SAFETY ASSESSMENT OF GRAVITY LOADS DESIGNED TEN-STORY RC BUILDINGS UNDER EARTHQUAKE LOADS

Ahmed M. EL-KHOLY¹, Hoda SAYED², Ayman A. SHAHEEN³

ABSTRACT

Nowadays, ten-story reinforced concrete (RC) residential buildings are widespread along Nile valley in all Egyptian cities and villages too. Exaggerated RC cross-sections and high construction cost are expected when applying popular seismic procedure in which simple approach for estimating the fundamental time period and the conservative equivalent static load method (ESL) are used. Few of these buildings were built in illegal procedure without considering earthquake loads prescribed in the Egyptian Code of Loads (ECL 1993-2016). Not only recent buildings but also many of old multi-story buildings (that were built before 1992 earthquake) were designed under gravity loads only. However, these gravity loads designed ten-story buildings (GLDT) often comprise significant number of RC beams which form framing system with columns to resist earthquakes. Moreover, the reinforcement details of GLDT assure limited ductile behavior under lateral loads. This study provides realistic assessment for the safety of typical regular GLDT buildings under earthquake loads. ECL 2016 and the international building code (IBC 2015) were considered in the study. Three-dimensional finite element analysis was performed. The fundamental time period of GLDT building was calculated according to realistic approach. Moreover, the modal response spectrum method (instead of common conservative ESL) was utilized in order to provide optimal seismic forces. The results showed that retrofitting of some RC columns is essential to achieve complete safety under earthquake loads. The maximum story drift exceeded the ECL limit. Also, the results revealed the conservativeness of ECL compared with IBC.

Keywords: Seismic analysis of gravity loads buildings; modal response spectrum; fundamental time period; Egyptian code of loads ECL, IBC

1. INTRODUCTION

The Egyptian dense population in the Nile valley encouraged the construction of multistory residential-office buildings to maximize the building area. Ten-story reinforced concrete (RC) building became prevalent in Egypt in the last two decades. Fayoum-Cairo region was hit by two damaging earthquakes in 1992 and 1847 at Dahshour and Fayoum, respectively. Badawi and Mourad (1994), and AbdEl-Ala (2010) reported the damage observations of these earthquakes.

The first Egyptian official regulation for seismic analysis and design was released in 1988. After 1992 earthquake, the first Egyptian code for seismic loads and analysis "Egyptian Code for Calculating Loads & Forces in Structural and Building Works (ECL)" was released in 1993. Significant updates were issued in 2003, 2008 and 2012 (ECL Committee, 2016). Multi-story RC buildings constructed before 1992 earthquake were designed based on the gravity loads (dead and live) without considering earthquake loads. Also, few illegal design and construction work (in which the seismic loads might be reduced or neglected in order to minimize the construction cost) had been raised in some regions in different cities in the previous decades. The engineers of these illegal designs have fictitious thought that the earthquake loads prescribed by ECL is highly conservative and highlight their need to optimize the construction cost. Indeed, the ECL loads are realistic and not conservative according to El-Kholy et al. (2018). However, the popular seismic procedure comprising both simple estimation of

¹"Corresponding Author", Lecturer of Structural Eng., Faculty of Engineering, Fayoum University, El-Fayoum, Egypt, aml000@fayoum.edu.eg, ahmed.elkholy@fayoum.edu.eg, ResearcherID, ORCID, mobile: +2-01008021711.
²Teaching Assistant, Faculty of Engineering, MUST University, Egypt, hodasaid927@yahoo.com & huda.hussien@must.edu.eg
³Professor of Reinforced Concrete Structures, Faculty of Engineering, Fayoum University, El-Fayoum, Egypt, aas08@fayoum.edu.eg.
the fundamental time period and the conservative equivalent static load method (ESL) is the real
reason behind the conservative designs, exaggerated cross-sections of RC vertical elements and the
overestimated construction cost. The old buildings (designed before 1992 earthquake) and the recent
ones that were constructed without considering earthquake loads are named gravity load designed ten-
story buildings (GLDT) in this paper. Important high rise buildings that comprise more than fourteen
stories are often analyzed according to international building codes such as UBC 1997 (IBCO 1997)
and IBC (ICC 2015) in additional to ECL. On the contrary, the seismic behavior of GLDT buildings
have never analyzed or assessed using such international codes.

This research focuses on the common structural system of GLDT buildings (in Egypt) which
comprises solid slab with beams (unlike modern prevalent flat slab system) supported on columns.
GLDT buildings contain no shear walls (unlike prevalent well-designed multi-story buildings in
Egypt) to resist earthquakes. Also, no seismic analysis was performed for the design of such buildings.
However, beams and columns form simple frames which retain certain level of rigidity in resisting
earthquakes.

Elmasry and Elkordi (2010) investigated the structural vulnerability to damage of four, six and ten-
story GLD building located in Alexandria. The buildings were laterally loaded the structures with the
forces generated by Equivalent static load method (ESL) according to ECL 2003, and two-dimensional
(2D) pseudo-static analysis was performed using DRAIN-2DX software (Prakash et al. 1992).
Ellassaly (2011) investigated the seismic behavior of twelve-story GLD building located in Cairo
through nonlinear time history analysis (THA) using IDARC2D (University at Buffalo 2006) software.
Ezz El-Arab (2011) explored the seismic analysis of GLD schools located in the middle region of
Nile-Delta through modal response spectrum method (MRS) and THA according to the provisions of
of seven-story buildings (comprising regular and vertical-irregular structural systems) through
nonlinear 2D THA using IDARC2D software.

The buildings studied by Elmasry and Elkordi (2010), Ellassaly (2011), Ezz El-Arab (2011) and El-
Kholy et al. (2012) are completely ideal cases and do not represent the real construction field truly
because of the following reasons: 1) the typical floors are completely symmetry in plan, 2) the frames
are continuous in all bays along the building whole dimension in each direction, 3) all the bays have
equal spans and the columns have typical square cross-sections in each floor, and 4) the beams width
is 25–30 cm. This imaginary idealization enabled the researchers to apply approximate 2D analysis.
However, this idealization does not exist in reality where symmetry is very rare case, some frames are
often continuous for one or two bays only, the bay span and columns cross-sections are not constant,
and the beam width is 12 cm and rarely 25 cm for exterior beams only.

This paper presents three-dimensional (3D) seismic analysis and safety assessment for real GLDT RC
residential buildings in Cairo-Fayoum zone in Egypt. Two building codes (ECL 2016 and IBC 2015)
were employed in the study. Realistic approach for estimating fundamental time period and Modal
response spectrum method were adopted in the seismic analysis in order to provide realistic optimal
base shear, distribution of forces, and safety assessment.

2. METHODLOGY

Standing regular RC GLDT building located in Cairo-Fayoum area was considered in this study. The
actual design of the building was based on gravity loads only without performing any seismic analysis.
ECL 2016 and IBC 2015 were employed to study the seismic behavior of the considered building.
ECL was applied because it is the national authorized code. Although the mapped spectral
accelerations for short and one-second periods are not yet available for Egypt lands, IBC was
investigated (in the study) because of the following two reasons: 1) it is the most recent popular
international code, and 2) IBC gained wide investigation in last few years in engineering design firms
inside Egypt. The fundamental time period $T$ was calculated according to realistic time approach
(RTA) that was interpreted by El-Kholy et al. (2018). RTA evaluates $T$ as the minimum of $T^0$ and $T_v$
which are defined as follows. $T^M$ is calculated using 3D finite element modal analysis, whereas $T_U$ is calculated using code formula $C_U C t H^{3/4}$ in which $C_U$ is upper limit coefficient, $C_t$ is structural system and construction material coefficient, and $H$ is the total height of the building. RTA provides realistic estimation for $T$ and consequently reliable (non-conservative) base shear unlike $T$ estimated by popular simple approach $T=C, H^{3/4}$. Modal response spectrum method (MRS) was applied because of its reliability compared with conservative equivalent static load method (ESL), and its simplicity (for design engineers) compared with time history analysis method (THA). The safety of RC columns and beams were assessed based on the resulted straining actions from two simulations (ECL and IBC) and according to the provisions of ACI 318-14 code of American Concrete Institute (ACI Committee 318, 2014). Complete report about the safety of each column and the required retrofitting (if needed) is presented.

3. THE STUDIED BUILDING

3.1 Description, materials, loads and reinforcement

Figure 1 illustrates the plan and structural system of the considered GLDT building. The plan area is 22.9×24.4 m. The building comprises ten stories with height of 4 m for ground floor and 3 m for typical floors. The slab thickness is 14 cm. The cross-section of interior beams is 12×60 cm, whereas it is 25×60 cm for exteriors. The flooring, wall and live loads were set to 2, 4 and 2 kPa, respectively. The characteristic strength of RC was 25 MPa for floors and 30 MPa for columns. The reinforcement steel grade (yield/ultimate stress) was 36/52 for longitudinal reinforcement and 28/37 MPa for transversal reinforcement, respectively. Table 1 provides the cross-sections and reinforcement steel for the standing RC columns.

![Figure 1. Typical floor plan and structural system of studied building](image)

3.2 Seismicity

The studied residential building is located in Cairo-Fayoum zone which is labeled as third seismic region (in Egypt) according to ECL. IBC relates the seismic intensity to $S_s$ and $S_1$ (the mapped spectral accelerations for short and one second periods, respectively) which have not been implemented in ECL up to now. This research assumes $S_s$ and $S_1$ values to be 0.4 and 0.095, respectively. These values were used by Nahhas (2011) for location#1 labeled as zone 2A in UBC 1997. Cairo is also labeled as zone 2A in UBC 1997 and therefore the used $S_s$ and $S_1$ values (in presented research) might have high level of confidence. It is worth mentioning that this assumption cannot be approved until exact values
of $S_s$ and $S_I$ are provided by ECL committee. The subsoil profile is stiff clay with undrained shear strength of 75 kPa. Table 2 introduces the seismic parameters, subsoil type, and schematic drawings for horizontal design response spectrum curve engaged with mathematical formulas for each curve interval according to ECL 2016 and IBC 2015. It worth mentioning that IBC refers to ASCE/SEI 7-10 (ASCE Committee, 2013). ECL and IBC (ASCE/SEI 7) specify the response modification factor ($R$) according to the classification of the structural system of the building as given in code tables 8-A and 12.2-1 respectively. ECL and IBC classify the lateral resisting system of the RC studied building as limited-ductility frames and intermediate moment frames, respectively. Table 2 shows that $R$ was set equal to 5 for both codes. Although these GLDT buildings are designed under vertical loads only, their reinforcement details assures limited ductile behavior in order to mitigate the risk of skipping the seismic analysis.

Table 1. ID, cross-section and reinforcement of RC columns

<table>
<thead>
<tr>
<th>ID</th>
<th>Cross-section (cm)</th>
<th>Actual reinforcement steel bars</th>
<th>% ratio from cross-section area</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_1</td>
<td>30×70</td>
<td>12 Ø 16</td>
<td>1.15</td>
</tr>
<tr>
<td>C_2</td>
<td>30×80</td>
<td>14 Ø 16</td>
<td>1.17</td>
</tr>
<tr>
<td>C_3</td>
<td>30×100</td>
<td>16 Ø 16</td>
<td>1.07</td>
</tr>
<tr>
<td>C_4</td>
<td>30×120</td>
<td>20 Ø 16</td>
<td>1.12</td>
</tr>
<tr>
<td>C_5</td>
<td>45×110</td>
<td>24 Ø 18</td>
<td>1.23</td>
</tr>
</tbody>
</table>

$x$ Ø $y$ indicates $x$ bars of diameter $y$ mm

3.3 Modeling and Analysis

Figure 2 shows the 3D finite element model that was built for simulating the GLDT building using Etabs software (Computer and Structures 2010). Shell elements were used to model the slabs, whereas frame elements were used to model the beams and columns. Each floor was clamped into rigid diaphragm. P-delta analysis was activated. Ritz modal analysis was employed and ten modes were enough to accumulate mass participation ratio more than 97%. Table 3 defines the cracked stiffness ratios (compared to gross stiffness) that were employed in the 3D analysis. Also, Table 3 presents the main load combinations utilized in the design of the building. The extraction of these combinations in each direction was presented by El-Kholy (2017).

4. RESULTS

4.1 Fundamental Time Period and Base Shear

Table 4 presents the calculation of the fundamental time period according to the RTA. It is noticeable that $T$ estimated with ECL is under-estimated compared with that of IBC because ECL upper limit coefficient $C_U$ is small (1.2) compared with that (1.6) of IBC. Figure 3-a illustrates the elastic horizontal response spectrum curves for both codes, whereas Figure 3-b illuminates the conjugate design response spectrum curves. Although IBC is more conservative than ECL in elastic spectrum for $T>0.4$ s (Figure 3-a), the minimum requirement of ECL (for $T>1.0$ s) overrode that of IBC in the design spectrum (Figure 3-b). The base shear is calculated according to the provisions of ESL in each code. The MRS base shear was scaled in the two presented simulations to the minimum requirement (0.85 of ESL base shear) according to the provisions of both considered codes. Table 4 provides the ESL and MRS base shear values according to each code. It could be argued that the gap between the values of $T$ in both codes (0.79 and 1.03 s for ECL and IBC, respectively) increased the base shear conservativeness of ECL with respect to that of IBC with about 25%. This increment has significant influence on the safety assessment of the columns.
Table 2. Seismic, soil and design response spectra data

<table>
<thead>
<tr>
<th>Item</th>
<th>ECL 2016</th>
<th>IBC 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic zone</td>
<td>Third</td>
<td>-----</td>
</tr>
<tr>
<td>Seismic intensity</td>
<td>$a_e=0.15g$</td>
<td>$S_s=0.4g$</td>
</tr>
<tr>
<td></td>
<td>$a_e$ is the design ground acceleration</td>
<td>$S_i=0.095g$</td>
</tr>
<tr>
<td>Soil type</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Seismic &amp; soil factors</td>
<td>$S=1.5$</td>
<td>$F_a=1.48, F_v=2.4$</td>
</tr>
<tr>
<td></td>
<td>$T_C=0.25$ s, $T_D=1.20$ s</td>
<td>$T_s=S_D/S_s=0.385$ s</td>
</tr>
<tr>
<td>Occupancy category</td>
<td>III</td>
<td>II</td>
</tr>
<tr>
<td>Importance factor</td>
<td>$\gamma=1$</td>
<td>$I=1$</td>
</tr>
<tr>
<td>Response modification factor</td>
<td>$R=5$</td>
<td>$R=5$</td>
</tr>
<tr>
<td>Seismic weight $W$ (ton)</td>
<td>7389</td>
<td>7095</td>
</tr>
<tr>
<td>Live load contribution in $W$</td>
<td>25%</td>
<td>-----</td>
</tr>
</tbody>
</table>

Horizontal design response spectrum for elastic structural analysis

- Maximum: $2.5a_e\gamma S/R$, $S_{DS}/(R/I)$
- Curve: $2.5a_e\gamma S(T_C/TR)$, $S_D/(RT/I)$
- Minimum: $0.2a_e\gamma$, $0.044 S_{DS}I$

$g$ is the gravity acceleration.

*Maximum is constant in ECL in only case that $T$ has mass participation ratio > 90%.

![Typical floor plan model](image1)
![Three-dimensional view](image2)

Figure 2. Three-dimensional finite element model
Table 3. Cracked stiffness ratios and basic load combinations

<table>
<thead>
<tr>
<th>Item</th>
<th>ECL 2016</th>
<th>IBC 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>column</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Cracked stiffness</td>
<td>Beam</td>
<td>0.5</td>
</tr>
<tr>
<td>ratio</td>
<td>Slab</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Basic ultimate load combinations

- $1.4D$
- $1.2D + 1.6L$
- $1.2D + aL + E$
- $0.9D + E$

$D=$dead load, $L=$live load, and $E=$earthquake load
$\alpha=0.25$ for ECL (residential buildings)
$\alpha=0.50$ for IBC (areas of live load $\leq 500$ Kg/m$^2$)

Table 4. Fundamental Time period and base shear calculations

<table>
<thead>
<tr>
<th>Item</th>
<th>ECL 2016</th>
<th>IBC 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_t$</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>$T = C_tH^{3/4}$</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>$C_U$</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>$T_u = C_U T$</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>$T^M$ (first mode)</td>
<td>2.39</td>
</tr>
<tr>
<td></td>
<td>$T^R = \text{Min}{T_u, T^M}$</td>
<td>0.79</td>
</tr>
<tr>
<td>Design spectrum acceleration $S_e (\text{m/s}^2)$ estimated at $T$</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>Base shear (kN)</td>
<td>ESL</td>
<td>2640</td>
</tr>
<tr>
<td></td>
<td>MRS</td>
<td>2244</td>
</tr>
</tbody>
</table>

a. Elastic response spectra
b. Design response spectra

Figure 3. Horizontal response spectra curves for the considered site and building in both codes
4.2 Story Drifts

Table 5 explains the drift estimation procedures in each code. For both ESL and MRS, the story drift was unsafe according to ECL unlike IBC which showed safe story drifts. This story drift conservativeness of ECL over IBC was also reported by El-Kholy et al. (2018) for shear walls RC multistory buildings. However, the intensity of conservativeness for GLD is higher than that noticed for shear walls modern buildings.

Table 5. Story drift calculations

<table>
<thead>
<tr>
<th>Item</th>
<th>ECL 2016</th>
<th>IBC 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procedure of calculating story drift</td>
<td>$d$</td>
<td>$0.7Rd_e$</td>
</tr>
<tr>
<td>displacement $d$</td>
<td>actual $d_r$</td>
<td>$\nu\Delta d/h$</td>
</tr>
<tr>
<td>story drift $d_r$</td>
<td>allowable</td>
<td>0.005</td>
</tr>
<tr>
<td>Estimated drift ESL</td>
<td>0.0075</td>
<td>0.012</td>
</tr>
<tr>
<td>Estimated drift MRS</td>
<td>0.0065</td>
<td>0.009</td>
</tr>
</tbody>
</table>

$d_r$=displacement resulted from the 3D elastic analysis according to Figure 3-b
$C_{d}$=deflection amplification factor
$\Delta d$=difference of the average lateral displacements $d$ at top and bottom of story
$h$=story height
$\nu$=drift reduction factor

4.3 Straining Actions on Columns and Beams

Figure 4 prescribes sample columns and beams whose straining actions are introduced in Table 6 and Table 7, respectively. For columns, IBC straining actions are relatively smaller than those of ECL especially for shear force and moment. However, the normal force in columns and the straining actions of beams have close values in both codes because of the coincidence of vertical loads in both simulations.
Table 6. The straining actions of sample columns

<table>
<thead>
<tr>
<th>Column</th>
<th>ECL 2016</th>
<th>IBC 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$ (kN)</td>
<td>$Q$ (kN.m)</td>
</tr>
<tr>
<td>$C_{1x}$</td>
<td>1700</td>
<td>70</td>
</tr>
<tr>
<td>$C_{1y}$</td>
<td>2100</td>
<td>50</td>
</tr>
<tr>
<td>$C_{3x}$</td>
<td>2510</td>
<td>100</td>
</tr>
<tr>
<td>$C_{3y}$</td>
<td>2910</td>
<td>190</td>
</tr>
<tr>
<td>$C_{4y}$</td>
<td>2680</td>
<td>145</td>
</tr>
</tbody>
</table>

$N$ is the normal force, $Q$ is the shear force, and $M$ is the bending moment for design combination.

Table 7. The straining actions of sample beams

<table>
<thead>
<tr>
<th>Beam</th>
<th>Cross-section (cm)</th>
<th>Shear force $Q$ (kN)</th>
<th>Bending moment $M$ (kN.m)</th>
<th>Flexural safety</th>
<th>Retrofitting cross-section (cm)</th>
<th>Required shear reinforcement (per meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mid-span</td>
<td>end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>12×60</td>
<td>139</td>
<td>92</td>
<td>195</td>
<td>unsafe</td>
<td>25×60</td>
</tr>
<tr>
<td>B</td>
<td>12×60</td>
<td>88</td>
<td>50</td>
<td>105</td>
<td>safe</td>
<td>-----</td>
</tr>
<tr>
<td>C</td>
<td>12×60</td>
<td>115</td>
<td>55</td>
<td>108</td>
<td>safe</td>
<td>-----</td>
</tr>
<tr>
<td>D</td>
<td>25×60</td>
<td>133</td>
<td>95</td>
<td>195</td>
<td>safe</td>
<td>-----</td>
</tr>
<tr>
<td>E</td>
<td>25×60</td>
<td>148</td>
<td>55</td>
<td>195</td>
<td>safe</td>
<td>-----</td>
</tr>
</tbody>
</table>

4.4 Safety of Columns

The design of all the columns (in both simulations) was accomplished according to ACI 318-14 code. The required reinforcement steel ratios of some columns were higher than the actual reinforcement ratios given in Table 1, and therefore these columns are considered unsafe. Figures 5-a and 5-b demonstrate the required reinforcement ratios for the unsafe columns in ECL and IBC simulations, respectively. Also, the required reinforcement steel ratio as a percentage of the actual existing reinforcement is shown inside between parentheses on the same figure. For ECL simulation, seventeen columns were unsafe, whereas only four columns were unsafe for IBC simulation. The unsafe columns are overstressed in the ground floor only except the two edge front columns which are overstressed in the ground, first and second stories. Therefore, retrofitting is essential for these overstressed RC columns. It is worth mentioning that retrofitting cross-sections $\bar{C}_i$ ($i = 1, 2, 3$), in which $\bar{C}_i$ dimensions is 10 cm larger (in width and depth) than the original $C_i$ dimensions given in Table 2, and reinforcement steel ratio of 1.0% are satisfactory to safe the columns under earthquake forces in both presented simulations.

4.5 Safety of Beams

The beams were designed according to ACI 318-14 code and based on the maximum straining actions provided in Table 7. The five studied beams are safe flexural except A which requires retrofitting by increasing the beam width to 25 cm. The beams A, C and E are unsafe shear and require additional stirrups at their ends.
5. CONCLUSIONS

GLDT building located in Cairo-Fayoum zone at Egypt was simulated under earthquake loads using two building codes (ECL 2016 and IBC 2015). RTA was adopted for estimation of fundamental time period, and MRS was employed in the seismic analysis in order to obtain realistic magnitude and distribution of the base shear. The safety of columns and beams was investigated according to ACI 318-14 code and based on the straining actions resulted from each simulation. The following conclusions can be drawn.

1. Conservativeness of the upper limit coefficient $C_U$ in ECL compared with that of IBC magnifies the base shear force, story drift and the reinforcement ratios in ECL simulation.
2. The story drift was safe based on IBC simulation results unlike conservative ECL.
3. Retrofitting is essential for about half of columns number based on ECL simulation unlike IBC one in which minor number of columns needs retrofitting.
4. Increasing the average reinforcement steel ratio of unsafe columns to 145% (range 105-191%) and 132% (range 124-140%) compared to existing reinforcement ratios is sufficient to achieve the column safety based on ECL and IBC simulations, respectively.
5. Enlarging the cross-section of the unsafe columns with 10 cm in each direction and maintaining reinforcement ratio of 1.0% on the enlarged cross-section is enough to achieve the safety of all columns for both simulations.
6. Width of 12 cm is not satisfactory for the beams with large spans (about 6 m and more).
7. The shear reinforcement (stirrups) of beams must be not less than diameter 8 mm spaced at maximum 12.5 cm near the columns.
8. The IBC results cannot be finally validated until $S_i$ and $S_j$ contour maps and precise values for the considered location are prepared by the national authorities.
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