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SEISMIC BEHAVIOR OF TORSIONALLY ASYMMETRIC NSC AND HSC 3-D MULTISTORY BUILDINGS

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ABSTRACT
The nonlinear seismic behavior of torsionally asymmetric reinforced concrete 3-D multistory buildings constructed from Normal-Strength Concrete (NSC) with characteristic cylinder compressive strength f_c' = 25 MPa and from High-Strength Concrete (HSC) up to f_c' = 100 MPa has been studied. In addition, the applicability of the Static Equivalent Lateral Force (SELF) methods used by the seismic codes in Europe (EC-8), in the United States (ASCE/SEI 7-16) and in Egypt (ECL-2012) have been examined when applied to torsionally asymmetric multistory buildings constructed from NSC and HSC. Inelastic dynamic analysis computer program has been used to solve the nonlinear equations of motions for two models of 3-D multistory buildings with different eccentricity (e equal to 0.10L, 0.15L, and 0.20L) and constructed from NSC and HSC. Many real and artificial earthquake records with wide ranges of frequency content have been selected as input ground motions, from them two suitable earthquake records have been used in the dynamic analysis. The results showed that increasing the design concrete strength from NSC (f_c' = 25 MPa) to HSC (f_c' = 75 MPa), generally decreases the average story displacement and the average story drift along the height of the models. The allowable limits of the story drift adopted by ASCE/SEI 7-16, EC-8 and ECL-2012 are conservative when applied to torsionally asymmetric NSC and HSC buildings with the studied eccentricities. The SELF method of ECL-2012 was unconservative especially for the upper stories when applied to torsionally asymmetric NSC and HSC multistory buildings with the studied different eccentricities while the SELF methods of ASCE/SEI 7-16 and EC-8 were conservative when applied to torsionally asymmetric NSC and HSC multistory buildings.

KEYWORDS: Seismic Behavior, Nonlinear; Torsionally Asymmetric, High-Strength Concrete, Codes.

السلوك الزلزالي للمباني ثلاثية الأبعاد المتعددة الطوابق والغير متماثلة في عزوم اللي من الخرسانة العادية والعالية المقاومة

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الملخص
هذا البحث يدرس السلوك الزازالي غير الخطي للمنشأت ثلاثيه الابعاد المتعدده الطوابق والغير متماثله في عزوم اللي والتي تم تنفيذها من الخرسانه عاديه المقاومه (المقاومة المميزة في الضغط للاسطوانة = ٢٥ ميجاباسكال) و من الخرسانة عاليه

المقاومة(المقاومة المميزة في الضغط للاسطوانة تصل إلى ١٠٠ ميجاباسكال) . كما تم أيضا دراسة إمكانية تطبيق طرق الأحمال العرضية الاستاتيكية المكافئة المستخدمة في الكودات الزلزالية الدولية (الكود الأوروبى الثامن للتصميم فى المناطق الزلزالية وفي الكود الأمريكي وفي الكود المصري الحالي للأحمال) على المباني الغير متماثله في عزوم اللي والمنفذة من خرسانة عادية المقاومة والخرسانة عالية المقاومة. وقد تم إجراء تحليل ديناميكي غير خطي بواسطة برنامج كومبيوتر خاص لحل معادلات الحركة الغير خطية لعدد مثالين لمباني متعددة الطوابق ثلاثية الأبعاد مع اختلاف المسافة بين مركز الكتله ومركز الصلابة e. وقد أوضحت النتائج أن زيادة مقاومة الخرسانة من عادية المقاومة إلي عالية المقاومة تقلل بصفة عامة التشكل الجانبي والحركة النسبية المتوسطة علي ارتفاع المبني الغير المتماثل في عزوم . كما أن الحدود الخاصة بالحركة النسبية للدور المسموح بها في الكود الأمريكي والكود الاوربي الثامن و الكود المصري للأحمال تكون آمنة عند تطبيقها علي المنشات المتماثلة والغير متماثله في عزوم اللي والمنفذة من الخرسانة العادية والعالية المقاومه والتي فيها اختلاف المسافة بين مركز الكتله ومركز الصلابة (e) تساوي ٠.١٠ و ٠.١٥ و ٠.٢٠ من بعد المنشأ. كما أوضحت النتائج أن طريقة الأحمال الاستاتيكية العرضية المكافئة و المستخدمة في الكود المصري للأحمال قد تعطي نتائج غير آمنة في الأدوار العليا عند تطبيقها على المنشات متعددة الطوابق والغير متماثلة في عزوم اللي من الخرسانة عادية المقاومة و عالية المقاومة بينما طريقة في الكود الأمريكي و الكود الاوربي كانت آمنة عند تطبيقها على المنشآت متعددة الطوابق الغير متماثله في عزوم اللي من الخرسانة عادية المقاومة و عالية المقاومة والتي تم دراسته.

الكلمات المفتاحيه: السلوك الزلزالي، الغير خطي ، الغير متماثل في عزوم اللي ،خرسانه عاليه المقاومة،الاكواد

1-INTRODUCTION

When the center of mass and center of rigidity does not coincide, eccentricities are developed in the buildings which further generate torsion and the structure is so-called torsionally asymmetric (with horizontal irregularity). Structural irregularities may vary dramatically in their nature and, in principle, are very difficult to define. Regarding buildings, for practical purposes, major seismic international codes, in the United States, the International Building Code (IBC-2018)[1] which uses the requirements of the American Society of Civil Engineers and Structural Engineering Institute (ASCE/SEI 7-16)[2], in Europe, Eurocode 8 (EC-8) [3] and in Egypt, the Egyptian Code for Loads (ECL-2012) [4], distinguish between irregularity in plan and in elevation. Many real reinforced concrete structures are usually torsionally asymmetric since symmetrical buildings is an idealization that is very rare because of architecture or environments considerations. When these buildings are subjected to lateral loads, then the phenomenon of torsional coupling occurs due to the interaction between lateral loads and resistant forces. Torsional coupling generates greater damage in the buildings as demonstrated by many real earthquakes [5,6]. Recently, the use of HSC ($f_c' > 50$ MPa) has increased significantly in tall buildings due to its improved performance characteristics when compared with NSC [7]. HSC has many benefits, both in performance and cost-efficiency, so HSC advantages are a reduction in structural element size, reduction in amount of longitudinal reinforcement, decreased time necessary for concrete's formwork. Therefore, the use of HSC provides slenderer elements with lower stiffness which may lead to many questions about the seismic behavior of torsionally asymmetric R/C buildings constructed with HSC. In comparison with research efforts dealing with NSC torsionally asymmetric structures [8-13], the seismic behavior of HSC buildings is very limited in the literature [14].

The main objective of the present study is to compare the overall seismic response of torsionally asymmetric 3-D multistory buildings constructed from NSC (with $\boldsymbol{f_c'}$ = 25 MPa) and HSC (with $\boldsymbol{f_c'}$ up to 100 MPa) with different eccentricity (e equal to 0.10L, 0.15L, and 0.20L). The applicability of the Static Equivalent Lateral Force (SELF) methods and the story drift limits used by the seismic codes in Europe (EC-8), in the United States (ASCE/SEI 7-16) and in Egypt (ECL-2012), have been also examined when applied to NSC and HSC torsionally asymmetric multistory buildings.

2- SELF METHODS, PERIOD OF VIBRATION EQUATIONS AND STORY DRIFT LIMITS ADOPTED BY THE SEISMIC CODES

2.1 ASCE/SEI 7-16

The total base shear V can be calculated using the following equation:

$$V = C_S W \tag{1}$$

(Where Cs is the seismic response coefficient, W is the design seismic weight of the structure (W is taken equal to the total dead load and 0.25 of the live load).

$$C_S = \frac{S_{DS}}{\frac{R}{I_e}} \tag{2}$$

Where S_{DS} is the design spectra response acceleration at short periods, R is the response modification factor (R = 7 for special reinforced concrete shear walls), I_e is the occupancy importance factors that depend on the risk category (I_e =1.0 for risk category II).

The seismic response coefficient, C_S not exceed the following equation:

$$C_S = \frac{S_{DS}}{T\left(\frac{R}{I_e}\right)} \qquad for\ T \le T_L \tag{3}$$

$$C_S = \frac{S_{DS}\, T_L}{T^2\left(\frac{R}{I_e}\right)} \qquad for\ T > T_L \tag{4}$$

C_s shall not be less than:

$$C_S = 0.044\, S_{DS}\, I_e \ \ge 0.01 \tag{5}$$

For structures located where S_1 is equal to or greater than 0.6g, C_S shall be not less than:

$$C_S = \frac{0.5 S_1}{\frac{R}{I_e}} \tag{6}$$

Where S_{D1} is the design spectra response acceleration at a period of 1.0 s, T_L is the long period transition period (s), T_L the mapped maximum considered earthquake spectral acceleration parameter and T is the fundamental period of vibration of response the structure and can be calculated from the following equation:

$$T = C_t (h_n)^x \tag{7}$$

where h_n is the total height of the building and C_t is a factor range from 0.0466 to 0.0731, while x varies from 0.75 to 0.9 according to structure type, C_t =0.0488 and x =0.75 (for all structure systems).

The design spectral response acceleration at a short period S_{DS}:

$$S_{DS} = \frac{2}{3} F_a S_S \tag{8}$$

The design spectral response acceleration at one second period S_{DS}:

$$S_{DS} = \frac{2}{3} F_V S_1 \tag{9}$$

Where the values of F_a and F_V (site coefficient) according to site class D and spectral response acceleration parameters S_S and S_1.

The base shear V is distributed over the height of the building according to:

$$F_{Story} = \frac{V\, W_{Story} h^{k}{}_{Story}}{\Sigma W_{Story}\, h^{k}{}_{Story}} \quad (10)$$

Where, W_{Story} is the weight of story level, h_{Story} is the story height distance from the base of the structure to story level and k is exponent applied to building height. The value of k depends on the value of the building period, T, used for determining the base shear. If T ≤ 0.5 seconds, k = 1. If T ≥ 2.5 seconds, k = 2. If 0.5< T < 2.5 seconds, k is linearly interpolated between 1 and 2.

According to this code, the allowable story drift taking into account the life-safety and damage control objective which limited as follows:

For structures in risk category I or II:

$$\Delta_a = 0.02 h_{sx} \quad (11)$$

For risk category III:

$$\Delta_a = 0.015 h_{sx} \quad (12)$$

, and for IV:

$$\Delta_a = 0.01 h_{sx} \quad (13)$$

Where h_{sx} is the story height below level x.

2.2 EC-8

The total base shear V can be calculated using the following equation:

$$F_b = S_d(T) W \lambda \quad (14)$$

Where $S_d(T)$ is the ordinate of the elastic design response spectrum given by the code for the fundamental period of the building, *W* is the design seismic weight of the structure as recommended in this code and λ is the correction factor $\lambda = 0.85 \quad if\ T \le 2T_C$ and the building has more than two stories or $\lambda = 1$ otherwise.

The design response spectrum $S_d(T)$ shall be determined as follows:

$$if\ 0 < T < T_B \qquad S_d(T) = a_g.S\left[\frac{2}{3} + \frac{T}{T_B}\left(\frac{2.5}{q} - \frac{2}{3}\right)\right] \quad (15)$$

$$if\ T_B < T < T_C \qquad S_d(T) = a_g.S\left[\frac{2.5}{q}\right] \quad (16)$$

$$if\ T_C < T < T_D \qquad S_d(T) = a_g.S\frac{2.5}{q}\left[\frac{T_c}{T}\right] \quad (17)$$

$$\ge \beta\, a_g$$

$$if\ T_D < T_1 < 4.0\,\text{sec} \qquad S_d(T) = a_g.S\frac{2.5}{q}\left[\frac{T_c T_D}{T_1{}^2}\right] \quad (18)$$

$$\ge \beta\, a_g$$

where $S_d(T)$ is the ordinate of the design spectrum for the reference return period and limited to gravity acceleration, a_g is the design ground acceleration on type A ground $a_g = \gamma\, a_{gR}$, S is the soil factor, β is lower bound factor the horizontal design spectra ($\beta = 0.2$), T_B and T_C are the constant limits for elastic response spectrum, T_D is the limit value for the start of constant displacements of the spectrum and T is the fundamental period of vibration of the building and shall be determined from:

$$T = C_t H^{\frac{3}{4}} \tag{19}$$

C_t is equal to 0.075 for space reinforced concrete frames and equal 0.05 for dual systems, q is the behavior factor (q= ٦for R.C dual systems).

The calculated base shear shall be distributed over the height of the building in conformance with the following equation:

$$F_i = F_b \frac{w_i \; h_i}{\sum_{j=1}^{n} w_j \; h_j} \tag{20}$$

The story drift *dr* should be limited as follows:

For buildings having non-structural elements of brittle materials attached to the structure (such as unreinforced masonry):

$$d_r \leq 0.005 hv \tag{21}$$

For buildings having non-structural elements of ductile materials:

$$d_r \leq 0.0075 hv \tag{22}$$

For buildings having non-structural elements fixed in a way that does not interfere with structural deformations:

$$d_r \leq 0.001 hv \tag{23}$$

where ν is a reduction factor equal to 2.5 and 2.0 for importance categories (I, II) and (III, IV), respectively.

2.3 ECL-2012

The provision of ECL-2012 is similar to that of EC-8. The total base shear F_b can be calculated as follows:

$$F_b = S_d(T_1)\lambda \frac{W}{g} \tag{24}$$

Where W is the equivalent structure weight and $S_d(T_1)$ is the design response spectrum and shall be determined as follows:

$$if\ 0 < T_1 < T_B \qquad S_d(T_1) = a_g \gamma_1 . S \left[\frac{2}{3} + \frac{T_1}{T_B}\left(\frac{2.5\eta}{R} - \frac{2}{3}\right]\right. \tag{25}$$

$$if\ T_B < T_1 < T_C \qquad S_d(T_1) = a_g . \gamma_1 S \left[\frac{2.5\eta}{R}\right] \tag{26}$$

$$if\ T_C < T < T_D \qquad S_d(T_1) = a_g . \gamma_1 S \frac{2.5\eta}{R}\left[\frac{T_C}{T_1}\right]\eta \geq 0.20 a_g \gamma_1 \tag{27}$$

$$if\ T_D < T_1 < 4.0\,\text{sec} \qquad S_d(T_1) = a_g \gamma_1 . S \frac{2.5}{R}\left[\frac{T_C T_D}{{T_1}^2}\right]\eta \geq 0.2 a_g \gamma_1 \tag{28}$$

where a_g is the design ground acceleration, *T* is the fundamental period of the building and shall be determined from Eq. (19), H is the total height of the building, T_B and T_C are the constant limits for elastic response spectrum, T_D is the limit value for the start of a displacement of the spectrum, R is the response modification factor according to the structural system (R=5 for R.C. dual system) and η is the damping design factor (η =1 for RC Structure).

The calculated base shear shall be distributed over the height of the building in conformance with Eq. (20). The limits of the story drift d_r are similar to that given in EC-8.

3.ANALYTICAL MODELING

The finite element computer program ETABS-17.1) [15, 16] was used to calculate the story displacement, story drift and story shear of 3-D building examples of the present study. In this program, the structure is modeled as a 3-D assemblage of elements connected by a finite number of deformable elements, or members. The effect of axial force on yield moment was considered for each column. The P-Δ effects are included. Shear and axial deformations are neglected. The structure mass is lumped at the nodes, and the mass matrix is diagonal. The stiffness properties of individual members are controlled by the rules of the Takeda hysteresis model [17]. The damping matrix was expressed as a linear combination of the mass and stiffness matrices, and the coefficients were selected to give 5% of critical damping in the first two vibrational modes. The differential equation of motion is formulated in incremental form and integrated using a small-time interval. For NSC and for HSC in compression, the model suggested by Daniel and Patrick [18] is adopted. This model neglected the effect of confinement on concrete strength. For this model, the value of the strain at a maximum strength of unconfined concrete is taken equal to 0.002 and the value of the strain for half of the maximum strength of unconfined concrete is taken equal to 0.004. The modulus of elasticity for NSC and HSC can be calculated using the equations recommended by the ACI 318-14 building code [19] and the ACI Committee 363 [7], respectively. For concrete in tension, the model used by Massicotte et al. [20] is adopted. This model can be expressed by three linear parts defined by the slope of the line and the calculated value of the tensile strength of concrete f_t. For NSC and HSC, f_t can be calculated, respectively, from the equations suggested in references [19] and [7]. For the steel reinforcement bars, a trilinear stress-strain relationship is adopted. The modulus of elasticity of the steel bars is taken equal to 200 KN/mm^2. The adopted model of pullout for the steel bars is that suggested by Fillippou et al. [21].

4. INPUT EARTHQUAKE RECORDS

In this study, the seismic analyses have been carried out using two different earthquake records. The first earthquake record is the Imperial Valley North-South component of the 1940 EL Centro (peak ground acceleration (PGA= 0.35g). The acceleration time history of this earthquake is shown in Fig. 1. This was chosen from four different earthquake records (El-Centro, Parkfield, New Mexico, and San Fernando) to match the “highest design level” earthquakes in the United States according to the ASCE/SEI 7-16 and in Europe according to EC-8 (regions of ductility class “High” required by EC-8). The second earthquake is an artificial earthquake record having peak ground acceleration of 0.3g and duration of 20 seconds and is chosen to represent the “probable design level” earthquakes for zone 5b in Egypt according to the ECL-2012. A response spectrum shape for soil type C (dense or medium-dense sand, gravel or stiff clay soils) with damping ratio 5% according to the ECL-2012 was taken as the target spectrum for this artificial earthquake. Twelve artificial acceleration time histories for different percentages of spectral values (Sv%) were generated using the computer program SIMQKE [22]. In order to choose the “Moderate Earthquake” as required by the ECL-2012, a time history analysis of Example 1 and 2 using these artificial earthquakes and the N-S component of El-Centro earthquake were compared. The artificial earthquake with (33%Sv) shown in Fig. 2 can be considered as that suitable for zone 5b in Egypt. The generated and target response spectra for this artificial earthquake are shown in Fig. 3.

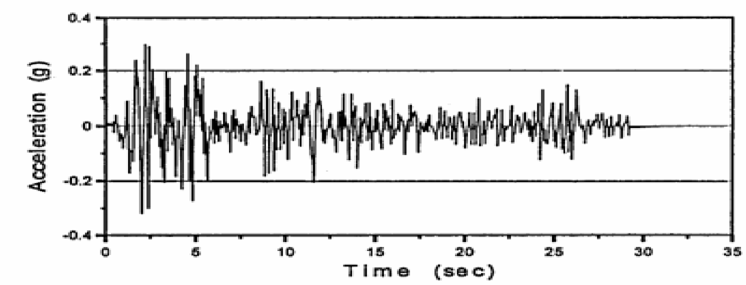


Fig. 1. Acceleration time history for N-S component of El Centro 1940 earthquake.

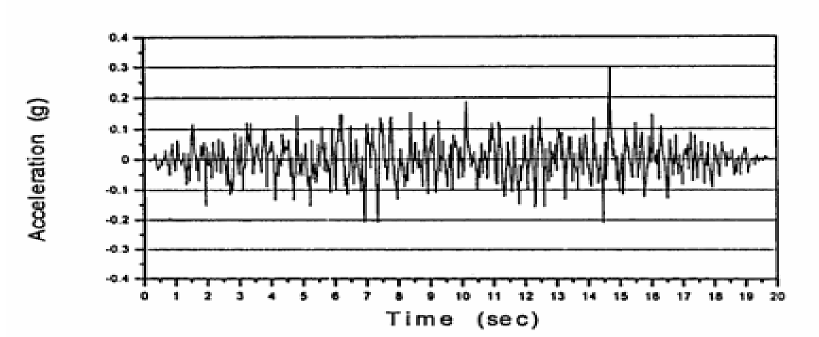


Fig. 2. Acceleration time history for the artificial earthquake of zone 5b in Egypt.

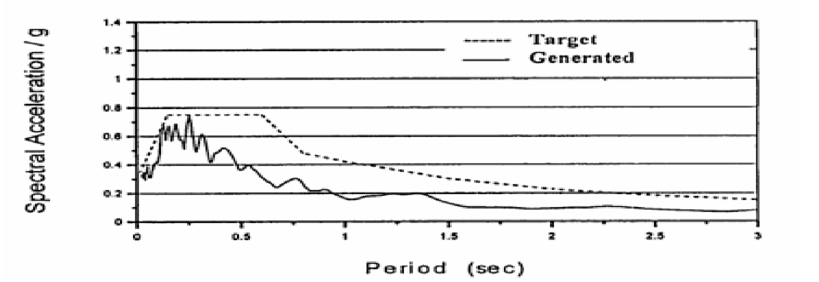


Fig. 3. Generated and target response spectra for the artificial earthquake.

3-BUILDING EXAMPLES

Two examples of reinforced concrete 3D multistory asymmetric buildings were used in the analysis of this study. The first example consists of one 12-story ductile moment-resisting frame and two 12-story dual systems as shown in Fig. 4. Table 1 describes the dimensions and details of the frames and the dual system of this example [23]. The columns, beams and shear walls of this example for the different cases (NSC with *fc′* = 25 MPa, HSC with *fc′* = 75 MPa and VHSC with *fc′* =100 MPa) were designed according to the requirements of ACI 318-14 building code [19]. Longitudinal steel bars with yield strength equal to 400 MPa were used for all the members of this example. This example was analyzed under earthquake time histories in the horizontal direction (Y-axis). In this example, the shown shear wall W1 was kept constant while the dimensions of the second shear wall W2 was changed to get the required eccentricity (e). For each case changing the width of shear wall (W_2) changed the eccentricity of the building example. The studied eccentricities (e = 0.10L, 0.15L and 0.20L) were chosen in order to study the limit determined by ECL-2012 to distinguish torsionally regular from irregular multistory buildings. It should be noted that according to ECL-2012 the building with e/L≤ 0.15 is considered as torsionally regular while for e/L> 0.15 the building is considered as torsionally irregular.

The second example is twelve stories asymmetric building has square in plan with dimensions (25m x 25m) with a symmetrical plan arrangement in columns and shear walls as shown in Fig. 5. The slab is a flat slab of thickness equal to 18 cm. the marginal beam of all floors is (25*70) cm. Table 2 shows columns and shear walls dimensions [8]. The place of the left shear wall remains constant in plan without change, while the place of the right shear wall W_R is changed to get the studied eccentricity e. It should be noted that the place of the right shear wall W_R is changed by a distance equal to 2.5 m to the right to get the case of e/L = 0.05 and additional 2.5 m to get the case of e/L = 0.10, and so on.

For each example, two cases (Case-I and Case-II) were considered under the horizontal N-S component of El Centro 1940 and the artificial earthquake record of Egypt. In Case-I, the cross-sections of the columns, beams and shear walls of the first story of the building example were designed using NSC (with *fc′* equal to 25 MPa) and reduced the cross section along the height of building. Three values of the design concrete strength were considered without changing the cross-sections of the building example (NSC with *fc′* equal to 25 MPa, HSC with *fc′* equal to 75 MPa and VHSC with *fc′* equal to 100 MPa). In Case-II, the cross-sections of the building example were changed according to the variation of the design concrete strength. It should be noted that the first part of the symbols shown in the following figures refers to the case condition (I: Case- I and II: Case-II). The second part refers to the design concrete strength (N: NSC = 25 MPa, H: HSC = 75 MPa and VH: VHSC=100 MPa) and the third part refers to the studied concrete strength. All the cases analyzed with different static eccentricity (e) 0.0L, 0.10L, 0.15L, and 0.20L.

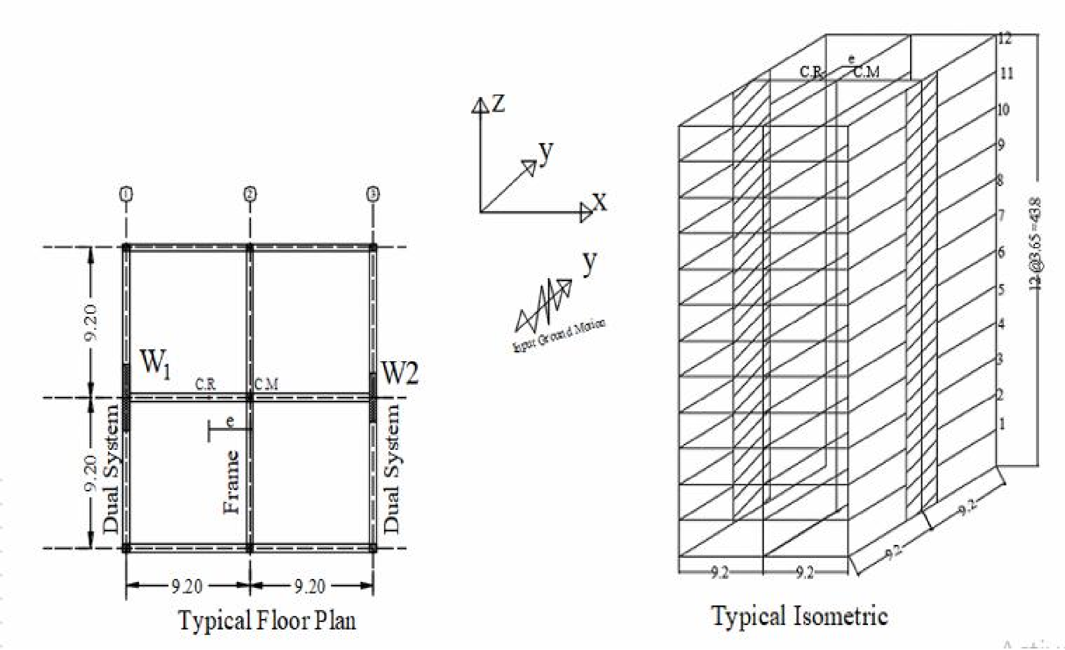


Fig. 4. Configuration of 3-D torsionally asymmetric building Example-1.

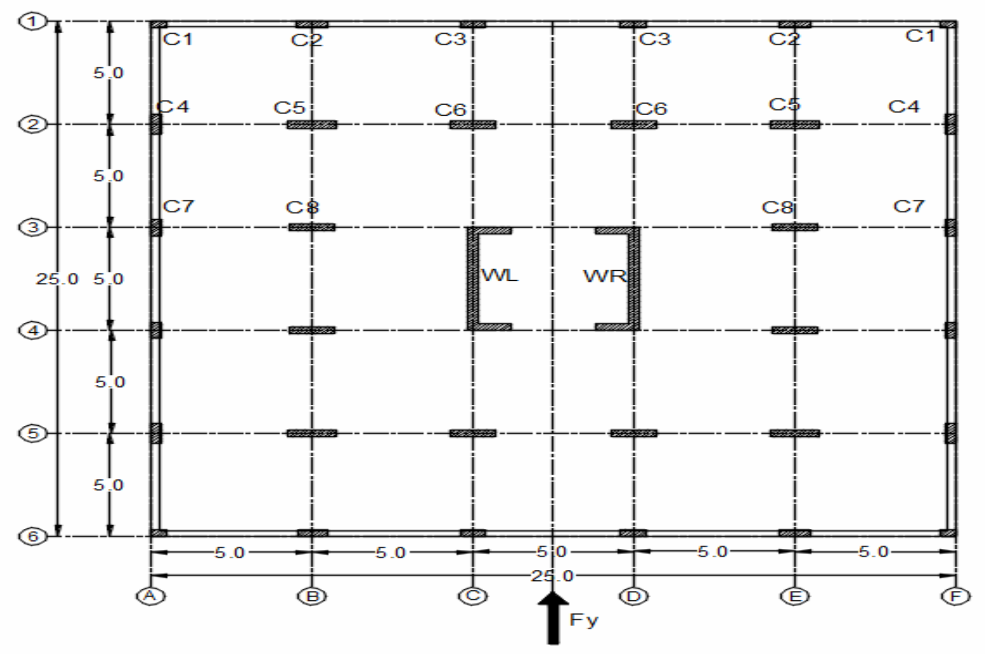
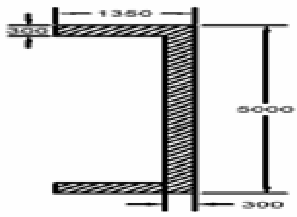


Fig. 5. Plan of typical 3-D torsionally asymmetric building Example-2.

Table 1. Principal data for 3-D building Example-1

Principal Data		NSC t * b mm	HSC t * b mm	VHSC t * b mm
12-Story Frame				
Size of Main Beams				
	1-6 Floor	750 * 400	700 * 300	650 * 300
	7-8 Floor	700* 400	650 * 300	600* 300
	9-10 Floor	650 * 400	600 * 300	550 * 300
	11-12 Floor	600 * 400	550 * 300	500 * 300
Size of Exterior Columns				
	1-3 Floor	725 * 500	700 * 350	650 * 300
	4-6 Floor	625 * 500	600 * 350	650 * 300
	7-8 Floor	575 * 500	550 * 350	500 * 300
	9-10 Floor	525 * 500	500 * 350	450 * 300
	11-12 Floor	500 * 500	450 * 350	400 * 300
Size of Interior Columns				
	1-3 Floor	725 * 725	625 * 625	600 * 600
	4-6 Floor	675 * 675	575 * 575	525 * 525
	7-8 Floor	625 * 625	525 * 525	475 * 475
	9-10 Floor	575 * 575	475 * 475	450 * 450
	11-12 Floor	550 * 550	450 * 450	400 * 400
12-Story Dual system				
Size of Main Beams				
	1-6 Floor	850 * 250	700 * 250	650 * 250
	7-12 Floor	750 * 250	650 * 350	600 * 250
Size of Exterior Columns		400 * 400	350 * 350	325 * 325
Size of Shear Wall				
	w1	4000 * 250	4000 * 250	4000 * 250
W2	e/L = 0.20	3000 * 250	3000 * 250	3000 * 250
	e/L = 0.15	3300 * 250	3300 * 250	3300 * 250
	e/L = 0.10	3500 * 250	3500 * 250	3500 * 250

`Table 2. Principal Data For 3-D Building Example-2

Principal Data	NSC (t * b mm)	HSC (t * b mm)	VHSC (t * b mm)
Columns			
(1-3) Floor			
C1	300*500	300*350	300*300
C2 =C4	300*950	300*700	300*600
C3=C7	300*800	300*600	300*500
C5	350*1500	350*1050	350*900
C6=C8	350*1400	350*1000	350*800
(4-6) Floor			
C1	300*450	300*350	300*300
C2 =C4	300*900	300*650	300*550
C3	300*750	300*550	300*450
C5	350*1450	350*1000	350*850
C6=C8	350*1350	350*950	350*750
(7-9) Floor			
C1	300*400	300*350	300*300
C2 =C4	300*850	300*600	300*500
C3	300*700	300*500	300*400
C5	350*1400	350*950	350*800
C6=C8	350*1300	350*900	350*700
(10-12) Floor			
C1	300*400	300*350	300*300
C2 =C4	300*800	300*550	300*450
C3	300*650	300*450	300*350
C5	350*1350	350*900	350*750
C6=C8	350*1250	350*850	350*650
shear wall ($W_R = W_L$)	Dimension 		

4- OVERALL RESPONSE OF TORSIONALLY ASYMMETRIC NSC AND HSC 3-D MULTISTORY BUILDINGS

6.1 Effect of Concrete Strength on the Story Displacement and Story Drift

The envelopes of the story drift along the height of the building Example-1 due to the variation of the concrete strength for Case-I and Case-II under N-S component of EL Centro 1940 earthquake and the artificial earthquake of Egypt for different e/L ratio as shown in Fig. 6 to 9. Increasing the actual concrete strength from NSC to HSC generally reduced the average story displacement and also the story drift along the height of the building for different e/L ratios. For Case–II, it can be seen that for (e/L) equal to 0.0, increasing the concrete strength from NSC to HSC resulted in a reduction in the average story drift by 32.14 %, while increasing the concrete strength from HSC to VHSC resulted in growth about 1.72%. For (e/L) equal to 0.10, increasing the concrete strength from NSC to HSC resulted in a reduction in the average story drift by 32.14 %, while increasing the concrete strength from HSC to VHSC resulted in a reduction by about 4.52 %. For (e/L) equal to 0.15, the ratio of the reduction of the average story drift became 33.15 % when increasing the concrete strength from NSC to HSC, while for (e/L) equal 0.20 the reduction value became 30.34%. Under the artificial earthquake, the reduction in the story drift due to increasing the concrete strength was relatively small compared with that resulted from the El-Centro earthquake. This was due to the low-frequency content of the artificial earthquake.

The envelopes of the story drift along the height of the building Example-2 due to the variation of the concrete strength for Case-I and Case-II under N-S component of EL-Centro 1940 earthquake and the artificial earthquake of Egypt are shown in Figs.10 to 13 for different e/L ratio. Increasing the actual concrete strength from NSC to HSC generally reduced the average story drift along the height of the building for different e/L ratio. For Case–II, it can be seen that for (e/L) equal to 0.0, increasing the concrete strength from NSC to HSC resulted in a reduction in the average story drift by 32.17 %, while increasing the concrete strength from HSC to VHSC resulted in a reduction by about 15.86%. For (e/L) equal to 0.10, increasing the concrete strength from NSC to HSC resulted in a reduction in the average story drift by 34.14 %, while increasing the concrete strength from HSC to VHSC resulted in a reduction by about 13.17%. For (e/L) equal to 0.15, the ratio of the reduction of the average story drift became 26.51% when increasing the concrete strength from NSC to HSC, while for (e/L) equal 0.20 the reduction value became 20.41%. Under the artificial earthquake, the reduction in the story drift due to increasing the concrete strength was relatively small compared with that resulted from El-Centro earthquake. In general, the overall response of the story drift for Example-2 for Case-I and case-II along the height of the building is similar to that of the lateral displacement under El-Centro earthquake and also under the artificial earthquake of Egypt for different e/L ratio.
Tables 3 and 4 show a comparison between the maximum values of the story drift required by ASCE/SEI 7-16, EC-8 and ECL-2012 due to the variation of the concrete strength with the envelopes of the story drift of Example-1 and Example-2 for Case-I and Case-II under N-S component of EL Centro 1940 earthquake and artificial earthquake record with different (e/L) ratio 0.10, 0.15 and 0.20. For the nonlinear time history analysis, the mean story drift shall not exceed two times the limits of SELF method of ASCE/SEI 7-16 code.
It can be seen that the limit of ASCE/SEI 7-16 and EC-8 codes are considerably conservative for NSC, HSC and VHSC buildings for the two examples with different (e/L) ratios. Comparing the maximum values of the story drift allowed by the ECL-2012 with the envelopes of the story drift of the studied examples under the artificial earthquake record showed that this limit is conservative for NSC, HSC and VHSC buildings for the two cases with different (e/L) ratio.

6.2 Effect of Concrete Strength on the Story Shear

The envelopes of the story shear along the height of the building Example-1 due to the variation of the concrete strength for Case-I and Case-II under N-S component of EL Centro 1940 earthquake and the artificial earthquake of Egypt are shown in Tables 5 to 8 for different e/L ratio. For Case-I, it can be seen that increasing the concrete strength from NSC to HSC resulted in a reduction in the average story shear by about 1.89%, 9.73%, 9.95%, and 9.31%, when (e/L) equal to 0.0, 0.10, 0.15 and 0.20, respectively, while increasing the concrete strength from HSC to VHSC increased the average story shear by 6.44%, 3.34%, 2.05%, and 2.65%, respectively. The trend of the story shear due to increasing the concrete strength for this case is not clear. This seems to be due to higher modes effect of EL-Centro earthquake.
For Case-II, it can be seen that when (e/L) equal to 0.0, 0.10, 0.15 and 0.20, increasing the design concrete strength from NSC to HSC resulted in a reduction in the average story shear by 28.24%, 30.43 %, 30.60 %, and 25.55 %, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by relatively small values 4.28%, 6.41%, 6.83% and 8.94%, respectively. This showed that the reduction of the cross-sections of the building example due to increasing the design concrete strength resulted in a considerable reduction in the story shear. The reduction rate became very low when increasing the concrete strength from HSC to VHSC.
For Case-I, under the artificial earthquake in Egypt, increasing the concrete strength from NSC to HSC resulted in a growth in the average story shear by 6.79%, 31.70%, 37.14% and 49.01% when (e/L) equal to 0.0, 0.10, 0.15 and 0.20, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by 2.77%, 4.14%, 4.85% and 1.62 %, respectively. For Case-II, under the artificial earthquake in Egypt, increasing the concrete strength from NSC to HSC, for the studied e/L ratio, resulted in a reduction in the average story

shear by 39.20%, 33.72%, 34.29% and 32.27%, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by 3.43%, 4.06 % , 5.19% and 2.78%, respectively. In general, under the artificial earthquake, the story shear was relatively small compared with that resulted from the El-Centro earthquake. This was due to the low-frequency content of the artificial earthquake.

The envelopes of the story shear along the height of the building Example-2 due to the variation of the concrete strength for Case-I and Case-II under N-S component of EL Centro 1940 earthquake and the artificial earthquake of Egypt are given in Tables 9 to 12 for different e/L ratio. For Case-I, it can be seen that increasing the concrete strength from NSC to HSC resulted in a growth of the average story shear by about 16.84%, 11.78 %, 8.53%, and 22.08%, when (e/L) equal to 0.0, 0.10, 0.15 and 0.20, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by 4.25%, 8.05 %, 4.90%, and 10.43%, when (e/L) equal to0.0, 0.10, 0.15 and 0.20 respectively. The trend of the story shear due to increasing the concrete strength for this case is not clear. This seems to be due to the higher modes effect of the EL-Centro earthquake.

For Case-II, it can be seen that the envelopes of the story shear along the height of the building Example-2 due to the variation of the concrete strength for Case-II is approximately similar to Case-I. When (e/L) equal to 0.0, 0.10, 0.15 and 0.20, increasing the design concrete strength from NSC to HSC resulted in a growth in the average story shear by 12.94%, 9.19 %, 6.03% and 17.76 %, respectively, This showed that the reduction of the cross-sections of the building example due to increasing the design concrete strength resulted in a considerable growth in the story shear. The response of the average story shear under the artificial earthquake in Egypt is the same of N-S component of EL Centro 1940 earthquake .while increasing the concrete strength from NSC to HSC resulted in a growth in the average story shear by 13.43%, 11.06%, 22.39% and 28.83% when (e/L) equal to 0.0, 0.10, 0.15 and 0.20, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by4.05%, 2.71% 0.21% and 4.96%, respectively. For Case-II, under the artificial earthquake in Egypt, increasing the concrete strength from NSC to HSC, for the studied e/L ratio, resulted in a growth in the average story shear by 9.05%, 7.31%, 20.55% and 21.16%, respectively, while increasing the concrete strength from HSC to VHSC decreased the average story shear by 6.15%, 1.26%, 5.97% and 2.41%, respectively. In general, under the artificial earthquake, the story shear was relatively small compared with that resulted from the El-Centro earthquake. This was due to the low-frequency content of the artificial earthquake. The trend of the story shear due to increasing the concrete strength is not clear.

5-EFFECT OF ECCENTRICITY RATIO ON THE OVERALL RESPONSE

7.1 Effect of (e/L) Ratio on the Story Drift

As shown from Figs. 6 to 12, increasing the eccentricity ratio (e/L), generally increased the story drift along the height of the building for different concrete strength for the two Examples. From Fig. 6 and Fig. 7, it can be seen that, for Case-I of Example-1, Increasing the eccentricity ratio (e/L) from 0.0 to 0.10 resulted in a growth of the average story drift by about 28.81%, 11.80% and 26.12% for NSC, HSC and VHSC respectively, while increasing the eccentricity ratio (e/L) from 0.10 to 0.15 resulted in a growth of the average story drift by about 6.75%, 3.97% and 0.74% for NSC, HSC and VHSC respectively, while increasing the eccentricity ratio (e/L) from 0.15 to 0.20 resulted in a growth of the average story drift by about 2.73%, 10.81% and 1.32% for NSC, HSC and VHSC respectively. For Case-II, it can be seen that, increasing the eccentricity ratio (e/L) from 0.0 to 0.10 resulted in a growth of the average story drift by about 28.81%, 20.37% and 24.91% for NSC, HSC and VHSC respectively, while increasing the eccentricity ratio (e/L) from 0.10 to 0.15 resulted in a growth of the average story drift by about 6.75%, 5.15% and 5.10% for NSC, HSC and VHSC respectively. Increasing the eccentricity ratio (e/L) from 0.15 to 0.20 resulted in a growth of the average story drift by about 2.73%, 7.05% and 7.24% for NSC, HSC, and VHSC respectively. Under the artificial earthquake of Egypt for Case-

I and Case-II, for Example-1, increasing the eccentricity ratio (e/L), generally increased the story drift along the height of the building for different concrete strength with a similar response as that under El Centro earthquake. For Case-II, it can be seen that, increasing the eccentricity ratio (e/L) from 0.0 to 0.10 resulted in a growth of the average story drift by about 10.11%, 38.70% and 14.23% for NSC, HSC and VHSC respectively, while increasing the eccentricity ratio (e/L) from 0.15 to 0.20 resulted in a growth of the average story drift by about 5.23%, 1.94% and 7.27% for NSC, HSC and VHSC respectively.

For Example-2, increasing the eccentricity ratio (e/L), generally increased the story drift along the height of the building for different concrete strength. The drift response of Example-2 is approximately similar to the result of Example-1. It can be seen that, for Case-II under the artificial earthquake in Egypt, increasing the eccentricity ratio (e/L), generally increased the story drift along the height of the building for different concrete strength. It can be seen that, increasing the eccentricity ratio (e/L) from 0.0 to 0.10 resulted a growth in the average story drift by about 25.92%, 29.21% and 22.58% for NSC, HSC and VHSC respectively, while increasing the eccentricity ratio (e/L) from 0.10 to 0.15 resulted a growth in the average story drift by about 13.24%, 3.20% and 8.50% for NSC, HSC and VHSC respectively. Increasing the eccentricity ratio (e/L) from 0.15 to 0.20 resulted in a growth in the average story drift by about 11.24%, 27.42% and 25.39% for NSC, HSC, and VHSC respectively.

7.2 Effect of (e/L) Ratio on the Story Shear

As can be seen from Tables 5 to 12, for the studied Example-1 and Example-2, for Case-I and Case-II, increasing the eccentricity ratio (e/L) resulted in a reduction in the average story shear. This can be attributed to the reduced cross-sections of shear wall W_2 of the building as a result of increasing the eccentricity ratio (e/L). For Case-I of Example-1, increasing (e/L) from 0.0 to 0.10 resulted in a reduction in the average story shear by about 1.30%, 9.18% and 11.75%, for NSC, HSC, and VHSC, respectively, while increasing (e/L) from 0.10 to 0.15 resulted in a reduction in the average story shear by about 4.69%, 4.93% and 6.20%, for NSC, HSC, and VHSC, respectively. Increasing (e/L) from 0.15 to 0.20 decreased the average story shear by 11.88%, 11.25%, and 10.73%, respectively. For Case-II of Example-1, increasing (e/L) from 0.0 to 0.10 resulted in a reduction in the average story shear by 1.30 %, 4.21 %, and 6.33 %, for NSC, HSC, and VHSC, respectively, while increasing (e/L) from 0.10 to 0.15 resulted in a reduction in the average story shear by 4.49 %, 4.93 %, and 5.36 %, for NSC, HSC, and VHSC, respectively. Increasing (e/L) from 0.15 to 0.20 decreased the average story shear by relatively small values 11.88%, 5.47% and 7.61%, respectively. The same trend is observed for Case-I and Case-II of Example-1, under the artificial earthquake of Egypt. For Example-2, the shear response is approximately similar to that of Example-1. For Case-I of Example-2, it can be seen that, increasing (e/L) from 0.0 to 0.10 resulted in a reduction of the average story shear by about 6.87%, 10.91% and 14.44% for NSC, HSC and VHSC respectively, while increasing (e/L) from 0.10 to 0.15 resulted in a reduction of the average story shear by about 5.60%, 8.35% and 5.21% for NSC, HSC and VHSC respectively. Increasing the eccentricity ratio (e/L) from 0.15 to 0.20 resulted in a reduction of the average story shear by about 11.73%, 0.71%, and 6.48%, respectively. For Case-II, increasing (e/L) from 0.0 to 0.10 resulted in a reduction of the average story shear by about 6.87%, 9.97% and 13.49% for NSC, HSC and VHSC respectively, while increasing (e/L) from 0.10 to 0.15 resulted in a reduction of the average story shear by about 5.60%, 8.33% and 5.40% for NSC, HSC and VHSC respectively, while increasing (e/L) from 0.15 to 0.20 resulted in a reduction of the average story shear by about 11.73%, 1.97% and 4.58%, respectively.

6-EVALUATION OF THE SELF METHODS WHEN APPLIED TO NSC AND HSC MULTISTORY BUILDINGS

The values of the story shear calculated from the SELF methods of ASCE/SEI 7-16, EC-8 and ECL-2012 for Example-1and Example-2 are compared in Tables 5 to 12 with the values calculated under EL Centro and the artificial earthquake of Egypt for the studied different (e/L) ratio. This comparison showed that the story shear calculated using the SELF method of ASCE/SEI 7-16 and EC-8 are safe and conservative for all concrete strength cases for the studied two examples with different e/L ratio. It should be noted that the story shear forces predicated by SELF methods of ASCE/SEI 7-16 and EC-8 are very conservative for example-2, while for Example-1 these predications were just conservative. The SELF method of ECL-2012 is unconservative for the upper stories of some cases of HSC, and VHSC of Example-1 and conservative for all cases of Example-2 as shown in Table (7) and Table (8). This showed that, the story shear calculated using the SELF method of ECL-2012 may lead to unsafe results when applied to NSC, HSC and VHSC torsionally asymmetric multistory buildings with the studied different (e/L) ratio.

7-CONCLUSIONS

Based on the results of this study on the seismic behavior of torsionally asymmetric 3-D multistory buildings constructed from NSC ($f_c^{'}$ = 25 MPa), HSC ($f_c^{'}$ = 75 MPa) and VHSC ($f_c^{'}$ = 100 MPa) for the studied different (e/L) ratios (0.10, 0.15 and 0.20), the following can be concluded:

1) Increasing the design concrete strength from NSC to HSC generally reduces the average story displacement and the average story drift along the height of 3-D torsionally asymmetric multistory buildings for the studied different (e/L) ratio. Increasing the design concrete strength to VHSC may cause an increase in the average story displacement and the average story drift (compared to the case of HSC) especially in the upper stories because of the mixed action of increasing the concrete strength and the reduction of the columns cross-sections in the upper stories due to the reduction in the column vertical loads.
2) The average story shear generally decreases with increasing the design concrete strength from NSC to VHSC (without a clear trend) for torsionally asymmetric multistory buildings with the studied different (e/L) ratio.
3) Increasing the studied eccentricity ratio (e/L), generally increases the story displacement and the story drift and reduces the story shear along the height of the studied building examples for different cases of concrete strengths.
4) The limits of the story drift adopted by EC-8, ASCE/SEI 7-16 and ECL-2012 are conservative when applied to NSC, HSC, and VHSC torsionally asymmetric buildings with the studied different (e/L) ratio.
5) The SELF methods of ASCE/SEI 7-16 and EC-8 are safe and conservative for all the studied cases of NSC, HSC, and VHSC torsionally asymmetric buildings with the studied different (e/L) ratio.
6) The SELF method of ECL-2012 is unconservative for some cases (especially for the upper stories) when applied to NSC, HSC, and VHSC torsionally asymmetric multistory buildings for the studied different (e/L) ratio, and consequently, it is recommended that this method should not be used for these cases.

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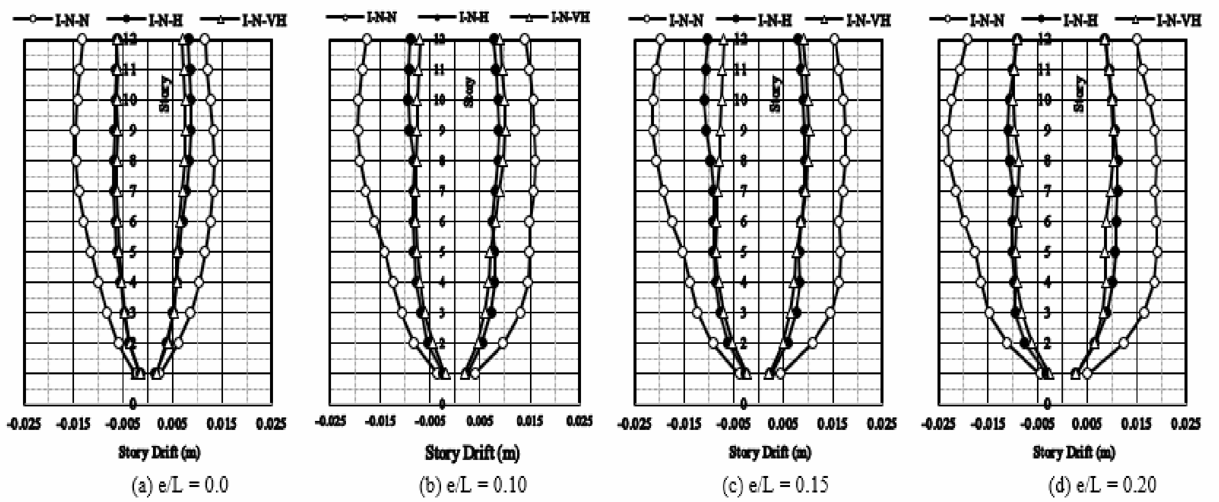


Fig. 6. Story drift response for Case-I of Example-1 under N-S component of EL Centro 1940 earthquake.

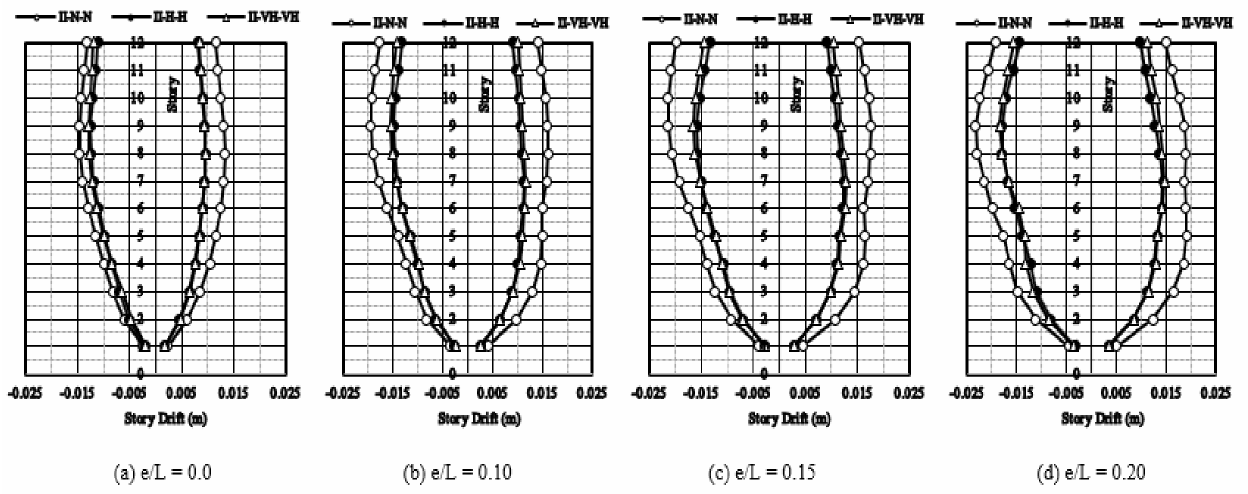


Fig. 7. Story drift response for Case-II of Example-1 under N-S component of EL Centro 1940 earthquake.

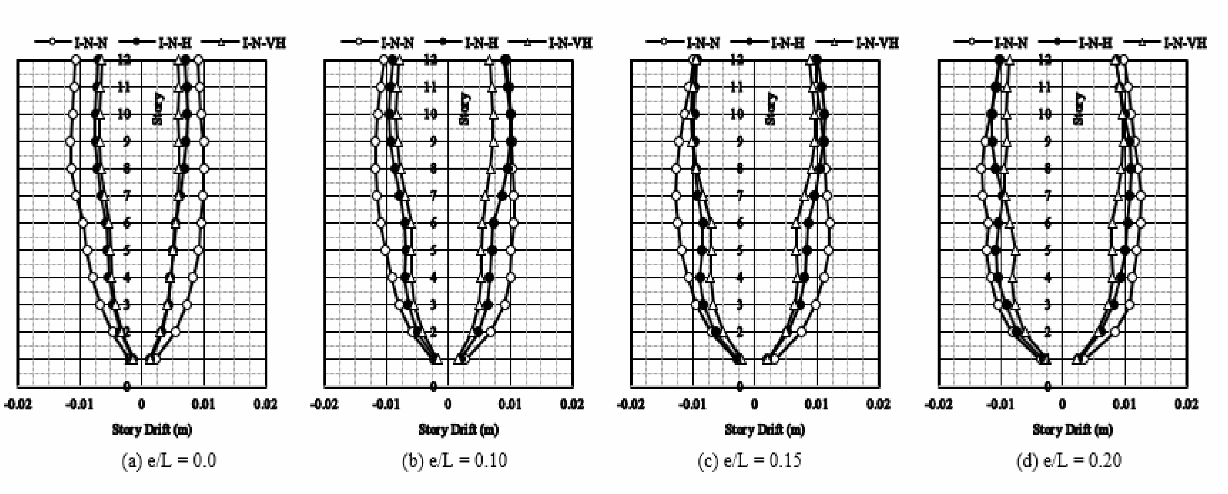
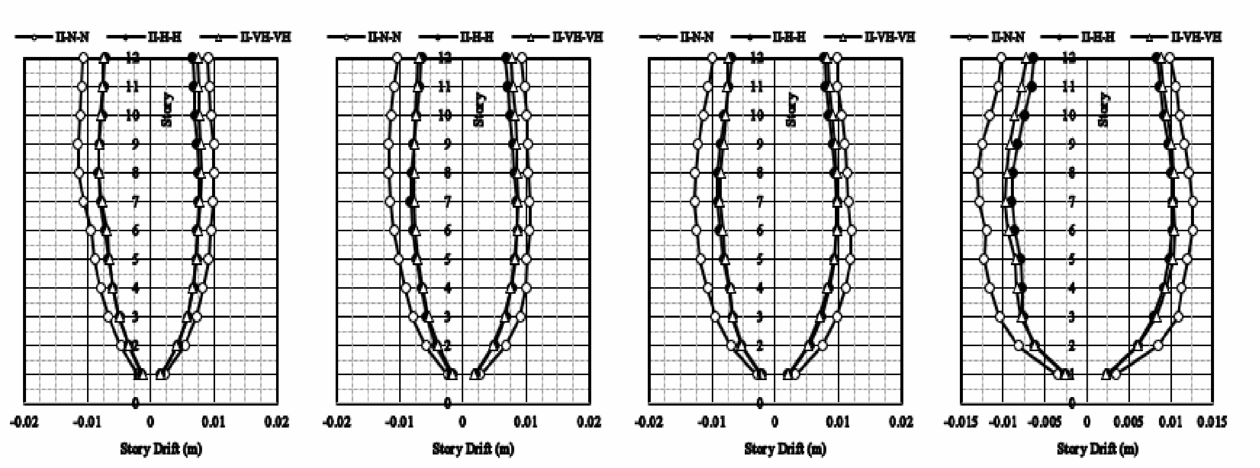
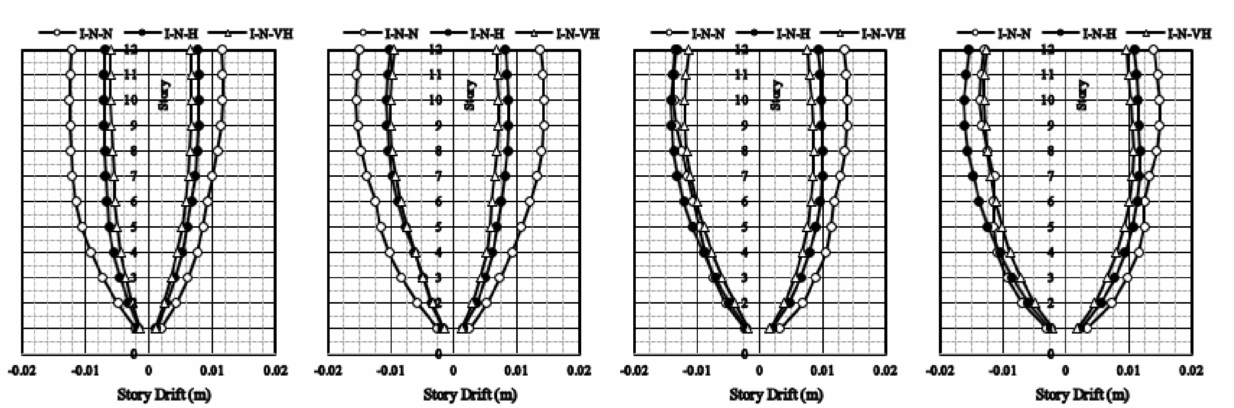


Fig. 8. Story drift response for Case-I of Example-1 under the artificial earthquake of Egypt.



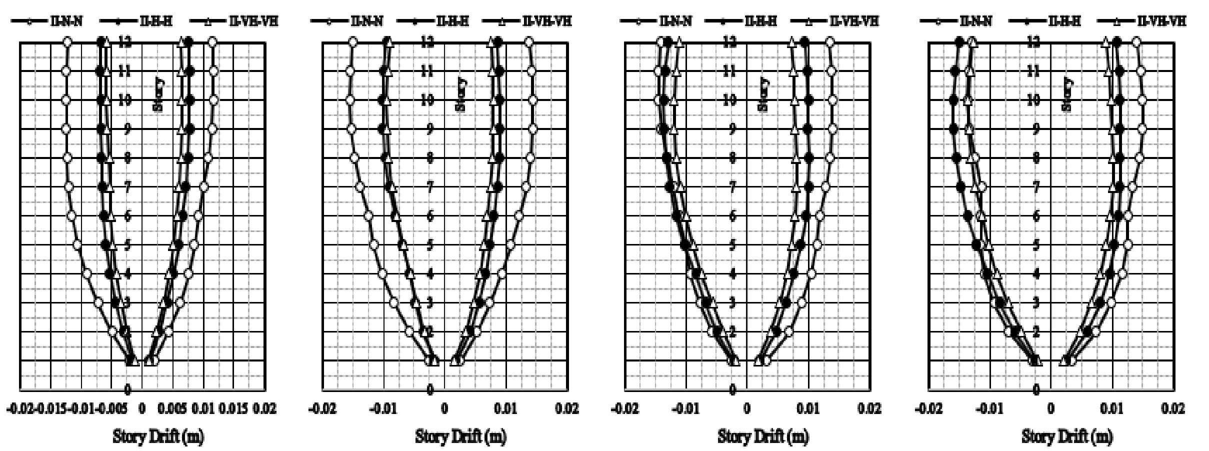
(a) e/L = 0.0 (b) e/L = 0.10 (c) e/L = 0.15 (d) e/L = 0.20

Fig. 9. Story drift response for Case- II of Example-1 under the artificial earthquake of Egypt.



(a) e/L = 0.0 (b) e/L = 0.10 (c) e/L = 0.15 (d) e/L = 0.20

Fig. 10. Story drift response for Case-I of Example-2 under N-S component of EL Centro 1940 earthquake.



(a) e/L = 0.0 (b) e/L = 0.10 (c) e/L = 0.15 (d) e/L = 0.20

Fig. 11. Story drift response for Case-II of Example-2 under N-S component of EL Centro 1940 earthquake.

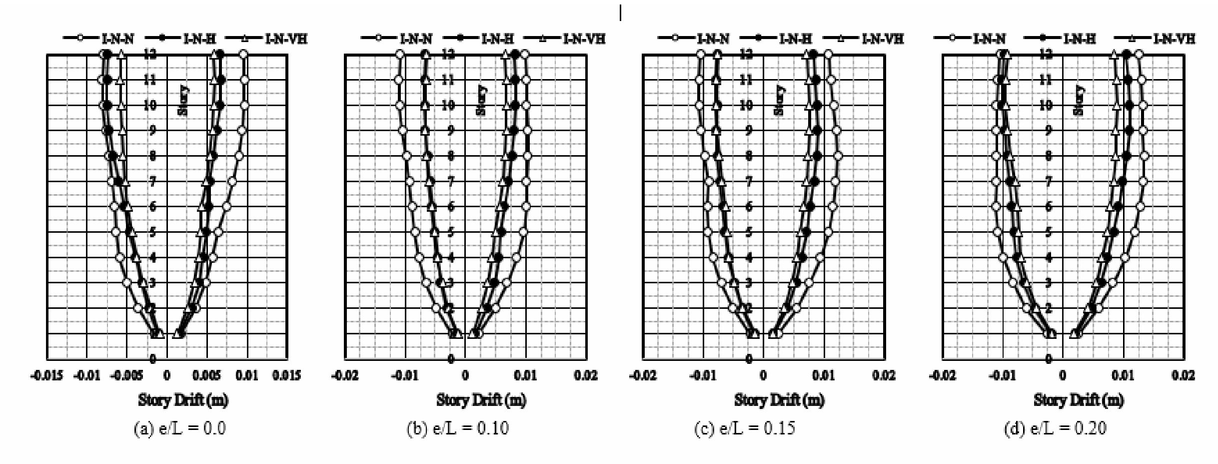


Fig. 12. Story drift response for Case-I of Example-2 under the artificial earthquake of Egypt.

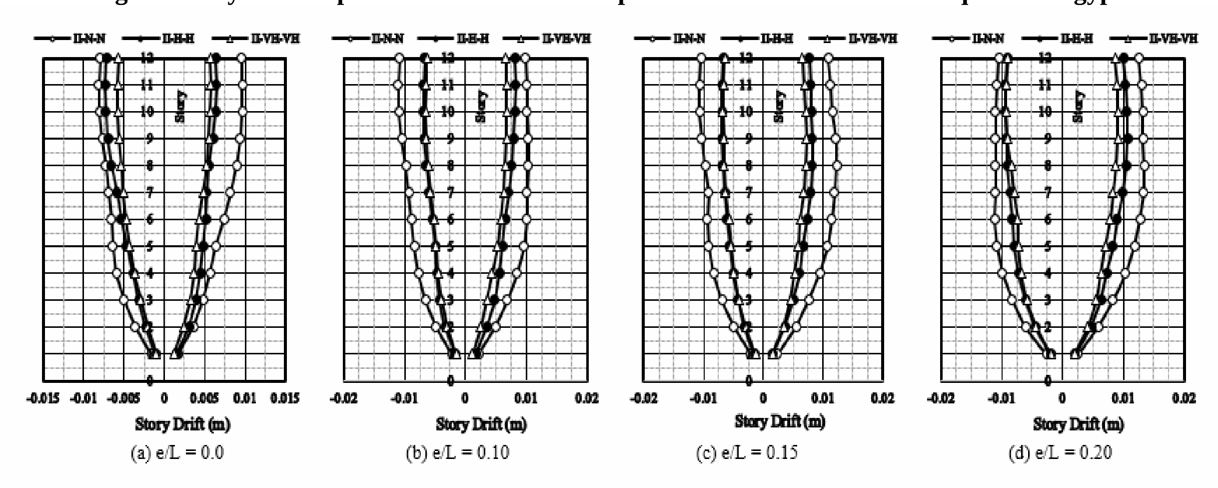


Fig. 13. Story drift response for Case-II of Example-2 under the artificial earthquake of Egypt.

Table 3. Comparison between the maximum values of the story drift of Example-1 required by ASCE/SEI 7-16, EC-8 and ECL-2012 and that calculating using the dynamic analysis.

Case	e/L	Story drift (m)				
		EL-Centro time History	ASCE/SEI 7-16	EC-8	Artificial time History	ECL-2012
I-N-N	0.00	0.01330	0.146	0.0456	0.01001	0.0456
I-N-H		0.00861			0.00732	
I-N-VH		0.00534			0.00458	
I-N-N	0.10	0.01604			0.01064	
I-N-H		0.00879			0.01003	
I-N-VH		0.01001			0.00727	
I-N-N	0.15	0.01756			0.01211	
I-N-H		0.00936			0.01124	
I-N-VH		0.01013			0.00973	
I-N-N	0.20	0.01903			0.01262	
I-N-H		0.01113			0.01111	
I-N-VH		0.01021			0.00978	
II-N-N	0.00	0.01330			0.01001	
II-H-H		0.00961			0.00765	
II-VH-VH		0.00948			0.00809	
II-N-N	0.10	0.01604			0.01064	
II-H-H		0.01128			0.00861	
II-VH-VH		0.01168			0.00881	
II-N-N	0.15	0.01756			0.01211	
II-H-H		0.01242			0.00982	
II-VH-VH		0.01286			0.00986	
II-N-N	0.20	0.01903			0.01262	
II-H-H		0.01435			0.01017	
II-VH-VH		0.01466			0.01044	

Table 4. Comparison between the maximum values of the story drift of Example-2 required by ASCE/SEI 7-16, EC-8 and ECL-2012 and that calculating using the dynamic analysis.

Case	e/L	Story drift (m)				
		EL-Centro time History	ASCE/SEI7-16	EC-8	Artificial time History	ECL-2012
I-N-N	0.00	0.0117	0.120	0.0375	0.0097	0.0375
I-N-H		0.0079			0.0067	
I-N-VH		0.0014			0.0046	
I-N-N	0.10	0.01444			0.01043	
I-N-H		0.00874			0.00835	
I-N-VH		0.00716			0.00685	
I-N-N	0.15	0.01398			0.01227	
I-N-H		0.00999			0.00899	
I-N-VH		0.00863			0.00760	
I-N-N	0.20	0.01498			0.01350	
I-N-H		0.01181			0.01106	
I-N-VH		0.01078			0.00894	
II-N-N	0.00	0.01167			0.00969	
II-H-H		0.00777			0.00645	
II-VH-VH		0.00646			0.00576	
II-N-N	0.10	0.01444			0.01043	
II-H-H		0.00904			0.00831	
II-VH-VH		0.00796			0.00684	
II-N-N	0.15	0.01398			0.01227	
II-H-H		0.01016			0.00815	
II-VH-VH		0.00807			0.00719	
II-N-N	0.20	0.01498			0.01350	
II-H-H		0.01130			0.01069	
II-VH-VH		0.01019			0.00914	

Table 5. Comparison between the values of the story shear calculated using the SELF method of ASCE/SEI 7-16 and EC-8 and that from time history analysis of EL-Centro earthquake for Case-I of Example-1.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
I-N-N	0.00	61.82	94.92	105.29	123.05	132.50	135.33	132.65	133.63	151.33	179.01	209.02	220.32
I-N-H		65.69	99.26	113.31	115.64	117.81	98.32	112.52	138.79	166.20	195.52	211.62	212.45
I-N-VH		65.02	122.44	117.54	108.85	106.84	107.30	120.88	138.58	184.69	216.37	231.65	233.07
ASCE/SEI 7-16		66.28	129.52	186.83	237.55	282.35	320.75	353.43	379.90	400.32	414.95	424.09	428.17
EC-8		69.80	137.36	199.56	255.58	306.02	350.22	388.81	421.03	446.80	466.17	479.11	485.58
I-N-N	0.10	50.65	83.77	118.02	142.93	147.82	133.51	129.39	131.64	141.16	172.65	191.71	213.86
I-N-H		50.08	77.39	98.09	104.54	110.76	94.28	95.58	129.68	156.61	176.60	194.06	208.18
I-N-VH		51.32	88.00	110.45	115.04	113.60	104.12	112.48	127.05	159.02	178.79	188.55	198.82
ASCE/SEI 7-16		66.21	129.27	186.41	236.98	281.65	319.94	352.54	378.94	399.30	413.89	423.01	427.08
EC-8		69.73	137.10	199.11	254.97	305.26	349.34	387.83	419.96	445.66	464.98	477.89	484.34
I-N-N	0.15	55.23	95.45	111.64	131.29	141.17	132.96	128.21	126.24	129.72	155.85	177.81	193.76
I-N-H		51.53	80.13	90.32	98.27	99.65	95.71	91.22	122.08	145.50	174.83	197.06	195.69
I-N-VH		44.28	80.15	103.87	112.37	109.35	91.47	101.29	126.55	151.28	156.37	162.43	175.82
ASCE/SEI 7-16		66.19	129.17	186.24	236.76	281.37	319.62	352.18	378.56	398.90	413.47	422.58	426.64
EC-8		69.70	136.99	198.93	254.73	304.96	348.99	387.44	419.54	445.21	464.51	477.41	483.85
I-N-N	0.20	36.97	67.43	90.86	107.87	118.97	126.49	128.29	122.31	134.46	148.16	156.29	153.54
I-N-H		43.85	70.96	79.95	90.23	92.94	93.30	111.30	118.22	123.64	136.51	141.61	159.56
I-N-VH		46.66	73.48	85.71	94.78	89.98	82.00	87.36	115.98	129.20	147.85	165.91	176.67

Table 6. Comparison between the values of the story shear calculated using the SELF method of ASCE/SEI 7-16 and EC-8 and that from time history analysis of EL-Centro earthquake for Case-II of Example-1.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
□ -N-N	0.0	61.82	94.92	105.29	123.05	132.50	135.33	132.65	133.63	151.33	179.01	209.02	220.32
□ -H-H		40.00	61.93	82.35	98.22	104.73	102.88	99.14	102.25	106.52	125.41	136.79	143.22
□ -VH-VH		41.95	63.98	79.58	92.67	99.75	100.27	95.70	91.57	101.24	117.60	129.39	138.19
ASCE/SEI 7-16 (NSC)		66.28	129.52	186.83	237.55	282.35	320.75	353.43	379.90	400.32	414.95	424.09	428.17
ASCE/SEI 7-16 (HSC)		62.20	121.32	174.77	222.09	263.78	299.52	329.78	354.29	373.19	386.73	395.19	398.96
ASCE/SEI 7-16 (VHSC)		61.20	119.23	171.71	218.17	259.10	294.18	323.89	347.94	366.49	379.79	388.09	391.80
EC-8 (NSC)		69.80	137.36	199.56	255.58	306.02	350.22	388.81	421.03	446.80	466.17	479.11	485.58
EC-8 (HSC)		65.52	128.70	186.74	239.01	285.97	327.12	362.86	392.70	416.56	434.49	446.47	452.46
EC-8 (VHSC)		64.47	126.49	183.47	234.79	280.89	321.28	356.38	385.66	409.09	426.69	438.45	444.33
□ -N-N	0.10	50.65	83.77	118.02	142.93	147.82	133.51	129.39	131.64	141.16	172.65	191.71	213.86
□ -H-H		39.48	66.97	82.65	91.42	100.95	99.25	99.31	96.76	99.92	109.94	127.69	138.48
□ -VH-VH		36.74	63.36	79.64	88.53	95.33	93.79	92.43	90.60	89.05	100.01	118.27	131.21
ASCE/SEI 7-16 (NSC)		66.21	129.27	186.41	236.98	281.65	319.94	352.54	378.94	399.30	413.89	423.01	427.08
ASCE/SEI 7-16 (HSC)		62.12	121.05	174.33	221.51	263.07	298.69	328.87	353.30	372.14	385.64	394.07	397.83

ASCE/SEI 7-16 (VHSC)		61.12	118.96	171.27	217.57	258.37	293.33	322.95	346.93	365.42	378.67	386.95	390.64
EC-8 (NSC)		69.73	137.10	199.11	254.97	305.26	349.34	387.83	419.96	445.66	464.98	477.89	484.34
EC-8 (HSC)		65.44	128.42	186.27	238.38	285.20	326.22	361.86	391.60	415.39	433.27	445.21	451.18
EC-8 (VHSC)		64.39	126.21	182.99	234.15	280.10	320.36	355.34	384.54	407.89	425.44	437.16	443.02
□ -N-N	0.15	58.63	95.45	111.64	131.29	141.17	132.96	128.21	126.24	129.72	155.85	177.81	193.76
□ -H-H		35.03	61.01	77.76	92.03	96.03	98.25	98.52	92.40	97.03	102.16	118.05	127.71
□ -VH-VH		35.35	60.00	74.56	88.34	91.76	89.71	90.62	85.55	87.28	91.75	108.17	118.06
ASCE/SEI 7-16 (NSC)		66.19	129.17	186.24	236.76	281.37	319.62	352.18	378.56	398.90	413.47	422.58	426.64
ASCE/SEI 7-16 (HSC)		62.09	120.94	174.16	221.27	262.78	298.35	328.49	352.89	371.71	385.19	393.62	397.37
ASCE/SEI 7-16 (VHSC)		61.09	118.85	171.09	217.33	258.07	292.99	322.57	346.52	364.99	378.22	386.49	390.18
EC-8 (NSC)		69.70	136.99	198.93	254.73	304.96	348.99	387.44	419.54	445.21	464.51	477.41	483.85
EC-8 (HSC)		65.41	128.31	186.08	238.13	284.88	325.85	361.44	391.15	414.91	432.77	444.69	450.66
EC-8 (VHSC)		64.36	126.09	182.81	233.89	279.79	319.99	354.93	384.09	407.41	424.94	436.65	442.50
□ -N-N	0.20	36.97	67.43	90.86	107.87	118.97	126.49	128.29	122.31	134.46	148.16	156.29	153.54
□ -H-H		29.39	53.94	75.52	89.55	93.93	94.42	95.73	89.51	91.80	93.61	107.86	120.77
□ -VH-VH		27.60	51.63	71.68	84.13	87.14	85.34	86.14	80.24	81.88	87.82	93.96	105.84
ASCE/SEI 7-16 (NSC)		66.15	129.02	186.00	236.44	280.98	319.16	351.67	378.01	398.31	412.86	421.96	426.01
ASCE/SEI 7-16 (HSC)		62.05	120.79	173.90	220.92	262.35	297.86	327.95	352.31	371.09	384.55	392.96	396.71
ASCE/SEI 7-16 (VHSC)		61.04	118.69	170.82	216.97	257.64	292.48	322.01	345.91	364.34	377.55	385.80	389.49
EC-8 (NSC)		69.66	136.84	198.68	254.39	304.54	348.49	386.88	418.93	444.56	463.83	476.70	483.14
EC-8 (HSC)		65.37	128.14	185.81	237.75	284.42	325.31	360.85	390.50	414.22	432.04	443.95	449.90
EC-8 (VHSC)		64.31	125.92	182.52	233.50	279.31	319.44	354.31	383.41	406.69	424.18	435.87	441.71

Table 7. Comparison between the values of the story shear calculated using the SELF method of ECL-2012 and that from time history analysis of the artificial earthquake of Egypt for Case-I of Example-1.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
I-N-N	0.00	35.85	77.52	91.83	112.07	125.61	119.55	114.09	124.84	122.78	142.00	144.75	145.27
I-N-H		49.92	77.69	99.10	109.13	110.07	104.33	107.55	122.59	132.83	155.68	178.74	200.61
I-N-VH		57.61	78.37	94.68	103.93	101.62	98.83	100.88	120.49	128.05	153.71	175.15	194.83
ECL-2012		36.56	70.07	100.94	128.73	153.79	175.72	194.89	210.87	223.65	233.29	239.71	242.92
I-N-N	0.10	35.07	59.53	71.40	81.84	100.53	107.73	101.92	99.20	101.75	107.90	110.07	120.02
I-N-H		48.16	83.05	108.43	114.36	101.89	105.58	99.95	118.57	142.83	155.34	168.59	178.92
I-N-VH		50.46	82.05	95.21	96.28	100.52	100.04	105.68	110.88	131.16	151.36	164.61	178.35
ECL-2012		36.46	69.88	100.67	128.37	153.37	175.24	194.37	210.31	223.06	232.67	239.07	242.27
I-N-N	0.15	38.92	61.92	68.44	73.82	86.83	88.96	90.18	98.90	98.63	105.70	119.06	106.82
I-N-H		49.02	78.94	95.22	102.65	104.96	113.04	103.88	122.36	143.18	160.47	174.99	175.10
I-N-VH		45.28	79.87	102.03	112.43	112.28	102.47	110.51	115.24	123.50	129.49	154.59	167.05
ECL-2012		36.42	69.80	100.56	128.24	153.20	175.05	194.16	210.08	222.82	232.42	238.81	242.01
I-N-N	0.20	33.52	50.96	58.59	63.89	68.22	73.49	76.74	79.15	80.10	90.54	100.05	118.85
I-N-H		42.35	73.68	91.43	95.60	88.75	94.88	115.35	125.83	127.74	153.21	172.90	182.47
I-N-VH		46.18	76.11	88.67	89.65	104.38	108.70	106.19	114.70	128.19	147.88	164.06	167.38
ECL-2012		36.36	69.69	100.40	128.04	152.96	174.77	193.85	209.75	222.47	232.05	238.44	241.64

Table 8. Comparison between the values of the story shear calculated using the SELF method of ECL-2012 and that from time history analysis of the artificial earthquake of Egypt for Case-II of Example-1.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
II-N-N	0.00	35.85	77.52	91.83	112.07	125.61	119.55	114.09	124.84	122.78	142.00	144.75	145.27
II-H-H		30.61	50.87	59.47	72.39	83.51	82.44	72.21	69.69	75.00	74.45	78.94	75.04
II-VH-VH		31.49	49.12	54.26	68.64	78.80	76.63	67.98	69.34	70.71	75.46	78.67	75.18
ECL-2012 (NSC)		36.36	69.69	100.40	128.04	152.96	174.77	193.85	209.75	222.47	232.05	238.44	241.63
ECL-2012 (HSC)		34.09	65.34	94.08	119.94	143.20	163.55	181.26	196.02	207.82	216.71	222.64	225.60
ECL-2012 (VHSC)		33.57	64.35	92.65	118.11	141.02	161.07	178.50	193.03	204.65	213.41	219.25	222.17
II-N-N	0.10	35.07	59.53	71.40	81.84	100.53	107.73	101.92	99.20	101.75	107.90	110.07	120.02
II-H-H		27.32	44.09	49.50	57.61	65.52	65.30	63.57	66.99	64.24	70.87	75.03	76.98
II-VH-VH		26.07	41.43	46.23	53.98	62.44	61.93	63.86	61.56	60.18	69.77	74.76	75.27
ECL-2012 (NSC)		36.46	69.88	100.67	128.37	153.37	175.24	194.37	210.31	223.06	232.67	239.07	242.27
ECL-2012 (HSC)		34.09	65.34	94.08	119.93	143.20	163.55	181.26	196.02	207.83	216.72	222.64	225.60
ECL-2012 (VHSC)		33.47	64.15	92.36	117.75	140.58	160.56	177.95	192.44	204.03	212.76	218.58	221.49
II-N-N	0.15	38.92	61.92	68.44	73.82	86.83	88.96	90.18	98.90	98.63	105.70	119.06	106.82
II-H-H		24.16	39.16	44.14	51.52	56.85	56.08	59.25	60.77	61.41	68.22	73.52	75.69
II-VH-VH		23.64	36.81	39.89	46.47	51.54	53.18	55.40	54.29	56.81	64.18	67.91	75.05
ECL-2012 (NSC)		36.42	69.80	100.56	128.24	153.20	175.05	194.16	210.08	222.82	232.42	238.81	242.01
ECL-2012 (HSC)		34.05	65.26	93.96	119.79	143.02	163.35	181.04	195.78	207.57	216.45	222.37	225.33
ECL-2012 (VHSC)		33.43	64.07	92.24	117.60	140.40	160.36	177.73	192.20	203.77	212.49	218.30	221.21
II-N-N	0.20	33.52	50.96	58.59	63.89	68.22	73.49	76.74	79.15	80.10	90.54	100.05	118.85
II-H-H		18.54	28.50	35.19	39.56	44.61	52.68	54.80	54.67	58.75	63.53	73.32	75.21
II-VH-VH		17.89	27.87	33.50	41.50	46.50	51.23	54.72	54.99	58.67	61.65	69.22	75.03
ECL-2012 (NSC)		36.36	69.69	100.40	128.04	152.96	174.77	193.85	209.75	222.47	232.05	238.44	241.64
ECL-2012 (HSC)		33.99	65.14	93.79	119.57	142.76	163.05	180.72	195.43	207.21	216.07	221.98	224.93
ECL-2012 (VHSC)		33.37	63.95	92.06	117.37	140.14	160.05	177.38	191.83	203.38	212.08	217.88	220.78

Table 9. Comparison between the values of the story shear calculated using the SELF method of ASCE/SEI 7-16 and EC-8 and that from time history analysis of EL-Centro earthquake for Case-I of Example-2.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
I-N-N	0.0	76.16	131.02	160.57	170.85	170.43	207.84	237.34	257.25	265.88	293.31	342.95	375.53
I-N-H		132.14	199.86	197.50	170.96	176.25	177.80	212.78	247.05	315.19	391.66	444.28	476.40
I-N-VH		127.43	192.08	189.27	173.15	166.86	170.19	209.27	239.93	314.29	372.30	414.05	439.42
I-N-N	0.10	76.61	132.22	159.84	162.49	158.72	192.17	216.62	230.98	258.11	269.35	306.60	340.60
I-N-H		102.16	161.09	168.58	166.19	173.65	171.94	197.77	224.31	289.09	348.67	383.59	412.17
I-N-VH		93.66	146.45	151.52	146.82	164.70	181.85	213.42	226.03	262.61	307.60	336.38	342.84
I-N-N	0.15	71.59	124.79	152.67	156.79	157.06	166.24	180.09	226.93	255.97	262.85	289.90	319.09
I-N-H		80.43	134.09	165.18	174.88	195.93	199.07	224.30	237.27	241.83	282.57	311.58	318.35
I-N-VH		70.06	123.77	154.78	166.35	167.34	201.56	220.57	220.21	236.05	275.21	302.02	301.82
I-N-N	0.20	61.31	106.77	129.45	133.56	135.14	125.74	130.78	157.05	202.56	255.88	312.36	336.01
I-N-H		74.84	137.37	179.45	200.87	204.28	216.54	233.91	232.68	234.89	250.90	270.90	310.63
I-N-VH		68.90	121.56	151.01	169.19	181.63	201.61	211.14	206.74	204.87	236.50	255.87	272.65
ASCE/SEI 7-16		165.02	328.34	475.29	606.39	721.75	821.25	905.35	974.24	1028.03	1067.25	1092.34	1103.97
EC-8		165.49	330.83	481.13	616.77	737.66	843.43	934.34	1010.30	1071.07	1116.76	1147.31	1162.58

Table 10. Comparison between the values of the story shear calculated using the SELF method of ASCE/SEI 7-16 and EC-8 and that from time history analysis of EL-Centro earthquake for Case-II of Example-2.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
II-N-N	0.0	76.16	131.02	160.57	170.85	170.43	207.84	237.34	257.25	265.88	293.31	342.95	375.53
II-H-H		128.92	193.84	191.41	168.04	168.16	168.61	202.95	235.97	307.57	380.34	430.23	460.98
II-VH-VH		120.79	180.26	177.06	161.33	156.25	164.37	200.28	227.37	294.65	346.27	383.04	406.51
II-N-N	0.10	76.61	132.22	159.84	162.49	158.72	192.17	216.62	230.98	258.11	269.35	306.60	340.60
II-H-H		104.14	161.56	166.60	160.90	163.23	161.50	189.66	215.06	282.58	341.28	384.36	403.49
II-VH-VH		90.68	140.25	144.74	137.30	151.44	172.86	201.46	210.64	251.31	295.10	319.83	322.42
II-N-N	0.15	71.59	124.79	152.67	156.79	157.06	166.24	180.09	226.93	255.97	262.85	289.90	319.09
II-H-H		81.02	126.12	155.38	164.84	182.26	185.26	213.38	227.74	248.53	285.60	308.09	328.35
II-VH-VH		64.01	113.71	144.52	157.67	156.80	185.43	208.30	212.36	217.11	255.93	279.65	310.77
II-N-N	0.20	61.31	106.77	129.45	133.56	135.14	125.74	130.78	157.05	202.56	255.88	312.36	336.01
II-H-H		70.82	130.46	172.09	194.11	197.44	205.16	226.73	230.30	220.45	233.89	268.43	307.38
II-VH-VH		63.01	111.15	149.08	172.16	180.37	190.14	202.52	200.91	189.62	211.48	247.03	283.09
ASCE/SEI 7-16 (NSC)		165.64	329.52	476.97	608.52	724.28	824.12	908.50	977.63	1031.61	1070.96	1096.13	1107.80
ASCE/SEI 7-16 (HSC)		162.30	320.28	462.41	589.22	700.82	797.08	878.44	945.10	997.15	1035.10	1059.38	1070.64
ASCE/SEI 7-16 (VHSC)		160.82	316.17	455.94	580.66	690.43	785.09	865.11	930.68	981.88	1019.20	1043.08	1054.16
EC-8 (NSC)		166.11	332.02	482.84	618.94	740.24	846.38	937.60	1013.82	1074.79	1120.64	1151.29	1166.61
EC-8 (HSC)		162.79	322.73	468.13	599.34	716.29	818.64	906.60	980.10	1038.91	1083.13	1112.70	1127.48
EC-8 (VHSC)		161.31	318.60	461.59	590.65	705.68	806.34	892.86	965.16	1023.00	1066.50	1095.58	1110.12

Table 11. Comparison between the values of the story shear calculated using the SELF method of ECL-2012 and that from time history analysis of the artificial earthquake of Egypt for Case-I of Example-2.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
I-N-N	0.0	76.03	114.84	127.36	130.42	128.15	141.85	145.08	189.11	225.90	248.98	258.54	265.42
I-N-H		77.81	137.80	172.62	183.32	172.76	156.19	178.70	215.34	226.81	247.42	267.30	291.22
I-N-VH		73.45	127.35	155.40	160.50	150.01	155.18	188.85	216.44	220.70	243.27	256.92	284.89
I-N-N	0.10	65.49	97.06	112.97	118.80	124.13	138.72	135.55	171.12	195.30	209.63	217.62	230.29
I-N-H		65.33	114.16	140.30	145.18	132.29	139.59	168.73	201.80	212.81	202.61	236.86	257.99
I-N-VH		66.50	112.41	132.51	131.31	119.19	132.57	167.83	193.43	199.85	201.95	234.72	270.78
I-N-N	0.15	58.05	83.96	97.39	106.32	118.98	127.37	130.73	140.18	147.23	160.81	182.33	189.10
I-N-H		64.12	107.04	124.14	125.93	120.84	139.12	155.86	185.07	195.35	183.89	228.86	257.64
I-N-VH		71.18	117.97	134.16	131.19	121.07	127.95	152.77	170.83	180.72	201.96	224.36	253.70
I-N-N	0.20	39.41	66.15	83.16	88.20	94.40	103.20	110.98	128.58	150.03	147.15	164.61	188.39
I-N-H		65.92	106.49	126.32	132.24	123.86	119.63	126.31	153.62	165.40	188.41	220.86	228.52
I-N-VH		64.63	113.08	140.12	148.27	140.97	122.49	137.16	152.29	175.13	206.46	219.48	224.65
ECL-2012		89.59	171.71	246.36	313.91	373.96	426.49	471.76	509.49	539.67	562.43	577.60	585.19

Table 12. Comparison between the values of the story shear calculated using the SELF method of ECL-2012 and that from time history analysis of the artificial earthquake for Case-II of Example-2.

Case	e/L	Story shear (ton)											
		12	11	10	9	8	7	6	5	4	3	2	1
II-N-N	0.0	76.03	114.84	127.36	130.42	128.15	141.85	145.08	189.11	225.90	248.98	258.54	265.42
II-H-H		75.92	133.19	166.00	175.47	164.56	152.02	175.82	210.51	221.04	240.47	250.89	271.40
II-VH-VH		68.59	117.46	142.58	146.84	140.05	144.31	179.52	204.30	207.71	226.15	246.20	275.90
II-N-N	0.10	65.49	97.06	112.97	118.80	124.13	138.72	135.55	171.12	195.30	209.63	217.62	230.29
II-H-H		62.18	107.98	132.81	138.27	127.45	133.57	166.73	197.23	206.17	199.36	223.41	254.32
II-VH-VH		65.74	111.74	134.03	135.56	121.46	129.88	162.87	185.55	189.54	194.81	229.29	264.37
II-N-N	0.15	58.05	83.96	97.39	106.32	118.98	127.37	130.73	140.18	147.23	160.81	182.33	189.10
II-H-H		63.47	106.78	125.33	122.17	116.38	130.01	155.77	183.72	193.81	184.30	218.53	259.18
II-VH-VH		66.81	110.29	126.31	118.44	106.07	118.28	140.89	165.31	180.72	179.53	193.25	242.52
II-N-N	0.20	39.41	66.15	83.16	88.20	94.40	103.20	110.98	128.58	150.03	147.15	164.61	188.39
II-H-H		63.90	103.86	114.54	115.13	106.10	107.22	120.03	152.27	168.42	178.76	206.97	215.67
II-VH-VH		58.99	100.90	122.53	127.27	119.99	105.67	121.95	155.25	174.04	183.84	209.10	213.24
ECL-2012 (NSC)		89.59	171.71	246.36	313.91	373.96	426.49	471.76	509.49	539.67	562.43	577.60	585.19
ECL-2012 (HSC)		86.46	165.71	237.76	302.96	360.92	411.64	455.34	491.76	520.90	542.87	557.52	564.84
ECL-2012 (VHSC)		85.07	163.06	233.94	298.13	355.19	405.11	448.15	484.01	512.70	534.33	548.74	555.95