Paper N° 1166
Registration Code: S-K1463179675

SIMPLIFIED SEISMIC EVALUATION OF OLDER CONCRETE BUILDINGS FOR COLLAPSE POTENTIAL (ATC 78)

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Abstract

The life safety risk from seismic vulnerabilities of older concrete buildings, particularly frame buildings, is well known. Existing evaluation methods – which are based on component performance – are reasonable to assess damage potential, but are generally judged to be too conservative to predict collapse and significant risks to life safety. For several years, the Federal Emergency Management Agency (FEMA), through the Applied Technology Council (ATC), has sponsored the development of a simplified method to estimate collapse risk, which can be used to rank older concrete buildings for the purpose of identifying the truly dangerous ones. It is expected that such a method would be applied to a significant inventory of buildings in a screening phase of risk mitigation, so the level of engineering effort must be minimized. The method developed includes estimation of an approximate period and tabular approaches to estimate drift distributions at each story based on relative strengths and strength ratios of vertical and horizontal structural elements and presence of walls. For buildings where columns govern collapse, drift demand is compared with plastic rotation capacity for each column and a column rating related to the probability of loss of vertical load capacity is determined. The ratings of columns in the critical story are then statistically combined to estimate a probability of story collapse at that story. In contrast to conventional component-based methodologies, a probability of complete story collapse is thus deduced and the final collapse risk rating depends on the condition of the combination of components. For wall buildings where columns do not govern, other rules about redundancy and wall failure apply. The method has been developed targeted at U. S. building types and covers gravity frames with or without lateral force design, slab-column frames, frame buildings with walls, and bearing wall buildings. Structures are limited to 13 stories, but can have both horizontal and vertical irregularities. Trial evaluations have been carried out for frame structures to compare this methodology to other procedures for seismic assessment of these buildings and assess the difficulty of conducting the assessment.

Keywords: collapse; non-ductile reinforced concrete buildings; frames; walls

1. Introduction

The ATC 78 methodology addresses the vulnerability of older (pre-1980) nonductile concrete buildings. It is well known that some of these concrete buildings represent a significant threat to life safety (e.g. [1]), constituting one of the most vulnerable subsets of the U.S building stock [2]. However, it is also clear that many buildings constructed with similar features and during the same time period may not represent such a serious threat. The ATC 78 project aims to provide a procedure whereby exceptionally high seismic risk or "killer" older reinforced concrete buildings, may be identified from among a large group of potentially vulnerable buildings. It is anticipated that the methodology will be used to identify, from among a group of buildings (e.g., pre 1980 concrete buildings), those that are the highest collapse risks and, therefore, the highest priorities for retrofit in the interest of public safety.

The ATC 78 assessment aims to evaluate the propensity of a structure to suffer global earthquake-induced collapse. The assessment of a structure through the method does not require a structural analysis model, instead relying on linear and hand (spreadsheet) calculations. These features are intended to reduce the time and expense required to evaluate each building and to ensure, through prescriptive criteria, that results for one building can be compared to results for another building obtained by a different engineer using the same procedure, enabling consistent ranking of a building inventory in terms of collapse risk. By evaluating the likelihood of global collapse, rather than component failures, the methodology aims to avoid excessive conservatisms inherent in other seismic evaluation documents, such as the ASCE/SEI 41 standard [3]. In its current form, the methodology applies to reinforced concrete buildings whose lateral resisting system consists of beam-column frames, slab-column frames and reinforced concrete structural walls. This paper introduces the guiding principles of the methodology, documents the steps required to evaluate a building, and describes ongoing calibration and methodology development efforts.

2. Overview of Methodology and its Outcomes

The outcome of an ATC 78 evaluation of a building is a measure of the building's seismic collapse risk. In this methodology, collapse is considered globally, focusing on the critical story, and depends on the performance of all of the columns and walls at the critical story. The building's assessed collapse risk depends on a number of factors, including building strength, period, column-to-beam strength ratios, number and distribution of walls, shear criticality of columns, and detailing of columns, walls and slab-column connections.

The methodology broadly assigns buildings to one of three categories: *exceptionally high seismic risk*, *high seismic risk* and *lower seismic risk*. *Exceptionally high seismic risk* buildings, having a high risk of partial or complete collapse under strong ground motion, should be given the highest priority among older concrete buildings for more detailed evaluation and mitigation. *High seismic risk* buildings can be given an intermediate priority among older concrete buildings. *Lower seismic risk* buildings can be given the lowest priority among older concrete buildings, possibly requiring no action. Structures that cannot easily be placed into the three main categories are given a numerical building rating resulting from quantitative assessment procedures. These numerical ratings range from 0 to 1 and can be mapped to the three categories, where a building rating < 0.3 corresponds to *lower seismic risk*, a rating between 0.3 and 0.7 corresponds to *high seismic risk,* and a rating above 0.7 corresponds to *exceptionally high seismic risk.*

3. Preliminary Calculations

To carry out the methodology, the analyst begins by collecting building drawings, information about expected material strengths, and seismic hazard for the building location. The methodology recommends carrying out the analysis at the spectral acceleration level corresponding to the 5% in 50 year hazard level. Once this information is obtained, the ATC 78 document also provides rules to estimate the base shear strength of the structure through a simplified mechanism approach. This mechanism approach also enables identification of the critical story or stories. For frame buildings, the building period is computed from the building strength and building height; the relationship between strength and building period is intended to quantify a secant stiffness for later analyses. For wall buildings, building period is related to the size and number of walls, and floor area.

4. Building Classification

After the preliminary calculations, the ATC 78 methodology classifies structures into one of the three categories of reinforced concrete buildings: frame buildings, wall-frame buildings and wall buildings. Conceptually, both frame buildings and wall-frame buildings are those whose collapse is governed by column failure. Wall buildings have so few columns that collapse is dominated by walls. Frames include beam-column, slab-column, or joist-column systems designed to resist gravity or gravity plus lateral loads, regardless of the level of ductile detailing. Frame buildings have no significant structural walls. There are minimum levels of reinforcement that must be satisfied for a component to be classified as a structural wall, a minimum length, and aspect ratio limitations. Any building with a significant number of structural walls is classified as a wall-frame or wall building. Wall structures are those configured to support gravity loads with bearing walls and few columns. Isolated columns could be employed to accommodate functional demands, but the performance of these columns will not control global collapse. In the methodology, wall buildings are those for which columns carry less than 25% of the gravity load at the critical story (often the first story).

5. "Early Outs"

At the time of building classification, the methodology identifies a set of "early outs". These are a series of checks which can be used to identify certain buildings as *exceptionally high seismic risk* (highest priority) or *lower seismic risk* (lowest priority among nonductile RC buildings) quickly and without detailed calculations. Buildings that are quickly classified by these rules need not to be analyzed further within the ATC 78 methodology.

At present, the ATC 78 methodology identifies several conditions that, if existing in the building of interest, automatically earn the building a rating of *exceptionally high seismic risk.* These conditions are:

1) Buildings that are very weak. Global weakness is assessed by computing the ratio of the seismic demand to the strength of the building, through

$$\mu_{strength} = \frac{S_a}{V_y / W} C_m \quad (1)$$

where S_a is the seismic demand at the period of the building and hazard level of interest, V_y is the estimated strength of the building, W is the total building weight and C_m is an effective mass factor determined in accordance with ASCE/SEI 41 [3]. The limiting threshold of $\mu_{strength}$ to qualify for this condition is approximately 5, but depends on the shear criticality of the columns and the number of walls in the building. Buildings are judged to be very weak if $\mu_{strength}$ exceeds the threshold. The definition of these thresholds was based on nonlinear dynamic analysis of more than 20 buildings (each subjected to 44 ground motion recordings), with varying frame conditions and numbers of walls.

2) Buildings that have an extreme torsional irregularity. Research is ongoing to develop simple criteria to identify when buildings are so torsionally irregular that the collapse risk is extremely high. The definition of this torsional irregularity criteria will likely also be a function of the building's overall strength.

3) As the methodology develops, there may be a criterion here applying to some buildings having discontinuous walls supported on columns or beams.

There are also several conditions that, if existing in the building of interest, move the building to the classification of *lower seismic risk*. These conditions are:

1) Buildings that are strong enough that they will remain elastic or essentially-elastic under the seismic level demand of interest. A building is considered to be essentially-elastic based on the same $\mu_{strength}$ parameter defined in Equation (1). If the building is a frame or wall-frame building with shear-controlled columns, $\mu_{strength}$ must be less than 0.75 to qualify as moderate seismic risk. For all other cases, $\mu_{strength}$ must be less than 1.5.

2) Buildings with a significant number of walls. The presence of walls is quantified with a wall index, which compares the area of walls to the total (floor) area of the building, through

$$WI = \frac{\sum A_w}{\sum A_f} \tag{2}$$

where ΣA_w is the summation of the plan area of walls at the story of interest and ΣA_f = the tributary area of floors above the story of interest. The idea of a wall index has been proposed by Sözen [4], and shown to correlate inversely with damage and collapse risk with data from a number of earthquakes [5]. The wall strength index (WSI) is taken as WI divided by the spectral acceleration demand at the estimated period of the building. Where WSI > 0.002 the building is judged to have so many walls that it is given a rating of *lower seismic risk*. The definition of the WSI and the cutoff value was based on nonlinear dynamic analysis of more than three dozen buildings with varying amounts of wall, as well as various frame characteristics. To qualify for for this condition, the building must not have extreme torsional irregularities.

6. Building Ratings for Frame and Wall-Frame Systems

6.1 Overview

For buildings that are classified as frame and wall-frame systems, collapse is governed by columns and their loss of ability to carry gravity loads. To assess the potential failure of columns, and subsequent story collapse, the building period and overall strength calculations described above are used to estimate column drift demands. The ratios of column drift demands and column drift capacities are used to identify component failures. Global collapse is predicted from the combination of column (component) failures observed. The presence of walls in the wall-frame systems alters the column drift demand, and gravity load redistribution from columns to the walls is accounted for through story collapse criteria. Column evaluations and story collapse evaluations are made at the critical story, as identified through global lateral mechanism analysis.

6.2 Determination of drift demands

Story drift demands are computed based on the estimated displacement of an equivalent single-degree-of-freedom oscillator subjected to the spectral acceleration level of interest. This displacement is predicted from the spectral displacement, modified with coefficients accounting for elastic response and hysteresis parameters. Once the displacement of the equivalent oscillator is obtained, the drift demands at each story are obtained by multiplying the oscillator drift by a modification factor that depends on the building design, framing and wall characteristics. The modification factor, α, amplifies the story drifts in certain stories to represent typical patterns of drift concentration. α factors are defined in a table, and describe the typical distribution of drift demands over the height of the building, accounting for the number of stories and the collapse mechanism identified in the strength calculations. The wall index is used to define when a building has enough walls such that walls dominate the response and the displacement demand is evenly distributed across all stories. Buildings with shear critical, rather than flexurally critical, walls will likely be assigned different α factors. These α factors are based on nonlinear time history analysis of dozens of frame and wall-frame buildings with different characteristics and subjected to a large number of ground motions (described for frame structures by [6]). Other factors may be necessary for walls that are discontinuous above the first story, and analysis to define these factors is ongoing.

In the next step, story drift demands are used to determine drift demands on every column. In particular, for buildings with non-negligible inherent eccentricity, a torsional amplification factor is used to increase the estimated drift demands at columns away from the center of rigidity. The methodology also accounts for the fact that columns and beams together share the story drift demand. A column drift factor estimates the fraction of the drift going to the column depending on column-to-beam strength ratios and the presence of walls.

6.3 Determination of drift capacities for column ratings

Column drift capacities are based on experimental data quantifying the deformation a column is capable of undergoing before losing vertical-load-carrying-capacity. The ATC 78 methodology provides equations that can be used to compute the column drift capacity as a function of expected axial load on the column and the column’s transverse reinforcement ratio. The development of these equations utilized a suite of data collected by Elwood et al. [7] and expanded to include shear critical columns tested to axial failure in recent years. The equations also build off recent work by Ghannoum et al. [8], [9]. Unlike older versions of ASCE/SEI 41 [3], the predicted drift capacities are explicitly defined as median values, such that there is a 50% chance a column with the characteristics of interest will have a true capacity that is greater than the tabulated value. The use of the axial failure criteria and median values for column drift capacities is intended to avoid some of the conservatisms inherent in existing evaluation methodologies. If a building has slab-column connections, these connections may be the critical component. In this case, the drift capacity of the slab-column connection is computed from median values provided in a table. The analyst must compute the drift capacity of every column or slab-column connection at the critical story in the building. For walls that span between columns or that have boundary elements acting as columns, those end columns or elements are also treated as a column and a drift capacity is determined by the same methods.

Column ratings are based on the ratio of column drift capacity to drift demand, and represent the probability that drift demand exceeds drift capacity or the likelihood of column failure, as determined from structural reliability methods. Column ratings vary from 0 and 1, where a rating of 1 indicates the very worst columns. These reliability methods relate a lognormal distribution of drift demand, defined by a median value obtained from the drift demand calculations and uncertainty reflecting record-to-record variability in structural response, and a lognormal distribution of drift capacity, defined by a median value obtained from the tabulated values and uncertainty reflecting epistemic and aleatory uncertainty in column capacities. In the methodology, these structural reliability calculations are streamlined, such that the analyst uses a table to determine the column rating from a computed ratio of median column drift capacity to median column drift demand. Each column at the critical story of the building is assigned a rating.

6.4 Story ratings and building ratings

Once all columns (or slab-column connections) are rated, the methodology proceeds to the determination of a rating for the critical story, and finally a building rating. Like column ratings, story ratings and building ratings vary from 0 (low likelihood of failure) to 1 (high likelihood of failure). The conversion between column ratings and story ratings provided in the methodology serves as a proxy for nonlinear structural analysis, and relates the failure of individual columns to the global collapse of the story. Story ratings are based on the ratings of columns in that story and the proximity of poor columns to each other, representing progressive collapse of a story. To determine story ratings, the analyst needs only to compute the average column rating in the critical story, which is then related to a story rating. This relationship was developed from Monte Carlo simulation of column drift demands and column drift capacities to determine what combinations contribute to story failure. Story failure is defined to occur if columns carrying 25% or more of the gravity load at the critical story fail. In wall-frame buildings, walls may carry a substantial portion of the gravity load. The analysis considers that these systems may have a greater potential to redistribute gravity loads in the event of column failure.

Column ratings and story ratings are to be computed in both orthogonal directions for the building, and the building rating is taken as the higher of the critical story ratings, considering the ratings in either of the two directions. The building rating represents the likelihood of building failure under the ground motion intensity level of interest.

7. Ongoing Work to Incorporate Buildings with Walls

The ATC 78 team is currently working to refine methods and parameters used to assess the collapse risk of wall-frame buildings. Ongoing areas of research for these buildings include:

1) development of procedures for buildings with discontinuous walls;
2) simplification of tables for α factors to minimize analyst effort; assessment of torsional irregularity measures as collapse indicators for *exceptionally high risk* buildings and refinement of torsional amplification factors;
3) study of collapse risk of buildings with shear-critical walls; and
4) refinement of strength and period relationships.

In addition, a short section on wall buildings that are not already covered by the criteria for wall-frame buildings is being developed. Buildings with full height infill walls will be added in the next phase of the project.

8. Calibration

Calibration of the ATC 78 methodology is ongoing. In 2015 and 2016, the City of Los Angeles and FEMA funded 16 teams of practicing engineers to apply the draft frame methodology in trial evaluations of real buildings. These buildings are mostly located in southern California, and range in height from 16 to 149 ft, with plan dimensions from 60 to 440 ft. in a single direction. These studies included a number of buildings that had been previously investigated under other procedures, such as ASCE/SEI 41, so that results could be directly compared to other assessment procedures [3]. These results identified a number of places where refinement was needed, in particular in dealing with frame systems with very strong columns relative to beams. Engineers also requested that the methodology be further simplified, prompting re-evaluation of procedures for building strength and period and other tables. These calibration efforts did not include calibration to observed earthquake damage.

9. Conclusions

The ATC 78 methodology addresses the need for a relatively quick procedure that can be used to identify the most seismically vulnerable older non-ductile concrete buildings. Such a tool is needed to prioritize retrofit of the most dangerous buildings, given limited resources. The wall and wall-frame methodologies are the subject of ongoing research and development efforts by the ATC 78 technical team to refine crucial factors employed in the methodology. In the next phase of the project, the team will focus on further validation for wall-frame and wall buildings, and the expansion of the methodology to account for the influence of masonry walls that may influence the response of the structure.

10. Acknowledgments

The authors of this paper are the members of the ATC 78 Project Technical Committee (PTC). The work forming the basis for this publication was conducted pursuant to a contract with FEMA. The substance of such work is dedicated to the public. The PTC is indebted to the significant contributions of current and former students who have worked on this project, including Panagiotis Galanis, Siamak Sattar, Cody Harrington, Travis Marcilla, Carlos Arteta, Pablo Parra, Constantine Demetracopoulos and Francesca Renouard. The project also has a review panel, whose contributions are gratefully acknowledged. The authors are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings and recommendations contained herein, either by FEMA, the Applied Technology Council, its directors, members or employees. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, product or processes included in this publication.

11. References

[1] A. B. Liel, C. B. Haselton, and G. G. Deierlein, "Seismic collapse safety of reinforced concrete buildings. II: Comparative assessment of nonductile and ductile moment frames," *Journal of Structural Engineering*, vol. 137, no. 4, pp. 492–502, 2010.

[2] L. M. Jones, "Resilience by Design: Bringing Science to Policy Makers," *Seismological Research Letters*, vol. 86, no. 2A, pp. 294–301, Mar. 2015.

[3] ASCE (American Society of Civil Engineers), *Seismic Rehabilitation of Existing Buildings: Seismic Rehabilitation of Existing Buildings ASCE 41*. Reston, VA: ASCE Publications, 2007.

[4] M. A. Sozen, "Earthquake response of buildings with robust walls," in *Proceedings of Fifth Chilean Conference on Seismology and Earthquake Engineering, Santiago*, 1989.

[5] M. A. Sözen, "Surrealism in Facing the Earthquake Risk," in *Seismic Evaluation and Rehabilitation of Structures*, A. Ilki and M. N. Fardis, Eds. Springer International Publishing, 2014, pp. 1–13.

[6] P. H. Galanis and J. P. Moehle, “Development of Collapse Indicators for Risk Assessment of Older-Type Reinforced Concrete Buildings,” *Earthquake Spectra*, vol. 31, no. 4, pp. 1991–2006, May 2014.

[7] K. J. Elwood *et al.*, “Update to ASCE/SEI 41 Concrete Provisions,” *Earthquake Spectra*, vol. 23, no. 3, pp. 493–523, Aug. 2007.

[8] W. M. Ghannoum and A. B. Matamoros, *Nonlinear modeling parameters and acceptance criteria for concrete columns*. Submitted for publication in ACI Special Publications, American Concrete Institute, Farmington Hills, Michigan, 2013.

[9] W. Ghannoum, “Updates to Modeling Parameters and Acceptance Criteria for Non-ductile and Splice-deficient Concrete Columns.,” in *Proc. of 16th World Conference on Earthquake Engineering*, Santiago, Chile, 2017.