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Understanding Concrete Building Vulnerability: Developing a Database of Critical Deficiencies

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Introduction

The Earthquake Engineering Research Institute (EERI) is the leading partner in the Concrete Coalition, a network of individuals, governments, institutions, and agencies with a shared interest in assessing the risk associated with dangerous nonductile concrete buildings and developing strategies for fixing them. Poor seismic performance of primarily older concrete buildings has been demonstrated dramatically in recent earthquakes. Buildings designed with insufficient detailing to resist seismic loads, referred to as nonductile, pose a significant life safety, economic and community risk. In particular, loss of life is a highly likely outcome when these buildings collapse, as evidenced in a number of earthquakes including San Fernando, California (1971); Chi Chi, Taiwan (1999); Kocaeli, Turkey (1999); Sichuan, China (2008); Haiti (2010) and even New Zealand (2011). Older concrete buildings without ductile detailing can be found throughout the United States and the world. A scenario based on a repeat of the San Francisco 1906 event in the San Francisco Bay Area today confirms that a large proportion of the deaths and serious injuries would be attributable to the collapse of nonductile concrete buildings [1].

Thousands of these dangerous concrete buildings pose a major risk in regions of high seismicity around the world. But the reliable prediction of "which ones" is elusive for several reasons. First the structural vulnerability characteristics of these buildings are not consistent. Reinforced concrete buildings are constructed with a wide range of structural systems which include moment frames, bearing walls, in-fills, and combinations of these. Performance of these structures is a function of the seismic deficiencies of multiple structural systems and their complex interaction. Second, reinforced concrete building components are not standardized with respect to design and construction making the deficiencies highly difficult to predict. Third, construction quality in concrete is highly variable in the US and throughout the world. Finally, the complex variability of system characteristics, deficiencies, and design and construction quality are not adequately represented by existing empirical tests or by systematic observation of performance in earthquakes. Understanding how many of these buildings might exist and which ones represent the greatest risk has been the focus of the Concrete Coalition.

Background

In order to begin to address the lack of systematic observations of performance of reinforced concrete buildings in earthquakes, the Concrete Coalition supplemented inventory work conducted in 2009 and 2010 in California, and started to compile and standardize observations from previous earthquakes.

Funding support from the U.S. Geological Survey supported the development a database of damaged concrete buildings. The original intent was to develop and populate a database of photographs from past earthquakes illustrating the common deficiencies that contribute to collapse of concrete buildings. The large inventory of images available from the EERI Learning from Earthquakes program, accumulated over the past 30 years in over 240 events, was to have been the primary source of damage photos. The intent was to categorize images according to type of deficiency. The Concrete Coalition had previously developed a list of typical deficiencies (e.g. weak stories, shear critical columns, pounding) to use as a starting point for sorting the material. It quickly became evident that without information on the building in the photograph it was impossible to identify the deficiencies, or to make a statement about the role of the deficiency in the damage experienced by the building.

Thus the project was modified to identify specific damaged concrete buildings and to systematically collect information on each building's performance, including sketches, drawings and information on retrofit. This information was then entered into a searchable database, developed as part of this project. The ultimate goal for the project was a credible and accessible online database of concrete building performance in past earthquakes. The initial database is now complete. As this database is further populated, it will be able to help analysts understand the relative importance of deficiencies with respect to collapse and performance more generally.

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The Process

Data Collection

The first step in developing the database was to outline the information to be collected. This process was guided by Concrete Coalition Technical Director, Craig Comartin. A total of 295 fields were identified for collection. These fields ranged from basic building information and earthquake ground motion characteristics to information on repair and retrofit of the buildings. A complete list of the fields in the database is included in Appendix A. An important data subset in these 295 fields is the list of 53 design and construction characteristics.

Once all fields were identified and finalized, a data collection system was developed. In order to collect the data for each building, an interactive pdf form was developed that was used for data entry. The form was designed to maintain uniformity between buildings. The use of drop-down menus and discussion of data formats for each field helped to ensure that data was uniform across all buildings in the database.

Data collection was completed by four summer interns in 2012: Sarah Bettinger, University of Alabama, Birmingham; Edwin Lim, Georgia Tech; Quinn Peck, Santa Clara University and their work was coordinated by Maggie Ortiz, EERI program associate and Jonathon Tai, graduate intern. The interns compiled an initial list of buildings for the database by reviewing special issues of Earthquake Spectra, EERI reconnaissance reports, and the EERI reconnaissance photo collections. Once the list of buildings was established, each intern selected individual buildings to research in more depth. For each building, additional reports, published articles, and personal resources from industry mentors served as additional resources. In addition to recording the basic information for each building, the interns scoured source materials for discussions of the role that the 53 design and construction characteristics may have played in the building's performance. For each characteristic, they indicated its contribution to observed damage as unlikely; possible; likely; unknown (no discussion in the sources), or not applicable (meaning that the particular characteristic was not present or otherwise not relevant for the particular building). Data for each case study was recorded in a fillable pdf form, included as Appendix B.

For each case study, the interns worked closely with professionals who were either part of a reconnaissance team after the relevant earthquake or conducted in-depth studies on the buildings of interest. The interns were not expected to conduct analyses themselves, but rather to report on what the published literature and their mentors suggested were contributing factors. After case studies were completed, they were reviewed by industry mentors for completeness and accuracy.

Integrated Mentoring Component

An exciting innovation in this project was the interaction of mentors and reviewers from California firms as well as several EERI members throughout the world. Throughout the summer, interns met at least weekly with mentors to discuss individual buildings, as well as reconnaissance observations in general. The interns also met several times with all the mentors together, in Northern and in Southern California. Mentors made presentations about buildings they were working on and discussed the damage visible in photos. Mentors also offered additional buildings that their firms had evaluated and/or retrofit for inclusion in the database. This type of "insider" knowledge proved very valuable both in identifying buildings for consideration and in helping the interns complete the case studies. In addition, mentors reviewed the individual building reports prepared by the interns. The opportunity for interaction with so many practicing engineers was given by the student interns as one of the learning highlights of the summer.

Coordination with the Applied Technology Council

Data were collected in coordination with the ATC 95 project, Development of a Collapse Indicator Methodology for Existing Reinforced Concrete Buildings, where experts assembled information on buildings that have collapsed in past earthquakes, primarily in California and New Zealand. While the ATC-95 project focused exclusively on

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collapsed buildings, the EERI interns and mentors worked with buildings that had varying levels of damage from many countries, including developing countries, the U.S. and New Zealand. Both projects collected data that included detailed information on the building itself. The ATC experts focused on identifying the damage that led to collapse, and the characteristics of the event that caused the damage. EERI interns identified the wide range of building characteristics in such a way that future analysis will be possible. Information was drawn from reports, drawings, photographs, and meetings with mentors and reviewers in an effort to provide insight into the important aspects of the performance of these concrete buildings.

The Online Database

The data in the case studies completed by the interns has all been uploaded into the online database titled, "Concrete Buildings Damaged in Earthquakes: A Collection of Case Studies". The database was developed specifically for online viewing and is accessible here: db.concretecoalition.org. As an online database, it is freely available to anyone and features high resolution color images and detailed information for 52 case studies from 10 countries. The buildings were damaged in twenty different earthquakes. Table 1 summarizes the countries and lateral load resisting systems of the buildings in the database.

Table 1. Damaged Concrete Buildings Reports Available

COUNTRY	LATERAL LOAD SYSTEMS OF DAMAGED BUILDINGS (where known)
Algeria	Frames with Masonry Infill
Armenia	Moment Frame & Shear wall combo
	Precast concrete
Haiti	Frames with Masonry Infill
	Moment Frame
	Shear wallrete
India	Shear wallrete
	Frames with Masonry Infill
Indonesia	Frames with Masonry Infill
	Moment Frame
Mexico	Moment Frame & Shear Wall combo
	Frames with Masonry Infill
	Moment Frame
New Zealand	Moment Frame
	Moment Frame and Shear Wall combo
	Shear wallrete
Peru	Frames with Masonry Infill
Turkey	Moment Frame
	Moment Frame and Shear Wall combo
U.S.	Moment Frame
	Moment Frame and Shear Wall combo
	Frames with Masonry Infill
	Shear wallrete

Landing Page

The homepage of the database features a slideshow of reconnaissance photos of damaged concrete buildings and a map showing the geographic locations of the 52 case study buildings. The homepage also includes background information about the project, a search form, and a quick link to all buildings in the database. Figure 1 is a screenshot of the database homepage.

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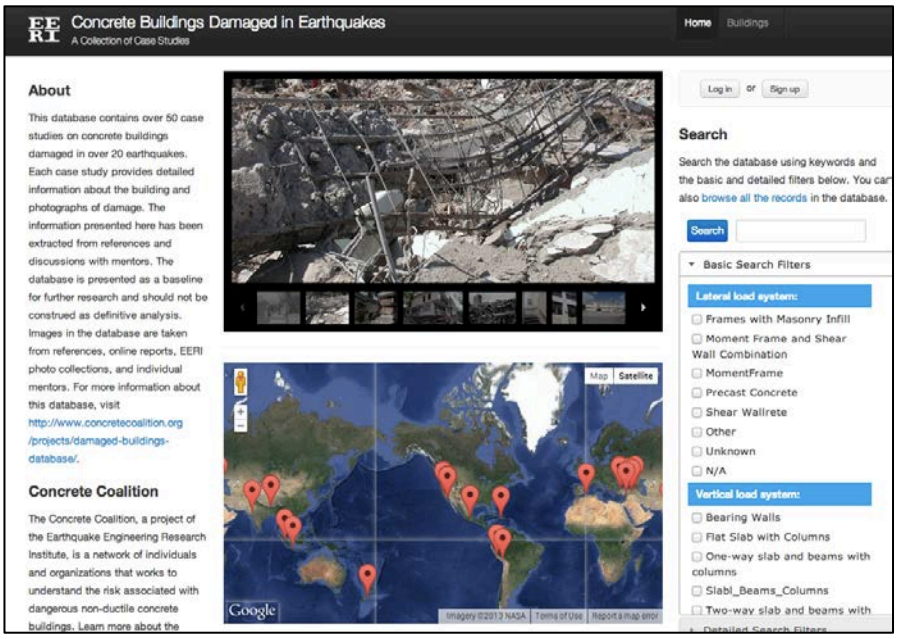

Figure 1: Online Database Homepage

Building Information Pages

Each building in the database has a dedicated page on the website with a unique url that makes it easy to reference. A representative picture, basic information, and any available structural drawings are displayed in the left sidebar. The center of the page features a set of five tabbed sections with more detailed information about each building. Each tab also contains thumbnails relevant to each section (e.g. shakemaps and ground motions records in the earthquake tab). Clicking on a thumbnail displays the high-resolution image. Figure 2 illustrates the left sidebar and the tabs that display information in each of these categories.

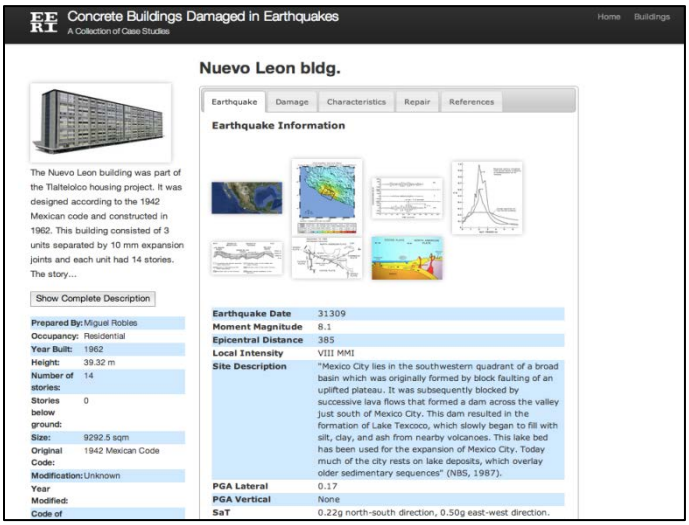

Figure 2. Note 5 tabs across the top, available for each building in the database.

In some cases the figures include sketches and line drawings provided by the mentors (see Figure 3). Such original sources of information can be very valuable in further analyses of the observed damage.

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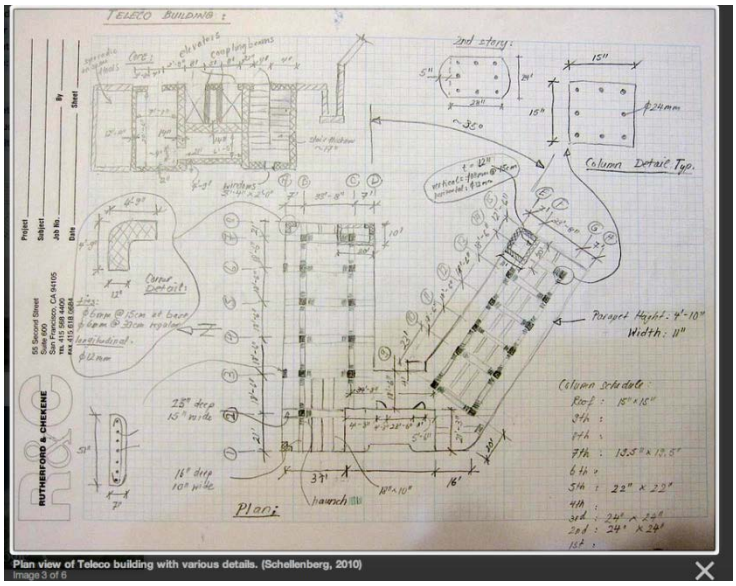

Figure 3. Example of hand sketch—plan view of Teleco building in Haiti

Searching the Database

The database has two search options that together provide the user with a powerful way to search the database. The first search option is a full text search of all fields of each building record using keywords entered by the user. The second search option is basic and detailed filters. Basic search filters, such as lateral and vertical load systems, foundation type, number of stories, occupancy, allows one to find and compare similar buildings. The detailed search filters allow users to search for buildings where the selected construction characteristics contributed to damage (See Figure 4). The search features are designed to aid researchers who are interested in conducting more detailed analyses, and/or adding information on additional buildings.

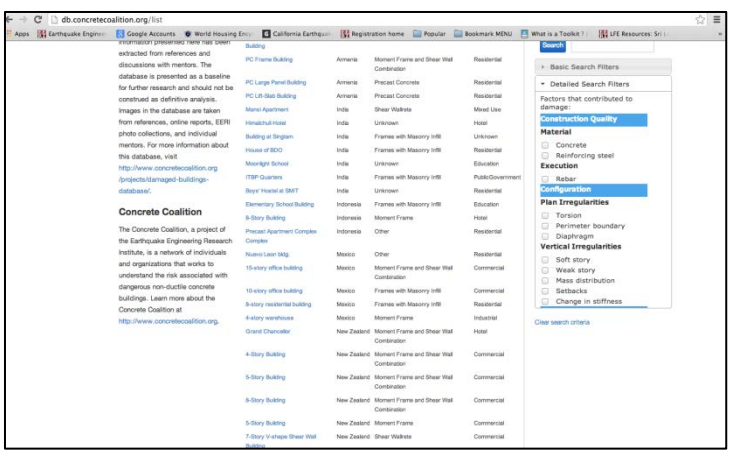

Figure 4. Detailed search criteria (to right)

Preliminary Trends in Data

The heart of the database is the listing of the 53 design and construction characteristics. With the 52 records in the database, preliminary trends in the data are already emerging. Over time, as more buildings are added, the correlations between each of the characteristics and observed damage should become clearer. Preliminary analyses

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of the buildings in the database show some trends. Figure 5 shows the likelihood that each characteristic contributed to the observed damage for four of the most common lateral load resisting systems.

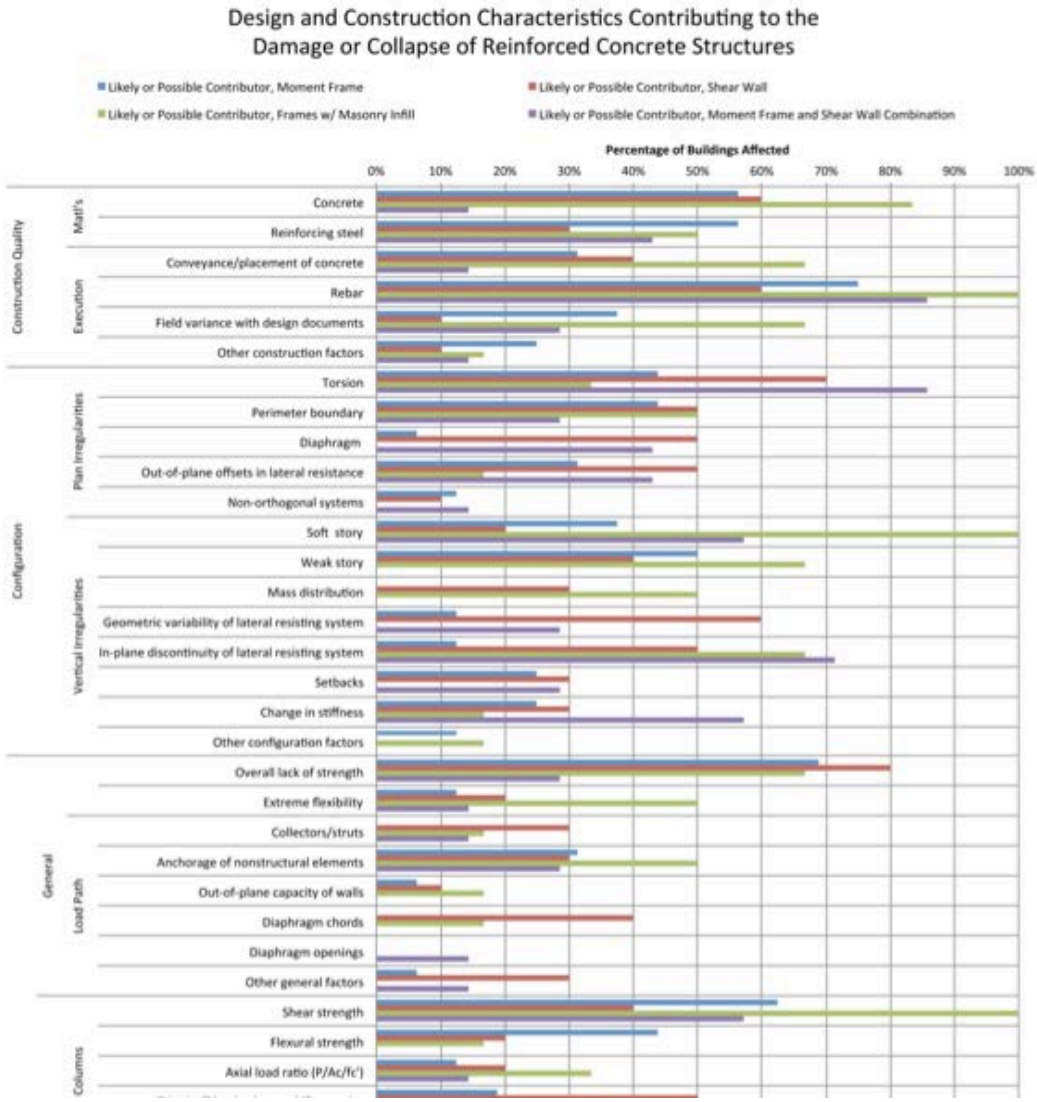

Figure 5: Design and Construction Characteristics Contributing to Damage, by Lateral Load System.

For example, the execution of the rebar, the presence of a soft story, and the shear strength of the columns were likely or possible contributors to damage in all frame with masonry infill wall buildings in the database. In contrast, for moment frame buildings there were no characteristics that were likely or possible contributors to damage in all the buildings in the database with this lateral load resisting system. For moment frame buildings, the poor execution of rebar, an overall lack of strength, and insufficient shear strength of the columns were likely or possible contributors to damage in 75%, 68%, and 62%, respectively, of the buildings in the database with this structural system.

It is also possible to examine the data across structural systems. Looking at the full database, a few characteristics emerge as the major contributors to damage. The poor execution of rebar was a possible or likely contributor to damage in 57 % of buildings in the database. Similarly, other major contributors include torsion (present in 54% of buildings), overall lack of strength (present in 52% of buildings), and insufficient shear strength in the columns

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(present in 59% of buildings). These observations are limited by the number of case studies in the database. As the database grows, more confidence can be placed in the characteristics that most contribute to damage for each type of structural system, and reinforced concrete buildings in general.

Growing the Database

While already a source of useful information, the database will increase in value as case studies are added. A contribution toolkit is being developed to encourage others to contribute additional case studies to the database. Case studies from additional countries with varying levels of damage and ground shaking will increase the range of the dataset and help to validate initial trends spotted in the data. Built into the online database is an administration console that allows for the submission and review of new case studies, which will make it easy to accept data from researchers and practitioners around the world.

Conclusions

The purpose of the effort is to provide reliable data to a broad range of individuals and organizations with a stake in improving the safety and sustainability of concrete buildings in seismically active areas of the world. Engineering practitioners and researchers can use the data to assess the relative contribution of various characteristics to the potential for collapse or serious damage, and to develop simplified procedures for use in practice to identify particularly dangerous buildings. Practitioners now have direct access to some basic performance data to improve their fundamental understanding of concrete building behavior. Engineering students are able to visualize the effects of earthquakes on buildings over broad temporal and geographic spectra. As the database grows and is used more widely, it will develop into an online resource that will help raise the awareness of public policy experts and the general public, particularly in developing countries where improving the performance of concrete buildings is especially challenging.

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Appendix 1. Partial list of Data Fields

Record ID
Building Name
Prepared By
Country
State/Province
City
Latitude
Longitude
Street Address
Occupancy
Height
Height Units
Number of Stories
Stories below Ground
Size
Size Units
Year Built
Original Code
Modification
Year Modified
Code of Modification
Lateral Load System
Other Lateral Load System
Vertical Load System
Other Vertical Load System
Foundation
Other Foundation
Building Description
Earthquake Date
Moment Magnitude
Epicentral Distance km
Local Intensity
Intensity Scale
Site Description
PGA lateral
PGA vertical
SaT
Ground Motion Recording Stations
Distance to Station
Station Latitude

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Station Longitude
Ground Motion Summary
Performance Summary
Damage State Description
Summary of Causes of Damage
Concrete Notes
Concrete
Reinforcing steel Notes
Reinforcing steel
Conveyance/placement of concrete Notes
Conveyance/placement of concrete
Rebar Notes
Rebar
Field variance with design documents Notes
Field variance with design documents
Other Factors Construction Quality Notes
Other Factors Construction Quality
Torsion Notes
Torsion
Perimeter boundary Notes
Perimeter boundary
Diaphragm Notes
Diaphragm
Out-of-plane offsets in lateral resisting system Notes
Out-of-plane offsets in lateral resisting system
Non-orthogonal systems Notes
Non-orthogonal systems
Soft story Notes
Soft story
Weak story Notes
Weak story
Geometric variability of lateral resisting system Notes
Geometric variability of lateral resisting system
In-plane discontinuity of lateral resisting system Notes
In-plane discontinuity of lateral resisting system
Mass distribution Notes
Mass distribution
Setbacks Notes
Setbacks
Change in stiffness Notes
Change in stiffness
Other Factors Configuration Notes
Other Factors Configuration

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Overall lack of strength Notes
Overall lack of strength
Extreme Flexibility Notes
Extreme Flexibility
Collectors/Struts Notes
Collectors/Struts
Anchorage of nonstructural elements Notes
Anchorage of nonstructural elements
Out-of-plane capacity of walls Notes
Out-of-plane capacity of walls
Diaphragm chords Notes
Diaphragm chords
Diaphragm openings Notes
Diaphragm openings
Other Factors Lateral Load Resisting System-General Notes
Other Factors Lateral Load Resisting System-General
Shear strength Notes
Shear strength
Flexural strength Notes
Flexural strength
Axial load ratio Notes
Axial load ratio
Vertical load columns drift capacity Notes
Vertical load columns drift capacity
Interference of frame action by infill Notes
Interference of frame action by infill
Strength relative to columns Notes
Strength relative to columns
Shear controlled behavior Notes
Shear controlled behavior
Continuity of longitudinal reinforcing Notes
Loss of vertical capacity Notes
Continuity of longitudinal reinforcing
Loss of vertical capacity
Interference of frame action by infill beams Notes
Interior Notes
Interference of frame action by infill beams
Interior
Exterior Notes
Exterior
Corner Notes
Corner
Other Factors Lateral Load Resisting System-Frames Notes

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Other Factors Lateral Load Resisting System-Frames
Diagonal tension/compression Notes
Diagonal tension/compression
Sliding shear Notes
Sliding shear
Flexure/shear Notes
Flexure/shear
Compression zone buckling capacity Notes
Discontinuity of wall Notes
Compression zone buckling capacity
Boundary reinforcing fracture/buckling Notes
Discontinuity of wall
Boundary Reinforcing at openings Notes
Other Factors Lateral Load Resisting System-Shear Walls Notes
Boundary reinforcing fracture/buckling
Boundary Reinforcing at openings
Other Factors Lateral Load Resisting System-Shear Walls
Unreinforced Notes
Unreinforced
Interference with frame action Notes
Interference with frame action
Out-of-plane Notes
Out-of-plane
Attachment to framing Notes
Attachment to framing
Other Factors Lateral Load Resisting Systems-Infills Notes
Other Factors Lateral Load Resisting Systems-Infills
Liquefaction Notes
Liquefaction
Pile/Pier tension capacity Notes
Pile/Pier tension capacity
Spread footing capacity Notes
Spread footing capacity
Other Factors Lateral Load Resisting Systems-Other-Foundations Notes
Other Factors Lateral Load Resisting Systems-Other-Foundations
Surface Rupture Notes
Surface Rupture
Pounding Notes
Other Factors Lateral Load Resisting Systems-Other-Misc Notes
Pounding
Other Factors Lateral Load Resisting Systems-Other-Misc
Type of Retrofit or Repair
Other Retrofit or Repair

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Performance Level
Hazard Level
Retrofit or Repair Code
Other Retrofit or Repair Code
Lateral Analysis
Other Lateral Analysis
Design Strategy
Retrofit Summary
Additional Notes: Section 1
Additional Notes: Section 2
Additional Notes: Section 3
Additional Notes: Section 4

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Appendix 2. Data Collection Form

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Concrete Coalition Phase II: Concrete Building Performance Record

Instructions: This form is for use in collecting data for phase two of the Concrete Coalition project: Developing a Global Database of Concrete Buildings Damaged in Earthquakes. For more information about how to use this form, see the sample form or view the demo at: http://concretecoalition.org.

Record ID: **Building Name:** **Prepared By:**

Section 1: Basic Building Information

Insert main image in this box

Type image caption here:

Country:		
State/Province:		
City:		
Latitude:		
Longitude:		
Street Address:		
Occupancy:	Unknown	
Height:		ft
Number of Stories:		
Number of Stories below ground:		
Size:		gsf
Year Built:		
Original Code:		
Modification:	Unknown	
Year Modified:		
Code of Modification:		

Section 1: Basic Building Information-(Continued)

Lateral Load System:	Unknown
Other Lateral Load System:	
Vertical Load System:	Unknown
Other Vertical Load System:	
Foundation:	Other
Building Description:	

Section 2: Earthquake Information

Earthquake Date:			
Moment Magnitude:			
Epicentral Distance (km):			
Local Intensity:		Intensity Scale:	MMI
Site Description:			
PGA (max horizontal):			
PGA (vertical):			
SaT:			
Ground Motion Recording Stations:			
Distance to Station (km):			
Station Latitude:			
Station Longitude:			
Ground Motion Summary:			

Record ID: **Building Name:** **Prepared By:**

Section 3: Damage Information

Performance Summary:	
Damage State Description:	
Summary of Causes of Damage:	

Concrete Coalition Phase II: Concrete Building Performance Record

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Construction Quality

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Materials						
Concrete						
Reinforcing steel						
Execution						
Conveyance/ placement of concrete						
Rebar						
Field variance with design documents						
Other Factors						
Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Configuration

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Plan Irregularities						
Torsion						
Perimeter boundary						
Diaphragm						
Out-of-plane offsets in lateral resisting system						
Non-orthogonal systems						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Configuration-(Continued)

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Vertical Irregularities						
Soft Story						
Weak story						
Mass distribution						
Geometric variability of lateral resisting system						
In-plane discontinuity of lateral resisting system						
Setbacks						
Change in stiffness						
Other Factors						
Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-General

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Strength						
Overall lack of strength						
Stiffness						
Extreme Flexibility						
Load Path						
Collectors/Struts						
Anchorage of nonstructural elements						
Out-of-plane capacity of walls						
Diaphragm chords						
Diaphragm openings						
Other Factors						
Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-Frames

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Columns						
Shear strength						
Flexural strength						
Axial load ratio (P/Ac/fc')						
"Vertical" load columns drift capacity						
Interference of frame action by infill						
Beams						
Strength relative to columns						
Shear controlled behavior						
Continuity of longitudinal reinforcing						
Loss of vertical capacity						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-Frames-Continued

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Beams –(continued)						
Interference of frame action by infill						
Joints						
Interior						
Exterior						
Corner						
Other Factors						
Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-Shear Walls

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Shear						
Diagonal tension/compression						
Sliding shear						
Flexure/shear						
Flexure						
Compression zone buckling capacity						
Boundary reinforcing fracture/buckling						
Discontinuity of wall						
Boundary Reinforcing at openings						
Other Factors						
Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-Infills

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Unreinforced						
Interference with frame action						
Out-of-plane						
Attachment to framing						

Other Factors

Please Specify:						

Record ID: **Building Name:** **Prepared By:**

Section 4: Observed Design and Construction Characteristics-Lateral Load Resisting System-Other

	Notes	Contribution to Observed Damage				
		Unlikely	Possible	Likely	Unknown	N/A
Foundations						
Liquefaction						
Pile/pier tension capacity						
Spread footing capacity						
Other:						
Please Specify:						
Miscellaneous						
Pounding						
Surface Rupture						
Other:						
Please Specify:						

Section 4: Repair and Retrofit Information

Type of retrofit or repair:	Unknown
Other:	
Performance Level:	Unknown
Hazard Level:	Unknown
Code:	Unknown
Other:	
Lateral Analysis:	Unknown
Other:	
Design Strategy:	
Retrofit Summary:	

Concrete Coalition Phase II: Concrete Building Performance Record

Record ID: **Building Name:** **Prepared By:**

Additional Notes:	
Section 1	
Section 2	
Section 3	
Section 4	

Appendix 1: Supplemental Basic Information

File Location	
File Caption	
File Location	
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File Location	
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Appendix 2: Additional Ground Motion Location

File Location	
File Caption	
File Location	
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File Location	
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File Location	
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File Location	
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Appendix 3: Illustrations of Damage

File Location	
File Caption	
File Location	
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File Location	
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File Location	
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File Caption	

Appendix 4: Illustrations of Repair/Retrofit

File Location	
File Caption	
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Appendix 5: References

Citation	
Link to Purchase	
File Location	
Citation	
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File Location	
Citation	
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Citation	
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Appendix 5: References-(Continued)

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Citation	
Link to Purchase	
File Location	
Citation	
Link to Purchase	
File Location	
Citation	
Link to Purchase	
File Location	

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