SEISMIC STUDY OF IRREGULAR BUILDING STRUCTURES: A REVIEW

Shahzad Anwar¹

¹Research Scholar, Department of Civil Engineering, A.M.U. Aligarh, 202002, UP, India.

Abstract - This paper presents an overview of seismic study of regular and irregular building structures. The vast devastation of engineered structures, loss of thousands of lives and the economy of the nation during the past few earthquakes has exposed serious deficiencies in the preferred design and construction practices. The main objective of this work is to study the relative advantage of carrying out performance based designed (PBD) of fixed, and base isolated structures over the usual method of design of the regular and irregular structures. Performance based design (PBD) is a more general design philosophy which aims at achieving multiple performance objectives when the structures are subjected to stated levels of earthquake ground motion. The general purpose of performance based design (PBD) engineering is to produce engineered structures with predictable performance during future earthquakes.

Keywords - Performance Based design, Fixed or Base Isolated Foundation, Seismic Risk Analysis of Structures, Probabilistic risk analysis of structure,

I. INTRODUCTION

The vast devastation of engineered structures, loss of thousands of lives and the economy of the nation during the past few earthquakes has exposed serious deficiencies in the preferred design and construction practices. Earthquakes are one of the most unpredictable and devastating of all natural disasters. Ironically, last several decades also experienced so many earthquakes of magnitude M 6.0 and above occurring in Himalayas, central India, and the peninsular region. These causalities would have been much higher, if these earthquakes had occurred in the neighbourhood of large urban centres like New Delhi city. Recently, in April 2015 Nepal earthquake of magnitude M 7.8 resulted into thousands of casualties, injuries and loss of economy of the country. India also experienced such devastating earthquake in Bhuj, Gujrat January 2001 of magnitude M 7.7 on Richter scale. Only this earthquake in India results more than 15000 death, injured more than 60000 people, destroy nearly 400000 homes and crippling effect on the economy of the region. These devastating consequences could have been avoided, if the structures had been analyses and designed to resist earthquake ground motions. Quoting from the declaration of the United Nations International Decade for Natural Disaster Reduction (UNIDNDR) Yokohama Convention 1994:

“The impact of natural disaster in terms of human and economic losses has risen in recent years, and society in general has become more vulnerable to natural disaster. Those usually most affected by natural and other disaster are the poor and social disadvantaged group in developing countries as they are least equipped to cope with them. Disaster prevention, mitigation, preparedness and relief are four elements which contribute to and gain from the implementation of sustainable development policies. These elements, along with environmental protection of sustainable development, are closely interrelated. Therefore nation should incorporated them in their development plan and ensure efficient follow-up measures at the community, sub-regional, regional, national and international levels”

The fundamental reality is that, we cannot prevent major destructive earthquake from occurring. These shows a continuing threat to lives and property to more than 55% area of this country i.e. India. Therefore, more than half of the area of this country is prone to earthquake.
However, it is possible to avoid the disastrous consequences of an earthquake, if the structures have been designed as per code of practice IS: 1893 (Part 1): 2002 and IS: 13920: 1993.

It has been observed that the principal reasons of failure of structures due to earthquake may accounted to soft stories, floating columns, mass irregularities, poor quality of construction materials and faulty construction practices, inconsistent earthquake response, soil and foundation effect and pounding of adjacent structures [Agarwal & Shrikhande 2010].

Apart from all the weaknesses in the structure, either due to code imperfection or error in the analysis and design, the structural configuration system has played a very important role in catastrophe. The IS: 1893 (Part 1): 2002 has recommended building configuration system in Clause 7.1, to perform well in an earthquake. A building should possess four main attributes, namely simple and regular configuration, and adequate lateral strength, stiffness and ductility. The building configuration has been described as regular or irregular in terms of size and shape of the building, arrangement of structural elements and mass. Regular building configuration are almost symmetrical (in plan and elevation) about the axis and have uniform distribution of the lateral force-resisting structure such that, it provides a continuous load path for both gravity and lateral load. A building that lacks symmetry and has discontinuity in geometry, mass, or load resisting element is called irregular. These irregularities may cause interruption of force flow and stress concentration. Asymmetrical arrangement of mass and stiffness of element may cause a large torsion force (where the centre of mass does not coincide with the centre of gravity).

Clause 7.1 of IS 1893 (Part 1): 2002 enlists the irregularity in building configuration system. As per code these irregularities are categorized in two types. (i) Vertical irregularities referring to sudden change of strength, stiffness irregularity-soft storey, stiffness irregularity-extreme soft storey, mass irregularity, vertical geometrical irregularity, in-plane discontinuity in vertical element resisting lateral force, and discontinuity in capacity-weak storey. (ii) Horizontal irregularities which refer to asymmetrical plan shapes or discontinuities in horizontal resisting element such as cut-out, large opening, re-entrant corner and other abrupt changes resulting in torsion, diaphragm deformation and stress concentration. The past earthquake records show that building having simple regular geometry and uniformly distributed mass and stiffness in plane as well in elevation, suffer much less damage than building with irregular configuration, which shows inadequacy of the seismic design codes based on which these buildings were designed. Therefore, structural configuration, especially irregularity aspect needs to be incorporated in formulating the seismic design methodologies.

Building usually designed as per design based earthquake, but as per IS 1893 (Part 1): 2002, Claus 6.1.3 “The design approach adopted in the code is to ensure that structure possess at least a minimum strength to withstand minor earthquakes, which occur frequently, without damage; resist moderate earthquake without significant structural damage though some non-structural damage may occur; and aims that structures withstand a major earthquake without collapse. But actual forces that appear on structure during earthquakes are much greater than the design forces specified in the code”. It is recognized that neither the complete protection against earthquake of all sizes is economically feasible nor design alone based on lateral strength criteria is justified. The basic approach of earthquake resistant design should be based on lateral strength as well as deformability and ductility capacity of structure with limited damage but no collapse. Thus, the ductility of a structure is in fact one of the most important factor affecting its seismic performance and it has been clearly observed that the well-designed and detailed reinforced structure behave well during earthquake and the gap between the actual and design lateral forces is narrowed down by providing ductility in the structure.

Earthquake resisting power of structure also depends on its foundation; either it may be a fixed foundation or base-isolated type foundation. From the result of the past major earthquake it is found that the earthquake resisting power of base-isolated type foundation much better than the fixed foundation. Base isolation of structure is an effective way of mitigating earthquake forces and has been widely used in practice. Base isolation (BI) is a mechanism that provides earthquake resistant to the building structure. The base isolation system decouple the building from the horizontal ground
motion induced by the earthquake, and offer a very stiff vertical components to the base level of the superstructure in connection to the foundation. It shift the fundamental lateral period, dissipates the energy in damping, and reduced the amount of lateral forces that transfer to the inter-story drift, and the floor acceleration [M.S.S. Ahmed et. al. (2012)]. A base isolation (BI) system reduces the ductility demand on a structures and minimize its deformation. These changes improve the building resistant to earthquake and allow much freedom in the choice of the structural types and its layout [R.I. Skinner et. al. (1975)].

Moreover, the code procedures of seismic design are based on elastic analysis and single degree of freedom system (SDOF) which is unrealistic. Basically the objective of the usual code method of design is to achieving the specified limit states which are specify in the code namely the ultimate limit state and the serviceability limit states. Performance based design (PBD) is a more general design philosophy which aims at achieving multiple performance objectives when the structure is subjected to stated levels of earthquake ground motion. The general purpose of performance based design (PBD) engineering is to produce engineered structures with predictable performance during future earthquakes. Now a days due advancement in research and development of structural analysis and design software, PBD is becoming more popular and efficient tool of design over the usual code methods.

Lots of research has been carried out in the area of base isolation. However, there is no much work done on performance based design (PBD) of base isolated buildings. In some guidelines (FEMA, ATC 40) the concept of base isolation is mentioned as a retrofit mechanism. But until the completion of this work there is no study which applies performance criteria for both isolators and the superstructure at the same time. Therefore, in performance based design (PBD) of base isolated buildings the concepts of PBD will be applied to both superstructure and isolators. In addition to the performance criteria for structural elements given in FEMA guide lines specific performance criteria for isolators shall be developed.

II. PERFORMANCE-BASED SEISMIC DESIGN OF IRREGULAR BUILDINGS

Performance based seismic design (PBSD) has been widely recognized as an ideal method for use in the future practice of seismic design. Several earthquake occurred in developed and developing area of the world, such as in Northridge, California (1994), Kobe, Japan (1995), and Turkey (1999). Performance based seismic design is a new tool and accepted by seismic engineering researchers and designers in many countries. Japan, United States and many other countries have already introduced performance-based design concept and method in the regulation or design code, such as SEAOC Vision 2000 (1995), ATC-40 (1996), FEMA 445 (2006) and new seismic design regulation of Japan. The performance-based seismic design (PBSD) process explicitly evaluates how a building is likely to perform; given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of the actual building response [Li Wei et. al.(2010)]. While the code design provides a pseudo-capacity to resist a prescribed lateral force, this force level is substantially less than that to which a building may be subjected during a postulated major earthquakes. It is assumed that the structure will be able to withstand the major earthquake ground motion by components yielding into the inelastic range, absorbing energy, and acting in a ductile manner as well as by a multitude of other actions and effects. This is the role of PBSD [Freeman et. al. (2004)].

III. ADVANTAGES OF PERFORMANCE BASED SEISMIC DESIGN

PBSD is a systematic methodology for design of structures whose performance under seismic loads is predefined based on needs of the stakeholder. In simple words, it requires that a building be designed to meet specific performance objectives under the action of the frequent or the rarer seismic events that it may experience in its lifetime. So, a building with a lifetime of 50 years may be required to sustain no damages under a frequent, “50% in 50 years” event, e.g., one that has a probability of 50% of being exceeded in the next 50 years. At the same time it should be able to
remain repairable, despite sustaining some damage, during a “10% in 50 years” event and remain stable and life safe for rare events of “2% in 50 years”, although, subsequently, it may have to be demolished.

The advantages of PBSD over the methodologies used in the current seismic design code are summarized as the following six key issues [Saba Bano, T. Naqvi and M. Anwar (2015)];
1. Multi-level seismic hazards are considered with an emphasis on the transparency of performance objectives.
2. Building performance is guaranteed through limited inelastic deformation in addition to strength and ductility.
3. Seismic design is oriented by performance objectives interpreted by engineering parameters as performance criteria.
4. An analytical method through which the structural behaviour, particularly the nonlinear behaviour is rationally obtained.
5. The building will meet the prescribed performance objectives reliably with accepted confidence.
6. The design will ensure the minimum life-cycle cost.

IV. PROBABILISTIC RISK ANALYSIS

There are different forms of the vulnerability analysis of structures. Whatever be the form, the main objective of the analysis is to determine the probability of failure of structures, failure being defined by some criteria. Different forms of vulnerability analysis of structures for seismic forces include analysis for probability of first passage failure, probability of joint or component failure, determination of damage probability matrix and probabilistic risk assessment. The latter is commonly performed by using the Probabilistic Risk Analysis (PRA) procedure. PRA procedure has been widely accepted as a powerful method for the determination of safety of structures against seismic hazard.

Probability of first passage failure deals with the probability of exceedance of a threshold level of stress for any response quantity of interest, for the first time over an interval of time. This is obtained by using the method of crossing analysis of the random vibration theory. Probability of joint or component failure deals with the probability of exceedance of the limit state of the joint or component of the structure for the possible earthquakes in future. Definition of the limit state function is the key element of the analysis. Determination of damage probability matrix of the structure involves the construction of a matrix of the probabilities of different states of failure of the structure for different magnitudes of earthquake. The different states of failure correspond to different degrees of damage caused by the earthquake. PRA procedure has three components namely, (i) development of risk consistent input (ii) fragility analysis of structure, and (iii) seismic risk evaluation of structures.

The fragility analysis refers to the analysis of structures for finding their probabilities of failure for a given level of the peak ground acceleration. Fragility curve is an indicator of risk or vulnerability of the structure associated with certain level of peak ground acceleration during earthquake. Rigorous fragility analysis is highly complex and computationally intensive. The complexity of the analysis involves considerations of soil structure interaction, nonlinear effects in random vibration analysis, determination of correct failure mode and failure criteria etc. As a result, several simplifications are made in the analysis. Since the fragility analysis for the complete structure is difficult to perform, either the main components of the structure or the idealized bare frame model of the structure are analysed. The fragility analysis of secondary systems or components is separately performed.

V. LITERATURE REVIEW

Performance based design of structures

Freeman et al (1975) developed a rapid evaluation method, which can be considered as a forerunner of the today’s “Capacity spectrum method”. Saiidi and Sozen (1981) proposed to perform
non-linear dynamic analyses on an equivalent SDOF system. Peter Fajfar et al (2000) presented a relatively simple nonlinear method for the seismic analysis of structures (the N2 method). It combines the pushover analysis of a multi-degree-of-freedom (MDOF) model with the response spectrum analysis of an equivalent single-degree-of-freedom (SDOF) system.

QiangXue, et al (2003) presented a performance-based seismic design procedure, which is directly associated with pre-quantified performance criteria, by employing a displacement-based approach. Andreas J. Kappos et al (2004) proposed a performance-based design procedure for realistic 3D reinforced concrete (RC) buildings, which involves the use of advanced analytical tools.

Vipul Prakash (2004) gives the prospects for Performance Based Engineering (PBE) in India. He lists the pre-requisites that made the emergence of PBE possible in California, compares the situation in India and discusses the tasks and difficulties for implementing PBE in India. X.-K. Zou et al (2005) present an effective computer-based technique that incorporates pushover analysis together with numerical optimization procedures to automate the pushover drift performance design of reinforced concrete (RC) buildings.

QiangXue, Chia-Wei Wu et al (2007) summarized the development of the seismic design draft code for buildings in Taiwan using performance-based seismic design methodology and case studied following the guidelines in the paper. They presented the design of a reinforced concrete building by using the draft code.

M. S. Ahmed et. al. (2012) presented a base isolation system for buildings, is introduced by decouple the building structure from potentially damaging induced by earthquake motion, preventing the building superstructures from absorbing the earthquake energy. The mechanism of the base isolator increases the natural period of the overall structure, and decreases its acceleration response to earthquake/ seismic motion. R. I. Skinner et al. (1975) studied that base isolation system reduces the variation in severity of attack resulting from differences in character between earthquakes.

Saba Bano, T. Naqvi et al gives the review of performance based design (PBD) of structures and enlist the advantage of performance based seismic design of structures.

Seismic risk analysis of structures

Takeshi (1985) developed risk analysis methodology for buried pipeline systems making use of a conversion factor to estimate the structural strain in the buried pipelines induced by the propagating seismic wave. Mashaly and Datta (1990) developed a procedure for the seismic risk analysis of buried pipelines that provides an estimation of the annual probability of occurrence of different damage states, called damage indices, in a component segment of the general network system of buried pipelines. Gusella (1991) proposed a model to estimate the failure probability of a structure loaded by stochastic discrete process of random events and applied it to analyze seismic vulnerability of the bell-tower of the ‘Chiesa dellaBadia’ of Florence. Costantino et al., (1991) developed a procedure which attempts to assess the risk of damage or failure of small earth dams and embankments when subjected to seismic input motions. The procedure is based on a linear finite element response analysis of the two phase soil-water system which satisfies the Biot equations of motion. Clark et al., (1991) intensified efforts to evaluate earthquake hazards and their potential effects on gas and electric power systems, with the goals of implementing reductions of earthquake vulnerability and increasing post-earthquake reliability. The earthquake lifeline engineering approach applied to the gas pipeline system involves (i) identifying potential locations of high-probability, large-magnitude scenario earthquakes; (ii) developing seismic zonation maps for surface fault rupture, liquefaction potential, and slope-failure potential; (iii) evaluating the condition of the existing gas pipeline system and the consequences of the scenario earthquakes in order to assess and implement mitigations. Yegian et al., (1991) combined the results of seismic hazard and seismic performance analyses to yield the risk of seismic damage or failure of a dam (seismic risk analysis). Further, Yegian et al., (1993) described a methodology for seismic risk analysis of earthen dams. The procedure utilizes seismological and geotechnical inputs together with the associated uncertainties and provides estimates of seismic risk of damage and failure of earth dams. Honegger (1995) studied
the seismic risk assessment for buried pipelines using analytically developed vulnerability relationships.

**Probabilistic risk analysis of structure**

Ravindra (1989) provided an overview of the seismic PRA methodology, described some of the recent PRA applications and discusses the role of structural and geotechnical engineers in the nuclear power plant PRA. Shinozuka et al., (1989) presented an application of a seismic PRA procedure to an apartment building, which also contains an electric substation for the surrounding area by evaluating the seismic hazard on the bed rock, taking the SSI effect into consideration in the fragility analysis, and performing all analyses on the basis of response spectra. Furthermore, the functional safety of the substation as well as the structural safety of the building are analyzed. Takemura et al., (1989) presented a method for seismic fragility evaluation for structure and equipment systems. Matsubara et al., (1993) estimated the failure probability of building based on observed earthquake records by evaluating annual flexural cracking frequency of the base-isolated building using the seismic probabilistic risk analysis (PRA) procedure. Vick et al., (1996) used probabilistic risk analysis (PRA) as a diagnostic and decision making tool in assessing the safety of existing dams. Dubord et al., (1996) proposed probabilistic risk assessment-related methodology to support performance-based regulation within the nuclear power industry by developing risk-to-burden ratios.

**VI. CONCLUSION**

There has been a dramatic rise in earthquake related losses in last few decades. India also experienced several earthquake of major or minor intensity in the last 15 years. In the past 15 years estimated losses were 20 times larger than in the previous 30 years combined losses. A massive earthquake of magnitude (ML = 6.9 on Richter scale, Mb = 7.0, Ms = 7.6, Mw = 7.7) occurred on the morning of 51st Republic Day of India (January 26, 2001, Friday) at 08:46:42.9 hours (Indian standard time) as reported by Indian Meteorological Department (IMD), New Delhi. This earthquake ranks as one of the most destructive events recorded so far in India in terms of death toll, damage of infrastructure and devastation in the last fifty years.

Every earthquake leaves a trail of miseries by the loss of life and destruction, but it also provides lessons to the human society particularly engineers, architects, builders and administration for improving design and planning practices, inadequate analysis, design deficiency and even poor quality of construction.

One of the major contributors to structural damage in structures during strong earthquake is the discontinuities or irregularities in the load path or load transfer. There are lot of example enlisted in the damage report of past earthquake in which the cause of failure of multi-storeyed buildings is irregularities in configuration.

Because of the increased damage due to earthquake forced us to rethink on the existing code i.e. the revision in the existing code. The present code also fails to predict expected damage in quantitative terms. Various studies have been made by various researchers on the seismic performance of irregular buildings. Very few studies are aimed at providing at seismic response of performance based designed (PBD) structures.

Lot of researches are carried out on performance based design (PBD) of buildings and base isolation independently. In FEMA guidelines the concept of base isolation is used as a retrofit mechanism for those structures/buildings failed to satisfy the performance requirements. Hence no performance criteria are set for base isolators in these guidelines. Therefore, with the intention of developing performance criteria for base isolators and study of the overall performance based designed (PBD) procedures for irregular fixed and base isolated buildings has been proposed in the present study. The main objective of this work is to study the relative advantage of carrying out performance based designed (PBD) of fixed, and base isolated structures over the usual method of design of the same structure.
REFERENCES

[1] Freeman, S.A., 1998, Development and use of Capacity Spectrum Method, proceedings of the 6th U.S. National Conference on Earthquake engineering, Seattle, CDROM, EERI, Oakland, CA.

[2] Saiidi, M. and Sozen, M. A., 1981, Simple nonlinear seismic analysis of R/C structures, Journal of Structural Division, ASCE, 107, 937-952.

[3] Peter Fajfar, M. EERI 2000. A Non Linear Analysis Method for Performance Based Seismic Design Vol. 16, No. 3, pages 573-592.

[4] Qiang Xue, et. Al. “The draft code for performance-based seismic design of buildings in Taiwan”, Civil and Hydraulic Engineering Research Center, Sinotech Engineering Consultants Inc., Taiwan, 2 October 2007.

[5] Mashaly, E. A. and Datta, T. K. Seismic risk analysis of buried pipelines, Journal of Transportation Engineering, 1990, 115, n 3, 232-252.

[6] Costantino, C. J. and Gu, Y. T. Seismic risk assessments of small earth dams, Proc 3 US Conf Lifeline Earthquake, 1991, Publ. by ASCE, New York, NY, USA, 704-713.

[7] Clark, J. A., Lee, C. H., Savage, W. U. Seismic/ geological risks as factors in prioritizing gas pipeline system replacement, Proc 3 US Conf Lifeline Earthquake, 1991 publ by ASCE, New York, NY, USA., 206-215.

[8] Yegian, M.K., Marciano, E.A. and Ghahraman, V.G. Seismic risk analysis for earth dams, Journal of Geotechnical Engineering, 1991, 117, n 1, 18-34.

[9] Yegian, M. K. and Ghahraman, V.G. Risk-based methodology for seismic rehabilitation of earth dams, Geotechnical Special Publication, 1993, n 35, Publ by ASCE, New York, NY, USA, 145-158.

[10] Honegger, D.G. Reexamining seismic risk assessment for buried pipelines, Proceedings of the 2nd International Conference on Advances in Underground Pipeline Engineering, 1995, ASCE, New York, NY, USA, 334-344.

[11] Ravindra, M. K. Recent seismic risk studies of nuclear power plants. An overview, Proc ICOSSAR 89 5THIntConfStructSafReliab, 1989. Published by ASCE, New York, NY, USA, 2211-2218.

[12] Shinozuka, M., Mizutani, M., Takeda, M., Kai, Y. Seismic PRA procedure in Japan and its application to a building performance safety estimation. Part 3. Estimation of building and equipment performance safety, Proc ICOSSAR 89 5th IntConfStructSafReliab, 1989. Published by ASCE, New York, NY, USA, 637-644.

[13] Takemura, M., Ishida, H., Amano, A., Mizutani, M. Seismic PRA procedure in Japan and its application to a building performance safety estimation. Part 1. Seismic hazard analysis, Proc ICOSSAR 89 5th IntConfStructSafReliab, 1989, publ by ASCE, New York, NY, USA, 621-628.

[14] Matsubara, M., Takeda, M. and Kai, Y. Estimation of the failure probability of building based on observed earthquake records, Proceedings of the IFIP WG7.5 5th Working Conference on Reliability and Optimization of Structural Systems, 1993, 157-164.

[15] Vick, S. and Stewart G. R.A. Risk analysis in dam safety practice, proceedings of the 1996 Conference on Uncertainty in the Geologic Environment, UNCERTAINTY’ 96. Geotechnical Special Publication, 1996, n 58/1, ASCE, New York, NY, USA, 586-603.

[16] Dubord, R. M., Golay, M.W. and Rasmussen, N.C. Probabilistic risk assessment-related methodology to support performance-based regulation within the nuclear power industry Nuclear Technology, 1996, 114, n2, 169-178.

[17] M. S. Ahmed et. al. Building with base isolation techniques presented in A1 – Azhar Engineering 12th International Conference, Cairo, Egypt, C 12 2012.

[18] R. I. Skinner et. al. Base isolation for increased earthquake resistant of building published in Bulletin of the New Zealand society for earthquake engineering, Vol. 8, No. 2, June 1975.

[19] P. Agarwal, M. Shrikhande, 'Earthquake resistant Design of Structures', PHI Learning Private Limited, New Delhi, 2010.

[20] Saba Bano, T. Naqvi and M.Anwar 2015, ‘Performance based design of structures-a review’, International journal of modern trends in engineering and research, ISSN (online): 2349-9745.