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Review of Documents on Seismic Evaluation of Existing Buildings

by

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1. GENERAL

Occurrences of recent earthquakes in India and in different parts of the world and the resulting losses, especially human lives, have highlighted the structural inadequacy of buildings to carry seismic loads. There is an urgent need for assessment of existing buildings in terms of seismic resistance. In view of this various organizations in the earthquake threatened countries have come up with documents, which serve as guidelines for the assessment of the strength, expected performance and safety of existing buildings as well as for carrying out the necessary rehabilitation, if required. The objective of this article is to review various documents on seismic evaluation of existing buildings from different countries. It is expected that this comparative assessment of various evaluation schemes will help identify the most essential components of such a procedure for use in India and other developing countries, which is not only robust, reliable but also easy to use with available resources.

2. REVIEWED SEISMIC EVALUATION DOCUMENTS

Documents from USA, New Zealand, India, Europe and UNDP projects have been studied and a comparison is made based on the key concepts of evaluation processes. A brief summary of various documents studied is as follows:

2.1 FEMA 310 - Handbook for the Seismic Evaluation of Buildings: A Pre-Standard

FEMA 310 (1998) is probably the most advanced seismic evaluation procedure for buildings developed in USA in the recent years which grew out of earlier document *NEHRP Handbook for Seismic Evaluation of Existing Buildings (FEMA 178)*. The evaluation procedure is based on rigorous approach to determine existing structural conditions. Buildings are evaluated for certain extent of structural damage that is expected in the building when subjected to earthquake. This level of damage (or *Performance Level*) is determined a priori by the design professional considering the importance of building and consequences of damage.

FEMA 310 considers two levels of performance defined as *Life Safety* and

Immediate Occupancy during design earthquake. For life safety performance, the building can sustain significant damage to both structural and nonstructural components with some margin against either partial or total structural collapse such that level of risk for life-threatening injury and getting trapped is low. Immediate occupancy building performance means very limited damage to both structural and nonstructural components during the design earthquake. The primary vertical and lateral-force-resisting systems retain nearly all of their original strength and stiffness; however, there could be some minor injuries and damage, which could be easily repaired while the building is occupied.

This document prescribes a three-tiered process of increasing detail and reducing margin of safety for the seismic evaluation of existing buildings, as described below:

Tier 1: Screening Phase

During the screening phase the design professional gets familiarized with the building, its potential deficiencies and its expected behavior, so that one can quickly decide whether the building complies with the provisions of the FEMA 310. This Tier 1 screening helps provides evaluation statements for structural, non-structural and foundation aspects in the form of checklists for the chosen level of performance and given region of seismicity. Initially based on the building data collected, one has to determine whether the building meets the requirements of concerned buildings codes (i.e., *Benchmark Building Criteria*). Non-benchmark buildings, which do not comply with respective building codes, the design professional has to follow and complete all checklists, whereas in case of benchmark buildings, evaluation steps concerning structural aspects can be ignored. After the completion of checklists, lists of deficiencies that are found to be non-compliant are compiled and further evaluation requirements are determined.

Tier 2: Evaluation Phase

For Tier 2, the design professional has two options: (a) a complete analysis of the building that addresses all of the deficiencies identified in Tier 1 or (b) a deficiency only analysis. This selection is based on the requirements of evaluation identified in Tier 1. In Tier 2 analysis and evaluation for the adequacy of the lateral-force-resisting system is performed. This analysis is limited to simplified linear analysis methods and it could be done using one of the common linear static or dynamic analysis methods. However, for unreinforced masonry bearing wall buildings with flexible diaphragms, a different method (i.e., *Special Procedure*) based on ABK methodology is used.

In addition a component-level analysis is also performed which is similar to the procedure outlined in the FEMA 273. This method is a displacement-based lateral force procedure combined with ductility related factors (i.e., *m*-factors) on an element-by-element basis. The acceptability criteria reconciles the calculated forces with component capacities using component ductility related factors, *m*. The linear procedures represent a rough approximation of the non-linear behavior of the actual structure and ignore redistribution of forces and other non-linear effects.

Tier 3: Detailed Evaluation Phase

If deficiencies are identified in a Tier 2 evaluation, a Tier 3 evaluation is performed only if one finds that Tier 1 and/or Tier 2 evaluations are too conservative and there would be a significant economic or other advantage to a more detailed evaluation. Acceptable analysis procedures for such a detailed evaluation include linear and nonlinear methods for static or dynamic analysis of buildings. Expected performance of existing components can be evaluated by comparing calculated demands on the components with their capacities.

Force levels used for above-mentioned Tier 2 and 3 analyses for evaluation of existing buildings are reduced from the conservative level used in design for new buildings by multiplying a factor of 0.75. This reduced force level is justified because (a) the actual strength of the components will be greater than that used in the evaluation and (b) an existing building does not need to have the same level of factor of safety as a new building since the remaining useful life of an existing building may be less than that of a new building.

2.2 New Zealand Draft Code – The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings

The document by New Zealand Society for Earthquake Engineering (NZSEE) is a draft code, which will be nominated in the New Zealand Building Code book (BIA 1996). This New Zealand Draft Code (NZDC) describes the key steps and procedures involved in assessing pre-1975 buildings of various material types and configurations.

NZDC begins with rapid evaluation procedure, which is based on a visual screening procedure of ATC 21 (1988) and can be carried out from external viewing of the building. The result of the rapid evaluation based on approximately fourteen structural criteria is presented in terms of a "*structural score*" which is an indicator of potential building damage. The total structural score has two components: (a) a basic structural score which reflects the standard used for original design and earthquake damage potential of the respective building types in their location of high, moderate or low seismicity zones and (b) a modification to the basic score on account of unfavorable characteristics present in the building. The intent of these vulnerability modifiers is to ensure that buildings with significant vulnerabilities are subjected to more detailed evaluation. The document places much greater emphasis on the presence of structural irregularities, such as torsion and weak storey, for the earthquake vulnerability of buildings.

Further, the structural score is combined with the building area to decide whether a detailed assessment is required. The building area parameter reflects the occupant population and potential causalities in the event of structural damage. This relationship is presented in a graph as shown in Fig. 1.

The detailed structural assessment is performed at the component level. A *knowledge factor (K)* is introduced to account for the uncertainty with regard to the reliability of available information on the configuration and condition of a component. Force-based and displacement-based methods are adopted for detailed assessment. Force-based assessment is based on determining the probable strength and ductility of the critical mechanism of post-elastic deformation of the lateral force-resisting elements whereas displacement-based methods place a direct emphasis on establishing the ultimate displacement capacity of lateral force resisting elements. Displacement-based assessment utilizes displacement spectra, which readily represent the characteristics of real earthquakes.

2.3 SERC Report – Formulation of Guidelines for Assessment of Strength and Performance of Existing Buildings & Recommendations on Retrofitting

This report is prepared by Structural Engineering Research Center (SERC), Chennai, on a sponsorship from the Building Materials and Technology Promotion Council (BMTPC), New Delhi. It presents guidelines for the assessment of strength and performance/safety of existing buildings for both masonry and multi-storied reinforced concrete structures. It also gives recommendations on retrofitting schemes for buildings to ensure resistance to earthquake forces.

The buildings are classified into five types as given below and an *n*-factor is assigned which accounts for the ductility and energy dissipation capacity of the building (i.e., a response reduction factor).

Unreinforced masonry load bearing wall buildings (n=1)
Reinforced masonry load bearing wall buildings with stiff diaphragms (n=2)
Reinforced concrete moment frames (n=3)
Reinforced concrete frames with infill masonry shear walls (n=4)
Reinforced concrete shear wall buildings (n=5)

The assessment begins with a rapid evaluation procedure (Level 1), which is a modified FEMA 154 (1988) procedure to suit the Indian conditions. As per information gathered about the building, a *Structural Score* (S) is calculated, which is dependent on seismic zone, age of the building, number of stories, eccentricity, soil type and foundation types. This score essentially consists of two parts, namely, the *basic structural score* (S_B) and the *structural score modifier* (S_M). If the calculated structural score is greater than 1, then the specified Level 2 Structural Analysis is carried out. For the second level analysis a safety assessment procedure is given for each of the five defined building types. The procedure is very similar to FEMA 310–Tier 1 method of evaluation for finding structural deficiencies but the demand base shear for the force calculations is done as per IS 1893:2002 (Part-I), with a different response reduction factor equal to (1+n/2).

2.4 UNIDO Vol. 4 – Post-Earthquake Damage Evaluation and Strength Assessment of Buildings under Seismic Conditions

This document is one of the seven volumes of regional project of "Building Construction under Seismic conditions in the Balkan Region", which was carried out with participation of the Governments of Bulgaria, Greece, Hungary, Rumania, Turkey and Yugoslavia along with United Nations Industrial Development Organization (UNDP/UNIDO 1985). This Manual combines technical descriptions of seismic mitigation measures for Balkan region structures with a discussion of policy issues surrounding seismic mitigation progress; also it discusses both post earthquake and pre earthquake assessment programs.

UNIDO document examines the existing structure for the aspects of principles of a good structural concept, necessary strength in the elastic range, allowed deformability and the necessary ductility measures.

Structures are classified from the viewpoint of the quality of their concept and layout as *good*, *acceptable* and *unclear*. The shear force capacity is compared to the required shear force capacity and a *strength index (R)* is calculated. The value of strength index is compared to specified limit values. Three intervals of values of the *R* have been defined, based on which, the decision whether the structure should undergo repair/strengthening is taken. Based on the estimated structural layout quality and the value of *R*, the building is classified in to five categories. After this the deformability and ductility requirements are checked and the decision regarding the type of strengthening is taken.

In order to simplify the determination of the strength index *R*, the axial load – moment interaction diagram is considered as shown in Fig. 2. Also, for a given column, it can be determined from the stress under gravitational loads and the required base shear coefficient (Fig. 3).

This document also realizes that the existing structure needs to be evaluated for its useable or the remaining life. A correction factor as defined below is used to modify the seismic demand intended for new buildings:

$$c_{corrected} = \left(\frac{T_{service}}{T_{code}} \right)^{1/2 \ldots 1/1.5} \times c_{code}$$

where T_{code} = reference lifetime of structures designed according to code provisions, c_{code} = design factor for structures of a given class designed according to standard code practice, $T_{service}$ = subsequent lifetime considered for an existing structure, $c_{corrected}$ = design factor for which the existing structure should be checked or designed.

2.5 Euro Code 8: Design Provisions For Earthquake Resistance of Structures – Parts 1-4 General Rules for Strengthening and Repair of Buildings

This document is a European Prestandard, which was approved by CEN in 1995 as a prospective standard for provisional application (CEN 1995). The scope of this document is to provide criteria for the evaluation of the seismic performance of existing individual structures, to describe the approach in selecting necessary corrective measures and to set forth criteria for the design of the repair/strengthening measures.

The evaluation process consists of the verification of the seismic resistance of an existing damaged or undamaged building, taking into account both non-seismic and seismic actions, for the period of its intended lifetime. As per Eurocode, analysis and redesign of existing structures may be based on appropriately modified actions and possibly modified safety-factors (in comparison with the design of new structures) in order to account for smaller remaining life times, smaller uncertainty with respect to dead loads, and for properties of existing materials. In the analyses, a model uncertainty factor may be introduced covering the additional uncertainties related to the analysis of the pertinent structure; higher values should be used for higher damage levels. In order to calculate the design action-effects under the actual conditions of the structure, the standard method or the time-domain dynamic non-linear analysis is carried out. Static non-linear methods are adopted for plain masonry buildings.

After the analysis, a computational verification is made at the component level, which is based on the verification of all cross-sections. In case of time domain method, the post yield deformations should be higher than the corresponding demand values and the level of damage predicted for both structural and non-structural elements is also kept within acceptable limits. The document also gives details for structural interventions and decision-making. At the end it gives procedure for repair/strengthening of buildings.

2.6 ASCE/SEI 31-03 – Seismic Evaluation of Existing Buildings

This standard is a publication of the American Society of Civil Engineers, which provides a process for seismic evaluation of existing buildings (ASCE 2003). This standard has evolved from and is intended to replace FEMA 310. It prescribes the three-tiered process for evaluating buildings as explained in FEMA 310. The checklists and acceptance criteria are same as in FEMA 310 and therefore, this document is not discussed further in this article.

3.0 Comparison of Key Concepts

A summary of key issues related to seismic evaluation procedure is presented in Table 1 whereas Fig. 4 to 8 provide flow-charts for these procedures. In the following sections, an attempt has been made to compare the key concepts of these procedures for better understanding and an assessment of their relative merits.

3.1 General Structure of Evaluation Procedures

All evaluation procedures follow similar assessment steps which can be broadly grouped into two categories: (a) configuration-related and (b) strength related checks. Further, for majority of procedures, these are explicitly or implicitly arranged in the two tiers of assessments. A general structure of seismic evaluation procedures can be schematically represented as shown in Fig. 9. The first tier involves a quick assessment of the earthquake resistance of the building and its potential deficiencies, with the objective to screen out the significantly vulnerable structures for the second tier detailed analysis and evaluation. The first tier evaluation typically consists of assessing the configurationally induced deficiencies known for unsatisfactory performance along with a few global level strength checks, whereas the next level of evaluation consists of proper force and displacement analysis to assess structural performance at both global and/or component level.

3.2 Configuration Related Checks

Good details and construction quality are of secondary value if a building has an odd shape that was not properly considered in the design. Although a building with an irregular configuration may be designed to meet all code requirements, irregular buildings generally do not perform as well as regular buildings in an earthquake. Typical building configuration deficiencies include an irregular geometry, a weakness in a given story, a concentration of mass, or a discontinuity in the lateral force resisting system. Vertical irregularities are defined in terms of strength, stiffness, geometry and mass. Horizontal irregularities involve the horizontal distribution of lateral forces to the resisting frames or shear walls.

Load Path:

Inertial forces, induced as a result of the seismic force effects from any horizontal direction, are transferred from the mass to the foundation through the load path. If there is a discontinuity in the load path, the building is unable to resist seismic forces regardless of the strength of the existing elements. FEMA 310 and SERC report specifies that there shall be one complete load path available. Eurocode 8 specifies that all lateral load resisting systems, like cores, structural walls or frames should run without interruption from their foundations to the top of the building. As per New Zealand Draft Code, the existing load paths should be identified, considering the effects of any past modifications, additions or alterations. UNIDO manual does not have any provision for the same.

Weak Story:

The story strength is the total strength of all the lateral force-resisting elements in a given story for the direction under consideration. Weak stories are usually found where vertical discontinuities exist, or where member size or reinforcement has been reduced. The result of a weak story is a concentration of inelastic activity that may result in the partial or total collapse of the story. According to FEMA, New Zealand draft code and SERC report, the strength of lateral force resisting system in any story shall not be less than 80% of the strength in an adjacent story, above or below. As per

Eurocode 8, the mass of the individual stories should remain constant or reduce gradually, without abrupt changes, from the base to the top. However, no such provision is given in UNIDO manual.

Soft Story:

Soft story condition commonly occurs in buildings with open fronts at ground floor or with particularly tall first stories. Soft stories usually are revealed by an abrupt change in interstory drift. Although a comparison of the stiffnesses in adjacent stories is the direct approach, a simple first step might be to compare the interstory drifts. According to FEMA, New Zealand draft code and SERC report the stiffness of lateral force resisting system in any story shall not be less than 70% of the stiffness in an adjacent story above or below, or less than 80% of the average stiffness of the three stories above or below. Eurocode 8 specifies that there should not be significant difference in the lateral stiffness of individual storeys and at any storey the maximum displacement in the direction of the seismic forces should not exceed the average storey displacement by more than 20%. No such provision is given in UNIDO manual.

Geometry:

Geometric irregularities are usually detected in an examination of the story-to-story variation in the dimensions of the lateral-force-resisting system. FEMA 310 and SERC report give a quantitative check for the geometry of the building, according to which there shall be no change in the horizontal dimension of lateral force resisting system of more than 30% in a storey relative to adjacent stories. UNIDO manual classifies the buildings based on the structural layout as Good, Acceptable and Unclear. As per New Zealand Draft Code plan irregularities include irregular mass distribution, re-entrant corners and buildings with 'wings' that form an 'L', 'T' or 'E' shape. As per Eurocode 8, the building structure should be approximately symmetrical in plan with respect to two orthogonal directions, in what concerns lateral stiffness and mass distribution. Also if setbacks are present, the specified provisions should be applied.

Effective Mass:

Mass irregularities can be detected by comparison of the story weights. The effective mass consists of the dead load of the structure tributary to each level, plus the actual weights of partitions and permanent equipment at each floor. Mass irregularities affect the dynamic response of the structure, and may lead to unexpected higher mode effects and concentrations of demand. Effective mass between adjacent stories shall not vary by more than 50% as per FEMA 310 and SERC report whereas there is no such provision in UNIDO. According to New Zealand draft document, a significant vertical irregularity results when the mass of a storey varies 30% from those adjacent. Eurocode 8 specifies that the individual storey mass should remain constant or reduce gradually without abrupt changes.

Torsion:

Whenever there is significant torsion in a building, the concern is for additional seismic demands and lateral drifts imposed on the vertical elements by rotation of the diaphragm. Buildings can be designed to meet code forces including torsion, but buildings with severe torsion are less likely to perform well in earthquakes. As per FEMA 310 and SERC report, distance between storey mass centre and story centre of rigidity shall be less than 20% of the building width in either plan dimension. New Zealand Code considers the torsional deformation in evaluating the required ductility demand for critical elements. UNIDO document does not give any provision for torsion in buildings. As per Eurocode 8, frame, dual and wall systems should possess a minimum torsional rigidity.

Pounding:

Buildings may impact each other, or pound, during an earthquake. Building pounding can alter the dynamic response of both the buildings, and impart additional inertial loads on both structures. There is a potential for extensive damage and possible collapse. According to FEMA 310, in order to avoid pounding, the building shall not be located closer than 4% of the height to an adjacent building and as per New Zealand Code separation of 2% the storey height induces pounding. There is no provision for pounding in UNIDO manual, SERC report and Eurocode 8.

3.3 Strength Related Checks

In addition to checks for unfavorable building characteristics, a number of checks are required to assess the load carrying capacity of the vertical load-resisting elements, such as columns, walls, etc. The evaluation procedures provide from a simple to a much rigorous method of calculation of seismic demand at both global level for overall structure and at local level for each components. Various aspects of these strength related checks are compared in the following:

Force Levels for Strength Analysis:

In FEMA 310, a pseudo static lateral force is applied to the structure to obtain "actual" displacements during a design earthquake. It represents the force required in a linear static analysis, to impose the expected actual deformation of the structure in its yielded state when subjected to the design earthquake motions, as shown in Fig. 10. The response reduction factor is neglected and therefore, it considers the maximum elastic force and not the design force intended for new buildings. However, the analysis forces for evaluation are only 75% of that for design of new buildings. UNIDO calculates the base force capacity of the structure in the elastic range, which causes the first column at ground floor level to reach its design limit strength and compares it to the required shear force according to the codes, reduced for the useable life of the structure.

NZDC considers the design force level based on inelastic behavior and seismic force capacity of the structure is calculated along with the post elastic mechanism of deformation. Further, the force level for evaluation of existing building is taken as 67% of that for a new building. SERC report calculates the seismic force for evaluation as per IS: 1893 (2002-Part I) with a different reduction factor is based on the type of the building (*n* factor). Eurocode 8 calculates the design base shear considering a behavior factor *q* which accounts for the ductility class, the structural regularity in elevation and the prevailing failure mode in structural systems with walls.

In summary, UNIDO manual, New Zealand Draft Code, SERC report and Eurocode take in to account the response reduction factor (inelastic behavior) in calculating the lateral forces, whereas FEMA 310 considers the maximum force level with no response reduction factor (elastic Behavior). However, FEMA 310 allows for inelastic behaviour at the component level analysis by assigning *m*-factors for the displacement-controlled ductile components. Further, all procedures recognize that force levels for seismic evaluation should be reduced to account for the remaining useable life of structure, however, details vary.

Global Level Checks:

The seismic evaluation documents specify some global level checks to quickly identify the major deficiencies. At the global level, buildings are mainly checked for shear stress and axial stress.

(a) Shear Stress Check

The shear stress check provides a quick assessment of the overall level of demand on the structure. According to FEMA 310 the shear stress in concrete columns shall be less than 0.68 MPa, while the shear stress in the unreinforced masonry shear walls shall be less than 0.20 MPa. In UNIDO no provision for shear stress check is given. But in NZDC, a check for shear is done at the component level. In SERC report shear stress in concrete columns shall be less than 0.7 MPa, while for unreinforced masonry load bearing wall buildings, the shear stress shall be less than 0.1 MPa.

(b) Axial Stress Check

Columns that carry a substantial amount of gravity load may have limited additional capacity to resist seismic forces. When axial forces due to seismic overturning moments are added, the columns may fail in a non-ductile manner due to excessive axial compression. The alternative calculation of overturning stresses due to seismic forces alone is intended to provide a means of screening out frames with high gravity loads, but is known to have small seismic overturning forces. According to FEMA 310 the axial stresses due to overturning forces alone shall be less than $0.30f'_c$ while in UNIDO the axial stress in the columns is calculated and the strength index R of the structure is determined. NZDC Checks axial stress at component level in the displacement-based analysis and according to SERC report axial stress due to overturning forces alone shall be less than $0.25f_{ck}$.

Component Level Analysis:

Component level analysis gives a more detailed assessment of the building and helps in identifying the weak links of the building. It is done on an element-by-element basis. Component actions are classified as either deformation-controlled or force-controlled. A deformation-controlled action is defined as an action that has an associated deformation that is allowed to exceed the yield value; the maximum associated deformation is limited by the ductility capacity of the component. A force-controlled action is defined as an action that has an associated deformation that is not allowed to exceed the yield value; actions with limited ductility are considered as force-controlled. The Table 2 provides an example of such actions.

In FEMA 310 acceptance criteria are based on force-controlled actions and deformation-controlled actions. Expected strength of the component is compared with the demand due to gravity and earthquake loading. There is no force reduction in case of force-controlled actions. While in deformation-controlled actions, an m-factor is applied to the demand to account for the expected ductility of the component.

The force-based method in New Zealand Draft Code is based on determining the probable strength and ductility of the critical mechanism of post-elastic deformation of the lateral force-resisting elements. Displacement-based methods place a direct emphasis on establishing the ultimate displacement capacity of lateral force resisting elements. Displacement-based assessment utilizes displacement spectra, which readily represent the characteristics of real earthquakes.

The final evaluation in Eurocode 8 is based on the verification of all cross-sections comparing the capacity design as required with the design resistance values of cross-sections of the structural elements. In UNIDO manual and SERC report no detailed component level analysis for all elements is done.

4.0 Discussion

Seismic evaluation procedures for buildings are a combination of configuration-related and strength-related checks. Though there have been no significant differences in which the configuration related assessments are carried out, there is considerable degree of non-uniformity in the manner strength–related assessments are carried out. All the documents except UNIDO manual provide explicit checking criteria for the configurationally induced irregularities. Strength checks are performed either at global (structure) or local (element) level or at both levels as in FEMA 310. At the global level, there is no shear stress check given by UNIDO manual and New Zealand Draft Code and no component level analysis is performed in UNIDO manual and SERC report.

The seismic evaluation procedure of FEMA 310 and New Zealand Draft Code is a better option compared to UNIDO manual, Eurocode 8 and SERC report, as much detailed and specific assessment techniques have been given in the first two documents. In particular, Eurocode 8 describes mostly the principles of evaluation and is seriously deficient of specifics which make it difficult to use. Further, there are many parameters for which no guidance is provided and is left to the judgment of the design professional.

Except for FEMA 310, all evaluation procedures require a building to be classified into one of the specified building category for evaluation. This becomes difficult to implement wherein the structural systems for building are vague and of mixed nature. For example, FEMA 310 is preferred choice for structural systems that cannot be clearly categorized as either frames or shear walls.

At the component level, the limitation of FEMA 310 is the prior assumption of ductility levels and hierarchical performance of structural elements, which may not necessarily occur in reality, and for which no alternate provisions are considered (D'Ayala and Charleson 2002).

All documents specify that there should be some reduction in the force level for analysis of existing building compared to new buildings. New Zealand Draft Code suggests a reduction factor of 0.67. UNIDO document specifies an equation for such a reduction factor to account for the subsequent lifetime of an existing structure in relation to its design life. For a structure with remaining life equal to half of its design life, this reduction factor varies from 0.63 to 0.70. Eurocode 8 also mentions that considering the smaller remaining lifetimes, the effective peak ground acceleration should be reduced for redesign purposes, however, no quantitative criterion is 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.

SERC Report follows the IS:1893 (2002-Part I) method for calculating the base shear, however, it uses a different reduction factor. A comparison of this reduction factor ($1+n/2$) with that of R of IS:1893 (2002-Part I) is shown in Table 3. It is clear that SERC Report does not reduce seismic forces for evaluation and either keeps it equal or increases up to 25% than those for new buildings.

5.0 Concluding Remarks

The review of various evaluation procedures indicates clearly that FEMA 310 and New Zealand Draft Code are more suitable for use in buildings of developing countries, which are not only difficult to classify in certain 'type buildings' but also their capacities can not be estimated with significant confidence. FEMA 310 provides a more generalized approach to seismic evaluation, which is thorough and provides several levels of assessment with varying degree of complexity suitable for a large class of structures. However, it requires a higher degree of understanding on the part of design professionals and at times can be confusing for the lack of specifics. On the other hand, NZDC is transparent and uses familiar basic principles as applicable to design of new buildings, though its approach is considerably non-generalized. Eurocode 8 and UNIDO manual lack specific steps of assessment and leave a lot to the judgment of the design professional. It appears that FEMA 310 and NZDC approaches can be suitably combined to develop a transparent, reasonably rigorous and generalized procedure for seismic evaluation of buildings in developing countries such as India.

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Appendix: List of Symbols

FEMA 310

V Pseudo Lateral Force
C Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response
S_a Response spectral acceleration at the fundamental period of the building in the direction under consideration
W Total dead load and anticipated live load on the structure
v_{avg} Average shear stress
m Component modification factor
n_c Total number of columns
n_f Total number of frames in the direction of loading
V_j Story shear
A_c Summation of the cross sectional area of all columns in the story under consideration
A_w Summation of the horizontal cross sectional area of all shear walls in the direction of loading
p_{ot} Axial stress of columns subjected to overturning forces
h_n Height above the base to the roof level
L Total length of the frame
Q_{CE} Expected strength of the component at the deformation level under consideration
Q_{UD} Action due to gravity and earthquake loading for deformation-controlled actions
Q_{UF} Action due to gravity and earthquake loading for force-controlled actions

UNIDO Document

S_{req} Required shear force capacity according to the codes
S_{cap} Base shear force capacity in the elastic range
$C_{s\ req}$ Required base shear force coefficient
W Total vertical load
R Strength Index
n Mean compression factor
σ_0 Mean compression stress in the columns under axial gravitational loads
f_c' Concrete strength (prismatic or cylindrical)
N Axial load
M Moment
b, h Cross-section dimensions
ΣA_c Total area of the columns

New Zealand Draft Code

V Horizontal seismic shear force acting at the base of a structure
C Lateral force coefficient for the equivalent static method
W_t Total seismic weight of a structure
$\mu_{\phi c}$ Member curvature ductility capacity
$\mu_{\phi d}$ Member curvature ductility demand
Δ_{sc} Structure displacement capacity
Δ_{sd} Structure displacement demand

SERC Report

V_B Base Shear

A_h Horizontal acceleration coefficient
W_s Seismic Weight
τ_{avg} Shear stress in columns
n_c Total number of columns
n_f Total number of frames in the direction of loading
V_j Storey shear at level j
A_c Total cross-sectional area of columns
λ Shear stress calculated based on net area in the direction of lateral loading
A_w Effective area in the direction of loading
F_o Axial force due to overturning in a column
H Total height
L Total length

Eurocode 8

F_b Seismic base shear force
$S_d(T_1)$ Ordinate of the design spectrum at period T_1
T_1 Fundamental period of vibration of the building for translational motion in thedirection considered
W Total weight of the building
r Minimum torsional radius for all relevant horizontal directions
l_s Radius of gyration of the structure in plan
γ_{Sd} Model uncertainty factor related to the analysis of the pertinent structure
$E_{new,d}$ Design action-effects under the actual conditions of the structure
γ_{Rd} Model uncertainty factor used for computing the structural elements' resistance
$R_{new,d}$ Design resistance values of cross-sections of the structural elements

Table 1: Comparison of key concepts among various evaluation procedures

	FEMA 310	UNIDO Vol. 4	New Zealand	SERC Report	EUROCODE 8
GENERAL					
	Three tiered approach with increasing complexity and decreasing conservatism, Very thorough and detailed	Principles are outlined while specifics are lacking	Based on basic principles, non-generalized and transparent approach	Based on Tier 1 and 2 of FEMA 310, sketchy and too restrictive	Sound principles for two tiered assessment but lacks specifics
CONFIGURATION RELATED CHECKS					
Load Path	The structure shall contain one complete load path	No Provision	Existing load paths should be identified.	One Complete Path should be available	A complete load path should be available, from top to bottom
Soft Storey	The stiffness of lateral force resisting system in any storey shall not be less than 70% of the stiffness of adjacent storey	No checking criteria specified.	A soft storey is considered where the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average stiffness of all storeys (Same criteria for weak and soft storey).	The stiffness of any storey should not be less than 70% of adjacent storey	At any storey, the maximum displacement in the direction of the seismic forces should not exceed the average storey displacement by more than 20%

Table 1: Continued

	FEMA 310	UNIDO Vol. 4	New Zealand	SERC Report	EUROCODE 8
Weak Storey	The strength of lateral force resisting system in any storey shall not be less than 80% of the strength in an adjacent storey	No checking criteria specified.		The strength of lateral force resisting system of storey shall not be less than 80% of that of an adjacent storey	Mass of the individual storeys should remain constant or reduce gradually, without abrupt changes, from the base to the top.
Geometry	There shall be no changes in horizontal dimension of lateral force resisting system of more than 30 % in a storey relative to adjacent stories.	Structures are classified as good, acceptable, unclear and inadequate based on the geometry, strength and stiffness properties.	Plan and Vertical irregularities are checked.	The horizontal dimension of lateral-force-resisting system in a storey relative to adjacent storey shall not differ by more than 30% in any horizontal direction.	Criteria for regularity in plan and elevation are checked.
Effective mass	There shall be no change in effective mass more than 50% from one storey to next	No checking criteria specified.	No provision	Effective mass between adjacent storey shall not vary by more than 50 %	There should not be abrupt changes in the mass of the individual storeys.
Torsion	Distance between storey mass center and story center of rigidity shall be les than 20% of the building width in either plan dimension	No checking criteria specified.	Torsional deformation is considered in evaluating the required ductility demand for critical elements.	Eccentricity between Mass Center & Center of rigidity should be less than 20 % of width	Frame, dual and wall system shall possess a minimum Torsional rigidity $\frac{r}{l_s} \geq 0.8$

Table 1: Continued

	FEMA 310	UNIDO Vol. 4	New Zealand	SERC Report	EUROCODE 8
Adjacent Buildings	An adjacent building shall not be located next to the structure being evaluated closer than 4% of the height.	No provision	Pounding is assumed to occur with building separations of 2% the storey height.	No provision	No Provision
STRENGTH RELATED CHECKS					
Analysis Philosophy	Calculates the pseudo lateral force to impose the expected actual deformation of the structure in its yielded state when subjected to design earthquake motions	Compares the base shear force capacity (Shear force which causes the first column at ground floor to reach its design limit strength) with required shear force capacity according to codes.	The lateral seismic force capacity of structure is determined along with the post elastic mechanism of deformation of the structure.	Calculates design base shear as per I.S. 1893-2002 (Part I).	Evaluation consists of the verification of the seismic resistance of an existing damaged or undamaged building, taking into account both non- seismic and seismic actions for the period of its intended life time
Force Levels	Considers the maximum elastic force. Response reduction factor is neglected. $V = CS_aW$	Considers the design force level. $S_{req.} = C_{sreq.}W$	Considers the design force level. $V = CW_t$	Considers the design force level. $V_b = A_hW_s$	Considers design force level $F_b = S_d(T_1)W$

Table 1: Continued

	FEMA 310	UNIDO Vol. 4	New Zealand	SERC Report	EUROCODE 8
Global Level Stress Analysis					
Shear Stress Check	The shear stress in concrete columns shall be less than 100 psi (0.7 MPa) or $2\sqrt{f'_c}$. $v_{avg} = \frac{1}{m}\left(\frac{n_c}{n_c - n_f}\right)\left(\frac{V_j}{A_c}\right)$ The shear stress in the unreinforced masonry shear walls shall be less than 0.2 MPa $v_{avg} = \frac{1}{m}\left(\frac{V_j}{A_w}\right)$	No provision	Check for shear is done at the component level.	Shear stress in concrete columns shall be less than 0.7 N/mm² or $0.10\sqrt{f_{ck}}$ $\tau_{avg} = \frac{1}{2}\left(\frac{n_c}{n_c - n_f}\right)\left(\frac{V_j}{A_c}\right)$ For unreinforced masonry load bearing wall buildings, the shear stress shall be less than 0.1N/mm² $\lambda = \frac{2}{3}\left(\frac{V_j}{A_w}\right)$	
Axial Stress	Axial stresses due to overturning forces alone shall be less than $0.30f'_c$. $p_{ot} = \frac{1}{m}\left(\frac{2}{3}\right)\left(\frac{Vh_n}{Ln_f}\right)$	The axial stress in the columns is calculated and the strength index *R* of the structure is determined (see fig. 1). $\sigma_0 = \frac{W}{\Sigma A_c}$	Check for axial stress is done at component level in the displacement-based analysis.	Axial stress due to overturning forces alone shall be less than $0.25f_{ck}$ $F_o = \frac{1}{3}\left(\frac{V_B}{n_f}\right)\left(\frac{H}{L}\right)$	

Table 1: Continued

	FEMA 310	UNIDO Vol. 4	New Zealand	SERC Report	EUROCODE 8
Component Level Analysis					
Component Level Analysis	Acceptance criteria are based on Force-controlled actions and Deformation-controlled actions. Expected strength of the component is compared with the demand due to gravity and earthquake loading in Force-controlled actions. No force reduction is done. $Q_{CE} \geq Q_{UF}$ In deformation-controlled actions, an m-factor is applied to the demand to account for the expected ductility of the component. $Q_{CE} \geq \frac{Q_{UD}}{m}$	No component level analysis is done.	Force-based and Displacement-based analysis is done. The component strengths are compared with the demand in force-based procedure. $\mu_{\phi c} > \mu_{\phi d}$ The displacement capacity is compared with the displacement demand in displacement-based procedure. $\Delta_{sc} > \Delta_{sd}$	No component level analysis is done.	$\gamma_{Sd}\ E_{new.d} \leq \frac{1}{\gamma_{Rd}} R_{new,d}$

Table 2: Typical deformation-controlled and force-controlled actions in FEMA 310

	Deformation-Controlled	**Force-Controlled**
Moment Frames		
Beams	Moment	Shear Force
Columns	Moment	Axial Load, Shear Force
Joints	-	Shear Force
Shear Walls	Moment, Shear Force	Axial Load
Braced Frames		
Braces	Axial Load	-
Beams	-	Axial Load
Columns	-	Axial Load
Shear Link	Shear Force	Axial Load, Moment
Connnections	-	Axial Load, Moment, Shear Force

Table 3: Comparison of response reduction factors in SERC Report and IS:1893 Part I

SERC Report $A_h = \dfrac{\left(\frac{z}{2}\right)\left(\frac{S_a}{g}\right)}{(1+n/2)}$		IS: 1893 (Part 1) $A_h = \dfrac{ZIS_a}{2Rg}$		
No.	***Type of Building***	***n***	$(1+n/2)$	***R***
1.	Unreinforced Masonry Load Bearing Wall Buildings	1.0	1.5	1.5
2.	Reinforced Masonry Load Bearing Wall Buildings with Stiff Diaphragms	2.0	2.0	2.5
3.	Reinforced Concrete Moment Frames	3.0	2.5	3.0
4.	Reinforced Concrete Frames with Infill Masonry Shear Walls	4.0	3.0	3.0
5.	Reinforced Concrete Shear Wall Buildings	5.0	3.5	3.0

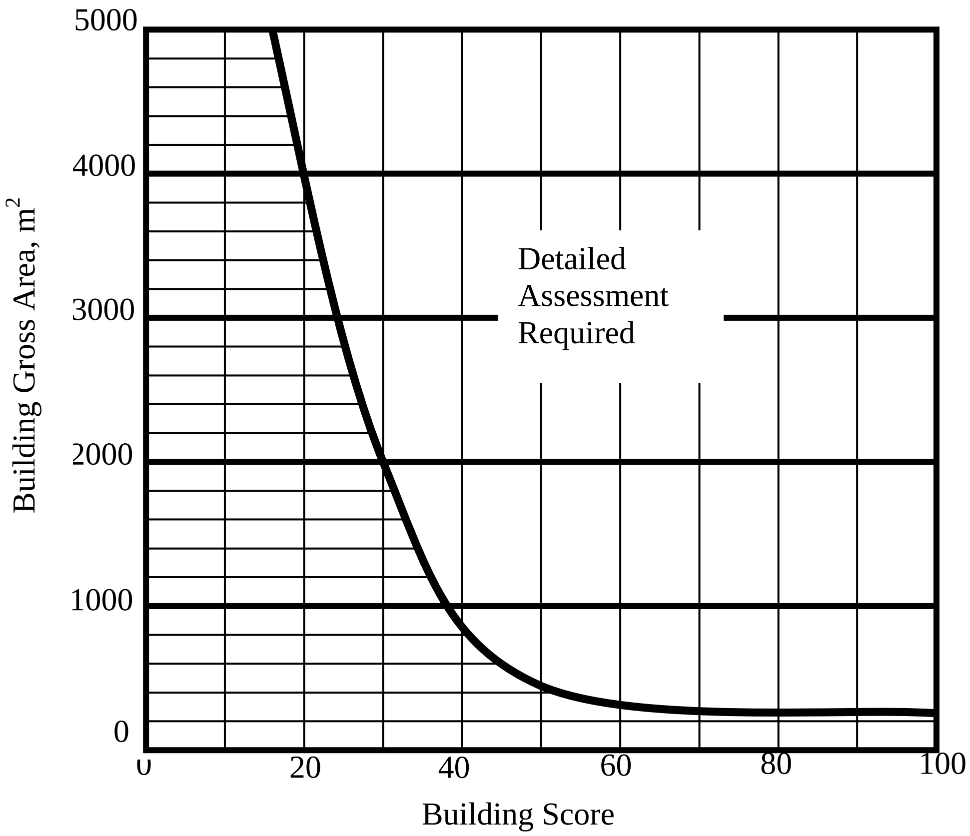

Figure 1: New Zealand Draft Code – Criteria for Detailed Assessment

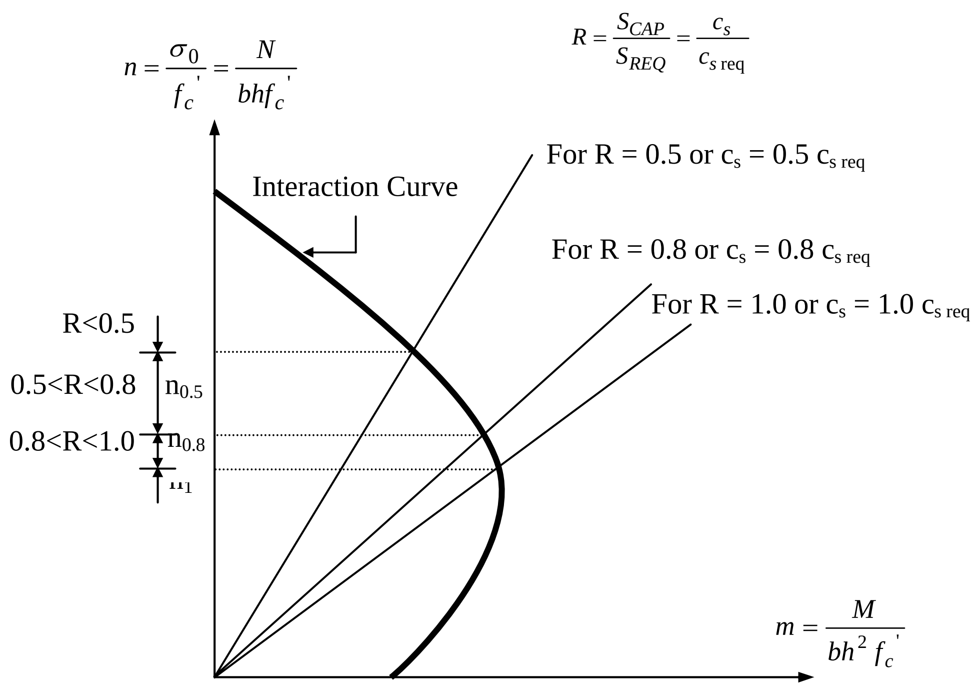

Figure 2: Relation Between Axial Compression Stress, Required Base Shear Coefficient and the Resulting R for a Reinforced Concrete Column

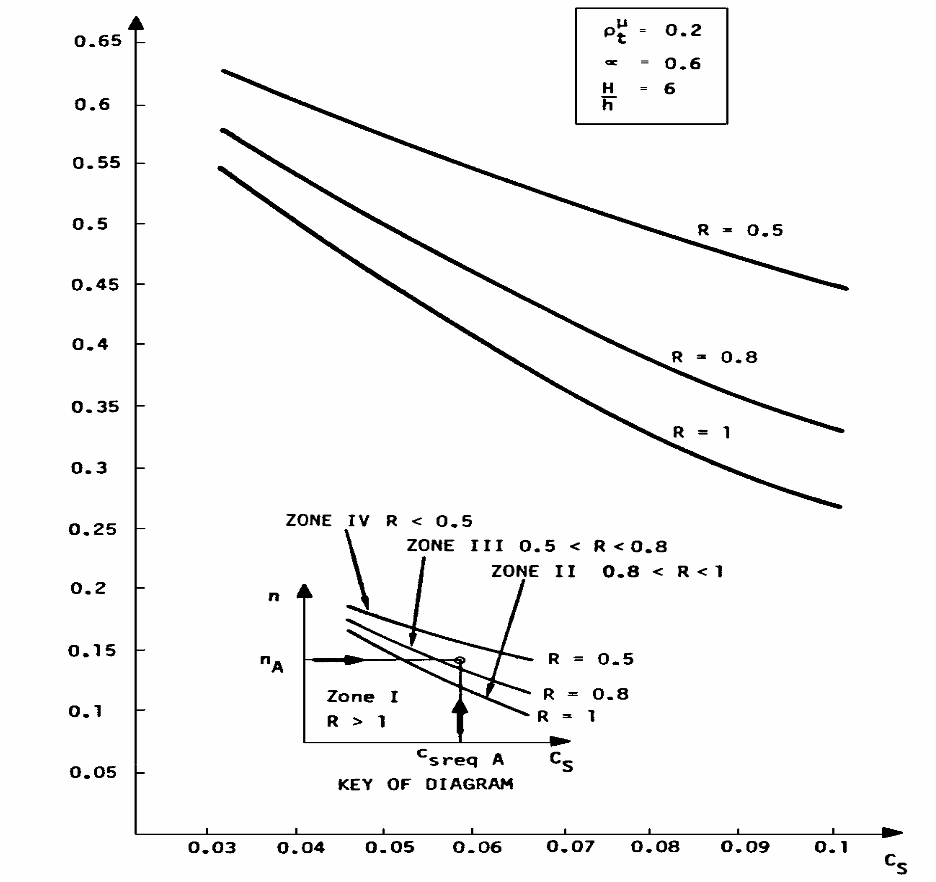

Figure 3: Determination of Strength Index R

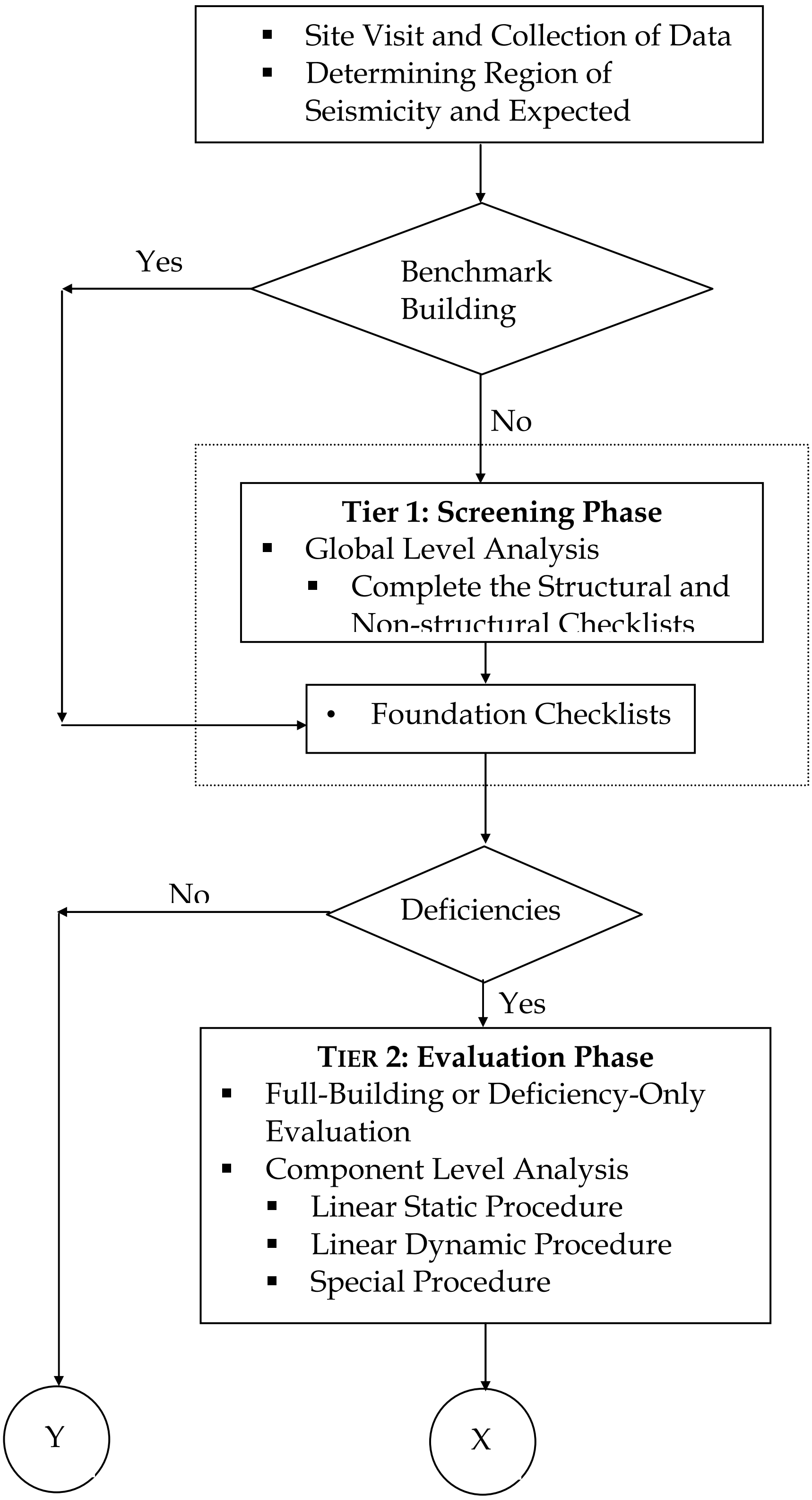

Figure 4: FEMA 310 – Evaluation Procedure (FEMA 310, 1998)

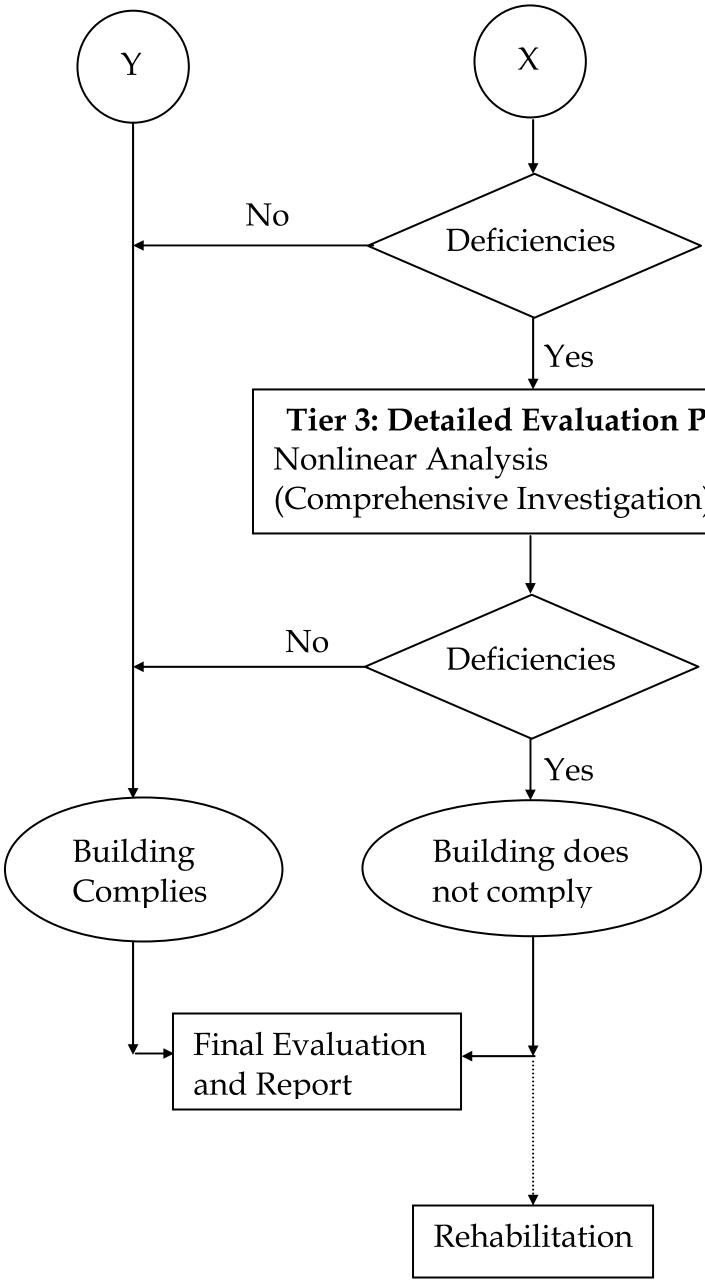

Figure 4: Continued…

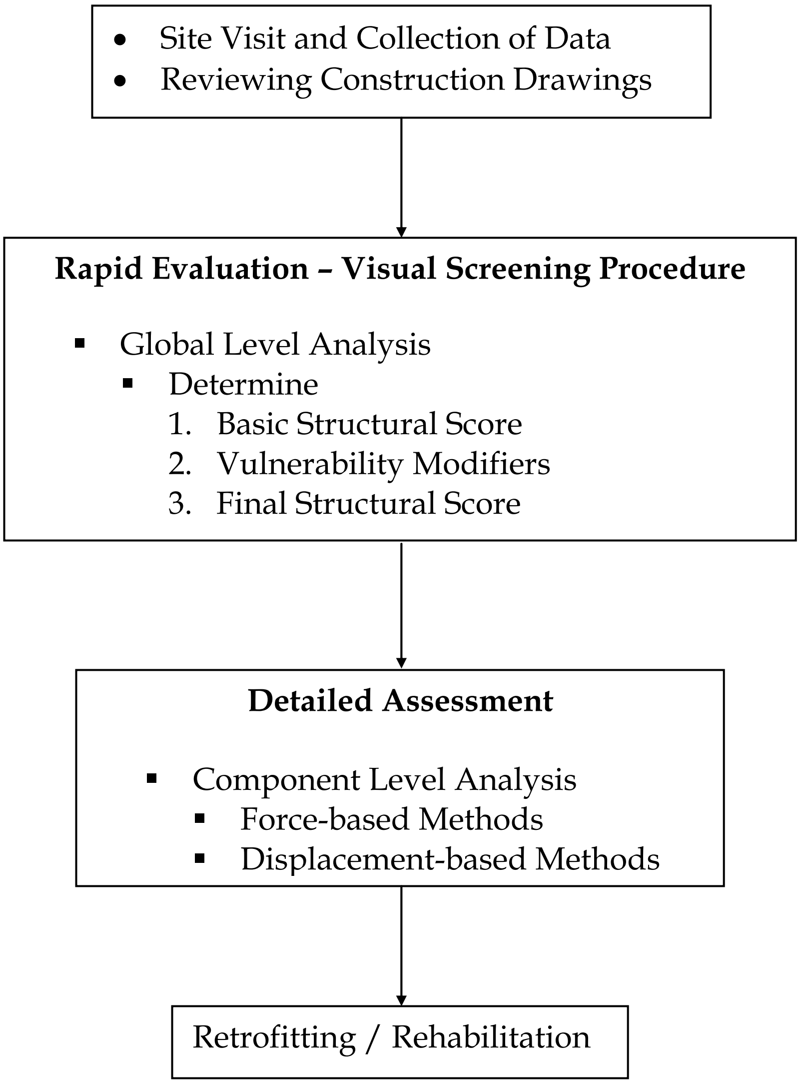

Figure 5: New Zealand Draft Code – Evaluation Procedure (NZDC, 1996)

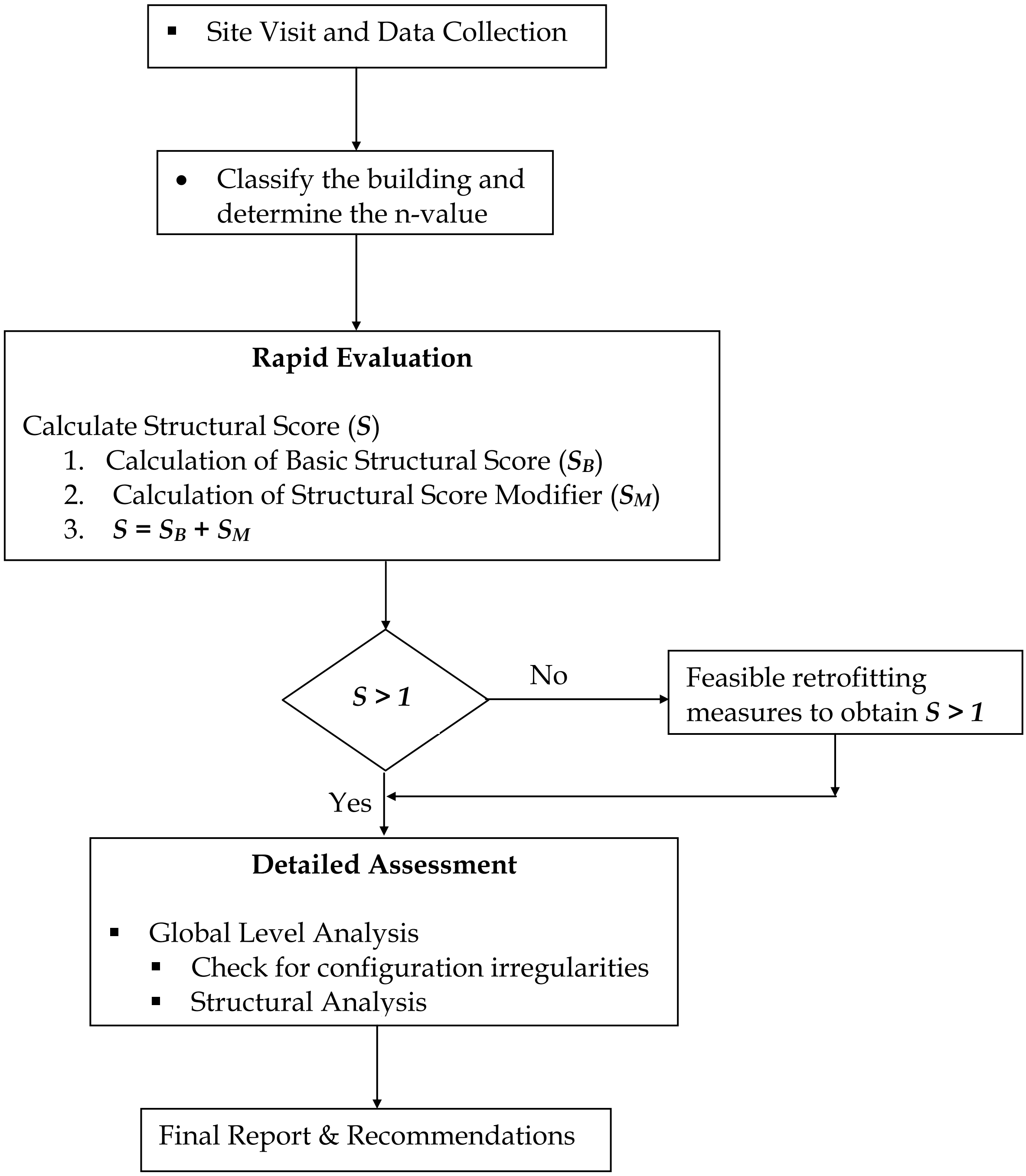

Figure 6: SERC Report – Evaluation Procedure (SERC, 2002)

- Site Visit and Data Collection

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Determine:
1. Quality of the structural layout
   - Good
   - Acceptable
   - Unclear
2. Strength Capacity – $S_{cap.}$
3. Strength Required – $S_{req.}$
4. Strength Index $R = \frac{S_{cap.}}{S_{req.}}$

↓

R \ **Layout**	Good	Acceptable	Unclear
R > 0.8	A	B	C
0.8 > R > 0.5	B	C	D
0.5 > R	C	D	E

↓

Classify the structure as A, B, C, D or E

↓

Determine the deformability and ductility requirements

↓

Determine the type of strengthening required

Figure 7: UNIDO Document – Evaluation Procedure (UNIDO, 1985)

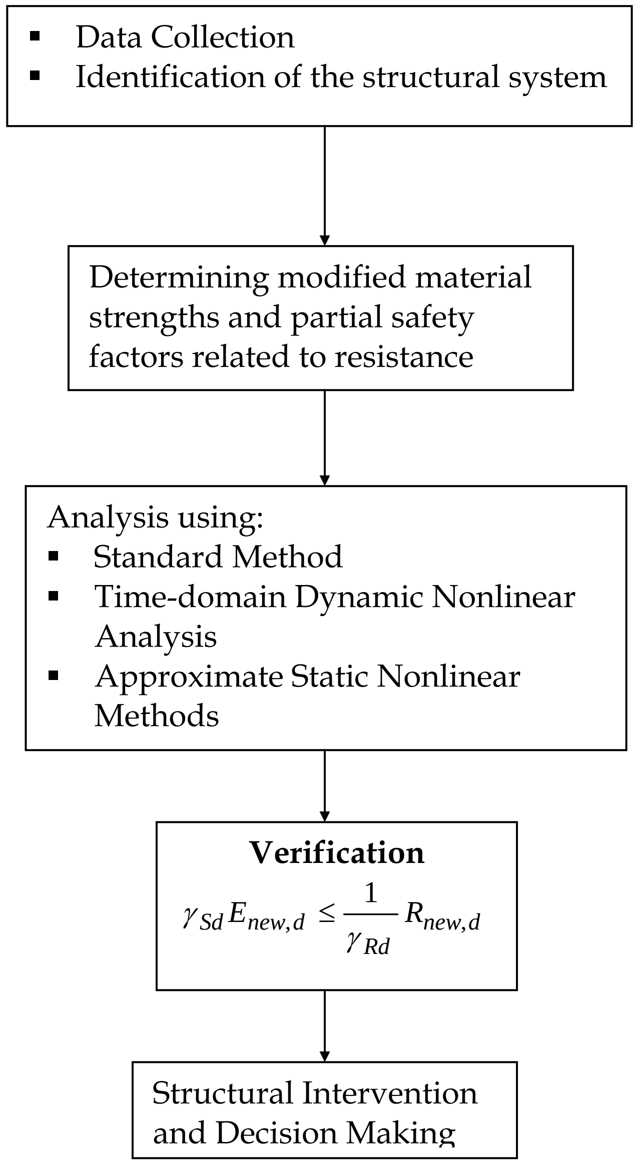

Figure 8: Eurocode 8 – Evaluation Procedure (Eurocode, 1996)

Seismic Evaluation

Configuration Based Checks

- Load Path
- Weak Storey
- Soft Storey
- Geometry
- Effective mass
- Torsion
- Pounding

Strength Checks

Global Level Checks

- Shear Stress Check
- Axial Stress Check

Component Level Checks

- Force Based Method
- Displacement Based Method

Figure 9: General Structure of Evaluation Procedures

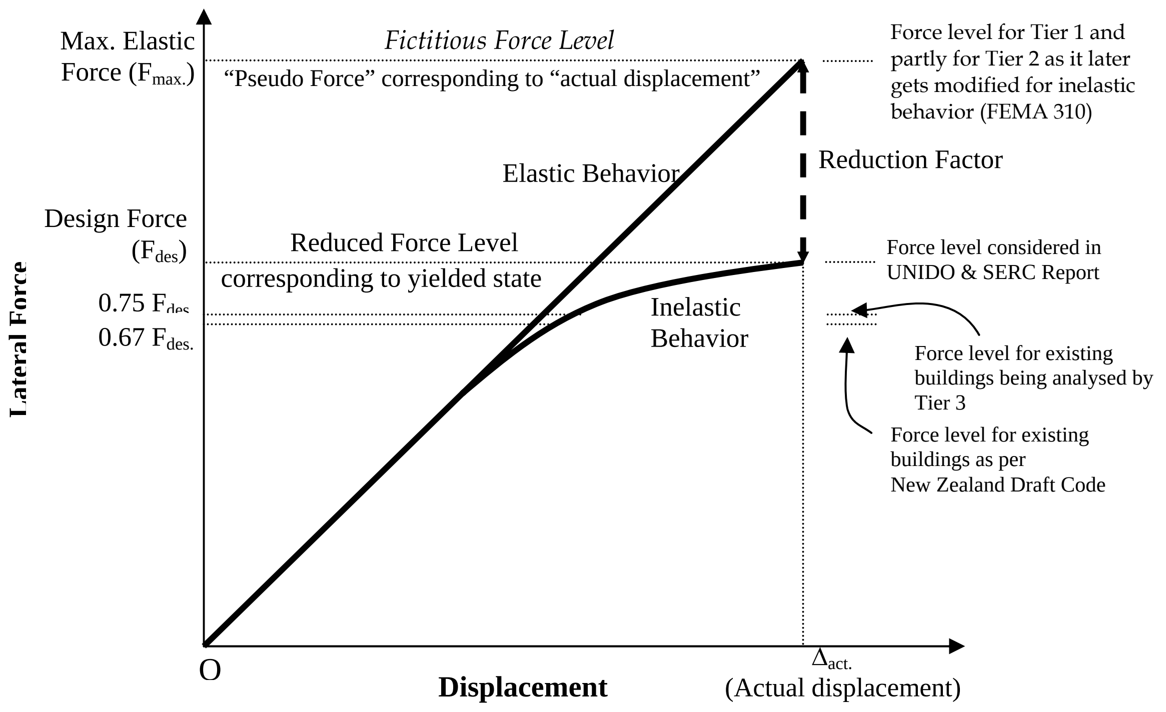

Figure 10: Force Levels for Analysis