The Effect of Gravity Loads on Seismic Lateral Displacements of R.C. Frames

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Author’s contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

ABSTRACT

This paper includes an analytical study for an investigation of the gravity load effect on the seismic lateral displacements of a R.C. building located in Khartoum city (which lies in zone 2, of zone factor, \( z = 0.1 \)), Sudan. The R.C. building used in this study is a 6-storey residential building with 3-bays in each direction. Two selected frames of the building were analyzed using STAAD-III software, linear static and dynamic analysis software, one in N-S direction and the other in E-W direction. The analysis was performed for two types of restraints: fixed and pinned, for both frames under the same loading. Four cases of damping ratios (0%, 5%, 10% and 20%) were used in the analysis. These ratios were taken as percentages of the critical damping. The software used the Dynamic Response Spectrum method (DRS) to solve the dynamic equilibrium equations of motion. The recorded ground motions of the 1940 El Centro earthquake were selected to be used as input data to calculate the seismic lateral displacements. Regardless of values of damping ratios and types of restraints used, it was found that the gravity load contributed in reducing the lateral displacements by an average amount of 25%. In other words, the lateral displacements caused by the combination of (gravity +seismic) loads are less than those caused by the seismic load only.

Keywords: Gravity load; seismic response; lateral displacements; damping ratios.
1. INTRODUCTION

There is growing responsiveness of multi-storey reinforced concrete structures, to accommodate growing population. The primary purpose of all kinds of structural systems used in the building type of structures is to undergo and transfer gravity loads effectively to the foundations. The most common loads resulting from the effect of gravity are dead load, live load and snow load. Besides these vertical loads, buildings are also subjected to lateral loads caused by wind, blasting or earthquake. Lateral loads can develop high stresses, produce sway movement and cause vibration. Therefore, it is very important for the structures have to be designed to support vertical loads together with adequate stiffness to resist lateral forces. Many researchers have investigated the contribution of gravity load on seismic response of structures, such as Kulkarni J. G. et al. [1] who presented an analysis of Multi-storey Building Frames Subjected to Gravity and Seismic Loads with Varying Inertia. This paper also highlighted the response of reinforced concrete frames for variation of axial force for spread of haunch and storey drift.

A. E. Hassaballa et al. [2] presented a paper on Seismic Analysis of a Reinforced Concrete Building by Response Spectrum Method. SAP2000 program was used as a tool for the analysis. The study found that the calculated drifts resulting from the nodal displacements due to the combination of static and seismic loads were about 2 to 3 times the allowable drifts and the compressive stresses in ground floor columns were about 1.2 to 2 times the tensile stresses. Mario Galli [3], evaluated the Seismic Response of Existing R.C. Frame Buildings with Masonry Infills. From his results obtained it can be noted that the presence of masonry infills had a dual effect on the overall structural response. When the infill panels are regularly distributed in the frame (uniformly infilled frame), the seismic response of the structure was characterized by a soft storey mechanism developing as a consequence of the brittle failure of masonry panels at a particular level, that produces a sudden reduction of strength and stiffness and an increase in the storey deformation demand.

Recent extensive analytical-numerical studies on the response of gravity load designed concrete frame buildings (with and without infills) underlined the peculiar vulnerability of the joint panel zone region. Focus has been given to the damage mechanisms occurring in the joint as well as to their interaction with the global frame response Guido [4], ANGELO MASI [5], Pampanin [6], Calvi [7].

The objective of the herein paper is to investigate the effect of gravity load on the lateral displacements of reinforced concrete frames, located in Khartoum city, subjected to seismic loads.

2. METHODS OF ANALYSIS

The most commonly used methods of analysis are based on the approximation that the building responses can be accounted for by linear analysis of the building, using the design spectrum for elastic system. Forces and displacements due to each horizontal component of ground motion are separately determined by analysis of an idealized building having one lateral degree of freedom per floor in the direction of the ground motion component being considered. Such analysis may be carried out by the seismic coefficient method (static method) or response spectrum analysis procedure.

2.1 Response Spectrum Analysis

A response spectrum is simply a plot of the peak or steady-state response (displacement, velocity or acceleration) of a series of oscillators of varying natural frequency, that are forced into motion by the same base vibration or shock. In the response spectrum method, the response of a structure during an earthquake is obtained directly from the earthquake response (or design) spectrum. This procedure [8] gives an approximate peak response, but this is quite accurate for structural design applications. In this approach, the multiple modes of response of a building to an earthquake are taken into account. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass. The responses of different modes are combined to provide an estimate of total response of the structure using modal combination methods such as complete quadratic combination (CQC), square root of sum of squares (SRSS), or absolute sum (ABS) method. Response spectrum method of analysis should be performed using the design spectrum specified or by a site – specific design spectrum, which is specifically prepared for a structure at a particular project site. The same may be used for the design at the discretion of the project authorities.
The following procedure is generally used for spectrum analysis:

1. Select the design spectrum.
2. Determine the mode shapes and periods of vibration to be included in the analysis.
3. Read the level of response from the spectrum for the period of each of the modes considered.
4. Calculate participation for each mode corresponding to the single-degree-of freedom response read from the curve.
5. Add the effect of modes to obtain combined maximum response.
6. Convert the combined maximum response into shears and moments for use in the design of structures.

3. FRAME DETAILS AND STUDY CASES

A residential six-storey three-bay R. C. frame building in Khartoum City with 15 m X 12.5 m plan, as shown in Fig. 1, was considered for the analysis. Two selected frames of this building were analyzed and checked using STAAD III software, one in North-South (N-S) direction and the other in East-West (E-W) direction as shown in Fig. 2. The sections of columns and beams are shown in Table 1.

Typical slab thickness is 125 mm.

The three designed loads used in the analysis were the actual dead load, live load and seismic load. Three combinations of load cases were applied as follows:

- Load Case 1 (LC1) is gravity load (dead and live).
- Load Case 2 (LC2) is seismic load only.
- Load Case 3 (LC3) is (gravity + seismic) loads.

The following load combinations \( A \) can be considered [9]:

\[
A = 1.4D + 1.6L \\
A = D + Lp + E \\
A = 0.85 D + E
\]

Where

\[
D = \text{dead load}; \\
L = \text{live load}; \\
P = \text{incidence factor for live load}; \text{ and} \\
E = \text{earthquake load}.
\]

In addition, seismic load only is used in this analysis as an assumed load combination aiming to investigate the impact of gravity load on lateral seismic displacements.

Load case 1 (LC1) follows the rules given in the (BS 8110) [10].

For the case of the Sudan [9], Incidence factor \( p \) is shown in Table (2).

A uniformly distributed gravity load of 20 kN/m was applied including the own weights of members. The software uses the Dynamic Response Spectrum method (DRS) to solve the dynamic equilibrium equations of motion. The ground accelerations versus time period were used as an input data to calculate the seismic response spectrum parameters, i.e., displacements in this research. The ground excitations used were selected from the 1940 El centro earthquake, as shown in Fig. 3, and a total time of vibration of 8 seconds was considered. The analysis was performed for two types of restraints; fixed and pinned for the same frames under the same loadings using four values of damping ratios (0%, 5%, 10% and 20%) as representative values of damping for the range of construction. The damping ratios were taken as percentages of the critical damping.

3.1 Lateral Displacement

It is displacement caused by the Lateral Force on the each storey level of structure. Each storey has its own displacement. The maximum lateral displacement is obtained at the top of the building. Hence after analyzing the Building the results obtained for these models in both longitudinal and transverse direction and the comparisons between them are presented in tabular form.

| Floor level | Ground floor | 1st floor | 2nd floor | 3rd floor | 4th floor | Roof |
|-------------|--------------|-----------|-----------|-----------|-----------|------|
| Columns' sections (mm) | 500*250      | 500*250   | 400*250   | 400*250   | 300*250   | 300*250 |
| Beams' sections (mm)   | 500*250      | 500*250   | 500*250   | 500*250   | 500*250   | 400*250 |
Table 2. Incidence factor for live load ($p$)

| Type of structure                                                                 | Incidence factor ($p$) |
|-----------------------------------------------------------------------------------|------------------------|
| 1. Residential buildings, hotels, offices, hospitals, public buildings, etc.      | 0.25                   |
| 2. Storage areas and warehouses                                                    | 0.50                   |
| 3. Tanks, reservoirs, silos and the like                                          | 1.00                   |

3.2 Damping Ratios

The damping ratio is a parameter, usually denoted by $\zeta$ (zeta) [11] that reflects capacity of dissipating energy and has significant influence on the vibrations of buildings, is regarded as a constant in the seismic design at present. The damping ratio is dimensionless, because it is the
result of dividing the units of the damping constant \( (N \cdot s/m) \) by the critical damping constant \( (N \cdot s/m) \); the units cancel out.

4. RESULTS OF THE ANALYSIS

The analysis was performed for static and seismic loads. The seismic analysis used horizontal input motion of earthquake with moderate horizontal peak ground acceleration (PGA\(_H\)). The results of the analysis are shown in Tables (3 and 4) and graphically depicted in Figs. (4 to 7) to show the influence of gravity load and damping ratios on reducing lateral displacements of the framed analyzed in this paper.

Fig. 3. Accelerogram from El centro earthquake, May 18, 1940

Fig. 4. Effect of gravity load on lateral displacements for damping ratio of 5%

Fig. 5. Effect of gravity load on lateral displacements for damping ratio of 10%
Results of N-S Frame Building

Table 3. The Effect of gravity load on lateral displacements (mm) for fixed restraint using four values of damping ratios

| Joints | Displacements (mm) due to seismic load only (LC2) | Displacements (mm) due to (seismic+gravity) loads (LC3) | Difference (%): (LC2 – LC3)/LC2*100 |
|--------|---------------------------------|-------------------------------------------------|----------------------------------|
|        | 2% | 3% | 4% | 5% | 6% | 7% | 8% | 9% | 2-6 | 3-7 | 4-8 | 5-9 | 0% | 5% | 10% | 20% |
| 5      | 7.533 | 2.460 | 1.840 | 1.516 | 5.647 | 1.842 | 1.376 | 1.134 | 25.044 | 25.134 | 25.179 | 25.216 |     |     |     |     |
| 6      | 7.551 | 2.466 | 1.844 | 1.519 | 5.662 | 1.848 | 1.382 | 1.138 | 25.015 | 25.015 | 25.060 | 25.076 |     |     |     |     |
| 7      | 7.551 | 2.466 | 1.844 | 1.519 | 5.665 | 1.851 | 1.384 | 1.141 | 24.985 | 24.956 | 24.935 | 24.931 |     |     |     |     |
| 8      | 7.533 | 2.460 | 1.840 | 1.516 | 5.653 | 1.847 | 1.383 | 1.140 | 24.957 | 24.986 | 24.821 | 24.781 |     |     |     |     |
| 9      | 14.380 | 4.703 | 3.514 | 2.888 | 10.787 | 3.529 | 2.637 | 2.167 | 24.990 | 24.971 | 24.957 | 24.952 |     |     |     |     |
| 10     | 14.371 | 4.700 | 3.511 | 2.886 | 10.778 | 3.526 | 2.634 | 2.165 | 24.997 | 24.990 | 24.988 | 24.985 |     |     |     |     |
| 11     | 14.371 | 4.700 | 3.511 | 2.886 | 10.777 | 3.525 | 2.633 | 2.164 | 25.003 | 25.010 | 25.014 | 25.016 |     |     |     |     |
| 12     | 14.380 | 4.703 | 3.514 | 2.888 | 10.784 | 3.525 | 2.634 | 2.165 | 25.010 | 25.031 | 25.040 | 25.048 |     |     |     |     |
| 13     | 22.173 | 7.265 | 5.421 | 4.439 | 16.629 | 5.448 | 4.064 | 3.328 | 25.005 | 25.015 | 25.022 | 25.024 |     |     |     |     |
| 14     | 22.177 | 7.266 | 5.421 | 4.439 | 16.632 | 5.449 | 4.066 | 3.329 | 25.002 | 25.006 | 25.007 | 25.009 |     |     |     |     |
| 15     | 22.176 | 7.266 | 5.421 | 4.439 | 16.633 | 5.450 | 4.066 | 3.330 | 24.998 | 24.995 | 24.992 | 24.991 |     |     |     |     |
| 16     | 22.173 | 7.265 | 5.421 | 4.439 | 16.631 | 5.450 | 4.067 | 3.330 | 24.995 | 24.983 | 24.979 | 24.972 |     |     |     |     |
| 17     | 28.476 | 9.340 | 6.961 | 5.679 | 21.359 | 7.007 | 5.223 | 4.261 | 24.993 | 24.980 | 24.972 | 24.967 |     |     |     |     |
| 18     | 28.470 | 9.338 | 6.970 | 5.678 | 21.354 | 7.005 | 5.220 | 4.259 | 24.998 | 24.993 | 25.102 | 24.987 |     |     |     |     |
| 19     | 28.470 | 9.338 | 6.959 | 5.678 | 21.352 | 7.003 | 5.219 | 4.258 | 25.002 | 25.008 | 25.010 | 25.012 |     |     |     |     |
| 20     | 28.476 | 9.340 | 6.961 | 5.679 | 21.355 | 7.003 | 5.219 | 4.258 | 25.007 | 25.021 | 25.028 | 25.033 |     |     |     |     |
| 21     | 35.516 | 11.651 | 8.671 | 7.043 | 26.636 | 8.737 | 6.503 | 5.281 | 25.003 | 25.008 | 25.011 | 25.013 |     |     |     |     |
| 22     | 35.519 | 11.652 | 8.672 | 7.043 | 26.639 | 8.739 | 6.504 | 5.282 | 25.001 | 25.003 | 25.003 | 25.004 |     |     |     |     |
| 23     | 35.519 | 11.652 | 8.672 | 7.043 | 26.639 | 8.739 | 6.504 | 5.283 | 24.999 | 24.998 | 24.997 | 24.995 |     |     |     |     |
| 24     | 35.516 | 11.651 | 8.671 | 7.043 | 26.638 | 8.739 | 6.504 | 5.283 | 24.997 | 24.992 | 24.989 | 24.986 |     |     |     |     |
| 25     | 39.168 | 12.842 | 9.552 | 7.740 | 29.381 | 9.636 | 7.168 | 5.809 | 24.988 | 24.963 | 24.950 | 24.938 |     |     |     |     |
| 26     | 39.168 | 12.842 | 9.551 | 7.740 | 29.377 | 9.633 | 7.165 | 5.806 | 24.996 | 24.988 | 24.983 | 24.980 |     |     |     |     |
| 27     | 39.168 | 12.842 | 9.551 | 7.740 | 29.374 | 9.630 | 7.162 | 5.803 | 25.004 | 25.013 | 25.016 | 25.021 |     |     |     |     |
| 28     | 39.168 | 12.842 | 9.552 | 7.740 | 29.377 | 9.627 | 7.159 | 5.800 | 25.012 | 25.037 | 25.049 | 25.061 |     |     |     |     |

% Average difference  25.000  25.000  25.000  25.000
Results of E-W Frame Building

Table 4. The Effect of gravity load on lateral displacements (mm) for fixed restraint using four values of damping ratios

| Joints | Displacements (mm) due to seismic load only (LC2) | Displacements (mm) due to (seismic+gravity) loads (LC3) | Difference (%): 
|        | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 2-6 | 3-7 | 4-8 | 5-9 |
|        | 0% | 5% | 10% | 20% | 0% | 5% | 10% | 20% | 0% | 5% | 10% | 20% |
| 5     | 6.859 | 2.153 | 1.615 | 1.341 | 5.141 | 1.612 | 1.208 | 1.003 | 25.043 | 25.142 | 25.187 | 25.229 |
| 6     | 6.878 | 2.160 | 1.620 | 1.345 | 5.159 | 1.619 | 1.215 | 1.008 | 25.004 | 25.014 | 25.021 | 25.022 |
| 7     | 6.878 | 2.160 | 1.620 | 1.345 | 5.159 | 1.620 | 1.215 | 1.009 | 24.996 | 24.986 | 24.985 | 24.978 |
| 8     | 6.859 | 2.153 | 1.615 | 1.341 | 5.147 | 1.618 | 1.214 | 1.009 | 24.956 | 24.858 | 24.816 | 24.774 |
| 9     | 12.879 | 4.048 | 3.033 | 2.513 | 9.661 | 3.037 | 2.777 | 1.886 | 24.988 | 24.964 | 24.952 | 24.941 |
| 10    | 12.865 | 4.043 | 3.030 | 2.510 | 9.649 | 3.033 | 2.773 | 1.883 | 24.999 | 24.997 | 24.999 | 24.997 |
| 11    | 12.865 | 4.043 | 3.030 | 2.510 | 9.648 | 3.032 | 2.777 | 1.882 | 24.997 | 25.002 | 25.002 | 25.001 |
| 12    | 12.879 | 4.048 | 3.033 | 2.513 | 9.658 | 3.034 | 2.774 | 1.883 | 24.879 | 25.036 | 25.048 | 25.057 |
| 13    | 19.902 | 6.263 | 4.688 | 3.870 | 14.926 | 4.696 | 3.515 | 2.901 | 19.904 | 25.016 | 25.023 | 25.029 |
| 14    | 19.903 | 6.263 | 4.688 | 3.870 | 14.927 | 4.697 | 3.516 | 2.902 | 19.903 | 25.002 | 25.002 | 25.005 |
| 15    | 19.903 | 6.263 | 4.688 | 3.870 | 14.928 | 4.699 | 3.517 | 2.903 | 19.902 | 24.982 | 24.977 | 24.972 |
| 16    | 19.902 | 6.263 | 4.688 | 3.870 | 14.928 | 4.699 | 3.517 | 2.903 | 19.902 | 24.982 | 24.977 | 24.972 |
| 17    | 25.654 | 8.079 | 6.041 | 4.970 | 19.242 | 6.061 | 4.532 | 3.729 | 25.654 | 24.979 | 24.972 | 24.965 |
| 18    | 25.646 | 8.077 | 6.039 | 4.968 | 19.235 | 6.058 | 4.529 | 3.726 | 25.646 | 24.998 | 24.996 | 24.997 |
| 19    | 25.646 | 8.077 | 6.039 | 4.968 | 19.234 | 6.057 | 4.529 | 3.726 | 25.646 | 25.002 | 25.003 | 25.003 |
| 20    | 25.654 | 8.079 | 6.041 | 4.969 | 19.239 | 6.058 | 4.529 | 3.726 | 25.654 | 25.022 | 25.030 | 25.034 |
| 21    | 32.221 | 10.149 | 7.578 | 6.207 | 24.165 | 7.610 | 5.683 | 4.655 | 32.221 | 25.010 | 25.013 | 25.016 |
| 22    | 32.221 | 10.149 | 7.578 | 6.207 | 24.166 | 7.611 | 5.684 | 4.655 | 32.221 | 25.001 | 25.001 | 25.001 |
| 23    | 32.221 | 10.149 | 7.578 | 6.207 | 24.166 | 7.612 | 5.684 | 4.656 | 32.221 | 24.999 | 24.999 | 24.998 |
| 24    | 32.221 | 10.149 | 7.578 | 6.207 | 24.167 | 7.612 | 5.685 | 4.657 | 32.221 | 24.990 | 24.987 | 24.983 |
| 25    | 35.626 | 11.216 | 8.371 | 6.842 | 26.724 | 8.417 | 6.283 | 5.136 | 35.626 | 24.960 | 24.947 | 24.936 |
| 26    | 35.626 | 11.216 | 8.371 | 6.842 | 26.720 | 8.413 | 6.279 | 5.132 | 35.626 | 24.966 | 24.993 | 24.992 |
| 27    | 35.626 | 11.216 | 8.371 | 6.842 | 26.719 | 8.412 | 6.278 | 5.131 | 35.626 | 25.002 | 25.006 | 25.008 |
| 28    | 35.626 | 11.216 | 8.371 | 6.842 | 26.715 | 8.408 | 6.274 | 5.127 | 35.626 | 25.039 | 25.053 | 25.066 |

% Average difference 25.000 25.000 25.000 25.000
5. DISCUSSION OF THE RESULTS

Tables (3 and 4) show that the displacements increase when using pinned restraint, being nearly double that for fixed restraint as depicted graphically in Figs. (4 to 7). The effect of damping ratios is clearly noticed for fixed and pinned restraints, i.e., when damping ratio increases, displacements decrease. It is found that the presence of gravity load in the analysis resulted in minimizing the lateral displacements by an amount of 25%. This effect of gravity load on displacements occurred in all cases of analysis, regardless of types of restraints, values of damping ratios and orientation of frames, whether in N-S or E-W direction.

6. CONCLUSIONS

The herein paper presents an investigation of the role of gravity load on seismic lateral displacements generated from a horizontal component of ground motion. From the results obtained it can be concluded that:

- It was found that the gravity load contributed in reducing the lateral displacements by an average amount of
25%, for all cases of damping ratios and types of restraints.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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