Collapse Assessment and Mitigation of Nonductile Concrete Buildings: ATC-76-5/ATC-78/ATC-95

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SUMMARY:
Reinforced concrete buildings designed and constructed prior to the introduction of seismic design provisions for ductile response (commonly referred to as *nonductile* concrete buildings) represent one of the largest seismic safety concerns in the United States and the world. Seismic retrofit of these existing buildings plays an important role in reducing urban seismic risk; however, with the massive inventory of existing concrete buildings and the high costs of seismic rehabilitation, it is necessary to start by identifying and retrofitting those buildings which are most vulnerable to collapse. This paper will introduce on-going projects by Applied Technology Council to improve methods of identifying collapse-hazardous concrete buildings using *collapse indicators*, design and response parameters that are correlated with "elevated" collapse probability.

Keywords: concrete; nonductile; collapse; probability; collapse simulation

1. INTRODUCTION

In the mid-1990s new seismic rehabilitation guidelines were introduced, providing the structural engineering profession with the first generation of 'performance-based' procedures for seismic assessment and rehabilitation design. The most common example of these was the National Earthquake Hazards Reduction Program (NEHRP) *Guidelines for the Seismic Rehabilitation of Buildings*, published by the Federal Emergency Management Agency (FEMA) as FEMA-273. These documents revolutionized the assessment of existing buildings by encouraging the use of nonlinear analysis, by enabling the engineer to select project-specific performance objectives, and perhaps most importantly, by recognizing that structural collapse was limited by both strength and deformation capacity. The past 15 years has seen modest improvements to this first-generation performance-based design procedure as *FEMA* 273 has evolved into a pre-standard (FEMA-356) and ultimately into an American Society of Civil Engineers, Structural Engineering Institute Standard ASCE/SEI 41. However, the overall framework remains essentially deterministic and inconsistent conservatism in specified deformation capacities throughout the document may impact the reliability of the predicted performance of a building structure. Furthermore, the component-based assessment procedures (*i.e.* once one component is determined to have exceeded a performance level, the entire structure is deemed to have exceeded the performance level) ignore the ability of a structural system to redistribute loads as damage accumulates and will tend to lead to conservative assessments of collapse vulnerability. Seismic evaluation documents based on checklist assessments (*e.g.* ASCE/SEI 31) are also generally conservative to ensure dangerous buildings are not misdiagnosed. As currently formulated, ASCE/SEI 31 and ASCE/SEI 41 are not capable of reliably determining the relative collapse risk between different nonductile concrete buildings. From a public policy standpoint, the ability to economically make this distinction across the large inventory of existing concrete buildings is a critical need and a necessary next step in the evolution of seismic rehabilitation documents.

The need for improvement in collapse assessment technology for existing nonductile concrete buildings has been recognized as a high-priority because: (1) such buildings represent a significant percentage of the vulnerable building stock in the United States and internationally; (2) failure of such buildings can involve total collapse, substantial loss of life, and significant economic loss; (3) at present, the ability to predict collapse thresholds for different types of older reinforced concrete buildings is limited; and (4) the high retrofit costs for such buildings represents a strong deterrent against seismic risk mitigation.

With support from the National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA), the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE) have joined forces to initiate a multi-phase project with the primary objective being the development of nationally accepted guidelines for assessing and mitigating the risk of collapse in older nonductile concrete buildings. The project leverages recent research results from the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Grand Challenge project on the identification of seismically hazardous older concrete buildings and the development of policies for cost-effective hazard mitigation. This paper summarises the on-going multi-phase project including the development of a long-term program plan, proposed methodology, and critical challenges.

2. PROGRAM PLAN FOR COLLAPSE ASSESSMENT (ATC-76-5)

The first stage, known as ATC-76-5, was to establish a long-term program plan for the development of collapse assessment and mitigation guidelines for nonductile concrete buildings. The program plan is described in detail in NIST GCR 10-917-7 and summarised briefly below. NIST GCR 10-917-7 identifies the following critical needs for addressing the collapse risk associated with older concrete construction:

- Improved procedures for identifying building systems vulnerable to collapse, including simple tools that do not require detailed analysis.
- Updated acceptance criteria for concrete components based on latest research results.
- Identification of cost-effective mitigation strategies to reduce collapse risk in existing concrete buildings.

To address these needs, the development of a series of eight guidance documents, under the umbrella title *Guidance for Collapse Assessment and Mitigation Strategies for Existing Reinforced Concrete Buildings*, was recommended:

1. Assessment of Collapse Potential and Mitigation Strategies
2. Acceptance Criteria and Modeling Parameters for Concrete Components: Columns
3. Acceptance Criteria and Modeling Parameters for Concrete Components: Beam-Column Joints
4. Acceptance Criteria and Modeling Parameters for Concrete Components: Slab-Column Systems
5. Acceptance Criteria and Modeling Parameters for Concrete Components: Walls
6. Acceptance Criteria and Modeling Parameters for Concrete Components: Infill Frames
7. Acceptance Criteria and Modeling Parameters for Concrete Components:

Beams

8. Acceptance Criteria and Modeling Parameters for Concrete Components: Rehabilitated Components

The first document is intended to focus on building system behavior, while the remaining documents focus on individual concrete components. Development of Documents 2 through 8 will be largely based on collection of existing experimental data and the application of a consistent methodology for the selection of acceptance criteria and modeling parameters based on this data. Document 1 requires the development of a methodology, using sophisticated collapse simulations, to identify building parameters, termed here *collapse indicators*, correlated with an elevated probability of collapse. Ideally there should be a variety of collapse indicators, ranging from those appropriate for rapid assessment to others used to identify collapse potential based on results of detailed nonlinear analysis. The proposed methodology for the identification of collapse indicators is described in the next section.

The risk associated with older nonductile concrete buildings is significant, and the development of improved technologies for mitigating that risk is a large undertaking. A multi-phase, multi-year effort is needed to complete all eight recommended guidance documents. Figure 1 indicates the recommended timeline for the development of the proposed guidance documents as depicted in the NIST GCR 10-917-7 Program Plan.

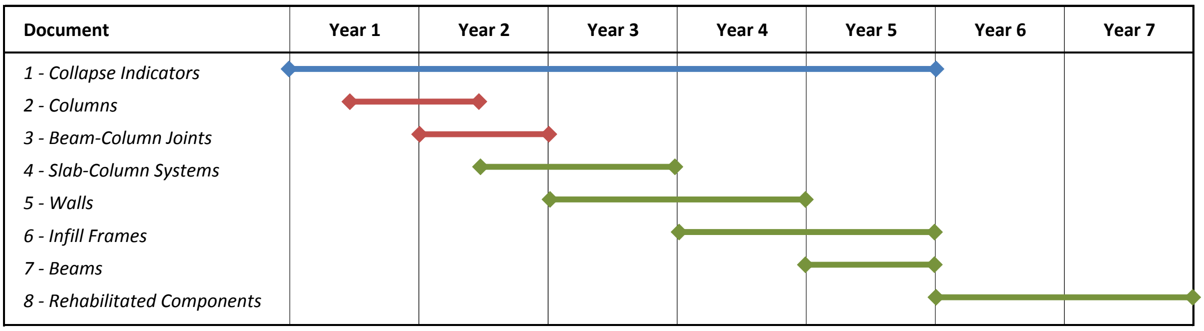

Figure 1. Recommended schedule for development of Guidance Documents

3. COLLAPSE INDICATOR METHODOLOGY

3.1 Potential Collapse Indicators

Ideally there should be a spectrum of collapse indicators, ranging from those appropriate for rapid assessment to others used to identify collapse potential based on results of detailed nonlinear analysis. Collapse indicators for rapid assessment must be very simple parameters which can be established from basic information available from a quick survey of the building or engineering drawings. Conversely, collapse indicators for detailed collapse prevention assessment can make use of the results from nonlinear analyses. It is proposed to categorize collapse indicators into two fundamental types:

Design parameter collapse indicators: These collapse indicators are determined based on design features of a concrete building, including reinforcement details, structural system layout, and relative strength and stiffness of members. These indicators can be further sub-categorized as “rapid assessment” (*RA*) or “engineering calculation” (*EC*) collapse indicators, where the former can be determined from a quick survey of the building or engineering drawings and the latter requires some calculation of capacities and demands based on engineering drawings. *RA* and *EC* collapse indicators will be useful for refining the seismic evaluation procedures in ASCE/SEI 31.

Response parameter collapse indicators: These collapse indicators reflect the response of the structure based on results from building analysis (*BA*). Generally the most refined collapse indicators are expected to be derived from results of nonlinear analysis and provide system-level acceptance criteria for the Collapse Prevention performance level.

Table 1 provides a list of potential collapse indicators. These collapse indicators have been grouped based on the classification described above, and further grouped as component or system-level parameters. Component Building Analysis indicators shown in Table 1 (*BA – C#*) can be interpreted as equivalent to component acceptance criteria in ASCE/SEI 41. It is anticipated that relationships may exist among the indicators, as vectors of indicators may be found to provide a better indication of collapse potential than any one indicator. For example, if the average minimum transverse reinforcement ratio (*RA-C1*) is less than a specific value, and the column-to-floor area ratios (*RA-S1*) are greater than a specific value, then collapse potential is expected to be high. Engineering judgment and experience with collapse analyses were used to select the preliminary list of potential collapse indicators below, and it is anticipated that this list will evolve as further experience is gained from the collapse analyses described in following sections.

Table 1. Examples of collapse indicators (from NIST GCR 10-917-7)

Type of Collapse Indicator		**System-level**		**Component-level**	
Design Parameters	**Rapid Assessment (RA)** *Quantities that can be determined from a quick survey of the building or engineering drawings.*	*RA-S1.*	Maximum ratio of column-to-floor area ratios for two adjacent stories.	*RA-C1.*	Average minimum column transverse reinforcement ratio for each story.
		RA-S2.	Maximum ratio of horizontal dimension of the SFRS in adjacent stories.	*RA-C2.*	Minimum column aspect ratio.
		RA-S3.	Maximum ratio of in-plane offset of SFRS from one story to the next to the in-plane dimension of the SFRS	*RA-C3.*	Misalignment of stories in adjacent buildings.
		RA-S4.	Plan configuration (L or T shape versus rectangular)		
		RA-S5.	Minimum ratio of column area to wall area at each story**		
	Engineering Calculations (EC) *Quantities that require some calculation of capacities and demands based on engineering drawings, but do not require structural analysis results from computer modeling.*	*EC-S1.*	Maximum ratio of story stiffness for two adjacent stories	*EC-C1.*	Maximum ratio of plastic shear capacity ($2M_p/L$) to column shear strength, V_p/V_n .
		EC-S2.	Maximum ratio of story shear strength for two adjacent stories.	*EC-C2.*	Maximum axial load ratio for columns with $V_p/V_n > 0.7$.
		EC-S3.	Maximum ratio of eccentricity (distance from center of mass to center of rigidity or center of strength) to the dimension of the building perpendicular to the direction of motion.	*EC-C3.*	Maximum ratio of axial load to strength of transverse reinforcement (45 deg truss model).
		EC-S4.	Portion of story gravity loads supported by columns with ratio of plastic shear demand to shear capacity > 0.7.	*EC-C4.*	Maximum ratio of joint shear demand (from column bar force at yield) to joint shear capacity for exterior joints.
		EC-S5.	Ratio of column-to-beam strength.		
				EC-C5.	Maximum gravity shear ratio on slab-column connections.
Response Parameters	**Building Analysis (BA)** *Quantities for detailed collapse prevention assessment using the results from nonlinear building analyses.*	*BA-S1.*	Maximum degradation in base or story shear resistance.	*BA-C1.*	Maximum drift ratio.
		BA-S2.	Maximum fraction of columns at a story experiencing shear failures.	*BA-C2.*	Maximum ratio of deformation demands to ASCE/SEI 41 limits for columns, joints, slab-column connections and walls.
		BA-S3.	Maximum fraction of columns at a story experiencing axial failures.		
		BA-S4.	Minimum strength ratio (as defined in ASCE/SEI 41).		

* Collapse indicator notation: RA = Rapid Assessment; EC = Engineering Calculation; BA = Building Analysis; S=System; C = Component.
** May not result in collapse but could help prevent collapse if a mechanism forms.

3.2 Collapse Simulation Studies

Collapse simulation studies are necessary to establish a correlation between building design and response parameters and the probability of collapse. In order to identify appropriate and reliable collapse indicators, analytical models using research oriented structural analysis software (e.g., *OpenSees* – Open Systems for Earthquake Engineering Simulation) are needed. Using these models, building characteristics (e.g., dimensions, geometry, and mass) can be varied parametrically to explore effects on building response and collapse probability. Such studies would be used to identify quantitative limits on collapse indicators that have strong correlation with collapse potential.

Building prototype models are full building nonlinear models to explore parametric variations on building characteristics and their effects on response. Building prototype models allow explicit consideration of collapse probability considering loss of vertical-load-carrying capacity, lateral dynamic instability, modeling uncertainty, and ground motion record-to-record variability. Since absolute probability of collapse is difficult to determine, the emphasis should be on relative probabilities of collapse, or changes in probability of collapse due to changes in building characteristics.

Collapse of real buildings is highly dependent on the complex behavior and interaction among individual components. Collapse probabilities must be considered for a cross section of building types to ensure the selected collapse indicators are appropriate for a relatively broad range of buildings characteristics. Based on an inventory of nonductile concrete building in the Los Angeles area, the NEES Grand Challenge project and the Concrete Coalition have collected a library of models of real concrete buildings. This will serve as an initial basis for the selection of concrete building prototypes.

Unlike ductile structures that are typically assumed to collapse due to side-sway (FEMA P695), nonductile concrete buildings can experience gravity-load collapse due to loss of vertical-load-carrying capacity prior to development of a side-sway collapse mode. Nonlinear building prototype models used in this study must incorporate elements capable of approximating loss of vertical-load-carrying capacity for critical gravity-load supporting components, such as columns (Elwood, 2004) and slab-column connections (Kang et al., 2009), and must account for P-Delta effects. One significant challenge that must be overcome is the distinction between gravity-load collapse and non-convergence due to numerical instability in the model. As envisioned in this study, collapse will be detected based on a comparison of floor-level gravity load demands and capacities (adjusted at each time step to account for member damage and load redistribution). Gravity collapse will be defined as the point at which vertical load demand exceeds the total vertical load capacity at a given floor, and non-convergence of the analysis prior to significant degradation in the capacity to resist gravity loads will not necessarily be considered as collapse.

One approach for selection of design parameter collapse indicators is illustrated in Figure 2. In this approach, limits are selected based on the relative changes in the collapse fragilities with respect to changes in the collapse indicator parameter. Figure 2 shows example collapse fragilities (conjectured) for changes in a selected collapse indicator (e.g., average column transverse reinforcement ratio, *RA-C1*). The curves in the figure suggest that once the transverse reinforcement ratio decreases below about 0.001, the probability of collapse increases rapidly. In this example, 0.001 could be selected as an appropriate limit for this collapse indicator. This assessment would be repeated for several different building types and different hazard levels, and the resulting limits would be compared. An ideal collapse indicator would have only limited variation in the limits suggested by different building types. For response parameter collapse indicators, the envisioned process would be similar.

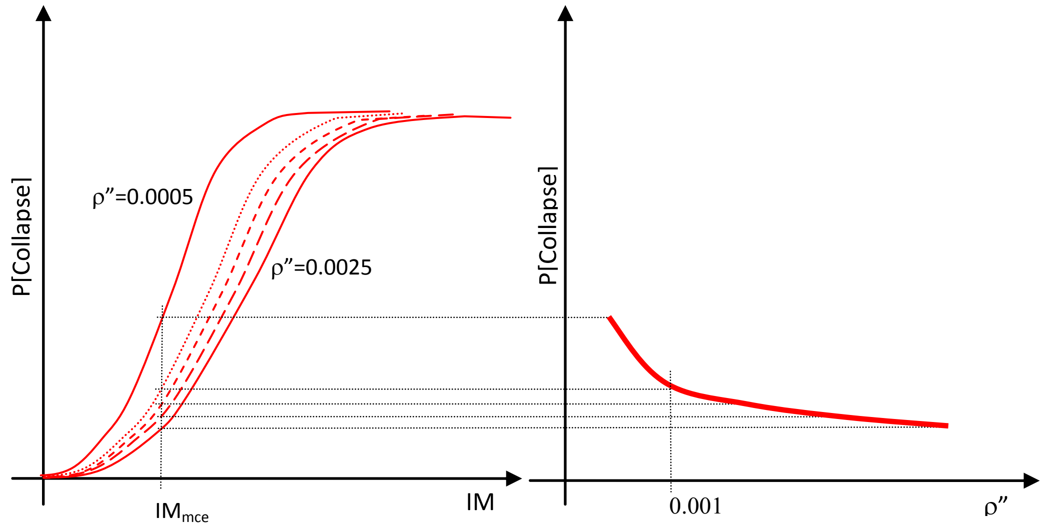

Figure 2. Approach for establishing collapse indicator limits based on the relative changes in the collapse fragilities with respect to changes in the collapse indicator parameter (ρ″ = transverse reinforcement ratio; IM = Intensity Measure).

As implemented in a performance assessment, response parameter collapse indicator limits would be compared with responses determined from nonlinear analysis of a building, while design parameter collapse indicator limits would be compared with the relevant design features of a building. Since assessment using design parameter indicators will not directly consider the seismic response of the building in question, it is expected that greater computational effort (i.e., more building prototypes) will be needed to develop reliable design parameter collapse indicators than will be needed to develop response parameter collapse indicators.

The methodology as described above requires considerable computational effort as the collapse simulations must be repeated for multiple ground motions, multiple hazard levels, multiple values of collapse indicators, multiple building prototypes with multiple building periods. This computational effort is reflected in the five-year time frame estimated for the development of Document 1 in Figure 1. Considering the computational effort, and investment involved, an on-going evaluation and refinement of the collapse indicator methodology was undertaken, and is described in the next section.

4. EVALUATION OF COLLAPSE INDICATOR METHODOLOGY (ATC-78)

An evaluation of the proposed collapse indicator methodology was undertaken by the ATC-78 project, with funding from FEMA. FEMA funded this effort with ATC starting in 2009 to address the need that had been suggested by the Concrete Coalition to develop a way to rapidly identify the buildings with the highest potential of collapse. This ultimately led to the idea of identifying and quantifying the most important parameters that indicted a potential for collapse. The collapse indicator methodology was applied to a six-story five-bay prototype perimeter moment frame building. The study considered the following collapse indicators from Table 1: *EC-S1*, the maximum ratio of story stiffness for two adjacent stories, *EC-S2*, the maximum ratio of story shear strength for two adjacent stories, and *EC-S5*, the ratio of column-to-beam strength. Models considering only flexural failures and models considering column shear and axial load failures were considered. The gravity system was not modeled.

This study also considered the influence of changes in collapse indicators on the overall building strength. Instead of determining the probability of collapse for a given intensity measure as shown in figure 2, the probability of collapse is determined for the ground motion intensity normalized with respect to the maximum shear capacity of the frame, V_{max}:

$$R_{Mb} = \frac{Sa_{MCE}(T_1)W}{V_{\max}} \tag{1}$$

Figure 3 shows an example of the results obtained in this preliminary evaluation. Here the variation in the probability of collapse with changes in the ratio of column-to-beam strength is explored. These preliminary results suggest that the probability of collapse increases rapidly at a column-to-beam strength ratio of 1.2 to 1.6 depending on the spacing of the transverse reinforcement. Further study is required validate these results and apply to different building prototypes, but the results shown in Figure 3 suggest that the ratio of column-to-beam strength may be an important collapse indicator in identifying the collapse vulnerability of frame buildings.

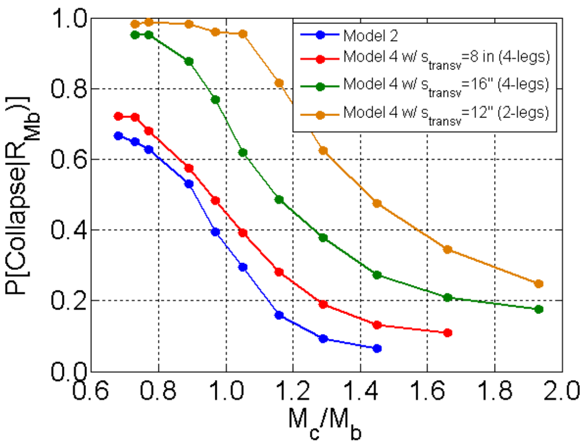

Figure 3. Normalized probability of collapse at the MCE level versus the collapse indicator $(M_c/M_b)_{\min}$

The evaluation described above identified some important issues with the proposed methodology and modeling approaches required to identify collapse indicator limits. The most significant of the issues are described in the following sections.

4.1 Combination of Collapse Indicators

It is reasonable to expect that buildings which possess multiple collapse indicators would likely have a higher overall risk of collapse than a building with just a single indicator. However, this depends on the nature of which indicators are present and the relative severity of each. For example, in a building with a severe weak story condition at the first floor (*EC-S2*), the risk of collapse may be so dominated by this behaviour that the presence or lack of a strong column/weak beam condition (*EC-S5*) at the upper floors may not have any significant impact on the overall risk of collapse.

Nevertheless it is expected that combining certain collapse indicators in a building may often result in a higher collapse potential than a single indicator. However, the formulation of combined risk can only emerge as these combined indicators are analyzed. A “brute force” approach would be to present the combination risk values in a multi-dimensional matrix in which each dimension is a separate deficiency. Over the course of this study, two potential approaches for combining collapse indicators have emerged. The first approach, the “matrix” methodology, could involve the creation of matrices for containing effective collapse risks based on the combination of two or more collapse indicators. The second approach, the “flow chart” methodology, could involve a series of linear progression to quickly evaluate the impacts and interaction between various potential collapse indicators.

4.2 Treatment and Variation of Gravity Load Systems

Buildings are commonly idealized as possessing a seismic force resisting system, which takes the majority of the lateral loads, and a gravity load system, which is typically assumed to “go along for the ride". However for many buildings the fraction of lateral load resisted by the gravity system can be non-trivial and may provide some additional stability to the building in the event of strength degradation in the lateral system. Conversely, the gravity frame systems of nonductile concrete frames may also be vulnerable to certain brittle failure modes, due to poor detailing of slab-column connections or inadequate transverse reinforcement in columns. The relative contribution of the gravity frame in helping or hurting the lateral system response depends on its strength, stiffness and deformation capacity, as it compares to the strength, stiffness and deformation capacity of the laterally-designed frames.

In the future, the methodology for identifying and evaluating collapse indicators should address the role of gravity-load bearing elements and their impact on seismic resistance. The gravity system should ideally be included directly in the model used to determine collapse probabilities, with component models capturing not only the additional strength and stiffness from the gravity system, but also the gravity-load failure of such systems due to limited deformation capacity. Consideration of the gravity system in the analytical models to determine collapse indicators will significantly increase the already high computational effort. Hence, alternatives, such as considering properties of the gravity system (type and detailing features) in the collapse risk evaluation matrix, need to be investigated.

4.3 Optimal Methods for Varying and Measuring Collapse Indicators

Several of the collapse indicators measure characteristic of local beam and/or column elements—for example, beam-column strength ratio or column transverse reinforcing ratio. Seldom will these parameters be uniform throughout a floor or between floors. Collapse indicators must be identified that both measure the effect of these potential deficiencies on performance, but also represent realistic building characteristics. Collapse indicator studies should strive to identify if variation of a parameter over the entire building is more or less critical than variation just at a single story.

The basic premise of the proposed methodology is to vary the intensity of a collapse indicator within the same "base building" to determine how this variation affects collapse probability. However, the variation of parameters can easily affect other structural characteristics that will secondarily affect collapse probability. For example when the beam/column strength ratio is varied significantly, the structure will quickly become stronger (if the columns are made stronger) or unrealistic (if the beams are made stronger). This issue possibly can be mitigated by careful selection and definition of collapse indicators, or by choosing variations that have least effect on performance.

4.4 Use of Relative Risk Versus Absolute Risk

The methodology described above advocates for using relative collapse risk to select the collapse indicator limits. This is attractive due to the approximate nature of the collapse simulations used to arrive at the collapse probabilities. The conceptual results in Figure 2 show a "kink point" where the collapse probability increase suddenly below a specific value of the collapse indicator under consideration, enabling the selection of a limit for the collapse indicator that is independent of the absolute probability of collapse. Unfortunately, not all collapse indicators have this idealized behaviour and for many collapse probability increases proportionally with changes in the collapse indicator making it impossible to define a "kink point". In such cases, collapse indicator limits must be identified by selecting a level of absolute collapse risk (e.g. 10% probability of collapse given MCE). To do this it may be necessary to benchmark the assessment of collapse risk as determined by the methodology described herein with that proposed for new buildings in FEMA P-695.

4.5 Refinement of Component Models for Collapse Simulation

To achieve reliable estimates of collapse probability, simulation models must be capable of capturing all likely modes of collapse in a structure. Models must balance the need for accurate building response simulation with the need for computational efficiency in the interest of managing the massive computational effort required to determine collapse indicators. A workshop will be convened as part of the ATC-95 project (see next section) to identify the best possible models to be used for future collapse indicator studies.

4.6 Development of Evaluation Methodology

An important goal of defining collapse indicators is to enable engineers to identify collapse-hazardous buildings with limited calculation or modelling. To achieve this goal, the results from the detailed analyses described above must be summarised in a form that facilitates the evaluation of existing buildings. It is envisioned that the evaluation tool would consist of a matrix providing the collapse risk for combinations of building strength (represented by *R*) and collapse indicator values. Some refinements on this basic concept may help to address some of the challenges indicated in the previous sections. For example, a three dimensional matrix may be developed to capture the heightened collapse risk expected for buildings with combinations of collapse indicators (section 4.1). Furthermore, to avoid the specifying an absolute probability of collapse (section 4.4) in the evaluation matrix, and to appropriately reflect the level of refinement of the collapse simulation studies, the matrix may simply provide a an indication if the collapse risk is “low”, “moderate”, “high”, or “extreme”. The eventual goal is to use the matrices to identify buildings in the “extreme” zone such that the collapse risk of these buildings can be mitigated as quickly as possible.

5. CONCRETE BUILDING PERFORMANCE DATABASE (ATC-95)

The first phase of the program plan defined in NIST GCR 10-917-7 was initiated in late 2011 to build on the accomplishments of the previous phases and identify critical concrete building deficiencies based on a review of documented collapses in past earthquakes. Known as ATC-95, this phase will lay the ground work for the identification of collapse indicators for a broad range of collapse-vulnerable concrete buildings and serves as a critical step in the development of nationally accepted guidelines for assessing and mitigating the risk of collapse in older nonductile concrete buildings.

A Concrete Building Performance Database is being developed by the Concrete Coalition. The Concrete Coalition is a network of individuals, governments, institutions, and agencies with shared interest in assessing the risk associated with dangerous non-ductile concrete buildings and developing strategies for fixing them. It is a program of the Earthquake Engineering Research Institute (EERI), co-sponsored by the Pacific Earthquake Engineering Research Center (PEER) at UC Berkeley, and the Applied Technology Council (ATC). Other partners include the Structural Engineering Association of California, the American Concrete Institute, BOMA of Greater Los Angeles and the United States Geological Survey.

The Concrete Coalition and ATC are building an online database documenting the seismic performance of concrete buildings. The format is case-history oriented focusing on individual buildings. Participants in the ATC-95 project, *Development of a Collapse Indicator Methodology for Existing Reinforced Concrete Buildings*, currently are assembling information on buildings that have collapsed in past earthquakes. Data includes detailed information on the building itself, the damage that led to collapse, and characteristics of the event that caused the damage. Records comprise tabular information, drawings, photographs, and written reports in an effort to provide insight into the important aspects of the performance of concrete buildings. The Concrete Coalition is developing an interactive user interface to facilitate access and utilization of the resource materials. Volunteer design professionals and academicians are serving as mentors to graduate student interns who are gathering and categorizing information. In addition to collapses, the scope will expand to incorporate buildings that have been critically damaged but did not collapse in past earthquakes.

The purpose of the effort is to provide reliable data to a broad range of those individuals with a stake in improving the safety and sustainability of concrete buildings in seismically active areas of the world. For example, engineering practitioners and researchers working on the ATC-95 project will use the data to assess the relative contribution of various deficiencies to the potential for collapse.

Their objective is to develop simplified procedures for use in practice to identify particularly dangerous buildings. Practitioners will also have direct access to the performance data to improve their fundamental understanding of concrete building behavior. Engineering students will be able to visualize the effects of earthquakes on buildings over broad temporal and geographic spectra. Beyond the technical disciplines, the online resource will help to raise the consciousness for public policy experts and the general public, particularly in developing countries where the problem of concrete buildings is particularly challenging.

6. CONCLUSIONS

Future phases of work will include further development of the collapse indicator methodology, identification of reliable collapse indicator parameters, and identification of an assessment methodology based on collapse indicators identified. In addition, a series of efforts to collect available test data and develop improved modelling parameters and acceptance criteria for important concrete elements, including columns, beam-column joints, slab-column systems, walls, infill frames, beams and rehabilitated components, will be initiated. Through the combined future efforts on these projects, and coordinated funding between NIST and FEMA, the knowledge and techniques will be developed to reduce the risks associated with non-ductile concrete buildings in the United States and the world.

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