NIST GCR 18-917-43

Recommendations for Improved Seismic Performance of Nonstructural Components

Applied Technology Council

This publication is available free of charge from:
https://doi.org/10.6028/NIST.GCR.18-917-43

September 2018
Disclaimer

This report was prepared for the Engineering Laboratory of the National Institute of Standards and Technology (NIST) under Contract SB1341-13-CQ-0009, Task Order 14-491. The contents of this publication do not necessarily reflect the views and policies of NIST or the U.S. Government.

This report was produced by the Applied Technology Council (ATC). While endeavoring to provide practical and accurate information, the Applied Technology Council, the authors, and the reviewers assume no liability for, nor express or imply any warranty with regard to, the information contained herein. Users of information contained in this report assume all liability arising from such use.

Unless otherwise noted, photos, figures, and data presented in this report have been developed or provided by ATC staff or consultants engaged under contract to provide information as works for hire. Any similarity with other published information is coincidental. Photos and figures cited from outside sources have been reproduced in this report with permission. Any other use requires additional permission from the copyright holders.

Certain commercial software, equipment, instruments, or materials may have been used in the preparation of information contributing to this report. Identification in this report is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that such software, equipment, instruments, or materials are necessarily the best available for the purpose.

NIST policy is to use the International System of Units (metric units) in all its publications. In this report, however, information is presented in U.S. Customary Units (inch-pound), as this is the preferred system of units in the U.S. engineering industry.
Recommendations for Improved Seismic Performance of Nonstructural Components

Prepared for
U.S. Department of Commerce
Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8600

By
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, CA 94065

This publication is available free of charge from:
https://doi.org/10.6028/NIST.GCR.18-917-43

September 2018

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter G. Copan, NIST Director and Under Secretary of Commerce for Standards and Technology
Participants

National Institute of Standards and Technology

Steven L. McCabe, Research Structural Engineer and Earthquake Engineering Group Leader
Matthew Hoehler, Research Structural Engineer, Fire Research Division
Engineering Laboratory
www.NEHRP.gov

Applied Technology Council

201 Redwood Shores Parkway, Suite 240
Redwood City, California  94065
www.ATCouncil.org

Program Management

Jon A. Heintz (Program Manager)
Ayse Hortacsu (Associate Program Manager)

Program Committee on Seismic Engineering

Jon A. Heintz (Chair)
Michael Cochran
James R. Harris
James Jirsa
Roberto Leon
Stephen Mahin
James O. Malley
Donald Scott
Andrew Whittaker

Project Technical Committee

Maryann Phipps (Project Director)
John Gillengerten
William T. Holmes
Bret Lizundia
Ricardo Medina
Eduardo Miranda
Robert Pekelnicky

Working Group Members

Hamidreza Anajafi
Dago de la Rosa
Athanasia Kazantzi
David Lam
Megan Leon
Matthew Namy
Dimitrios Vamvatsikos

Project Review Panel

Robert Bachman (Chair)
Andre Filiatrault
James R. Harris
Michael Mahoney (ex officio)
Shannon Rose
Jeff Soulages
William Staehlin (ATC Board Contact)
Chris Tokas
In 2014, the Applied Technology Council (ATC) commenced a task order project (ATC-120) under National Institute of Standards and Technology (NIST) Contract SB1341-13-CQ-0009 to improve the seismic design of nonstructural systems and components in the areas that will have the largest impact to public safety and economic welfare, with an emphasis on construction regulated by building codes. This project was conceived in direct response to recommendations provided in the NIST GCR 13-917-23, Development of NIST Measurement Science R&D Roadmap: Earthquake Risk Reduction in Buildings, (NIST, 2013). In particular, NIST GCR 13-917-23 identified nonstructural issues as a top priority, calling for problem-focused studies in critical areas related to nonstructural design criteria. In the first phase of the ATC-120 project, a year-long study was undertaken to collect and summarize the body of available knowledge related to nonstructural components that could serve as the foundation for future investigations. The study drew from documented earthquake observations, past code development efforts related to nonstructural requirements, analytical research, and nonstructural component and system testing. This work also included a practitioners’ workshop to identify the most pressing needs of the profession. This background information was used to identify and prioritize research needed to improve technical aspects of nonstructural system design. The findings and recommendations of this study are summarized in NIST GCR 17-917-44, Seismic Analysis, Design, and Installation of Nonstructural Components – Background and Recommendations for Future Work, (NIST, 2017).

The goal of this second phase of work is to improve technical aspects of nonstructural system design in the areas that will have the largest impact for public safety and economic welfare. This report summarizes the body of knowledge gathered and developed to advance the understanding of the response of nonstructural components to earthquakes. The report also makes recommendations for changes to building codes and practice.

ATC is indebted to the leadership of Maryann Phipps, who served as Project Technical Director, and to the members of the Project Technical Committee consisting of John Gillengerten, Bill Holmes, Bret Lizundia, Ricardo Medina, Eduardo Miranda, and Bob Pekelnicky, for their contributions in developing this report and the resulting recommendations. They were assisted by Working Group members including Hamidreza Anajafi, Dago De La Rosa, Nancy Kazantzi, David
Lam, Megan Leon, Matthew Namy, and Dimitrios Vamvatsikos. The Project Review Panel, consisting of Bob Bachman (chair), Andre Filiatrault, Jim Harris, Mike Mahoney (ex officio member), Shannon Rose, Jeff Soulages, Bill Staehlin (ATC Board Contact), and Chris Tokas provided technical review and comment at key developmental stages of the project. The names and affiliations of those who contributed to this report are provided in the list of Project Participants at the end of this report. In addition, Tali Feinstein, Steve Mahin, Marlou Rodriguez, John Silva, and Jim Tauby provided valuable input.

The Applied Technology Council also gratefully acknowledges Steven L. McCabe (NIST Program Manager and Contracting Officer’s Representative) and Matthew Hoehler (NIST Project Manager and Technical Point of Contact) for their input and guidance in the preparation of this report, Scott Schiff for project management support, and Carrie Perna for ATC report production services.

Jon A. Heintz          Ayse Hortacsu
Program Manager          Associate Program Manager
# Table of Contents

Preface ........................................................................................................................................... v  

List of Figures ................................................................................................................................ xiii  

List of Tables ................................................................................................................................ xx  

## 1. Introduction ................................................................................................................ 1-1  
1.1 Project Background and Purpose ............................................................................. 1-1  
1.2 Intended Audience ................................................................................................. 1-2  
1.3 Holistic Approach to Understanding the Response of Nonstructural Components to Earthquakes .................................................................................................................. 1-2  
1.4 Report Organization ............................................................................................... 1-5  

## 2. Performance Objectives for Nonstructural Components .................................. 2-1  
2.1 Introduction ............................................................................................................ 2-1  
2.2 Background ............................................................................................................. 2-2  
2.3 Development of Nonstructural Performance Objectives for Building Code ................................................................................................................................. 2-7  
2.3.1 General .............................................................................................................. 2-7  
2.3.2 Philosophy for Nonstructural Performance Objectives .................................. 2-9  
2.4 Recommended Framework for Nonstructural Performance Objectives ................ 2-14  
2.4.1 Hazard Definition ............................................................................................... 2-14  
2.4.2 Risks Associated with Nonstructural Damage ................................................. 2-15  
2.4.3 Nonstructural Performance Descriptions ......................................................... 2-18  
2.4.4 Recommended Performance Objectives for Nonstructural Components .......... 2-18  
2.5 Enhanced Nonstructural Performance Objectives ................................................. 2-22  
2.5.1 Strategies for Enhanced Performance ................................................................ 2-23  
2.5.2 Beyond Design .................................................................................................... 2-28  
2.5.3 Objectives for Community Resilience ............................................................... 2-29  
2.5.4 Shelter-In-Place Objectives .............................................................................. 2-29  
2.5.5 Damage Control Objectives ............................................................................. 2-30  

## 3. Review of ASCE/SEI 7-16 Seismic Requirements for Nonstructural Components ................................................................. 3-1  
3.1 General ....................................................................................................................... 3-2  
3.2 General Design Requirements ................................................................................ 3-6  
3.3 Seismic Demands on Nonstructural Components .................................................. 3-7  
3.4 Nonstructural Component Anchorage ..................................................................... 3-8  
3.5 Architectural Components ....................................................................................... 3-10  
3.6 Mechanical and Electrical Components ................................................................. 3-12
3.6.1 Distribution Systems: Conduit, Cable Tray, Raceways, Ducts, Piping, and Tubing ................................................ 3-13
3.6.2 Distribution Systems: Trapezes with a Combination of Systems ................................................................. 3-14
3.6.3 Boilers and Pressure Vessels ............................................. 3-15
3.6.4 Elevator and Escalator Design Requirements ............... 3-15

4. Understanding the Response of Nonstructural Components to Earthquakes ................................................................. 4-1
4.1 Current Equation ................................................................................................................................. 4-2
4.2 Influence of Parameters .................................................................................................................. 4-4
4.2.1 Peak Ground Acceleration, PGA ................................................................................................. 4-4
4.2.2 Seismic Force-Resisting System .................................................................................................. 4-7
4.2.3 Fundamental Period of the Building, $T_{bldg}$ ............................................................................ 4-8
4.2.4 Building Ductility, $\mu_{bldg}$ ....................................................................................................... 4-10
4.2.5 Inherent Building Damping, $\beta_{bldg}$ ..................................................................................... 4-14
4.2.6 Building Configuration .................................................................................................................. 4-15
4.2.7 Floor and Roof Diaphragm Rigidity ............................................................................................ 4-16
4.2.8 Vertical Location of Component within the Building, $z/h$ ................................................................ 4-17
4.2.9 Component Period, $T_{comp}$ ..................................................................................................... 4-19
4.2.10 Inherent Component Damping, $\beta_{comp}$ .............................................................................. 4-21
4.2.11 Component and/or Anchorage Ductility, $\mu_{comp}$ .................................................................. 4-24
4.2.12 Component Reserve Strength Margin ....................................................................................... 4-27
4.2.13 Summary ................................................................................................................................. 4-29
4.3 Proposed Primary Equation and Combined Effect of Multiple Parameters ...................................................... 4-31
4.3.1 Other Recent Studies .................................................................................................................. 4-31
4.3.2 General Framework for Proposed Primary Equation ..................................................................... 4-32
4.3.3 Initial Proposed Primary Equation .............................................................................................. 4-33
4.3.4 Refined Equation .......................................................................................................................... 4-36
4.4 Proposed Minimum for Nonstructural Component Design ................................................................. 4-57
4.5 Proposed Maximum for Nonstructural Component Design ........................................................................ 4-59
4.5.1 Background ............................................................................................................................... 4-59
4.5.2 Proposed Maximum ..................................................................................................................... 4-60
4.6 When Building SFRS, Height, and/or Location of Component within the Building are Not Known .................. 4-61
4.6.1 When Location within the Building is Not Known .................................................................... 4-61
4.6.2 When SFRS and Height are Also Not Known .......................................................................... 4-61
4.7 Use of Dynamic Analysis to Determine Nonstructural Design Forces ...................................................... 4-62
4.7.1 ASCE/SEI 7-16 Provisions .......................................................................................................... 4-62
4.7.2 Proposed Revisions ......................................................................................................................... 4-62
4.8 General Comparisons between ASCE/SEI 7-16 and Proposed Nonstructural Design Equation ...................... 4-62
4.8.1 Comparisons of Proposed Equations with ASCE/SEI 7-16 ........................................................ 4-67
4.9 Case Study Example Comparisons between ASCE/SEI 7-16 and Proposed Nonstructural Design Equation .................................................................................................................. 4-70
4.9.1 Interior Wall and Partition Case Study Example ........................................................................ 4-70
4.9.2 Floor-Mounted Cabinet Case Study Example ............................................................................. 4-71
4.10 Conclusions and Recommendations ............................................. 4-72

5. Ductile Design of Nonstructural Supports and Attachments .......... 5-1
  5.1 Introduction ............................................................................... 5-1
  5.2 Effect of Resonance on Design ................................................. 5-1
  5.3 Ductile Design Philosophy ......................................................... 5-3
  5.4 Elevated Vessel Design Example ............................................... 5-5
  5.5 Partition Wall Design Example ................................................. 5-11
  5.6 Mechanical Unit Design Example ............................................. 5-15
  5.7 Piping Support Design Example ............................................... 5-18
  5.8 Conclusions and Recommendations ......................................... 5-19

6. Holistic Approach to Protecting Nonstructural Components ......... 6-1
  6.1 Introduction ............................................................................... 6-1
  6.2 Scope ....................................................................................... 6-1
  6.3 Uncertainty and Reliability ....................................................... 6-2
  6.4 Holistic Approach .................................................................... 6-3
    6.4.1 Assign Responsibility ......................................................... 6-3
    6.4.2 Select Performance Objectives ........................................... 6-4
    6.4.3 Establish Structural Design Parameters ............................. 6-6
    6.4.4 Select Nonstructural Components ..................................... 6-8
    6.4.5 Design Nonstructural Component Restraint ....................... 6-9
    6.4.6 Testing, Inspection, and Observation of Installed Components ....................................................................... 6-9
    6.4.7 Additional Strategies to Increase Resilience ....................... 6-11

7. Recommendations ........................................................................... 7-1
  7.1 Seismic Performance Objectives for Nonstructural Components ...... 7-2
  7.2 Response of Nonstructural Components in Earthquakes ............. 7-3
  7.3 Ductile Design of Nonstructural Supports and Attachments ....... 7-5
  7.4 Review of ASCE/SEI 7-16 Seismic Requirements for Nonstructural Components ......................................................... 7-5
  7.5 Additional Recommendations to Improve Nonstructural Performance ................................................................. 7-6

Appendix A: Detailed Review of ASCE/SEI 7-16 Seismic Requirements for Nonstructural Components ................................................. A-1
  A.1 General .................................................................................... A-1
    A.1.1 Scope ................................................................................. A-3
    A.1.2 Seismic Design Category .................................................. A-7
    A.1.3 Component Importance Factor .......................................... A-7
    A.1.4 Exemptions ....................................................................... A-9
    A.1.5 Pre-Manufactured Modular Mechanical and Electrical Systems .......................................................................... A-12
    A.1.6 Application of Nonstructural Component Requirements to Nonbuilding Structures ........................................... A-12
    A.1.7 Reference Documents ......................................................... A-13
    A.1.8 Reference Documents Using Allowable Stress Design .......... A-13
  A.2 General Design Requirements .................................................... A-13
A.2.1 Applicable Requirements for Architectural, Mechanical, and Electrical Components, Supports, and Attachments.......................................................... A-13
A.2.2 Special Certification Requirements for Designated Seismic Systems.................................................. A-14
A.2.3 Consequential Damage.......................................................... A-15
A.2.4 Flexibility........................................................................ A-16
A.2.5 Testing Alternative for Seismic Capacity Determination.......................................................... A-16
A.2.6 Experience Data Alternative for Seismic Capacity Determination..................................................... A-17
A.2.7 Construction Documents........................................................ A-17
A.3 Seismic Demands on Nonstructural Components.......................................................... A-17
A.3.1 Seismic Design Force.......................................................... A-17
A.3.2 Seismic Relative Displacements ........................................ A-18
A.3.3 Component Period................................................................ A-18
A.4 Nonstructural Component Anchorage.......................................................... A-19
A.4.1 Design Force in the Attachment............................................. A-19
A.4.2 Anchors in Concrete or Masonry............................................ A-20
A.4.3 Installation Conditions.......................................................... A-21
A.4.4 Multiple Attachments.......................................................... A-21
A.4.5 Power-Actuated Fasteners.................................................... A-22
A.4.6 Friction Clips................................................................... A-22
A.5 Architectural Components............................................................ A-22
A.5.1 General............................................................................ A-22
A.5.2 Forces and Displacements...................................................... A-24
A.5.3 Exterior Nonstructural Wall Elements and Connections.......................................................... A-24
A.5.4 Glass................................................................................ A-25
A.5.5 Out-of-Plane Bending.......................................................... A-25
A.5.6 Suspended Ceilings............................................................. A-26
A.5.7 Access Floors ................................................................ A-26
A.5.8 Partitions......................................................................... A-26
A.5.9 Glass in Glazed Curtain Walls, Glazed Storefronts, and Glazed Partitions............................................ A-27
A.5.10 Egress Stairs and Ramps...................................................... A-27
A.6 Mechanical and Electrical Components............................................... A-27
A.6.1 General ............................................................................ A-27
A.6.2 Mechanical Components...................................................... A-28
A.6.3 Electrical Components........................................................ A-28
A.6.4 Component Supports.......................................................... A-28
A.6.5 Distribution Systems: Conduit, Cable Tray, and Raceways................................................................ A-30
A.6.6 Distribution Systems: Duct Systems........................................ A-30
A.6.7 Distribution Systems: Piping and Tubing Systems.................. A-33
A.6.8 Distribution Systems: Trapezes with a Combination of Systems .................................................................. A-35
A.6.9 Utility and Service Lines......................................................... A-36
A.6.10 Boilers and Pressure Vessels.................................................. A-36
A.6.11 Elevator and Escalator Design Requirements.......................... A-36
A.6.13 Other Mechanical and Electrical Components .............. A-37
A.7 Consensus Standards and Other Referenced Standards ........ A-37

**Appendix B: Studies to Support the Development of Revised Nonstructural Design Force Equations**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1</td>
<td>Buildings, Seismic Force-Resisting Systems, and Ground Motions</td>
</tr>
<tr>
<td>B.1.1</td>
<td>Instrumented Buildings and their Ground Motion Recordings</td>
</tr>
<tr>
<td>B.1.2</td>
<td>Archetype Numerical Models and Selected Ground Motions</td>
</tr>
<tr>
<td>B.2</td>
<td>Effect of Ground Motion Intensity</td>
</tr>
<tr>
<td>B.2.1</td>
<td>Evaluation Based on the Response of Instrumented Buildings</td>
</tr>
<tr>
<td>B.2.2</td>
<td>Evaluation Based on the Response of Archetype Structures</td>
</tr>
<tr>
<td>B.3</td>
<td>Influence of the Building Modal Periods and Seismic Force-Resisting System</td>
</tr>
<tr>
<td>B.3.1</td>
<td>Evaluation Based on the Response of Multistory Instrumented Buildings</td>
</tr>
<tr>
<td>B.3.2</td>
<td>Evaluation Based on the Response of Archetype Building Models</td>
</tr>
<tr>
<td>B.4</td>
<td>Effect of Building Nonlinearity</td>
</tr>
<tr>
<td>B.4.1</td>
<td>Potential Amplification of Peak Component Acceleration Demands</td>
</tr>
<tr>
<td>B.4.2</td>
<td>Alternative Evaluation of Building Nonlinearity Based on Global Ductility</td>
</tr>
<tr>
<td>B.5</td>
<td>Effect of Inherent Building Viscous Damping</td>
</tr>
<tr>
<td>B.6</td>
<td>Effect of Building Configuration</td>
</tr>
<tr>
<td>B.7</td>
<td>Effect of Building Floor and Roof Diaphragm Rigidity</td>
</tr>
<tr>
<td>B.8</td>
<td>Incorporation of the Effect of Building Nonlinearity in the Proposed Equation</td>
</tr>
<tr>
<td>B.9</td>
<td>Studies on the Effect of Using Different Ground Motion Record Sets</td>
</tr>
<tr>
<td>B.9.1</td>
<td>Role of Component Ductility for Short, Stiff, Elastic Buildings</td>
</tr>
<tr>
<td>B.10</td>
<td>Evaluation of Proposed ( F_p ) Equation Using Archetype Models</td>
</tr>
<tr>
<td>B.10.1</td>
<td>Evaluation of Proposed Equation for Different Component Ductilities</td>
</tr>
<tr>
<td>B.10.2</td>
<td>Evaluation of Proposed ( F_p ) Equation at Different Relative Heights</td>
</tr>
</tbody>
</table>

**Appendix C: Component Period, Damping, and Ductility Studies**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>C.2</td>
<td>Background, Study Focus, and Methodology</td>
</tr>
<tr>
<td>C.2.1</td>
<td>Literature Review and Project Focus</td>
</tr>
<tr>
<td>C.2.2</td>
<td>Record Selection</td>
</tr>
<tr>
<td>C.2.3</td>
<td>Identification of the Building Modal Periods, ( T_{IMbdg} )</td>
</tr>
<tr>
<td>C.2.4</td>
<td>Normalization</td>
</tr>
<tr>
<td>C.3</td>
<td>Statistics and Fitting of PCA/PFA Data and the Effect of Component Damping</td>
</tr>
</tbody>
</table>