FEMA 307

EVALUATION OF EARTHQUAKE DAMAGED CONCRETE AND MASONRY WALL BUILDINGS

Technical Resources

Prepared by:

The Applied Technology Council
555 Twin Dolphin Drive, Suite 550
Redwood City, California 94065

Prepared for:

The Partnership for Response and Recovery
Washington, D.C.

Funded by:

Federal Emergency Management Agency

1998
The Applied Technology Council (ATC) is a nonprofit, tax-exempt corporation established in 1971 through the efforts of the Structural Engineers Association of California. ATC is guided by a Board of Directors consisting of representatives appointed by the American Society of Civil Engineers, the Structural Engineers Association of California, the Western States Council of Structural Engineers Associations, and four at-large representatives concerned with the practice of structural engineering. Each director serves a three-year term.

The purpose of ATC is to assist the design practitioner in structural engineering (and related design specialty fields such as soils, wind, and earthquake) in the task of keeping abreast of and effectively using technological developments. ATC also identifies and encourages needed research and develops consensus opinions on structural engineering issues in a nonproprietary format. ATC thereby fulfills a unique role in funded information transfer.

Project management and administration are carried out by a full-time Executive Director and support staff. Project work is conducted by a wide range of highly qualified consulting professionals, thus incorporating the experience of many individuals from academia, research, and professional practice who would not be available from any single organization. Funding for ATC projects is obtained from government agencies and from the private sector in the form of tax-deductible contributions.

1998-1999 Board of Directors

Charles H. Thornton, President
Edwin T. Dean, Vice President
Andrew T. Merovich, Secretary/Treasurer
C. Mark Saunders, Past President
James R. Cagley
Arthur N. L. Chiu
Robert G. Dean

Edwin H. Johnson
Kenneth A. Luttrell
Newland J. Malmquist
Stephen H. Pelham
Richard J. Phillips
Charles W. Roeder
Jonathan G. Shipp

Notice

This report was prepared under Contract EMW-95-C-4685 between the Federal Emergency Management Agency and the Partnership for Response and Recovery.

Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of the Applied Technology Council (ATC), the Partnership for Response and Recovery (PaRR), or the Federal Emergency Management Agency (FEMA). Additionally, neither ATC, PaRR, FEMA, nor any of their employees makes any warranty, expressed or implied, nor assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process included in this publication. Users of information from this publication assume all liability arising from such use.

For further information concerning this document or the activities of the ATC, contact the Executive Director, Applied Technology Council, 555 Twin Dolphin Drive, Suite 550, Redwood City, California 94065; phone 650-595-1542; fax 650-593-2320; e-mail atc@atcouncil.org.
Preface

Following the two damaging California earthquakes in 1989 (Loma Prieta) and 1994 (Northridge), many concrete wall and masonry wall buildings were repaired using federal disaster assistance funding. The repairs were based on inconsistent criteria, giving rise to controversy regarding criteria for the repair of cracked concrete and masonry wall buildings. To help resolve this controversy, the Federal Emergency Management Agency (FEMA) initiated a project on evaluation and repair of earthquake damaged concrete and masonry wall buildings in 1996. The project was conducted through the Partnership for Response and Recovery (PaRR), a joint venture of Dewberry & Davis of Fairfax, Virginia, and Woodward-Clyde Federal Services of Gaithersburg, Maryland. The Applied Technology Council (ATC), under subcontract to PaRR, was responsible for developing technical criteria and procedures (the ATC-43 project).

The ATC-43 project addresses the investigation and evaluation of earthquake damage and discusses policy issues related to the repair and upgrade of earthquake-damaged buildings. The project deals with buildings whose primary lateral-force-resisting systems consist of concrete or masonry bearing walls with flexible or rigid diaphragms, or whose vertical-load-bearing systems consist of concrete or steel frames with concrete or masonry infill panels. The intended audience is design engineers, building owners, building regulatory officials, and government agencies.

The project results are reported in three documents. The FEMA 306 report, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual*, provides guidance on evaluating damage and analyzing future performance. Included in the document are component damage classification guides, and test and inspection guides. FEMA 307, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources*, contains supplemental information including results from a theoretical analysis of the effects of prior damage on single-degree-of-freedom mathematical models, additional background information on the component guides, and an example of the application of the basic procedures. FEMA 308, *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings*, discusses the policy issues pertaining to the repair of earthquake damaged buildings and illustrates how the procedures developed for the project can be used to provide a technically sound basis for policy decisions. It also provides guidance for the repair of damaged components.

The project also involved a workshop to provide an opportunity for the user community to review and comment on the proposed evaluation and repair criteria. The workshop, open to the profession at large, was held in Los Angeles on June 13, 1997 and was attended by 75 participants.

The project was conducted under the direction of ATC Senior Consultant Craig Comartin, who served as Co-Principal Investigator and Project Director. Technical and management direction were provided by a Technical Management Committee consisting of Christopher Rojahn (Chair), Craig Comartin (Co-Chair), Daniel Abrams, Mark Doroudian, James Hill, Jack Moehle, Andrew Merovich (ATC Board Representative), and Tim McCormick. The Technical Management Committee created two Issue Working Groups to pursue directed research to document the state of the knowledge in selected key areas: (1) an Analysis Working Group, consisting of Mark Aschheim (Group Leader) and Mete Sozen (Senior Consultant) and (2) a Materials Working Group, consisting of Joe Maffei (Group Leader and Reinforced Concrete Consultant), Greg Kingsley (Reinforced Masonry Consultant), Bret Lizundia (Unreinforced Masonry Consultant), John Mander (Infilled Frame Consultant), Brian Kehoe and other consultants from Wiss, Janney, Elstner and Associates (Tests, Investigations, and Repairs Consultant). A Project Review Panel provided technical overview and guidance. The Panel members were Gregg Borchelt, Gene Corley, Edwin Huston, Richard Klingner, Vilas Mujumdar, Hassan Sassi, Carl Schulze, Daniel Shapiro, James Wight, and Eugene Zeller. Nancy Sauer and Peter Mork provided technical editing and report production services, respectively. Affiliations are provided in the list of project participants.

The Applied Technology Council and the Partnership for Response and Recovery gratefully acknowledge the cooperation and insight provided by the FEMA Technical Monitor, Robert D. Hanson.

Tim McCormick
PaRR Task Manager

Christopher Rojahn
ATC-43 Principal Investigator
ATC Executive Director
# Table of Contents

**Preface** ................................................................. iii  
**List of Figures** .................................................. ix  
**List of Tables** .................................................. xiii  
**Prologue** ............................................................... xv  

1. **Introduction** ..................................................... 1  
   1.1 Purpose And Scope ............................................. 1  
   1.2 Materials Working Group  
      1.2.1 Tests and Investigations ................................ 1  
      1.2.2 Component Behavior and Modeling ..................... 1  
      1.2.3 Repair Techniques ........................................ 2  
   1.3 Analysis Working Group ....................................... 3  
   1.4 References ..................................................... 4  

2. **Reinforced Concrete Components** .................................. 7  
   2.1 Commentary and Discussion .................................... 7  
   2.1.1 Development of Component Guides and \( \lambda \)-Factors .... 7  
   2.2 Typical Force-Displacement Hysteretic Behavior .......... 10  
   2.3 Tabular Bibliography ......................................... 28  
   2.4 Symbols for Reinforced Concrete ............................. 33  
   2.5 References for Reinforced Concrete ........................... 35  

3. **Reinforced Masonry** ............................................... 39  
   3.1 Commentary and Discussion .................................... 39  
   3.1.1 Typical Hysteretic Behavior .............................. 39  
   3.1.2 Cracking and Damage Severity ............................ 39  
   3.1.3 Interpretation of Tests ................................... 46  
   3.2 Tabular Bibliography for Reinforced Masonry ............. 46  
   3.3 Symbols for Reinforced Masonry ............................... 53  
   3.4 References for Reinforced Masonry ............................ 54  

4. **Unreinforced Masonry** ............................................. 59  
   4.1 Commentary and Discussion .................................... 59  
   4.1.1 Hysteretic Behavior of URM Walls Subjected to In-Plane Demands ...... 59  
   4.1.2 Comments on FEMA 273 Component Force/Displacement Relationships .... 72  
   4.1.3 Development of \( \lambda \)-factors ......................... 75  
   4.2 Tabular Bibliography for Unreinforced Masonry ............ 77  
   4.3 Symbols for Unreinforced Masonry ............................. 80
4.4 References for Unreinforced Masonry .............................................. 81

5. Infilled Frames  .............................................................................. 85
  5.1 Commentary And Discussion .................................................. 85
     5.1.1 Development of $\lambda$-Factors for Component Guides .......... 85
     5.1.2 Development of Stiffness Deterioration—$\lambda_K$ .............. 85
     5.1.3 The Determination of $\lambda_Q$ for Strength Deterioration ...... 86
     5.1.4 Development of $\lambda_D$—Reduction in Displacement Capability .. 87
  5.2 Tabular Bibliography for Infilled Frames ................................. 89
  5.3 References for Infilled Frames ................................................. 91

6. Analytical Studies ...................................................................... 95
  6.1 Overview .................................................................................. 95
  6.2 Summary of Previous Findings ................................................. 95
     6.2.1 Hysteresis Models .............................................................. 95
     6.2.2 Effect of Ground Motion Duration ....................................... 98
     6.2.3 Residual Displacement ....................................................... 98
     6.2.4 Repeated Loading .............................................................. 98
  6.3 Dynamic Analysis Framework .................................................. 99
     6.3.1 Overview ......................................................................... 99
     6.3.2 Dynamic Analysis Approach ............................................. 99
     6.3.3 Ground Motions ............................................................... 100
     6.3.4 Force/Displacement Models .............................................. 120
     6.3.5 Undamaged Oscillator Parameters .................................... 122
     6.3.6 Damaged Oscillator Parameters ....................................... 123
     6.3.7 Summary of Dynamic Analysis Parameters ....................... 125
     6.3.8 Implementation of Analyses .............................................. 126
  6.4 Results Of Dynamic Analyses .................................................... 126
     6.4.1 Overview and Nomenclature ............................................. 126
     6.4.2 Response of Bilinear Models ............................................ 127
     6.4.3 Response of Takeda Models ............................................. 127
     6.4.4 Response Statistics ......................................................... 151
  6.5 Nonlinear Static Procedures ...................................................... 155
     6.5.1 Introduction .................................................................... 155
     6.5.2 Description of Nonlinear Static Procedures ....................... 156
     6.5.3 Comments on Procedures ................................................. 159
     6.5.4 Application of Procedures to Undamaged and Damaged Oscillators .. 160
  6.6 Comparison of NSP and Dynamic Analysis Results .................. 160
     6.6.1 Introduction .................................................................... 160
     6.6.2 Displacement Estimation .................................................. 160
     6.6.3 Displacement Ratio Estimation ......................................... 161
  6.7 Conclusions and Implications .................................................... 177
  6.8 References ............................................................................. 178
7. **Example Application** ................................................................. 181
   7.1 **Introduction** ................................................................. 181
   
   7.1.1 Objectives ............................................................. 181
   7.1.2 Organization ............................................................ 181
   
   7.2 **Investigation** ................................................................. 183
   
   7.2.1 Building Description ..................................................... 183
   7.2.2 Postearthquake Damage Observations ................................. 183
   7.2.3 Preliminary Classification (by Observation) of Component Types, Behavior Modes, and Damage Severity ......................................................... 189
   7.2.4 Final Classification (by Analysis) of Component Type, Behavior Mode and Damage Severity ......................................................... 190
   7.2.5 Other Damage Observations ............................................... 195
   7.2.6 Summary of Component Classifications .................................. 195
   
   7.3 **Evaluation by the Direct Method** ........................................ 199
   
   7.3.1 Structural Restoration Measures ....................................... 199
   7.3.2 Nonstructural Restoration Measures ..................................... 201
   7.3.3 Restoration Summary and Cost .......................................... 201
   
   7.4 **Evaluation by Performance Analysis** .................................... 201
   
   7.4.1 Performance Objectives .................................................. 202
   7.4.2 Nonlinear Static Analysis ............................................... 203
   7.4.3 Force-Displacement Capacity (Pushover Analysis) Results ............. 206
   7.4.4 Estimation of Displacement, de, Caused by Damaging Earthquake .......... 209
   7.4.5 Displacement Demand .................................................... 210
   7.4.6 Analysis of Restored Structure ......................................... 212
   7.4.7 Performance Restoration Measures ...................................... 214
   
   7.5 **Discussion of Results** .................................................... 214
   
   7.5.1 Discussion of Building Performance ..................................... 214
   7.5.2 Discussion of Methodology and Repair Costs ............................ 215
   
   7.6 **References** ................................................................. 215

   **Appendix A. Component Damage Records for Building Evaluated in Example Application** ................................................................. 217

   **ATC-43 Project Participants** .................................................. 237

   **Applied Technology Council Projects And Report Information** .................. 241