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Evaluating Performance of Earthquake Damaged Buildings

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ABSTRACT

The pushover analysis technique is currently a widely accepted method of evaluating the behavior of buildings to earthquake ground motions. Despite limitations, such as using a static lateral force to represent dynamic loading, the pushover analysis technique has been demonstrated to produce reasonably accurate representations of the progression of nonlinear behavior of a building. Confidence in the procedure has lead to the incorporation of the pushover analysis technique in recent guidelines for the seismic evaluation of existing buildings. The pushover analysis technique is an integral part of the performance based evaluation procedures. In these procedures, the behavior of a single governing component is used to describe the performance of the building.

A recent project by the Applied Technology Council (ATC 43) has applied the performance based approach to the evaluation of earthquake damaged concrete and masonry wall buildings. A brief description of the guidelines is presented. With this procedure, the effect of damage on the future performance can be evaluated. An example building that was prepared for the project is presented to demonstrate the use of the procedure. In this example, the effect of damage on the future performance is demonstrated: first using the behavior of the governing component as the basis for determining the acceptability of the performance; then using the global behavior to assess the acceptability of the performance. The results are compared and discussed in terms of the implication to the seismic design, response and retrofit of building structures.

INTRODUCTION

In areas that are subjected to earthquakes, a building can experience earthquake shaking at various times in its life. Those buildings that have been designed using modern building codes are expected to:

- Resist minor earthquake ground motion with no damage;
- Resist a moderate level of earthquake ground motion without structural damage, but possibly some nonstructural damage;
- Resist a major level of earthquake ground motion without collapse, but possibly with some structural as well as nonstructural damage. (SEAOC 1990)

After a building is subjected to an earthquake, engineers are typically asked to evaluate the building in its post-earthquake condition. Initially, the local building department or damage assessment engineer may use the procedures specified in ATC 20, *Post-Earthquake Safety Evaluation of Buildings*, to assess the safety of the building. Following that initial evaluation however, there are no published guidelines on how to quantitatively evaluate a building structural adequacy of a building that has been damaged by an earthquake or other disaster. This has led to vastly different interpretations by engineers as to what constitutes earthquake damage and what repairs are necessary for restoring the building (Kehoe 1998).

Following the 1994 Northridge earthquake, the Federal Emergency Management Agency (FEMA) sponsored a program through the Applied Technology Council (ATC) to develop guidelines for the evaluation of earthquake damage to concrete and masonry wall buildings (ATC 43). The goal of the project was to prepare a report on the state of knowledge concerning the evaluation and repair of earthquake-damaged buildings. The project used as a tool in the development of

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the guidelines, the principles of performance-based seismic design to put forward a rational and technically based guideline.

PERFORMANCE-BASED SEISMIC DESIGN

Over the last several years, performance based design has become a widely discussed topic with regard to seismic design. The basic idea of performance based design is to consider how the building will respond to actual earthquake forces rather than applying traditional design-level forces with allowable stress levels. Performance based seismic evaluations include a number of considerations that have not been expressed explicitly in previous building codes. Among these considerations are performance objectives for which the building can be evaluated. These objectives can range from Immediate Occupancy to Collapse Prevention. Another consideration is the seismic hazard, which is expressed in terms of earthquakes with varying return periods or probabilities of exceedence. Most important however, is the explicit consideration that the effects of the earthquake shaking on the building will cause the structural components of the building to respond in the post-yield range. The most comprehensive guidelines describing these considerations for the use in performance based seismic design is FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings.*

Four methods of analysis are described in FEMA 273: the Linear Static Procedure, the Linear Dynamic Procedure, the Nonlinear Static Procedure, and the Nonlinear Dynamic Procedure. Of these, the Nonlinear Static procedure is considered one of the more popular methods of performance based analysis. The procedure, otherwise referred to as a pushover analysis, involves applying a static lateral load to the structure in a designated pattern. The load is increased until some of the elements reach their elastic limit. After an element reaches its elastic limit, the properties of the yielded element and adjusted based on the post-yield behavior of the element. The behavior and acceptability of an element is based on comparison of the deformation of the element to deformation limits presented in the guidelines, as shown in Figure 1. The load is increased until the structure becomes unstable, until a designated global displacement is reached, or until the deformation limit of a primary element is reached. The results of the pushover analysis are represented by a plot of the global displacement of the building versus the base shear. The results can also be converted into a format of spectral acceleration versus spectral displacement, referred to as an ADRS plot. Plotting the pushover in these coordinates allows the pushover curve for the building to be compared directly to the response spectra for a postulated or an actual earthquake as shown in Figure 2.

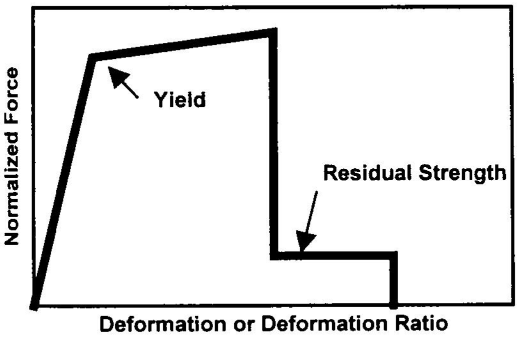

Figure 1 - Component Deformation Limits

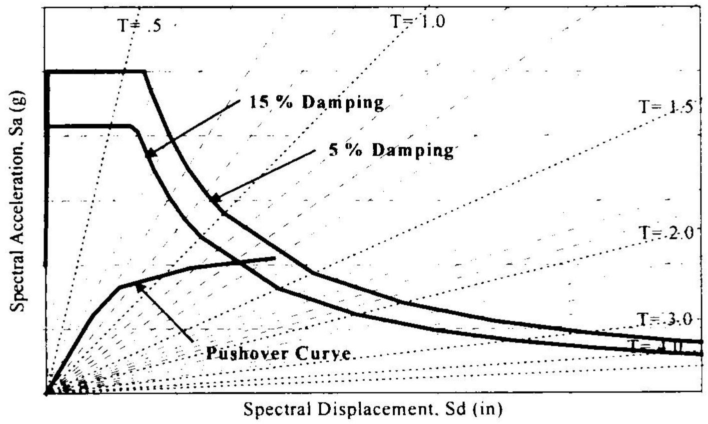

Figure 2 - Pushover Curve in ADRS Format

Conceptually, the pushover analysis is a relatively simple procedure. It is very effective at allowing an engineer to understand how the structure will respond after initial yielding of the elements. The method, however, does not account for the cyclic nature of dynamic loading; the lateral loads are applied in only one direction. The results can be sensitive to the distribution of loading over the height of the building. For buildings that respond with significant higher mode contributions, it may not be possible to develop a load distribution that properly accounts for the actual behavior. For highly irregular buildings, the analysis may be difficult, if not impossible to carry out. Another significant limitation to the procedure is the reliance on the deformation limits of a single element of the structure to assess the global acceptability of the structure. Despite these limitations, the pushover analysis has been shown to be able to provide a reasonably accurate assessment of the seismic behavior of a structure subjected to an earthquake.

ATC 43 METHODOLOGY

The ATC 43 project has produced three documents that are published by FEMA to describe a new methodology for evaluating the effects of earthquake damage on a building:

- *FEMA 306, The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings – Basic Procedures Manual*, (ATC 1998a) which describes the basic procedures and methodology

- *FEMA 307, The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings – Technical Resources*, (ATC 1998b) which includes the technical basis for the guidelines and also includes an illustrated example

- *FEMA 308, Repair of Earthquake Damaged Concrete and Masonry Wall Buildings*, (ATC 1998c) which provides a discussion of policy considerations for repair of damage.

The methodology includes two procedures for estimating the loss associated with earthquake damage to a building: the Direct Method and the Relative Performance Analysis Method. The latter involves describing the pre-earthquake performance of the building in terms of a pushover analysis. The damage to the building due to the earthquake is then introduced by applying modification factors to the stiffness, strength, and deformation limits. A second pushover analysis is then conducted with the modified component properties and the results are compared to the pre-earthquake performance. If a significant change in performance is deemed to have occurred, repairs can be implemented in the analysis until the performance of the repaired structure matches that of the pre-earthquake structure, or some other designated performance level. The procedure thus uses the change in the performance, as measured by the pushover analysis, as a means of assessing the significance of the earthquake damage. This is an improvement over previously used methods of assessing damage that use the cost of repair as or comparison to current building codes as a basis for assessing the degree of damage.

A fundamental tenet of the component evaluation methods presented in FEMA 306 is that the severity of damage in a structural component may not be determined without understanding the governing behavior mode of the component, and that the governing behavior mode is a function not only of the component properties, but of its relationship and interaction with surrounding components in a structural element. Careful consideration of the actual behavior of the elements is important to understanding the behavior of the building. The methodology also stresses that the results of the analysis must be compared with the observed behavior. If different, the analysis needs to be modified until the analysis can closely approximate the observed behavior.

One of the key elements in the development of the methodology, and one of the most controversial, is the damage guides that have been prepared for walls constructed of each of the applicable structural materials: reinforced concrete, reinforced masonry, unreinforced masonry, and infilled frames. These damage guides describe the behavior modes for the material as well as the methods of identifying the behavior mode by observation and by analysis. The damage severity levels (from Insignificant through Extreme) for each behavior mode and the associated modification factors are also presented. It is important to note that the modification factors are based on a thorough review of available research results. The example that is presented in the FEMA 307 document is described below to demonstrate the use of the procedure.

EARTHQUAKE DAMAGE EXAMPLE

The example building example is a two-story concrete building located on a sloping site. The building is in a "T" shape in plan with the stem of the T on the downhill side containing an additional lower story below the other two stories. The building was designed and constructed in the late 1950's. The building is located about 3.6 miles (6 km) from the epicenter of the Damaging Earthquake.

The overall plan dimensions of the building are 362 feet in the North-South direction by 299 feet in the East-West direction. The floor slabs cantilever about 6 feet from the perimeter columns forming exterior sunscreens/balconies. The building facade along the perimeter is set back 8 feet from the edge of the slab. A floor plan of the typical floor is shown in Figure 2.The floors and roof are constructed with waffle slabs comprised of a 4-½ inch thick slab and 14 inch deep pans (18-½ inches total depth). Columns supporting the slabs are typically spaced at 26 feet in each direction. The interior columns are 18-inch square and the perimeter columns are 18-inch diameter and are supported on spread footings.

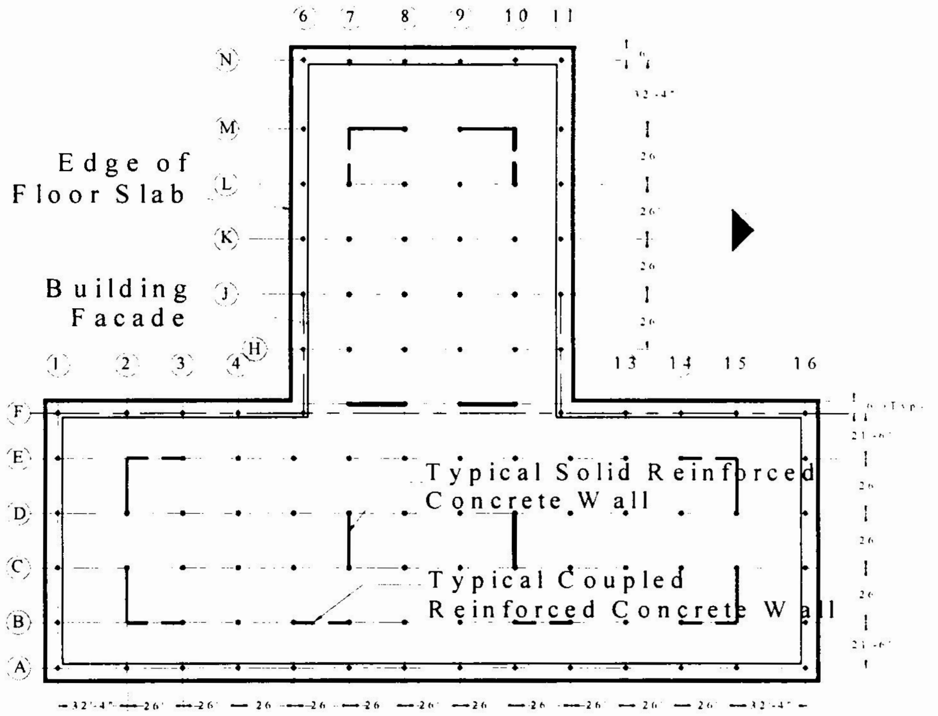

Figure 3 - Typical Floor Plan of Example Building

Reinforced concrete walls in both directions of the building resist lateral forces. The walls are 12 inches thick and are cast monolithically at each end with the gravity-load-carrying columns. The walls are typically located along corridors, and the corridor side of the wall has a 1-inch thick plaster coat. Several of the reinforced concrete walls have door openings in the middle of the wall, creating a coupled wall. In the three-story section of the building (the stem of the T), the walls are discontinued at the lower level. This lower level contains a single reinforced concrete wall in the north-south direction centered between the two walls above.

The concrete shear walls experienced minor to moderate amounts of cracking. Based on the visual observations, component damage records were prepared for each of the shear walls in the building. The two first-story coupled shear walls in the stem of the T section of the building experienced significant cracking in the coupling beams (Column lines 7 and 10, L to M). One of the other coupling beams (Column Line B, 14 to 15) also experienced heavy cracking. The damage to the coupling beams included some spalling of the concrete, buckling of reinforcing bars, and cracking of the floor slab adjacent to the wall.

The first step in the process of identifying the components is conducted by observation, keeping in mind that the definition of a component type is not a function of the geometry alone, but of the governing mechanism of lateral deformation for the entire element or structure. Thus the identification of structural components requires consideration of the wall element over multiple floor levels. Once the component types have been identified, an initial classification of the behavior modes and damage severity is made by inspecting the visible damage with reference to the damage classification and repair guides in FEMA 306.

The typical solid shear walls were calculated to behave in a Rocking. Mode. There are no damage guides provided in the document for this behavior mode since there was not sufficient available research on which to base guidelines. However component behavior description for this mode of behavior considers this mode to have moderate to high ductility. The damage associated with this behavior mode may not be apparent based on the observations of the walls. Damage to other structural and nonstructural elements, such as damage to the floor slab at the base or to the beams framing into the ends of the walls, were used to consider the damage severity to be Insignificant. Based on calculations, the behavior mode of the coupling beams is Preemptive Diagonal Tension. Based on the damage observations and the component guides, the damage for the coupling beams with the significant cracking was classified as Heavy. For the coupling beams with less cracking, the damage is judged to be Moderate. The walls adjacent to the coupling beams are expected to behave in a mode of individual pier rocking. Similar to the solid shear walls, the lack of damage to the adjacent structural and nonstructural elements was used to classify the damage as Insignificant.

The building is analyzed in its pre-event, post-event and repaired conditions using a three-dimensional finite element program. The reinforced concrete walls and coupling beams ware modeled using beam elements. Modeling of the building is done using the recommendations of FEMA 273 and FEMA 306. The model is subjected to a pushover analysis in the East-West direction to assess the performance of the building. This direction is chosen since it represented the direction that experienced the most significant damage. The pushover analysis is continued to beyond the displacement range of interest, which is based on a preliminary estimate of the maximum displacement demand. A global pushover curve is then developed.

The initial slope of the component force deformation curves is based on the initial elastic stiffness of the component. The pre-event structure is modeled using the effective initial stiffness values recommended in FEMA 273. The post-event structure is modeled with the same stiffness values, multiplied by the λ_k factors recommended in FEMA 306. Heavily damaged coupling beams have their stiffness reduced to 20 percent of the pre-event value. Moderately damaged coupling beams have their stiffness reduced to 50 percent of the pre-event value. For the solid shear walls where damage is classified between Insignificant and None, stiffness is reduced to between 80 percent to 100 percent of the pre-event stiffness depending on the amount of cracking.

For the post-event structure, the pre-event strength is multiplied by the λ_Q factors recommended in FEMA 306. Heavily damaged coupling beams have their strength reduced to 30 percent of the pre-event value. Moderately damaged coupling beams have their strength reduced to 80 percent of the pre-event value. For components where damage is classified either Insignificant or None, the strength is not reduced. The global results of the pushover analysis are shown in Figure 4.

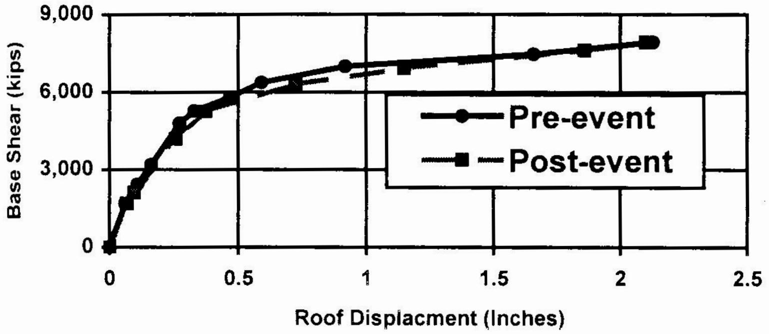

Figure 4 - Pushover Analysis Comparison

For the post-event structure, the progression of displacement events is essentially the same as that outlined for the pre-event structure. The results of the post-event pushover analysis are also shown in Figure 4. In the pre-earthquake analysis, the first story coupling beams are the first element to reach the Life Safety acceptability limit. The displacement limit for the Life Safety limit is reached at about 1.0 inch. In the post-earthquake analysis, the first story coupling beams reach their Life Safety acceptability limit when the roof control node deflection reaches about 0.75 inches.

The performance of the post-event building was slightly different than the pre-event performance; the overall building is softer since more deflection obtained for the same magnitude of applied load. The reduced stiffness of the damaged components resulted in a global reduction of stiffness of the post-event structure. The Moderate and Heavy damage to some of the components required a reduction in their strength. However, after the roof displacement reached about 2 inches, the behavior of the pre-event and the post event models are nearly identical.

DISCUSSION OF RESULTS

The critical component in the example building, as determined by analysis and confirmed with the field observations, is the shear capacity of the coupling beams. Using the FEMA 273 approach to evaluating the performance, the global performance of the building can be governed by the acceptability of one or more components. In this example, the coupling beams are the governing components. Using the acceptability of the governing component as an indication of the global performance indicates that the damage from the earthquake has caused a decrease in the global performance of the building. However, when the behavior of the building in its pre-event and post-event conditions are compared, the ultimate behavior of the building, compared at the end of the pushover curve, has not been affected by the earthquake damage.

The ATC 43 methodology is a significant departure from the past methods of assessing the significance of earthquake damage. Engineers have typically relied on their professional judgement to assess what repairs are required for a building. Building departments have developed policies to determine when repairs are necessary and when the damage has triggered an upgrade in addition to the damage repair. These policies have, for the most part, relied on measurement quantities such as the cost of repair that have no technical basis. In the ATC 43 methodology, the recently developed concepts of performance based design are used to provide a rational basis for which to compare the pre-earthquake and the post-earthquake conditions of the building to establish the significance of the damage.

The nonlinear static procedure described in FEMA 273 was used in the ATC 43 analysis to assess the performance of the building in the pre-event, post-event and repaired conditions. This analysis method is relatively new and is still subject to further refinements. This procedure can be time-consuming to implement properly. As the method and the analytical tools become further developed, this method should be easier to implement.

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