Received Date: 5th November, 2022
Accepted Date: 10th April, 2023

Response Reduction Factor of Steel – RC Hybrid Structure

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***Abstract*—Civil Engineering structures should have sufficient strength and stiffness to control deflection and prevent possible collapse of the structure during a seismic event. The design force levels currently specified by most seismic codes are calculated by dividing the base shear for elastic response by the response modification factor (R). Seismic codes consider a reduction factor in designing the loads in order to cause the structure to enter into the nonlinear behavior region and then use the advantages of its energy dissipation. The seismic response of such mixed structure having different structural system at different floor levels is entirely different to the response of the pure steel or RC structure. During an earthquake excitation, upper steel stories behave as a structure built upon a fixed base RC structure. So, the response of such structure needs to be studied and the computation of appropriate response reduction factor is required in order to minimize the risk.**

***Keywords* — Base shear, Ductility, Pushover analysis, Redundant, Response reduction factor, Seismic response**

I. Introduction

There is extensive growth in construction of high rise building in present scenario. Based on utility and structural requirements, addition of further RC stories may not be feasible due to which addition of steel stories above it will be the better option which lead to the construction of steel – RC hybrid structure. Also, the steel frame building resting on the fixed RC Mat footing or RC basements gives Steel – RC transition which leads to hybrid structure. But there is no specific consideration in codes for determining the response reduction factor of hybrid structures. The response of lower RC floor is completely different in comparison to that of upper Steel story. Upper steel structure behaves as an individual structure built upon fixed base concrete floor. The level of excitation of two entirely varying story in terms of mass and stiffness causes complex mechanism. So, in order to determine the actual response, we need to study and analyze the structural behavior of such structures.

The concrete stories are considered along with the steel stories for different application such as store, car park, stockroom etc. in the mixed structure due to the advantage of concrete parts such as their fire proof specifications. The structure taken into consideration are composed of upper steel stories of the building and lower RC stories. These structural systems have non-uniform distribution of stiffness, mass, material and damping in vertical direction. Upper steel stories are considered as the flexible part and lower RC stories are considered as the rigid part of the building in relative comparisons. All hybrid stories consist of one transition storey interface of steel and RC.

Rectangular concrete frames (both beams and columns) are used for RC stories and Steel channel section and Steel I-sections are used for steel columns and beams respectively. The structural system considered for this building is categorized under 3 storey, 6 storey and 9 storeys building with the following sub divisions:

TABLE 1

Hybrid structures considered for modeling

No of stories (N)	Structure Name	No of steel stories (N_S)	No of concrete stories (N_C)	$K = N_S / N$
3	0S3C	0	3	0
	1S2C	1	2	0.333
	2S1C	2	1	0.667
	3S0C	3	0	1
6	0S6C	0	6	0
	2S4C	2	4	0.333
	3S3C	3	3	0.5
	4S2C	4	2	0.667
	6S0C	6	0	1
9	0S9C	0	9	0
	2S7C	2	7	0.222
	4S5C	4	5	0.444
	5S4C	5	4	0.556
	7S2C	7	2	0.778
	9S0C	9	0	1

TABLE 2

Material properties

Sections	Initial Size (in mm)
Steel Beam	ISMB 125
Steel Column	Double channel section and I-sections
Concrete Beam	10” x 14”
Concrete column	14” x 14”
Slab	5”

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II. Methodology

A. Numerical Modeling

The numerical modeling of all the above-mentioned structures is performed in SAP 2000 v20. This program is finite element software which is capable of conducting Linear static analysis, nonlinear static Pushover analysis and step by step non-linear time history analysis. The connection for all types of joints (steel-steel, concrete-concrete, steel-concrete) is assumed to be rigid. The upper steel storeys are assumed to rest on fixed base concrete floors. RC floors with rigid diaphragm are considered for all floors.

Symmetrical grid of 6 bay in each direction is provided for each building. Length of bay in both X and Y direction is 4m

TABLE 3

Sections	Initial Size (in mm)
Steel Beam	ISMB 125
Steel Column	Double channel section and I-sections
Concrete Beam	10” x 14”
Concrete column	14” x 14”
Slab	5”

Section properties

B. Analysis

Analytical approach will be adopted for this research. Selected representative buildings are modeled in SAP with proper approximation of design procedure to be adopted, assumptions to be made and input and output from the analysis. Linear static analysis (Seismic Coefficient method), Linear dynamic (Response Spectrum) Analysis and Non-linear Static (Pushover) Analysis are performed for determination of Base shear for different condition. Seismic inputs in the structures are provided based on IS 1893:2016

Linear static analysis is conducted using seismic coefficient method. The response reduction factor for the initial analysis is taken as that recommended by IS 1893: 2016. Design base shear of the structure is determined from the analysis.

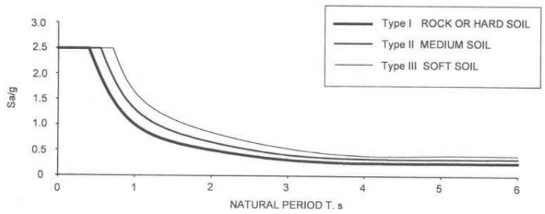

Fig 1: Spectra for equivalent static method (IS 1893: 2016)

Pushover is basically static non-linear analysis by which the response of the building structure can be calculated under non-linear loadings like earthquake. It is referred as the ideal method for representing the non-linear behavior of the structure. Nonlinear static analysis is performed in the building to obtain the pushover curve. In pushover analysis, the structure is subjected to monotonically increasing lateral loads, which represents the inertial forces the structure shall experience when the seismic event occurs. Pushover analysis result gives the sequential plastic hinge formation and state of hinge at various level of building performance. The bilinear idealization of pushover curve thus obtained can be used to evaluate the parameters required to obtain Response Reduction Factor. The performance level of the structure can be idealized by the aid of moment curvature relationship of the weakest member of the structure.

The Capacity Curve or Pushover Curve represents the nonlinear behavior of the structure and is a load-deformation curve of the base shear force versus the horizontal roof displacement of the building. Pushover analysis transforms a dynamic problem to a static problem. Pushover curve is converted into capacity curve, expressed in terms of spectral acceleration vs spectral displacement. The Capacity Curve or Pushover Curve represents the nonlinear behavior of the structure and is a load-deformation curve of the base shear force versus the horizontal roof displacement of the building. Pushover analysis transforms a dynamic problem to a static problem. Pushover curve is converted into capacity curve, expressed in terms of spectral acceleration vs spectral displacement. It is the inelastic response spectrum curve used for calculating the maximum displacement of the structure. The intersection of capacity curve and demand curve gives the actual performance point of the building. The design base shear of the building is optimized at Life safety performance point.

III. Results and discussion

A. Time Period

It is observed that the time period increases with the increase in steel stories. It is due to increase in the flexibility of the structure due to the addition of steel stories. For 3 storey building, time period from static analysis differs with the time period of response spectrum and pushover. The time period from response spectrum nearly coincides to that of pushover analysis. For 6 storey buildings time periods from static analysis smoothly increases with the increase in the steel stories while the time period from response spectrum, there is a sharp increase for 3S3C. The time period from Pushover analysis, there is a sudden decrease from 0S6C to 2S4C even after introduction of steel stories

For 9 stories building there is a continuous increase in time period for static and response spectrum but for pushover analysis there is gradual decrease in time period from 0S9C to 5S4C and then increases with the mild slope from 5S4C to 9S0C.

Storey	Name of storey	Time Period		
		Static	RS	Pushover
3 Storey (H=9m)	0S3C	0.39	0.5997	0.72
	1S2C	0.5302	0.6051	0.677
	2S1C	0.623	0.75565	0.768
	3S0C	0.64	0.967	1.043
6 Storey (H=18m)	0S6C	0.66	0.996	1.374
	2S4C	0.87	1.074	1.079
	3S3C	0.961	1.4	1.198
	4S2C	1.011	1.445	1.478
	6S0C	1.2794	1.82	1.492
9 Storey (H=27m)	0S9C	0.889	1.42	1.701
	2S7C	1.407	1.644	1.675
	4S7C	1.427	1.66	1.618
	5S4C	1.487	1.859	1.604
	7S2C	1.585	2.084	1.669
	9S0C	2.067	2.6	1.816

B. Pushover Analysis

Non-linear static Pushover analysis of 15 buildings were conducted in sap 2000 by defining pushover load cases in X and Y direction. Auto hinges were assigned to the frame elements (M3 hinge on beam and P-M2-M3 hinge on column) at a relative position of 0.1L and 0.9L. The result of pushover analysis was obtained to plot a pushover curve as shown in figure below.

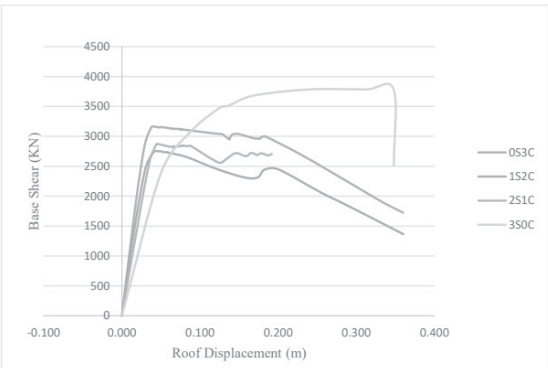

Fig 2: Pushover Curve for 3 storey building

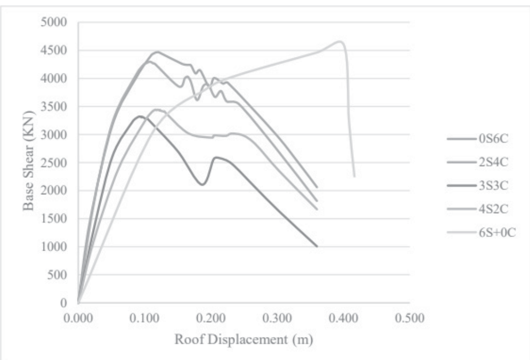

Fig 3: Pushover Curve for 6 storey building

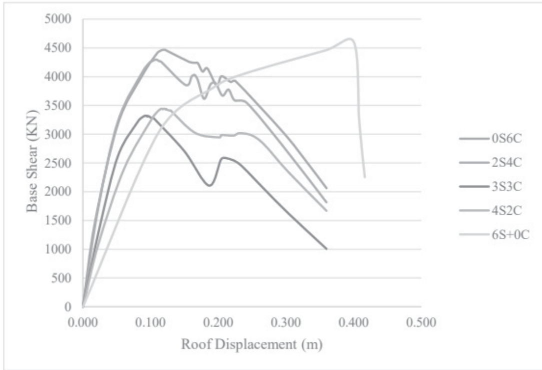

Fig 4: Pushover Curve for 6 storey building

For 3 and 6 storey buildings, pushover curve signifies that more the structure approaches to the steel structure the stiffness and lateral load carrying capacity of the structure decreases while the ultimate displacement increases. But for complete steel structure though the stiffness decreases the ultimate capacity of the structure increases along with increase in ultimate displacement. This is due to the greater plastic moment of resistance of steel sections which increases extent of formation of plastic hinge in the structure.

For 9 storey building, the result of pushover curve is quite different. The stiffness and lateral load carrying capacity decreases from 0S9C to 2S7C. With the increase in steel structure the formation of hinges in lower RC structure initiates failure before the hinge formation in upper steel stories due to which the stiffness of the overall building increases even after the increase in the steel stories in the building. So, the stiffness and capacity of building suddenly increases for 4S5C and decreases slightly for 5S4C and 7S2C. The stiffness of complete steel building is least of all but the ultimate capacity of building is more than that of other.

C. Response Reduction Factor

Similarly, response spectrum curve of IS1893:2016 is taken as the demand spectrum. The point of intersection of demand spectrum and capacity curve gives the actual performance point of the structure. Bilinear idealization of pushover curve was done and the linear range of pushover curve was further extrapolated to intersect it on the demand spectrum and this intersection gives the elastic demand of the structure. The result of pushover analysis in summarized in table given below.

With the increase in number of stories the stiffness of the building decreases, due to which time period increases. Due to increase in time period elastic demand of the structure decreases. So, the ductility factor decreases with the increase in number of steel stories in the building. From above chart we can see that the ductility factor decreases gradually from complete RC building to complete steel building. While the ductility factor increases with the increase in number of stories of the building.

Storey	Name of storey	Base Shear					RRF			
		Elastic Demand	Idealized yield strength	Performance Point BS	Significant Yield Base Shear	Design Base Shear	R_μ	R_R	R_S	R
3 Storey	0S3C	4769.5	3125	2987.8	2852.7	830.6	1.53	1.10	3.43	5.74
	1S2C	4387.5	2785.6	2705.8	2772	815.46	1.58	1.00	3.40	5.38
	2S1C	4058.9	2859.5	2643.5	2704.51	747	1.42	1.06	3.62	5.43
	3S0C	3789.5	3142.7	3094.6	3049.5	595.67	1.21	1.03	5.12	6.36
6 Storey	0S6C	6543.3	4462.5	4394.2	1963.97	1250.8	1.47	2.27	1.57	5.23
	2S4C	5204.5	4223.9	4383.4	1975.6	1205.8	1.23	2.14	1.64	4.32
	3S3C	4732.5	3397.95	3312.768	1898.3	910.5	1.39	1.79	2.08	5.20
	4S2C	4670.2	3490	3745.95	1810.54	843.5	1.34	1.93	2.15	5.54
	6S0C	4398.7	3780	4254.3	3125.29	715.8	1.16	1.21	4.37	6.15
9 Storey	0S9C	7076.7	4618.5	4487.845	1969.3	1480	1.53	2.35	1.33	4.78
	2S7C	5469.2	4917.84	4529.29	3069.76	1400.8	1.11	1.60	2.19	3.90
	4S5C	5879	4897.35	4720.3	2137.56	1342.5	1.20	2.29	1.59	4.38
	5S4C	5671.8	4784.84	4459.607	3296.7	1248	1.19	1.45	2.64	4.54
	7S2C	5082.7	4833.4	5263.83	1883.97	1132.9	1.05	2.57	1.66	4.49
	9S0C	4775	5142.5	2720.218	2720.218	840.54	0.93	1.89	3.24	5.68

Redundancy factor is more or less same for 3 storey buildings as it basically depends upon the number of bays present in the structure. But for 6 storey and 9 storey buildings there is random pattern of redundancy factor with the addition of number of steel stories. Redundancy factor is more or less same for 3 storey buildings as it basically depends upon the number of bays present in the structure. But for 6 storey and 9 storey buildings there is random pattern of redundancy factor with the addition of number of steel stories. Redundancy factor is more or less same for 3 storey buildings as it basically depends upon the number of bays present in the structure. But for 6 storey and 9 storey buildings there is random pattern of redundancy factor with the addition of number of steel stories. Over strength factor increases with the addition of steel stories. The overstrength factor is decreased with the increase in number of stories. For example, the overstrength factor of 6 storey complete RC building is less than that of 3 storey complete RC building.

Response reduction factor value decreases with the increase in number of stories. This is basically due to decrease in over strength of the structure. Response reduction factor shows sudden decrease with the introduction of steel stories but increases with further addition of steel stories. Here, for three story building R value for 0S3C is 5.95 which is decreased to 5.01 for 1S2C with the addition of steel stories. But the R value again increases with the addition of the number of steel stories of the building and is maximum for complete steel structure.

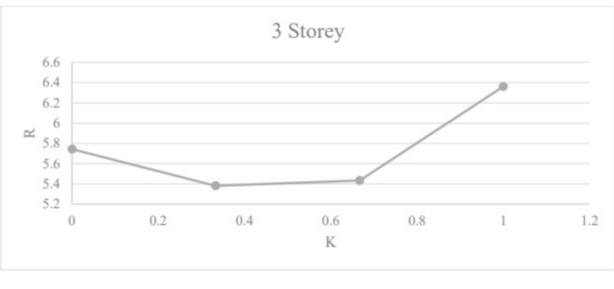

Fig 5: Response Reduction Factor of 3 storey building

The maximum difference in R value between pure RC structure to hybrid structure is 0.36 (6.3%) while that between hybrid and pure steel structure is 0.98 (15.41%).

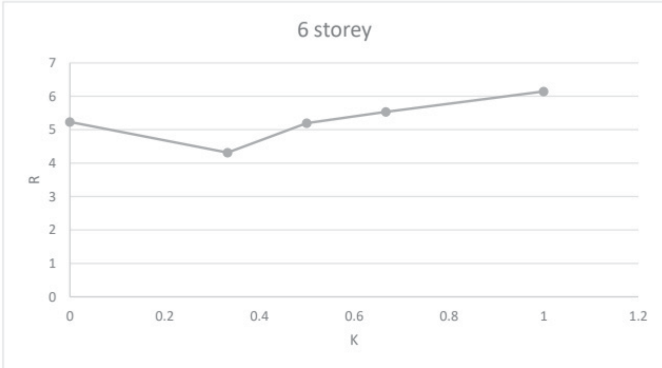

Fig 6: Response Reduction Factor of 6 storey building

For 6 storey building, there is a slight reduction of R value at k = 0.33 and then further increases with the increase in k value. The maximum difference of R value between hybrid structure and pure RC structure is 0.92 (17.6%) and that between hybrid structure and pure steel structure is 1.84 (29.92%). For 9 storey building R value considerable decreased from k=0 to k=0.22 and further increases with increase in value of k up to k=0.556, again decreases at k=0.776 and finally increase at k=1. The maximum difference in R value between hybrid structure and purely RC structure is 0.88 (18.41%) and that of hybrid and purely steel structure is 1.78 (31.34%).

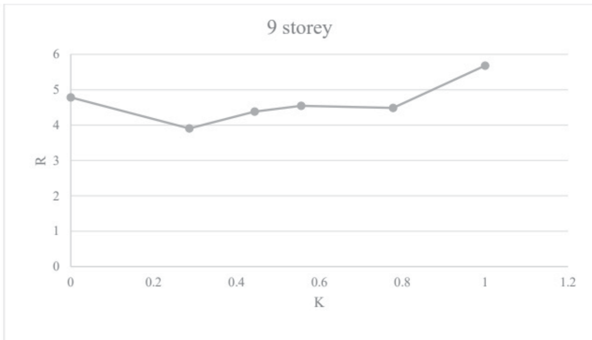

Fig 7: Response Reduction Factor of 9 storey building

The percentage difference in response reduction factor is increased with the increase in number of stories. The maximum percentage difference in R value of hybrid structure to that of pure RC structure for 3 storey building is 6.3% which suddenly increases to 17.6% for six storey and increases slightly to 18.41% for 9 storey buildings.

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IV. Conclusion

Following conclusion can be derived based upon the above results:

i. The value of response reduction factor for hybrid structure is less than that of both pure steel and pure RC structure.

ii. Response reduction factor decreases with the increase in number of stories of the buildings.

iii. Response reduction factor of both steel and RC special moment resisting frames as specified by IS 1893:2016 is 5. For three storey buildings, R value of both steel and RC frame including the hybrid building is more than 5. For six storey buildings, R value of steel and RC frame buildings is more than 5 but that of the hybrid structure is less than 5. For 9 storey buildings, R value for RC frame building along with hybrid structure is less than 5 but for steel frame building it is more than 5. So, the codal provision of response reduction factor is not valid for 9 storey steel frame and hybrid buildings.

iv. The maximum percentage difference between response reduction value of hybrid structure to the code recommended value is 13.6% and 22% for six storey buildings and 9 storey buildings respectively. With the increase in number of stories, the reliability of using same response reduction factor as that of pure steel or pure RC structure for hybrid structure decreases.

v. The maximum percentage difference in response reduction factor of hybrid structure to that of concrete structure are 6.3%, 17.6% and 18.41% for 3 storey, 6 storey and 9 storey building.

vi. The percentage difference of maximum response reduction factor of hybrid structure to that of purely steel structure are 15.41%, 29.92% and 31.34% for 3 storey, 6 storey and 9 storey building.

vii. The maximum percentage difference between response reduction values of hybrid buildings with pure steel or RC frame structure increases with the increase in number of stories

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