their omission from many investigations into reinforced concrete behavior, crack maps can be a valuable tool when used in conjunction with the myriad other measurement techniques utilized in advanced experiments.

Figure 1. Typical use of concrete shear walls
1.2 Research Objectives

The primary objective of this portion of the project is to develop comprehensive crack maps for use in the analysis of the 9 concrete wall specimens. These crack maps will serve as another measurement available to help in the post-processing and the eventual development of working performance-based design tools for designers in the industry. This project will explore concrete damage mechanics far more than any previous experiment.

1.3 Literature Review

There have been a number of studies exploring the response of walls during seismic events, but most have been extremely limited by the inadequacies of their laboratory facilities. Previous experiments have used simple wall geometries, simple loadings, inaccurate boundary conditions, and planar load histories, all of which will be further developed in this study. One such study (Lefas and Kotsovos 1990) tested thirteen scale wall models while investigating the effects of parameters such as height-to-width ratio, axial load, concrete strength, and amount of web reinforcement on the behavior of shear walls. The results of this study were useful in identifying the causes of wall failure and the mechanics of shear resistance. However, the study considered only planar walls with only fixed-base boundary conditions, meaning that the results are not fully applicable to real-world structural walls. In addition, the results did not provide sufficient quantitative data to develop accurate performance models. Another, similar study (Tasnimi, A.A. 2000) was conducted on four one-eighth scale planar walls with identical properties. The only variable was the type of slow, reversed cyclic lateral displacement. Again, in this experiment, the full, in-depth behavior of a real-world wall cannot be experienced due to limitations of the testing equipment.

There are a select few studies addressing more complex wall geometries, slenderness, and advanced loading conditions. Some researchers have evaluated the impact of slenderness by simulating axial demands from upper stories (Vallesas 1979). This experiment analyzed results in terms of hysteretic properties such as strength, deformation, and energy dissipation, as well as constructability and failure mechanics. One shortcoming is that most such studies have not incorporated variation in upper-story demands or the impact of moment distribution on wall response, as this study will.
Several analytical investigations have considered the effects of foundation flexibility and have determined that this parameter impacts dynamic characteristics of the wall, stress distribution, and foundation demands (Chaallal and Ghlamallah 1996 and Fillatrault et al. 1992). These studies are not confirmed either experimentally or using field data, therefore the influence of flexibility at the wall base is largely unknown.

A survey of practicing engineers suggests that advanced research needs to be directed at the issues of vertical load distribution, moment gradients, soil-structure interaction, flexible foundations, three-dimensional configurations, and bi-directional loading in order to develop performance-based design tools. Previous analytical research has attempted to investigate some of these parameters using a variety of modeling approaches. The results of these studies indicate that high-resolution finite-element models can be quite effective in predicting observed behavior (Bolander and Wight 1991, Sittipunt and Wood 1993, Reynouard and Fardis 2001), including load-displacement history, damage distribution, and response mechanics. However, these results do not include verification of the models for broad ranges of configurations nor do they include provisions for using simplified versions of the models to support design. These studies have lacked high-resolution experimental data to validate predictions of local damage mechanisms. Therefore, further research is required to create more comprehensive models incorporating complex geometries and advanced loading, as in this project (Figure 2).

![Figure 2. Proposed experimental specimens](image)

Previous research has also investigated the accuracy of using simplified nonlinear beam-column elements to predict wall response. Experimental data has verified that flexural strength of rectangular walls can be predicted to some
precision using classical beam theory (Pilakoutas and Elnashai 1995, Paulay and Goodsr 1985). Previous studies have also suggested that simple nonlinear line-element models can be calibrated to meet observed response simulations (Bolander and Wight 1991). The applicability of these results is drawn into question by the fact that no provisions or recommendations are given for model calibration with complex wall geometries and loadings.

Finally, some previous effort has been put into developing performance-based design tools. To develop truly useful design-centric models, engineers require that predicted demand parameters be linked to damage measures. Previous research has begun to develop such models for reinforced concrete columns (Lehman 2004), but little development has been attempted for structural walls, and analysis cannot progress without significantly more advanced experimental data than currently exists.

2. Methods

2.1 Photogrammetry

Photogrammetry is the method of determining the physical dimensions of an object through photographs. Photogrammetry works by using multiple images to gather information about the geometry and scale of an image. In order to utilize it, coded targets which can be identified digitally must be physically attached to the wall (Figure 3). By using multiple photos of each target from varying angles and heights, software such as PhotoModeler (used in this project) can identify the targets and compare their appearance in the different photos to triangulate the points and measure distances. Depending on the specifics of the photography equipment and the targets in use, this technique can produce measurements that are accurate to thousandths of an inch.
This method had several important applications to the project. First, PhotoModeler was used to create an orthographic projection of the wall surface. This projection is based on the photogrammetric targets’ locations on the wall and results in a perfectly proportioned base-image (Figure 4), which can be used to apply projective transformations to all of the experimental images. The second application utilized the accuracy of the method to find gage distances between photogrammetric targets for future strain measurements (Figure 5). Since some of the targets were mounted to the linear potentiometer posts embedded in the concrete, the software could measure the initial, un-deformed lengths of these gauges.
2.2 Image Manipulation

Before the raw images can be used for crack mapping, they must be transformed to a more usable form. The base images that were gathered from each load step...
during the experiment split the wall specimen into six equal sectors. The photos were gathered from six cameras mounted to rigid I-beams securely fastened to the strong floor of the MUST-SIM facility. The cameras were oriented in a manner such that each was roughly the same distance from the center of its respective sector. This was important because the parameters of the cameras, including focal length, had to be identical in all six photos for the lens correction to work for all of the images.

The ultimate goal of the image manipulations was to create a single, full-sized, high-resolution image for each step with near-perfect continuity at the seams. In order to achieve this, it was crucial that the lens distortion be removed from the raw photos. Lens distortion is a phenomenon inherent to all cameras due to the rounded shape of the optical element used to focus the light. The distortion results in a barreling effect that makes objects near the center of the frame appear larger and objects approaching the edge of the frame taper off. This is undesirable in this case since we need all of the straight lines on the specimen, i.e. the seams between sectors, to remain straight. To remove the lens distortion, a lens correction map, specific to the cameras used during the experiment, was created with a MATLAB script called “Undistort” by Harri Ojanen (Figure 6).

![Figure 6. Before and after the lens correction](image)

Note: the left-hand edge of the wall becomes straight

Once the images were corrected, they need to be mapped to their proper position on the total wall specimen photo. This is done by correlating the photogrammetry targets seen on each raw photo to their counterparts from the base-image created with PhotoModeler. By doing this in Matlab, the function `tform` could be used to
create a linear transformation matrix that remaps the pixels from the raw photo, taken from an angle, to their actual orientation on the wall specimen. After that, a simple MATLAB code can be used to reposition each of the raw photos and stitch them together to form a single, high-resolution photo of the entire wall (Figure 7).

Figure 7. The compiled total image

3. Results

3.1 Final Crack Maps

Several possible methods were explored for the actual extraction of the crack information from the experimental photos. A differential method was tried, in which an original, undistorted image is overlaid with an image showing concrete damage and the difference between the two photos is extracted. The resulting image from this trial was extremely noisy and generally unusable in terms of being able to gather practical information from it. Ultimately, the decision was made to manually trace the cracks in a Photoshop document. Although this route was more labor intensive, it was simple, reliable and offered numerous benefits, such as the ability to easily separate out the black & white cracked image layer from the base jpeg. In addition, it was much easier to differentiate between the cracks that propagated and developed from the two different loading directions. The desired final result was a
very clean and simple image (Figure 8) that would allow for simple post-processing to extract information about crack spacing, crack angles, and crack widths.

![The extracted crack map](image)

**Figure 8.** The extracted crack map

### 3.2 Movie

Another application of the crack maps aside from extracting physical information was to use them as a simple qualitative illustration of wall damage vs. time and engineering demands. The product was a movie that simultaneously shows the loading protocol of the wall experiment, in the form of a base shear-top displacement plot, with the extracted crack layers (Figure 9). When these two are shown at the same time, it really gives a sense of how the cracks develop and propagate with respect to the motion and forces of the wall. When all of the movies from the wall specimens are compared, it is relatively easy to see the difference between their behaviors with large shear forces and displacements.
4. Conclusion

The results showed that at the very least, crack maps can be useful as tools for qualitative interpretation of the wall specimens’ behavior. In terms of applications to the analysis of wall damage mechanisms, there is still work to be done in terms of combining methods to get practical information from the cracked image. The crack maps would have to be used in conjunction with another measurement system such as Krypton LEDs or photogrammetry in order to gather useful information about stress and strain on the wall surface. For example, since the location of a crack on the wall surface is known, an analysis could be done using the closest Krypton LED on each side of the crack to determine how far the points have separated, which in turn shows the stress conditions necessary for crack development and widening. Future work will be concerned with establishing successful methods for interpreting the data contained in the crack maps, automating the creation of the crack maps, and finding a logical way to map cracks for the future, 3-dimensional specimens. In conclusion, reinforced concrete crack maps have some usefulness as visual tools for general interpretations of wall damage vs. engineering demands, but they have the potential to be extremely useful as a redundant measurement system for monitoring stress and strain. They could serve as the primary indicator of concrete surface damage, which is one of the main objectives of the overall project.
5. References


6. Acknowledgements

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