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Spectral Seismic Analysis of Reinforced Concrete Structures

Ramneek Paul Singh[1], Er. Ajay Vikram[2]

[1]M Tech Student, University School of Engineering & Technology,
[2]Assistant Professor, University School of Engineering & Technology,
[1,2]Rayat Bahra University, Mohali, Punjab, India

ABSTRACT

In this research the seismic analysis of a multi-tiered reinforced concrete (RC) frame in Jammu city was conducted to determine its functionality under mild tectonic forces. The research focused to investigate the structure response to seismic hazards in compliance with Indian's proposed seismic provisions. The frame was analyzed using the response spectrum method to determine seismic induced movements and stresses. The findings highlighted that the nodal displacements caused displacements exceeding 2-3 times the permissible limits. Horizontal motion substantially affected the axial compression loads of exterior columns compared to interior columns. Additionally compressive stresses in the bottom floor column were 1.5-2 times greater than tensile stresses. Shear forces in beams B505, B506 and B507 due to load combination 3(L/C3) were around three times higher than those due to load combination 1 (L/C1). The maximum compressive and tensile stresses in beams and columns induced by seismic excitation were substantially greater than those caused by gravity loads.

KEYWORDS: *Seismic Analysis, Reinforced Concrete, Loads, Stresses, Shear Force, Columns.*

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INTRODUCTION

Seismic tremors, triggered by shifts in the earth's crust, yield varying degrees of ground tremors, culminating in structural devastation and collapse of buildings and civil infrastructure, landslides on unstable slopes, and soil liquefaction. Recent earthquakes worldwide have underscored the dire consequences of subpar performance of reinforced concrete beam-column connections. These joints are critical zones within reinforced concrete moment-resisting frames, facilitating efficient load transfer between interconnected elements (beams and columns). Traditional seismic design methodologies stipulate that structures should withstand minor, frequent tremors without sustaining damage, ensuring post-event functionality. Structures must also endure moderate earthquake ground motion without structural damage, although some non-structural damage may occur. This performance threshold corresponds to earthquake intensities equivalent to the strongest recorded or predicted at the site. The findings are examined using the response spectrum method. The primary objective of this study is to investigate the seismic resilience of a reinforced concrete moment-resisting frame building subjected to earthquake ground motion. The building, situated in Jammu City (zone 4), was analyzed in accordance with proposed seismic provisions for India.

EARTHQUAKE RESPONSE SPECTRUM ANALYSIS

The response spectrum represents a boundary of maximum potential responses, derived from multiple ground motion records. This approach employs an elastic dynamic analysis methodology, predicated on the assumption that a structure's dynamic response can be determined by analyzing the independent response of each natural vibration mode and subsequently combining these responses in a manner that accurately represents the overall structural behavior. A key advantage of this method lies in the fact that typically, only a limited number of the lowest vibration modes significantly impact the calculation of moments, shear forces, and deflections at various levels of the building.

The following procedure is commonly employed for spectrum analysis:

A. Select a suitable design spectrum.

B. Determine the vibration modes and periods to be incorporated into the analysis.

C. Extract the corresponding response levels from the spectrum for each mode's period.

D. Calculate the participation factor for each mode, which corresponds to the single-degree-of-freedom response read from the curve.

E. Combine the effects of individual modes to obtain the maximum aggregate response.

F. Convert the combined maximum response into shear forces and moments for use in structural design.

RESPONSE SPECTRUM ANALYSIS USING STAADPRO: A PRECISE APPROACH

STAADPro facilitates a comprehensive seismic analysis by computing design lateral forces at each floor level for multiple modes. The software generates results for design values, modal masses, and storey base shear. To derive lateral seismic loads, STAADPro employs the following step-by-step procedure:

A. The program calculates natural time periods for the first six modes or as specified by the user.

B. Utilizing time periods and damping ratios for each mode, the program computes Sa/g values.

C. The program generates design horizontal acceleration spectra (Ak) for various modes.

D. Mode participation factors are calculated for different modes.

E. The peak lateral seismic force at each floor level is computed for each mode.

F. Response quantities, such as displacements and stresses, are calculated for each mode.

G. Finally, the peak response quantities are combined using methods such as Complete Quadratic Combination (CQC), Square Root of the Sum of the Squares (SRSS), Absolute Sum (ABS), Ten Percent (TEN), or Conditional Sum (CSM), as defined by the user, to obtain the final results.

LOAD COMBINATION FOR SEISMIC DESIGN

When designing structures to withstand seismic forces, two possible load combinations can be taken into account:

$$A = DL + LL \times IF + EL \quad (1)$$

$$A = 0.85DL + EL \quad (2)$$

Where:
DL = permanent load (dead weight)
LL = variable load (live load)
IF = live load factor (incidence factor)
EL = seismic load (earthquake load)

BUILDING DETAILS AND CASE STUDY

A conventional eleven-storey residential building with a regular reinforced concrete frame structure, situated in Jammu City, was analyzed to assess its seismic behavior. The building has a rectangular plan with dimensions of 14 m × 22 m. The primary parameters influencing the analysis of this frame were the permanent load, imposed load, and seismic forces. Seismic forces were calculated using the Response Spectrum Approach (RSA). Three load combinations were applied to the structure:

Load Combination 1 (L/C1): Static loads (permanent and imposed) were applied in accordance with the guidelines specified in BS 8110 (1997).

Load Combination 2 (L/C2): Seismic forces were applied.

Load Combination 3 (L/C3): A combination of static and seismic loads was applied.

A uniformly distributed gravity load of 22 kN/m was applied, incorporating the self-weight of structural members. The cross-sectional dimensions of the columns and beams are presented in Table 1

Table 1: Cross-Sectional Dimensions of Columns and Beams in the Frame Building

Floor level	Ground Floor- 5th Floor	6th Floor- 7th Floor	8^{th} Floor- Top
Typical Beam	400mm × 300mm	400mm× 300mm	400mm ×300mm
Column	600mm × 300mm	500mm ×300mm	400mm ×300mm

A critical frame was selected and analyzed using the STAAD PRO software. The same ground acceleration-time period data used in the seismic hazard assessment of Jammu was utilized as input to calculate the seismic response spectrum parameters, including displacements and stresses. A damping ratio of 0.05 (5% of the critical damping) was assumed, and the typical slab thickness was 120 mm. Certain members of the frame building were chosen for analysis purposes. The selected members are-

Columns: C501, C502, C556,C557,C589 and C590

Beams: B505, B506 and B507

Table 2: Frame Member Movement

Frame Node	L/C	Horizontal X	Vertical Y	Horizontal Z	Resultant
1	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 20.541mm 20.540mm	-0.276 mm 1.390 mm 1.120 mm	0.028 mm 0.024 mm 0.055 mm	0.272 mm 20.499 mm 20.479 mm
28	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 54.102mm 54.102mm	-0.519 mm 2.582 mm 2.077 mm	0.119 mm 0.013 mm 0.134 mm	0.528 mm 54.264 mm 54.242 mm
55	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 89.391 mm 89.390 mm	-0.729 mm 3.578 mm 2.850 mm	0.258 mm 0.015 mm 0.270 mm	0.773 mm 89.564 mm 89.538 mm
85	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 123.257mm 123.258mm	-0.920 mm 4.366 mm 3.455 mm	0.440 mm 0.021 mm 0.462 mm	1.018 mm 123.606 mm 123.575 mm
111	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.002 mm 155.272mm 155.272mm	-1.077 mm 4.977 mm 3.884 mm	0.666 mm 0.012 mm 0.676 mm	1.263 mm 155.442 mm 155.414 mm
141	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 188.989mm 188.988mm	-1.236 mm 5.848 mm 4.266 mm	0.925 mm 0.028 mm 0.954 mm	1.545 mm 190.068 mm 190.038 mm
168	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.001 mm 218.762mm 218.761mm	-1.353 mm 5.840 mm 4.480 mm	1.223 mm 0.031 mm 1.255 mm	1.820 mm 219.831 mm 219.801 mm
199	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.003 mm 244.990mm 244.993mm	-1.455 mm 6.030 mm 4.576 mm	1.548 mm 0.025 mm 1.571 mm	2.123 mm 244.055 mm 244.031 mm
230	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 270.210mm 270.209mm	-1.533 mm 6.158 mm 4.630 mm	1.892 mm 0.039 mm 1.934 mm	2.433 mm 269.292 mm 269.266 mm
257	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.005 mm 280.888mm 280.294mm	-1.566 mm 6.184 mm 4.617 mm	0.038 mm 2.272 mm 2.309 mm	2.758 mm 283.953 mm 283.939 mm
302	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.006 mm 293.889mm 293.893mm	-1.653 mm 6.229 mm 4.657 mm	0.048 mm 2.283 mm 2.339 mm	3.011 mm 317.224 mm 317.202 mm

Table 3: Structural Drift Evaluation

Node	L/C	Displacement Resultants	Drift
1	Seismic+ Static	20.479	-
28	Seismic+ Static	54.242	33.751
55	Seismic+ Static	89.538	35.290
85	Seismic+ Static	123.575	34.035
111	Seismic+ Static	155.414	31.833
141	Seismic+ Static	190.038	34.648
168	Seismic+ Static	219.801	29.777
199	Seismic+ Static	244.031	24.230
230	Seismic+ Static	269.266	25.216
257	Seismic+ Static	283.939	14.644
302	Seismic+ Static	317.202 mm	10.947

Table 4: Vertical Stresses In Frame Columns

Column	L/C	Length	Compressive Strength(N/mm^2)	Tensile Strength(N/mm^2)
C501	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	6.855 59.956 63.998	 -36.360 -30.972
C502	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	8.92 54.603 62.903	 -53.48 -46.039
C556	1:DL+LL1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	6.117 34.669 33.743	 -33.632 -32.466
C557	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	5.979 50.821 54.951	 -50.226 -45.973
C589	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	5.682 28.22 30.821	-2.739 -27.588 -29.222
C590	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	3.965 41.205 43.68	 -40.567 -39.102

Table 5: Structural Beam Stress Evaluation

Beam	L/C	Length	Compressive Strength(N/mm^2)	Tensile Strength (N/mm^2)
B505	1:DL+LL 2:Seismic Load 3:Static+Seismic	5 5 5	3.959 56.652 60.116	-3.987 -55.999 -59.925
B506	1:DL+LL 2:Seismic Load 3:Static+Seismic	5 5 5	3.99 50.487 54.255	-3.935 -50.387 -54.222
B507	1:DL+LL 2:Seismic Load 3:Static+Seismic	5 5 5	3.947 56.765 57.848	-3.987 -56.440 -59.118

INTERPRETATION OF ANALYSIS OUTCOMES

The analysis results revealed that the frame experienced a maximum horizontal displacement of 30.39 cm at its uppermost level. This displacement corresponds to approximately 0.96% of the frame's total height. The resulting nodal displacements led to excessive drifts, surpassing the permissible limits. The drift reached a maximum of 33 mm at certain levels, whereas the allowable drift for this frame should not exceed 0.005 times the storey height (12 mm) . In essence, the calculated drifts were roughly 2 to 3 times the allowable limits. Seismic excitation caused axial forces, shear forces, and bending moments to increase in columns and beams. Observations indicate that the axial force due to Load Combination 3 (L/C3) increased in exterior column C001, whereas interior column C002 exhibited an opposite trend, with higher axial forces due to Load Combination 1 (L/C1) compared to C001, and lower axial forces due to L/C3 compared to C001. However, columns at upper floor levels displayed lower force values. These values indicated that horizontal motion has a greater effect on the axial compression loads of the exterior columns compared to the interior columns.

Shear forces resulting from the combined effect of static and seismic loads in interior columns were found to be greater than those in exterior columns and decreased at upper levels. The values of shear forces due to Load Combination 3 (L/C3) in beams B001, B002, and B003 were approximately four times the values due to Load Combination 1 (L/C1). These substantial increases in compressive and shear forces can lead to compression shear failure, particularly if accompanied by inadequate detailing . The seismic excitations caused maximum compressive stresses at the base of C001 and C002. In other columns, these stresses occurred at varying distances along the columns. It is also observed that no tensile stresses were exhibited due to L/C1. Tensile stresses in C001 and C002, generated by seismic excitation, occurred at their base levels. In general, compressive stresses in columns displayed greater values than tensile stresses. The maximum values of compressive and tensile stresses in beams are approximately equal. These stresses primarily occurred at the ends of the beams.

CONCLUSION

Based on the results obtained from the analysis of the reinforced concrete frame building in Jammu city, the following conclusions can be drawn:

1. The interior columns at all floor levels were the most affected by compressive forces resulting from all load combinations.
2. Bending moments in beams and columns due to seismic excitation exhibited significantly larger values compared to those due to static loads.
3. The compressive stresses generated from all load combinations in ground floor columns were greater than tensile stresses in these columns, whereas at other levels, the difference was negligible. The compressive stresses in ground floor columns were approximately 1.5 to 2 times the tensile stresses.
4. Compressive and tensile stresses in the studied beams were approximately equal.
5. The calculated drifts resulting from nodal displacements due to the combination of static and seismic loads were approximately 2 to 3 times the allowable drifts.
6. The frame was inadequate to resist the applied seismic load.

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