3. SEISMIC EVALUATION METHODS AND RETROFIT STRATEGIES

3.1 General

Seismic evaluation is one of the challenging tasks in the earthquake engineering field. The seismic evaluation of structures is required to carry out for the purpose of seismic responses of structures so as to understand the actual behavior of the structure. In earthquake prone areas, there is a need to do the seismic evaluation of structures for safety purpose. This can be done either by static or dynamic analysis. A linear static method can be used for regular structure with limited height, and a linear dynamic analysis can be executed by the response spectrum method. A lot of research is carried out in the earthquake engineering field to propose simplified methods that will predict the results with reasonable accuracy. It was found that the pushover analysis is a simple and efficient approach for the evaluation of existing structures, and the time history analysis method is generally used for complex structures. Seismic evaluation and retrofit is the best option to avoid the loss of infrastructure and life. Most of the constructions are not able to sustain the seismic load due to many reasons, *viz.*, aging of structure, design and construction deficiency, poor materials and workmanship, etc. So, there is a need to go for retrofitting strategies. These retrofitting strategies are especially needed in an earthquake prone area. In this study, we have been used two different stages of seismic evaluation: (1) preliminary evaluation, and (2) detailed evaluation. The Earthquake Disaster Risk Index (EDRI) method is used for the preliminary evaluation. The nonlinear static adaptive pushover analysis, Quadrants assessment method & Material strain limit approach are used for the detailed evaluation of RC buildings. This study aims to evaluate the seismic performance of existing RC buildings and suggest the retrofit solutions based on their deficiencies.

3.2 Earthquake Disaster Risk Index (EDRI)

Earthquake Disaster Risk Index (EDRI) method has been developed by the National Disaster Management Authority (NDMA), Govt. of India to suit the Indian conditions and it is utilized for the risk assessment of the Koyna-Warna region based on the rapid visual screening (RVS) of individual buildings. The risk assessment part of this study is focused on reinforced concrete structures. Earthquake risk is the product of earthquake hazard (H) of the area, exposure (E) of structures to the earthquake hazard, and vulnerability (V) of the houses in that area as shown in Eq.(3.1). The controllable pre-earthquake factors are exposure and vulnerability, because exposure is in the hands of government organization like Municipal Corporation and vulnerability is in the hands of architects and engineers.

$$\text{Earthquake Risk (R)} = H \times E \times V \tag{3.1}$$

The Hazard is divided into two sub-factors, *viz.*, collateral hazard and the ground shaking as shown in Figure 3.1. Exposure depends on the importance and floor area ratio (FAR) of the building as shown in Figure 3.2. The vulnerability is the most critical factor in predicting the potential damage in a structure. This vulnerability parameter is further subdivided into two categories: life threatening factors (LTF) and economic loss inducing factors (ELIF) as shown in Figure 3.3. The LTF indicates the parameters that are directly associated to the loss of life, whereas ELIF indicates the damages expected in the building. The method for assessing the risk of an individual building includes a series of questions related to siting issues, soil and foundation condition, architectural features, structural aspects, and construction details. Each question has a weightage. This weightage varies depending on the questions. The questions are selected in such a way that they cover all three components of risk, i.e., hazard, exposure and vulnerability. The risk of RC building typology is estimated in a specific earthquake prone area (i.e., Koyna-Warna region), and the risk index of Koyna-Warna region is projected using census data of total number of RC buildings in that region based on the surveyed buildings. The 0.4 risk index is the alarming number for detailed evaluation of buildings. From the preliminary evaluation the moderate, severe, and collapse damage state of buildings need to go for the detailed evaluation, except the single and double storey RC buildings having total floor area less than 300 square meter as per IS 15988:2013 code. The correlation between risk index and type of damage is shown in Table 3.1

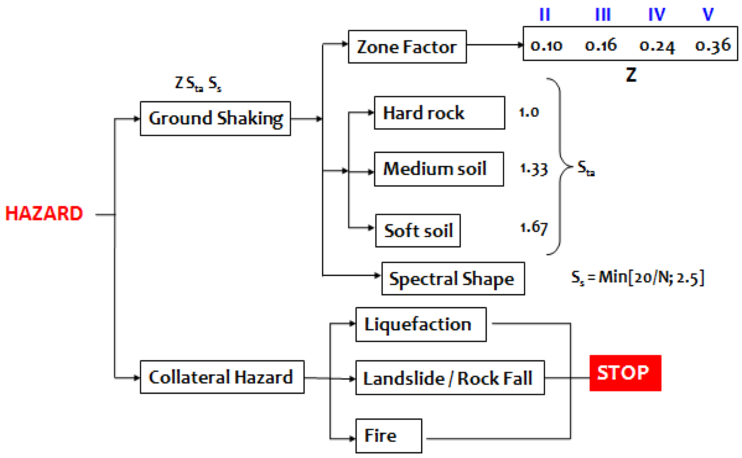

Figure 3.1 Flowchart of hazard parameter

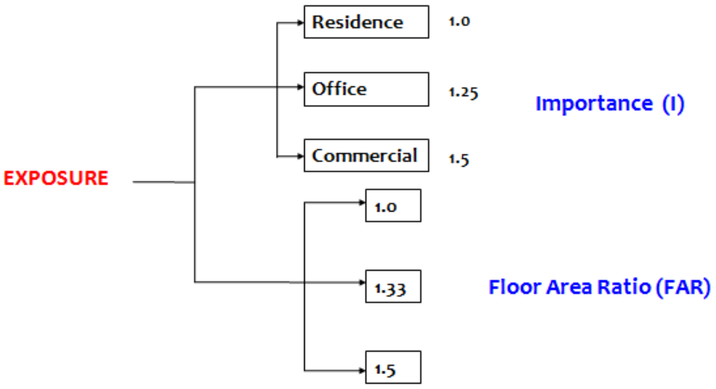

Figure 3.2 Flowchart of exposure parameter

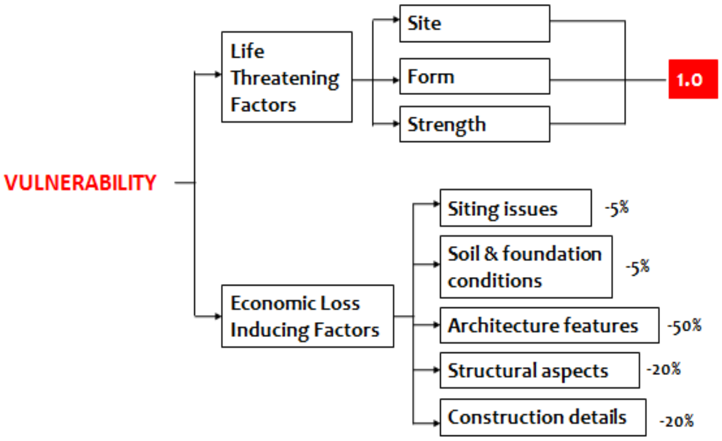

Figure 3.3 Flowchart of vulnerability parameter

Table 3.1 Correlation of risk index with level of damage (NDMA, 2019)

Risk Index	Level of Damage
0.0-0.2	No damage
0.2-0.4	Slight damage
0.4-0.6	Moderate damage
0.6-0.8	Severe damage
0.8-1.0	Collapse

3.2.1 EDRI of Koyna-Warna region for RC buildings

$$EDRI_{koyna-warna} = \frac{N_1 R_{b1} + N_2 R_{b2} + \ldots + N_T R_{bT}}{N_1 + N_2 + \ldots + N_T} \qquad (3.2)$$

N_1= Number of buildings of typology-1(Reinforced Concrete)

R_{b1}= Average risk of buildings of typology-1(Reinforced Concrete)

3.3 Nonlinear static adaptive pushover analysis

Over the last few years, the application of pushover analysis is usually used to verify the non-linear response of structures. The pushover analysis is a non-linear static analysis under the permanent vertical loads and gradually increasing lateral loads. A plot of total base shear versus top displacement in a structure is obtained by this analysis that would indicate a premature failure or weakness.

In the case of multistoried structure, ignoring the effect of higher modes is one of the limitations of such approaches. So Kalkan and Kunnath (2006) & Gupta and Kunnath (2000) have proposed to consider the higher mode effects depending on the adaptive pushover procedures which include the increasing variation in the dynamic properties. Here, the applied load is revised at every incremental action depending on the current dynamical properties of the structure.

Antoniou and Pinho (2004) employed a force-based adaptive pushover analysis, in which, the lateral load is continuously revised at each single step during the eigen-value analysis. The square root of sum of squares (SRSS) method is used to combine the responses of each mode.

In this advanced method, the spectral amplification part is also important for updating the load vectors. As per the literature for the adaptive pushover case, one can introduce the record of earthquake ground motion and defines the level of damping. In the present study, the design basis earthquake (DBE) acceleration response spectrum of the Koyna-Warna region is used for spectral amplification purpose.

3.4 Quadrants assessment method - A Quick Approach

In this study, the Quadrants assessment method is based on the results of the nonlinear static adaptive pushover analysis, and this generates the capacity curve, which represents the overall capacity of the whole structure against lateral forces. The actual response reduction factor and performance point of structure is evaluated from the capacity curve. The Quadrants assessment method depends on the two seismic parameters, *viz.*, actual response reduction factor (R-factor) and the performance point of a structure. The necessity of a structural intervention/retrofit depends on the location of the intersection of these two seismic parameters. In this method, the two main structural parameters are taken into account as the first one is the design response reduction factor (Design R-value) based on the type of structure (ordinary moment-resisting frame / special moment-resisting frame) and the second parameter is the threshold damage limit state, i.e., the first yield point of the RC structure. The threshold value is fixed to the yield deformation of the structure. Both values are used to define two axes, the design response reduction factor (Design R-value) defines a horizontal axis, and the threshold damage limit state defines a vertical axis, so ultimately four quadrants are created, as shown in Figure 3.4

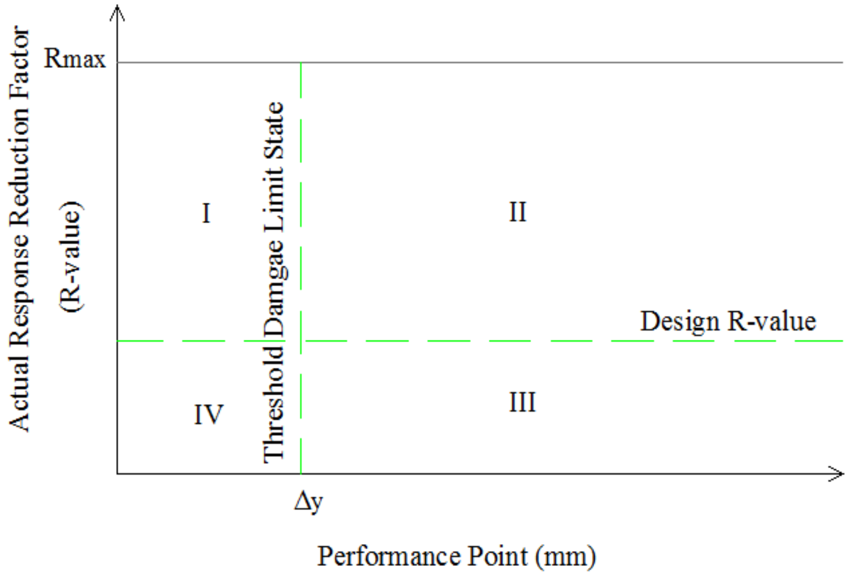

Figure 3.4 A representation of actual response reduction factor versus performance point graph and the axis that define the Quadrants assessment method

The performance point of the structure is calculated as per ASCE 41-06 (ASCE/SEI 41-06, 2006) for life safety & collapse prevention purposes (i.e., the basic performance objective). The intersection of demand and capacity curve is a common procedure accepted among the scientific community to evaluate the seismic performance of a structure under a specific demand. If the intersection point of actual response reduction factor and performance point is in Quadrant Ist, the structure has enough lateral strength and stiffness, so it does not need to be reinforced. If the intersection point is in Quadrant IInd, it is necessary to provide additional stiffness by using RC or steel jacketing, and if the intersection point is in Quadrant IIIrd / IVth, the structure requires a more radical intervention, adding stiffness and lateral strength.

3.5 Material strain limit approach

Engineers must be capable of identifying the instants at which different structural damages are reached. This can be efficiently carried out in SeismoStruct software through the definition of performance criteria, whereby the attainment of a given threshold value of material strain is monitored during the analysis of a structure. Material strains are usually the best parameter for the identification of the structural damages of a given structure. It is easy to identify the actual damage phenomena based on the material in a structure due to the distributed inelasticity given to each structural member. The material strain limit approach is useful to identify the deficient members based on the demand to capacity ratio for retrofitting purpose.

To check the damage patterns of the structures, the performance criteria based on material strain used in the present study are (1) yield strain limit for steel: 0.0025, (Aswin Prabhu, 2013, SeismoStruct-manual, 2020), (2) crushing strain limit for unconfined concrete in beam: 0.0035 (Aswin Prabhu, 2013, IS 456:2000), (3) crushing strain limit for unconfined concrete in column: 0.002 (IS 456:2000), (4) crushing strain limit for confined concrete: 0.008 (Chen, 2009, Aswin Prabhu, 2013), and (5) fracture strain limit for steel: 0.06. (Aswin Prabhu, 2013, SeismoStruct- manual, 2020)

3.6 Proposed refined procedure for the seismic evaluation and retrofit of RC buildings

Figure 3.5 presents the flowchart of the proposed refined procedure for the seismic evaluation and retrofit of RC buildings, involving the two seismic evaluation methods, *viz.*, “Quadrants assessment method” and “Material strain limit approach”. The material strain limit approach is the micro-level evaluation used for the identification of deficient members. The identification of the deficient members is based on the provisions of ASCE 41-06 as shown in Table 3.2, and the RC structure is to be strengthened by using local or global retrofitting techniques.

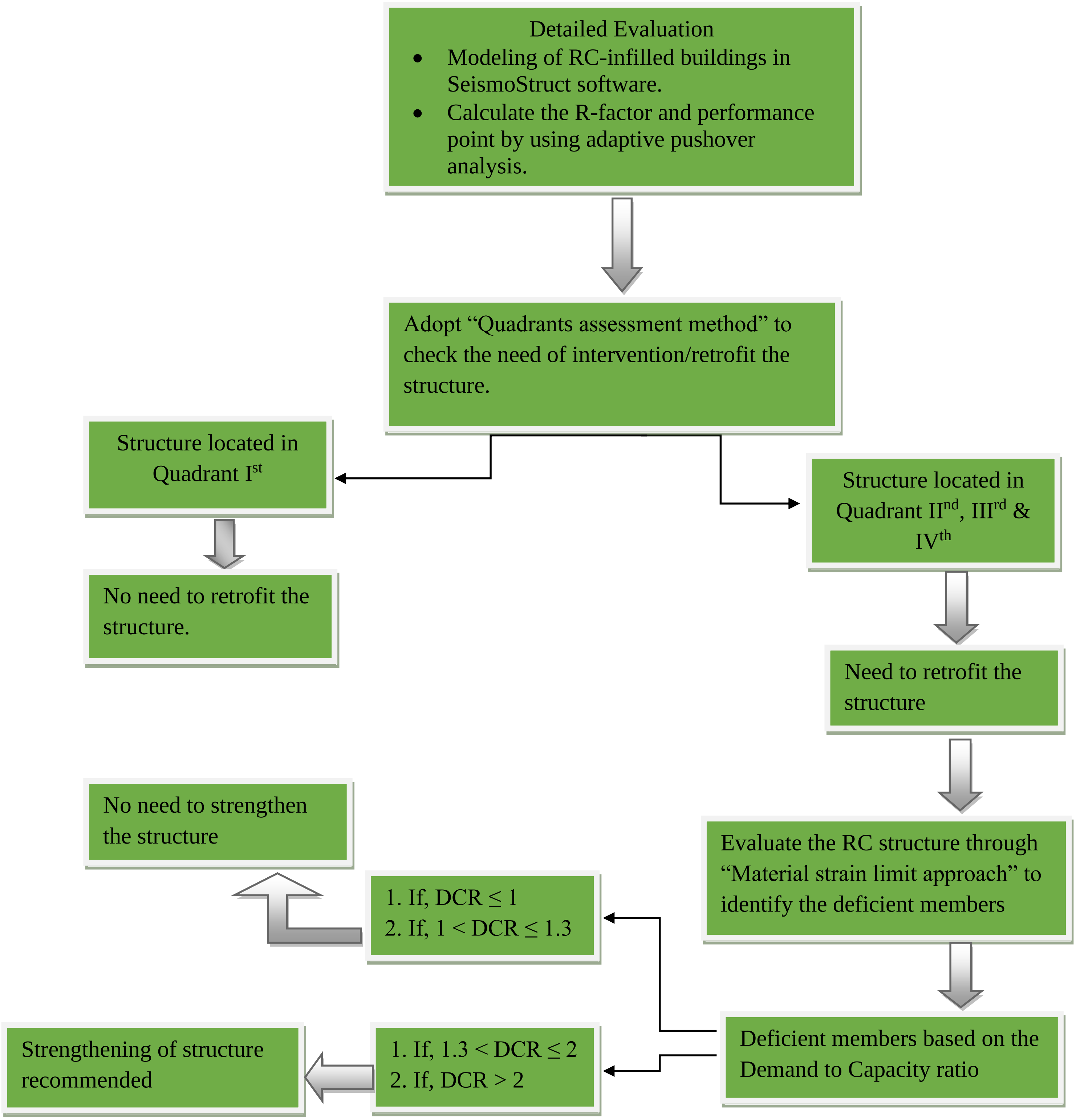

Figure 3.5 Flowchart of the proposed refined procedure for the seismic evaluation and retrofit of RC buildings

Table 3.2 Criteria for Demand to Capacity Ratio

Condition	Demand to Capacity Ratio (DCR)	Remark
Safe	If, DCR ≤ 1	No need of rehabilitation
Marginally Inadequate	If, 1 < DCR ≤ 1.3	
Significant damage/ failure	If, 1.3 < DCR ≤ 2	Must need of rehabilitation
	If, DCR > 2	

The “Quadrants assessment method” is a global approach for the seismic evaluation of structures based on the intersection point of actual response reduction factor and performance point of the structure. The need for structural intervention/retrofit depends on the location of that intersection point, so the rapid seismic evaluation of the structure can be possible through this “Quadrants assessment method”. After this evaluation, the “Material strain limit approach” is the local approach for the seismic assessment of the RC structure based on the threshold strain limit of concrete and steel to identify the actual damage state of structural members, i.e., micro-level evaluation. Ultimately, the proposed combination of these two methods can provide a refined way for the seismic evaluation and retrofit of reinforced concrete structures.

3.7 Retrofit methods

The need for seismic retrofitting of buildings arises under two circumstances: (1) earthquake-damaged buildings, and (2) earthquake-vulnerable buildings that have not yet experienced severe earthquakes. Generally, the retrofitting of a building depends on the type of structures, condition of materials, type & amount of damage, etc. The basic concepts of retrofitting techniques are aimed at (CEB, 1997) (a) upgradation of lateral strength of the structure, (b) increase in the ductility of structure, (c) increase in the strength and ductility of structure.

There are two ways to enhance the seismic capacity of existing structures. The first is a structural (global) level approach, and the second is a member (local) level approach of retrofitting. Generally, structural level retrofits are applied when the entire structural system is deemed to be deficient. Common approaches in this regard are employed to increase stiffness and strength with limited ductility. The most common modifications include the addition of structural walls, steel braces, infill walls, base isolators or supplementary energy dissipation devices. The most popular and frequently used method in local retrofitting is reinforced concrete, steel, and fiber-reinforced polymer (FRP) jacketing.

In the present study, the retrofit strategy is used to strengthen a structure based on its current deficiencies in accordance with IS 15988:2013 code. Among the different strategies, one local retrofit scheme is used namely; RC jacketing for the deficient column members having a crush of confined concrete and fractured steel failure. This retrofit technique enhances the stiffness & strength of the structure.

3.8 Concluding remarks

This chapter presented the detailed information on different seismic evaluation methods & retrofit strategies. In this chapter, we have discussed the several seismic evaluation methods, *viz.*, EDRI method, adaptive pushover analysis, Quadrants assessment method, and Material strain limit approach in detail and also the retrofit methods adopted in the present study. Quadrants assessment method is global & quick approach to check the need of intervention/retrofit the structure and Material strain limit approach is a local method to identify the structural damages.