EVALUATION OF SEISMIC PROVISIONS IN BUILDING CODES OF DEVELOPING NATIONS - CASE STUDY OF EGYPT

M. Afifi[1], R. Ahmed[2]

[1] Graduate Student, McGill University, Canada, mohamed.afifi@mail.mcgill.ca
[2] Graduate Student, Concordia University, Canada, reem.ahmed@mail.concordia.ca
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Abstract

Continuous improvement of existing building codes is a crucial responsibility of researchers, industry sponsors, and government officials. An integral part of any building code is its seismic provisions that need to be regularly updated as different aspects are revealed whenever an earthquake strikes. Egypt is a country of moderate seismicity. It has experienced a limited number of damaging earthquakes throughout history. However, in the absence of any seismic provisions in design codes till 1989, many structures were deemed vulnerable to earthquakes. The 1992 Cairo earthquake drew major attention to enforcing earthquake resistant design the Egyptian code of building. Knowing that the Egyptian seismic provisions have not been majorly updated since last decade imposes a huge question of is it safe or is it overly conservative? And while major building codes are adding emphasis on the complex dynamic nonlinear analysis, the Egyptian provisions still utilize the traditional equivalent static load method as the main method of analysis. To answer these questions a comparison, of the Egyptian seismic provisions with its counterparts in the Canadian and US codes, is performed to identify possible recommendations to current practice. This is followed by an application of the different provisions on the design of a steel building as a case study to verify the safety and feasibility of the current practice. Results reveal that the strict limits on drifts imposed by the Egyptian code, as well as the conservatism in calculating the seismic weight of the structure, yielded a structure with at least 23% more steel tonnage compared to structures designed according to other building codes. Major steps need to be taken in order to optimize current code provisions to achieve the goal of building more sustainable and resource efficient cities.

Keywords: Building code, Static analysis, Seismic, Steel structures.

1. Introduction

Seismic events around the world draw the attention to structural flaws in buildings and other structures to resist earthquake loading. Assessment of failures is essentially carried out to identify failure modes and reasons, followed by reviews and updates to building codes and specifications. Historically, major updates to American seismic provisions were introduced following the 1985 Northridge earthquake in California and similarly, provision alterations were applied to the Japanese code of practice following the 1995 Kobe earthquake. In Egypt, the Cairo earthquake in 1992 (5.8 mb) which left over 9,000 buildings either completely or severely damaged and about 50,000 people homeless, was mainly due to the buildings were designed to resist only vertical loads and had insufficient lateral resistance [1]. Thus, the columns and beam column connections were found to have inadequate shear capacity, ductility, and confinement in plastic hinges [2,3]. This event has drawn attention of officials in Egypt to the necessity of regularly updating the national building code to account for probabilistic loads like wind and earthquake, which were accounted for in subsequently published codes and specifications.

The design methods given by modern building codes guarantee acceptable safety level that depends on the probability of occurrence of the event. Global specifications allow designers to use various methods for seismic analysis staring from the simple equivalent static load analysis till the complex nonlinear dynamic analysis. Equivalent Static Load (ESL) is most popular among engineers for deign of buildings due to its simple methodology and lack of alternative methods [3] The most recent Egyptian code for load and forces, ECP2011 [4] and most of the global building codes depend on the conventional approach of equivalent static load analysis as the main method for evaluating seismic forces on symmetrical buildings. Hence, this paper aims at evaluating the ESL method of the Egyptian seismic provisos and how it compares to its international counterparts. In the last section of the paper, the design of the prototype structure is performed for each country and similarities and differences are highlighted.

2. Prototype Building

During the past two decades, the building environment in Egypt had extensively utilized medium-rise buildings having 6-12 stories, which is the maximum height allowed by the local authorities in most districts. These buildings are built with different configurations and structural systems having varying stiffness parameters that may have great influence on their seismic behaviour [3]. The structure plan and the braced frame elevation are shown in figure 1. The building is assumed to be an office building of a normal importance category. The building's layout is essentially five equal bays with a typical bay width of 9 m in both directions, and is representative of steel buildings in current practice in Egypt. Although more common in US and Canada, these modular buildings are expected to be more demanded in the future in Egypt, especially in fast moving giant projects (e.g. New Administrative Capital). The height of every story (column height) is taken equal to 5m, as a normal height for office buildings. Columns are assumed to be fixed to the foundation, and beams are assumed on all grid lines.

The structure is assumed to be located at sites in Canada, United States and Egypt where similar seismic conditions and data prevail. Sites are located as follows: Montreal, QC, in Canada; Las Vegas, NV, in the U.S.; and Taba – South Sinai, in Egypt. For all three sites, the structure is assumed to be constructed on firm ground or very dense soil conditions, corresponding to site class C in USA and Canada with shear wave velocity between 360 and 760 m/s and site class B in Egypt with shear wave velocity between 360 and 800 m/s. In Egypt, the seismic input for design is preliminarily characterized by the maximum effective ground acceleration at the site. Taba is located in seismic zone 5B where ag is equal to 0.30 g. This parameter can be compared to peak ground accelerations (PGA) specified in NBCC2015 [5] and ASCE 7-16 [6] for class C sites in Montreal and Las Vegas: 0.377 g and 0.298 g, respectively.

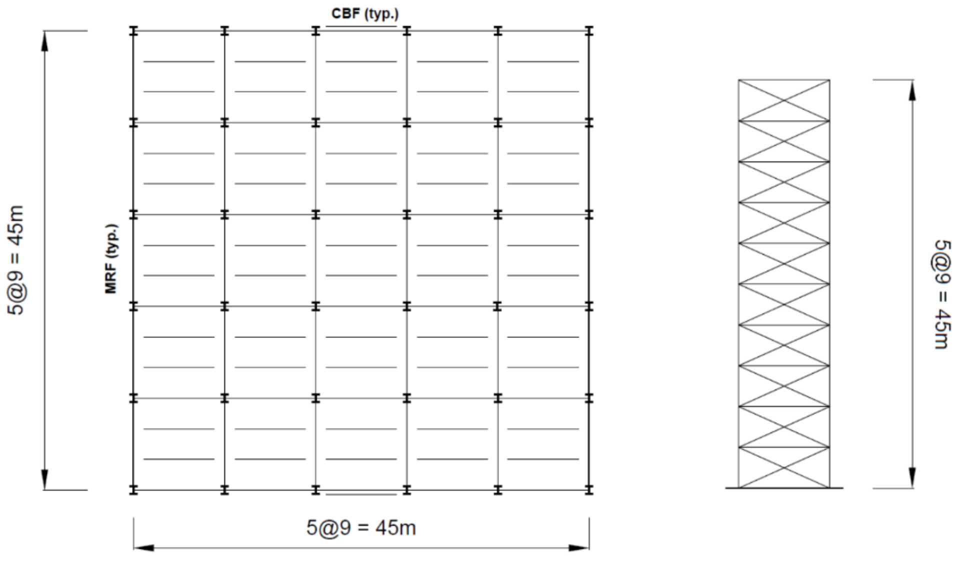

Figure 1 - Prototype Structure

3. Seismic Design Provisions in USA and Canada

This section briefly discusses the equivalent static force procedure of both the NBCC2015 [5] and ASCE7-16 [6]. Reports by Trembly et al. in 2015 [7] and Naqqash et al. in 2012 [8] were used extensively as basis for drafting this section of the paper. Stability requirements, P-delta effects as well as effects of accidental torsion were analysed but not indicated in the text for length limitations.

3.1 Canada: NBCC 2015 & CSA S16-14

In NBCC 2015, the minimum design base shear, V, is specified as:

$$V = \frac{S(T)M_V I_E W}{R_d R_o} \quad (1)$$

,where S is the design spectrum, T is the period of the structure, M_v accounts for higher mode effects, I_E is the importance factor based on the use and occupancy, W is the seismic weight and R_d and R_o are the ductility and overstrength modification factors. The design spectrum for T>0.2 is generally given as the product of spectral acceleration S_a(T) and site coefficient F(T). Values of S_a(T) are given in terms of uniform hazard spectral (UHS) ordinates, S_a, specified at periods 0.2, 0.5, 1.0, 2.0, 5.0 and 10 s for a return period of 2475 years or probability of exceedance of 2% in 50 years. The values for the chosen location are given in table 1. F(T) is site coefficient that depend on the site class and soil type. Site class C corresponds to the reference ground type considered for the determination of S_a values and F is therefore equal to 1.0 at every period. Fundamental lateral period of vibration, T is dependent on height and type of Seismic Force Resisting System (SFRS) used, and is computed as shown in figure 2.

The M_v factor depends on the ratio S (0.2)/S (5.0) at the site, the period of the structure and the SFRS type. For moment frames and braced frames M_v = 1.0 in most situations except for ratios S (0.2)/S (5.0) greater than 40 in which case it may reach up to 1.03 and 1.07 for moment frames and braced frames, respectively. Importance factor (I_E)takes a value of 1.0, 1.3 or 1.5 for normal, high or post-disaster importance categories of structures. The seismic weight of the building, W, shall be determined to include the sum of dead loads, plus 25% of snow loads, plus 60% of storage loads and full contents of any tanks (Rogers, 2019). In the NBCC, R_d varies from 1.0 for the less ductile SFRSs to 5.0 for the most ductile systems. The factor R_o reflects the dependable overstrength present in the SFRS, depending on the difference between factored and nominal resistances and minimum level of strain hardening anticipated in tension [7], and varies between 1.5 and 1.0. For short period structures, the value of V from Equation (1) should not exceed 2/3 the value computed at a period of 0.2 s. For steel frames with long periods, V must not be less than the value computed at a period of 2.0 s.

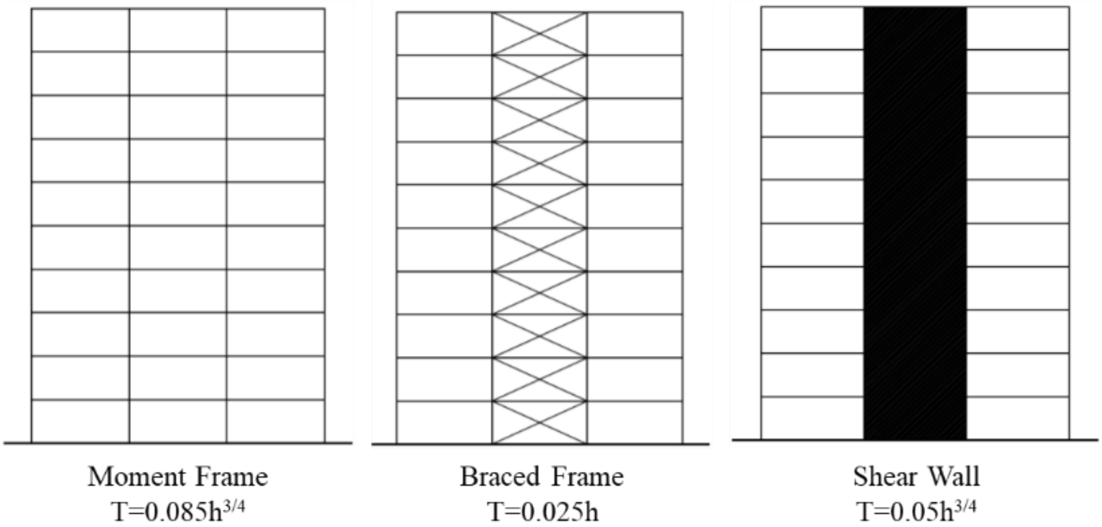

Figure 2 - NBCC2015 Fundamental period of vibration for different steel SFRSs.

$$Fx = (V - F_t)\left(\frac{W_X h_X}{\sum W_i h_i}\right), \quad \text{where } F_t = 0, \text{ for } Ta<0.7s \quad (2)$$

$$=0.07T_aV \leq 0.25, \text{ for } T_a \geq 0.7s$$

In this expression, F_t is a concentrated horizontal load applied at the top of the structure to account for higher mode effects. For buildings of the normal importance category, the design storey drifts Δx obtained from the displacements δx must not exceed the value of 0.025 h_{sx}, where h_{sx} is the storey height at level x. In the NBCC, gravity dead (D) and live (L) are combined to earthquake loads (E) in load combination V: 1.0 D + 0.5 L + 1.0 E.

3.2 USA: ASCE 7-16 & AISC341-16

Please According to ASCE7-16, the design base shear is specified as:

$$V=C_sW \quad (3)$$

Where W is the seismic weight and C_s is the seismic coefficient based on the value of the period. There are 3 ranges for the period values, short, intermediate and long, and for each range Cs is given by a different term. Minimum values are also specified that may govern long or intermediate ranges. Generally, C_s is function of either the short spectral acceleration (S_{DS}) or one-second spectral acceleration (S_{D1}), which are equal to 2/3 of the modified MCE_R spectral values S_{MS} and S_{M1} specified for a certain location. For buildings or structures falling within the intermediate period range, C_s is specified as:

$$C_s = \frac{S_{D1}}{T\,(R/I_e)} \quad (4)$$

where R is the force modification factor that varies from 3.0 for steel SFRSs not designed or detailed for ductile response to 8.0 for the most ductile SFRSs; I_e is the importance factor ranging from 1.0 to 1.5 depending on risk category; and T is the fundamental dynamic period that can be obtained from dynamic analysis and cannot exceed C_uT_a, where $T_a = 0.0731h_n^{0.75}$ and C_u varies from 1.4 in active seismic regions to 1.7 for low-seismic regions. The ASCE7-16 permits analysis using the equivalent static lateral force procedure if the height of the building is less than 48.8m and the period is less than 3.5Ts. The distribution of lateral forces can be computed by:

$$Fx = V\left(\frac{W_X h_X^k}{\sum W_i h_i^k}\right), \text{ where k=1.0 for T< 0.5 s} \quad (5)$$

$$=0.75+0.5T \leq 2.5 \text{ for } T \geq 0.5s$$

Table 1 - Spectral ordinates in the 2015 NBCC and ASCE 7-16

T(s)	S_a(g) NBCC2015	S_M(g) ASCE7-16
0.2	0.595	0.677
0.5	0.310	-
1.0	0.148	0.209
2.0	0.068	-
5.0	0.018	-
10	0.006	-

4.Seismic Design Provisions in Egypt:

In this section, a brief historical survey of seismic provisions in Egyptian codes of practice will be done as well as a review of current code of practice and how it compares to the North American Codes.

4.1 Historic Review of Egyptian Seismic Provisions:

Seismic loading was not found in Egyptian codes of practice until the early 1990's. Classically, structures were designed to withstand gravity loads, and the only lateral load resistance was provided through applying wind loads in very specific cases. Although in 1989, the Egyptian Ministry of Housing, Utilities and New Communities published the first official code to consider seismic loading, it lacked a lot of basic seismic considerations including the dynamic features of buildings and the effect of soil conditions [3]. The building code issued in 1993 following the 1992 Cairo earthquake provided a better approach for obtaining seismic loads, however it adopted a significantly basic way for loading and design procedure. These shortcomings, particularly on the loading side, were avoided in the 2004 version of the code. Table 2 shows a summary of the development of the base shear formulas in code editions issued from 1993 to 2008, to present the major changes introduced to the seismic provisions.

Table 2 – Development of Egyptian Seismic Provisions [9]

Parameter	ECP-1989	ECP-1993	ECP-2008
ESL	$V = C_s\ Wt$ C_s = Z.I.S.M.R.Q	V = Z.I.C.K.S.W	$F_b = S_d(T)\ \lambda\ W/g$ $S_d(T)$ is response spectrum related to (ag, S, R,T, γI, η)
Seismic hazard parameter	Z = (0.0, 0.02, 0.04, 0.08) g	Z = (0.1, 0.2, 0.3) g	a_g = (0.1, 0.125, 0.15, 0.2, 0.25, and 0.3) g
Importance categories and importance factor	I = 1.0, 1.3, and 1.5	I = 1 or 1.25	γI = 0.8, 1.0, 1.2, and 1.4
Structural resistance system	$0.67 \le S \le 3.20$	$0.67 \le K \le 1.33$	$2 \le R \le 7$
Site response factor	F = 1.0, 1.3, and 1.5	S =1, 1.15, or 1.3	S is related to soil class and spectrum type
Period effect	$T=(0.09H)/\sqrt{d}$	T=0.1N, $C=1/15\sqrt{T}$	$S_d(T_1)$ is related to period T_1
Correction factor	N/A	N/A	λ = 0.85 or 1.0
Damping correction	N/A	N/A	$0.95 \le \eta \le 1.2$

4.2 Current Seismic Provisions – ECP2011:

According to ECP2011, seismic design base shear, F_b, is specified as:

$$F_b = \gamma S_d(T_a)\lambda \frac{W}{g} \tag{6}$$

where γ is the importance factor taking values of 1.4,1.2,1.0 and 0.8 for post-disaster, high, normal and low importance categories, respectively. $S_d(T_1)$ is the ordinate of design spectrum at the fundamental period of vibration T_1; λ is the effective modal mass correction factor taking the value of 0.85 for $T \leq 2Tc$ (Upper limit of period of constant spectral acceleration as seen in Figure 3), and n>2 stories. W is the total weight of the building above the foundation level and g is the gravity acceleration=9.81 m/s^2.

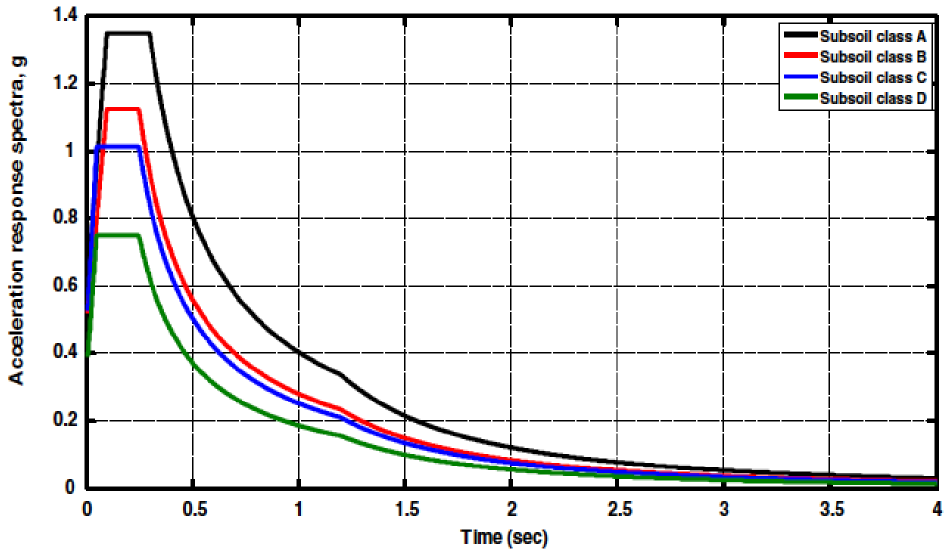

Figure 3. ECP (2008) design response spectrum for different subsoil classes [3].

The value of the fundamental period of vibration, T_a, is specified as follows:

$$T_a = C_t \text{ x } H^{3/4} \tag{7}$$

where C is a factor dependant on the structural system and material valued at 0.085 for steel moment resisting frames, 0.075 for concrete moment resisting frames and 0.050 for all other structures. H is the height of the structure above the foundation level. It is worth mentioning that the code allows computation of the fundamental period using an acceptable software package (T_1), provided that it remains within acceptable range of T_a. The ordinate of the design spectrum, S_d (T_a), can generally be calculated from the following formula:

$$S_d(T_a) = a_g \gamma\, S \frac{2.5}{R} \frac{T_c}{T} \geq 0.20\, a_g \gamma_1 \tag{8}$$

where a_g is the ground acceleration depending on the seismic zone for a return period of 475 years as seen in figure 4, S is the soil factor ranging from 1.0 to 1.6 depending on subsoil class, R is the reduction factor depending on structure type and material; there are 2 ductility levels for steel frames; Limited ductility (R=5.0) and moderate ductility (R=7.0), T_c is the upper limit of the period of the spectral acceleration chosen.

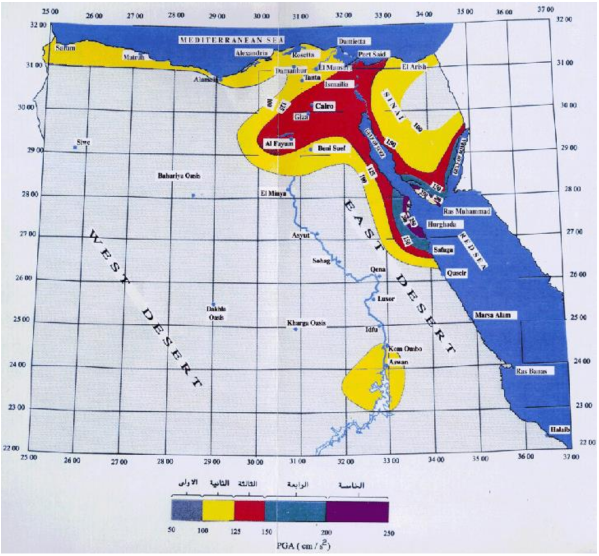

Figure 4 - Seismic map of Egypt according to current Egyptian code – ECP2011 [4].

The total base shear, F_b, shall be distributed among the different levels according to the following expression:

$$F_i = \left[\frac{z_i W_i}{\sum_{j=1,n} z_j W_j}\right] . F_b \qquad (9)$$

where F_i is the force acting horizontally on each floor i; F_b is the seismic base shear force obtained from equation 1; z_i and z_j are the heights of masses m_i and m_j, respectively; W_i and W_j are the weights of these masses; and n is the number of stories above the foundation level. Equation 4 gives a linear shear distribution depending only on the storey height.

5. Seismic Design of Prototype Building

In this section, the seismic code provisions for the three countries are applied for the design of the 9-storey regular building structure described in Section 2. Key design parameters and results for the equivalent static force procedure are given in table 2 for the three codes used. Gravity loads are assumed to be as follows; 3.6kPa (DL), 1.0(partitions), and 2.4 (LL). For this structure, lateral resistance is provided by two identical perimeter X braced frames (figure 1), having total height h_n= 45m from ground level. In-plane torsion is ignored in this study; however, each braced frame is assumed to resist 50% of the applied lateral loads, including stability effects. Climatic loads like snow and wind loads were also ignored in the calculations. The study does not take in consideration any socioeconomic, political or human error factors (e.g. corruption).

5.1 Design Data

The braces of the structures are designed assuming a yield stress of F_y = 300 MPa. The modification factors for tension (ω) and compression (β) are taken equal to 1.4 and 1.1, respectively. In the analyses, the bracing members are assumed to have an equivalent cross-sectional area equal to 1.5 times the core cross-section area A_{sc}. This ratio is typical for braces detailed for high axial stiffness, when drift limits are expected to control the frame design. Beams and columns are assumed to be fabricated from ASTM A992 I-shaped members (US and Canada) with a F_y of 345 MPa, and grade C St-52 I-shaped members (Egypt) with a F_y of 360 MPa. Beams are non-composite and the frames are designed assuming that the beam-to-column connections are pinned.

5.2 Design using the equivalent static force procedure

A linear modal dynamic analysis has been developed for the seismic design of the frames. Key design parameters and results for the equivalent static force procedure are given in table 2 for the three codes used. For all three codes, the frame members were sized to satisfy minimum strength requirements and was then re-analyzed to obtain the fundamental period and the storey drifts. The procedure was iterative till convergence was reached and the final design values are presented in Table 2.

Table 3 - Seismic design parameters and results - Equivalent static force procedure (/building).

Parameter	NBCC2015	ASCE7-16	ECP2011
T(s)	1.125	1.271	0.868
Modification Factor	R_dR_0=3.9	R=6.0	R=7.0
Seismic Weight	W=86 065	W=85 705	W=105 200
Base Shear	V=3045	V=1565	F_b= 4287
Base Shear Ratio	V/W=0.035	V/W=0.018	F_b/W= 0.040
Design Base Shear	3540	2034	5015
Maximum Drift (/h_s)	0.031	0.019	0.002
Steel Tonnage	175	94	215

As can be observed form the table, values of both the seismic weight and base shear are significantly higher through the Egyptian code compared to its counterparts in the US or Canada. This is can be partially related to the shorter period computed with the Egyptian provisions (0.868s) compared to 1.125s and 1.271s for the Canadian and US standards, respectively. The value of the reduction factor (R=7.0) in the ECP2011 came in line with the value specified by the American code (R=6.0), but its worth noting that majority of steel structural systems in Egypt take a reduction factor of either 5.0 or 7.0 based on anticipated ductility, regardless of types or geometry. The Canadian code specify lower reduction factor but this is compensated not applying the 2/3 factor applied to the spectral ordinates obtained. The Egyptian code came the most conservative in obtaining the seismic weight since a factor of 1.4 is applied to the dead load to obtain the ULS combination. The design base shears were obtained after applying the amplification factors specified by each code to satisfy the notional loads and the P-Δ effects. In the NBCC 2015 U_2=1.16 was applied to amplify the base shear, and the redundancy factor ρ=1.3 was applied in the US case. The Egyptian code specifies an amplification factor of 1/(1-θ) based on the ratio of gravity and lateral load applied at each storey, in this building θ =0.23 and the amplification factor was 1.17 which came in agreement with the factor specified by the NBCC2015. The design base shear specified by the ECP2011 came 1.4 and 2.46 times the ones specified by the NBCC2015 and ASCE7-16, respectively. Satisfying the stringent drift limitations had a major impact on design, the final frame design in Egypt came the heaviest with 215t tonnes, which is 23% heavier than Canadian frame (175t) and 128% heavier than the American frame (94t).

6. Conclusions

Seismic design provisions of the Egyptian code of practice were reviewed and compared to their counterpart in American and Canadian design codes. The seismic design requirements were applied to a prototype building located at three different sites with similar seismic and soil conditions. Earthquake effects were determined using the equivalent static force procedure method. The main conclusions/recommendations of the study can be summarized as follows:

- Egyptian code has a single formula for computing the period of a structure that depends on structural system/material and height of building. However, the formula is very general and does not include much variation of systems or geometries, and was found to yield shorter period value when compared to other codes.

- Base shear values obtained from ECP2011 were found to be much higher than ones computed by other codes, mainly because of the conservatism in calculating the seismic weight taking in consideration entirety of ultimate combination of dead load in addition to a portion of the live loads.
- Force modification factors, base shear ratio, and stability requirement factors (P-Δ effects) of ECP2011 lie within similar ranges compared to other codes.
- ECP2011 imposes stricter drift limits and that has directly affected the design. The final frame design in Egypt came 23% heavier than Canadian frame and 128% heavier than the American frame.
- Using the equivalent static method of the ECP2011 has an overall similar methodology compared to other codes but has proven to be somehow conservative and many resources can be saved if current provisions are further optimized.
- In addition to proper auditing on current construction practices, the objective of more sustainable construction is achievable in the near future in Egypt.

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