International Journal of GEOMATE, July., 2021, Vol.21, Issue 83, pp.1-10
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.83.j2121
Geotechnique, Construction Materials and Environment

ASSESSMENT OF BASE-ISOLATED BUILDINGS DESIGNED USING INTERNATIONAL DAMPING MODIFICATION FACTORS

Mohamed Hesham Mansour[1], *Manar Maher Hussein[2] and Adel Yehia Akl[3]

[1] Housing and Building National Research Center, Egypt; [2,3] Faculty of Engineering, Cairo University, Egypt

*Corresponding Author, Received: 21 Feb. 2021, Revised: 15 Mar. 2021, Accepted: 28 Mar. 2021

ABSTRACT: Base-isolation is an efficient technique for improving the seismic performance of building structures. The damping modification factor is a spectral scaling factor adopted in international seismic codes for the design of such structures. The suitability of national expressions for damping modification factor proposed for the Egyptian code was assessed. These national expressions were used for the first time to design base-isolated buildings and study their seismic performance compared to their fixed-base counterparts using response history analyses. The output responses used for comparison included stories' displacements, stories' shear forces, inter-storey drift ratios and stories' accelerations. It was shown that roof storey displacement can be reduced by up to 28% when using base-isolation for taller buildings. The base-isolated buildings were characterized by small inter-storey drifts not exceeding 0.13% and small floor accelerations which cannot be achieved simultaneously for fixed-base cases. The base shear forces were also reduced considerably by using base-isolation and they in some cases reached 29% of the values for the fixed case. In addition, the isolators' displacements and the base shear forces were computed using code static analysis based on national and international damping modification factors where good agreement was shown. However, the national expressions tended to be more conservative for taller buildings due to their period dependent nature. This study have shown the suitability of the proposed national expressions to upgrade the Egyptian code rather than adopting international codes' expressions.

Keywords: Base-isolation, Damping modification factor, Code provisions, High damping rubber bearing, Time history analysis

1. INTRODUCTION

The primary reasons causing damage to the structures during an earthquake are the floor accelerations and inter-storey drifts [1]. Base-isolation has a sufficient efficiency to controlling the earthquake damage in structures caused by the increased floor accelerations and inter-storey drifts. This characteristic of base-isolation is needed for strategic buildings that require post-earthquake operability. In addition, the significant reduction in damage for base-isolated buildings reduces post-earthquake repair costs which can compensate the increased initial costs. Base-isolation has regulations in international seismic codes incorporating spectral scaling factors (damping modification factors) to get the highly damped spectra of base-isolated structures from the 5%-damped ones. The damping modification factor depends upon the ground motions used to derive it. Consequently, it is recommended to use local ground motions for each country to derive expressions or values for that factor. The adoption of such national expressions in the national seismic codes would be logical to reflect the seismicity of each country. Previous researches [2, 3] have pointed that the Egyptian code for calculation of loads on Structures (ECP201-2012) [4] lacks provisions for seismic isolation. In addition, these researches included the first proposed expressions for the damping modification factor to upgrade the Egyptian code based on Egyptian earthquakes' records. The behaviour of base-isolated buildings compliant with international seismic codes was studied in [5-8]. These studies included studying the effects of base-isolation on the dynamic response of the buildings. The efficiency of isolation systems in enhancing the seismic performance was shown for different building heights and for new constructions as well as for retrofit purpose. The proposed expressions [2, 3] were assumed to be primarily applicable to seismic zone (5) in Egypt. For this reason, the derived expressions were used to design buildings lying in seismic zone (5) in Egypt. Then, these buildings were analysed using time history method to assess their seismic performance compared to their fixed-base counterparts. This aims at investigating the efficiency of using base-isolation for buildings lying in the Egyptian seismic zone having the highest risk when designed based on national expressions. In addition, code static analysis was used to compute some response indicators implementing the national expressions to compare them with the outputs when implementing international codes' expressions.

2. RESEARCH SIGNIFICANCE

This study continues previous studies [2, 3] that included derivation of national expressions for damping modification factor. The main goal is to perform the first design application on the new proposed expressions. This application was needed for verification purpose to test the suitability of these expressions practically. Also, a practical comparison of these expressions with international codes was performed using code static analysis to compare seismic responses when calculated using national expressions and international codes.

3. DESCRIPTION AND DESIGN OF THE STUDIED BUILDINGS

The buildings studied are reinforced concrete moment resisting frame buildings assumed to lie at seismic zone (5-B) in Egypt. The buildings are residential buildings regular in plan as shown in Fig. 1.

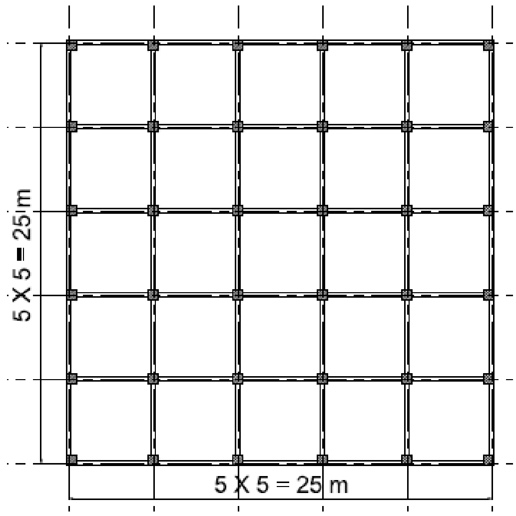

Fig.1Typical structural plan for the studied buildings

Three different heights were studied which are 4, 8 and 12 stories. The buildings are also regular in elevation with a storey height of 3 m except for the ground storey which is 4 m height. The slab thickness is 0.15 m which is a reasonable thickness for the 5*5 m slab dimensions in plan for a residential building. The live load intensity was taken as 2 kN/m^2 for all floor slabs while the flooring load intensity was taken as 1.5 kN/m^2 for all the floors except for the roof it was taken as 3.5 kN/m^2. The brick wall loads were assumed to be 10 and 6 kN/m on the perimeter and the interior beams respectively. For each building height, the building was designed twice: first as a fixed-base building under gravity and seismic loads and second as a base-isolated building under gravity and reduced seismic loads corresponding to the isolated case. Concrete compressive strength was assumed to be 30 MPa and reinforcing steel yield strength was 360 MPa.

3.1 Design of Fixed-base Buildings

The design was done according to the provisions of the Egyptian code for design and construction of concrete structures (ECP203-2017 [9]) and the Egyptian code for calculation of loads on Structures (ECP201-2012 [4]). The buildings were assumed to be residential type lying at seismic zone (5-B) in Egypt on a soil class C. This leads to using type (1) spectrum in the Egyptian code with a design ground acceleration of 0.3 g. Also, the framed buildings were assumed to be with limited ductility so the response modification factor was taken as 5. The concrete dimensions for the columns were chosen as given in Table 1. The dimensions of the beams were taken as 0.25*0.6 m for the 4-storey and the 8-storey building while for the 12-storey building their dimensions were slightly increased to 0.25*0.65 m. Table 2 gives the required reinforcement of the columns of the fixed-base buildings for the design based on seismic loads combination while Table 3 gives the required reinforcement of the beams.

3.2 Design of Base-isolated Buildings

The Eurocode 8 (EC8) [10] is the main reference for the Egyptian seismic provisions that currently do not contain regulations for seismic isolation. For this reason, the design of base-isolated buildings followed the EC8 [10] strategy but using the national expression for damping modification factor derived from natural earthquakes recorded in Egypt [2, 3]. The first step in the design of base-isolated building is to calculate the design displacement for the isolation system using Eq. (1). The resulting value of the design displacement gives a guide for a preliminary choice for the isolator type.

$$S_{De}(T_{eff}) = \frac{S_e(T_{eff})}{B}\left[\frac{T_{eff}}{2\pi}\right]^2 \qquad (1)$$

Where: S_{De} (T_{eff}): design displacement of the isolation system for a base-isolated building having effective period of vibration T_{eff} and effective damping ξ_{eff}.

S_e (T_{eff}): elastic response spectral acceleration corresponding to isolated vibration period T_{eff} and the conventional damping ratio of 5%.

B: damping modification factor calculated using national expressions (Eq. (2)) [2, 3] and corresponding to isolated vibration period T_{eff} and effective damping ξ_{eff}.

Table 1 Concrete dimensions for the columns of the three buildings (in metres)

	4-storey building columns dimensions		8-storey building columns dimensions		12-storey building columns dimensions	
Stories numbers	Interior columns	Exterior columns	Interior columns	Exterior columns	Interior columns	Exterior columns
1-2	0.45×0.45	0.40×0.40	0.55×0.55	0.50×0.50	0.65×0.65	0.60×0.60
3-4	0.40×0.40	0.35×0.35	0.50×0.50	0.45×0.45	0.60×0.60	0.55×0.55
5-6	-	-	0.45×0.45	0.40×0.40	0.55×0.55	0.50×0.50
7-8	-	-	0.40×0.40	0.35×0.35	0.50×0.50	0.45×0.45
9-10	-	-	-	-	0.45×0.45	0.40×0.40
11-12	-	-	-	-	0.40×0.40	0.35×0.35

Table 2 Reinforcement of the columns (fixed-base case)

	4-storey building columns reinforcement		8-storey building columns reinforcement		12-storey building columns reinforcement	
Stories numbers	Interior columns	Exterior columns	Interior columns	Exterior columns	Interior columns	Exterior columns
1-2	12 ϕ 20	12 ϕ 22	12 ϕ 20	12 ϕ 22	12 ϕ 25	16 ϕ 25
3-4	8 ϕ 18	8 ϕ 18	8 ϕ 20	8 ϕ 20	12 ϕ 22	12 ϕ 20
5-6	-	-	8 ϕ 18	8 ϕ 20	12 ϕ 20	8 ϕ 22
7-8	-	-	8 ϕ 18	8 ϕ 16	8 ϕ 22	8 ϕ 20
9-10	-	-	-	-	8 ϕ 20	8 ϕ 20
11-12	-	-	-	-	8 ϕ 18	8 ϕ 18

Table 3 Reinforcement of the beams (fixed-base case)

	4-storey building beams reinforcement		8-storey building beams reinforcement		12-storey building beams reinforcement	
Stories numbers	Bottom	Top	Bottom	Top	Bottom	Top
1-2	6 ϕ 16	7 ϕ 18	4 ϕ 20	7 ϕ 20	5 ϕ 20	6 ϕ 22
3-4	3 ϕ 16	6 ϕ 16	3 ϕ 20	7 ϕ 20	5 ϕ 20	6 ϕ 22
5-6	-	-	4 ϕ 16	5 ϕ 20	4 ϕ 20	6 ϕ 22
7-8	-	-	3 ϕ 16	5 ϕ 16	3 ϕ 20	5 ϕ 22
9-10	-	-	-	-	3 ϕ 16	6 ϕ 18
11-12	-	-	-	-	3 ϕ 16	5 ϕ 16

$$B = C_1\, T^{(C_2 + C_3 \ln T)} + C_4 \ln T \tag{2}$$

Where (T) is the vibration period and the coefficients C_1, C_2, C_3 and C4 are given as functions in the damping ratio (ξ) as follows in Eqs. 3-6:

$$C_1 = \sqrt{49.3 - (\xi - 7.002)^2} \tag{3}$$

$$C_2 = \frac{0.02364}{\xi} - 0.4801 \tag{4}$$

$$C_3 = -0.2432 - 0.0815 \ln \xi \tag{5}$$

$$C_4 = 0.4626 - \frac{0.02279}{\xi} \tag{6}$$

By consulting a manufacturer's catalogue for isolators [11], the effective stiffness, effective damping and design displacements for the high damping elastomeric bearings seemed suitable for the buildings studied. Initial values for the periods of the three buildings were assumed between 2 to 3 seconds which is the typical range for isolated buildings [1]. Several trials were done to choose suitable isolators' sizes from the catalogue [11] based on the initial time periods, initial design displacements and the vertical load capacities required for the isolators. These trials lead to choosing the isolators having the properties listed in Table 4 where an isolator is placed under each column. The final isolated time periods for the 4, 8 and 12-storey buildings were 2.04, 2.51 and 3.01 seconds respectively based on the effective stiffness of the isolation systems chosen. It is worth noting that the corresponding fixed-base periods using the Egyptian code approximate formula were 0.51, 0.83 and 1.13 seconds for the 4, 8 and 12-storey buildings respectively. The final design displacements for the 4, 8 and 12-storey buildings were 0.0914, 0.0931 and 0.0946 m respectively. These displacements included the torsional effect on the outermost isolator and a reliability factor of 1.2 [10]. After choosing the suitable isolators for the buildings, the superstructures were designed based on reduced base shear forces of 1671, 2067 and 2154 kN for the 4, 8 and 12-storey buildings respectively. These base shear values correspond to spectral accelerations calculated using the elongated periods, the effective damping of the isolated buildings and a behaviour factor of 1.5. This is the response modification factor recommended by EC8 [10] to reduce the base shear force for the superstructure design only. The concrete dimensions were kept constant for the design of fixed-base and base-isolated buildings so that the floors seismic masses for the two building types would not be a variable in the comparative time history analyses. Table 5 gives the required columns reinforcement for the base-isolated buildings while Table 6 gives the required beams reinforcement.

Table 4 Characteristics of the chosen high damping elastomeric isolators

Properties of isolator	4-storey building	8-storey building	12-storey building
Diameter (mm)	500	650	800
Total rubber thickness (mm)	78	108	160
Total height of isolator (mm)	204	231	315
Maximum horizontal displacement (mm)	150	200	300
Maximum vertical load at non-seismic load combination (kN)	7260	10430	14940
Maximum vertical load under seismic displacement (kN)	1800	2760	4050
Horizontal stiffness (kN/m)	1010	1230	1260
Damping (%)	10	10	10

Table 5 Reinforcement of the columns (base-isolated case)

	4-storey building columns reinforcement		8-storey building columns reinforcement		12-storey building columns reinforcement	
Stories numbers	Interior columns	Exterior columns	Interior columns	Exterior columns	Interior columns	Exterior columns
1-2	8 ϕ 16	8 ϕ 16	12 ϕ 18	8 ϕ 18	12 ϕ 22	12 ϕ 20
3-4	8 ϕ 16	8 ϕ 12	8 ϕ 18	8 ϕ 16	12 ϕ 20	12 ϕ 18
5-6	-	-	8 ϕ 16	8 ϕ 16	12 ϕ 18	8 ϕ 18
7-8	-	-	8 ϕ 16	8 ϕ 12	8 ϕ 18	8 ϕ 16
9-10	-	-	-	-	8 ϕ 16	8 ϕ 16
11-12	-	-	-	-	8 ϕ 16	8 ϕ 12

Table 6 Reinforcement of the beams (base-isolated case)

	4-storey building beams reinforcement		8-storey building beams reinforcement		12-storey building beams reinforcement	
Stories numbers	Bottom	Top	Bottom	Top	Bottom	Top
1-2	3 ϕ 16	5 ϕ 16	3 ϕ 16	5 ϕ 18	3 ϕ 16	6 ϕ 18
3-4	3 ϕ 16	4 ϕ 16	3 ϕ 16	5 ϕ 16	3 ϕ 16	5 ϕ 18
5-6	-	-	3 ϕ 16	4 ϕ 16	3 ϕ 16	6 ϕ 16
7-8	-	-	3 ϕ 16	4 ϕ 16	3 ϕ 16	5 ϕ 16
9-10	-	-	-	-	3 ϕ 16	4 ϕ 16
11-12	-	-	-	-	3 ϕ 16	4 ϕ 16

4. PROCEDURE FOR NUMERICAL MODELLING

The seismic performance of the studied buildings was assessed using nonlinear time history analyses. Due to the regularity of the buildings, a two-dimensional modelling was done for a representative interior frame using the SeismoStruct® [12] software. This software implements the fibre approach which represents the behaviour of the cross-section by dividing it into fibres assigned a uniaxial stress-strain relationship. The frame element used for modelling beams and columns in the current study is the inelastic force-based frame element with distributed inelasticity feature. The Mander et al. concrete model was used for material modelling of concrete. This model is based on the constitutive behavior that Mander et al. [13] have set. The material modelling for the reinforcing steel is using the Menegotto-Pinto steel material model which is based on the constitutive material law proposed by Menegotto and Pinto [14]. The nonlinear material models used for the inelastic frame elements in the software allowed taking the hysteretic damping into account.

The high damping rubber bearings used in this study were modelled using the link element available in the library of SeismoStruct® [12]. The modelling of the vertical force-deformation response of the bearings was achieved using linear elastic behavior of stiffness in tension equals to 0.01 the stiffness in compression [15]. The horizontal force-deformation response of the elastomeric bearings was modelled using linear symmetric force-deformation behavior. In such case, the energy dissipation of the isolation system in the lateral direction was expressed in terms of an equivalent viscous damping (also known as the effective damping which is given in Table 4). The latter modelling procedure for the horizontal response is allowed by EC8 [10] for elastomeric bearings that do not contain a lead plug.

Table 7 Ground motions used in the time history analyses

Ground motion number	Event name	Event year	Station
Ground motion - 1	CENTRAL ITALY	2016	SNG
Ground motion - 2	NORTHERN ITALY	2012	MRN
Ground motion - 3	CENTRAL ITALY	2016	CLF
Ground motion - 4	CENTRAL ITALY	2009	MI03
Ground motion - 5	SOUTHERN ITALY	1998	LRG
Ground motion - 6	GREECE	1999	ATH3
Ground motion - 7	SICILY	1990	SRT

The studied buildings were assumed to lie at seismic zone (5-B) in Egypt with site class (C). Seven ground motions were downloaded from the European strong motion database [16] using the SeismoSelect® software [17] and scaled such that their average spectrum matches the Egyptian code spectrum of seismic zone (5-B) with site class (C). The ground motions were given numbers from 1 to 7 and the names of the events, years of occurrence and stations are given in Table 7. Figure 2 shows the response spectra of these ground motions with their average spectrum and the target spectrum of the Egyptian code.

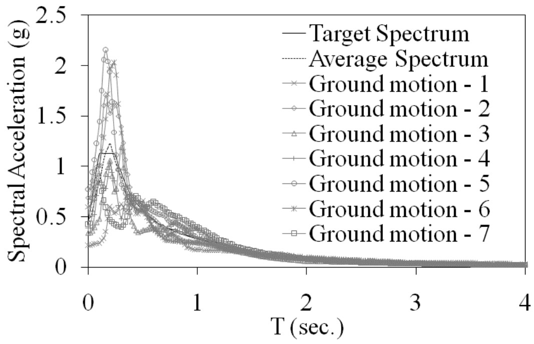

Fig.2 Response spectra of the ground motions used in time history analyses

5. OUTPUT RESPONSES FROM TIME HISTORY ANALYSES

5.1 Maximum Stories' Displacements

The maximum stories' displacements for the studied buildings were plotted in Fig. 3. This figure shows the average responses for the seven ground motions. The displacement of storey number zero (or base-diaphragm) is the displacement of the isolation system. If the final design displacements given in section 3.2 were calculated excluding torsion and reliability factor, they become 0.0686, 0.0699 and 0.071 m for the 4, 8 and 12-storey buildings respectively. The ratios between the average isolation systems' displacements from time history analyses and the latter values were 94, 78 and 71% for the 4, 8 and 12-storey buildings respectively. This means that the values from time history diverge away from Eq. (1) as the building's height increases. This is because Eq. (1) gives preliminary values based on an assumption of rigid superstructure response. This assumption becomes farther from the real behaviour as the building's height increases. For the 4-storey building, the roof storey displacement of the base-isolated building was 15% greater than that of the fixed-base one. In contrary, the 8-storey and the 12-storey buildings have greater roof storey displacements for the fixed-base case than the base-isolated case by 25 and 38%, respectively.

Figure 4 shows the calculated design displacements for different damping ratios using

Eq. (1) employing different damping modification factors. The damping modification factors were those of EC8 [10], ASCE 7-16 [18] and Eq. (2). The European code EC8 [10] gives values for that factor based on the damping ratio ξ (Eq. (7)) while ASCE 7-16 [18] gives values for that factor in a tabular form (Table 8).

$$B = \sqrt{\frac{5+\xi}{10}} \tag{7}$$

Table 8 Damping modification factor (B) in ASCE 7-16 [18]

Damping Ratio (%)	B
5	1.0
10	1.2
20	1.5
30	1.7
40	1.9

The highest values of design displacements were given by Eq. (2) for the 8-storey and the 12-storey buildings. For the 4-storey building, Eq. (2) gives designs displacements between EC8 [10] and ASCE 7-16 [18] except for damping ratio of 40% due to the upper bound applied on the damping modification factor by EC8 [10]. It is worth noting that Eq. (2) is period dependent while the values in EC8 [10] and ASCE 7-16 [18] does not depend on time period. This explains why Eq. (2) gives more conservative design displacements relative to the international codes by increasing the buildings' heights. As the Egyptian code for calculation of loads on Structures (ECP201-2012) [4] lacks provisions for seismic isolation, it has no expression for computing the damping modification factor corresponding to highly-damped base-isolated buildings. Table (8-4) in the code gives values for the damping modification factor dependent only upon the type of building material and structural system. These values correspond to nominal damping ratios of fixed-base structures. For reinforced concrete structures, table (8-4) in the code gives a value of unity for the damping modification factor assuming 5% damping. Consequently, this factor cannot be used for design of highly damped base-isolated buildings as it will give unrealistic high values for design displacements.

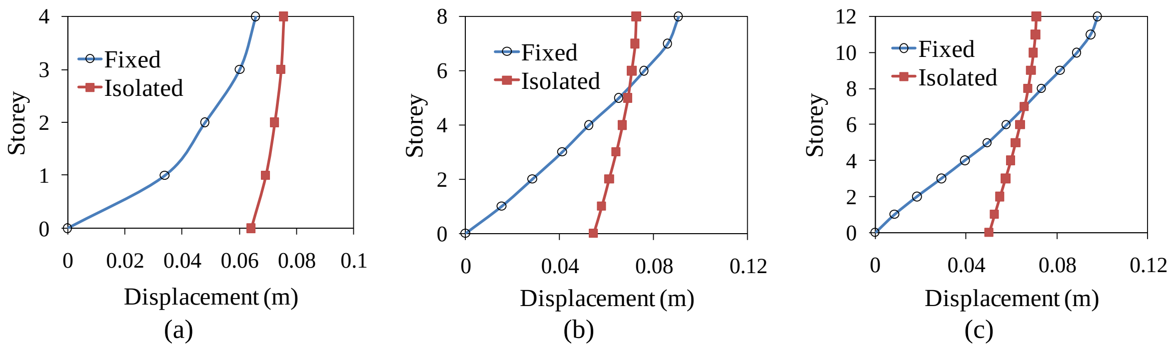

Fig.3 Maximum stories' displacements: (a) 4-storey (b) 8-storey (c) 12-storey

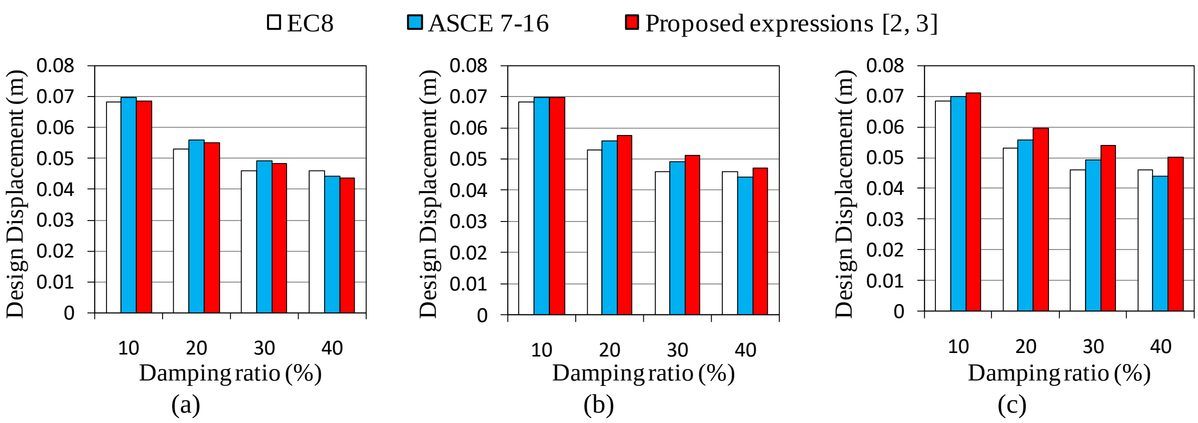

Fig.4 Design displacements using Eq. (1) for proposed national expressions [2, 3] and two international codes: (a) 4-storey (b) 8-storey (c) 12-storey

5.2 Maximum Stories' Shear Forces

The maximum stories' shear forces for the studied buildings were plotted in Fig. 5. This figure shows the average responses for the seven ground motions. The stories shear forces had larger values for the fixed-base case compared to the base-isolated case for all the buildings studied at all the stories levels. It is worth noting that the total base shear of the fixed-base building is equal to the storey shear force in storey number one while in the base-isolated case the total base shear is equal to that in storey number zero (isolation system). The decrease in the base shear force due to the base-isolation is remarkable. The ratio between the base shear of the isolated case and the fixed case for the 4-storey building ranged from 35 to 68% for all the ground motions used. The latter ratio ranged from 29 to 48% for the 8-storey building and ranged from 31 to 57% for the 12-storey building. These ratios show that the efficiency of the base-isolation technique is not limited to low-rise buildings.

The base shear forces calculated in section 3.2 for the superstructures' design of base-isolated buildings corresponded to spectral accelerations calculated using the elongated periods and the effective damping of the isolated buildings. The calculations of these elastic response spectral accelerations included the effect of damping modification factor to further reduce the base shear as the damping is higher than 5%. The effect of using damping modification factors in international codes in calculating the base shear was studied. Figure 6 shows the calculated base shear forces for different damping ratios employing damping modification factors of Eq. (2) and two international codes. This figure shows similar behaviour to that of the design displacements outlined in section 5.1. This is because both of the base shear and the design displacement are dependent upon spectral acceleration. This yields that Eq. (2) gives the highest base shear forces for the 8-storey and the 12-storey buildings. Also, for the 4-storey building Eq. (2) gives base shear forces between EC8 [10] and ASCE 7-16 [18] except for damping ratio of 40%.

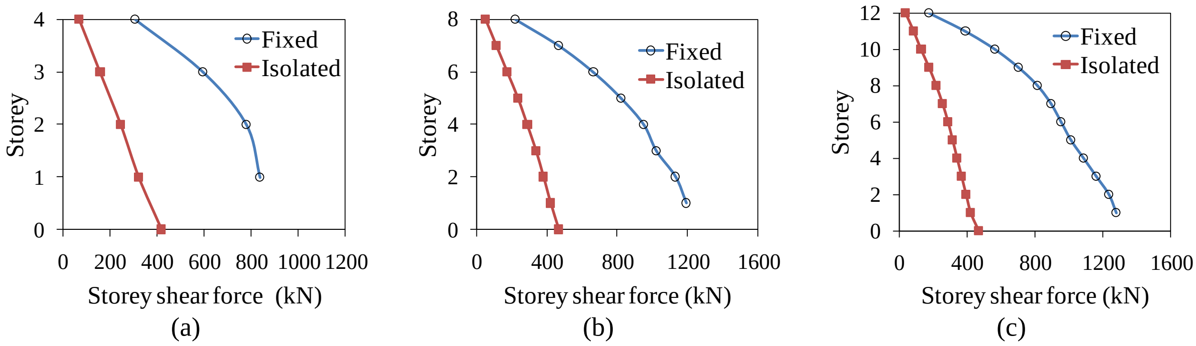

Fig.5 Maximum stories' shear forces: (a) 4-storey (b) 8-storey (c) 12-storey

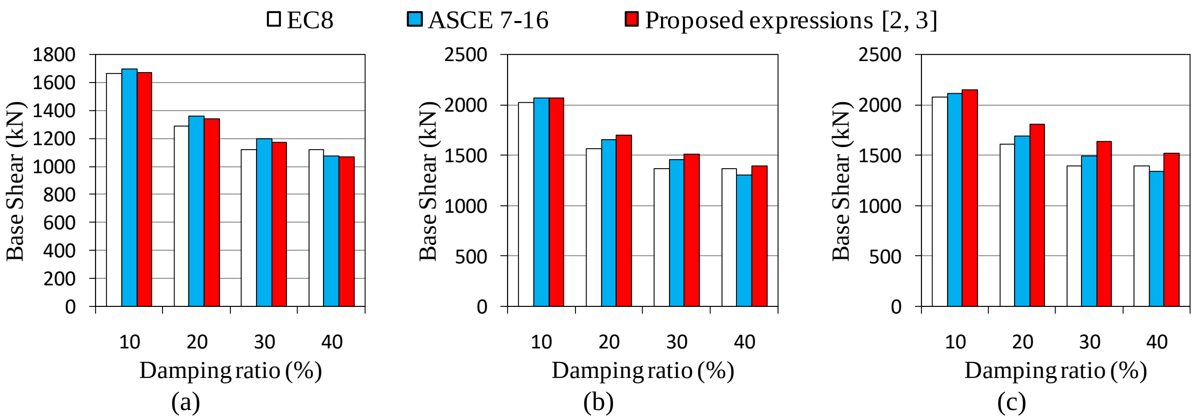

Fig.6 Base shear forces for proposed national expressions [2, 3] and two international codes: (a) 4-storey (b) 8-storey (c) 12-storey

5.3 Maximum Inter-storey Drift Ratios

The maximum inter-storey drift ratios for the studied buildings were plotted in Fig. 7. This figure shows the average responses for the seven ground motions. The inter-storey drift ratio is a measure for the damage that occurs for the structure due to earthquake excitation. It is noted that the inter-storey drift ratios for the base-isolated buildings are significantly smaller than their fixed-base counterparts. The inter-storey drift ratios have ranges for their values that define the degree of damage in the building [19]. The inter-storey drift ratios in the range of 0.2% to 0.5% correspond to damage of non-structural components. The inter-storey drift ratios in the range of 0.5% to 1.5% correspond to moderate structural damage. The inter-storey drift ratios in the range of 1.5% to 3% correspond to severe structural damage. It is noted that the maximum inter-storey drift ratio occurs at the first storey in the 4-storey building for both the fixed-base and the base-isolated cases. For the 8-storey and the 12-storey buildings, the inter-storey drift ratio increases with height and then decreases again. The latter behavior is more obvious with increasing the building's height due to the increased contribution of higher modes by increasing the building's height.

5.4 Maximum Stories' Accelerations

The maximum stories' accelerations for the studied buildings were plotted in Fig. 8. This figure shows the average responses for the seven ground motions. The values of the accelerations for the fixed-base case were always greater than those of the base-isolated case. This assures another important merit for the base-isolation technique as it reduces the stories accelerations and at the same time it reduces the inter-storey drifts. It is noted that the stories' accelerations for the base-isolated buildings are nearly uniformly distributed along the height. This emphasizes the assumption of the isolated building nearly vibrating in a rigid body mode. The fixed-base cases are not characterized by this feature. For the 4-storey building, the ratio between the maximum stories' accelerations of the base-isolated case and the fixed-base case ranged from 20 to 59% due to all the ground motions used. The latter ratio ranged from 12 to 34% for the 8-storey building and it ranged from 10 to 34% for the 12-storey building. The ratios of the maximum stories' accelerations to the peak input ground accelerations for the fixed-base buildings were 108, 90 and 86% for the 4, 8 and 12-storey buildings respectively. Regarding the base-isolated buildings, the latter ratios were 38, 18 and 14% for the 4, 8 and 12-storey buildings respectively.

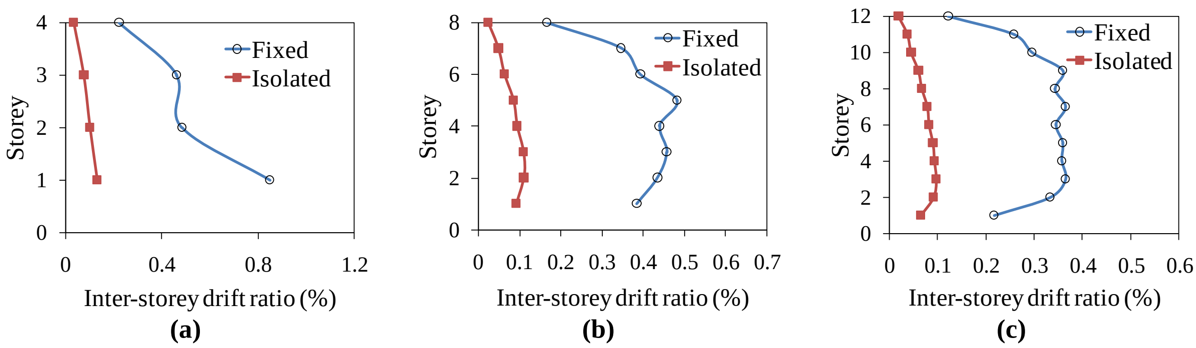

Fig.7 Maximum inter-storey drift ratios: (a) 4-storey (b) 8-storey (c) 12-storey

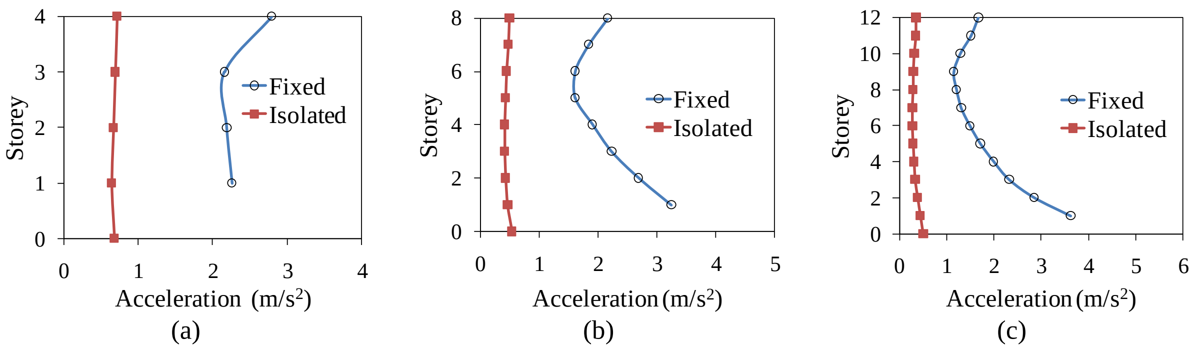

Fig.8 Maximum stories' accelerations: (a) 4-storey (b) 8-storey (c) 12-storey

The considerable reduction in stories' accelerations due to using base-isolation assures its capability in decoupling the structure from strong earthquake accelerations. This advantage can be used to protect expensive items or sensitive equipment in buildings such as museums and telecommunication buildings.

6. CONCLUSIONS

In this study, the suitability of national expressions for damping modification factor derived using Egyptian seismic records was tested. This was achieved by using these expressions proposed to upgrade the Egyptian code for the first time to design base-isolated buildings lying in seismic zone (5) in Egypt. The seismic performance of these buildings was assessed using time history analyses compared to their fixed-base counterparts. Also, code static analysis was used to compare some response indicators calculated using national and international damping modification factors. From the current study, the following conclusions can be extracted:

1. The first base-isolation design application using expressions for damping modification factor derived from local earthquakes in Egypt has shown satisfactory results. This assures the benefit of these expressions as a good option that can be used to add base-isolation design regulations for upgrading the Egyptian code.
2. The national and international damping modification factors were in good agreement regarding the computations of isolators' displacements and base shear forces by code static analysis. However, the national proposed expressions become more conservative by increasing building height due to the period dependent nature of the proposed expressions in contrast to the international ones.
3. The isolation system displacements for the studied buildings calculated preliminarily based on the assumption of rigid superstructure response are comparable to the average isolation system displacements from time history analyses. There is a good agreement between the two calculation methods for low-rise buildings while a divergence occurs with increasing height because this assumption is more realistic for low-rise buildings. However, the error did not exceed 29% for taller buildings.
4. The roof storey displacement is not essentially greater for the base-isolated case than the fixed-base case. For low-rise buildings, the roof storey displacement is often greater for the base-isolated case. By increasing the building's height, the roof storey displacement became greater for the fixed-base case than the base-isolated case and it reached a percentage increase of 38%.
5. The stories' shear forces and the base shear forces for the base-isolated buildings are considerably smaller than those of their fixed-base counterparts. The efficiency of base-isolation in reducing the base shear forces is evident for all the building heights studied and it is not limited to low-rise buildings. The base shear forces for the fixed-base cases were reduced by 32% to 71% when base-isolation was used.
6. The efficiency of base-isolation in reducing the inter-storey drift ratio (damage to the building) is clear. The values of the inter-storey drift ratios in the base-isolated buildings studied were fairly less than 0.2% which corresponds to an elastic behaviour with no damage even for non-structural elements. The values of inter-storey drift ratios for the fixed-base buildings studied corresponded mainly to damage in non-structural elements and in some cases they exceeded 0.5% to reach moderate structural damage.
7. The efficiency of base-isolation in reducing the stories' accelerations is remarkable compared to the fixed-base cases as they were reduced by about 41% to 90%. Also, the maximum stories' accelerations for the base-isolated buildings are significantly smaller than the peak acceleration of the input ground excitation. This is not true for the fixed-base buildings.
8. The current study has tested the seismic performance of reinforced concrete moment-resisting frame buildings with isolation systems designed based on national expressions for damping modification factor. This study can be extended to other buildings with different construction material types and structural systems.

7. ACKNOWLEDGMENTS

The Seismosoft Ltd. is greatly acknowledged for providing access to the software used in this study.

8. REFERENCES

[1] Naeim F., and Kelly J., Design of Seismic Isolated Structures, New York, John Wiley & Sons, 1999.

[2] Mansour M.H., Derivation of national expressions for damping modification factor for the design of base-isolated buildings, Ph.D. dissertation, Structural Engineering Department, Cairo University, 2020.

[3] Mansour M.H., Hussein M.M., Akl A.Y., and Abd El-Aal A.K., Derivation of damping modification factor using Egyptian seismic records, Journal of Engineering and Applied Science, Vol. 67, No. 4, 2020, pp. 885–903.
[4] ECP201-2012, The Egyptian Code for calculation of loads on structures, Housing and Building National Research Center, Giza, Egypt.
[5] Mazza M., Nonlinear analysis of r.c. framed buildings retrofitted with elastomeric and friction bearings under near-fault earthquakes, Earthquake Science, Vol. 28, No. 5, 2015, pp. 365–377.
[6] Pant D., Influence of scaling of different types of ground motions on analysis of code-compliant four-story reinforced concrete buildings isolated with elastomeric bearings, Engineering Structures, Vol. 135, 2017, pp. 53-67.
[7] Amin N. M., Ayub N., and Alisibramulisi A., Design of Base Isolated Reinforced Concrete Building Subjected to Seismic Excitation using EC8, International Journal of GEOMATE, Vol. 17, No. 63, 2019, pp. 23-28.
[8] Jara J.M., Hernández E.J., and Olmos B.A., Effect of epicentral distance on the applicability of base isolation and energy dissipation systems to improve seismic behavior of RC buildings, Engineering Structures, Vol. 230, 2021, pp. 111727.
[9] ECP203-2017, The Egyptian code for design and construction of concrete structures, Housing and Building National Research Center, Giza, Egypt.
[10] CEN, EN 1998-1, Eurocode 8: design of structures for earthquake resistance, Part 1: general rules, seismic actions and rules for buildings, Brussels: European Committee for Standardization, 2005.
[11] FIP Industriale Isolators Catalogues, 2018, available from www.fipindustriale.it.
[12] SeismoStruct® version 2018 online help, Seismosoft Ltd., Pavia, Italy, Available from http://www.seismosoft.com.
[13] Mander J.B., Priestley M.J.N., and Park R., Theoretical stress-strain model for confined concrete, Journal of Structural Engineering, Vol. 114, No. 8, 1988, pp. 1804-1826.
[14] Menegotto M., and Pinto P.E., Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behaviour of elements under combined normal force and bending, Proc. of IABSE symposium on resistance and ultimate deformability of structures acted on by well defined repeated loads, Zurich, Switzerland, 1973, pp. 15-22.
[15] Erduran E., Dao N.D., and Ryan K.L., Comparative response assessment of minimally compliant low-rise conventional and base-isolated steel frames, Earthquake Engineering and Structural Dynamics, Vol. 40, No. 10, 2011, pp. 1123-1141.
[16] European Strong Motion database web site, 2019, http://www.esm.mi.ingv.it.
[17] SeismoSelect® version 2020 online help, Seismosoft Ltd., Pavia, Italy, available from http://www.seismosoft.com.
[18] ASCE, Minimum design loads and associated criteria for buildings and other structures: provisions. ASCE/SEI 7-16, Reston, Virginia: American Society of Civil Engineers (ASCE), 2017.
[19] Elnashai A.S., and Di Sarno L., Fundamentals of earthquake engineering, United Kingdom, John Wiley & Sons, 2008.