Proceedings of 12th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: October Volume: 12

Seismic Response Modification Factor Estimation of Vertically Mixed Structure (Reinforced Cement Concrete and Steel)

Subodh Panthi [a], Gokarna Bahadur Motra [b]

[a] *Department of Civil Engineering, Thapathali Campus, IOE, Tribhuvan University, Nepal*
[b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
✉ [a] subodh76mseqe17@tcioe.edu.np, [a] subodhpanthi11@gmail.com, [b] gmotra@ioe.edu.np

Abstract

To design a building which is able to withstand earthquake load without undergoing any kind of deformation would be uneconomical. The goal of making the building structure economical and achieve life safety has resulted in the adaptation of a certain factor that is used to significantly reduce the lateral load experienced by the building, known as seismic response modification factor or response reduction factor. Practice of constructing buildings with lower RCC and upper steel structural elements has increased since the 2015 Gorkha earthquake. For performance evaluation and comparison of such buildings, a total of forty-two building models consisting of twenty-eight vertically mixed buildings, seven pure concrete buildings and seven pure steel buildings of two, three, four, five, six, seven and eight stories are analyzed. Monotonic pushover analysis is performed to obtain force-deformation curve and calculation is done to obtain ductility factor, redundancy factor, overstrength factor and finally response reduction factor. The study showed the value of five, as provided in IS 1893 2016 for special moment resisting frame to be suitable for the selected vertically mixed models of regular configuration.

Keywords

mixed, response modification factor, response reduction factor, ductility, overstrength, redundancy

1. Introduction

1.1 Background

Nepal lies between Indian and Tibetan tectonic plates and has experienced at least one major earthquake each century since the first documented record of the earthquake on 7th June, 1255. Structures are designed with sufficient stiffness and strength as specified by different international codes of practice to ensure desired performance in the event of an earthquake. The design force as specified in the codes are obtained by dividing the actual force by a certain factor called seismic response modification factor (R). Different values of such seismic response reduction factor are provided in codes relying on the inelastic behavior of the structure. The buildings are categorized as per moment resisting frame type and the value depends on over strength factor (R_S), ductility factor (R_μ) and redundancy factor (R_R).

Use of steel sections as structural members in existing RCC buildings has resulted in the construction of structures having mixed structural systems which have both RCC and Steel as structural components. Observing recent construction practices of mixed structure has shown the use of both steel and RCC in same floor levels with certain portion made up of RCC and the other portion of Steel but most of the

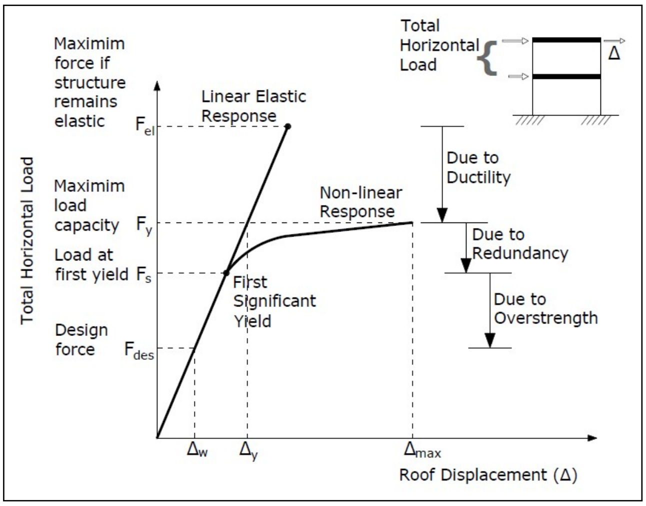

Figure 1: Definition of response reduction factor.

mixed structures are made up of lower RCC stories and upper steel stories resulting in the lower rigid and upper flexible stories. Hence, this study deals with the calculation of seismic response reduction factor for such kinds of vertically mixed structures.

1.2 Objectives

This study has the following research objectives:

1. To calculate the value of seismic response modification factor for different configuration of vertically mixed buildings.
2. To evaluate deviation of the calculated seismic response modification factor to that of pure concrete, pure steel and codal provisions.

2. Literature Review

Past studies show multiple investigation on RCC or steel structures but the study on mixed structures is limited. Monotonic pushover analysis is selected as the most suitable analysis method due to its accuracy, similarity to dynamic analysis and computational advantage.

Bhattarai, Abishek (2022), calculated response reduction factor for fifteen Steel-RC hybrid buildings which comprised of 4 models of 3 storey, 5 models of 6 storey and 6 models of 9 storey of regular configuration. He identified that the value of response reduction factor decreases with the increase in number of stories due to decrease in overstrength of the structure. He also pointed out that response reduction factor shows sudden decrease with the introduction of steel stories but increases with further addition of steel stories.[1]

Fanaie, N. and Shamlou, S. (2015), performed over 4600 nonlinear analyses using 15 earthquake records on 17 structures of 5, 9 and 15 stories with different numbers of concrete and steel stories to calculate ductility factor, overstrength factor and response reduction factor. They concluded that the values of response reduction factor of mixed structures are lower than that of pure concrete or pure steel structures. This was observed to be more obvious in 9 storey structures and hence construction of 9 storey mixed structures is deemed to be risky. [2]

ATC-19 (1995) reviews the role of seismic response modification factor in the design of buildings and proposes its systematic and methodical evaluation by calculation of its components. It also concludes that a single value of R for a given frame type, irrespective of the plan and vertical geometry cannot be justified. It splits seismic response modification factor in terms of reserve strength, ductility and redundancy and proposes its calculation using commercially available analytical tools. [3]

Lee et al. (2005), studied overstrength factors for five, ten and fifteen stories RCC buildings of low and high seismicity regions using three dimensional static pushover analysis and concluded that the overstrength factor in low seismicity regions is higher in comparison to high seismicity region when structures are designed with same response modification factor. They have reported factor ranging from 2.3 to 8.3. [4]

Newmark, N. M.; Hall, W. J. (1982), provided relationships that can be used to estimate the ductility factor (R_μ) for elasto-plastic single degree of freedom systems. [5]

Krawinkler, H.; Nassar, A. A. (1992), provided a $R_\mu - \mu - T$ relationship for SDOF system on rock or stiff soil sites using the result of statistical study based on fifteen western United States ground motion records from earthquakes ranging in magnitude from 5.7 to 7.7. They also studied the implication of extending their relationship to MDOF systems. Their objective was to develop a procedure where the maximum storey displacement ductility ratio in a MDOF system could be limited to the corresponding ductility ratio in the single degree of freedom system. [6]

Miranda, E,; Bertero, V. V. (1994), provided general $R_\mu - \mu - T$ equations for rock, alluvium and soft soil sites developed using 124 ground motions recorded on a wide range of soil conditions assuming five percent critical damping. [7]

Tena-Colunga, A.; Cortés-Benítez, J. A. (2015), performed formal assessment of the redundancy factor for reinforced concrete special moment resisting frame by analyzing 4, 8, 12 and 16 storey buildings of varying number of bays. They concluded that it is justifiable to account directly the structural redundancy in the design by using a redundancy factor as currently proposed and adapted in some international codes. [8]

Amiri, R.; Patel, T. (2018), calculated redundancy factor and response reduction factor for five storey building models with one, two, three, four and five bays in X-direction. With the increase in number of bays, they found that both redundancy and response reduction factor increase. This value is found to be critical in the direction with smaller number of bays. The study showed that the selected building models failed to achieve the target value of response reduction factor as recommended by IS 1893 2016. [9]

3. Methodology

The philosophy of earthquake resistant design of structures is that a atructure should be able to resist the earthquake forces without complete collapse while damages to structural and non-structural elements are permitted to a certain extent ensuring life safety. Seismic coefficient method and response spectrum method are the most widely used methods of earthquake resistant design of structures but they are unable to capture the inelastic behavior of a structure and its members. Pushover analysis incorporates the inelastic static analysis in the design phase and has hence been adapted as the means to obtain the required seismic response modification factor.

3.1 Modeling

Finite element modeling on structural analysis software Etabs 2018 v18.0.2 has been selected for the modeling and analysis of the building models for this study. For each storey building type, pure RCC and pure Steel each are also analyzed and all the possible combinations consisting of upper steel and lower RCC buildings are analyzed. The mixed building models comprise of a single transition storey interface of RCC and steel. Rectangular concrete frames are used for columns and beams and hollow square section and I-Section are used for steel columns and beams respectively. The connection for all types of joints is assumed to be rigid and floor diaphragm is assumed to be fully rigid for all floors. Fixed support is provided at the base if each column.

In a similar pattern to the nomenclature example above, five, six, seven and eight storey building models are named. Grade of selected concrete is M20, rebar is Fe500 and Steel is Fe250. Five grid lines are selected in each axis with a spacing of four meters and a storey height of three meters.

Table 1: Building Nomenclature Example.

No. of stories	No. of RCC Stories	No. of Steel Stories	Nomenclature
2	2	0	2C-0S
	1	1	1C-1S
	0	2	0C-2S
3	3	0	3C-0S
	2	1	2C-1S
	1	2	1C-2S
	0	3	0C-3S
4	4	0	4C-0S
	3	1	3C-1S
	2	2	2C-2S
	1	3	1C-3S
	0	4	0C-4S

Table 2: Preliminary Section Properties.

Section Types	Size (mm)
Concrete Column	350 x 350
Concrete Beam	230 x 350
Concrete Slab	127
Steel Column	Hollow square section 150x150x6
Steel Beam	ISMB 200

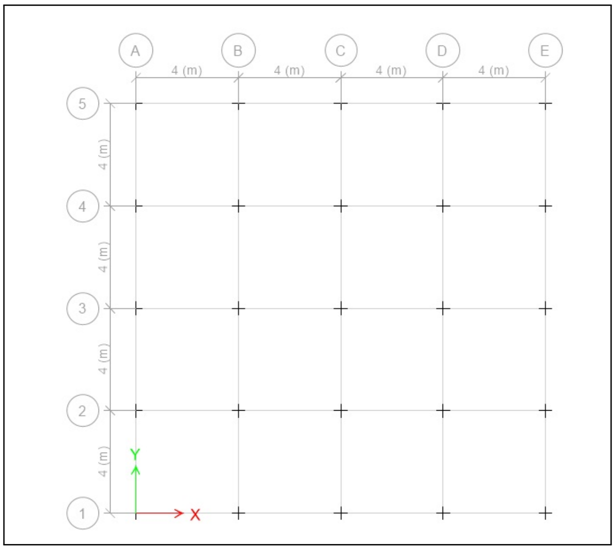

Figure 2: Grid layout for modeling.

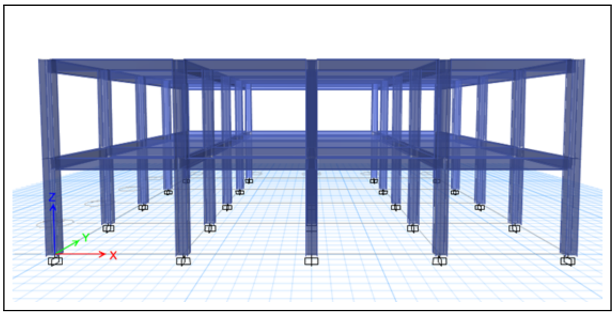

Figure 3: Sample 3D Model of building in Etabs2018 (2C-0S).

3.2 Analysis

The above mentioned building types are modeled in Etabs2018 with all the aforementioned assumptions and all kinds of loads are applied to the models. $11.11kN/m$ for 230mm walls without opening, $7.77kN/m$ for 230mm walls with opening, $6.13kN/m$ for 127mm walls without openings and $4.3kN/m$ for 127mm walls with openings. Live load is applied as $2.0kN/m^2$ for normal rooms, $3.0kN/m^2$ for balcony, corridor and staircase. Live load on the roof is taken as $1.5kN/m^2$. Floor finish load is applied as $1.5kN/m^2$.

Linear static analysis, response spectrum analysis and non-linear static pushover analysis are performed on the building models. Zone factor is taken as 0.36, importance factor as one and response reduction factor as five. Medium soil type is selected for the study. Response Spectra as provided in the IS 1893 2016 has been adopted for the analysis. After linear static analysis and response spectrum analysis, displacement controlled pushover analysis is performed on the model to obtain base shear versus displacement plot. Nonlinear behavior of the frame elements is represented by the specified hinges in the software. Auto hinges are assigned for the frame elements as P-M2-M3 in column and M3 in beam at relative distance of 0.1L and 0.9L.

3.3 Theoretical Calculation

Response reduction factor(R) is calculated as a product of ductility factor(R_μ), overstrength fator(R_S) and redundancy factor(R_R). Mathematically:

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

Overstrength factor is obtained as:

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

Redundancy factor is obtained as:

$$R_R = \frac{V_u}{V_y} \tag{3}$$

Ductility factor is obtained using Miranda and Bertero relationship as:

$$R_\mu = \frac{\mu - 1}{\emptyset} \tag{4}$$

where, for alluvium sites:

$$\emptyset = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T} e^{-2(\ln(T)-0.2)^2} \tag{5}$$

Here, V_y is idealized yield base shear, V_u is ultimate base shear, V_d is design base shear, μ is global ductility demand and T is time period of the structure.

4. Results and Discussions

4.1 Numerical Computation

Linear Static Analysis, Response Spectrum Analysis and Pushover Analysis were performed on the selected forty-two models and the information shown in table 3 is extracted.

Sample Calculation of 2C-0S model is shown below: Taking required data from table 3,

R_S = V_y/V_d = 4.404

R_R = V_u/V_y = 1.153

μ = Δu / Δy = 3.186

R_μ = 2.835

Hence, R = 7.197

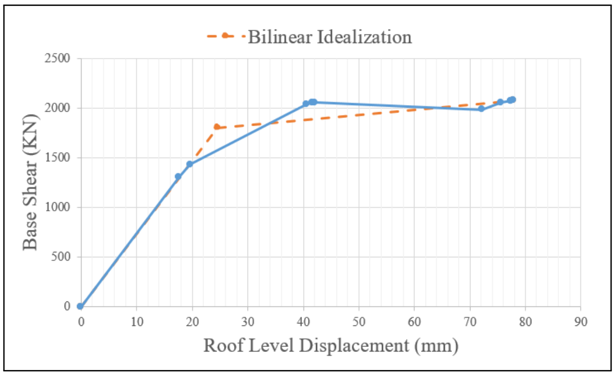

Figure 4: Pushover Curve for 2C-0S model.

Table 3: Values obtained from Linear Static Analysis, Response Spectrum Analysis and Static Pushover Analysis.

SN	No. of Storey	Model Name	Design Base Shear (V_d)	Time Period (T)	Ultimate Displacement (Δu)	Yield Displacement (Δy)	Base Shear at Idealized Yield Point (V_y)	Base Shear at Ultimate Displacement (V_u)
1	2	2C-0S	408.975	0.450	77.909	24.450	1801.151	2076.645
2		1C-1S	363.077	0.521	99.302	41.821	2020.285	2469.764
3		0C-2S	197.841	0.893	116.008	73.233	1075.000	1219.402
4	3	3C-0S	513.021	0.707	92.799	43.333	2065.824	2588.110
5		2C-1S	455.580	0.741	109.436	57.459	2104.981	2559.897
6		1C-2S	349.029	0.896	149.433	80.051	1961.101	2506.228
7		0C-3S	257.019	1.141	136.387	96.523	1388.536	1564.353
8	4	4C-0S	513.743	0.971	113.677	61.899	2141.121	2729.163
9		3C-1S	493.672	0.968	123.442	67.059	2037.781	2708.200
10		2C-2S	429.364	1.056	143.194	79.524	1926.672	2674.177
11		1C-3S	351.245	1.209	185.035	111.282	1990.759	2627.776
12		0C-4S	280.515	1.429	190.894	133.548	1660.005	1908.266
13	5	5C-0S	516.755	1.244	157.000	106.618	2905.191	3474.666
14		4C-1S	506.462	1.220	165.770	109.812	2779.176	3403.949
15		3C-2S	467.741	1.268	156.066	85.898	1874.283	2820.026
16		2C-3S	413.380	1.367	178.495	97.991	1794.839	2778.460
17		1C-4S	356.725	1.505	222.100	131.473	1919.253	2731.022
18		0C-5S	306.394	1.674	211.594	161.274	1844.772	2006.283
19	6	6C-0S	515.566	1.511	183.946	112.128	2502.081	3754.804
20		5C-1S	510.914	1.484	189.571	104.921	2252.922	3693.273
21		4C-2S	487.085	1.505	206.404	125.292	2421.437	3602.054
22		3C-3S	449.665	1.568	224.569	131.114	2222.189	3445.978
23		2C-4S	405.425	1.670	256.106	165.652	2408.759	3333.192
24		1C-5S	364.330	1.782	295.423	200.594	2510.095	2940.339
25		0C-6S	324.806	1.925	237.924	181.111	1902.957	2132.189
26	7	7C-0S	574.143	1.645	231.548	141.512	3231.123	4694.645
27		6C-1S	569.755	1.608	242.480	159.477	3421.195	4750.122
28		5C-2S	548.461	1.619	258.266	172.548	3400.029	4629.002
29		4C-3S	515.390	1.670	276.175	188.849	3344.444	4496.019
30		3C-4S	467.919	1.782	306.674	209.896	3212.657	4255.099
31		2C-5S	423.939	1.903	328.754	231.011	3093.393	3657.176
32		1C-6S	387.348	2.013	326.918	221.222	2624.242	3074.568
33		0C-7S	352.326	2.154	278.665	211.121	2133.789	2340.218
34	8	8C-0S	571.245	1.904	259.125	185.091	3636.366	4671.880
35		7C-1S	569.540	1.846	236.858	170.282	3303.999	4332.600
36		6C-2S	556.194	1.840	260.983	199.199	3555.252	4392.716
37		5C-3S	531.606	1.866	290.655	211.111	3478.825	4492.436
38		4C-4S	495.942	1.938	319.284	218.063	3222.985	4416.194
39		3C-5S	457.583	2.032	384.191	265.009	3503.883	4397.391
40		2C-6S	421.767	2.132	455.404	279.235	3295.595	3920.782
41		1C-7S	384.977	2.255	429.700	252.867	2659.912	3201.373
42		0C-8S	352.624	2.391	348.457	244.124	2206.643	2394.178

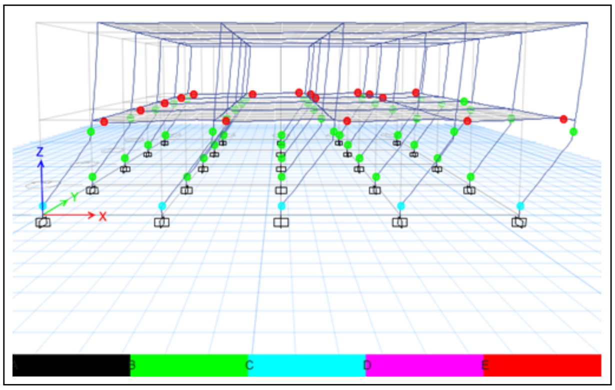

Figure 5: Hinge result for 2C-0S model

Similar to the sample calculation shown above, required modification factors are calculated for all the forty-two selected models. The values obtained are shown in the table 4.

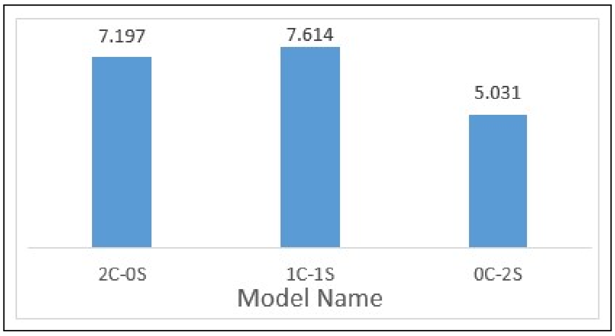

Figure 6: Response reduction factor for 2 storey models.

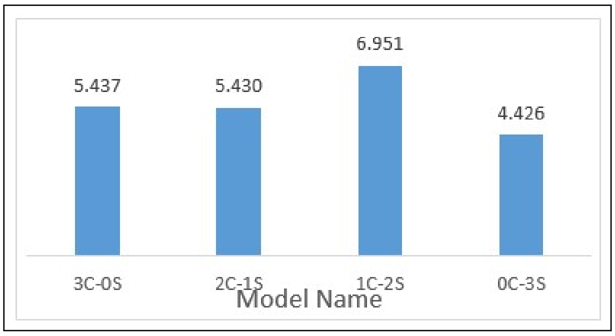

Figure 7: Response reduction factor for 3 storey models.

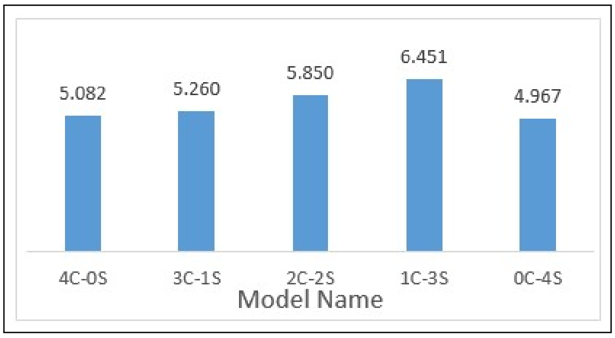

Figure 8: Response reduction factor for 4 storey models.

4.2 Results

The values of Seismic Response Modification Factors calculated in table 4 are diagrammatically represented in figures 6, 7, 8, 9, 10, 11, 12 and 13 as shown below.

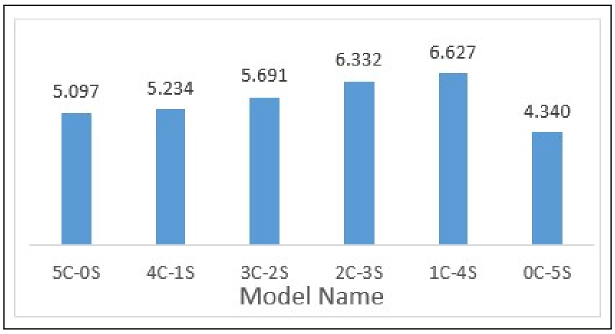

Figure 9: Response reduction factor for 5 storey models.

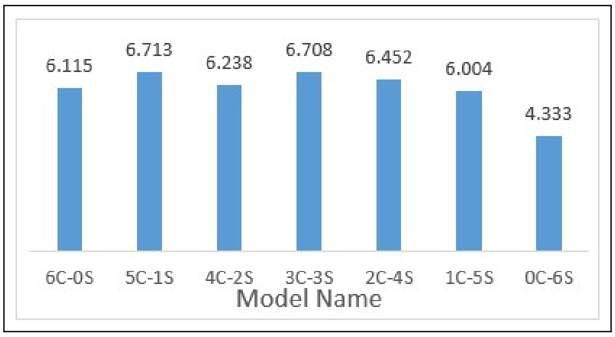

Figure 10: Response reduction factor for 6 storey models.

Table 4: Calculation of Response Reduction Factors.

SN	No. of Storey	Model Name	R_S	R_R	R_μ	R
1	2	2C-0S	4.404	1.153	2.835	7.197
2		1C-1S	5.564	1.222	2.239	7.614
3		0C-2S	5.434	1.134	1.633	5.031
4	3	3C-0S	4.027	1.253	2.156	5.437
5		2C-1S	4.620	1.216	1.933	5.430
6		1C-2S	5.619	1.278	1.936	6.951
7		0C-3S	5.402	1.127	1.454	4.426
8	4	4C-0S	4.168	1.275	1.913	5.082
9		3C-1S	4.128	1.329	1.918	5.260
10		2C-2S	4.487	1.388	1.879	5.850
11		1C-3S	5.668	1.320	1.725	6.451
12		0C-4S	5.918	1.150	1.460	4.967
13	5	5C-0S	5.622	1.196	1.516	5.097
14		4C-1S	5.487	1.225	1.557	5.234
15		3C-2S	4.007	1.505	1.888	5.691
16		2C-3S	4.342	1.548	1.884	6.332
17		1C-4S	5.380	1.423	1.731	6.627
18		0C-5S	6.021	1.088	1.326	4.340
19	6	6C-0S	4.853	1.501	1.679	6.115
20		5C-1S	4.410	1.639	1.857	6.713
21		4C-2S	4.971	1.488	1.687	6.238
22		3C-3S	4.942	1.551	1.751	6.708
23		2C-4S	5.941	1.384	1.570	6.452
24		1C-5S	6.890	1.171	1.488	6.004
25		0C-6S	5.859	1.120	1.320	4.333
26	7	7C-0S	5.628	1.453	1.665	6.807
27		6C-1S	6.005	1.388	1.546	6.447
28		5C-2S	6.199	1.361	1.521	6.419
29		4C-3S	6.489	1.344	1.483	6.466
30		3C-4S	6.866	1.324	1.476	6.711
31		2C-5S	7.297	1.182	1.432	6.178
32		1C-6S	6.775	1.172	1.484	5.890
33		0C-7S	6.056	1.097	1.322	4.389
34	8	8C-0S	6.366	1.285	1.409	5.760
35		7C-1S	5.801	1.311	1.401	5.330
36		6C-2S	6.392	1.236	1.319	5.207
37		5C-3S	6.544	1.291	1.386	5.857
38		4C-4S	6.499	1.370	1.473	6.558
39		3C-5S	7.657	1.255	1.455	6.992
40		2C-6S	7.814	1.190	1.634	7.596
41		1C-7S	6.909	1.204	1.698	7.062
42		0C-8S	6.258	1.085	1.425	4.838

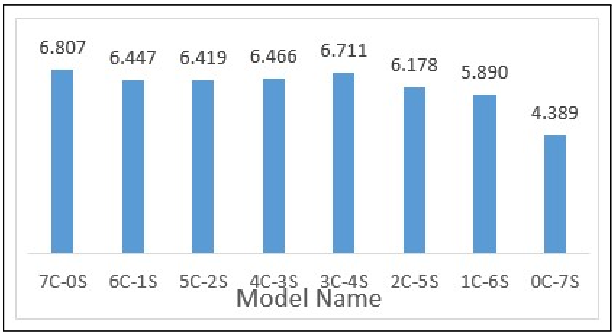

Figure 11: Response reduction factor for 7 storey models.

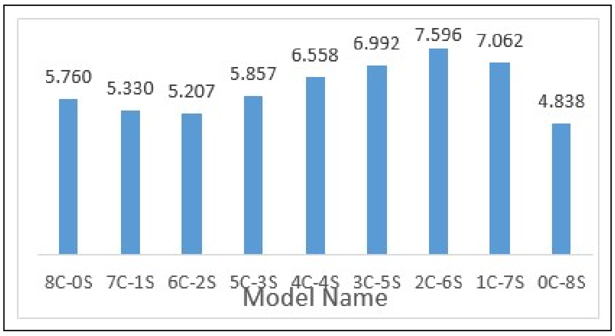

Figure 12: Response reduction factor for 8 storey models.

4.3 Discussions

Here, it can be observed that the time period of the building gradually increases with the introduction of steel stories as a result of the increased flexibility and reduced stiffness of the steel stories. The seismic weight of the building decreases with the use of steel stories resulting in reduced design base shear (Vd), base shear at idealized yield point (Vy) and base shear at ultimate displacement (Vu). Storey displacement and stiffness graphs show the variation in displacement and stiffness with the introduction of steel stories. Displacement is increased with the steel story replacing a RCC storey and there is significant decrement in stiffness. The graphs show comparison among the selected models for this study.

The steel and RCC interface consists of lower rigid and upper flexible storey. Increased displacement and reduced stiffness of steel stories show the connection of RCC and Steel stories to be sensitive point in the selected mixed building models. Well engineered rigid connection is required for safe transfer of forces and moments. Cross bracing may be provided in the sensitive interface storey to ensure gradual decrease in stiffness in the upper steel stories as suggested in past studies on mixed structures. In each storey models, the overstrength factor generally increases with the reduction of concrete stories and addition of steel stories. This is because the size of columns are provided constant for a particular storey models resulting in higher stiffness models for reduced base shear and seismic weight.

With the addition of steel stories, time period of the structure increases resulting in decreased ductility demand of the structure. This results in the decrement of ductility factor with the increase in number of steel stories. Redundancy factor is also observed to decrease with the increase of steel stories however, its value always remains greater than 1 for the multiple bay building models selected for the study.

For two storey models, response reduction factor for mixed building is calculated to be similar to that of pure concrete building but 51.34% more than that of pure steel building. For two, three, four and five storey models, maximum value of response reduction factor is calculated for 1C-1S, 1C-2S, 1C-3S and 1C-4S building models respectively i.e. vertically mixed buildings with lower one storey RCC and upper storeys steel. For six storey models, the value of response reduction factor gradually increases with the addition of steel stories up to when there are equal number of steel and RCC stories i.e. 3C-3S model. The value then gradually decreases with the further addition of steel stories and is the lowest for pure steel building.

For seven storey models, the value of response reduction factor gradually decreases with the introduction of steel stories and is minimum for pure steel structure while for eight storey models, R value decreases up to 6C-2S model and then increases. It is maximum for 2C-6S model i.e. 7.596 and then decreases with the addition of steel stories.

Of the forty-two models selected in this study, there are seven pure reinforced cement concrete buildings, seven pure steel buildings and twenty-eight vertically mixed buildings. The calculated values of seismic response modification factor of the forty-two models show that the value for vertically mixed buildings is similar to that of pure reinforced cement concrete building. The value is found to be greater than five as provided in IS 1893 2016, in all the vertically mixed and pure RCC models. This is because the building models selected are symmetrical and both vertically and horizontally regular in configuration. The number of bays and grid spacing are same in both X and Y directions. Rigid joints are assumed at all connections and the buildings are assumed to be designed and constructed following all the ductility and design guidelines.

The calculated value of response reduction factor of only one pure steel building model is greater than five. Two storey pure steel model i.e. 0C-2S has R value of 5.031. Response reduction factor is calculated to be less than five for three, four, five, six, seven and eight storey pure steel buildings. Redundancy factor and ductility factor are calculated to be the lowest for pure steel buildings which finally result in lower value of seismic response reduction factor.

5. Conclusion and Recommendation

In this way, linear static analysis, response spectrum analysis and nonlinear static pushover analysis were performed on the forty-two models of two, three, four, five, six, seven and eight stories with all possible combination of upper steel and lower RCC stories as well as one pure steel and one pure RCC for each storey. Based on the results obtained from the model analysis, the values of overstrength factor, redundancy factor and ductility factor are calculated whose product finally gives the value of seismic response reduction factor(R). The following conclusion can be derived on the basis of the results obtained:

1. The values of response reduction factor vary greatly depending on the number of steel stories for vertically mixed buildings.
2. The design base shear, base shear at yield point and ultimate base shear are observed to decrease with the increase in steel stories while time period increases with the addition of steel stories.
3. Proper provision should be made in the codes to address redundancy factor as its value is found to be a minimum of 8.50 % to a maximum of 63.90 % greater than codal provision for the multi-bay building models selected in this study.
4. The calculated value of response reduction factor is found to be less than 5 for pure steel building models (6 out of 7 models). As IS 1893 2016 suggests the value: five for special moment resisting frames, the study shows a more detailed investigation and appropriate modifications necessary in the codal provisions.
5. The study shows a response reduction factor of five to be sufficient for the design of vertically

mixed buildings. This does not necessarily mean that it is appropriate for all types of mixed buildings. Further investigation is required for the horizontally mixed structures and structures with irregular configuration having non-parallel load resisting systems.

References

[1] A. Bhattarai. Response reduction factor of steel-rc hybrid structure. 2022.

[2] N. Fanaie and S. O. Shamlou. Response modification factor of mixed structures. 2015.

[3] Applied Technology Council. Structural response modification factors. 1995.

[4] D.G. Lee, S.H. Cho, and H. Ko. Response modification factors for seismic design of building structures in low sesimicity regions. 2005.

[5] N.M. Newmark and W.J. Hall. Earthquake spectra and design. 1982.

[6] A. A. Nassar and H. Krawinkler. Seismic demands for sdof and mdof systems. 1991.

[7] E. Miranda and V. V. Bertero. Evaluation of strength reduction factors for earthquake-resistant design. 1994.

[8] A. Tena-Colunga and J. A. Cortés-Benítez. Assessment of redundancy factors for the seismic design of special moment resisting reinforced concrete frames. 2015.

[9] R. Amiri and T. Patel. Assessment of seismic response reduction factor according to redundancy of rc buildings. 2018.