Improved Seismic Design of Nonstructural Components and Systems (ATC-120)

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Abstract

NIST, through the ATC-120 Project, sponsored a detailed investigation into the basis of nonstructural seismic design provisions, with the intent of recommending improvements that will have the largest impact to public safety and economic welfare. Research, development and targeted investigations are in the final stages of completion. The project included a detailed knowledge study documenting performance of nonstructural components in past earthquakes, history and evolution of nonstructural seismic design provision and criteria, analytical investigations and shake table testing. A practitioners’ workshop, which included participation from many SEAOC members, was convened to obtain broad-based industry input on nonstructural seismic design issues. Building on this knowledge, a comprehensive analytical study of relevant factors contributing to seismic performance of nonstructural components and systems was undertaken, providing a technically sound basis for proposed code changes. A set of nonstructural performance objectives is proposed, in addition to code changes that seek to clarify, organize and simplify nonstructural design requirements. Finally, a new design philosophy for nonstructural components is proposed.

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.
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 to serve as the foundation for future advancements (1). This “Knowledge Study” included examining information from seismic performance observations, analytical studies and testing programs. Practice issues were explored through a workshop that included a diverse cross-section of design practitioners. 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.

The second and final phase of the project includes a holistic assessment of current design procedures with three areas of focus: (1) evaluating current building code requirements for clarity, consistency, completeness and technical soundness; (2) developing clear nonstructural performance objectives as a foundation for code requirements; and (3) understanding the response of nonstructural components to earthquake motions through analytical investigations. A new design philosophy for nonstructural components is conceived based on the concepts of capacity-based design similar to what is done in the design of structural systems. This paper summarizes key findings of the ATC-120 project to date and recommended changes to improve seismic design of nonstructural components and systems.

**Simulated Seismic Testing of Nonstructural Components and Systems**

Many experimental studies of nonstructural components and systems have been conducted to better understand their seismic performance. Testing includes system-level building shake table tests, component tests, and designated seismic system qualification tests, each providing useful insights into performance.

In recent years, a number of system-level shake table experimental research projects on nonstructural components and systems were completed. One recent test was a unique research collaboration between academia, government, and industry, coined the Building Nonstructural Components and Systems (BNCS) project. The test, performed at the University of California, San Diego, was undertaken to contribute to understanding the earthquake resiliency of nonstructural components and systems [2]. 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 nonstructural components. 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 medical facilities on two floors of the building. The building was tested as a fixed base and base-isolated structure.

Several nonstructural components and systems in the test program demonstrated quite good performance, attaining design expectations and remaining functional despite the very large demands imposed upon them. These included the fire sprinkler system, seismically designed ceilings, roof-mounted...
equipment, and restrained contents. Some components 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.

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 [3]. A total of fifteen suspended ceiling assemblies were tested, ranging in size from 400 square feet to 1000 square feet in area. 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).

The introduction of special seismic certification requirements into the building codes provides a greater assurance that critical nonstructural components will perform as expected at design level seismic motions. Compliance with these requirements generally involves shake table testing. The expectation for special seismic certified components is that the equipment will maintain structural integrity with minor yielding and damage allowed and, more importantly, the equipment must retain its functionality/operability following the design earthquake shaking intensity. The most commonly used shake table testing requirements and acceptance criteria for buildings is AC156 [4]. An extensive listing of equipment with Special Seismic Certification can be found on the website of the California Office of Statewide Health, Planning and Development (www.oshpd.ca.gov).

A wide variety of mechanical, electrical and architectural components have been tested. Testing reveals vulnerabilities in the equipment and changes are often made to improve the seismic ruggedness of nonstructural equipment as part of the testing program. The testing has revealed that some types of equipment are inherently robust and rugged. Conversely, testing exposes vulnerabilities in other equipment, such as inadequate seismic load path bracing, like screws used to resist out-of-plane loads in sheet metal, and anchorage which has spawned changes to the design practice.

**Evolution of Modern Standards for Nonstructural Components**

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. 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 shaking amplification based on soil conditions were added in the 1976 Uniform Building Code (UBC) [5].

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 [6], 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. In 1997, the last edition of the UBC [7] adopted the nonstructural design approach of the 1994 NEHRP Recommended Provisions.

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 [8]. The next edition of the International Building Code (IBC) and California Building Code (CBC) will reference ASCE/SEI 7-16, Minimum Design Loads and Associated Criteria for Buildings and Other Structures [9], 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 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. Component requirements are based primarily on the Seismic Design Category and the Importance Factor assigned to the them, with many components not having any requirements except in regions of highest seismicity (Seismic Design Category D and
higher). 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.

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.

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. 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 widespread 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 reductions 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 is subject to increases of 100%, depending on the values of the amplification, response and overstrength factors applied to the component.

Practice Issues

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

Practice issues were explored in a 2009 EERI study undertaken by Masek and Ridge [10]. 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 actual compliance was often 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 inadequate, 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 independent recommendations from the attendees. Participants identified those aspects of the nonstructural component design and analysis requirements contained in ASCE/SEI 7 that they believe work well and those aspects that should be changed to reduce future nonstructural losses in seismic events.

Participants judged 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.
Nonstructural Performance Objectives

Performance objectives help define the target expectations for buildings and nonstructural components at different earthquake hazard or shaking levels. Performance objectives are commonly expressed as a pairing of an earthquake shaking intensity with a specified performance level. The performance level can be either the non-occurrence of something, i.e. no collapse or loss of function, or a probabilistic metric. For buildings, performance objectives vary depending on the type of building and what use it serves. For nonstructural components, performance objectives, other than protecting against falling hazards in general, currently vary primarily depending on the function of the component and its importance in the functional objectives for the building. As such, nonstructural components objectives are somewhat dependent on the building performance objectives.

Code-based design requirements for new buildings, for both structural and nonstructural components and systems, focus on checking performance in the Design Earthquake, with the assumption that a design satisfying the design level requirements will implicitly lead to an acceptable level of performance at lower “serviceability” level or higher “maximum considered earthquake” levels. In the current ASCE 7 code, there are also risk categories where there are different levels of performance expectations and objectives for different types of buildings. Thus, “special” buildings that provide important functions following a major event—such as a hospital, fire station, police station, or emergency operations center—have higher objectives than more “ordinary” buildings. It can be directly inferred that that these higher objectives are achieved at the design earthquake level by reducing the inelastic behavior in structures and nonstructural components (represented by the inelastic reduction factor, R, divided by I or Ip in calculations of design demands) and adding other requirements such as more restrictive story drift limits, evaluation of equipment for operability following design earthquake shaking intensity, and enhanced quality assurance requirements.

The building code represents a minimum required lower bound or “floor” for design depending on the specified risk category. The level of seismic performance provided by a minimum code design, however, may not be uniform. It depends on the lateral force-resisting system selected and attention given to the structural and nonstructural systems design and detailing. A well-designed code minimum building is likely to meet the performance objectives described in the ASCE/SEI 7 commentary. Owners are free to select higher performance objectives if they have important functions and contents they wish to protect, and the level of performance described for a code minimum design will not meet their requirements. Increasingly, discussions of community and business resilience have raised questions as to whether it may be prudent for the local building code or a community to encourage or require higher seismic performance to improve the speed and effectiveness of recovery from a major earthquake, or whether higher risk categories than currently assigned should be required for certain types of facilities that are deemed vital to community recovery following a strong earthquake.

While structural performance objectives have evolved considerably over time, both qualitative and quantitative expressions of nonstructural performance have lagged behind. Presently, quantitative expressions of structural performance are in use and are the subject of ongoing development. For buildings of ordinary importance designed for code compliance, the structural performance objectives focus primarily on protection of life safety, expressed as an acceptably low probably of collapse in a rare, powerful seismic event, the MCE. Performance of buildings when subject to more frequent, less severe earthquakes is expressed in qualitative terms, focusing on reparability and limited loss of function. Nonstructural performance objectives, however, are described in more general terms. There are no criteria for nonstructural performance in MCE shaking. The clearest nonstructural performance goal is prevention of collapse or detachment of nonstructural components that pose a serious risk to life safety when subject to the Design Earthquake, defined as two-thirds of the corresponding MCE effects. Provisions also attempt to provide protection for items that may represent a serious threat to property, but the lack of specificity as to exactly what is trying to be achieved means that there is no clear foundation for related building code requirements. For components identified as critical, the code intends to protect function of those components following the design earthquake.

The ATC-120 project proposes explicit performance objectives for nonstructural components and systems subjected to seismic shaking. The performance objectives are intended to serve as a transparent basis for nonstructural code requirements. The performance objectives developed and proposed by the ATC-120 project are intended to be a starting point for community-wide discussion with the intent of arriving at a consensus set of objectives that will be adopted by future code and standards writers. These objectives can also be translated in to explicit goals for performance-based design of nonstructural components and systems. ATC-120 also provides guidance to building owners and communities who
elect to establish higher performance objectives than the minimum objectives prescribed by the code.

In addition, there are desires to more clearly define a functional level earthquake, where the building and important components within it continue to function. In theory, the size of this level varies depending on the use or risk category of the building. It should be noted that the current version of ASCE 7 presumes that the Design Earthquake is the functional level earthquake for Risk Category IV buildings and other structures, and for designated seismic systems, those nonstructural systems with Ip = 1.5) such as egress stairs and fire protection systems, in all buildings.

In order to develop consensus performance objectives, an underlying philosophy must first be established. To help develop and refine a philosophy for nonstructural performance objectives, the ATC-120 project considered a range of issues that were discussed and/or debated, within the project team. Not all issues were brought to resolution with the unanimous agreement of all project participants. The recommendations of the project participants are described below.

**Should goals for nonstructural components be the same or less stringent than those for buildings?** Generally, nonstructural goals can be less stringent than those for buildings because for most nonstructural components and systems the risk to safety given failure is less. However, a limited number of nonstructural components may need to maintain their safety function in strong but less severe shaking even though some structural damage may be acceptable. This is consistent with the performance objectives in the SEAOC Bluebook [11] as well as ASCE 7.

**Should there be performance objectives for nonstructural components at multiple levels of earthquake shaking?** Yes. It is desirable to establish clear expectations for the performance of nonstructural components in a range of earthquake shaking levels. For small and more frequent levels of ground shaking, it is typical to ask for and expect no or limited damage. For shaking at design level demands, some nonstructural damage can generally be tolerated in ordinary buildings, while limitations on damage are required in buildings that need to remain in service after an earthquake. A key question is whether there should be performance objectives for nonstructural components in the MCEω. There may be a small subset of nonstructural components whose failure is as bad or worse than partial collapse of a building and thus, should have performance objectives in the MCEω. Additionally, there may be some components that, because of the consequences of damage, should have performance objectives in the MCER.

**Should there be prescriptive design requirements for nonstructural components associated with multiple levels of earthquake shaking?** No, the building code is already complicated enough. Design should be required for one level of earthquake shaking as we do now. Calibration studies should be conducted to demonstrate that design for one level will generally provide the desired performance at the other earthquake levels.

**Approximately how many people have to be at risk from damage to a nonstructural component before making a mandatory requirement to try to limit the risk?** Damage to nonstructural components can often result in potential harm to a small number of people, such as if a single component falls and hurts one individual in the falling path or an unlucky maintenance worker is in a mechanical room when an unanchored large piece of equipment moves and impacts the worker. Or the component failure could be more severe such as heavy cladding blocking an egress path or falling through a neighbor’s roof. Or the component failure could be quite severe such as a large hazardous material release or gas line break than could endanger many. A desirable target is to provide a reasonable degree of protection against failure mechanisms that could realistically be seen to cause casualties, even if the impact is localized and the number of people impacted is small.

**Should there be guidance on how to achieve improved performance for owner-selected or community-selected enhanced performance?** Yes. This will be increasingly important. Providing a framework for how owners can implement enhanced performance will increase the likelihood this is done and that it is done effectively and economically. While the code will continue to regulate minimum requirements, the framework is applicable for implementing performance-based design and achieving enhanced performance.

In order to develop performance objectives that are applicable to all components and systems, an overarching framework that identifies the essential requirements is needed. The ATC-120 project examined a comprehensive list of components and systems to understand the consequences of damage and identified three broad design objectives: (1) protect safety, (2) limit property damage and (3) maintain building function. Each is described below.
Safety – The most basic performance objective in the building code is the protection of safety. Nonstructural damage can create safety breaches in many different ways depending on the size and nature of the component. Floor-mounted nonstructural components can slide or overturn under seismic shaking, and wall-mounted or suspended components can become dislodged and fall. The consequences of these behaviors will vary depending on the size and weight of the component, its contents, the contents of interconnected systems, and location. For example, damage to a lightweight acoustic tile ceiling grid has a low probability of causing serious injury or death. On the other hand, suspended equipment and/or a heavy ceiling over an auditorium would place many more people at risk of serious injury or death. In extreme cases, damage to nonstructural components could pose a serious safety threat to large numbers of people. In some cases, the threat is not to occupants inside the building, but to people outside the building who are vulnerable to dislodged cladding or release of hazardous materials.

Central to modern building code requirements is the premise that in large earthquakes, structural and nonstructural damage are expected, but building occupants will be able to safely exit the building and first responders will be able to enter the building. Thus, nonstructural components should be designed to protect paths of egress including stairwells and exit ways. There is general agreement in the ATC-120 project that stairs should be free of falling debris, doors from primary egress stairs should be operable and areas immediately outside the egress doors should be free of heavy falling debris. Safety can also be compromised if a fire ignites. Nonstructural components are often the direct source of ignition such as when a gas-fueled piece of equipment moves and breaks the gas line. People can also be put at risk of injury or death if a fire ignites and the fire protection system is inoperable due to damage.

Function – Nonstructural damage can make it difficult or impossible to carry out functions that are normally accomplished in a building. For buildings that house functions critical to post-earthquake recovery, providing continuity of operations is an essential objective. Depending on the nature of the operations conducted in a building, loss of use or business interruption costs can pose long term financial risks to an organization. If a manufacturing facility loses the use of customized equipment and does not have an alternate means for production, for example, its financial viability could be in jeopardy. If the data systems that underpin an organization are not available due to nonstructural damage, business activities may need to be temporarily suspended until restoration. Protection against these kinds of financial losses are not mandated in the building code, but represent risks that can be addressed on a voluntary basis by concerned building owners.

Some jurisdictions planning strategies for post-earthquake recovery recognize the value of continued habitation. It is highly desirable to allow residents to continue to occupy their dwellings rather than develop temporary housing for large numbers of people after an earthquake. Some protection of nonstructural systems would be needed to provide an acceptable level of risk to building occupants, particularly in aftershocks that can be anticipated. This is not currently a code-mandated performance objective, but could be addressed on a voluntary basis by building owners, communities or jurisdictions.

The level of earthquake shaking associated with performance objectives has been the subject of some debate. Since the publication of the 1974 SEAOC Blue Book, there is general agreement that, as a minimum, buildings should resist minor earthquakes without damage, moderate earthquakes without structural damage but some damage to nonstructural components, and major earthquakes with substantial structural and nonstructural damage but without significant risk of collapse. The challenge is to quantify the hazard levels to allow for the development of clearly defined performance objectives.

The ATC-120 project recommends describing performance at three hazard levels consistent with the general tenets of the Blue Book. In order to translate the performance objectives into the current code framework, the ATC-120 project recommends using the Design Earthquake and Maximum Considered Earthquake as two of the hazard levels. Definition of the lower level event, often referred to as the “function-level earthquake” or “serviceability limit state”, was the subject of some debate. Consideration was given to defining the lower level event as: 50% in 50-year hazard level, 50% in 30-year
hazard level, or a percentage of the MCE. Probabilistic characterizations result in a level of shaking that it is a different percentage of the Design Earthquake at every site, which means a separate analysis might be required to establish compliance in function-level earthquake. Using a percentage of the MCE as the function-level earthquake results in relatively large seismic demands in areas of low and moderate seismicity. A related ATC-120 recommendation is still pending.

Using the performance descriptions and hazard levels described above, the ATC-120 project identified minimum performance objectives for two classes of components: those not required to function after an earthquake and those required to function. For ordinary buildings (Risk Category II), ASCE 7 assigns an Importance Factor of 1.5 to those components requiring post-earthquake functionality, which include:

- Fire protection systems
- Egress stairways
- Components containing a sufficient quantity of hazardous substances
- Components in a Risk Category IV structure needed for continued operation

The assignment of performance objectives is based on the recognition that complete protection against earthquake damage may not be economically feasible for many types of nonstructural components and systems. The proposed objectives maintain the philosophy described in the ASCE 7 commentary that the code requirements are intended to provide property and economic protection for small events, to the extent practical, as well as to improve the probability that critical facilities will be functional after severe earthquakes. Key to assigning an objective is identifying whether it is required for continued operation of a building. To eliminate the judgment associated with this distinction, some jurisdictions mandate that all nonstructural components and systems in a Risk Category IV building should be identified as being required for post-earthquake occupancy.

Table 1 summarizes the current nonstructural performance objectives recommended by the ATC-120 project. Adjustments may be made during final review by the project team.

**Usability of Code Requirements**

The ATC-120 project undertook a detailed examination of ASCE/SEI 7-16 Chapter 13 to assess clarity, consistency, and completeness of code requirements. A “roadmap” was created to describe the administrative and technical requirements in the code, including flowcharts to describe complex interrelationships between different design requirements. To supplement this effort, 5 nonstructural design examples were developed and given to four different firms to execute. The purpose of this exercise was to help identify areas where designers have different interpretations of code requirements or challenges understanding or implementing them.

Based on the roadmap and design examples, the following improvements were recommended (partial list):

- Revise the scoping of nonstructural design provisions to clearly identify components subject to the design requirements
- Clarify exemptions to the seismic design requirements
- Provide improved definitions of “permanently attached” and “movable” components
- Develop a method of classifying items as nonstructural components versus "nonbuilding structures"
- Clarify criteria for accommodating displacements.

These recommendations are expected to be considered and implemented as part of the development of the next NEHRP Recommended Seismic Provisions.

**Code Force Design Equation**

Most nonstructural design in buildings includes calculation of a seismic design force. The current nonstructural horizontal design force equation is:

\[
\frac{F_p}{W_p} = \left( \frac{0.4 S_{Ds,a_p}}{R_p} \right) \left( 1 + \frac{2z}{h} \right)
\]
where:

- $F_p$ is the horizontal seismic design force;
- $a_p$ is a component amplification factor based on component period;
- $S_{DS}$ is the spectral response acceleration parameter at short period;
- $R_p$ is a component response modification factor;
- $I_p$ is the component importance factor;
- $z$ is the height of the point of attachment of the component with respect to the base;
- $h$ is the average roof height of structure; and
- $W_p$ is the component operating weight.

The equation is based on work conducted in the early 1990’s and has undergone only minimal adjustment since that time. The ATC-120 project had as one of its objectives to study the demands on nonstructural components to assess whether the equation in its current form is adequate and appropriate for use as the basis of design, and to recommend changes if needed.

Examination of the force equation required investigation of all the factors that influence seismic demands on nonstructural components. Recognizing that the earthquake force on a nonstructural component is dependent on the level of ground shaking, the modification of shaking resulting from building response, and the further modification of shaking associated with the component itself, the force design equation can be rewritten in general terms as:

$$\frac{F_p}{W_p} = PGA \times \frac{PFA}{PGA} \times \frac{PCA}{PFA}$$

where:

- $PGA$ = Peak ground acceleration measured at the foundation of the structure
- $PFA = \frac{PGA}{PGA}$ = A factor which converts the peak ground acceleration into the peak floor acceleration ($PFA$)
- $PCA = \frac{PCA}{PFA}$ = A factor which converts the peak floor acceleration into the peak component acceleration ($PCA$)

Each of the three terms may be influenced by one or more of the following building and nonstructural component properties or parameters:

1. Ground shaking intensity
2. Lateral force-resisting system of the building
3. The building’s modal periods
4. Building ductility
5. Building damping
6. Building configuration (such as plan and vertical irregularities)
7. Floor diaphragm rigidity
8. Vertical location of component within the building
9. Component and/or anchorage ductility
10. Component damping

Each of these properties or parameters was investigated through a systematic examination of available strong motion instrumentation data supplemented by linear and nonlinear analytical studies.

One of the most challenging issues to resolve was the apparent dichotomy between the high amplification theoretically expected when the component period matches one of the fundamental building periods, and the lack of earthquake damage attributable to this phenomenon. Figure 1 illustrates the amplification parameter with the spectral ordinates of eight different motions average based on $T_{comp}$ and the same motions with the x-axis normalized to $T_{comp}/T_{1bldg}$.

The ratio of the component period to the building’s first, second or third mode periods can clearly have a significant effect on the peak amplification. The normalized graph
illustrates the narrow-banded nature of the amplification. In order for a component to experience the extreme amplification, its period needs to match one of the building periods in the first, second, or third modes. For non-isolated components, it is estimated that there is roughly a 10% chance of a component being in the narrow band. Thus, if a 10% probability of exceedance is acceptable, the amplification could be capped at about 3, which is more consistent with expectations based on most earthquake observations.

Figure 1 - Relationships between peak component acceleration to peak floor acceleration averaged

ATC-120 studies of each of the listed parameters/properties are in progress, as is development of a revised nonstructural force equation that captures the impact of each, and their interrelationship. One formulation under consideration is:

\[ \frac{F_p}{W_p} = PGA \times \left( \frac{PFA}{PGA} \right) \times \frac{Y_{tor} \times Y_{diaph}}{R_{bldg}} \times \left( \frac{PFA}{PGA} \right) \times \frac{B_{comp}}{R_{comp}} \times I_p \]

The PGA parameter can be obtained directly from the forthcoming USGS multi-period spectra or approximated as 0.4S0. The second bracketed portion of the equation relates to how the foundation input acceleration is amplified/de-amplified to the floor spectra. The elastic relationship of can be based on Fathali and Lizundia (2011) per the table below:

<table>
<thead>
<tr>
<th>T_{bldg}</th>
<th>\frac{PFA}{PGA}</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5 s</td>
<td>1 + 2\left( \frac{z}{h} \right)</td>
</tr>
<tr>
<td>0.5 s \le T_{bldg} &lt; 1.5 s</td>
<td>1 + \left( \frac{z}{h} \right) 0.7</td>
</tr>
<tr>
<td>T_{bldg} \ge 1.5 s</td>
<td>1 + 0.5\left( \frac{z}{h} \right) 3</td>
</tr>
</tbody>
</table>

\[ \gamma_{tor} \] is a parameter to account for building configuration irregularity, particularly torsional irregularity. A default of 1.2 is being considered, which could be reduced if it can be demonstrated that the building does not have a significant irregularity which may amplify force or the component is in a plan location where the irregularity does not amplify the floor acceleration at the component location more than the acceleration at the center of mass of the floor.

\[ \gamma_{diaph} \] is a parameter to account for amplification in floor acceleration due to the diaphragm being flexible. Studies have shown that a factor of 1.5 may be appropriate when the floor or roof diaphragm is classified as flexible.
$R_{\text{bldg}}$ is a parameter to account for nonlinear yielding in the structure.

The third bracketed portion of the equation relates to how the floor acceleration is amplified to produce the component spectra. The component spectra can be expressed as a function of either the component period or component period normalized against the first, second or third mode ($T_{\text{comp}}/T_{\text{bldg}}$), as shown in Figure 1. Component spectra are very sensitive to component damping. A study of common nonstructural components indicated that the component damping is often around 2%, as opposed to 5% commonly assumed for buildings.

$B_{\text{comp}}$ is a factor to adjust the component spectra from the 5% damped spectra that the PGA parameter is based on. ATC-120 studies have shown that a value of up to about 1.6 may be appropriate as a default assuming 2% damping, which could be adjusted for other damping levels.

$R_{\text{comp}}$ is a parameter to account for nonlinear yielding in the component or the component’s anchorage. The studies carried out by ATC-120 indicated that even a small amount of component ductility, on the order of 1.5 or 2, can produce a significant reduction in the maximum acceleration a component experience.

The proposed equation is currently undergoing review and validation by the ATC-120 team. Upper and lower limits will also be proposed.

**New Design Philosophy**

Estimating design demands on a nonstructural component is subject to a series of four uncertainties. First is the uncertainty associated with the ground motion itself. Second, there is the uncertainty associated with the response of the building, including its damping, irregularities, diaphragm stiffness and nonlinear response. Third is the relationship between the component and building natural periods of vibration. Finally, the fourth uncertainty is the response of the component, including the complete load path from the component to the structure which often contains a series of connectors and fasteners.

When taken together these uncertainties suggest that the force demand on a nonstructural component cannot be predicted with a high level of confidence. For ductile components with ductile connectors, the uncertainty in design force may not have serious consequences. However, for components that possess brittle fasteners or elements as part of the system, the consequences could lead to undesirable nonstructural failures.

ATC-120 research has shown that a relatively small amount of nonlinearity in component response may dramatically reduce the component seismic demand. By focusing the nonlinearity in a ductile fuse, seismic demands are reduced and anchors can be designed based on the capacity of the yielding element. Such an approach, similar to and consistent with the approach used for designing buildings, provides a more rational and reliable basis than traditional nonstructural design approaches.

Practical implementation of this philosophy is in progress within the ATC-120 project. Over time, it is expected that ductile fuses will be developed and manufactured for use in common applications.

**Acknowledgments**

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<table>
<thead>
<tr>
<th>Issue/Performance</th>
<th>Components <em>not</em> required for post-earthquake function</th>
<th>Components required for post-earthquake function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequent Earthquake</td>
<td>Design Earthquake</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prevent minor falling/overturning hazard with limited safety consequence</td>
<td>X</td>
<td>E</td>
</tr>
<tr>
<td>Prevent significant falling/overturning hazard that causes a casualty to an individual or several individuals</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prevent significant falling/overturning hazards that cause casualties to a significant number of people</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Maintain egress</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prevent hazardous material release</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prevent fire</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prevent falling hazard that causes casualties outside building footprint</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Property</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limit local nonstructural damage/repair</td>
<td>X</td>
<td>E</td>
</tr>
<tr>
<td>Limit extensive nonstructural damage/repair</td>
<td>X</td>
<td>E</td>
</tr>
<tr>
<td>Prevent nonstructural damage that causes damage to structural system</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintain intended building function</td>
<td>X</td>
<td>E</td>
</tr>
<tr>
<td>Enable reoccupancy/habitation</td>
<td>X</td>
<td>E</td>
</tr>
</tbody>
</table>

1. Performance objectives are targets; there is no guarantee that damage more severe than the target will not occur.
2. Design requirements are intended to apply at the Design Earthquake level only. It is assumed that targets at other levels are likely to be achieved by design at the Design Earthquake Level.
3. “X” denotes minimum required performance objective; “E” denotes enhanced performance objective (discretionary)

Table 1 - Framework of Performance Objectives for Nonstructural Components (Preliminary)
References


