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Assessment of seismic response reduction factor for moment resisting RC frames

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Assessment of seismic response reduction factor for moment resisting RC frames

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Abstract. The response reduction factor or response modification factor (*R*) plays an important role in the non-linear response of the moment resisting reinforced concrete (RC) frames. Implementing this factor in the design, accounts for the non-linear response of a structure. The study emphasizes on evaluating the actual values of the response reduction factor for moment resisting RC frames. The estimation of this factor is carried out by performing a detailed non-linear static pushover analysis of 2D framed structures of both ductile and ordinary moment resisting frames.Different parameters considered for the study includes variation of height of the structure, the zone factor and considering the effect of geometric non-linearity of the structure in the analysis. The results indicate that the values of *R* as given by the codes are of higher degree. From the analysis, arelationship between *R*-*T*-*Z*has been studied. It is found that the values of over-strength, ductility and response reduction factors are highly affected by seismic zones and time period of the structure.

1. Introduction

When a structure is subjected to an earthquake of design intensity level, only selected elements will be considered for non-linear response according to design philosophies. This consideration is based on the guidelines of IS 1893 [6], ASCE7 [1] and Eurocode 8 (EC8) [9]. While designing a structure, the above codes do not properly incorporate the non-linear response of that structure. Instead of the displacement-based analysis method, the force-based analysis is explicitly carried out while designing a structure. To make the structure safe, durable and economical, an engineer has to design accordingly, by reducing the forces acting on the structure. Hence, for designing earthquake resistant structures, the implementation of the reduction factor in the design, reduces the force acting on the structure, thus making the structure safer and economic. The consideration of the reduction factorin the design also accounts for the non-linear response of the structure.

The seismic response reduction factor (*R*), also called response modification factor is used to reduce the linear elastic design spectrum. To determine the lateral forces acting on the structure, this factor can be assumed as specified by the codes. The inclusion of *R* in the linear design implicates the inclusion of non-linear characteristics in it.The response reduction factor (R) is a function of various structural parameters, such as over-strength, ductility, redundancy and damping

$$R = R_S R_\mu R_R R_\zeta \tag{1}$$

Over-strength factor, R_S - Defined as the ratio of ultimate strength to the shear strength, the factor indicates the measure of the built-in over-strength of a structure.

$$R_S = \frac{V_u}{V_d} \tag{2}$$

Ductility factor, $R\mu$ - It is a factor in which, through the plastic deformation capacity of a structural system; the overall nonlinear response of a structural system can be estimated.Ductility capacity is the ratio of the base shear considering plastic response to the ultimate shear considering the nonlinear response. Here, the relationship given by Miranda et al [12] for R_μ-μ-T relationship is used.

$$R_\mu = \left(\frac{\mu - 1}{\phi}\right) + 1 \tag{3}$$

Where, $\mu = \dfrac{\Delta u}{\Delta y}$ and (4)

$$\phi = 1 + \left(\frac{1}{12T - \mu T}\right) - \left(\frac{2}{5T} e^{\left(-2(\ln T - 0.2)^2\right)}\right); 2 \le \mu \le 6 \tag{5}$$

The expression developed by Krawlinker and Nassar [15] can also be used for evaluating the ductility factor,

$$R_\mu = \left[C(\mu - 1) + 1\right]^{1/C} \tag{6}$$

Where C is a parameter, which is based on the elastic vibration period and ratio of the post- to pre-yield stiffness (α) of the inelastic system.

$$C = \frac{T^a}{1 + T^a} + \frac{b}{T} \tag{7}$$

Where, a and$b$ are regression parameters, based on α. All the required parameters like design shear (V_d), yield displacement(Δy), yield displacement(Δy), and ultimate displacement (Δu)are obtained from the idealized-bilinear pushover curve as shown in Figure 1. $R_R$is the redundancy factor which is considered as 1.0 as suggested by American code (ASCE7) [1]. $R_\zeta$is the damping factor which is of prime importance, when damping devices are installed in the structure, otherwise the factor shall be considered as 1.0 [4]. Thus, the response reduction factor value varies based on all these parameters.

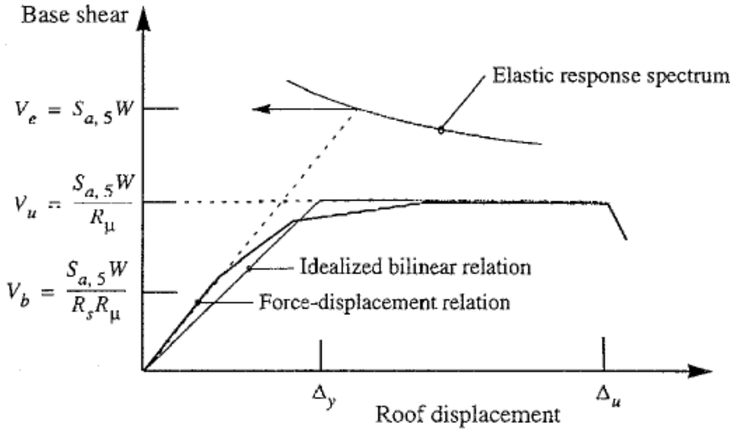


Figure 1. Base shear vs roof displacement relationship

The codes suggest that the response reduction values are independent of these parameters and recommendto considera particular value based on type of structure. The values of response modification factors for different types of RC moment resisting frames suggested by various codes.Whittaker et al [4] found the variation of response reduction factor based on building type, seismic zone and height of the structure. The factor ranging from 2.3 – 8.3 has been reported for low seismic zone and high ductile structure according to Lee et al [10]. Ghosh et al, [3] has considered two performance criterions, based on the structural and member performance limits and also the inclusion of P-Δ effect in the inelastic analysis on the plastic hinges are explained. Visuvasam and Nishanth [18] identified that the ductility factors of special moment resisting frames change significantly with increasing zone factor and time period. In this study, a detailed analysiswas carried out considering different zones, height of structure and geometric non-linearityto find out the variation of response reduction factor.

2. Modelling and Analysis

For the study- G+3, G+6, G+9, G+12, G+15 RC structural systems have been considered, which are symmetrical in plan, intended for regular residential building. The linear and non-linear analysis of multi storey buildings was studied under blast and seismic loading [20, 21]. The modelling and the pushover analysis of the structural systems are carried out in SAP2000 v.15 software. The structure consists of 3 bays in both the direction, with a span of 5m each.Here, an intermediate span has been considered and the load calculations are done according to the IS codes. The grade of concrete considered for the structure is M25 and that of steel is Fe415. The storey height is kept 3.5 m throughout the structure. The plan and a typical elevation of the G+6 structure are shown in Figure 1. The study is carried out for different seismic zones, different number of stories, and effect of inclusion of the geometric non-linearity in the analysis.The values of the ordinary moment resisting frame (OMRF), *R*=3.0 has been considered and for special moment resisting frame (SMRF),*R*=5.0 has been considered, the importance factor for the building is taken as 1.0, all these factors are as per IS 1893 [6]. Live load on the structure is considered as 4 kN/m^2 [8].The response spectrum analysis and design as per IS 456 [7] and IS1893 [6] has been carried out. The design base shear (V_d) is calculated as:

$$V_d = \frac{ZIS_a}{2Rg} \times W \tag{8}$$

Where, *Z* is the zone factor; *I*is the importance factor; *R* is the response reduction factor and *W* is the seismic weight of the structure [6, 16]. A damping of 5% is considered for the structure [6]. As per the codes, the correction factor of V_b/V_d is multiplied for all the response quantities [6], for this, the design base shear (V_d) is compared with the dynamic base shear (V_b). Since, both OMRF and SMRF structures are considered, the detailing of the RC sections are carried out according to IS 456 provisions [7]. Also the strong column- weak beam (SCWB) criterion is checked for all the joints for the safety purpose and since it is practiced widely [5]. The dimensions of beams and columns after the consideration of SCWB criteria are given in the Table 1.

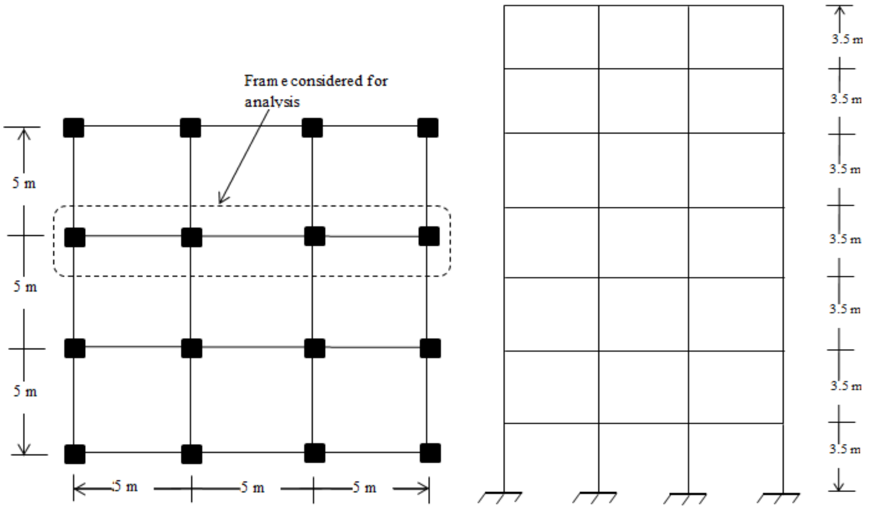


Figure2. Typical plan and elevation of the RC framed structure

Table 1. Dimensions of the RC sections (after SCWB design criteria)

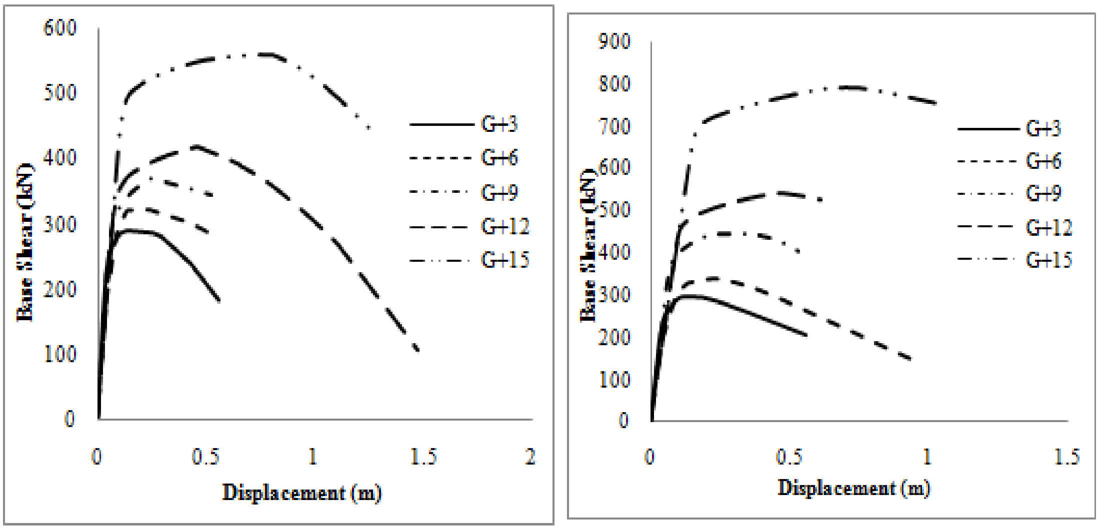
Frame	Members	Dimension (mm)	Frame	Members	Dimension (mm)
G+3	B	300 x 350	G+12	B (G-3)	450 x 500
	C	450 x 450		B (4-6)	400 x 450
G+6	B (G-3)	350 x 400		B (7-12)	350 x 400
	B (4-6)	250 x 300		C (G-3)	650 x 650
	C (G-3)	500 x 500		C (4-6)	550 x 550
	C (4-6)	450 x 450		C (7-12)	500 x 500
G+9	B (G-3)	450 x 500	G+15	B (G-6)	450 x 500
	B (4-6)	400 x 450		B (7-12)	400 x 450
	B (7-9)	300 x 350		B (13-15)	350 x 400
	C (G-3)	550 x 550		C (G-6)	700 x 700
	C (4-6)	500 x 500		C (7-12)	600 x 600
	C (7-9)	450 x 450		C (13-15)	500 x 500

*B-beams, C-columns

To carry out this study, pushover analysis is carried out to achieve the nonlinear response of the structure. Pushover analysis isa nonlinear-static analysis method where a structure is subjected to full gravity loading and a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behaviour until an ultimate condition is reached [17]. The nonlinear static pushover analysis (NSPA) is performed to estimate the over-strength and the ductile capacity of the structures. Since the *R* values are evaluated on the basis of NSPA, it has to be observed that all the members participate in the analysis for efficient results. As the non-linear behaviour is of prime importance, the concept of plastic hinges will appear. The plastic hinges affect the moment-rotation behaviour of the members, which depends upon the moment-curvature characteristics [11]. The properties of the plastic hinges shall be defined manually [3] and provisions given as per Federal Emergency Management Agency (FEMA). For the analysis purpose, auto-hinge property available in SAP2000 v.15 is adopted. Flexural hinges (M3) and axial-moment interaction behaviours of hinges (P-M3) were defined for beams and columns respectively in this study as per FEMA356 [13]. Different stages in the plastic hinges, such as immediate occupancy (IO), life safety (LS) and collapse prevention (CP) were checked with the codal provisions of FEMA 356 [13,14] or ATC-40 [2].

3. Evaluation of Response Reduction Factor (*R*)

After the pushover analysis is completed, the structural components are checked for its hinge properties, and the pushover capacity curve is obtained. The force versus displacement curve i.e. the pushover curve has been then plotted to study the behaviour of structure under incremental lateral loading. This curve shall be idealized, i.e. an idealized-bilinear relation shall be established, in order to obtain values, such as design shear (V_d), yield shear (V_y), ultimate shear (V_u), yield displacement (Δ_y) and ultimate displacement (Δ_u). The evaluation of R is based on the idealized-pushover curve, and the over-strength factors are determined using the equation (2). Similarly the values of ductility factors were then estimated using (3-6) equations. The base shear versus displacement push over curves for all structures for zone IV (OMRF) and for all zones of G+12 (OMRF & SMRF) structures is shown in Figure 2 and 3 respectively. After a detailed calculation, the values of$R_S$and R_μ were reported and are presented in Table. 2.



(a) SMRF (b) OMRF

Figure 3. Push over curve of (a) SMRF and (b) OMRF buildings

Table 2. Details of estimation of reduction factor for SMRF and OMRF buildings

Zone	Storey	Time Period	R_s		R_μ		R	
			SMRF	OMRF	SMRF	OMRF	SMRF	OMRF
II	G+3	0.4	4.21	2.56	1.81	1.77	7.59	4.53
	G+6	0.62	2.69	1.64	3.05	3.05	8.21	4.99
	G+9	0.72	2.27	1.39	4.25	4.1	9.65	5.74
	G+12	1	2.09	1.45	4.24	3.77	8.86	5.46
	G+15	1.2	2.53	1.76	4.11	3.26	10.41	5.74
III	G+3	0.4	2.64	1.6	1.76	1.75	4.64	2.8
	G+6	0.62	1.69	1.02	3.04	2.44	5.12	2.49
	G+9	0.72	1.44	0.98	4.15	3.43	5.97	3.36
	G+12	1	1.39	1.05	4.06	3.06	5.65	3.21
	G+15	1.2	1.89	1.43	3.36	2.39	6.36	3.44
IV	G+3	0.4	1.76	1.07	1.75	1.73	3.07	1.85
	G+6	0.62	1.12	0.69	3.04	2.9	3.42	2.02
	G+9	0.72	1.05	0.77	3.59	2.75	3.76	2.1
	G+12	1	1.13	0.87	3.26	2.36	3.66	2.06
	G+15	1.2	1.52	1.18	2.47	1.89	3.75	2.23
V	G+3	0.4	1.17	0.72	1.73	1.66	2.03	1.19
	G+6	0.62	0.75	0.5	2.99	2.46	2.26	1.23
	G+9	0.72	0.8	0.62	2.93	2.15	2.36	1.35
	G+12	1	0.91	0.68	2.55	1.81	2.32	1.22
	G+15	1.2	1.4	1.21	1.87	1.26	2.63	1.53

4. **Results and Discussions**

To understand the concept of reduction factor effectively and to obtain more conclusions, various parameters were considered for the study and the pushover analysis was carried out. The parameters considered are effect of zone factor, effect of time period and effect of types of frames.

4.1. Over strength factor: (R_s)

4.1.1. Effect of zone factor (Z). The over-strength factor is the ratio of ultimate base shear to the design base shear. From the graphs obtained from NLSP analysis, the values were calculated. As the structures response varies with respect to different seismic zone, it is obvious to consider the effect of zone factor on response of the structure in terms of response reduction factor. Hence, plots between zone factor and over-strength factor were drawn for both ductile and ordinary buildings. From figure, for all buildings, it is observed that the over-strength factor for zone II is higher. As the seismic zone increases, the factor reduces, which shows that the zone factor has inversely proportional effect on over-strength factor. The over-strength factor is high in ductile buildings in comparison with ordinary buildings. In both the type of buildings, the factor varies in accordance with seismic zone. Similarly, non-uniformity in plot shows that the factor varies with increasing zone factor.

4.1.2. Effect of time period (T). Similar to the response of structure between seismic zone and over-strength factor, plots also made for time period of the structure. The ductile buildings provide higher seismic response than the ordinary frames as anticipated. As the time period of the buildings increases, the over-strength factor decreases. Similarly, as explained in previous section, buildings analysed for lesser seismic zone exhibit higher values in both the ordinary and special moment resisting frames.

4.2. Ductility Factor (R_μ)

4.2.1. Effect of zone factor (Z). The ductility factor is the ratio of ultimate displacement to the yield displacement. Both ultimate and yield displacements were obtained from idealized inelastic push over curve. The graphs between ductility factor and zone factor were plotted for both SMRF and OMRF building. The variation of the ductility factor for all types of buildings with respect to seismic zones is studied. From figure, it is noted that short period buildings (G+3 and G+6) provide uniform response in terms of ductility as the zone factor varies. Other buildings (G+9, G+12 and G+15) provide inversely proportional response to the zone factor. It is meant that, for both the type of SMRF and OMRF buildings, the zone factor has uniform effect on ductility factor for short period buildings and decreasing effect for other buildings. Therefore, it is understood from the plots that, as the zone factor increases, the inelastic response of the buildings reduce which results into ductile deficiency.

4.2.2. Effect of Time Period (T). As explained for zone factor, the ductility of the building frames for seismic analysis also varies with respect to their natural time period. The building frames which are modelled and analysed for low seismic zones give higher ductility than those analysed for higher seismic zones in both type of OMRF and SMRF buildings. The ductility based on seismic response of the buildings is highly variable for long period structures. As the natural time period of the structures increases, the ductility of the building decreases. For short period buildings ($T \leq 0.7$ sec), it increases irrespective of seismic zones.

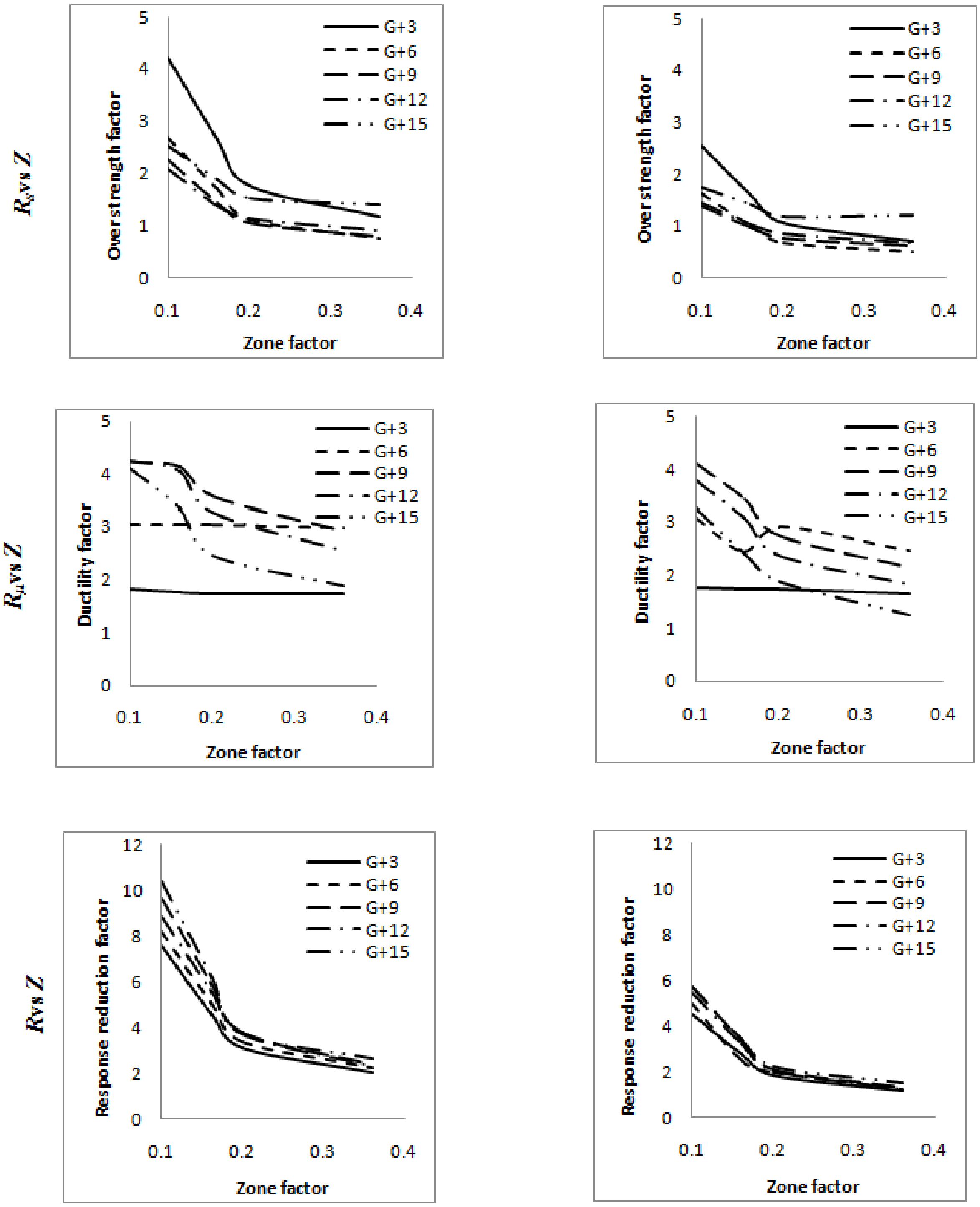
4.3. Response Reduction Factor (R)

4.3.1. Effect of zone factor (Z). Many researchers have performed study the effect of seismic zones on response reduction factor. Tamang et al [19] studied the elastic and inelastic response of RC infilled structure and their variation of reduction factor due to different seismic zones. The seismic response reduction factor is obtained by multiplying over-strength factor and ductility factor. The values of response reduction factor for different zones of ordinary and ductile moment resisting frames were obtained. From Figure, it is noted that, the overall structural performance is influenced by seismic zones. As the seismic zone factor increases, the value of response reduction factor decreases abruptly. Compared to ductile frames, ordinary building frames produce less performance for seismically active zones. Therefore, the inelastic structural performance is highly based on the amount of seismic forces acting on them.

4.3.2. Effect of time period (T). Similarly, graphs between response reduction factor and natural time period of the structures were plotted for both OMRF and SMRF buildings. From figure, it is seen that the overall structural performance for seismic forces based on natural time period of the buildings increases gradually. In addition to that the ductile buildings provide high seismic response in comparison with ordinary frames. Thus it is understood from the study that seismic response reduction factors vary in accordance with time period of the structure and type of building frames.

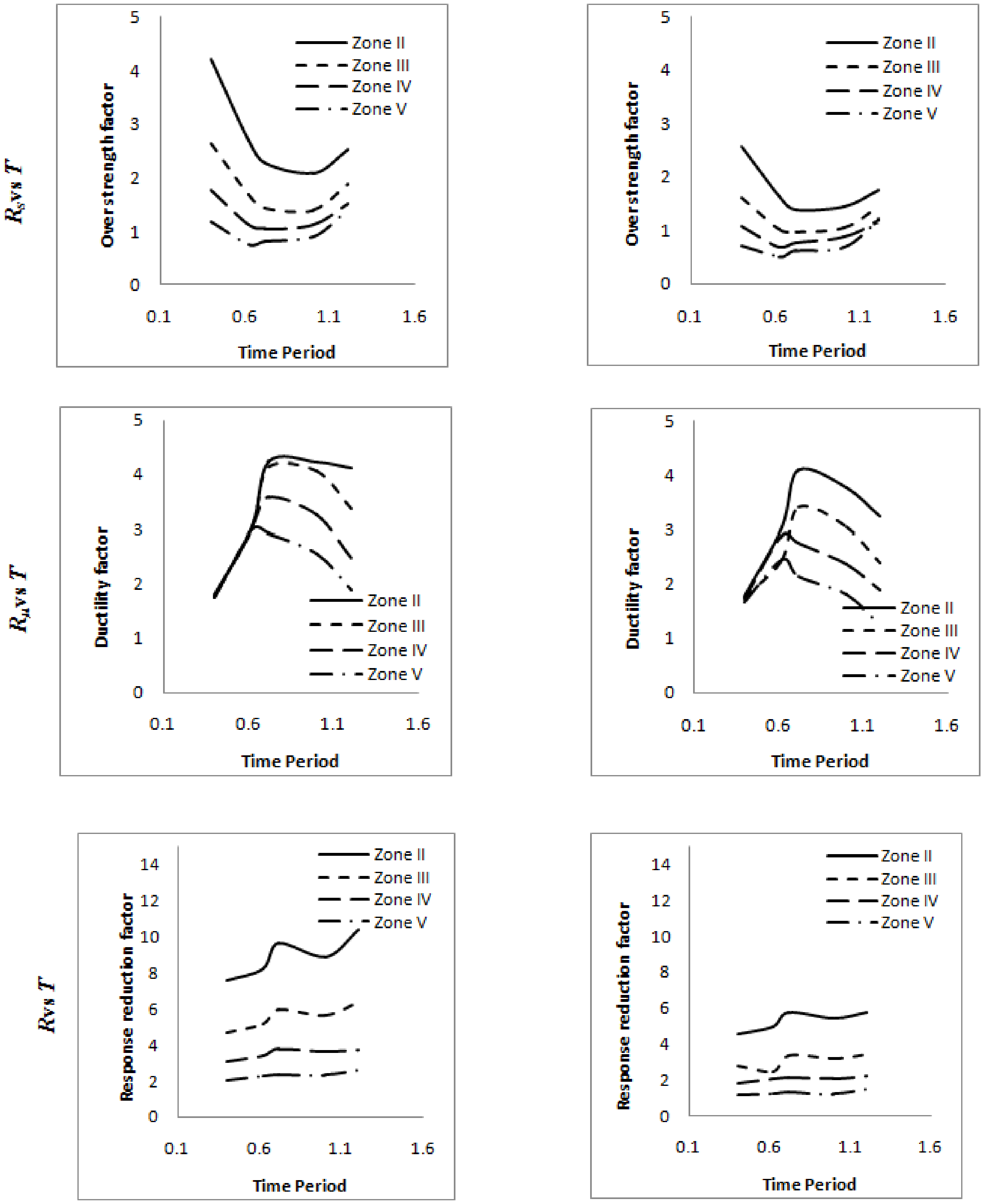
5. **Conclusion**

- A detailed non-linear static push over analysis of ordinary and ductile 2D building frames considering various time period and seismic zones was studied. The values of over-strength factor, ductility factor and overall response reduction factors were obtained from the idealized inelastic push over curve. From the study carried out, the following conclusion points were drawn.



SMRF OMRF

Figure 4. Effect of zone factor (Z) on $R_{s,}$ $R_\mu$and$R$



SMRF OMRF

Figure 5. Effect of time period (T) on R_s, R_μ and R

- The over-strength factor, which is based on design and ultimate base shear, varies with respect to seismic zones and natural time period of the building frames. The structures modelled and analysed for low seismic zones provide high over-strength factor. Similarly, as the time period of the structure increases, the factor decreases for both ordinary and ductile frames. As compared to ordinary moment resisting building frames, ductile buildings give high over-strength response.

- The ductility factor, which is based on ultimate displacement, yield displacement and a parameter which depends on post to pre yield stiffness of the system, provides no variation for the short time period buildings in all seismic zones. But for other buildings, it reduces as the zone factor increases. It increases significantly from short period to long period buildings.

- The overall seismic response reduction factor, which depends on over-strength and ductility factors, decreases abruptly as the seismic zone increases. Both short and long period building frame's factors increases slightly as the time period of the structure increases.

- Thus for the elastic analysis and design of buildings for seismic forces, it is necessary to consider the effect of seismic zones and time period of the structure to avoid the inaccuracy in predicting the design seismic forces.

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