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FUTURE DEVELOPMENTS IN THE SEISMIC ANALYSIS AND DESIGN OF NONSTRUCTURAL COMPONENTS FOR BUILDINGS

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Abstract

Damage to nonstructural components has accounted for the majority of earthquake losses in recent earthquakes, especially in the United States and Chile. This damage primarily occurred to nonstructural components located within buildings. The current procedures for seismic design of nonstructural components were first introduced in the 1994 edition of the *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings* with the intention of lessening this damage. The procedures were subsequently incorporated into the 1997 edition of the *Uniform Building Code* and into the 2000 edition of the *International Building Code* and provided a substantial improvement in seismic design practice. Many new concepts, new to the building codes, were introduced, including consideration of dynamic properties of the component, location of the component within the supporting structure, and explicit attention to the relative importance of the component and component ductility. The nonstructural concepts developed in the 1994 *NEHRP Recommended Provisions* have been in use for over two decades, and since 1995 have been incorporated in the American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI) ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures*. Because of the timing and epicenter locations of recent earthquakes, nonstructural components designed and installed to satisfy these current seismic design procedures have not yet been subjected to significant damaging earthquakes.

In 2013, the National Institute of Science and Technology (NIST) published GCR 13-917-23, *Development of NIST Measurement Science R&D Roadmap: Earthquake Risk Reduction in Buildings* [1]. This document identified nonstructural issues as a top-priority for studies related to earthquake engineering for new and existing buildings. New research tools and analysis results as well the availability of new international standards, makes reexamination of nonstructural design criteria possible at this time. Accordingly, NIST initiated the ATC-120 project with the Applied Technology Council (ATC) in late 2014. The goal of this project is to improve technical aspects of nonstructural system design in the areas that will have the largest impact for public safety and economic welfare with an emphasis on determining whether or not a disconnect exists between current design requirements and observed (or expected) performance of nonstructural building systems and components. Where significant gaps are identified, technical solutions are proposed. The project is being conducted in two phases. In the first phase, knowledge studies were performed looking at both the literature and the current state of practice. The goal of the first phase was to understand performance criteria objectives and measures and to prioritize potential areas for further study. In the second phase, focused studies are performed on the priority areas identified in the first phase.

Summaries of the recently completed ATC-120 project knowledge study and workshop are presented. Recommendations for improving seismic analysis and design of nonstructural components and systems (NCSs) are discussed.

Keywords: nonstructural; components; architectural; equipment, seismic; performance

1. Introduction

The goal of the ATC-120 project, *Seismic Analysis and Design of Nonstructural Components and Systems*, is to improve technical aspects of nonstructural system design in the areas that will have the largest impact for public safety and economic welfare, with an emphasis on construction subject to building codes. The improvements are intended to have practical application to the most common types of structures, and be conceived in a manner that facilitates ease of implementation throughout those areas of the country with significant seismic hazard.

The focus of the first phase of the ATC-120 project effort was to collect and summarize the body of available knowledge related to nonstructural components that can serve as the foundation for future advancements. Substantial efforts have been made over the last 50 years to study the seismic performance of nonstructural components. The intent of this first phase effort was not to summarize all past research and development, but rather to describe the context for current code requirements and highlight select areas in which code developers would benefit from additional technical information to improve nonstructural design provisions. These areas include seismic performance observations, analytical studies, testing programs and practice issues. An important task was to determine if disconnects exist between current design requirements and observed (or expected) performance of nonstructural systems and components in buildings. Additional input was solicited through a workshop that included a diverse cross-section of design practioners. Problem-focused studies are recommended in areas where significant gaps or opportunities for improvement exist.

2. Earthquake Performance of Nonstructural Components

Post-earthquake observations of damage have provided the impetus for many of the advancements in seismic-resistant design. These efforts have emphasized describing and analyzing earthquake damage to the primary seismic force-resisting systems of structures. While damage to nonstructural components has been the primary source of losses in nearly all earthquakes, nonstructural performance is rarely discussed in depth. While there are hundreds of articles and reports that cover nonstructural performance at some level of detail, the initial phase of the ATC-120 project focused on the following select samples to provide better insight on how nonstructural performance is presented in post-earthquake reports, causes of nonstructural damage, and the effectiveness of building code provisions.

2.1 1964 Great Alaska Earthquake

A study was prepared by the firm of Ayres & Hayakawa for the U.S. Army Corps of Engineers Alaska District, Anchorage Alaska, in the aftermath of the magnitude-9.2 Great Alaska Earthquake on March 27, 1964 at the request of the National Academy of Sciences, Committee on the Alaska Earthquake, Engineering Panel [2]. A multi-disciplinary team of mechanical and electrical engineers, with the assistance of architects and an elevator consultant, completed this study in August 1967. Subsequently, the Consulting Engineers Association of California made this study broadly available in 1971. The 460-page report includes extensive descriptions of the performance of a wide range of nonstructural components, including elevators, mechanical and electrical systems, architectural components and systems, and building contents. With the exception of fire protection sprinkler systems, none of the nonstructural components were designed considering earthquake shaking. The scope of the report was limited to damaged nonstructural components in buildings in the Anchorage area, along with a few structures in Whittier, Alaska.

Nonstructural damage was widespread, with elevators and vibration-isolated equipment found to be especially vulnerable. Piping failures were attributed to large displacements of unbraced pipe, with damage commonly occurring at threaded fittings. Failures of pipe hangers were also observed and sections of piping fell. Fire sprinkler piping, the only nonstructural system consistently braced for lateral loads, performed well. Most tanks were unanchored and many failed. Damage to architectural systems was also widespread. Unreinforced masonry partitions failed, in some cases blocking exits in the buildings. Precast concrete panels fell from a department store in Anchorage, killing two people. Suspended lath and plaster and gypsum board ceilings suffered little damage, while suspended acoustical tile ceilings generally performed poorly. Lath and plaster partitions were badly cracked; stud and drywall partitions sustained minor damage.

The report includes a summary of the nonstructural design process in the mid-1960s. The building code requirements of the time focused on minimum standards to safeguard life. Seismic performance for most nonstructural components was considered a property damage rather than life safety issue. The design of nonstructural components was performed by subcontractors with limited review by the structural engineer or architect, a practice that persists to this day, especially in areas outside of California.

2.2 1971 San Fernando Earthquake

The 1971 San Fernando Earthquake caused significant damage to a large number of modern structures in the greater Los Angeles region, especially in the San Fernando Valley of Southern California. While the reports published following the magnitude-6.6 earthquake tended to focus on structural performance and damage, Ayres and Sun [3] documented and evaluated nonstructural damage to elevators, mechanical equipment, piping systems and light fixtures. The report did not address the performance of ceilings, partitions, electrical systems, exterior facades, and contents.

As in the 1964 Great Alaska Earthquake, damage to elevators was widespread, extending beyond the epicentral area into regions that experienced low ground shaking intensities. While the patterns of elevator damage were similar to those noted in the 1964 event, Ayres and Sun believed the increased lateral flexibility of modern buildings in the Los Angeles area contributed to the widespread damage. Except for fire sprinkler piping systems, little consideration was given to the seismic resistance of nonstructural components prior to the earthquake. While many mechanical components survived the earthquake with little damage, unanchored components shifted, rupturing pipe and duct connections. Little or no damage was observed to non-isolated components that were well anchored. Much of the damage to equipment was attributed to failures of vibration isolators.

2.3 1989 Loma Prieta Earthquake

Centered south of San Francisco in the Santa Cruz Mountains of Northern California, the magnitude-6.9 Loma Prieta Earthquake lasted less than fifteen seconds but caused more than $7 billion in damage and killed 62 people. An article covering nonstructural performance was published in an Earthquake Engineering Research Institute (EERI) special issue of Earthquake Spectra [4]. Nonstructural damage was widespread with the severity of damage strongly influenced by proximity to the epicenter and local ground conditions. The earthquake was one of the first significant tests of buildings constructed to the modern seismic codes of the time. Much of the data in the article is general in nature with limited specific descriptions of damage to individual structures. This was due in part to difficulty gaining access to the interior of building and lack of visibility from the exterior, making the actual level of damage to individual structures difficult to assess.

Some modern buildings suffered nonstructural damage severe enough to limit access. Damage to exterior glazing was observed throughout the region, and glazed storefronts in older buildings were particularly vulnerable. Damage to suspended acoustical ceiling systems was thought to result from the lack of splay-wire bracing. The article attributes great monetary losses to failure or lack of seismic restraints to utility systems. The reconnaissance observers noted failures of fire sprinkler mains and piping joints, with resulting flooding collapsing ceilings and in some cases causing the abandonment of entire floors. Patterns of damage to elevators similar to those occurring in earlier earthquakes were observed although seismic provisions for elevators had been adopted by the State of California in 1975, including requirements to upgrade existing elevators retroactively.

A study by Rihal [5] explored the nonstructural performance in detail of a thirteen-story, steel moment-resisting frame building in San Jose, California that was designed in 1972. This building was outfitted with strong motion recording instruments installed at grade level; the second, seventh, and twelfth floors; and at the roof. The recorded peak ground acceleration was about 0.10 g, while the peak acceleration at the roof was

0.34 g. Because a video survey of the building was immediately conducted following the earthquake, the performance of nonstructural components was available. Rihal correlated the shaking intensity at different levels to damage, including identification of different failure modes for nonstructural components. The study illustrates what could be achieved if nonstructural performance is properly documented immediately following an earthquake. The data can be used to understand reasons for poor performance during an earthquake and justify recommendations to improve the seismic performance of nonstructural components and systems.

2.4 1994 Northridge Earthquake

On January 17, 1994, a strong earthquake struck the San Fernando Valley west-northwest of downtown Los Angeles. The magnitude-6.7 event struck the same general region as that impacted by the 1971 San Fernando Earthquake. Following the earthquake, a series of reports on nonstructural performance were produced for the California Office of Statewide Health Planning and Development (OSHPD) [6]. Three reports examined seismic design factors for nonstructural components, water damage in hospitals, and elevator performance in hospitals. The reports utilized the extensive field reports generated by the OSHPD field teams immediately following the earthquake.

The seismic design factor study utilized data from the Olive View Medical Center, which includes an instrumented six-story steel plate shear wall structure built on the site of a hospital demolished following the 1971 San Fernando Earthquake. Designed in 1976 and completed in the mid-1980s, the hospital was located ten miles from the epicenter of the Northridge Earthquake and experienced very strong shaking, with peak horizontal acceleration of 0.8 g measured at the ground floor and 1.5 g measured at the roof of the Main Building. The authors of the study report had access to the original drawings and calculations for the nonstructural components and systems. Hundreds of nonstructural components were examined, comparing design forces and connection capacities to the actual earthquake demands. Given the strong shaking the site experienced, there was surprisingly little damage to equipment. However damage to ceiling systems and piping was extensive and led to evacuation of approximately 300 patients.

2.5 Observations on Post-Earthquake Damage Evaluations

Fifty years after the Great Alaska Earthquake, similar patterns of nonstructural damage emerge from many earthquakes today. This similarity in damage patterns is due to the age of the building stock, but perhaps more importantly, to a persistent reluctance to deal with three critical aspects of the nonstructural problems in new construction: design responsibility, code enforcement, and construction oversight. Technical enhancements and updated codes do not always lead to substantially improved performance, as evidenced by the changes in California to the elevator design requirements following the 1971 San Fernando Earthquake. Earthquakes in California over the 20 years following implementation of the elevator seismic requirements continued to reveal vulnerabilities. Translating the knowledge accumulated by post-earthquake reconnaissance efforts and implemented in building codes and standards into finished construction is an ongoing challenge.

3. Development of Standards for Nonstructural Component Seismic Design

Provisions for seismic design of nonstructural components have been present in building codes for nearly 90 years. From 1927 to 1976, slow progress was made on seismic provisions. Towards the end of this period, the nature of building construction began to change rapidly, with the introduction of modern heating and air condition systems, complex electrical systems, and modern cladding systems. Structures also changed, as flexible, drift-controlled frame structures gained popularity. Towards the end of this same period, damaging earthquakes increased interest in improving the seismic performance of nonstructural components. During this period, lateral design forces for nonstructural components were based on simple formulas that included variables for expected shaking intensity and a factor dependent on the type of components. At the same time, few detailing requirements were incorporated. Factors to account for the importance of the structure and soil-structure resonance were added in the 1976 *Uniform Building Code* (UBC) [7].

3.1 Evolution of Modern Standards for Nonstructural Components

The late 1970s saw rapid advances in the seismic design of nonstructural components, beginning with the publication of a groundbreaking document, ATC-3-06, *Tentative Provisions for the Development of Seismic Regulations for Buildings* [8], which profoundly influenced the development of seismic design. ATC-3-06 introduced nonstructural requirements based on Performance Characteristic Levels, a function of the type of component and the seismic hazard. The lateral force calculation for mechanical and electrical components considered amplification of lateral loads due to dynamic interaction between the component and the structure, and accounted for floor acceleration increases in the upper levels of structures. ATC-3-06 triggered a period of parallel developments in nonstructural component design. The UBC developed along traditional lines, with limited, simple nonstructural design provisions, while the ATC-3-06 provisions where further developed in new series of documents, starting with FEMA 95, *NEHRP Recommended Provisions for Seismic Regulations for New Buildings* [9] published in 1985, which has been periodically updated for decades and become a key seismic design resource document for U.S. building codes and standards.

In 1997, the last edition of the UBC [10] adopted the nonstructural design approach of the 1994 *NEHRP Recommended Provisions* and in 2000 the first edition of the *International Building Code* (IBC) [11] adopted the nonstructural design approach of the 1997 *NEHRP Recommended Provisions* [12], beginning a period of convergence between the codes and the *NEHRP Recommended Provisions.* Building codes had also begun a transition from an all-inclusive document into which text from different reference standards was transcribed, to a document that adopted standards by reference. To support the transition, ASCE/SEI 7-02, *Minimum Design Loads for Buildings and Other Structures* [13], was updated from the first (1988) edition of ASCE/SEI 7 to incorporate the seismic provisions of 2000 *NEHRP Recommended Provisions* [14]. The 2003 IBC [15] adopted ASCE/SEI 7-02 by reference for seismic design. From this point forward, revisions to the design procedures for nonstructural components were made in ASCE/SEI 7 rather than in the building codes themselves.

3.2 Seismic Design Provisions for Nonstructural Components in New Structures

The seismic design provisions for nonstructural components in new structures are currently contained in Chapter 13 of ASCE/SEI 7-10 including Supplement No. 1 [16]. The next edition of the *International Building Code* (IBC) in 2018 will reference ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [17], which represents the latest iteration of the nonstructural procedures that been continuously developed since their first appearance in the 1997 UBC. The nonstructural provisions of ASCE/SEI 7-10 are organized in six sections, covering information on the applicability of the nonstructural design provisions, determination of the relative importance of the component and methods for establishing compliance with the standard, procedures for determining acceleration and displacement demands, design of attachments of components to the structure, and detailed requirements for architectural, mechanical, and electrical components. Components are classified by their importance and those identified as critical to life safety or essential to facility function are classified as “designated seismic systems” and are subject to more stringent design and quality assurance requirements. Smaller non-critical components may be completely exempt from seismic design based on their weight, size (for distribution systems), and mounting configuration. Most furniture and building contents are exempt from the seismic provisions of ASCE/SEI 7-10 and ASCE /SEI 7-16.

ASCE/SEI 7-10 provides several options for establishing compliance with the nonstructural requirements, including project-specific design and documentation, and manufacturer’s certification. Designated seismic systems may be subject to special certification requirements if they are required to remain operable following the design earthquake, or if they exceed certain amounts of hazardous substances. Special certification may require shake table testing, experience data, or more advanced analysis to establish compliance. Acceleration demands on nonstructural components may be determined using several approaches. The most commonly used formula accounts for variation of acceleration with relative height within the structure, without regard for the specific nature or dynamic properties of the building structure.

Dynamic analysis methods are available for determining building-specific values of the seismic design force if the dynamic properties of the building are known. These methods are intended for use on base-isolated and long-period structures, where component acceleration demands are expected to be lower than those predicted using the commonly used formula. ASCE/SEI 7-16 also includes options for determining component accelerations using nonlinear response history analysis and floor response spectra methods.

3.3 Design Forces for Nonstructural Components and Attachments

The magnitude of the design forces for nonstructural components are dependent on a number of variables including the type of component, the seismic hazard level, the importance of the component, and its location in the structure. Different design standards over the years have considered some of these variables; the current standard considers them all. To illustrate the variations in component design force over time, consider a rooftop air-handling unit mounted on a structure in San Francisco, California, a region of high seismic risk. Per ASCE/SEI 7-16, the Seismic Design Category (SDC) of the structure is D, and the short-period ground spectral acceleration, S_{DS}, equals 1.0. Table 1 lists the horizontal strength-level, nonstructural component design force required by selected editions of the UBC, IBC, *NEHRP Recommended Provisions*, and ASCE/SEI 7. Note that ASCE/SEI 7 was adopted by reference in the 2003 and later editions of the IBC. It should be noted that in some cases, a small changes in a value listed in Table 1 from one edition to the update of next edition was in fact due to substantial counteracting changes in some of the parameters used to calculated the design force. Since 2002, the design force for this example component has remained constant at around 50 percent of the weight of the component (W_p).

Table 1 – Comparison of Nonstructural Component Design Force in Various Code and Resource Documents for a Rooftop Air-Handling Unit in San Francisco

Edition	UBC/IBC	NEHRP	ASCE/SEI 7
1927-1973	--	--	--
1976	0.63 W_p	--	--
1979-1982	0.42 W_p	--	--
1985	0.42 W_p	0.80 W_p	--
1988	0.84 W_p	0.80 W_p	--
1991	0.84 W_p	0.40 W_p	--
1994	0.84 W_p	0.53 W_p	--
1997	1.46 W_p	0.48 W_p	--
2000	1.46 W_p	0.48 W_p	--
2002	--	--	0.48 W_p
2003	0.48 W_p	0.48 W_p	
2005	--	--	0.50 W_p
2006-2016	0.50 W_p	0.50 W_p	0.50 W_p

A great many nonstructural components are attached to concrete slabs and walls, or masonry walls. Post-installed anchors are often preferred for the attachment of nonstructural components, due to both the difficulty of accurately locating cast-in-place anchors, and because in many cases the exact nonstructural component has not been selected when the slabs or walls are constructed. Prior to the 1994 Northridge Earthquake, post-installed anchors were designed to withstand the calculated seismic force on the component without modification, and allowable anchor capacities were based on static tests with a factor of safety of four for anchors installed with special inspection and eight if installed without special inspection. Following reports of nonstructural component damage due to failures of anchors in the 1994 Northridge Earthquake, both the anchor capacities and the calculated seismic demands were reexamined. Over the next two decades, there were substantial changes in the design of nonstructural component anchorage, with reduction in anchor capacities under seismic loading, and increased anchor design forces. In ASCE/SEI 7-16, the design force for anchors, deemed to have nonductile behavior, depends on the values of the amplification, response and overstrength factors of the component, and can range from 50 % to 100 % higher.

4. Simulated Seismic Testing of Nonstructural Components and Systems

To complement analytical studies and field observations, experimental studies of nonstructural components and systems (NCSs) have been conducted to advance the state of understanding regarding their seismic performance. Depending on the experimental scope and objective, the simulated seismic testing of NCSs are categorized as system-level building shake table tests, component tests, and designated seismic system qualification tests.

4.1 System-Level Building Shake Table Tests

In recent years, a number of system-level shake table experimental research projects on nonstructural components and systems were completed. A representative example of one of the most recent tests was a unique research collaboration between academia, government, and industry, coined the Building Nonstructural Components and Systems (BNCS) project. The test was undertaken to contribute to understanding the earthquake resiliency of nonstructural components and systems [18]. The centerpiece of this research effort involved shake table testing of a full-scale five-story reinforced concrete building outfitted with a large variety of essential NCSs. These tests were completed in 2012, contribute a wealth of high-resolution physical data to the earthquake and fire engineering communities and will provide direct input to modeling tools, future design codes, and construction practices.

The shake-table test program was performed at the University of California, San Diego (UCSD) and involved two test phases: (1) earthquake shaking while the building was isolated at its base (BI Phase); and (2) earthquake shaking while the building was fixed at its base to the shake table (FB Phase). The test building, consisting of a cast-in-place five-story reinforced concrete structure with moment resisting frames providing lateral resistance in the direction of shaking, was outfitted with operable egress systems (elevator and steel stairs), a complete façade, a broad array of architectural layouts, and two floors of the building equipped as medical facilities.

The test building was subjected to a sequence of dynamic input motions at the base of the building, while the building was first tested in base isolated and subsequently in fixed base configurations. These excitations, 13 earthquake motion tests, 31 low amplitude white noise base excitation tests and 45 pulse-like base excitation tests, were conducted using the UCSD Large High-Performance Outdoor Shake Table. Each of the input motions was applied in the east-west direction using the single-axis shake table, whose axis coincided with the longitudinal axis of the building. The earthquake input motions selected in the test program encompassed a broad range of characteristics including different frequency contents as well as varied strong motion durations and amplitudes. The largest amplitude motion, recorded in the 2002 Denali Earthquake at TAPS Pump Station No. 9, was a spectrally matched code-shaped target response spectrum with spectral acceleration values of S_{MS} = 2.1 g and S_{M1} = 1.4 g.

In the BI Phase, the seismic demands were low, with peak interstory drift ratios less than 0.4 % and peak floor accelerations less than 0.3 g. The building sustained only minor damage to its most brittle nonstructural components such as partition walls and very little damage to its structural components. In the FB Phase, earthquake motions were applied with increasing intensity to progressively damage the structure. For the design level event, the test building achieved the design target peak interstory drift ratio of about 2.5 %, while the final test represented an event well above the design event scenario with peak interstory drift ratios of 6 % observed. The building sustained extensive damage during the last two FB tests from large seismic drift demands.

The observed damage of the NCSs was classified as three discrete damage states: minor, moderate, or severe. Damage states were subsequently correlated with either measured peak interstory drift ratio or peak floor acceleration. Several NCSs in the test program demonstrated quite good performance, attaining design expectations and remaining functional despite the very large demands imposed upon them. These NCSs, which were limited to mostly minor damage throughout the test program, included the fire sprinkler system, seismically designed ceilings, roof-mounted equipment, and restrained contents. The precast concrete cladding panels and the passenger elevator were subjected to moderate or severe damage only during the last two earthquake motions in the FB test phase. Some NCSs installed in the test building experienced unacceptable levels of damage, including prefabricated steel stairs, a cold-formed steel balloon framed exterior wall system overlaid with synthetic stucco, and unrestrained medical equipment.

4.2 Component Testing

Representative of component tests are a series of shake table experiments to study the seismic behavior of suspended ceiling systems conducted at the University at Buffalo–The State University of New York [19]. A total of fifteen suspended ceiling assemblies were tested, ranging in size from 400 square feet to 1000 square feet in area. In each of the fifteen test configurations, the suspended ceiling was subjected to a series of test motions with increasing amplitude. The motions were intended to target a floor response spectrum at the roof level of the test frame, which followed the required response spectrum as defined in ICC-ES AC156 [20]. The peak vector sum of the horizontal table acceleration varied from 0.16 g to 2.56 g, which resulted in a maximum of 3.40 g for the horizontal accelerations at the center of the roof level. The maximum vertical table acceleration was 0.68 g, which resulted in a vertical acceleration of 1.54 g in the mid-bay of the roof level. Damage to the suspended ceiling systems occurred in the form of panel tile damage (e.g., dislodged panels, fallen panels) and ceiling grid connection damage (e.g., seismic clip failure, grid connection failure).

4.3 Designated Seismic System Qualification Testing

Special seismic certification was introduced to provide a greater assurance that designated nonstructural components will perform as expected at design level seismic motions. Expectations for special seismic certified components is that the equipment will maintain structural integrity with minor yielding and damage allowed; however, the equipment must retain its functionality/operability following the design earthquake. Seismic qualification of equipment has been prevalent in the nuclear and defense industries since the 1970s. The requirements for special seismic certification of designated seismic systems in commercial, industrial, and institutional structures was first introduced into the building code in the 2000 IBC.

Seismic certification may be conducted using several code accepted methods. Under ASCE/SEI 7-05, seismic certifications can be conducted via analysis, testing, or experience data. Nonstructural components are grouped into two categories of either active or passive. Active components have either mechanical moving parts or energized electrical systems or a combination of both. In general, active components can be certified only by testing or experience data due to the complex nature of trying to predict operability of electrical circuits and moving parts in analysis software. Passive components can be certified by analysis, testing or experience data. The shake table testing requirements and acceptance criteria are contained in AC156.

A wide variety of mechanical, electrical and some architectural components have been tested. Testing has revealed vulnerabilities in the equipment and resulting changes have been made to improve the seismic ruggedness of nonstructural equipment. The test results have been positive for some types of robust/rugged equipment. The testing has also exposed vulnerabilities in some equipment, such as inadequate seismic load path bracing, screws used to resist out-of-plane loads in sheet metal, and anchorage which has spawned changes to the design provisions.

5. Analytical Studies on Horizontal Floor Response Spectra

Many studies have evaluated individual parameters that form part of equations to estimate the horizontal design force for nonstructural components, F_p. These studies tend to focus on a single equation, ASCE/SEI 7-16 Eq. 13.3-1, or individual variables within the equation. Estimates of peak floor accelerations represented by ASCE/SEI 7-16 Eq. 13.3-1 increase linearly with height to a maximum value of three (3) at the roof level independently of the fundamental period of the supporting structure. These estimates are subject to the minimum and maximum forces given in Eq. 13.3-2 and Eq. 13.3-3. There are numerous studies using analytical models of varying degrees of sophistication that suggest that the simplified equation will produce overly conservative results, especially when applied to tall, longer period structures. Studies also suggest that amplification of horizontal motions due to dynamic interaction of the component and the structure may be underestimated by the simplified method. However, a comprehensive, holistic review of all factors contributing to seismic demands and observed performance of nonstructural components and systems, using the latest information from instrumented buildings, laboratory tests and analytical studies is lacking.

The effectiveness of various ASCE/SEI 7 force equations to estimate seismic force demands for nonstructural components and systems, and whether the ASCE/SEI 7 requirements provide cost-effective protection of nonstructural components and systems has been difficult to evaluate from recorded earthquake data. This evaluation has not been possible primarily because earthquakes that generated design-level or greater ground motions in populated areas have not occurred in regions with many structures designed using modern codes. Even when instrumentation is present, nonstructural components, their supports, and attachments are generally not instrumented. An evaluation of design force equations for nonstructural components and systems in the context of all the different requirements for nonstructural components is needed.

6. Practice Issues

Reducing nonstructural earthquake losses requires not only technically sound code requirements, but also effective implementation during all phases of design and construction. Many parties, including design professionals, contractors, subcontractors, manufacturers, inspectors and building officials, are responsible for implementation.

Practice issues were explored in a 2009 study undertaken by Masek and Ridge [21]. This was the first effort designed to build on anecdotal evidence and provide an understanding of the reasons for compliance and noncompliance with code requirements related to nonstructural design. The EERI study focused on identifying the primary inhibiting and enabling factors affecting nonstructural seismic design and construction practices. Factors included perceptions of current compliance with existing codes and standards, why compliance was lower than required by building codes, and who should be responsible for nonstructural seismic design and construction. There was consistent agreement that the state of practice for nonstructural seismic design and construction was not adequate, and agreement that noncompliance with current building codes occurred frequently.

As part of the first phase of the ATC-120 project, a facilitated workshop was conducted to solicit input from practicing nonstructural component designers, equipment qualification test engineers and engineers involved with the structural design of nonstructural components and systems for buildings about the challenges they face with nonstructural code provisions, design guidelines, and related implementation. The workshop was structured to obtain an independent recommendation from the attendees. Participants identified those aspects of the nonstructural component design and analysis requirements contained in ASCE/SEI 7-10 that they believe work well and those aspects that should be changed to reduce future nonstructural losses in seismic events.

Participants felt that building code requirements for life-safety are generally adequate. There was a general belief that the current code provisions are adequate to limit most serious injuries and avoid casualties. Force levels were generally judged to be reasonable and sufficient. However, enforcement of nonstructural code provisions, quality control, and protection from hazards posed by building contents and furniture all are in need of improvement, and it was believed that loads required for anchorage to concrete are too high. In addition, it was felt that differential movement and story drift requirements need improvement, and that code performance objectives are unclear. Finally, there were concerns that architects, and mechanical and electrical engineers do not generally understand the nonstructural component design provisions in ASCE/SEI 7. The standard should be more clearly written, or contain introductory language in the commentary, to help these individuals know which of the building elements under their responsibility require design and seismic restraint.

7. Conclusions

The vulnerabilities of nonstructural components in modern buildings were identified following the 1964 Great Alaska Earthquake. At that time, there was a debate regarding seismic performance objectives for nonstructural components, and whether codes and standards should provide any level of performance other than life safety in a strong earthquake. Recommendations for changes to the building code were made, and over the next 50 years, many other changes were implemented based on observations of nonstructural performance in earthquakes. In almost every earthquake, nonstructural damage is a leading source of losses. While codes and standards evolve, the effectiveness of the new procedures for nonstructural components is difficult to gauge. In any earthquake, only a fraction of the impacted structures has been subject to modern nonstructural design standards, and an even smaller fraction of the structures actually comply with those standards especially for nonstructural components.

One of the observations made following the 1964 Great Alaska Earthquake was that the very nature of the design and construction process was a major impediment to good nonstructural performance. While the design and construction of buildings is a combined effort of a large group of skilled individuals, often only a few individuals on the project are familiar with seismic design of nonstructural components. Those most knowledgeable about seismic design may only be involved in the primary structural system, which usually represent only a fraction of the investment in the project.

There is a tendency to minimize the potential safety risks posed by nonstructural damage, based on the assumption that the vast majority of deaths and serious injuries in earthquakes will be the result of full or partial building collapses. This belief is supported by the low death tolls in earthquakes that have occurred in United States. The low casualty figures may be due in part to chance. The 1964 Great Alaska Earthquake occurred after 5:00 PM on Good Friday. Most people were either home or on their way home, few were in schools and businesses. The 1971 San Fernando and 1994 Northridge Earthquakes both occurred in the early morning hours, when schools and businesses were empty. Had any of these earthquakes occurred during the work week when schools and businesses were crowded, casualties due to nonstructural damage would have been much higher.

The first phase of the ATC-120 project identified opportunities for improvement in the nonstructural component design and construction process. If addressed, they will have a substantial impact for public safety and economic welfare. The recommendations extend beyond code development, and include implementation and practice issues believed to be essential for making measurable progress in reducing nonstructural earthquake damage. Technical subjects for research and development are specifically highlighted, as opposed to policy development, and include the suggested scope and approach for proposed problem-focused studies.

The primary objective of this research plan is to present a list of recommended studies that will lead to improved seismic performance of nonstructural components. This list is the result of a comprehensive background knowledge study that collected and summarized the body of available information on nonstructural design and performance, and identified areas of needed research. A workshop with participants representing a broad spectrum of the nonstructural design and construction industry was conducted in parallel to gather a practitioner perspective on the challenges associated with nonstructural code provisions, design guidance, and related implementation. Although there was considerable general agreement between issues identified in the background knowledge study and the workshop, workshop participants particularly emphasized concerns about the installation, attachment, and inspection of nonstructural components. Recommendations from the workshop are integrated into this research plan.

A secondary objective of this plan is to identify an approach for conducting each recommended problem-focused study to facilitate planning for future work. Each study was developed in sufficient detail to describe: (1) the importance of the proposed study; (2) a general methodology for completing each study; and (3) recommended sub-projects to facilitate planning and implementation. Although the details of each recommendation are not provided in this paper, they can be found in *Seismic Analysis, Design, and Installation of Nonstructural Components and Systems – Background and Recommendations for Future Work* [22], along with more information about the background knowledge study and the workshop.

Studies have been grouped by topic into six subject areas and placed in two priority tiers. Priority 1 studies represent efforts that are judged to be foundational for the further development of nonstructural seismic design requirements, or that will have immediate impact on the practice of design and installation of nonstructural components and systems. Priority 2 studies are important, but are not judged to have as great an impact on overall improvement of the performance of nonstructural components and systems. Each study has been broken down into smaller sub-studies. Some of these sub-studies are linked to other sub-studies and need to be completed sequentially, while other sub-studies may be independent enough that the completion of the sub-study could lead to incremental improvement in the seismic performance of nonstructural components and systems. The breakdown of each of the six subject areas for studies into selectable sub-studies are provided in Table 2.

Table 2 – Summary of Recommended Future Studies and Sub-Studies

Priority	Study or Sub-Study No.	Description
1	1.0	Conduct Holistic Assessment of Current Code Design Approaches
	1.1	Create Archetype Building(s)
	1.2	Define Ground Motions for Study
	1.3	Conduct Building Analyses and Develop Generic Floor Spectra
	1.4	Analytically Determine Demands on Nonstructural Components
	1.5	Evaluate Code Design Force Equations
	1.6	Evaluate Anchor Design Procedures
	1.7	Propose Nonstructural Components and Systems Code Changes
1	2.0	Develop Nonstructural Component and System Performance Objectives
	2.1	Create a Framework for Nonstructural Performance Objectives
	2.2	Build Consensus for Nonstructural Performance Objectives
1	3.0	Improve Implementation and Enforcement of Code Requirements
	3.1	Hold Workshops to Identify Opportunities for Improvement
	3.2	Develop Targeted Materials and Related Training
1	4.0	Clarify Requirements for Displacement Capability Design of Nonstructural Components and Systems
	4.1	Determine Nonstructural Displacement Demands and Associated Acceptance Criteria
	4.2	Develop Enforcement and Inspection Criteria for Displacement Control
	4.3	Create Guidelines for Designers
2	5.0	Create a Plan for Post-Earthquake Reconnaissance and Data Collection
	5.1	Develop Framework for Data Collection
	5.2	Create Data Collection Protocols
2	6.0	Conduct Component Testing
	6.1	Identify Vulnerable Components for Testing
	6.2	Create Testing Protocols
	6.3	Conduct Tests

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