



Structural Assessment Considering Architectural Constraints with Seismic Retrofitting

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Authors' contributions

All the authors designed, analyzed, and interpreted the research activity.

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ABSTRACT

The Kingdom of Saudi Arabia is located in a low to medium earthquake zone. Therefore, the inclusion of seismic loads in building design was limited to specific building structures such as highrise and midrise in the past decades. Recently, the development and adoption of the Saudi Building Code (SBC) and the experienced seismic activity at many regions in the Kingdom necessitate detailed seismic design considerations for all buildings. Given this, the current work initially emphasizes assessing structural grids obtained from an architectural plan for an existing building in AL Madina. Then the structure has been analyzed critically in such a way to reduce columns and simplify the structural grid. Also, the orientation of columns has been modified to obtain structure symmetry keeping in view the architectural constraints. Two cases have been developed initially: flat slab and solid slab and designed to withstand gravity loads using Saudi Building Provisions. These cases are analyzed for the seismicity of the Medina Region. Since Medina is less prone to seismicity, the building withstands the lateral load calculated based on static analysis. To assess these buildings for stronger earthquakes, we increased the applied load to assess their capacity. Since both the proposed cases fail to withstand the increased seismic load, a bracing system has been introduced at the locations where it does not disturb the architecture of the building. It was observed that introducing bracing improves the performance of the structures. Therefore concluding that complex structural grids schemes can be simplified, regularized, and economized as well. In addition, bracings provide an easy technique to retrofit already existing RC buildings.

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1. INTRODUCTION

The Kingdom of Saudi Arabia is located in a low to medium earthquake zone. Seismic load ought to be considered an essential aspect that must be considered in the structure model. Additionally, following the Saudi Vision 2030 [1] and to meet net-zero goals by 2050 [2], countries must eliminate coal, install renewable energy projects, retrofit buildings & shift to Electrical Vehicles [3,4,5].

In the past decades, the inclusion of dynamic loads in building design in Saudi Arabia was considerably limited, mainly to multistorey buildings [6,7,8]. Currently, the development and adoption of a national code and the experienced seismic activity at many regions in the Kingdom necessitate the detailed consideration of seismic loads in the design of all buildings.

Previously, the main focus of the construction industry has been the design for gravity loads. Hence, the details were not enough to accommodate lateral loads [9,10].

Nevertheless, the Western region of Saudi Arabia lies within a moderate seismic zone, and a seismic event of magnitude 5.7 was recorded in 2009 in areas close to the holy city of Madinah. A historical event involving ground cracking due to volcanic activity in the year 1256

[11,12,13]. Additionally, The recent seismic events have led to issues on the safety and vulnerability of buildings, which were designed just for gravity loads in the past, lacking ductile detailing. Therefore, retrofitting techniques may fulfill the ductility demand of structures to withstand seismic events where buildings are designed only for gravity loadings. Therefore, bracing systems are most convenient for retrofitting frames [14]. Such systems contribute to the lateral load resistance of the structure through the horizontal projection of the axial force (mainly axial tension) developing in their inclined members (braces), such as Diagonal bracings, X-diagonal (or cross-diagonal) bracings, and V- or inverted-V bracings. This study objective includes

- a) Plan optimization as per architectural constraints considering the actual architectural Plan of the building as shown in Fig. 1.
- b) SAP2000 software [15] to be utilized to design the building initially for gravity only
- c) Saudi Building Code 301 to be adopted to check the adequacy of the gravity designed building for different seismic events
- d) Finally, bracings to be incorporated to improve the performance of the building.



Fig. 1. The selected architectural plan

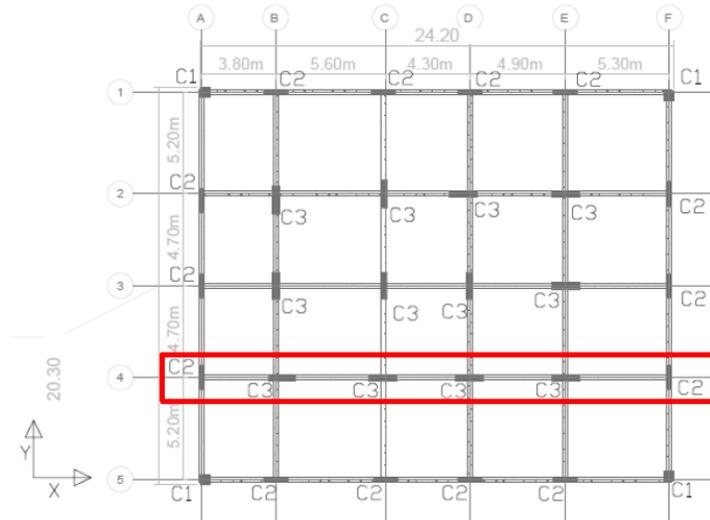


Fig. 2. Plan of the modified structural grid

After finalizing a suitable architectural plan that fulfills architectural constraints, the Plan shown in Fig. 2 was selected. The reason for choosing is the simplicity and clarity of the Plan. The building is a residential Reinforced Concrete (RC) building consisting of six floors, located in Medina. Since it is a six-floor building, therefore seismic loads are influential. Also, it is viable to study and apply different methods to retrofit it against seismic loads [16–19].

2. METHODOLOGY

2.1 Analysis and Design

The Kingdom of Saudi Arabia has been divided into seven regions for determining the maximum

considered earthquake ground motion, as shown in Fig. 3 [20,21].

Considering Saudi Building Code, Some Factors need to get it from the SBC code to apply Earthquake Loads as follow: Factors S1 & SS: Site Class: B (Soil Type), Design Category: A (Importance of the building), $F_a = 1$, $F_v = 1$ (Site coefficients depends on soil profile type): therefore, $S_1 = 7.3 / 100 * g = 0.073$ and $SS = 25.4 / 100 * g = 0.254$.

Calculations for short, 1 sec and fundamental period are based on the expressions shown by Equations (1) to (4).

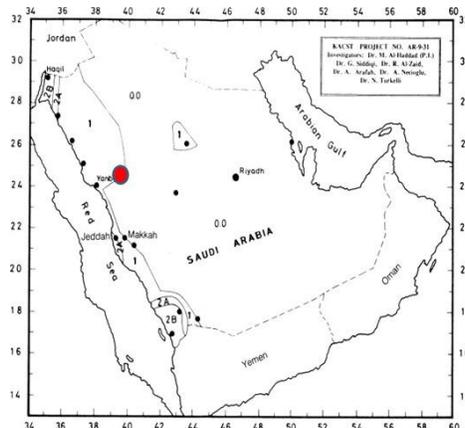


Fig. 3. Regions for determination of the maximum considered earthquake ground motion in Saudi Arabia

$$SMS = Fa SS = (1) \times 0.254 = 0.254 \quad (\text{Eq. 9.4.3-1 of SBC301}) \quad (1)$$

$$SDS = \frac{2}{3} \times SMS = \frac{2}{3} \times 0.254 = 0.169 \quad (\text{Eq. 9.4.4-1 of SBC301}) \quad (2)$$

$$SM1 = Fv S1 = (1) \times 0.073 = 0.073 \quad (\text{Eq. 9.4.3-2 of SBC301}) \quad (3)$$

$$SD1 = \frac{2}{3} \times SM1 = \frac{2}{3} \times 0.073 = 0.0486 \quad (\text{Eq. 9.4.4-2 of SBC301}) \quad (4)$$

Where SDS is the design spectral response acceleration parameter at a period of 1.0 sec. Ss is the mapped spectral response acceleration parameter at short period, and S1 is the mapped spectral response acceleration parameter at a period of 1.0 sec. Ss and S1 are determined from maps given in SBC 301 depending on the earthquake intensity for the specified site with the probability of occurrence of 2% in 50 years ($\approx 2,500$ year return period).

Fundamental period T is calculated using Equation (5)

$$T = C_{(t)}(H)^{0.75} \quad (5)$$

Where: T = Fundamental period, $C_{(t)}$ = constants (take it 0.075), for concrete frames, H = Building height (21 m), therefore

$$T = C_{(t)}(H)^{0.75} = 0.075 \times (21)^{0.75} = 0.736 \text{ sec.}$$

The Fundamental period T was obtained from SAP2000 for the solid. Slab equals 1.09 s, and for the flat slab, it is 1.48 s (See Fig. 4). We analyzed the model using SAP 2000 program that satisfies all the checks [17].

2.2 Seismic Weight

First, we calculated the Volume of the concrete needed for both flat and solid slabs and the Volume of all columns and beams. Then we calculated the total concrete quantity for both one and six floors. Correspondingly we multiplied it with the density of the concrete 2402 kg/m^3 to get the self-weight of the building in kg and converted it to kN. The self-weight of the solid and flat slab corresponds to 2375 kN and 1738 kN, respectively. Then we added 1 kN/m^2 an additional dead load, and 2 kN/m^2 live load, but we considered only 30% of the live load, which means 0.6 kN/m^2 . Since these loads are distributed along the building floor, we multiplied them with area to get the result in kN. The total weight of the whole building by summing the dead, super dead, and live loads that correspond to 4737 kN and 3675 kN, respectively. Base shear estimates the maximum expected lateral force due to seismic ground motion at the structure base. Calculations of base shear (V) depend on soil conditions at the site. From the Saudi building code, Equation (6) is used for the calculation of the base shear:

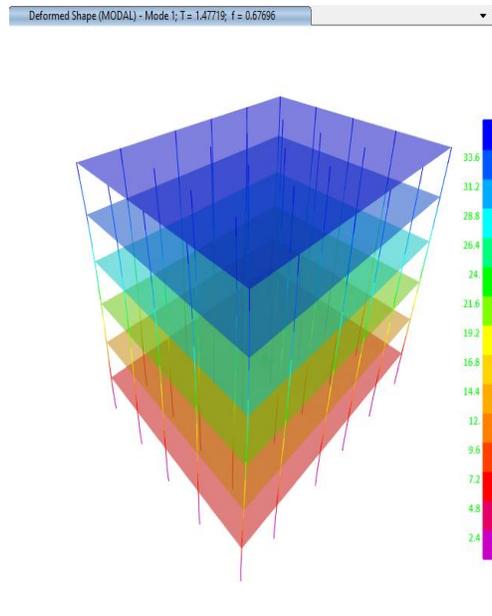


Fig. 4. Displacement contours for the first model (T= 1.47 sec)

$$F_x = C_{vx}V \text{ (Eq. 10.9.4-1 of SBC301)} \quad (6)$$

$$C_{vx} = \frac{w_x (h_x)^k}{\sum_{i=1}^n w_i (h_i)^k} \text{ (Eq. 10.9.4-2 of SBC301)} \quad (7)$$

Where, C_{vx} = vertical distribution factor and V = total design lateral force or shear at the base of the structure, (kN) shown by Equation (8)

$$V = C_s W \text{ (Eq. 10.9.2-1 of SBC301)} \quad (8)$$

$$C_s = \frac{S_{DS}}{(R/I)} \text{ (Eq. 10.9.2.1-1 of SBC301)} \quad (9)$$

w_i and w_x = the portion of the total gravity load of the structure (W) located or assigned to Level i or x , h_i and h_x = the height (m) from the base to Level i or x , k = an exponent related to the structure period as follows: for structures having

a period between 0.5 and 2.5 seconds, k shall be 2 or shall be determined by linear interpolation between 1 and

$$k = 1 + \frac{T - 0.5}{2} = \frac{0.736 - 0.5}{2} = 1.19$$

Design Coefficient R and Strength Factor Ω_0 : ($R=2.5$, $\Omega_0=3$, $C_d=2.5$).

3. RESULTS AND DISCUSSIONS

Different types of analysis include 1. Linear Static Analysis, 2. Linear Dynamic Modal Response Spectrum Analysis, 3. Linear Dynamic Modal Response History Analysis, and 4. Linear Dynamic Explicit Response History Analysis. Among all the analyses, deformation can be predicted in nonlinear static and dynamic analysis. In this case, we perform a Linear Static model analysis. The fundamental period of vibrations for both cases is shown in Fig. 5.

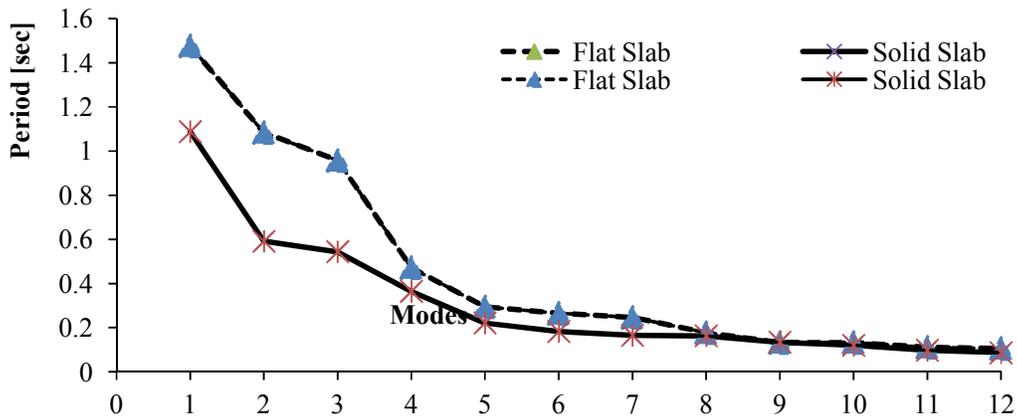


Fig. 5. Comparison of the modes of vibration

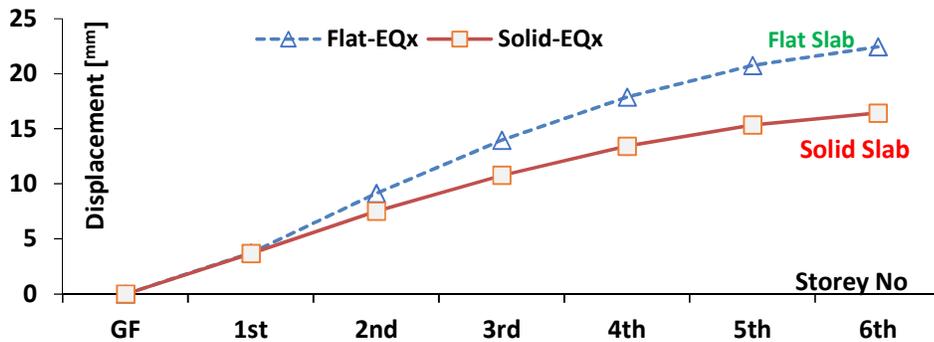


Fig. 6. Story displacements with seismic excitation in the X-axis

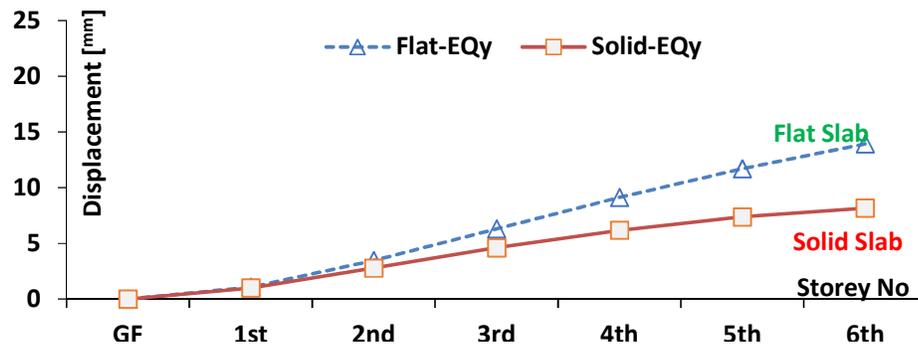


Fig. 7. Story displacements with seismic excitation in the Y-axis

Table 1. Dimension of the columns after last modification

Flat slab				
Column	Dimension (cm)		No of columns	Area (cm ²)
C1	25	60	4	6000
C2	25	90	14	31500
C3	25	120	12	36000
The total area of columns				73500
Solid slab				
Column	Dimension (cm)		No of columns	Area (cm ²)
C1	25	70	4	7000
C2	25	100	14	35000
C3	25	120	12	36000
The total area of columns				78000

Flat slab displacement of the top story under Seismic load in X and Y directions is 22.4 mm and 13.9 mm, respectively (see Fig. 6 and Fig. 7). In contrast, Solid slab displacement of the top story under Seismic load in X and Y directions is 16.4 mm, and 8.1 mm. This shows that the structure is stiff along the Y-axis.

The building fulfills the design carried out for the applied seismic load considering the seismicity of the Al-Madinah Al-Munawwarah region. We will now double the seismic load until failure. We noticed that the flat building and solid building fail when we multiply the lateral load four times. After that, we added bracings (200 mm x 200 mm SHS with 6mm thickness) to the building along the perimeter at two locations; these improve the building performance. It successfully fulfilled the capacity and demand without any failure, and the displacement results also improved. The second frame, as highlighted in red shown in Fig. 2, has been considered during the analysis. The displacement is usually minimal in the lower stories compared to the displacement in the upper storeys. In the case of the solid slab

(Fig. 8), the displacement at the first storey was 14.4 mm and on the third storey 45.3 mm, and reach on the sixth storey five times the first floor by a value of 72.3 mm. After adding the bracing, the displacement decreased dramatically, reaching the first storey to 3.0 mm; on the third storey the displacement became 12.5 mm. The displacement became 27.5 mm on the sixth storey, representing a decrease of more than 100% from what it was before the addition of bracing [22], [23].

In the case of the flat slab (Fig. 9), before adding the bracing, the displacement on the first storey was 21.8 mm and on the third storey 87.1 mm, to reach on the sixth storey seven times the first storey by a value of 146.2 mm. After adding the bracing, the displacement decreased dramatically, reaching on the first storey to 3.3 mm. On the third storey the displacement became 11.5 mm, and on the sixth storey the displacement became 34.5 mm. We also noticed that adding bracing in a flat slab has a more significant effect on displacement than in a solid slab.

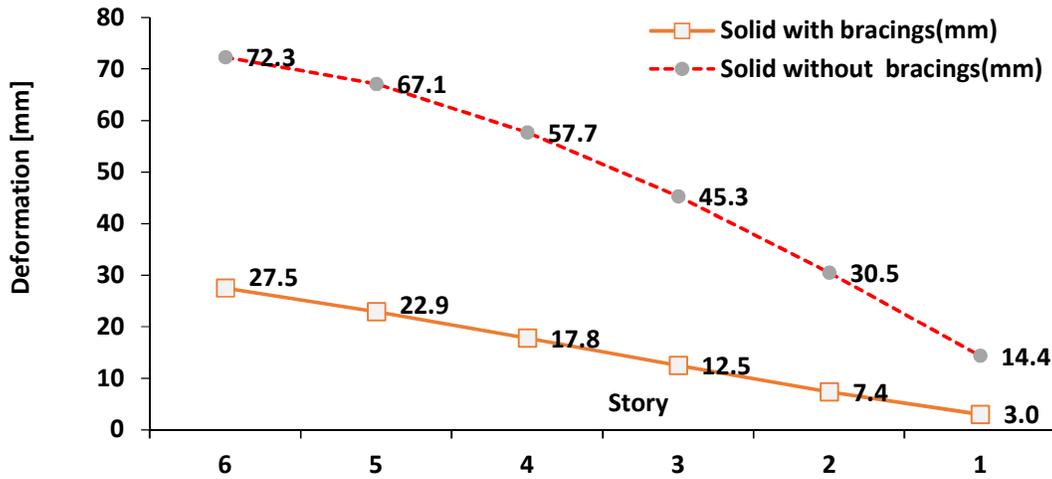


Fig. 8. Displacement before and after the addition of bracings (Solid slab)

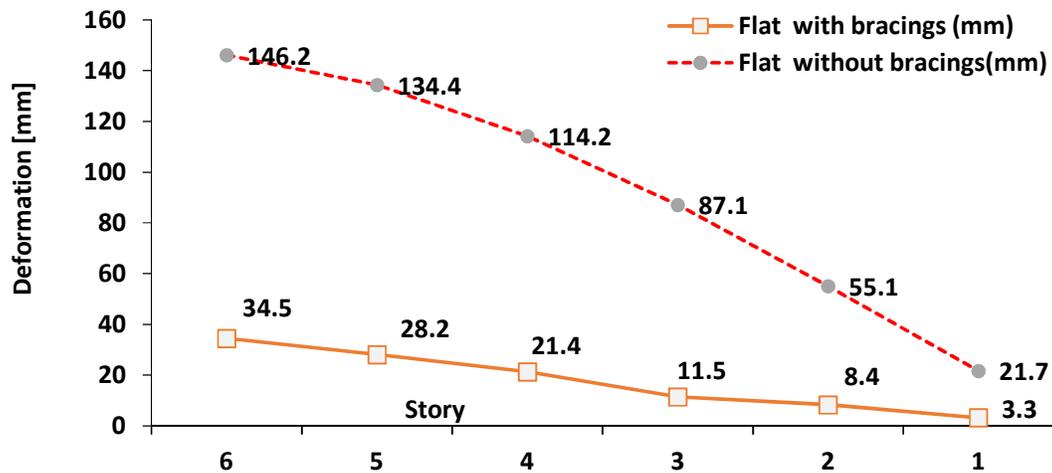


Fig. 9. Displacement before and after the addition of bracings (flat slab)

4. CONCLUSION

This study, we assessed an existing structure that has been redesigned for gravity loads. Then we applied seismic loads to determine its earthquake resistance. The structural model was supplemented with additional structural elements (bracing). Finally, we determined how well the structure can withstand seismic loads. The building was analyzed using the base shear analysis to see if it could withstand a seismic load. Based on the SBC, a seismic response load for Site Class B was evaluated using the seismicity of the Madinah Al Munawwarah region. SBC recommends a live load of 2 kN/m² for residential applications. In the beginning, we redesigned the building and modified some of

the locations of the structural elements while duly respecting architectural constraints. The number of columns was reduced from 35 to 30 to provide more space inside the building; the modified dimensions are shown in Table 1. After that, we applied the gravity load to find out the resistance of the new design to these loads, which successfully resisted the load.

We then proceeded to the next stage: to design two slabs: solid and flat slabs, and we applied seismic loads. The solid slab, which achieved a period ($T = 1.08$ sec), was better than the flat slab ($T = 1.47$ sec) in resisting the seismic load due to the beams. We multiplied the load twice and three times to measure how much it could withstand. We observed that the building failed

when it experiences four times the earthquake load of the Madinah region. With this, we introduce the bracing to avoid failure considering the architectural Plan. The result of providing bracing is that the building succeeded to fulfill the design limitations to withstand the seismic load both for Solid and Flat slabs in both directions (X and Y). The following are further concluded:

- The bracing increases the strength and stiffness of the building and, therefore, resistance to lateral forces, which prevent the building from collapsing and thus save the resources used in reconstruction and restoration.
- With seismic retrofitting, essential facilities such as archaeological and government buildings can be strengthened, preserved, and economic damage caused by building collapses and falls during an earthquake can be reduced.
- Seismic retrofitting can increase the stability of the building through the placement of bracing and its resistance to earthquakes, which can reduce the insurance cost of old buildings.
- Different retrofitting schemes can be considered, such as shear walls, V or chevron bracings, and a comparison of these systems can be a potential future study keeping into account architectural restrictions.
- Retrofitting of the existing facilities fulfill the requirements of Saudi Vision 2030 as well as the UN 2050 Net Zero goals toward effectively slashing carbon dioxide emissions to zero.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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