

Analysis of Irregular Structures and the Application of Reliability in Retrofitting

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ABSTRACT: Now Reinforced cement concrete (RCC) as a construction material has come into applicability from the last one century. In India, RCC has been used nearly in last 50-60 years. During this period, we have created large number of infrastructural assets in terms of buildings, canals, dams, bridges etc, which cannot even dream of recreating such assets out of limited national resources. It is, essential to maintain them in functional condition. Since, deterioration of RCC is a natural phenomena and has started exhibiting in large number of structures, a systematic approach is needed in dealing with such problems. Identification of deterioration and consequent repair/rehabilitation strategy at optimum cost needs a scientific evaluation and solution.

Repair, Retrofit and Rehabilitation have proven its significance in the past and also near future. It is chosen mainly when cost estimation of repair structural deficiency does not exceed the replacement cost. In the present work vulnerability of retrofitting and its application not on only seismic sensitive region but also for old structures is motivated. An existing 3-storey, 2- Bay reinforced concrete structure with plan irregularity, both in as-built before and as retrofitted is subjected only to gravity load in the framework of performance of existing structure and its rehabilitation research project. The structure is analyzed by a linear-dynamic statistical method to get the response of structure for computing time period, storey shear and maximum storey displacement in each mode of vibration, In this episode the structure is retrofitted by column- jacketing.. The retrofitting intervention was carried out, consisting of RC-jacketing a strengthening technique to increase the system capacity and ductility of selected vertical elements with the aim of relocating the centre of strength of the structure to reduce torsion effects. The rehabilitation approach aimed at reducing demands by reducing the strength eccentricity also proved to be effective. The design of retrofitting technique is incorporated by using extended three dimensional analysis of building system (ETABS 2015).

The attempts to gather the available information particularly on the nonlinear behavior, and the various approaches available to evaluate the seismic safety of buildings. It is emphasized that the existing procedure is grossly approximate, and hence improving sections of the approach to high levels of accuracy would not necessarily lead to a better result. The need of the present hour is to see what needs to be done in the Indian context. The growing understanding of the risk from existing buildings by owners and government is creating a demand for more efficient and reliable analytical methods, as well as innovative techniques for retrofit. A benchmark analytical tool is needed to test and set limitations on simplified nonlinear procedures. Reliable and consistent simplified linear or force based procedures are also needed for small, regular buildings. 20%.

KEYWORDS: Green Reinforced Cement Concrete (RCC), Retrofitting, Rehabilitation, Structural irregularity, Reliability analysis, Column jacketing, Linear-dynamic analysis, ETABS, Seismic safety.

I. INTRODUCTION

Most of the buildings were constructed before the introduction of modern building codes have either collapsed or experienced different levels of damage. The construction material mainly reinforced concrete is being used extensively for various types of construction. However, the deterioration of reinforced concrete structures is recognized as a major problem worldwide. Due to Low-quality concrete, poor confinement of the end regions, weak column-strong beam behavior, short column behavior, inadequate splice lengths and improper hooks of the stirrups were some of the important

Volume 15, Issue 5, May 2026**|DOI: 10.15680/IJRSET.2026.1505141|**

structural deficiencies. They usually cannot provide the required ductility, lateral stiffness and strength. Vulnerable structures are subjected to large displacement demands, which cannot be met adequately as they have low ductility which is definitely lower than the limits imposed by the modern building codes. Hence apart from requiring regular maintenance, many structures require extensive repair, rehabilitation & retrofitting. Over a period of time, as these structures become older, we find in them certain degradation or deterioration with resultant distress manifested in the form of cracking, splitting, delaminating, corrosion etc. Such deteriorated structures can be rehabilitated and retrofitted by using various types of techniques & modern repair materials Difference between repair and rehabilitation

Repair techniques are used to restore the structural integrity and shape of a concrete element. For example, a balcony slab can be repaired so that it does not have any damaged concrete or unsafe indentations. Repair techniques generally include removal of damaged concrete and placement of new concrete in its place. Repair methods, however, do little to address the cause of deterioration.

Rehabilitation methods, in addition to restoring structural integrity and shape, mitigate or stop the process responsible for the damage. Because rehabilitation includes addressing the cause of the problem itself, the repairs last significantly longer. The statistical analysis is used to study the rehabilitation of structure and is used to determine Safety or Reliability Index.

Reliability

Designing structures under the expectation that they will continue to function safely, economically, and efficiently over a certain anticipated period of time is mainly based on assumptions as to load effects, material behavior and geometry. Large uncertainties exist about actions on structures, as well as their resistances which possibly deteriorate in time. It is therefore general practice to inspect and, if necessary, repair and/or strengthen them. In view of the large uncertainties involved, the consequences of structural failure and the considerable cost of inspection and possible repair, a probabilistic approach for the quantification of the actual uncertainties and the structural reliability state appears natural.

Retrofitting

The behavior of the existing buildings is affected due to design deficiency, construction deficiency, additional loads, additional performance demand, etc. The retrofitting is one of the best options to make an existing inadequate building safe against future probable earthquake or other environmental forces. Retrofitting reduces the vulnerability of damage of an existing structure during a near future. It aims to strengthen a structure to satisfy the requirements of the current codes. The Significant amount of research work has been carried out in recent years to develop various strengthening and rehabilitation techniques to improve the performance of structures. This study aims to present of overview on different innovative and cost effective techniques of retrofitting for strengthening the damaged structures.

Reinforced Concrete Jacketing, Steel Jacketing, Fiber Reinforced Polymer Composite (FRPC) Jacketing, Steel Bracing System, Addition of Shear, Shotcrete Technique, Walls.

II. LITERATURE SURVEY

This chapter reviews literature on the analytical study of reinforced concrete (RC) frames using reliability and retrofitting techniques evaluated via ETABS.2.2 Literature Review Concrete Strength Evaluation (Shimizu et al.): In-situ core testing is crucial for retrofitting. Strength in older structures varies significantly and fits a normal distribution, while the coefficient of variation follows a log-normal distribution. Vulnerability Assessment (Shrestha et al.): Quantifying structural risks through vulnerability analysis determines whether a structure requires retrofitting or complete replacement. Jacketing Techniques (Gorai & Maiti; Yalciner & Hedayat): Reinforced Concrete Jacketing (RCJ) improves lateral load capacity, ductility, and stiffness while correcting eccentricity. It outperforms steel bracing in enhancing beam-column joint shear safety. Steel and FRP jacketing also effectively increase shear resistance. Intervention Classification (N. Lakshmanan): Retrofitting is categorized into system-level (shear walls, bracing, base isolation) and local-level (element jacketing, crack injection) modifications. Component Repairs (Shaw & Andrawes; Karthik & Sundaravadivelu): Mortar paired with FRP laminates restores degraded bridge girder ends. For beams, Reactive Powder Concrete overlays with steel fibers restore original flexural strength economically. Risk & Reliability Frameworks (Holmes; FEMA 310; Biondini & Frangopol; Stanojev & Stojic; Holicky & Vrouwenvelder): Risk evaluation requires explicit nonlinear analysis due to low deformation capacities. Frameworks like FEMA 310 utilize Life Safety and Immediate Occupancy

performance levels. Governed by ISO 2394 and Eurocode EN 1990, modern design must incorporate life-cycle reliability indices (β) to account for real-world uncertainties and structural deterioration.

III. METHODOLOGY

In this chapter we discuss the implementation of modern probabilistic methods in the reliability evaluation of existing structures. The difference between prior uncertainty modeling and reliability updating based on available information is emphasized. Possibilities for applications of first-order reliability methods are applied and methodology is listed below. For performance evaluation, a structural analysis of the analytical model of the structure is required to determine force and displacement demands in various components of the structure.

Several analysis methods, both elastic and inelastic, are available to predict the performance of the structures.

This Chapter is splinted into three sections:

- First section deals with the reliability analysis of structure and its applicability for deciding retrofitting techniques.
- Second section deals with brief description of various linear method of analysis that are available for the analysis of structure and the best vulnerable method is chosen amongst the various methods.
- Third section deals with application of Non-Linear analysis of method and its significance in an irregular structure over an regular structure.

Reliability Analysis

The largest uncertainties exist at the design stage. Not only is the loading environment only partially known but the specific quality of manufacture and construction is under control

Reliability Methodology.

Numerical methods for reliability calculation have been developed during the past decade and the first order reliability methods FORM have been recognized as very accurate and efficient. The basic principles implied in FORM are the following:

1. The simplification is achieved through transforming the random variables from their original random space into a standard normal space To make the shape of the integrand $f(x)$ regular, all the random variables X_1, X_2, \dots, X_n are transformed from X -space to a standard normal space, where the transformed random variables U (U_1, \dots, U_n) follow the standard normal distribution. The transformation from X to U is based on the condition that the cdfs of the random variables remain the same before and after the transformation.

It should be noted that after the transformation, the integration in Equation 2 in U -space is identical to that in Eq.3.1 in X -space without any loss of accuracy, but the contours of the integrand $f(U)$ become concentric circles (or hyperspheres for a higher dimensional problem). The circular contours are shown in Figs. 3.3 and 3.4. It is obvious that the integrand $f(U)$ is easier to be integrated.

2. The point that has the highest probability density on the performance $g(U) = 0$ is termed as the Most Probable Point (MPP). Maximizing the joint pdf $f(U)$ at the limit state of $g(U) = 0$ gives the location of the MPP. The limit state surface $g(U) = 0$ formulated in this new space is shown graphically in Fig. 3.1.4, the MPP is the shortest distance point from the limit state $g(U) = 0$ to the origin 0 in U -space is approximated by its tangent hyper plane at the point of smallest distance β to the origin as shown in Figure 3.1.4 for the case of two random variables. β is defined as distance in standard deviation units from the center of the joint density to the "Most Probable Point." The distance β is called the reliability (or safety) index.

Limitations of MVFOSM

1. Information regarding distribution of the variables is completely ignored
2. Truncation errors due to linearization at mean point for non-linear limit state function
3. Different though mechanically equivalent equations did not give the same safety index. In other words, the safety indices depend on the how the limit state equation is formulated. This was commonly called the invariance problem.

An accurate determination of performance requirements and thus an accurate specification of the term failure are of uttermost importance. In many cases, when considering the requirements for stability and collapse of a structure, the specification of the failure is not very complicated. In many other cases, in particular when dealing with various requirements of occupants' comfort, appearance and characteristics of the environment, the appropriate definitions of

failure are dependent on several vagueness's and inaccuracies. The transformation of these occupants' requirements into appropriate technical quantities and precise criteria is very hard and often leads to considerably different conditions.

Methods of analysis

Method of analysis are classified as elastic and inelastic. Elastic methods are classified as Equivalent Static Method, Response Spectrum Method and Linear Time-history Analysis, while inelastic methods are classified as Static Pushover analysis, Incremental Dynamic Analysis and Non-Linear Time-history Analysis. Here Equivalent Static Method, Response Spectrum Method of analysis as per IS 1893(Part-1):2002 and Pushover Analysis are discussed

Equivalent Static Method

It is a linear static analysis based on the assumption that the structure responds in its fundamental mode. Following are the assumptions in linear analysis:

1. All loads are applied gradually and slowly until they reach their full magnitude.
2. After reaching the full magnitude, load remains constant.
3. Inertial and damping forces to small velocities and accelerations are neglected.

This is applicable only when the structure is of low rise and there are no twisting effects. The base shear, which is the total horizontal force on the structure, is calculated on the basis of structure mass and fundamental period of vibration and corresponding mode shape. The base shear is distributed along the height of the structure in terms of lateral forces. The procedure for the Equivalent Static Analysis as per IS 1893:2002 is as follows:

(a) Fundamental Natural Period

The fundamental natural time period as mentioned in clause 7.6 IS 1893(part 1): 2002 for moment resisting RC frame building without brick infill walls and moment resisting steel frame building without brick infill walls, respectively is given by:

$$T_a = 0.075h^{0.75} \text{ For RC frame} \dots\dots\dots 3.9$$

Where, h = height of the building (in meter) excluding basement storey

(b) Seismic Weight

The seismic weight of each floor is its dead load plus appropriate amount of imposed load as specified. While computing the seismic weight of each floor, the weight of columns and walls in any storey shall be equally distributed to the floors above and below the storey. The seismic weight of the whole building is the sum of the seismic weights of all the floors.

(c) Design Base Shear

The total design lateral force or design seismic base shear (V_b) along any principal direction of the building shall be determined by the following expression:

$$V_b = A_h W \dots\dots\dots 3.10$$

Where A_h the horizontal seismic forces coefficient and W is the seismic weight of building. The design horizontal seismic forces coefficient A_h for a structure, shall be determined by following expression:

$$A_h = Z I S_a / 2 R_g \dots\dots\dots 3.11$$

Z = zone factor for the maximum considerable earthquake (MCE) and service life of the structure in a zone.

Factor 2 in denominator is to reduce the MCE to design basis earthquake (DBE).

I = Importance factor, depending on the functional purpose of the building.

R = Response reduction factor, depending upon the perceived seismic damage performance of the structure, characterized by ductile or brittle deformations however the ratio I/R shall not be greater than 1

S_a/g = Average response acceleration coefficient.

(d) Distribution of Design Force

The design base shear, computed above shall be distributed along the height of the building as per the following expression

$$Q_i = \frac{V_b W_i h_i}{\sum_{l=1}^n W_l h_l^2}$$

Where,

Q_i = lateral force at ith floor.

W_i = weight of ith floor.

h_i = of ith floor measured from base.

Numbers n = of storey in the building is the number of the levels at which the masses are located.

The actual distribution of base shear over the height of building is obtained as the superposition of all the modes of vibration of the multi degree of freedom system.

Response Spectrum Analysis

Response Spectrum Analysis (RSA) is a linear-dynamic statistical analysis method which measures the contribution from each natural mode of vibration to indicate the likely maximum seismic response of an essentially elastic structure. Response-spectrum analysis provides insight into dynamic behavior by measuring pseudo-spectral acceleration, velocity, or displacement as a function of structural period for a given time history and level of damping. It is practical to envelope response spectra such that a smooth curve represents the peak response for each realization of structural period. Response spectra are curves plotted between maximum response of SDOF system subjected to specified earthquake ground motion and its time period (or frequency). Response spectrum can be interpreted as the locus Of maximum response of SDOF system for given damping ratio response spectra this help

In obtaining the peak structure responses under linear range , which can be used for obtaining lateral forces developed in structure

IV. EXPERIMENTAL RESULTS

Result and Discussion for Reliability Analysis.

The basic concepts of the probabilistic theory of reliability are characterized by two valent terms, the probability of failure Pf and the reliability index . Although they provide limited information on the actual frequency of failures, they remain the most important and commonly used measures of structural reliability. Using these measures the heory of structural reliability may be effectively applied for further harmonization of nability elements and for extensions of the general methodology for new, innovative uctures and materials.

Table 4.1 Probability of Failure

No. of Storey	Safety Index	Probability of Failure
Story 1	2.7145	0.0033
Story 2	2.7308	0.0032
Story 3	2.7105	0.0034
Story 4	2.6971	0.0035
Story 5	2.6680	0.0038

For many reasons the two methods discussed are important for the analysis and design of placement controlled structures. It is often tempting to discard an old "approximate" ESM method when the state of the art reaches a level where the latest technology can be effectively eed. This is, however, not always the best approach. With tight financial and delivery budgets, it advisable to use the best of both worlds to streamline the design process, while insuring that surate data is developed at each step,

Maximum Storey Displacement

Sarry Displacement is total displacement of ith storey with respect to ground and there is maximum permissible limit prescribed in IS codes for buildings. Maximum Displacements obtained by ESM is 20.546 mm and by RSM is 28.325 mm as RSM shows more accuracy and Sturry Displacement for Retrofitted Model is 24.612 mm. It can be seen that with increase in section area and stiffness of column in structure storey displacement is reduced hence signifying he increase in stiffness of the column and the overall building.

Volume 15, Issue 5, May 2026

|DOI: 10.15680/IJIRSET.2026.1505141|

Analysis and Result for Non Linear Analysis

This section presents a summary of the results obtained for the both structures studied. In particular, for the five-storey building a comparison of the outcomes reached for all the non-linear static analyses performed and compared with the outcomes of irregular building. The sequence of plastic hinge formation and state of hinge at various levels of building performance can be obtained from ETABS output. This gives the information about the weakest member and so the one which is to be strengthened in case of a building need to be retrofitted. Accordingly the detailing of the member can be done in order to achieve the desired pattern of failure of members in case of severe earthquakes. It is concluded that pushover analysis is a successful method in determination of the sequence of yielding of the components of a building, possible mode of failure, and final state of the building after a predetermined level of lateral load is sustained by the structure. Although the majority of formation of hinges is in the columns, the behavior of the building is adequate as indicated by the intersection of the demand and capacity curves and the distribution of hinges in the beams and the columns. From demand capacity curve, it is concluded that both the demand curve intersects the capacity curve near the event point B. Therefore, it can be concluded that the margin safety against collapse is high and there are sufficient strength and displacement reserv Hinge States of the Irregular Building with Im projection.

Hinge states have been shown in Figure 4.11 and Figure 4.12. Hinges are formed at various stages of push over analysis. Green color of hinge represents that all hinges formed are in elastic state. And no hinges are formed in plastic zone. Hence the structure is under serviceable criteria.

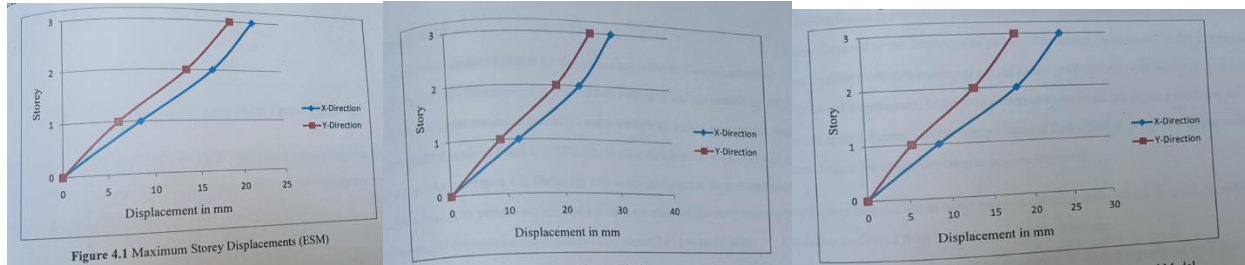
Hinges are points on a structure where one expects cracking and yielding to occur in relatively higher intensity so that they show high flexural (or shear) displacement, as it approaches its ultimate strength under cyclic loading. These are locations where one expects to see cross diagonal cracks in an actual building structure after a seismic mayhem, and they are found to be at the either ends of beams and columns, the 'cross' of the cracks being at a small distance from the joint- that is where one is expected to insert the hinges in the beams and columns of the corresponding computer analysis model

Step	Monitored Displacement	Base Force	A-B	B-C	C-D	D-E	A-IO	IO-LS	LS-CP	>CP	TOTAL
0	0	0	2600	0	0	0	2600	0	0	0	2600
1	-3.078	703.672	2590	10	0	0	2600	0	0	0	2600
2	-21.657	3367.65	2260	340	0	0	2600	0	0	0	2600
3	-50.92	5042.18	2156	444	0	0	2596	0	0	0	2600

Base Shear versus Monitored Displacement

Step	M3	R3	R3 max	R3 min	State	Status
	kN	Rad	Rad	Rad		
0	0	0	0	0	A to <=B	A to <=IO
1	-57.956	0	0	0	A to <=B	A to <=IO
2	-344.3801	0	0	0	A to <=B	A to <=IO
3	-376.4561	-0.001809	0	-0.001809	B to <=C	A to <=IO

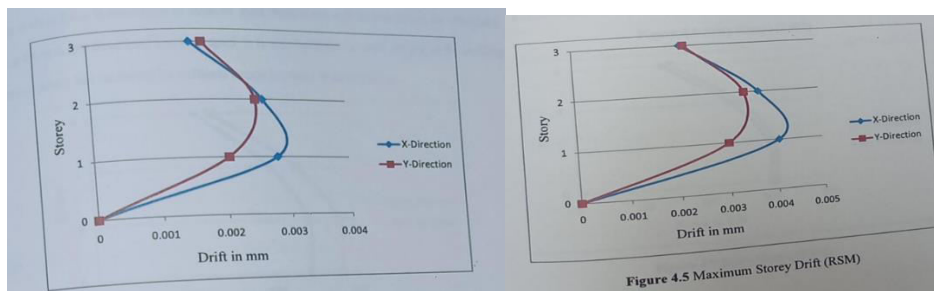
Hinge Response Value



(a)

(b)

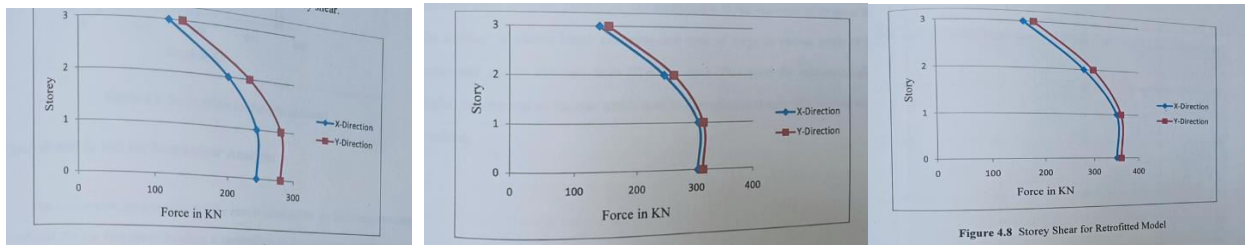
(c)



(d)

(e)

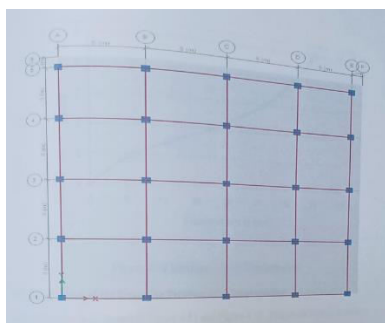
(a) Figure 4.1 Maximum Storey Displacements (ESM) (b) Figure 4.2 Maximum storey displacement (RSM) (c) Figure 4.3 Maximum Storey Displacement of Retrofitted Model (d) Figure 4.4 Maximum Storey Drift (ESM) € Figure 4.5 Maximum Storey Drift (RSM).



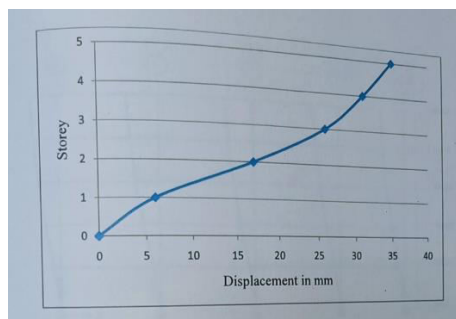
(a)

(b)

(c)



(d)



(e)

(a) Figure 4.6 Story Shears (ESM)Weight Loss due to Acid Attack of Different Mixes of Concrete on Different Water Cement Ratios (b) Figure 4.7 Story Shears (RSM) (c) Figure 4.8 Storey Shear for Retrofitted Model (d) Figure 4.9 Plan of Building (e) Figure 4.10 Maximum Storey Displacements.Mixes.

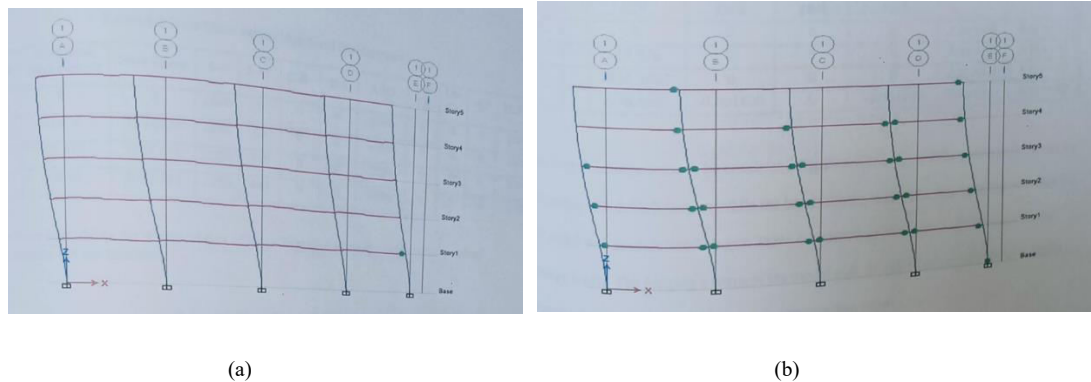


Figure 4.11 (a) Hinge states Developed in first step, Figure 4.12 (b) Hinge States Fully Developed .Periods.

V. CONCLUSION

The attempt is done to gather the available information particularly for studying the nonlinear behavior, and the various approaches available to evaluate the safety of buildings. It is emphasized that the existing procedure is grossly approximate, and hence improving sections of the approach to high levels of accuracy would not necessarily lead to a better result. The need of the present hour is to see what needs to be done in the Indian context. The growing understanding of the risk from existing buildings by owners and government is creating a demand for more efficient and reliable analytical methods, as well as innovative techniques for retrofit. A benchmark analytical tool is needed to test and set limitations on simplified nonlinear procedures. Reliable and consistent simplified linear or force based procedures are also needed for small, regular buildings.

Conclusion for Reliability Analysis

In EN 1990 [1] the basic recommended reliability index for ultimate limit states B_a 3.8 corresponds to the design failure probability P_a 7.2×10^{-5} , for serviceability limit states B_1 5 corresponds to P_d 6.7×10^{-2} . In general greater - values should be used when a short reference period (one or five years) will be used for verification of structural reliability. It is observed that value of reliability index is in the range of 3.85 to 21.5. Our Structure is within the serviceable limits and it is a little less stiff from ultimate state. To make the structure more resistant and increase its stiffness we can apply in various techniques of retrofitting to enhance its capability if needed.

Conclusion for Method of Analysis

The structures are analyzed by using methods Equivalent Static Method of analysis and Dynamic method of analysis.

- The Dynamic analysis method can be performed by Response spectrum method and by nonlinear static analysis i.e. pushover analysis is carried out.
- Different type of analysis methods is adopted in order to study the Displacement & Base Shear graph for Validation for Method of Analysis.
- Response Spectrum Method gives us most accurate results in comparison of original structure data obtained. Hence it will be chosen as Analysis Method for future Research.
- Non-Linear Analysis Method gives us the satisfactory result to study the behaviour of building at various hinge formation state.
- Hinge formation sequence is tried to study in relative to the reliability of building.
- Reliability Index and Probability of failure has been worked out by FORM and result of which has been found in relevance to the results obtained by Non-Linear Analysis i.e. Push Over Analysis.
- All Hinges formed are in elastic region and no hinges are formed in Column, It means that structure is sufficiently safe enough from the collapse limit and the same can be depicted by the reliability analysis as $f_c = 3.8$ concrete.

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