SEISMIC VULNERABILITY ASSESSMENT OF EXISTING RC BUILDINGS - COMPARATIVE STUDY OF CODAL PROVISIONS OF VARIOUS COUNTRIES

Rajeev Goel
Chief Scientist and Head, Bridge Engineering and Structures, CSIR-Central Road Research Institute

INTRODUCTION

In the past, during the earthquakes in several counties including India, loss of human lives and damage to property has occurred due to the collapse of existing buildings. Though, occurrence of an earthquake cannot be predicted and prevented, the loss of human life and damage to the property can be minimized by taking necessary steps on the existing buildings. Several countries have made codes of practices/guidelines for seismic vulnerability assessment of existing structures including RC buildings.

Out of the seven continents of the world, Asia is the most affected by earthquake. Most seismic prone countries include Japan, Nepal, India, Turkey, Ecuador, Philippines, Mexico and Indonesia. Global seismic hazard map is shown in Fig. 1. There is a growing perception that the built environment, both historic and recent construction, is characterised by an unacceptably high level of seismic risk. The efficient normative documents, allowing for rational and cost-effective interventions are required for mitigation of this risk.

REVIEW OF SEISMIC EVALUATION CODES AND GUIDELINES

Seismic evaluation codes and guidelines of USA, New Zealand, India, Europe and Turkey have been studied. A brief summary of reviewed seismic evaluation codes and guidelines is given below.

FEMA 310

The seismic vulnerability assessment of existing buildings is based on rigorous approach to determine their present condition. Existing buildings may be structurally damaged during the earthquake. The level of structural damage is predicted considering the importance of building and consequences of damage on human lives. For the existing buildings subjected to the design earthquake, two levels of performance defined as Life Safety and Immediate Occupancy are given in FEMA 310.

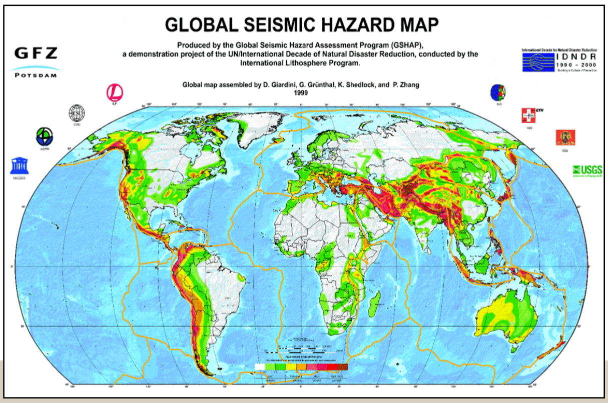

Fig. 1: Global Seismic Hazard Map

Under life safety performance, level of risk for life-threatening injury and getting trapped should be low, when there are significant damages to both structural and non-structural components of the building. For this, the structural system should have some margin, even after damages, against either partial or total structural collapse.

Under immediate occupancy building performance, there could be very limited damage to both structural and non-structural components during the design earthquake so that the building could be easily repaired during its occupancy. The structural members of the building may retain nearly all of their original strength and stiffness. However, there could be some minor injuries to human being.

For seismic vulnerability assessment, one of these performance levels needs to be selected. After that, three-tier assessment process of increasing detail and reducing margin of safety as summarized below needs to be followed.

> **There is a growing perception that the built environment, both historic and recent construction, is characterised by an unacceptably high level of seismic risk.**

Tier-1: Screening phase
Under this screening phase, data of structural, non-structural and foundation of the existing building is collected through checklists for the chosen level of performance and given region of seismicity. Based on this collected data, conformity of the building with the requirements of concerned buildings codes (i.e., Benchmark Building Criteria) is checked. After that, lists of non-compliant deficiencies are compiled for further evaluation. If non-compliant deficiencies do not exist, then it indicates that building is not vulnerable to earthquake and hence there is no need for further assessment.

Tier-2: Evaluation phase
In this evaluation phase, structural analysis and assessment of the adequacy of the lateral-force-resisting system is carried out by selecting either (a) complete analysis of the building considering all of the deficiencies identified in Tier-1 or (b) a deficiency only analysis, based on the requirements of evaluation identified in Tier-1. Structural analysis is limited to simplified linear analysis and could be done using one of the commonly available linear static or dynamic analysis softwares. Component-level analysis considering displacement-based lateral force procedure combined with ductility related factors on an element-by-element basis is also carried out. The acceptability criterion is that the existing structural members should be able to take the calculated forces safely.

Tier-3: Detailed evaluation phase
If some structural members are unable to take the calculated forces safely as per evaluation done in Tier-2 and it is observed that evaluations as per Tier-1 and/or Tier-2 are too conservative and there may be a significant economic or other advantage by carrying out a detailed study, then the detailed evaluation is carried out by using linear and nonlinear methods for static or dynamic analysis of buildings. Expected performance of existing structural members is evaluated by comparing calculated demands with their capacities.

For carrying out the evaluation of existing buildings under Tier-2 or Tier-3, only 75% values of the forces for which a new building is designed, are considered. This reduction is done due to following reasons:

- Actual strength of structural members will be greater than that used in the evaluation,
- Existing buildings do not need to have the same factor of safety as a new building since the remaining useful life of an existing building will be less than that of a new building.

ASCE/SEI 31-2003

This code has evolved from FEMA 310 and is intended to replace FEMA 310. This code provides the three-tier procedure for seismic vulnerability assessment of existing buildings. As the checklists and acceptance criteria are same as in FEMA 310, so this document is not discussed here.

> **Structural analysis is limited to simplified linear analysis and could be done using one of the commonly available linear static or dynamic analysis softwares.**

EUROCODE 8 PART-3

Eurocode 8 Part 3 (EN 1998-3:2005), which was adopted by EU and EFTA member countries, deals with the assessment and retrofitting of buildings subjected to seismic loads. This code adheres in full to the displacement-based approach. The hazard is described in the form of elastic, 5% damping response spectra having specified average return periods. To start with, three levels of hazard are selected, and a performance requirement is then associated with each of these levels. The earthquake forces are then applied to the structure without any ductility-related reduction factor and linear or non-linear analyses of the structure, depending on the characterisation of the structure and the choice of the engineer is carried out to find out the displacements and stresses. The verifications of the obtained results of structural elements/mechanisms of the structure vary, depending on their nature. For 'ductile' (bending with and without axial force) type elements/mechanisms, the calculated deformation (curvature, drift) should be within the admissible deformation for the considered performance level. For 'brittle' (shear, beam-column joints) type elements / mechanisms, their capacity in terms of strength should not be less than the corresponding forces transmitted to them.

The fundamental requirements refer to the state of damage in the structure, attention being focussed on the following three Limit States: Near-Collapse, Significant Damage and Damage Limitation. The return periods of the design action for these three limit states and for buildings of ordinary importance are 2475, 475 and 225 years, respectively. Four options for the analysis of the buildings

> **"The hazard is described in the form of elastic, 5% damping response spectra having specified average return periods."**

> **"The verifications of the obtained results of structural elements / mechanisms of the structure vary, depending on their nature."**

are possible, i.e. linear and non-linear methods, either static or dynamic. The use of linear methods, however, is subject to more restrictive conditions than in the case of new buildings. When the linear methods of analysis are not applicable, then non-linear static method is generally used for a given much larger complexity of the nonlinear dynamic.

In linear analysis, the demands on 'ductile' and 'brittle' types of elements are evaluated differently according to a 'capacity design' philosophy. The demands on ductile mechanisms consist of the chord rotations at the ends of columns and beams, as taken directly from the analysis. The demands in the 'brittle' mechanisms are calculated by means of equilibrium conditions, considering the actions transmitted to them by the pertinent ductile components.

In non-linear method of analysis, the demands on both 'ductile' and 'brittle' mechanisms are directly taken from the analysis.

In this code, the most commonly used strengthening methods (concrete or steel jacketing and FRP plating and wrapping) are covered. Externally bonded FRP can enhance shear strength as well as flexural ductility at the member ends and prevent lap-splice failure through added confinement.

TURKISH CODE

Chapter 7 of the 2006 Turkish seismic code entitled "Assessment and Strengthening of Existing Buildings" sets procedure for the assessment and rehabilitation of existing buildings.

Four options for the analysis of the buildings are possible, i.e. linear and non-linear methods, either static or dynamic.

Linear elastic and nonlinear static analytical procedures are proposed for structural evaluation. In the analysis, the considered material strengths are based on the statistical evaluation of field data. A performance-based evaluation is done under three levels of earthquake ground motion intensities with different return periods. The performance acceptance criteria are based on demand to capacity ratios at critical sections for the linear procedures, and material strains for the nonlinear procedures.

Depending upon the mode of failure of the structural, the members are classified as "ductile" and "brittle" for determining the damage limits. For ductile members, three damage limits namely minimum damage limit, safety limit and collapse limit are defined at the cross section level. Minimum damage limit defines the onset of significant post-elastic behaviour at a critical cross section. Brittle members are not permitted to exceed this minimum damage limit.

Linear elastic or nonlinear (pushover) procedures can be employed for analysis where the seismic intensity is defined by linear elastic response spectra representing three different intensity levels, with respective exceeding probabilities of 50, 10 and 2% in 50 years. The reference design spectrum in the Turkish code has 10% probability of exceeding in 50 years. Based on Turkish strong motion data, it is estimated that the spectral ordinates for 50% probability of exceeding in 50 years are half of the reference spectrum whereas the ordinates for 2% probability of exceeding in 50 years are 1.5 times that of the reference spectrum.

Seismic performance level of building is determined after determining the member damage states.

Performance Level-1

If in any story, in the direction of the applied earthquake loads, not more than 10% of beams are in the significant damage state whereas all other structural members are in the minimum damage state, then the building is said to be safe and requires no retrofitting measures.

Performance Level-2

If in any story, in the direction of the applied earthquake loads, not more than 20% of beams and some columns are in the extreme damage state whereas all other structural members are in the minimum or significant damage states and shear carried by those columns in the extreme damage state is less than 20% of the story shear at each story, then retrofitting of the building may be required depending on the number and distribution of members in the extreme damage state.

In the analysis, the considered material strengths are based on the statistical evaluation of field data.

Performance Level-3

If in any story, in the direction of the applied earthquake loads, not more than 20% of beams and some columns are in the collapse state whereas all other structural members are in the minimum, significant or extreme damage states; shear carried by those columns in the collapse state is less than 20% of the story shear at each story; and such columns do not lead to a stability loss, then occupancy of the building should not be allowed. Decision on retrofitting or demolishing of the building depends on the feasibility of retrofitting.

Performance Level-4
If the building fails to satisfy any of the above performance levels, it is accepted as in the collapse state. Occupancy of the building should not be permitted. The building should be retrofitted; however its retrofit may not be economically feasible.

> **"Decision on retrofitting or demolishing of the building depends on the feasibility of retrofitting."**

Other details
In any story, in the direction of the applied earthquake loads, inter-story drift ratios should satisfy the limits for each performance level.

Retrofit techniques are also given in the code for reinforced concrete buildings. These consist of detailing requirements for concentric and eccentric added shear walls; jacketing of beams and columns; and strengthening of masonry infill walls by adding new material layers.

ACI 369R-11
The guidelines for seismic rehabilitation of existing concrete frame buildings and commentary was published by American Concrete Institute in year 2011 under ACI 369R-11. Using these guidelines, results of research can be implemented more quickly. These guidelines update design professionals with the latest recommendations for the seismic assessment and rehabilitation of concrete buildings.

Most sections in this guide are similar to Chapter-6 of ASCE/SEI 41 Supplement-1 (ASCE / SEI Ad Hoc Committee 2007). These guidelines shall be used in conjunction with Chapters-1 to Chapter-4 of ASCE/SEI 41-06 which focus on general design requirements, geotechnical engineering provisions, detailed description of linear as well as non-linear analysis procedures, and rehabilitation requirements. Short descriptions of potential seismic rehabilitation measures for each concrete building system are given this guide.

Modelling procedures, acceptance criteria, and rehabilitation measures for precast concrete frames, infill frames, braced frames, shear walls, diaphragms, and foundations are not given in this guide. Repair techniques for earthquake-damaged concrete components are not included in ACI 369R. The design professional shall refer to FEMA 306, FEMA 307, and FEMA 308 for details on evaluation and repair of damaged concrete wall components.

INDIAN CODE
Indian code IS: 15988-2013 gives guidelines for seismic evaluation and strengthening of existing reinforced concrete buildings. As per this code, assessment of existing buildings under earthquake forces shall be done using the criteria, given in IS: 1893 (Part-1), for new reinforced concrete buildings. Seismic forces shall then be computed by following the provisions of IS: 1893 (Part-1). For preliminary as well as detailed assessments of existing buildings, modification factors to the computed seismic forces and material strengths shall be then applied.

> **"In any story, in the direction of the applied earthquake loads, inter-story drift ratios should satisfy the limits for each performance level."**

Modification factor for lateral force
The lateral force shall be determined using provisions of IS:1893 (Part-1). For computing the base shear, to be resisted by existing building, this lateral force then shall be multiplied by the useable life factor U, which shall be determined as follows:

$$U = (Trem/Tdes)^{0.5} \geq 0.70 \qquad (1)$$

Where,
Trem = remaining useful life of the building; and
Tdes = design useful life of the building.

Modification factor for material strength

Probable or measured nominal strengths are the best indicator of the actual strength. Measured strength can be obtained by conducting field tests or lab tests on a series of samples. Probable strengths are either based on actual tests or the default values given in the code. Probable strengths may also be assessed from the values given in the structural drawings and designs. However, these values need to be further modified for the uncertainty regarding the reliability of available information and present condition of the component. The probable material strengths need to be multiplied with a Knowledge Factor K, given in the code.

> **"Measured strength can be obtained by conducting field tests or lab tests on a series of samples."**

Evaluation process

a) Preliminary evaluation

In preliminary evaluation of building, broad assessment of its physical condition, robustness, structural integrity, strength of structure and simple calculations are done. Based on site visit and collection of data, configuration-related checks (Load path, geometry, weak/soft storey, vertical discontinuities, mass irregularity, torsion, adjacent buildings, short columns) and strength-related checks (determination of modified demand lateral force considering occupancy risk factor and factor for useable life, shear stress check in columns and walls, axial stress check in moment frame columns) are then applied.

If the results of preliminary evaluation for strength, overall stability and integrity indicate no deficiency in the building, then no further action is required. Otherwise, detailed evaluation is to be carried out unless exempted. Exemption in carrying out detailed investigations is given to those single or two storey buildings (not housing essential services required for post-earthquake emergency response) whose total floor areas is less than 300 sq.m and where seismic retrofitting is carried out to remove these deficiencies.

b) Detailed evaluation

In detailed evaluation, numerical checks on stability and integrity of the whole structure as well as the strength of each member are done. The steps given below are followed in this detailed evaluation:

- Estimate the probable flexural and shear strengths of the critical sections of the structural members and joints of vertical lateral force resisting elements. These calculations shall be performed as per respective codes for various building types and modified with knowledge factor K.
- Calculate the total lateral force (design base shear) in accordance with IS:1893 (Part-1) and multiply it with U, a factor for the reduced useable life, given in the code.
- Perform a linear equivalent static or a dynamic analysis of the lateral load resisting system of the building in accordance with IS:1893 (Part-1) for the modified base shear determined in the previous step and determine resulting member actions for critical components.
- Evaluate the acceptability of each component by comparing its probable strength with the member actions.
- Calculate whether the inter-storey drifts and decide whether it is acceptable in terms of the requirements of IS:1893 (Part-1).

> **"Numerical checks on stability and integrity of the whole structure as well as the strength of each member are done."**

Acceptability criteria

A building is said to be acceptable if either of the following two conditions are satisfied along with ductility and detailing related evaluation:

- All critical elements of lateral force resisting elements have strengths greater than computed actions and drift checks are satisfied.
- Except a few elements, all critical elements of the lateral force resisting elements have strengths greater than computed actions and drift checks are satisfied. Non-linear analysis such as pushover analysis needs to be carried out up to the collapse load to ensure that the failure of these few elements shall not lead to loss of stability or initiate progressive collapse of the building.

Seismic strengthening

Following seismic strengthening options and strategies at a general level are described in detail:

- strengthening at member level
- eliminating or reducing structural irregularities
- strengthening at structural level
- use of supplemental damping and isolation

Strengthening of structural members can be done either by Jacketing of deficient structural members or by addition of new structural elements.

NEW ZEALAND CODE

New Zealand code "Seismic Assessment of Existing Buildings (Guidelines)", July 2017 provides guidelines to carry out seismic assessment of existing buildings. The guidelines provide two levels of assessment namely i) initial seismic assessment for a broad indication of the likely level of seismic performance of a building, and ii) detailed seismic assessment for a more comprehensive assessment.

> **Strengthening of structural members can be done either by Jacketing of deficient structural members or by addition of new structural elements.**

> **Both seismic assessment levels rate the existing building as a percentage of the minimum life safety performance requirements of Building Code.**

Both seismic assessment levels rate the existing building as a percentage of the minimum life safety performance requirements of Building Code, applied to an equivalent new building on the same site. The guidelines are structured in following three parts:

Part A: Assessment objectives and principles

This part outlines the scope and application of the guidelines, and provides an overview of the seismic assessment process. The linkage with the relevant requirements of the Building Act and the associated regulatory requirements is also described.

Part B: Initial seismic assessment

This part describes the method of application of the Initial Seismic Assessment (ISA) methodology (including the Initial Evaluation Procedure), which enables a broad indication of the likely level of seismic performance of a building.

Part C: Detailed seismic assessment

This part describes the method of application of the Detailed Seismic Assessment (DSA) methodology, which provides a more comprehensive assessment of the likely seismic performance of a building.

For DSA, the guidelines place greater emphasis on understanding the 'deformability' of the building in order to obtain more appropriate ratings, rather than assigning the overall building rating just on the basic strength of the weakest member or element. This focus on displacement capacity allows the capacity of different structural systems to be appropriately added together by providing direct allowance for non-linear behaviour. Emphasis is placed on the use of the simple lateral mechanism analysis at the initial stages of DSA.

“Emphasis is placed on the use of the simple lateral mechanism analysis at the initial stages of DSA.”

The guidelines also place particular emphasis on the need to assess the primary gravity structure as well as the primary lateral structure, recognising that it is the performance of the former and the degree of protection afforded to it by the latter that determines how well the whole building will meet its life safety objectives under different levels of earthquake shaking. Within Part C, a new section on Geotechnical Issues (C4) provides guidance on the geotechnical considerations in assessing existing buildings, including when they can be expected to significantly influence the overall behaviour of a particular building.

A further new development is the provision for an Assessment Summary Report to summarise the key points from both Initial Seismic Assessments and Detailed Seismic Assessments. This summary will provide more consistency both in the information provided and the way it is provided, and hence enable clearer communication between all parties, including situations where there is a need to reconcile different assessments.

ASCE/SEI 41-17

ASCE/SEI 41-17, “Seismic Evaluation and Retrofit of Existing Buildings”, describes deficiency-based and systematic procedures to evaluate and retrofit existing buildings to withstand the earthquake forces. Three-tiered process for seismic evaluation is given according to a range of building performance levels, by connecting targeted structural performance and the performance of non-structural components with seismic hazard levels. The deficiency-based procedures allow evaluation and retrofit efforts to focus on specific potential deficiencies deemed to be of concern for a specified set of building types and heights. The systematic procedure gives methodology to evaluate the entire building in a rigorous manner.

This code establishes analysis procedures and acceptance criteria, and specifies requirements for foundations and geologic site hazards; components made of steel, concrete, masonry, wood, and cold-formed steel; architectural, mechanical, and electrical components and systems; and seismic isolation and energy dissipation systems. Checklists are provided in this code for a variety of building types and seismicity levels in support of the Tier-1 screening process. This code updates the basic performance objectives for existing buildings and to the evaluation of force-controlled actions. It revises the nonlinear dynamic procedure and changes provisions for steel and concrete columns, as well provisions for unreinforced masonry.

“The systematic procedure gives methodology to evaluate the entire building in a rigorous manner.”

This code describes general requirements which includes evaluation and retrofitting process, seismic evaluation process and seismic retrofitting process; performance objectives and seismic hazards; evaluation and retrofit requirements; Tier-1 screening; Tier-2 deficiency-based evaluation and retrofit; Tier-3 systematic evaluation and retrofit;

analysis procedures and acceptance criteria; foundations and geologic site hazards; various construction materials such as steel, concrete, masonry, timber etc.; evaluation and retrofit procedures for non-structural components; seismic isolations; supplemental energy dissipation devices; etc.

DISCUSSIONS

In all the codes, seismic vulnerability assessment procedures for the existing buildings involve configuration-related and strength-related checks. There are no significant differences in which the configuration related assessments are carried out in various codes. However, considerable degree of non-uniformity is observed in the strength–related checks for the existing buildings in the codes of various countries.

Eurocode 8 describes mostly the principles of evaluation. Further, no guidance is given for the determination of the values for many parameters. Due to this, it is difficult to use.

In almost all the codes, the existing building needs to be classified into one of the specified building category for the evaluation. This becomes difficult to implement wherein the structural systems for building are vague and of mixed nature. In FEMA 310, assumption of ductility levels and hierarchical performance of structural elements is must, which may not necessarily occur in reality, and for which no alternate provisions are given.

All documents specify that there should be some reduction in the force level for analysis of existing building compared to new buildings (0.67 in New Zealand code, 0.70 maximum in Indian code). Eurocode 8 mentions that the effective peak ground acceleration should be reduced for redesign purposes, considering the reduced remaining life of the existing buildings, however, no details are given for the same. In FEMA 310, a reduction factor of 0.75 is explicitly applied to seismic forces in the Tier-3 evaluation; however, this reduction factor is implicitly present in m-factors Tier-2 analysis.

Fundamental differences in the Turkish Code compared to Part 3 of Eurocode 8 are less stringent requirements for linear elastic procedures, and the assembly of member performances for obtaining a global system performance level.

CONCLUSIONS

Brief summary of codes and guidelines of several countries (USA, New Zealand, India, Europe and Turkey) on Seismic Vulnerability Assessment of Existing Reinforced Concrete Buildings is presented in this paper.

ACKNOWLEDGEMENTS

Author acknowledges the support and encouragements of Director, CSIR-CRRI in preparing this paper.

REFERENCES

1. ACI 369R (2011). “Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary”. American Concrete Institute.
2. ASCE/SEI 31 (2003). “Seismic Evaluation of Existing Buildings”, American Society of Civil Engineers.
3. ASCE/SEI 41 (2006). “Seismic Evaluation and Retrofit of Existing Buildings”, American Society of Civil Engineers.
4. ASCE/SEI 41 (2017). “Seismic Evaluation and Retrofit of Existing Buildings”, American Society of Civil Engineers.
5. Durgesh C. Rai. “Review of Documents on Seismic Evaluation of Existing Buildings”, Document No. IITK-GSDMA-EQ03-V1.0.
6. EN 1998-3 (2005). “Eurocode 8 - Design of Structures for Earthquake Resistance: Assessment and retrofitting of buildings”.
7. FEMA:310 (1998), “Handbook for the Seismic Evaluation of Buildings”.
8. Haluk Sucuoglu (2006). “The Turkish Seismic Rehabilitation Code”. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, September 3-8, 2006.
9. IS: 15988 (2013). “Seismic Evaluation and Strengthening of Existing Reinforced Concrete Buildings - Guidelines”. Bureau of Indian Standards, New Delhi.
10. IS: 1893-Part 1 (2016). “Criteria for Earthquake Resistant Design of Structures: General Provisions and Buildings”. Bureau of Indian Standards, New Delhi.
11. Turkish Earthquake Code for Buildings (2006), Ministry of Public Works and Resettlement, Ankara, Turkey.