

An Evaluation of Seismic Response Reduction Factor for Irregular Structures Using Non Linear Static Analysis

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ABSTRACT: The response reduction factor R reflects the capacity of structure to dissipate energy through inelastic behavior. It is a combined effect of over strength, ductility and redundancy. Response modification factors play a key, but controversial role in the seismic design process. No other parameter in the design base shear equation impacts the design actions in a seismic framing system as does the value assigned to R . Despite the profound influence of R on the seismic design process, and ultimately on the seismic performance of buildings in India. No scientific basis exists for the values of R adopted in seismic design codes in India. Without such a basis, it will be difficult to advance the practice of force-based seismic design in its current form. In present work efforts has been made in estimating the actual value response reduction factor (R) of reinforced concrete medium rise special moment resisting frame (SRMF) having irregularity in elevation and as well as in plan by using non-linear static pushover analysis and compare it with codal values. The frames were designed as per guidelines of IS 456:2000. The lateral loads acting on the frames were obtained from the guidelines of IS 1893: 2002 (Part1).

KEYWORDS: Base shear, Irregular structures, Lateral Displacement, Pushover analysis, Response reduction factor.

I. INTRODUCTION

In reality, many existing buildings contain irregularity, and some of them have been designed initially to be irregular to fulfill different functions e.g. basements for commercial purposes created by eliminating central columns. Also, reduction of size of beams and columns in the upper story's to fulfill functional requirements and for other commercial purposes like storing heavy mechanical appliances etc. This difference in usage of a specific floor with respect to the adjacent floors results in irregular distributions of mass, stiffness and strength along the building height. In addition, many other buildings are accidentally rendered irregular due to variety of reasons like non-uniformity in construction practices and material used. The building can have irregular distributions of mass, strength and stiffness along plan also. In such a case it can be said that the building has a horizontal irregularity.



(a)



(b)



(c)

Fig 1.1.Examples of Irregular structures.

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Fig 1.1. (Examples of Irregular structures) shows the example of geometrically irregular structure. The figure (a) and (c) basically shows gradual type vertical irregularities while (b) shows sudden type vertical irregularity. In this paper, effects of such different types of irregularities on response reduction factor are studied.

II. RELATED WORK

- **Apurba Mondal, et al.** focused on estimating the actual value of R for realistic RC frame building design and detailed following the Indian standard for that they makes model of G+2, 4,8,12 Story RC frames and analysis was carried out with nonlinear static method using static pushover analysis. The results show that the Indian standard recommendation for a higher value R than actual value of R is potentially dangerous.
- **Bhavin Patel .et al.** studied the key factors for seismic modification factor of RCC framed staging of elevated water tank were formulated. The analysis revealed that three major factors, call reserved strength, ductility and redundancy affect the actual value of response modification factor. Conclusion was made that the water tank which is well design by using codal procedure has the response reduction factor 4.0
- **Sunagar.P, et al.** studied RCC framing systems are investigated with regards to their lateral load carrying capacity and in this context seismic response modification factors of individual systems are analyzed, to determining the values of response modification factors or R factors tabulated in seismic design code. For this study 3, 9 and 20 stories RCC Moment Resisting Frame (MRF) buildings were designed to satisfy the seismic requirements for the RCC moment resisting frame (MRF) buildings. Frames, designed according to Indian standard IS 456 – 2000 and seismic code (IS 1893 - 2002), are investigated by nonlinear static analysis with the guidance of previous studies and recent provisions of FEMA.
- **Tande.S.N.et al.** estimated the seismic Response reduction factor (R) of reinforced concrete special moment resisting frame (SMRF) with and without shear wall using static nonlinear (pushover) analysis. Calculation of Response reduction factor(R) is done as per the new formulation of Response reduction factor (R) given by Applied Technology Council (ATC) 19.

III. RESPONSE REDUCTION FACTOR

The response reduction factor, R, simply represents the ratio of the maximum lateral force if structure remains elastic (V_e), to the lateral force (V_d), which it has been designed to withstand. Response reduction (R) factors are essential seismic design tools, which are typically used to describe the level of inelasticity expected in lateral structural systems during an earthquake. The response reduction factor (R) is depends on Over strength (R_s), Ductility (R_μ), Redundancy (R_R). According to ATC-19, it is described as

$$R = R_s * R_R * R_\mu$$

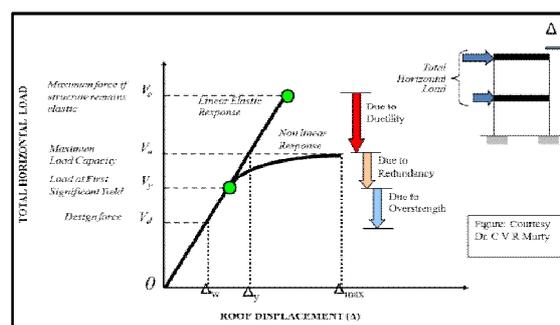


Fig 3.1. Concept of Response Reduction Factor

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Over strength factor (R_s) accounts for the yielding of a structure at load higher than the design load due to various Partial safety factors, strain hardening, oversized members, confinement of concrete. Non-structural elements also contribute to the over strength. Ductility factor (R_{μ}) is a ratio of ultimate displacement or code specified permissible displacement to the yield displacement. Higher ductility implies that the structure can withstand stronger shaking without collapse. Redundancy factor (R_R) depends on the number of vertical framing participate in seismic resistance. Yielding at one location in the structure does not imply yielding of the structure as a whole. Hence the load distribution, due to redundancy of the structure, provides additional safety margin. The Over strength factor, Ductility factor and Redundancy factor can be workout on the basis of generalized pushover curve shown in figure 2.1 (Concept of Response Reduction Factor).

IV. PUSHOVER ANALYSIS

Pushover analysis can be performed as force-controlled or displacement-controlled. In force- controlled pushover procedure, full load combination is applied as specified, that is, force- controlled procedure should be used when the load is known. Also, in force-controlled pushover procedure some numerical problems that affect the accuracy of results occur since target displacement may be associated with a very small positive or even a negative lateral stiffness because of the development of mechanisms and P-delta effects.

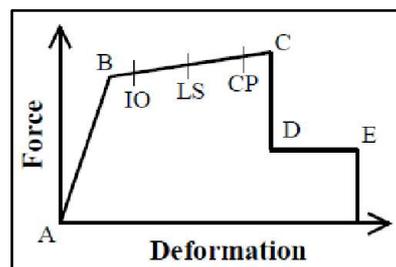


Fig 4.1. Force-deformation criterion for hinges used in pushover analysis

V. PROBLEM FORMULATION

In present study FEM based software SAP2000 has been used to model RC ductile frames to evaluate response reduction factor. Frame is designed as per provision of I.S 456:2000, I.S 875:1987, I.S:1893:2000 (Part 1) and I.S 13920:1993 (Ductile detailing of reinforced concrete structures subjected to seismic forces- code of practice). The building frame is 6 bays and 10 stories with height 3 m located in seismic zone V in India on hard rock soil type. Ten models were selected (five having irregularity in elevation & five having irregularity in plan) having different percentage of irregularity in elevation & as well as in the plan. General information regarding to the buildings & preliminary design consideration are tabulated in tables as below.

Sr. No.	Contents	Description
01	Type of structure	Multi Storied RC Rigid jointed Plane Frame(Special moment resisting frame)
02	Number of stories	G+10
03	Floor Height	3.0m

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04	Materials	Concrete (M25) Steel Reinforcement (Fe415)
05	Size of Beams	300X500 mm
06	Size of Column	600X600 mm
07	Depth of slab	200 mm
08	Specific weight of RCC	25 KN/m ³
09	Type of soil	Hard soil
10	Impose load	3 KN/m ²
11	Importance factor	1
12	Seismic zone	V
13	Zone Factor	0.36
14	Response Reduction factor	5

Table 1.Description of modelled buildings

In order to differentiate models from each other various abbreviations are used such as

For Plan Irregularities: **P**: Plan Irregularities **C**: Re-entrant corner **D**: Diaphragm Irregularity

For Vertical Irregularities: **V**: Vertical irregularities **G**: Gradual Irregularities **S**: Sudden Irregularity

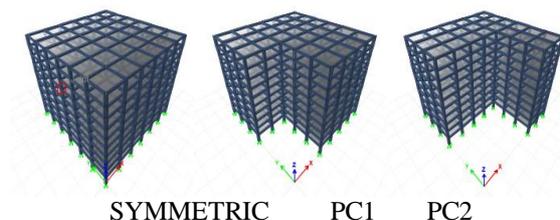
For Example:**PC1**: Model no 1 with re-entrant corner type plan irregularity.

PD1: Model no 1 with diaphragm type plan irregularity.

VG1: Model no 1 with gradual vertical irregularity.

VS1: Model no 1 with sudden vertical irregularity.

As stated earlier, different buildings are modelled with difference in plan irregularities which are shown below in fig 4.1. (Three dimensional view of example building having irregularity in plan).Plan irregularities which are considered are of two types, first one is re-entrant corner type and second one is diaphragm type irregularity. In the same way, other five buildings with vertical irregularities are modelled and shown in Fig 4.2. (Three dimensional view of example building having irregularity in elevation).Vertical irregularities are of two types which are sudden vertical irregularity and gradual vertical irregularity. All the models are analysed by linear static analysis to obtain the base shear required to calculate response reduction factor. Nonlinear static pushover analysis had been carried out on these models so as to obtain performance point.



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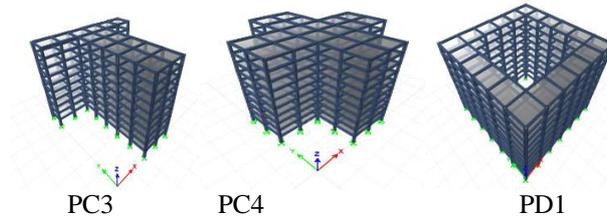


Fig 5.1. Three dimensional view of example building having irregularity in plan.

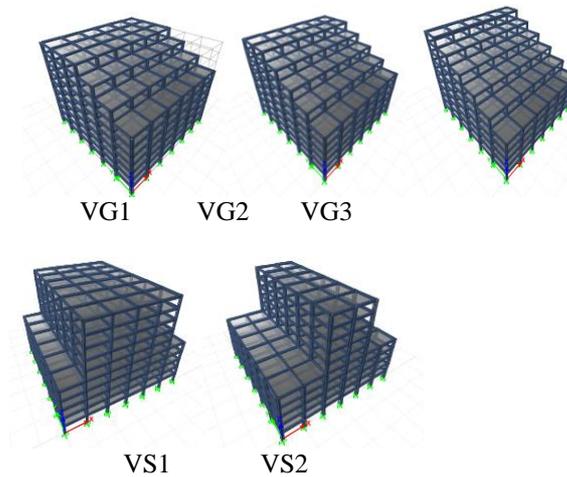


Fig 5.2. Three dimensional view of example building having irregularity in elevation.

VI. RESULTS & CONCLUSIONS

6.1. Comparison of Pushover curve:

Comparison of pushover curve having irregularity in plan is shown in Fig-5.1.1 (Comparison of pushover curve having irregularity in Plan). The figure describes the pushover curves of different models with re-entrant type as well as diaphragm type irregularities. This shows that as percentage of irregularity goes on increasing push over curve drops down to the lower values. As we can clearly observe that graph of PC4 is on lower value than PC3, PC2, PC1 and SYM. In case of diaphragm type irregularity, pushover curve of PD4 shows lower values than SYM.

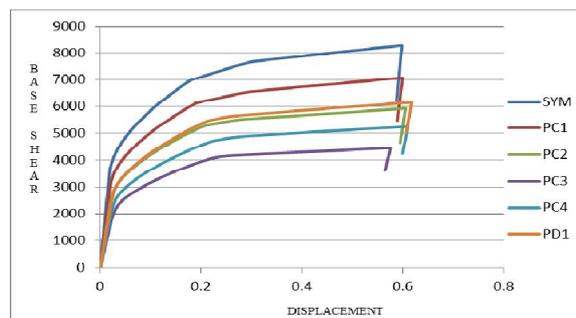


Fig 6.1.1-Comparison of pushover curve having irregularity in Plan

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Comparison of pushover curve having irregularity in elevation is shown in Fig-5.1.2 (Comparison of pushover curve having irregularity in Elevation). The figure shows the pushover curves of different models with vertical irregularities with sudden and gradual irregularities. This explains that as percentage of irregularity goes on increasing for sudden vertical irregularity push over curve drops down to the lower values. As we can clearly observe that graph of VS2 is on lower value than VS1, SYM. But In case of gradual vertical irregularities there is not a considerable difference in push over curves.

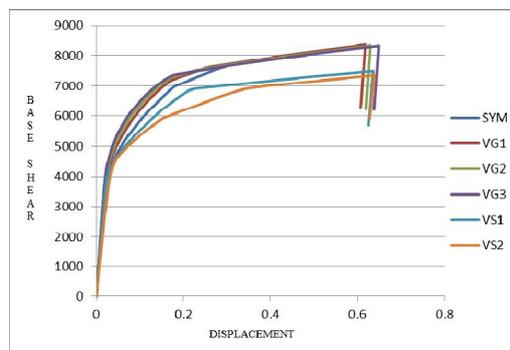


Fig 6.1.2-Comparison of pushover curve having irregularity in Elevation.

6.2. Estimation of Performance point:

It is observed that the demand curve tend to intersect the capacity curve in the building performance level of Life Safety Level, which means substantial damage as occurred to the structure, thus it may lose a significant amount of its original stiffness. However, a substantial margin remains for additional lateral deformation before collapse would occur

E.g. For symmetric Building, on the above symmetric building frames the nonlinear static pushover analysis is performed to investigate the performance point of the building frame in terms of base shear and displacement. The various load combinations are also used for this purpose. After pushover analysis the demand curve and capacity curves are obtained to get the performance point of the structure. The performance point is obtained as per ATC 40 capacity spectrum method. The demand curve and capacity curve for symmetric building is shown in Fig 5.2- (ATC 40 Capacity Spectrum).

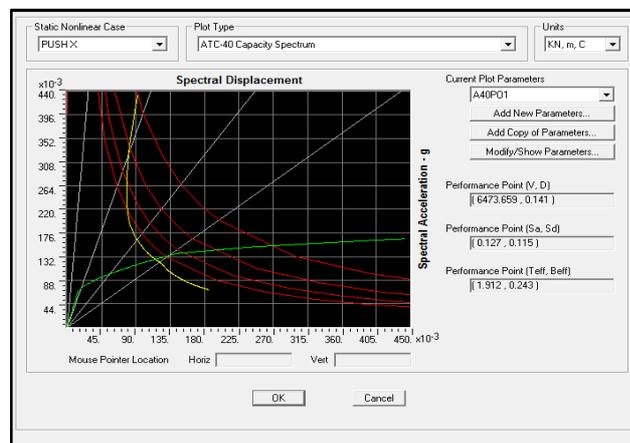


Fig 5.2- ATC 40 Capacity Spectrum

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Performance point = 6473.659 kN

The Performance points of all the buildings are obtained and stated in the table below. The table specifies the performance points of all the buildings along with their designation and type of irregularity.

Table 2 Performance points for modelled buildings from capacity spectrum method

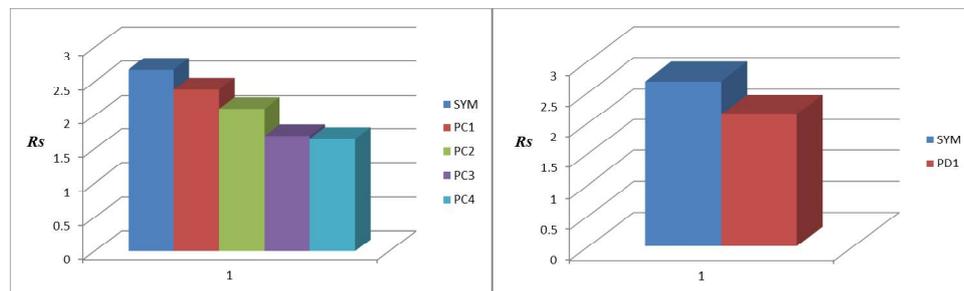
SR. NO	DESIGNATION	TYPE	PERFORMANCE POINT
1	SYM	Regular	6473.659
2	PC1	Re-entrant corner plan irregularity	5791.459
3	PC2	Re-entrant corner plan irregularity	5085.94
4	PC3	Re-entrant corner plan irregularity	4069.24
5	PC4	Re-entrant corner plan irregularity	4001.28
6	PD1	Diaphragm type plan irregularity	5200.54
7	VG1	Gradual vertical type irregularity	6778.8
8	VG2	Gradual vertical type irregularity	6895.11
9	VG3	Gradual vertical type irregularity	6998.09
10	VS1	Sudden vertical type irregularity	6124.61
11	VS2	Sudden vertical type irregularity	5872.92

6.3. Estimation and Comparison of Overstrengthfactor:

Variation of Overstrength factor with respect to irregularities in plan is shown below in fig 5.3.1 (Comparison of overstrength factors having irregularity in Plan). This figure explains the value of overstrength factor of symmetric structure to be 2.65 and also states that plan irregularities are introduced into the structure the overstrength factor reduced from 2.65 to 1.64. In case of diaphragm type irregularity, it drops to 2.14.

$$R_s = 6473.59 \text{ (Performance point)} / 2423.496 \text{ (EQ Calculation)}$$

= 2.65



Re-entrant corner Irregularity Diaphragm Irregularity

Fig 6.3.1-Comparison of overstrength factors having irregularity in Plan

Variation of Overstrength factor with respect to irregularities in elevation is shown below in fig 5.3.2 (Comparison of overstrength factors having irregularity in elevation). This figure explains the value of overstrength factor of symmetric structure to be 2.67 and also states that vertical irregularities with gradual change are introduced into the structure the overstrength factor increased a little bit from 2.67 to 2.9. While for structures with sudden vertical irregularities, the overstrength factor goes on reducing from 2.67 to 2.42.

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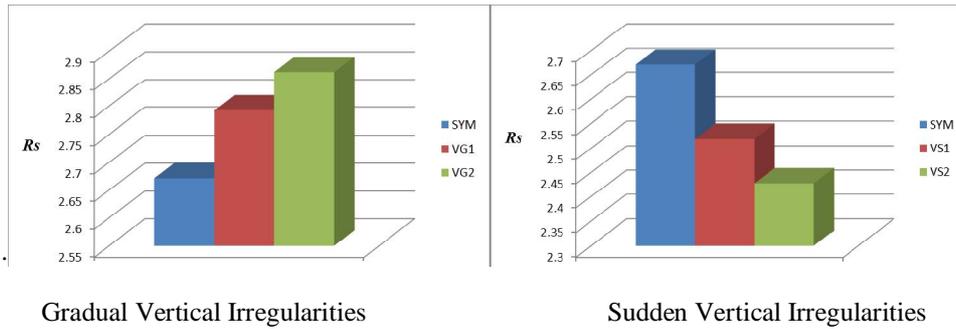


Fig 6.3.2-Comparison of overstrength factors having irregularity in elevation

6.4. Estimation and Comparison of Ductility reduction factor:

Variation of Ductility reduction factor with respect to irregularities plan is shown below in fig 5.4.1 (Comparison of ductility reduction factors having irregularity in Plan). The figure shows the value of ductility reduction factor of symmetric is found to be 2. It is observed that for irregular structures with plan irregularities is goes on reducing up to 1.94. The ductility reduction factor is also found out for diaphragm type irregular structure which is 1.96.

Eg. For symmetric Building, $R_{\mu} = \mu$
 $= \Delta_{max} / \Delta$ (from pushover curve)
 $= 1.2 / 0.597$
 $= 2$

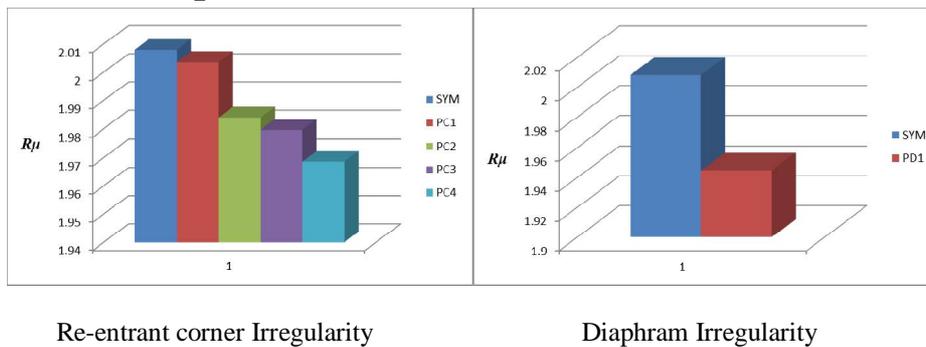


Fig 6.4.1-Comparison of ductility reduction factors having irregularity in Plan.

Variation of Ductility reduction factor with respect to irregularities elevation is shown below in fig 5.4.2 (Comparison of ductility reduction factors having irregularity in elevation). The figure shows the value of ductility reduction factor of symmetric is found to be 2. It is observed that for irregular structures with vertical type irregularities is goes on reducing up to 1.84.

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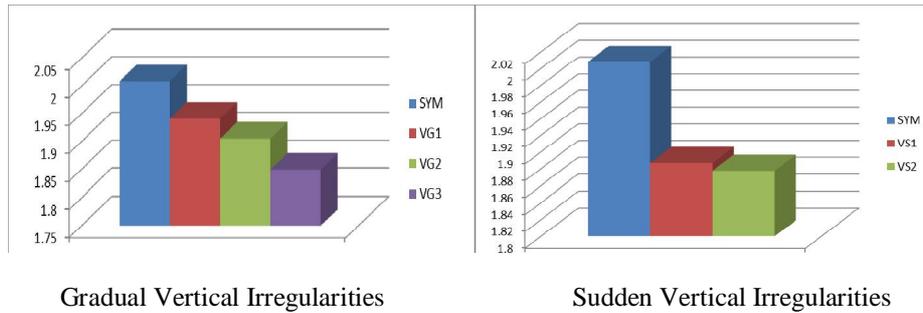


Fig 6.4.2-Comparison of ductility reduction factors having irregularity in elevation.

6.5. Estimation redundancy factor:

ATC 19 established a relationship between lines of vertical seismic framing and drift redundancy factor as shown in table 3 (Redundancy factor (R_R) was taken from ATC – 19).

Table 3 Redundancy factor (R_R) was taken from ATC – 19.

Lines of vertical seismic framing	Drift redundancy factor
2	0.71
3	0.86
4	1.00

RC structural systems with multiple lines of lateral load resisting frames are generally in the category of redundant structural systems, as each of the frames are designed and detailed to transfer the earthquake induced inertia forces to the foundation.

$$R_R = 1$$

6.6. Estimation and Comparison of Response reduction factor:

Variation of Response reduction factor with respect to irregularities in plan are shown fig 5.6.1(Comparison of Response reduction factors having irregularity in Plan). The figure gives the value of response reduction factor of symmetric is found to be 5.3 while code specifies that for special moment resisting frame, it should be 5. It is observed that for irregular structures with re-entrant corner plan irregularities is goes on reducing up to 3.24. The response reduction factor is also found out for diaphragm type irregular structure which is 4.16 which is less than 5.3.

Eg. For symmetric Building, $R = R_s * R_R * R_\mu$
 $= 2.65 * 2 * 1$
 $= 5.3$

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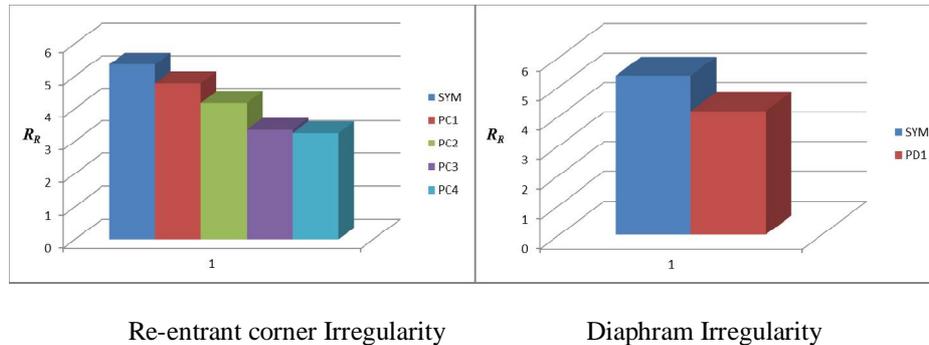


Fig 6.6.1-Comparison of Response reduction factors having irregularity in Plan

Variation of Response reduction factor with respect to irregularities elevation is shown below in fig 5.6.2 (Comparison of Response reduction factors having irregularity in elevation). The figure shows the value of response reduction factor of symmetric is found to be 5.3. It is observed that for irregular structures with gradual vertical type irregularities does not show any distinguishable variation. While in case of sudden vertical irregularities response reduction factor reduced up to 4.55.

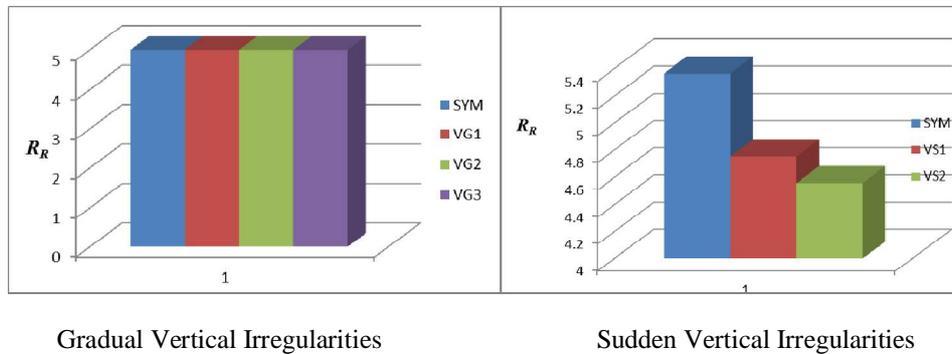


Fig 6.6.2-Comparison of Response reduction factors having irregularity in elevation

Table 4 Response reduction factor for modelled buildings

SR. NO	DESIGNATION	TYPE	R_S	R_μ	R_R	R	CODAL VALUE
1	SYM	Regular	2.65	2	1	5.3	5
2	PC1	Re-entrant corner plan irregularity	2.38	2	1	4.78	5
3	PC2	Re-entrant corner plan irregularity	2.1	1.98	1	4.17	5
4	PC3	Re-entrant corner plan irregularity	1.69	1.97	1	3.35	5
5	PC4	Re-entrant corner plan irregularity	1.64	1.96	1	3.24	5
6	PD1	Diaphragm type plan irregularity	2.14	1.94	1	4.16	5

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7	VG1	Gradual vertical type irregularity	2.79	1.94	1	5.4	5
8	VG2	Gradual vertical type irregularity	2.86	1.9	1	5.4	5
9	VG3	Gradual vertical type irregularity	2.9	1.84	1	5.3	5
10	VS1	Sudden vertical type irregularity	2.52	1.88	1	4.75	5
11	VS2	Sudden vertical type irregularity	2.42	1.87	1	4.55	5

6.7. Conclusions:

On the above building frames the nonlinear static pushover analysis is performed to investigate the performance point of the building frame in terms of base shear and displacement. The various load combinations are also used for this purpose. After pushover analysis the demand curve and capacity curves are obtained to get the performance point of the structure. The performance point is obtained as per ATC 40 capacity spectrum method. From the above study followings conclusions were drawn.

1. The evaluated value of “R” in the present work were obtained by nonlinear static (pushover) analysis of structures with horizontal irregularities are found to be less than as those specified in the IS 1893.
2. As percentage of horizontal irregularities increases, the response reduction factor is goes on decreasing.
3. A response reduction factor for structures having sudden vertical irregularities are less than those specified in the IS 1893.
4. As percentage of sudden vertical irregularities increases, the response reduction factor is goes on decreasing.
5. A structure with gradual irregularities in elevation does not show considerable deviation in response reduction factor.
6. Amongst all these ductile or non-ductile behaviour plays important role as, it’s related with response factor R, hence more efforts is needed to work out the corresponding value of R which will show the realistic seismic performance.

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