STATE OF ART IN THE DEVELOPMENT OF RESPONSE REDUCTION FACTOR (R) IN SEISMIC DESIGN

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Abstract

Earthquake being one of the unpredictable natural disaster has caused extensive collapse of elevated buildings with large scale unrecoverable damages such as risk of life, occupancy and economy to the nations. Absence of earthquake resistance structures and non-implementation of seismic practices are found as the root cause behind the above damages. Designing and constructing an earthquake resistant reliable structure is the need of the time which will protect it against all natural disasters. Response reduction factor (R) is one of the most vital parameter in designing of such buildings. This study focuses on comparison of seismic provisions of different countries around the world in order to highlight the variations in response reduction factor in seismic designs dealing with steel lateral load resisting systems. In this review paper, an attempt has been made to survey the past papers associated in the field of evaluation of response reduction factor. Observations reveals that the 'R' values intended to conform for reserve strength, ductility and redundancy. Several researchers have proved that value of 'R' is affected by many parameters like building height, number of bays in building, irregularity (both vertical and horizontal) of structure, seismic region of structure, number of bracings etc. As this 'R' factor for inelastic state of system is merely based on professional judgement, numerical study and very little experimental test on small scaled models of lateral load resisting systems, a further attention is required to overcome these unreliable facts for safe and economic design.

Keywords— Response modification factor, Seismic design, design codes

1. Introduction

Earthquake is one of the most destructive natural hazard for the structures and results into huge economic and human losses. As it is an unavoidable and unpredictable event, modern analytical and design approaches are proposed not only to minimize the damage but to withstand such strong earthquakes. Researches also include anti-seismic devices to be installed in new as well as old buildings to be retrofitted. These devices target to dissipate seismic energy through their plastic deformations leaving structural elements intact. Plastic deformations easily dissipate energy and provide 'ductility' to the structural element than strength. These devices includes base isolation, dampers, fuses, shear link, bracings etc. Braced frames are analytical simple and cheaper to construct. It easily resists lateral loads caused by wind and seismicity

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simultaneously confirming tolerable ductility.

The conventional seismic design codes of practice are force-based and are applicable for actions that are permanently applied with the fact that inelastic deformations may be used to absorb certain level of seismic energy. This fact has resulted in reduction of seismic forces by a single reduction factor, to attain the design force level, which is no doubt a traditional design method but is still used extensively. This is because though displacement based design focusses on deformation- the major cause of failure, but the target displacement is to be thoroughly studied and is then to be allotted for structural analysis by the designer. Although, the displacement based strategy is observed to be more reliable but its actual impact on seismic design practice is yet an ongoing research and requires advanced computational tools to compute and control the deformations within the structure. It must be understood that the force based design is applicable for both elastic as well as inelastic behaviour of the structure but the design strategy must be to make the structure withstand lateral loads as well as gravity loads in high seismic region. As the chances of earthquake occurrence are rare, to design an earthquake resistant structure with linear elastic response, consequently results to be too costly. Hence the theory of equal energy is used to reduce the design force from elastic base shear (V_e) to design base shear (V_d) as seen in figure 1.

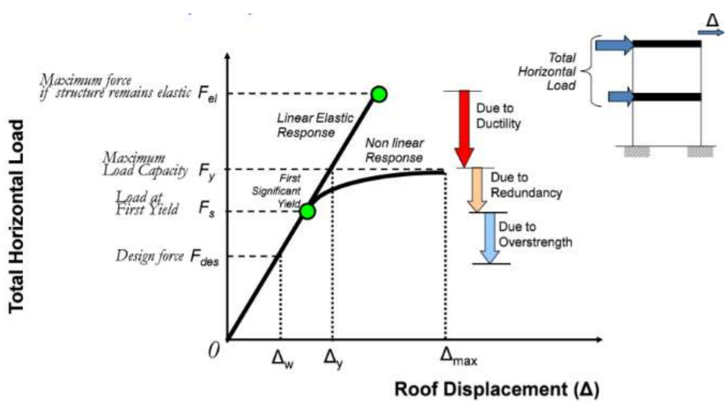

Figure 1. Force- displacement response of elastic and inelastic system [Courtesy: JK Lodi]

The philosophy of reduction in forces in force based design, has led to development of force-reduction factor which is unique and different for different type of structures and materials used. This kind of force reduction factor is known as Response reduction factor (R) This 'R' reflects the ability of structure to dissipate energy through inelastic actions. As it is understood that earthquake resistant structures are designed for considerably low seismic forces than actual seismic force acting on them, based on factor 'R'. This factor, thus mainly depends on sub factors such as ductility, redundancy and overstrength of the system. From the fig.1 if a structure has good ductility (red arrow), good overstrength (blue arrow) and good redundancy (orange arrow, usually having 1 value), then the structure will obviously be designed for lower seismic force and will have higher value of 'R' as 'R' factor being product of these sub factors. For example, 'R' value defined in IS 1893:2016 for steel building with special moment resisting frame (SMRF) is 5 (having good ductility) as compared to unreinforced masonry without horizontal RC seismic bands having R as 1.5 (having poor ductility). This, one of the vital parameter in seismic design have limitation such as it does not account for performance objective and lack of validation for evaluating this factor as its just established based on only professional judgement and no scientific reasoning. In this paper, a comprehensive review is provided on importance of 'R' for various steel braced frame, hybrid/dual frame system and its various ways of calculations, to account non-linear behaviour with respect to different design standards.

2. Experimental/ analytical research for evaluating Response reduction factor 'R'

According to codal provision, the structure is designed for earthquake force much lesser than that expected under strong earthquakes, if the structure were to remain linearly elastic. In force-based seismic design procedures, behaviour / response reduction factor is a force reduction factor applied to modify linear elastic spectra to obtain the nonlinear response spectra. Almost for all country's design code, response reduction values are applicable for specified building system which are not only limited in variety but also does not stand true for any change in geometrical parameter. Hence, excessive research is carried out on formulation of R factor suitable for respective country and building system therein, based on seismic performance of structure. A brief review of research for R factor by different author is taken and noted below.

A. Nadeem Hussain and M. Shahria Alam (2016) [1] In their paper they have selected 4 high rise regular steel buildings in the range of 8 to 20 stories. These building have been seismically designed as per IBC (ICC 2012) and ASCE 7-10 (2010) in order to verify seismic response modification factor. The seismic response factor (R) used in this study was suggested by Mwafy and Elnashai (2002)[2] which was as follows:

$$R = R_{ideal} \,.\, \Omega_y = [(S_a)_c/(S_a)_y].\, \Omega_y$$

where, R_{ideal} is the response modification factor for an ideal structure that is dependent on ground motions, $(S_a)_c$ is the spectral acceleration at collapse earthquake, $(S_a)_y$ is the spectral acceleration at first significant yield and Ω_y is the first yield over strength defined as the ratio of first significant yield strength to the design strength.

$$\Omega_y = \frac{Yield\ strength}{Design\ strength}.$$

Safety margins of these factors are found by performing Incremental Pushover Analysis (IPAs) and Incremental Dynamic Analysis (IDAs) which indicated rise in design response factors. These buildings were revaluated after increasing value of response factor, a proposal for seismic design factor was made along with cost comparison between code based, and proposed method of building design.

B. Mussa Mahmoudi and Mahdi Zaree (2013) [3] evaluated the overstrength factor, reduction due to ductility factor and response modification factor considering life safety structural performance levels for 20 storey Buckling resistant braced frames based on Iranian National building code. Pushover analysis was performed to evaluate above parameters. Testing models consisted of single and double bracing bays, variation in stories, different BRBFs and a conventional braced frame. After analysis authors found that variation in number of bracing bays and height of building had a great impact on response modification factor.

C. Amin Alavi, etal. (2017) [4] has highlighted the use of FUSEIS bolted splices as an innovative dissipation device. Apart from the standard building frame system described in EC8, author have tried to investigate the behaviour of 'regular' building frames associated with above dissipative element on a SDOF system and have proposed formulation of behaviour factor for this system. The proposed behaviour factor (force-reduction factor) was stated to be the product of overstrength, ductility factor and redundancy factor. On performing nonlinear static analysis on modelled structure, comparison was made with conventional frame and resulted that plastic deformations in dissipative structure were primarily concentrated in beam splices keeping other main elements of structure in elastic region along with safety.

D. Cheol- kyu Kang and Byong- Jeong Choi (2011) [5] performed nonlinear dynamic or time history analysis and their work based on precedent studies on evaluation of response modification factor. Author says that it is a complex, time consuming and involves lot of efforts. Authors suggested simple but effective rules for evaluation of response modification factor (R) for steel moment resisting frames by performing nonlinear static analysis (Pushover analysis) instead of complex nonlinear dynamic analysis. About 108 existing steel MRFs with MRFs distributed along (a) perimeter and (b) interior of building frame were evaluated. On comparing the response modification factor for above frames, for Non Linear Dynamic Analysis (NLDA) and Non Linear Static Analysis (NLSA), it was concluded that proposed NLSA is a simplified method to evaluate R and can be applicable for new as well as existing structure.

E. Apurba Mondal et al., (2013) [6] in their study stated that most seismic design codes today include the nonlinear response of a structure implicitly through a 'response reduction/modification factor' (R). This factor allows a designer to use a linear elastic force-based design while accounting for nonlinear behaviour and deformation limits. This research focuses on estimating the actual values of this factor for realistic RC moment frame buildings designed and detailed following the Indian standards for seismic and RC designs and for ductile detailing, and comparing these values with the value suggested in the design code. The primary emphases are in a component-wise computation of R, the consideration of performance-based limits at both member and structure levels, a detailed modelling of the RC section behaviour, and the effects of various analysis and design considerations on R. Values of R are obtained for four realistic designs at two performance levels. The results show that the Indian standard recommends a higher than actual value of R, which is potentially dangerous.

F. Hemchandra Chaulagain et al., (2014) [7] stated in their study that most current seismic design includes the nonlinear response of a structure through a response reduction factor (R). This allows the designer to use a linear elastic force-based approach while accounting for nonlinear behaviour and deformation limits. In fact, the response reduction factor is used in modern seismic codes to scale down the elastic response of a structure. This study focuses on estimating the actual 'R' value for engineered design/construction of reinforced concrete (RC) buildings in Kathmandu valley. The ductility and overstrength of representative RC buildings in Kathmandu are investigated. Nonlinear pushover analysis was performed on structural models in order to evaluate the seismic performance of buildings. Twelve representative engineered irregular buildings with a variety of characteristics located in the Kathmandu valley were selected and studied. Furthermore, the effects of overstrength on the ductility factor, beam column capacity ratio on the building ductility, and load path on the response reduction factor, are examined. Finally, the results are further analyzed and compared with different structural parameters of the buildings.

G. Y. Y. Lin and K. C. Chang (2003) [8] discussed the rationality of the design force and damping reduction factors adopted by a few seismic design provisions for buildings with and without added passive energy dissipation systems. The issue will first be pointed out that the damping reduction factors adopted by those provisions are derived from the effects of viscous damping on displacement responses, but are used to reduce the design force of buildings. Statistical results from 1053 ground motions recorded in the U.S. show that it may lead to unconservative results, especially for systems with damping ratios greater than 10% and periods longer than 0.15 s. Furthermore, although there is no doubt that the additions of extra damping to a structure will always reduce the displacement responses, many documents argue the effect of added damping to reduce the force responses of the buildings. Therefore, this paper also addresses the effects of viscous damping on the inertial force and elastic restoring force in order to use the damping reduction factors correctly. Results of this study suggest that if the damping of structures comes from the hysteretic response of the building, the design force of the structures should be the inertial force and the damping reduction factors should be derived from the acceleration responses. Otherwise, if the additional damping of structures comes from the added energy dissipation devices, the design force should be the restoring force and the damping reduction factors should be derived from the displacement responses.

H. H. Moghaddam and R. Karami Mohammadi (2001) [9] in their paper presented the results of recent studies on inelastic seismic response of MDOF shear-building structures. In the last few decades, the concept of response modification factor R has been introduced and developed to account for inelastic nonlinear behaviour of structures under earthquakes. In this paper, an attempt has been made to adjust and extend this concept through introducing a modifying factor R_T. This factor is used for dynamic analysis of MDOF structures, including the calculation of inelastic response spectra. Sensitivity analysis was carried out to identify the parameters that have influence on R_T. It has been demonstrated that R_T is predominantly a function of number of stories, and accordingly a relationship has been suggested. Finally, an approximate approach has been developed for evaluating the seismic strength and ductility demands of MDOF structures.

I. Nelson Lam, et al., (1998) [10] presented new trends in the relationship between the ductility reduction factor and the ductility demand in the seismic design of buildings. A total of 4860 inelastic time-history analyses were carried out to study this relationship using 60 single-degree-of-freedom models excited by an ensemble of 81 earthquake accelerogram records from around the world. The asymmetrical distribution of the results highlighted the inaccuracies associated with assuming a normal distribution simply described by the mean and standard deviation to represent the data. A probability of exceedence approach has been used based on counting the number of occurrences the ductility demand exceeds a specified level. The ductility reduction factors developed in this study are consistent with other studies in the long-period range but are different in the short-period range. The ductility reduction factor for very short period buildings of limited ductility has been found to be greater than previously predicted.

J. Chang-Hai Zhai, et al., (2015) [11] investigated the strength reduction factor of single degree of freedom system with constant ductility performance subjected to the mainshock–aftershock sequence-type ground motions. The recorded and artificial sequence-type ground motions are used. The aftershock ground motions in sequence are scaled to have different relative intensity levels. Four hysteretic models are used to simulate the different type of structures. The effects of period, ductility factor, site condition, aftershock, hysteretic behaviour and damping are studied statistically. The results indicate that the strong aftershock ground motion has more obvious influences on strength reduction factors in short period region than on those in long period region. The degrading behaviour would decrease the strength reduction factor of structure with short period at a magnitude of <20 %, while it would increase that of structure with medium-long period at a maximum level of 20 %. Finally, a predictive model, incorporating the effect of aftershock, is proposed to determine the strength reduction factor in the seismic design.

K. Mitsumasa Midorikawa, et al., (2002) [12] developed the rocking structural systems that can reduce earthquake responses of buildings by causing rocking vibration. This paper aims to examine the effects of the rocking system. To cause rocking vibration under appropriate control, weak base plates are attached at the bottom of each steel column at the first story. When the weak base plates yield during a strong earthquake, the building causes rocking vibration. In this paper, the earthquake responses of this rocking system (the base plate yielding system) are examined comparing with those of the simple rocking system and the fixed-base system by nonlinear time history analyses. The results are summarized as follows: 1) Story shear forces of the base plate yielding systems are reduced as much as those of the simple rocking system. The roof displacements and axial forces are less than those of the simple rocking system are. 2) The roof displacements and axial forces of the base plate yielding systems are almost similar to those of the fixed-base system under a certain input level. It is concluded that the rocking system with weak base plates can reduce earthquake responses of buildings.

L. A. S. Elnashai and A. M. Mwafy (2002) [13] addressed the issue of horizontal overstrength in modern code-designed reinforced-concrete (RC) buildings. The relationship between the lateral capacity, the design force reduction factor, the ductility level and the overstrength factor are investigated. The lateral capacity and the overstrength factor are estimated by means of inelastic static pushover as well as time-history collapse analysis for 12 buildings of various characteristics representing a wide range of contemporary RC buildings. The importance of employing the elongated periods of structures to obtain the design forces is emphasized. Predicting this period from free vibration analysis by employing 'effective' flexural stiffnesses is investigated. A direct relationship between the force reduction factor used in design and the lateral capacity of structures is confirmed in this study. Moreover, conservative overstrength of medium and low period RC buildings designed according to Eurocode 8 is proposed. Finally, the implication of the force reduction factor on the commonly utilized overstrength definition is highlighted. Advantages of using an additional measure of response alongside the overstrength factor are emphasized. This is the ratio between the overstrength factor and the force reduction factor and is termed the inherent overstrength (Ω i). The suggested measure provides more meaningful results of reserve strength and structural response than overstrength and force reduction factors.

M. Behnoud Ganjavi and Hong Hao (2014) [14] in their study stated that in most of the seismic design provision, the concept of strength reduction factor has been developed to account for inelastic behavior of structures under seismic excitations. Most recent studies considered soil–structure interaction (SSI) in inelastic response analysis are mainly based on idealized structural models of single degree-of-freedom (SDOF) systems. However, an SDOF system might not be able to well capture the SSI and structural response characteristics of real multiple degrees-of-freedom (MDOF) systems. In this paper, through a comprehensive parametric study of 21600 MDOF and its equivalent SDOF (E-SDOF) systems subjected to an ensemble of 30 earthquake ground motions recorded on alluvium and soft soils, effects of SSI on strength reduction factor of MDOF systems have been intensively investigated. It is concluded that generally, SSI reduces the strength reduction factor of both MDOF and more intensively SDOF systems. However, depending on the number of stories, soil flexibility, aspect ratio and inelastic range of vibration, the strength reduction factor of MDOF systems could be significantly different from that of E-SDOF systems. A new simplified equation, which is a function of fixed-base fundamental period, ductility ratio, the number of stories, structure slenderness ratio and dimensionless frequency, is proposed to estimate strength reduction factors for MDOF soil–structure systems.

N. Veneziano, Daniele, and Andreas Langousis (2005) [15] stated in their study that the areal reduction factor (ARF) is a key quantity in the design against hydrologic extremes. For a basin of area a and a duration d, ?(a, d, T) is the ratio between the average rainfall intensity in a and d with return period T and the average rainfall intensity at a point for the same d and T. Empirical ARF charts often display scaling behavior. For example, for large (equation image/d) ratios and given T the ARF tends to behave like (equation image/d)-a for some a. Here we obtain scaling properties of the ARF under the condition that space-time rainfall has multifractal scale invariance. The scaling exponents of the ARF are related in a simple way to the multifractal properties of the parent rainfall process. We consider regular and highly elongated basins, quantify the effect of rainfall advection, and investigate the bias from estimating the ARF using sparse rain gauge networks. We also study the effects of departure of rainfall from exact multifractality. The results explain many features of empirical ARF charts, while suggesting dependencies on advection, basin shape, and return period that are difficult to quantify empirically. The theoretical scaling relations may be used to extrapolate the ARF beyond the empirical range of a, d, and T.

O. Changhai & Lili (2006) [16] In this paper the provisions on the strength reduction factors in US seismic code (UBC1997), Eurcode 8, Japanese Building Standard Law, Mexico seismic code, Canada seismic code and Chinese seismic codes are summarized and some important remarks on the application of strength reduction factors in seismic codes are presented. At the end, the existing problems in the field are pointed, and the trends of future study are discussed.

P. Mulchandani and Mittal (2017) [17] In the present study five different bridge design codes are considered and table is prepared comparing the response reduction factor values for various components of the bridges and its shown how much conservative or non-conservative values are followed in the Indian codes and aspects in which Indian codes are needed to be updated is also indicated in the paper.

Q. Lakhade et al., (2017) [18] The study on appropriateness of response reduction factor for reinforced concrete tank staging is sparse in literature. In this paper a systematic study on estimation of key components of response reduction factors was presented. By considering the various combinations of tank capacity, height of staging, seismic design level and design response reduction factors, forty-eight analytical models are developed and designed using relevant Indian codes.

R. Gautam K. & Gupta (2020) [19] This study reviewed the recent developments in finding the response reduction factor for RC framed building and the influence of soil-structure interaction (SSI) effects in the various responses of the building. For Response Reduction Factor, the nonlinear analysis was done in order to capture all the hysteretic Energy beyond the elastic limit. Various approaches to pushover analysis and time history analysis have been mentioned in this review paper.

S. Katsanos et al., (2010) [20] This paper reviews alternative selection procedures based on established methods for incorporating strong ground motion records within the framework of seismic design of structures. Given the fact that time history signals recorded at a given site constitute a random process which is practically impossible to reproduce, considerable effort has been expended in recent years on processing actual records so as to become ‘representative’ of future input histories to existing as well as planned construction in earthquake-prone regions.

T. Thiers-Moggia & Málaga-Chuquitaype (2021) [21] This paper assesses the seismic response of post-tensioned timber rocking walls combined with inerters as a means to control the rotation amplitude and suppress higher-mode effects on the system.

U. Uang & Bruneau (2018) [22] The work presented here is intended to provide the reader with an appreciation of why the current seismic design requirements for steel structures are as framed, highlighting in the process several unresolved issues and inconsistencies that will require attention in future research. Implications of the Christchurch, New Zealand, rebuilding after the 2010–2011 earthquakes there for future U.S. seismic code development are also presented.

V. Tannert et al., (2021) [23] This article reflects the state-of-the-art on seismic design of CLT buildings including both, the global perspective and regional differences comparing the seismic design practice in Europe, Canada, the United States, New Zealand, Japan, China, and Chile.

W. Gkimprixis et al., (2019) [24] This results in uncontrolled values of the failure probability, which vary with the structure and the location. Risk targeting has recently emerged as a tool for overcoming these limitations, allowing achievement of consistent performance levels for structures with different properties through the definition of uniform-risk design maps.

X. Gidaris et al., (2017) [25] This paper provides a comprehensive review of state-of-the-art fragility and restoration models for typical highway bridge classes that are applicable for implementation in multihazard risk and resilience analyses of regional portfolios or transportation networks in the United States. An overview of key gaps in the literature is also presented to guide future research.

Y. Asteris et al., (2011) [26] In this paper, the advantages and disadvantages of each macromodel are pointed out, and practical recommendations for the implementation of the different models are indicated.

Z. Rao & Gupta (2016) [27] In this paper, the effect of building height and seismic zones on overstrength and ductility factors of steel frames were investigated. It has been seen that overstrength and ductility factors varies with number of storys and seismic zones. It is also observed that for different seismic zones and for different building heights, ductility reduction factor is found to be different from overall structural ductility. The overstrength factor decreases as the number of story increased. These observations are very much significant for building seismic provision codes, which at present not taking into consideration the variation of response reduction factor (R).

AA. Deoda et al., (2019) [28] The obtained results show that the performance of precast structure gets enhanced with the reduced value of R considered for design and analysis. Moreover, it is interesting to note that for the precast structure with soil–foundation system the failure pattern follows a more realistic seismic design philosophy as compared to monolithic structure with soil–foundation system.

BB. Panchal & Panchal (2020) [29] The results show that the value of R drastically changes with different earthquake zones, which is not specified in Indian standards. Other significant conclusions are also provided in this study.

CC. Siddiqui & Azeem (2020) [30] It was observed that the response reduction factor decreases when the height of the models increases and considering the effect of irregularity in the frame the response reduction factor increases. All the models buildings are analysed and compared for the outcomes such as maximum storey drifts, storey displacements, time periods and modes of frequencies and the conclusions are presented at the end of the paper.

DD. Soni et al., (2021) [31] The main objective of the present work is to verify the value recommended for the dual system using Non-linear Static Pushover Analysis and compare the obtained R value with code specified value.

EE. Sharifi & Toopchi-Nezhad (2018) [32] The main objective of this research study is to evaluate the response modification factor, R, of moment-resisting RC-frame structures that are designed based on a limit state design methodology. The study is focused on the ordinary and special RC-frames of 1, 2, and 3 bays at 3, 5, 7, and 9 stories. To evaluate the R-factor of each frame structure, a nonlinear static pushover analysis is performed and the capacity curve of structure until a maximum lateral displacement that is typically prescribed by seismic design codes is plotted.

FF. Coccia et al., (2017) [33] In the paper two local collapse mechanisms are considered, the two sided and the one sided rocking. The influence of considering a simplified trilinear moment-rotation law is also discussed. For each mechanism, the force-reduction factor, defined as the ratio between the seismic acceleration value causing the collapse of the masonry element and the one corresponding to the activation of the rocking motion, is evaluated.

GG. Shrestha (2020) [34] This study focuses on evaluating the response reduction factor for masonry buildings with different mechanical properties, which are used in modern codes to scale down the elastic response of the structure. Using a similar frame-approach, a nonlinear static pushover analysis is carried out on the analytical models of masonry building in finite element analysis software SAP 2000v 20.0.0.

HH. Lande & Wankhade (2018) [35] this study proposed the response reduction factors for reinforced concrete structures equipped with viscous damper devices and investigated the effect of implementing such devices in reinforced concrete structures on the response reduction factor. Response reduction factor was formulated based on three aspects, namely, overstrength, redundancy, and ductility factors.

II. Mitchell et al., (2010) [36] The purpose of this paper is to provide a summary of the evolution of seismic design in Canada. This paper presents the significant changes to the approach taken in determining seismic hazards and seismic hazard maps, and describes the evolution of the seismic design provisions of the

JJ. National building code of Canada.

KK. Zameeruddin & Sangle (2016) [37] This study reviewed recent developments in performance-based seismic design by defining the performance objectives (levels), evaluation techniques, and assessment procedures. In addition, the current state-of-practice in performance-based seismic evaluations were compared. In contrast to the performance evaluation procedures of previous studies, in which the pros and cons were highlighted, the performance evaluation procedure of the present study was implemented for force-based design structures.

LL. Kappos & Stefanidou (2010) [38] The proposed method was applied to irregular multistorey R/C 3D frame buildings with setbacks, and their performance for several levels of earthquake action was assessed using a fully inelastic model and additional ground motions not used at the design phase. The same buildings were designed according to the provisions of Eurocode 8. Comparison of the two methods of seismic design, revealed the advantages of the proposed design method, in particular the more economic detailing of transverse reinforcement in the members that develop very little inelastic behaviour even for very strong earthquakes.

MM. Castillo, T., & Ruiz (2014) [39] Conducted a study on a simple mathematical expression is proposed to estimate spectra reduction damping factors for seismic design of systems with viscous dampers. The expression is obtained from the ratios between ordinates of uniform hazard spectra associated with two different return intervals (50 and 125 years), corresponding to sites with different types of soil within the Valley of Mexico.

NN. Priestley et al., (2007) [40] Explained that the concept of designing structures to achieve a specified performance limit state defined by strain or drift limits was first introduced, in New Zealand, in 1993. Over the following years, and in particular the past five years, an intense coordinated research effort has been underway in Europe and the USA to develop the concept to the stage where it is a viable and logical alternative to current force-based code approaches. Different structural systems including frames, cantilever and coupled walls, dual systems, bridges, wharves, timber structures and seismically isolated structures have been considered in a series of coordinated research programs.

OO. Sullivan et al., (2013) [41] The results of non-linear time-history analyses of a series of single degree of freedom supporting structures indicate that the new methodology is very promising. Future research will aim to extend the methodology to multi-degree of freedom supporting structures and run additional verification studies.

PP. Varela et al., (2006) [42] This paper addresses the development and application of a rational procedure to select the seismic force reduction factor (R) and the displacement amplification factor (C_d) for the design of autoclaved aerated concrete (AAC) structures. The values of R and (C_d) are proposed based on a combination of laboratory test results and numerical simulation. The test results were obtained from 14 AAC shear-wall specimens tested under simulated gravity and quasistatic reversed cyclic lateral loads.

QQ. Shamim & Rogers (2015) [43] Explained that Seismic design provisions for steel-sheathed cold-formed steel framed shear walls, specific to Canada, are not provided in the existing AISI S213 Standard “North American Standard for Cold Formed Steel Framing – Lateral Design”. A multi-phase approach was adopted in order to develop appropriate seismic design provisions for inclusion in the new AISI S400 Standard “North American Standard for Seismic Design of Cold-Formed Steel Structural Systems”.

RR. Palermo et al., (2018) [44] In the present work a direct procedure for the preliminary seismic design of building structures with added dampers is described which represents the simplification of the so-called “five-step procedure” originally developed in 2010 by some of the authors. The procedure is applicable to yielding frame structures with a generic along-the-height distribution of inter-storey viscous dampers. It is aimed at guiding the structural engineer through the sizing of both viscous dampers and structural elements making use of an equivalent static analysis approach.

SS. Mohsenian & Mortezaei (2018) [45] the present study has been conducted to improve the current understanding about failure mechanism in the structural systems equipped with vertical links. For this purpose, following definition of demand and capacity response reduction factors, these parameters are computed for three different buildings (4, 8 and 12 stories) equipped with this system.

In this regards, pushover and incremental dynamic analysis have been employed, and seismic reliability as well as multi-level response reduction factor according to the seismic demand and capacity of the frames have been derived. Based on the results, this system demonstrates high ductility and seismic energy dissipation capacity, and using the response reduction factor as high as 8 also provides acceptable reliability for the frame in the moderate and high earthquake intensities.

TT. Pei et al., (2012) [46] In the present study described in this paper, the 10-story CLT building was designed with 80% non-exceedance probability of remaining below 4% inter-story drift when subjected to a maximum credible earthquake intensity level (2500 year return period) for the City of Los Angeles, California. The DDD of the building was refined and verified with nonlinear time history simulation using a suite of bi-axial ground motions scaled to the predefined hazard levels. Based on the performance-based design results and laboratory testing of individual CLT shear walls, a response modification factor (R-factor) is proposed for structures with CLT wall components according to current force-based design approach (i.e. ASCE 7), thus providing quantitative insight into CLT design using traditional design procedures in North America .

UU. Priestley & Grant (2005) [47] The attitude of the paper is deliberately iconoclastic, tilting at targets it is hoped will not be seen as windmills. It is suggested that our current emphasis on strength-based design and ductility leads us in directions that are not always rational. A pure displacement-based design approach is advanced as a viable alternative. Improvements resulting from increased sophistication of analyses are seen to be largely illusory. Energy absorption is shown to be a mixed blessing. Finally, accepted practices for flexural design, shear design, development of reinforcement, and the philosophic basis of capacity design are questioned.

VV. Lu et al., (2018) [48] In this paper, a practical displacement-based framework is presented for seismic design of flexible-base structures in near-fault regions. Particular attention is given to pulse-like motions that may cause significant damage to building structures. The proposed design methodology utilises displacement response spectra constructed using a new procedure, which takes into account the effect of pulse period. An equivalent fixed-base single-degree-of-freedom oscillator is adopted to capture the salient features of an actual soil-structure interaction (SSI) system in order to facilitate the design process.

WW. Pian et al., (2020) [49] Conducted a study on a performance-based seismic design method for plane reinforced concrete (R/C) moment-resisting frames (MRF) is proposed. This method is based on a hybrid force/displacement (HFD) seismic design scheme, which has been successfully applied to the seismic design of steel structures and is extended in this paper to plane RC-MRFs. The proposed HFD method combines the familiar to engineers force-based design (FBD) method, used in all seismic design codes, with the displacement-based design (DBD) method, which efficiently controls the deformation and hence the damage in a performance-based design (PBD) framework.

XX. Merino et al., (2020) [50] In this study observed that one of the existing methodologies is generally unable to predict consistent absolute acceleration and relative displacement floor response spectra. An improved procedure is developed for estimating consistent floor response spectra for building structures subjected to low and medium-high seismic intensities. This new procedure improves the predictions of a relative displacement floor response spectrum by constraining its ordinates at long non structural periods to the expected peak absolute displacement of the floor.

YY. AlHamaydeh et al., (2011) [51] This study investigates the seismic design factors for three reinforced concrete (RC) framed buildings with 4, 16 and 32-stories in Dubai, UAE utilizing nonlinear analysis. The buildings are designed according to the response spectrum procedure defined in the 2009 International Building Code (IBC'09). Two ensembles of ground motion records with 10% and 2% probability of exceedance in 50 years (10/50 and 2/50, respectively) are used.

3. Response reduction factor (R) in various design standards

The Response reduction factor (R) represents the structure's ductility, damping and past seismic performance of structure with various framing system. This factor plays a vital role in seismic design calculation/ process of Base shear and ultimately on seismic performance of building. In reality, the necessity of incorporating R factor in base shear formula is to consider structure's inelastic characteristics in linear analysis method so as to provide an economical and desirable seismic resistant structure. For inelastic behaviour of structure, R contributes to reduction in seismic design force. This reduction depends on two major factors (1) **Ductility reduction factor** which lowers the elastic demand force to the level of maximum yield strength of structure and (2) **Overstrength factor** which is due to overstrength introduced in code based on design of structure. Thus R factor is usually the product of above two factors (refer figure 2)

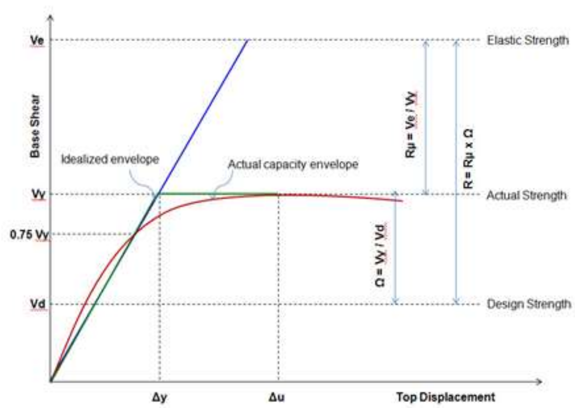

Figure 2. Relationship between force reduction factor (R), structural overstrength (Ω), and ductility reduction factor (Rμ)[58]

Further, there are generally four methods to obtain 'R' factor viz Ductility factor theory approach, Extrapolation of inelastic dynamic response analysis of Single Degree of Freedom (SDOF) system, Energy approach and Damage accumulations method [4].

A brief overview of response reduction factor in various seismic codes is presented in following paragraphs:

- *Seismic design requirements as per American Society of Civil Engineers [ASCE 7]* [55]

Almost every seismic analysis procedure for base shear calculation of ASCE 7 consists of a Response reduction factor (R). The basic vertical and horizontal seismic force-resisting system shall adapt to one of the types prescribed in the Table of ASCE 7 (in Cl. 9.5.2.2). The selected structural system shall conform to the seismic design category and height limitations as indicated in Table 3. With reference to R values from table, it must me noted that R value reduces forces to a strength level, and not an allowable stress level. Table 3 displays R, $\mathbf{\Omega_0}$ and C_d values of ASCE7 in respect of steel braced framed (the actual table consists of more than 80 seismic force resisting system).
Table 12.14-1 of ASCE 7-2016 indicates the variation of response modification coefficient for various structures and ranges from 3.5 to 8 for ductile structures. This code also does not clearly specify details about dual frame systems resisting lateral seismic loads but has mention alternate lateral load resisting system, which comprises of combination of framing systems in horizontal and vertical direction. When various LLRS are used in each of the two orthogonal directions of building it is said to be horizontal combination and the 'R' value to be used for this combination system should not be greater than the least value of 'R' in any other systems used in same direction. When various LLRs are used different stories it is said to be vertical combination and here the 'R' value of combined system in considered direction should not be greater than the least value of any other system in the same direction.

- *International Standardization Organization [ISO 3010]* [56]

ISO is a worldwide alliance for national standards bodies. The 'R' factor in ISO 3010 is structural factor (k_D) and it is used to reduce design seismic forces and shear forces, considering the ductility, acceptable deformation, restoring the characteristics of forces and overstrength (or overcapacity) of the structure. The factor k_D can be divided into two sub factors, namely $k_{D\mu}$ and k_{Ds} and expressed as the product of them, where $k_{D\mu}$ is related to ductility, acceptable deformation and restoring force characteristics, whereas k_{Ds} is related to overstrength. This factor k_D is applicable in formulation of design lateral force for Ultimate Limit State and not for Serviceability Limit State. Recent studies specifies that $k_{D\mu}$ also depends on the structure's natural period of vibration and for the structures with shorter natural period, the possible reduction in strength remains marginal. k_{Ds} is a function of the difference between the actual strength and calculated strength and it varies according to the method of strength calculation. Computation of these factors is a matter of debate, and one standard term k_D has been adopted in most of the design codes. The structural factor k_D ranges as,
1/5 to 1/3 for systems with excellent ductility,
1/3 to 1/2 for systems with medium ductility,
1/2 to 1 for systems with poor ductility.
These values of k_D are under continuing investigation and may take other values in some

circumstances. [6, 52]

- *Eurocode [EC8]* [57]

In EC8, R factor is signified as **behaviour factor (q).** In design it helps to reduce the forces found from a linear analysis. So, to consider the non-linear response of a structure, allied with the material, the structural system and the design procedures, 'q' is period independent and are therefore inverse scaling factors of the site response spectra. It is given as $q= q_0. k_d. k_r. k_w.$ with basic behaviour factor, q_0 , (ranging from 2.5 to 5) and three modification factors associated with the ductility class, kd (1 to 0.5), a structural irregularity in elevation function, kr, (1 or 0.8), and a wall modifier, kw,(1-0.4) which is used to address the prevailing failure mode of wall systems. Table 6.2 of Eurocode 8 gives the upper limiting values of behaviour factor 'q' based on their ductility class for regular elevation systems. Medium ductility class ranges from 2 to 4 for steel frames while high ductility class is a function of $\frac{\propto u}{\propto 1}$ α1 is the multiplying factor applied to horizontal seismic design action, keeping all other design actions to be constant, so as to achieve the plastic resistance in any of the structural member.
α_u is the multiplying factor applied to horizontal seismic design action keeping all other design action constant, in order to build up structural stability by creating plastic hinges in sufficient number of sections. This factor may be obtained from pushover (static nonlinear global) analysis.
q is taken as per above table for regular frame structure; if the building is non-regular in elevation the upper limit values of q listed in Table 6.2 of Eurocode should be reduced by 20 % (ie. reference value from above table to be multiplied by 0.8), The maximum value of $\alpha u/ \alpha_1$ that may be used in a design is equal to 1.6. For concrete structures, it specifies to use 'q' factor directly as 1.5 irrespective of regularity of elevation and structural system.

- *Iranian code [Standard No. 2800]* [58]

In this code the response modification factor is known as Building Behaviour Factor 'R'. This factor depends on redundancy, ductility and overstrength capacity of the structure. The values of R for steel building frames are mentioned in Table 6 of Iranian seismic code. This code has classified the lateral load resisting system into 4 main categories viz. Bearing wall system, building frame system, moment resisting frame system and dual systems which also depends on height of structure. It is based on method of Allowable Stress Design. While using this factor for limit state design method, it must be suitably scaled in accordance with reliable codes.
As the R factor depends on height of structure, construction of building rising above the limiting heights of that given in table, is strictly prohibited except for important structure where prior permission from Technical committee of this code is essential.
The code categorises the building system as follows:

Table 1. Classification of building system as per Iran seismic design standard

Sr. No.	Type of steel building system	Description and remarks
1	Special structural system	These are extremely important buildings in high seismic zone
2	Special Moment Resisting frames Or Dual system	These are building with storey height more than 50 m or storeys with 15 or more in numbers.
3	Moment Resisting Frame with flat slab and column system	These are building with storey height not more than 10 m or storeys with 3 or less in numbers. The above limit may be increased if shear wall and braced frames contribute to resist lateral seismic loads.

The code also recommend the selection criteria of 'R' for design based on Combination of Structural System (two or more Lateral Load Resisting System, LLRS) in plan and in height. For combinational LLRS in plan, corresponding 'R' factor to be used for designing individual system. If bearing wall present in structure along any axis (among the two), then the 'R' value for orthogonal axis shall not exceed 'R' used for bearing wall in structure. In case of combinational LLRS in height, the upper portion must be flexible and should be supported on rigid lower portion. Both structures are regular structures having mean storey stiffness of lower part atleast 10 times that of upper and the fundamental period of whole structure not greater than 1.1 times that of upper part. For such system, the 'R' factor for lower system should not exceed that of above. Iranian code suggests two design procedures for this system. In one of the procedure, the earthquake load is calculated for total height of building based on smaller 'R' value in considered direction and lower of the two fundamental periods must be chosen. In other procedure, the upper flexible part is to be designed separately with rigid support considering corresponding 'R' factor of its structural system. The lower part, which is rigid, must be designed separately using corresponding 'R' factor. It must be noted that the reaction force from upper flexible part must be modified by ratio of R_{upper} to R_{lower} and must be added with load acting on lower part.

The 'R' factor varies from 5 to 10 for steel frame systems and for dual system it varies from 7 to 11. Dual system has various combinations such as:

a. Intermediate steel moment-resisting Frame + Steel concentric braced frame
b. Special moment-resisting frame(steel or concrete) + special reinforced concrete shear walls
c. Intermediate steel moment-resisting frame + intermediate reinforced concrete shear walls
d. Special steel moment-resisting frame + Steel concentric braced frame
e. Special steel moment-resisting frame + Steel eccentric braced frame
f. Intermediate steel moment-resisting frame + Steel eccentric braced frame

- *New Zealand Code [SNZ 1992]* [59]

In this code, the following inelastic response spectra indicates that for short period structure, period dependency with equal energy concepts is applicable while for long period structures, equal displacement is applicable. In both above cases, the structures ability to sustain level of inelastic response relies on material and detailing employed in order to meet desired level of ductility.

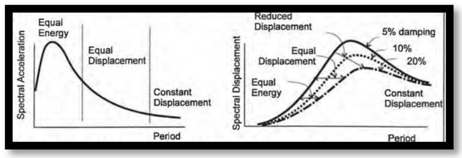

Fig. 3 Acceleration and displacement response spectra (Courtesy: Priestley, 1993)

In New Zealand, the ductility factor, **μ**, is used to reflect the structural ductility present and the structural performance factor, **Sp** (= 2/3), is used to adjust the inelastic structural response spectra to reflect the building damage associated with several inelastic excursions. No methodology is provided as to how, the magnitude of Sp should be set considering (i) the structures expected to sustain ULS(ultimate limit state) shaking only, or (ii) structures hoped also to sustain the Maximum Considered Earthquake (MCE) shaking.

- *Australian Seismic Standard [AS1170.4-2007]* [60]

This code functions similar to New Zealand code. 'Sp' is the Structural factor ranging from 0.67 to 0.77 for steel structures.

- *Korean Building Code [KBC- 2009*[61]

In the Korean code, the seismic base shear depends on seismic response coefficient Cs which is expressed in terms of response modification factor 'R'. This 'R' value for steel seismic force resisting systems varies with 3.25 for ordinary frames upto 8 for special and dual frame systems. It covers Concentrically Braced Frames (CBF), Eccentrically Braced Frames (EBF) as well as Dual frame systems. Here the dual frame systems consists of total lateral load resistance delivered by combination of moment frames with EBFs or shear walls based on their rigidity levels where moment frames to provide minimum 25 percent seismic force resistance. Other than dual system one can use combination of lateral load resisting systems in same as well as vertical directions. For such combinations, this code provides necessary terms and conditions for consideration of 'R' values. For same direction, 'R' shall not be larger than the smallest value of any of the systems utilized in the same direction. For vertical direction 'R' value used for design at a particular floor shall not surpass the lowest value of 'R' that is used in the same direction at any floor above that floor except roof story. This code permits for two stage equivalent lateral force resisting system with flexible top portion and rigid lower provided period of whole structure must not exceed 1.1 times the period of upper flexible portion which is considered as a separate structure fixed at bottom, stiffness of upper flexible structure must be less than 10 times that of bottom rigid structure, both flexible and rigid structure must be designed as individually considering appropriate value of 'R' and the reaction from upper portion will be that obtained by amplifying the analytical reaction of upper portion with the ratio of $\frac{R\ upper}{R\ lower}$. In no condition, this ratio must be below 1.

- *Indian Standard Code:[IS 1893:2016,Part I]* [62]

Indian seismic code was developed based on seismic hazard analysis performance from past seismic data. With reference to IS 1893:2016, Part I, Response reduction factor, and damping: (a) effects the nonlinear behaviour of buildings during severe earthquake shaking, and (b) leads to inherent system ductility, redundancy and overstrength normally available in buildings. **Response reduction factor (R)** for various steel lateral force resisting building systems is given in Table 1. R values shall be considered during design of buildings with lateral load resisting elements, and NOT for just the lateral load resisting elements, built separately. The structure designed for reduced force level performs effectively, if properly detailed. R-value increases with increase in structural ductility, its energy dissipation capacity and degree of redundancy. Thus, brittle buildings are assigned lower R values while ductile buildings are provided with higher R value.[36] Dual system in Indian seismic code comprises of combination of moment resisting frame and structural walls such that both system resist total designed lateral load depending on individual lateral stiffness capability in addition, interaction to be considered at floor level. Also, moment resisting frames to resist atleast 25% of design base shear force. Table 9 of IS 1893:2016 part 1 demonstrate the range of 'R' values ranging from 3 to 5 for dual steel structures.

- *Nepal National Building Code [NBC 105: 1994]*[63]

Taken into consideration all faults in the boundary range of 150km, and the outcome of probabilistic seismic hazard analysis, the Nepali seismic was prepared. In Nepal, the R factor for the ductility, redundancy and overstrength in known as **Structural performance factor (K).** *It is a multiplying factor in base shear formulation and therefore higher K value implies larger design forces due to seismicity.* [Pujan 14, 24]. The K – values varies with 1 for ductile moment-resisting, 1.5 for ductile frame with steel bracing members and 2 for ductile diagonally-braced steel frame acting in tension only. These values are applicable if member comply with the detailing for ductility requirements specified in NBC111-94. When more than one structural type is used in the structure, for the direction under consideration, the structural performance factor to be applied for the element which transmit the majority of the seismic load resistance provided that, the elements of the other structural types is capable of accepting the resulting deformations. These factors to be applied only if the steel braced member are considered during calculating stiffness as well as lateral strength and if the frame happens to act alone it must be capable of resisting at least 25% of the design seismic forces.

- *Jordanian Code for Loads and Forces* [64]

In this code, the energy absorbing capacity of a structure is specified as a behaviour factor (ϴ) and which depends on ductility of the structure. For lateral force resisting steel frame with or without bracing, ϴ is to be taken as 0.67. For dual bracing structural system of ductile Moment

Resisting Space Frame [MRSF] along with shear wall the ϴ value of 0.8 or 1.33 is to be considered. It is to be ensured that the ductile frame must be capable to resist atleast 25% of total lateral force while shear wall must be capable to resist complete lateral load. This is possible based on individual member's rigidity characteristics.

- *Japan Building Code 2010* [65]

The term Ds (Structural characteristic coefficient) is a value specifying structure characteristic for each story in accordance with construction method for structural strength of building, ductility and damping of each story.

While the term Fes (Form coefficient) also represents characteristic of each story in accordance with calculation method based on stiffness ratio (Fs) and eccentricity ratio (Fe). Ds range between 0.25 to 0.5 for steel frame system. Fes= Fs x Fe where Fs ranges between 1 to $\left(2-\frac{Rs}{0.6}\right)$, where Rs represents stiffness of each storey and Fe ranges between 1 to 1.5.

- *Turkish Seismic Code* [66]

In this code, the Structural Behaviour Factor (R) depends on Seismic load reduction factor [Ra (T)], natural vibration period (T) and spectrum characteristic period (T_A). Here the 'R' factor is specified for two different ductility levels viz. Normal and High. For structural steel buildings it lies between 4 to 5 in case of normal ductility level. For High ductility level, it lies between 4 to 8, with 5 for CBF fully resisting seismic loads and 6 when CBF and cast-in-situ reinforced structural wall jointly resists seismic loads. Similarly, 7 for EBF fully resisting seismic loads and 8 when EBF and cast-in-situ reinforced structural wall jointly resists seismic loads.

- *Bangladesh Seismic Code [BNBC Part 6]* [54, 67]

The method of calculating spectral acceleration is somewhat similar to Indian seismic code with a gravitational acceleration replaced by normalized acceleration response spectrum Cs. The response reduction factor 'R' ranges from 3.5 to 8 for various types of structural steel frames contributing to resist earthquake loads. Also, the ratio 1/R shall not exceed 1.

- *Israel Seismic Code [SI 413-2013]* [68]

In this Israel code, the seismic coefficient (Cd) and weight (W) contributes to calculate horizontal base shear value (V). This Cd value inversely depends on one of the factor, the Reduction factor (K), which ranges as 4 for steel braced frames, 7 for steel ductile dual system and 8 for steel ductile space frame.

From the above study, it is understood that, the design standards governed by high seismic region such as United States of America, Europe, Iran have provided 'R' factor for advance configuration of lateral load resisting system viz. couple wall, composite shear panel, hybrid frames etc.

- *Uniform Building Code [UBC-1997]* [69]

This code mentions a wide range of 'R' factor ranging from 3.5 to 8.5 for the building frame system comprising gravity frame system, moment resisting frame system. It has also clearly specified the 'R' values for Dual system having various combinations of (i) Shear wall with other concrete and steel frames, (ii)Steel EBF with OMRF and SMRF, (iii) ordinary braced frame with other steel and concrete frames and (iv) special CBF with OMRF and SMRF. The 'R' values for dual system ranges from minimum of 4.2 to maximum 8.5. This code mentions that the MRF must be capable of resisting atleast 25 percent of base shear when participating in dual system and
Each dual system must resist complete lateral load in equivalent to its rigidity. Many countries follow this code of practice especially those who do not have their own seismic design code like Dubai, Singapore follow this code of practice.

Thus the response reduction/ modification/ behaviour factor which enhances the inelastic behaviour of building structure subjected to seismic force has been explicitly presented for various countries in the world. It is understood that this factor is one of the crucial part in design of earthquake resistant structure and needs to be thoroughly studied.

4. Summary

R factor, its concept, calculations in this paper dealt with several number of journal papers and standard seismic design codes of different countries. It is seen that R is one of the most vital parameter in seismic design of any structures. It was noted that R factor prescribed in design codes are based on past practices and collective judgement of the code committee with known response of some of the framing systems and these responses in many cases did not offer uniform margin of safety and economy of buildings for different seismic regions.
Evaluation of Response reduction factor is based on large numerical study and very little experimental study on small scale models. R which implicitly accounts for inelastic state of system appearing in various design standard is based on professional judgement, numerical study and very little experimental test on small scaled models of lateral load resisting system. R is quantified using nonlinear analysis tools peak ground motion and spectral parameters. Any building frame can be designed for any other value of *R* provided the performance based design framework is adopted to ensure the performance objective.
The response modification factor (R) values seem to be intended to conform for reserve strength, ductility and redundancy. Many researchers have proved that value of response reduction factor is affected by many parameters like height of building, number of bays in building, irregularity (both vertical and horizontal) of structure, seismic region of structure. A structure is designed based on modern philosophy that "a well-designed structure should have a limited number of members with required ductility and defined failure mechanism. Such an approach will minimize the cost of repair of structure after a major earthquake. Any increase in seismic response factors will reduce the overall cost of the structural systems hence strength and ductility factors should be evaluated for each seismic framing system in each seismic zone using standardized definitions of reserve strength and ductility.

Indian seismic design code fails to specify other combinations (vertical/ horizontal direction) of dual / hybrid lateral load resisting system along with corresponding response reduction factor as compared to few other design standards. It also does not postulate the location of individual members of hybrid frame system and its effective consideration of response reduction factor. Author's further study will account for these drawbacks for Indian standard seismic code (IS 1893:2016).

5. Observed limitations of work on evaluation of response reduction factor

- Evaluation of real Response reduction factor 'R' for advanced earthquake engineering. R factor does not account for performance objective.
- No validation for the said work, only professional judgement perceives.

In the upcoming research authors will address these limitations.

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