ASCE 41-06: Seismic Rehabilitation of Existing Buildings

A New Tool for Achieving Seismic Safety

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The wide range of damage at the epicenter of the 1994 Northridge earthquake illustrates that not all existing, non-compliant buildings are dangerous. One building partially collapsed while others of similar vintage remained usable. Courtesy of Lloyd Cluff, 1994.

Earthquakes wreak havoc on our lives, our businesses and our communities. For the last 140 plus years, scientists and engineers have been working to understand where they can occur and how to best mitigate their effects. What started as a concern centered along the West Coast has become known as a real threat that affects the vast majority of states in the United States. Thanks to the work of the United States Geological Survey, we now have a science-based understanding of earthquake hazards nationwide, which has become the source for national earthquake hazard maps.

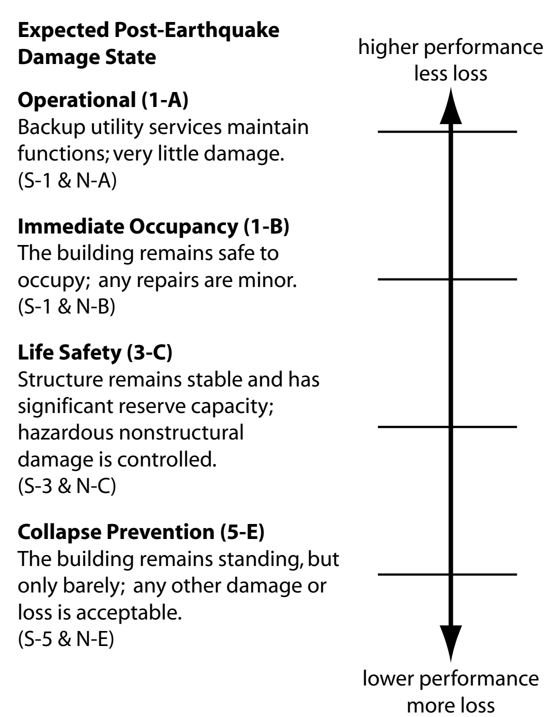
For over 50 years, engineers have focused on protecting lives and the vitality of our communities by writing building codes and seismic provisions. Engineers are identifying and rehabilitating "dangerous" buildings nationwide, and the need for conversations about community resilience are refining how we approach design. Unfortunately this progress achieved full stride just 20 years ago and has left us with an inventory of buildings nationwide where more than 80 percent are unable to meet the recognized seismic standards where they are located. The seismic rehabilitation of the existing building stock is a key element in the process of achieving seismic safety and turning our cities into resilient communities.

Unsurprisingly, when owners understand and accept the risk of an earthquake, they want it brought under control and mitigated to an appropriate level. Often it takes a personal, life-changing earthquake experience to bring home the reality of an earthquake's consequences. For those owners who lack such personal experiences, the consequences of earthquakes must be described in intuitive terms in order to appreciate the importance of seismic mitigation. Another barrier to mitigation is cost; many interested owners have done nothing because they think that the investment required to bring older buildings "up to code" is ridiculously high. Finally, we structural engineers are too often reluctant to speak up and declare what is going to happen because we sense that somehow we will be held responsible when it does. Our personal liability fears often stop us from speaking up, even though our silence leaves the impression that there is not a problem.

If you are reading this from a practice along the West Coast, you recognize the situation and the need. From the Wasatch Front in Utah, many of you know this same situation exists in your region, but it remains a tough sell. From Memphis to the eastern seaboard, the skepticism runs high among owners and their design professionals and only limited recognition is evident.

Fortunately, the American Society of Civil Engineers' Standard Number 41, *Seismic Rehabilitation of Existing Buildings* (ASCE 41) provides useful tools to assist design professionals in tackling all three of these barriers; risk perception, cost of rehabilitation, and professional liability. It provides the next generation of tools needed to achieve seismic safety nationwide. ASCE 41 is the culmination of over 25 years of work that began with a FEMA sponsored dream for a library of guidelines and standards related to the seismic evaluation and rehabilitation of buildings. Having successfully completed the balloting process, ASCE 41 is now approved by the American National Standards Institute (ANSI) as a standard that can be referenced without amendment by local codes. As a standard, it provides the liability shield that we all need to practice with confidence. No one expects perfection; they just expect us to practice at the "state of the practice" level, and ASCE 41 clearly defines what that means.

Target Building Performance Levels and Ranges



ASCE 41 defines ranges for performance levels for structural and non-structural elements that serve as the basis of a rehabilitation objective. This chart illustrates the range from minimum safety to high performance. Courtesy of ASCE 41, 2005.

Predicting Performance

Buildings respond to earthquakes in a wide variety of ways, but always within the same patterns. As the ground shaking begins, the building moves and develops distortions in proportion to its mass, stiffness, and the frequency of the ground motion. The accelerations that are experienced join with the mass that is present and generate forces that the building needs to resist. If the forces are within the strength of the building, little distortion develops and only minor damage occurs. If the forces that are developed exceed the capacity of the building, then the building starts to break up, the distortions increase, and damage becomes more severe. As the building breaks up, it destroys its lateral strength and the building experiences extensive distortions and, in some cases, partial or complete collapse.

The design guidelines for new buildings are set to prevent the breaking up process from starting in moderate earthquakes, and to prevent the building from distorting to the point of pulling apart in extreme earthquakes. The code uses the base shear to achieve the minimum strength required, and requires specific details of construction to contain the breaking up process and achieve the desired performance for the buildings usage. The required details provide the "ductility" needed to control the level of damage. The new building code has achieved its purpose through a thoughtful balance of strength and ductility defined as prescriptive requirements.

Existing buildings may not have the required balance of strength and ductility that new buildings possess. Attempts to apply the prescriptive requirements of the new code will lead engineers to the conclusion that most old buildings need new lateral force resisting systems. That is, unfortunately, the key driver of the high rehabilitation costs that often result. However, earthquake damage patterns illustrate that new lateral systems are not always necessary, and ASCE 41 provides the tools to distinguish when strengthening is actually needed and to what extent. It provides the ability to judge the adequacy of the ductility that is available given the strength that is present. As such, ASCE 41 is a toolbox of procedures that can be applied as appropriate for the detailed evaluation and rehabilitation of existing buildings in order to minimize the cost of strengthening. It provides a systematic process that defines target performance levels, considers earthquakes of various sizes, and provides four distinct analysis techniques and a wide variety of modeling techniques to guide the evaluating engineer into an appropriate conclusion about a building's rehabilitation needs.

Residence in Paso Robles, California that successfully withstood the 2003 San Simeon Earthquake with limited damage due to its inherent strength and ductility as a wood building and the moderate level of shaking that occurred. The first level of analysis, the LSP, is sufficient. Courtesy of Chris Poland, 2003.

ASCE 41 Process

Regardless of whether ASCE 41 is being used as an evaluation tool in conjunction with the American Society of Civil Engineers' Standard Number 31, *Seismic Evaluation of Existing Buildings* (ASCE 31) or for a rehabilitation project, it begins with the seismic hazard and the desired performance levels. Unlike the prescriptive requirements for new buildings, ASCE 41 makes recommendations for basic safety, enhanced, and limited performance levels, and detailed options can be applied as needed to match the project needs. Performance levels are defined that range from "collapse prevention" to "operational" in ASCE 41 that, when combined with hazard levels, yield the rehabilitation objective.

The ASCE 41 process continues with requirements for gathering data and for carrying out the evaluation. Instructions for obtaining as-built information are given, along with adequate default values for use when specific information is not available. Detailed material testing requirements, appropriate for existing buildings, are also included. Additionally, two rehabilitation methods are provided: Simplified and Systematic. The Simplified Method is aimed at small, regular, simple buildings and follows a process of correcting the deficiencies identified using ASCE 31 procedure in order to achieve a life safety performance level. The Systematic Method is a step-by-step process that uses up to four levels of analysis to accurately predict performance of a rehabilitation plan and in the process minimize the cost of rehabilitation. The process of developing and validating a rehabilitation plan using the Systematic Method addresses the deficiencies found by ASCE 31 by showing they have been corrected or that they are acceptable.

In the process of defining the requirements for rehabilitation, Chapter 1 of ASCE 41 explains the background and importance of each step of the evaluation process, and

1950s Firehouse located in Paso Robles that also withstood the 2003 earthquake. The second level of analysis, the LDP, is suitable to demonstrate the systems adequacy since there is only a single lateral load path at the first level. Courtesy of Chris Poland, 2003.

provides the most definitive statement on performance based seismic evaluation and design currently available. Within the section on Performance Levels, there are a series of tables that describe the expected damage for each of the four levels. This information is particularly useful in describing the expected performance of buildings to owners.

The four levels of analysis provided by ASCE 41, which are explained below, give progressively detailed information about the need for, and extent of, strengthening. The first two levels match the model code style of force-based design, and cannot be used on buildings with long periods or significant irregularities. The second two are based on displacement and serve to directly determine the post yield capability of the buildings. In addition to a set of general analysis requirements, each analysis method is defined in terms of specific modeling requirements and procedures. A common acceptance criterion is provided for linear methods (force based) and also for the non-linear methods (displacement based). The criteria are extensive, organized by material type, and based on the amount of available information, including applicable test results.

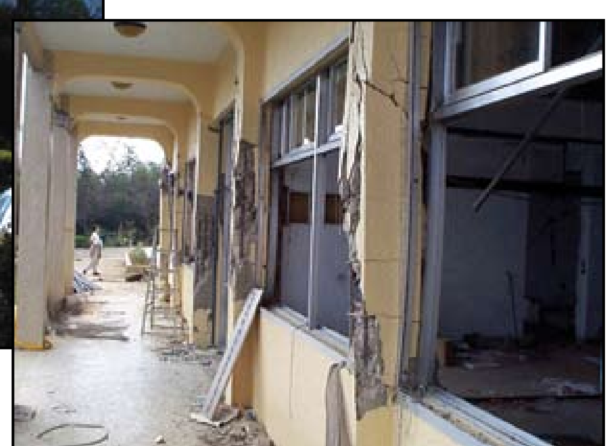
The four analysis methods for judging the need for strengthening or the suitability of a rehabilitation plan come with the idea that the simplest technique should be used to show adequacy. Buildings deserve a break and owners should not be required to strengthen perceived deficiencies that are not truly a problem. Buildings should not be considered in need of strengthening until all four techniques are considered, and possibly used, to minimize the extent of work needed and the cost of correcting the deficiency.

1960s University Library located near Palo Alto, California that was rehabilitated using the third level of analysis, the NSP. By relying on the new cantilever concrete walls located at each corner to arrest the deflection of the building, the existing concrete frame was held to within its limits for safe performance. Courtesy of Chris Poland, 2003.

The first level of analysis is the **Linear Static Procedure** (LSP) that provides an equivalent lateral force, vertical distribution of forces and rules for modeling, and acceptance criteria. A first glance, it looks like the equivalent lateral force procedure from the codes of the 1970s and 1980s, except that the base shear is much higher and the ductility factors, the "m" factors, are much smaller. It is intended to be simple and very conservative to allow one and two story buildings of regular configuration to pass because of their excessive strength. Unfortunately, many first time users of ASCE 41 gravitate to this section and base their work on it alone because it looks familiar. They never take the time to explore the other processes. Few existing buildings, except wood frame or light metal construction, can pass this conservative test. The LSP should only be used to show that a building is okay, not to determine the extent of strengthening it might need. If a building is immediately strengthened to meet the LSP requirements, it will miss the beneficial, cost saving opportunities that ASCE 41 provides.

The second level of analysis is the **Linear Dynamic Procedure** (LDP) that uses modal analysis and site-specific response spectra to determine the force demands. The LDP also includes modeling rules that encourage consideration of soil structure interaction and appropriate acceptance criteria. It is much more beneficial than the LSP analysis since it utilizes a site-specific response spectra, calculated building periods, and the beneficial effects of multiple modes. It does have a serious limitation in that it cannot properly evaluate a building with significant redundancy, that is, significant strength even after damage begins to occur. The rules for judging the building to be adequate still triggers unacceptable performance when the first significant element within the stiffest lateral system exceeds its limits. For some buildings, this technique is satisfactory since once significant yielding occurs, there is nothing else to step in and provide resistance.

The first of the displacement-based procedures is the **Non-linear Static Procedure** (NSP), commonly referred to as the push over method. Using analytical techniques, accessible in commercially available advanced computer programs, a model of the building is literally and analytically subjected to increasing deflection while the impact on the lateral force resisting elements is monitored. As the yield limits are exceeded, the elements are allowed to yield and the computer program tracks their post yield displacement to determine when the building loses its lateral force resisting ability. In the process, first significant yield does not signal a problem; instead, it signifies that other elements need to step up and take over. Using a series of approximations, a target displacement is calculated based on site-specific response spectra. If there is a lateral system within the



1960s Concrete Weather Station in Taiwan successfully resisted over 125 percent ground shaking without collapse because of the multiple lateral load resisting systems that includes concrete frames and masonry walls. Only the fourth level of analysis, NDP can come close to predicting such performance. Courtesy of Chris Poland, 1999.

building that can arrest the movement to within the target displacement, the building is judged adequate. If not, then there is one more level of analysis, if the building is worth the cost of running it. This process of analysis matches the way buildings behave in earthquakes since it estimates the building's actual movement and resulting damage.

The second displacement based method is a **Non-linear Dynamic Procedure** (NDP) that uses time history records to represent the possible shaking that the site could experience. By working with a full time series of motion, it is possible to take advantage of the beneficial effects of shaking since the ground motion is applying as much restoring force to the building as it is applying forces that cause damage. The frequency content of the record is used directly to determine the displacement demand and gives a more accurate representation. Also, the number of cycles of non-linear behavior can be monitored and used to more accurately predict the extent of damage that will result from the non-linear behavior. Buildings that need to rely on a high level of non-linear behavior to achieve their target displacement benefit most from the NDP. Buildings that are heavily damaged in earthquakes, but remain standing straight up, illustrate the beneficial effects of the time history record. Only the NDP can come close to predicting such behavior.

Summary and Conclusion

Having a new state-of–the-art standard to evaluate and rehabilitate buildings is only part of what is needed to achieve seismic safety. ASCE 41 allows the use of a variety of earthquake threats and defines three performance levels: immediate occupancy, life safety and collapse prevention. The ASCE 41 process assists the engineer in determining the expected performance, but seismic safety is achieved when a proper evaluation is done, the resulting options are understood, and appropriate answers selected and implemented. Owners need to know what is going to happen in terms of life threatening injuries, what it will cost to repair their buildings, and how long the buildings will not be usable. Fortunately, this information can be deduced from the ASCE 41 analysis. When reporting the results to owners, it is best to focus on the description of expected damage before and after the proposed rehabilitation, as opposed to the minutia of the evaluation itself. In that way, owners will be able to relate the impact the performance will have on their use of the buildings and they will have a basis for determining what to do.

As structural engineers, we need to advocate seismic safety in our communities and carry out the role of earthquake engineers on every project. We need to develop a clear understanding of the difference between designing a new building following the prescriptive requirements of the code and design existing buildings following the performance-based evaluation approaches. The nation's inventory of existing buildings that do not meet minimum seismic safety levels is very large, and the cost to replace them is out of the question, not to mention unnecessary. ASCE 41 is the best "tool kit" of procedures available that allows for site specific and deliberate performance based evaluation for rehabilitation. And, when applied properly, the necessary rehabilitation can be completed at a minimum cost for the owners and without liability for the structural engineers.■

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