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Evaluation of Static Nonlinear Behavior of Coupled Reinforced Concrete Shear Walls with Steel Beams

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Abstract

The shear walls are divided into two types of reinforced concrete and steel, which behave differently. In the present study, the linear and nonlinear static behavior of coupled reinforced concrete shear walls is investigated. Therefore, to validate the results, Yuan Cheng and coworkers' laboratory model is investigated. The results of this study show that the stresses caused by external loading in the coupled shear walls are lower compared to the separate shear walls. In addition, the behavior of this system depends on the rigidity of the coupling beams. The excessive rigidity of the coupling beams does not significantly affect the behavior of these structures. Therefore, by using the continuous analytical method and ABAQUS software, a formula is proposed to calculate the dimensions of the ideal coupling beams cross-section. Based on the reviews, the proposed formula accurately predicts the nonlinear performance of the systems under investigation.

Keywords

coupled reinforced concrete shear walls, ideal coupling beams, linear and nonlinear static behavior, continuous analytical method, ABAQUS software

1 Introduction

The earthquakes which occurred in Kobe, Northridge, Tabas and the Japan's tsunami caused extensive damages; moreover, all these catastrophic events indicate the need for appropriate structures which can withstand the wrath of nature. Today, with the advancement of engineering knowledge, a variety of structural systems have been developed. One of these systems is considered to be shear walls. These walls are categorized into two types of reinforced concrete and steel. Based on the previous research, a brief description of the behavior of these walls is presented.

Reinforced concrete shear walls are flat elements that have a high out-of-plane stiffness. Therefore, the out-of-plane deformation of these walls is minimal as a result of high thickness of the walls. Behavior these walls similar to a deep console beam provides lateral stability for the building which is resistant to forces and bending moment [1].

In recent years, steel shear wall has been considered by designers as a suitable structural system. This structure is less weighty compared to reinforced concrete shear wall. The steel shear wall is a flat element having very minimal out-of-plane stiffness. This structure offers a large deal out-of-plane deformation due to the low thickness of steel plate. Buckling of the steel plate is an important feature of these walls which causes the diagonal tension field on the steel plate. As these lines increase and become more uniform, the shear capacity of the system increases as well. For this purpose, a 'stiffener' is used on the steel plate. Moreover, the stiffeners are attached to the steel plate in various forms which reduce the out-of-plane deformation of the steel plate and improve the behavior of the structure. The presence of stiffeners in these structure increases the seismic parameters such as the ductility and response modification factor [2–6].

Converting steel shear wall to a composite reduces lateral displacement or increases lateral stiffness due to the expansion of the diagonal tensile field as well as the delay in buckling of the steel plate. By adding the reinforced concrete panel to the steel shear wall and using proper connections between them, buckling of the steel plate is reduced. In fact, the buckling exists in both steel and composite shear walls. However, the buckling in the steel shear wall is global; therefore, not the maximum steel plate strength is

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applied. In the composite shear wall, the buckling is localized. Thus, the maximum shear strength of steel plate is used. Despite the boundary element around the concrete panel and the deformations of the system, the large forces due to the compressive stresses cause the global buckling of the concrete panel. This causes a large crack in the concrete panel. Although there are many cracks in the concrete, the shear studs are separated and cause a global buckling of the steel plate. Therefore, having a 2.5 to 5 centimeters seam around the concrete panel can reduce stresses and can be highly efficient which increases the ductility and decreases the structural damage. The thickness of the reinforced concrete panel has a significant effect on the shear capacity and the ultimate strength of the composite shear wall system. In addition, the presence of reinforced concrete panel is highly effective in the design of steel plate thickness. However, excessive increase in the thickness of the concrete panel has no effect on the behavior of this system. In this structure, as the shear studs distance decreases, the energy dissipation of the system and its ductility increase as well [7–14].

According to the previous research, it is accepted that shear walls have significant structural parameters such as lateral stiffness, shear capacity and energy absorption. The shear walls in tall structures experience significant flexural deformations caused by lateral loads. However, the coupled walls having rigid beams offer an efficient method to minimize these deformations. Therefore, the behavior of this system is studied based on the aforementioned research. The coupled steel shear walls consist of two walls having flat plate and boundary elements that are connected at each story by rigid beams. This system has more ductility compared to separate steel shear walls. The most important purpose is to couple the shear walls for controlling the drift of structures. The coupling walls are capable of causing plastic deformation at the plan and height of the structure. The design of coupled steel shear walls reduces structural weight by 15 to 40 percent over its separate counterpart. The coupling beams in the steel shear wall system increase the diagonal tensile field in steel plates. Since the shear walls stiffness is much greater than the rigidity of the coupling beams, the greatest vulnerability is created in the coupling beams. Therefore, the rigidity of the coupling beams is greatly reduced by creating a shear plastic hinge in the middle web of the beams and a bending plastic hinge at the beam connection. Steel coupled beams that are designed based on shear yields have the ability to absorb more energy and have more stable cyclic behavior compared to coupled beams as are designed based on bending yields. As the rigidity of the coupling beams increases, their bending behavior tends to shear. Thus, the lateral stiffness, shear capacity and energy dissipation of the coupled steel shear walls system are increased. In fact, the increased rigidity of the coupling beams is somewhat effective [15–19].

According to laboratory studies, coupled reinforced concrete shear walls have excellent displacement control. By coupling this system, it is possible to use thin walls without compromising the structural members. The deformation response of this system is not affected by higher dynamic modes. By applying proper reinforcement, they have larger dampers compared to separate shear walls. Coupled reinforced concrete beams having a length to depth ratio of less than 2 require special diameter reinforcement. Due to the difficulties in constructing these beams, steel coupling beams having appropriate supports are used. Composite (steel-concrete) beams have greater rigidity, shear capacity and ductility compared to reinforced concrete beams [20–23].Separate shear walls are highly resistant and have been well researched. In addition, the capability of coupling shear walls is quite evident. The behavior of the coupled reinforced concrete shear walls has been considered in the aforementioned research. In the present study, the effects of steel beams on linear and nonlinear static behavior of coupled reinforced concrete shear wall systems are investigated based on the following sections.

- The static linear behavior (elastic behavior) of 5, 10, 15 and 20-story coupled shear walls is investigated based on the 'continuous analytical method' and compared with the numerical results of ABAQUS software. One of the significant results in this section is a formula for calculating the dimensions of the ideal coupling beams cross-section [24].
- To verify the results of the nonlinear static behavior of coupled reinforced concrete shear walls by ABAQUS software, the experimental model of Cheng has been investigated. Next, the proposed formula is considered in the previous section for several examples of coupled reinforced concrete shear walls having different number of stories. According to the resistance and seismic parameters of these models, the performance of the proposed formula in the discussion of nonlinear behavior of structures is controlled [25].

2 Evaluation of elastic behavior of coupled shear walls

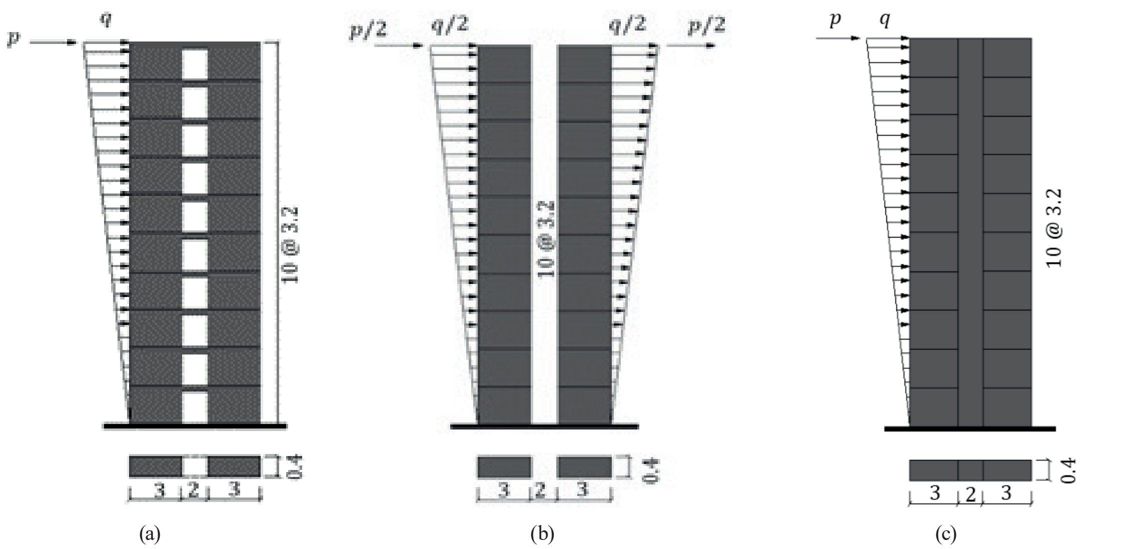
Based on the contents of the previous section, the behavior of the coupling shear walls was determined to some extent. At the beginning of the present section, the elastic behavior of coupled shear walls is investigated based on the continuous analytical method. This method determines the behavior of shear walls and coupling beams against lateral loads. The equations for this method can be calculated based on the 'virtual working method' and the following assumptions [26]:

- The specifications of walls and coupling beams do not change at the height of the structure. In addition, the height of all stories stays identical.
- To verify The 'Bernoulli principle' is valid for all members of the structure after bending.
- To verify Due to the symmetry of the structure, the horizontal deformation of the walls stays the same. Therefore, according to the 'slope-deflection method', bending hinge are created in the middle of the coupling beams.
- To verify Flexural and axial deformations of shear walls as well as flexural and shear deformations of coupling beams are considered in computations.

The reason for the aforementioned assumptions is to understand the proof of the equations of this method. The equations for this method are not provided in this article. At the beginning of this section, based on the continuous analytical method, several models of 10-story coupled shear walls having different beams are analyzed. Subsequently, the results of these models are compared using the software. In all models, the coupled beams cross-section are rectangular. According to Fig. 1(a), the cross-sectional width of the coupling beams is equal to the width of the shear walls; however, the depth of the beams varies. In addition, the above structure has been elastically analyzed according to Fig. 1(b) as 'separate' and Fig. 1(c) as 'steady'.

The maximum stresses caused by external loading and lateral elastic stiffness of each of the models are shown in Figs. 2 and 3. According to Figs. 2 and 3, if the shear walls are considered separately (l = 0) (l is the depth of the coupling beam each story), the least lateral elastic stiffness and the greatest stress due to external loading in the system are created. As the system is coupled, its behavior changes significantly in such a way that its impacts up to (l = 1.2 m) are very high. In this case, the lateral elastic stiffness of the system increases by approximately 800%. In addition, the maximum stress caused by external loading is reduced by approximately 400%. If the depth of the coupling beams is increased to 3.2 meters, the changes in lateral elastic stiffness and the maximum stress caused by external loading will be negligible. Therefore, the ideal behavior of coupled shear walls is created at (l = 1.2 m). If the coupling beams depth is more than 1.2 meters, the behavior of the system does not change and only the dead load of the structure is increased.

To ensure the results, the shear force in each of the coupling beams of the models is calculated based on the continuous analytical method. Fig. 4 shows the results of these calculations. As documented in 'indeterminate structures analysis science', the forces created by each member of the system depend on their rigidity. According to Fig. 4,



(a) (b) (c)

Fig. 1 (a) 10-story coupled shear walls system, (b) 10-story separate shear walls system, (c) 10-story steady shear wall system (p = 1231.14 kN, q = 459.92 kN/m)

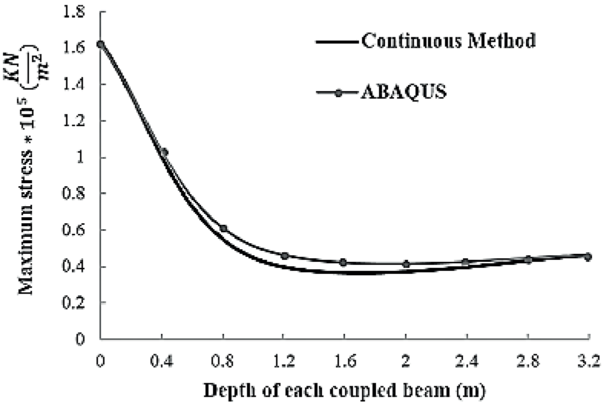


Fig. 2 The maximum stress in each wall varies according to the depth of the coupling beams.

$$\sigma_{\max}(l)_{\substack{Continuous\\Analytical\\Method}} =$$

$$\left[-0.207\frac{1}{u^3}-17.993\frac{1}{u^2}\sinh(86.36u)+701.19\frac{1}{u}\right]\tanh(86.36u)$$

$$+17.993\frac{1}{u^2}\cosh(86.36u)+41660.803,$$

$$u=\sqrt{\frac{l^3}{30+20.7l^2}} \quad If\ 0<1>3.2m$$

l is the depth of the coupling beam each story.

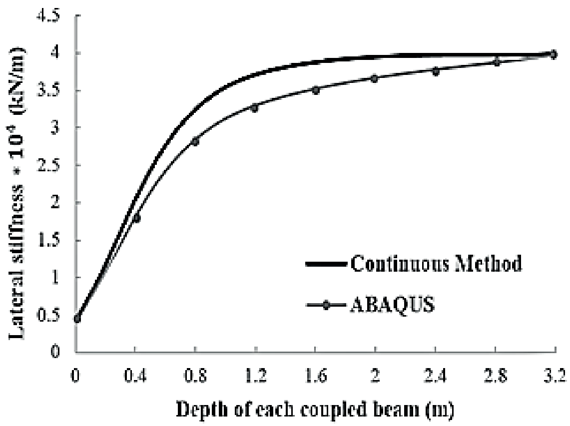


Fig. 3 The lateral elastic stiffness of the system varies according to the depth of the coupling beams.

$$K(l)_{\substack{Continuous\\Analytical\\Method}} = \frac{4.368*10^7}{-0.04157\frac{1}{u^3}\tanh(86.36u)+3.582\frac{1}{u^2}+1070},$$

$$u=\sqrt{\frac{l^3}{30+20.7l^2}} \quad If\ 0<l<3.2m$$

l, is the depth of the coupling beam each story

by increasing the depth of coupling beams to 1.2 meters, the shear force in each beam is constantly increasing. By increasing the depth of the beams again, the shear force changes very minimal. Therefore, the results of Figs. 2, 3 and 4 are perfectly consistent.

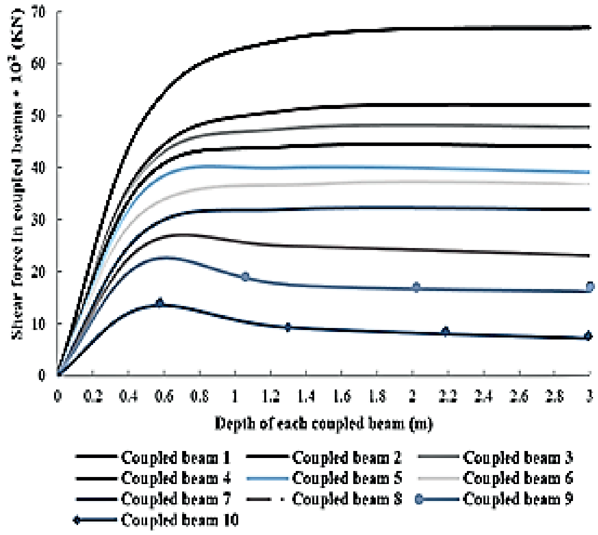


Fig. 4 Shear force created in each beam of varies according to the depth of the coupling beams

$$v_i(l,z_i)_{\substack{Continuous\\Analytical\\Method}} = \int_{z_i-1.6}^{z_i+1.6}\left\{\begin{array}{l}\frac{\cosh(86.36u-2.7zu)}{\cosh(86.36u)}(30.43\frac{1}{u}\sinh(86.36u)\\+\frac{0.35}{u^2}-1533.8)-30.43\frac{1}{u}\sinh(86.36u-2.7zu)\\-\frac{0.35}{u^2}-1.28z^2+1534\end{array}\right\}dz,$$

$$u=\sqrt{\frac{l^3}{30+20.7l^2}} \quad If\ 0<l<3.2m$$

Parameter z_i is distanced from the center of the coupling beam of each story to the bottom of the shear walls.

Based on the models investigated, the coupling beams have significant effects on the separate shear walls. The strength and behavior of these structures are highly dependent on the rigidity of the coupling beams. The excessive rigidity of the coupling beams does not significantly affect the elastic behavior of the system. As the shear walls are coupled, the bending moment is reduced. Accordingly, the behavior of the walls tends from flexural deformations to shear deformations. Moreover, as the walls are coupled, large shear forces are created in the coupling beams, which are axially transferred to the walls. In general, according to Fig. 2, the stresses due to external loading are lower in the coupled shear walls.

In the following study, using the continuous analytical method and software, a formula for computing the dimensions of the ideal coupled beams cross-section is presented. According to Fig. 3, the ideal behavior is the point in the graph; furthermore, increasing the rigidity of the coupling beams does not change the behavior of the system. This point is considered to be an approximation. According to the proposed method, several models of 5, 10, 15 and 20-story separate shear walls system having different dimensions are selected. These models have been elastically analyzed by coupling beams of varying rigidity in the software. The results of these models are shown in Fig. 5. Parameters, $K_{Separate}$, $K_{Ideal\ Coupled}$ and K_{Steady} represent the stiffness of the separate shear walls, stiffness of the ideal coupled shear walls and the steady shear wall stiffness, respectively.

The stiffness of the separate shear walls depends on the dimensions of the cross-section and height of the walls as well as the properties of the materials that have been experimentally considered according to the following items.

- In 5 to 10-story structures, the walls are nearly 2 to 5.5 meters length and 0.30 to 0.60 meters thickness. In addition, In 10 to 20-story structures, the walls are about 6 to 10 meters length and 0.60 to 0.90 meters thickness.
- The height of shear walls in each story is typically between 3.2 and 4 meters.
- The used for concrete on all models is 30 MPa.
- The thickness of the coupling beams in each model is equal to the thickness of the shear walls; however, their depth are different. Moreover, the length of the beams is approximately 2 to 3 meters.
- The element used in the software is 'Solid (C3D8R)' and is a type of 'Static-General' structural analysis (ABAQUS/standard) [24].

According to Fig. 5, the change in stiffness of the separate shear walls has no effect on the behavior of the ideal coupled shear walls. The behavior of these walls varies with the number of different stories.

According to Fig. 5(a), by increasing depth of coupling beams, the lateral elastic stiffness of the system is constantly increased. However, after the vertical line shown in the graph, the changes in lateral elastic stiffness is decreased. This issue is quite logical since the overall height of the structure is low and the drift of the structure decreases by increasing the depth of the coupling beams. Therefore, increasing the depth of the coupling beams is continuously effective. Accordingly, the vertical line shown in the figure is considered as the ideal behavior of the system. In this case, ratio of the ideal coupled shear walls stiffness and the steady shear wall stiffness is nearly 0.6. According to Figs. 5(b), 5(c) and 5(d), the ideal behavior of the system is improved by increasing the number of stories of the coupled shear walls. In this structure, if the number of stories is higher than 15, the ideal coupled shear

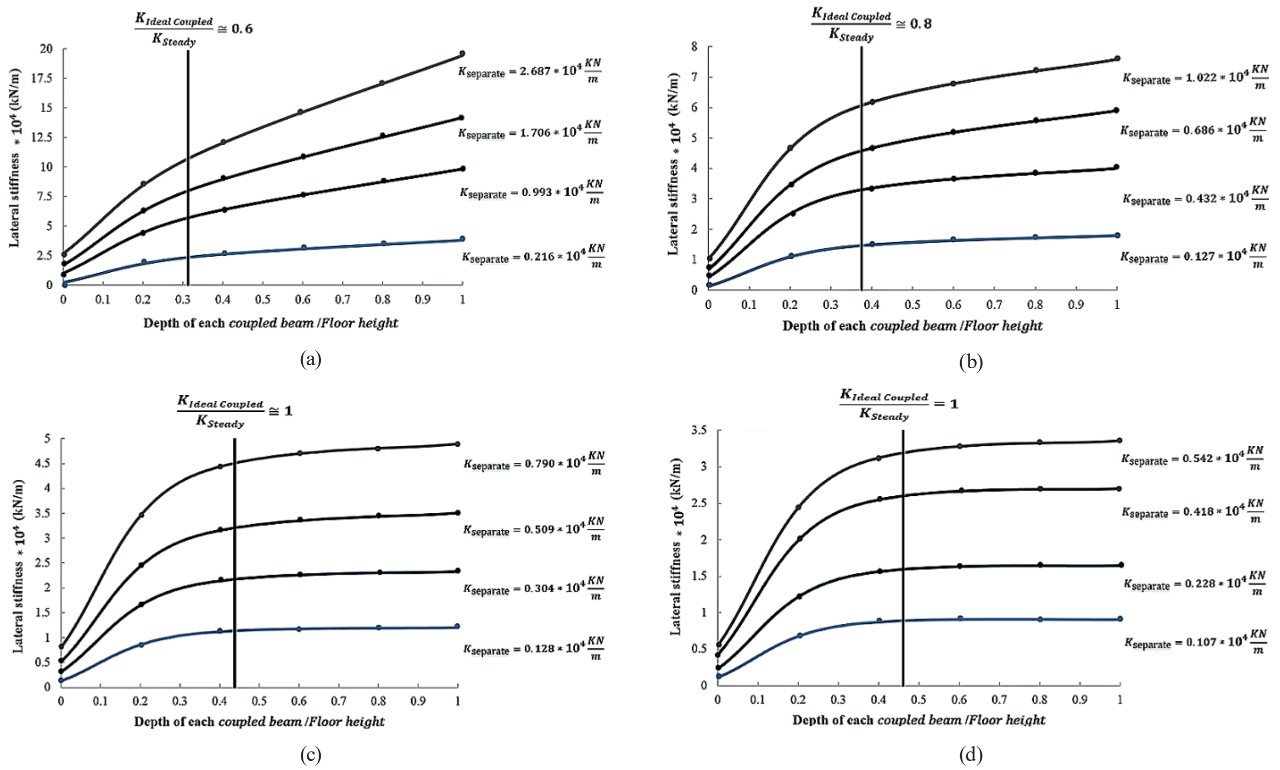


Fig. 5 (a) The lateral elastic stiffness of the 5-story system varies according to the depth of the coupling beams, (b) The lateral elastic stiffness of the 10-story system varies according to the depth of the coupling beams, (c) The lateral elastic stiffness of the 15-story system varies according to the depth of the coupling beams, (d) The lateral elastic stiffness of the 20-story system varies according to the depth of the coupling beams

walls behave similar to their steady shear wall. Therefore, according to Fig. 5, the ratio of ideal coupled shear walls stiffness and the steady shear wall stiffness is nearly 0.8 in the 10-story structures, nearly 1 in the 15-story structures and 1 in the 20-story structures, respectively.

Next, by combining the results of the software and the continuous analytical method equations, the dimensions of the ideal coupled beams cross-section are calculated as follows:

The lateral elastic stiffness of the system based on the continuous analytical method is [26]:

$$K = \frac{3E_c I}{H^3} \frac{1}{\left[\frac{k^2-1}{k^2}\right] + \frac{3}{k^2}\left[\frac{1}{(k\alpha H)^2} - \frac{1}{(k\alpha H)^3}\tanh\left(k\alpha H\right)\right]} \tag{1}$$

In the above equation, the values of E_c, I and H represent the modulus of elasticity of the concrete, the sum of the moment of inertia of the shear walls and the total height of the walls, respectively. The k and α parameters are used to simplify the above equation and their values are provided as:

$$k^2 = 1 + \frac{AI}{A_1 A_2 L^2} \tag{2}$$

$$\alpha^2 = \frac{12 I_e L^2}{b^3 h I} \tag{3}$$

In the above equations, A_1 and A_2 is the cross-sectional area of each coupling walls and A stands for the sum of these values. In addition, the parameters L, h, b and I_e are the distance from the center to the center of the walls, the height of each story, the length of the coupling beams and the effective moment of inertia of each coupling beam.

In Eq. (1), $(k\alpha H)$ is constantly greater than one $(k\alpha H > 1)$ and $(\tanh(k\alpha H))$ is zero as the minimum and the maximum is equal to one $(0 \leq (\tanh(k\alpha H) \leq 1$. Next, if $(\tanh(k\alpha H))$ reaches 1, the coefficient is $\left(\frac{1}{(k\alpha H)^3} = \frac{1}{(k\alpha H)^2}\right)$ therefore, to simplify Eq. (1), the value of $\left(\frac{1}{(k\alpha H)^3}\tanh\left(k\alpha H\right)\right)$ is ignored. In addition, by assuming that the stiffness of the coupled shear walls is ideally n percent of the stiffness of the steady shear wall, Eq. (1) is modified as follows: $\left(\frac{K_{Ideal\ Coupled}}{K_{Steady}} = n\right)$.

$$nK_s = \frac{3E_c I}{H^3} \frac{1}{\left[\frac{k^2-1}{k^2}\right] + \frac{3}{k^2}\left[\frac{1}{(k\alpha H)^2}\right]} \tag{4}$$

Eq. (2) can be written as follows:

$$\alpha^2 = \frac{1}{\left[\frac{E_c I}{nK_s H^3} + \frac{1-k^2}{3k^2}\right] k^4 H^2} \tag{5}$$

In Eq. (5), the parameter n represents the ideal stiffness coefficient of the system whose value is obtained from Fig. 5. Hence, Eq. (6) can be used to consider this coefficient.

$$n = \begin{cases} 0.04S + 0.4 & for \quad 5 \leq S \leq 15 \\ 1 & for \quad S > 15 \end{cases} \tag{6}$$

The parameter S in Eq. (6) shows he number of stories in the coupled shear walls system. This equation is a linear interpolation of the results of Fig. 5.

According to Fig. 3, the lateral elastic stiffness of the continuous analytical method is greater than that of the software. This issue makes a great deal of difference in the computation of the dimensions of the cross-section of ideal coupling beams. The continuous analytical method offers assumptions that are stated at the beginning of this section. These assumptions produce errors, and the lateral elastic stiffness of this method is approximately 15% higher than that of the software. The results of software are obtained by 'Solid (C3D8R)' elements and are more accurate. Thus, Eq. (5) is modified by a proper approximation as follows:

$$\alpha^2 = \frac{1}{\left|\frac{E_c I}{1.15nK_s H^3} + \frac{1-k^2}{3k^2}\right| k^4 H^2} \tag{7}$$

K_s represents steady shear wall stiffness in the above equation and is calculated by Eq. (8) (P. Popo 1913).

$$K_s = \left[\frac{1}{\frac{H^3}{3E_c I_s} + \frac{H}{\frac{5}{6}G_c A_s}}\right] \tag{8}$$

In the Eq. (8), the parameters H, I_s and A_s represent the height, the moment of inertia and the cross-sectional area of the steady wall, respectively. In addition, the parameters E_c and G_c represent the modulus of elasticity and the shear modulus of the concrete.

By combining Eq. (3) and Eq. (7), the effective moment of inertia of each ideal coupling beam is obtained based on Eq. (9).

$$I_{eIdeal} = \frac{b^3 hI}{12L^2H^2k^4} \frac{1}{\left|\dfrac{E_c I}{1.15nK_s H^3} + \dfrac{1-k^2}{3k^2}\right|} \quad (9)$$

By calculating the effective moment of inertia of the coupling beams from the above equation, the cross-sectional dimensions of the beams are obtained by Eq. (10).

In Eq. (10), A_b and I_b are the cross-sectional area and moment of inertia of each coupling beam, respectively. The proposed equation for symmetrically coupled shear walls is proven to be accurate. In addition, the cross-sectional area of the coupling beams should be a rectangular shape.

$$I_{eIdeal} = \frac{I_b}{1 + \left(\dfrac{14.4 I_b}{b^2 A_b} \dfrac{E_c}{G_c}\right)} \quad (10)$$

Therefore, it is assumed that the width of the coupling beams is equal to the thickness of the shear walls; hence, the depth of the beams can be obtained from the following equation:

$$D^3 - \left(\frac{14.4 I_{eIdeal}}{b^2 t} \frac{E_c}{G_c}\right) D^2 - \left(\frac{12 I_{eIdeal}}{t}\right) = 0 \quad (11)$$

In Eq. (11), the parameters D and t represent the depth and width of the coupling beams, respectively.

The goal of this study is to investigate the effects of steel beams on the behavior of coupled reinforced concrete shear walls system. To prove the equations of continuous analytic method, shear walls materials and coupling beams are assumed to be identical. Therefore, these equations cannot be used for steel coupled beams. For this purpose, the flexural and shear rigidity of the concrete beams having rectangular cross-section can be equal to the steel cross-section (I-shape) and the research objective can be calculated. According to the proposed method, the dimensions of the cross-sectional area of steel beams are obtained from the following equations:

$$\begin{gathered} t_f^4 + \left(\frac{n_1 n_2 Dt}{1.96 - 2.88 n_1^2}\right) t_f^2 + \left(\frac{0.141 n_1 n_2^2 D^2 t^2 - 0.0833 n_3 D^3 t}{0.4 n_1 - 0.588 n_1^3}\right) = 0 \\ b_f = 0.6 n_1 t_f \\ h_w = \sqrt{2.041 n_1 n_2 Dt - 2.941 n_1^2 t_f^2} \\ t_w = \frac{h_w}{2.45 n_1} \\ n_1 = \sqrt{\frac{E_s}{F_y}},\ n_2 = \frac{G_c}{G_s},\ n_3 = \frac{E_c}{E_s} \end{gathered} \quad (12)$$

In Eq. (12), parameters t_f and b_f stand for the thickness and width of 'flange' and parameters t_w and b_w represent the thickness and depth of 'web' of the I-shape steel coupled beam. The parameter F_y indicates the yield strength of the steel coupled beam. In addition, the parameters E_s and G_s represent the modulus of elasticity and the shear modulus of the steel, respectively.

Regarding the steel beams, due to the low thickness of steel plate, local buckling is highly important. As a result, in the Eq. (12), the seismic design criteria for steel beams having high ductility are considered in accordance with the AISC [27].

3 Evaluation of static nonlinear behavior of coupled reinforced concrete shear walls

In the previous section, the elastic behavior of coupled shear walls is investigated based on the continuous analytical method and software. In this section, a formula for calculating the cross-section dimensions of ideal coupled beams is presented. In the present section, the effects of steel beams on the static nonlinear behavior of the coupled reinforced concrete shear walls are investigated.The nonlinear model of structures ought to be capable of examining the exact behavior of structural systems. Boundary conditions, nonlinear shear deformation and interactions of axial force, shear force and bending moment are the most important factors in the response of structural systems. The software is mainly used to predict the nonlinear behavior of coupled shear walls. This software predicts the global and local behavior of walls such as concrete cracking, yielding of reinforcement, buckling of steel beams and other related factors. This software spends a great deal of time to analyze the structure due to the solution of large equations in 3D space.

3.1 Model verification

At the beginning of this section, to verify the results of the nonlinear static behavior of coupled reinforced concrete shear walls in software, the experimental model of Cheng is investigated. This model is tested under cyclic loading.

The following parameters are used to model this structure in the software.

A) All the properties of the materials used in the structure are available in the article.

B) The stress-strain curve of concrete used in shear walls is calculated based on the Kent and Park equations [28].

C) The elements used in the software are as follows:

- 'Shell (S4R)' for steel coupling beams
- 'Solid (C3D8R)' for concrete shear walls
- 'Wire-Truss-3D (T3D2)' for reinforcement

D) The 'Concrete Damage Plasticity Model (CDP)' is used [29].

E) Structural analysis is considered to be 'Dynamic Implicit' type (ABAQUS/Implicit) [24].

F) The laboratory model foundation in the software is ignored. The boundary conditions of the walls in each of the x, y and z directions are considered as fixed support.

Fig. 6 shows the desired model in the software.

According to the presented parameters, Fig. 7 shows the matching of the push-over curve obtained by the software and the hysteresis curve is obtained by the laboratory model.

The contour of the maximum plastic strains in the final loading and deformations generated after testing this model is shown in Figs. 8 and 9. As can be seen, the cracks created in the concrete walls of the laboratory model and software are nearly identical. In addition, the compression of the concrete is visible at the connections of the first story coupling beam.

Based on the verification performed in this section, the accuracy of the software in the nonlinear analysis of structures is well known.

3.2 Original 5-story model

At the beginning of the present section, the static nonlinear behavior of separate reinforced concrete shear walls is investigated. Afterwards, these walls are assumed to be coupled and without any change in their design dimensions, the proposed formula for this system is examined. For this purpose, the separate reinforced concrete shear walls are elastically analyzed and designed based on the ACI. While designing this structure, the gravity forces caused by dead and living loads are considered to be 8 and 3 kPa. Earthquake-induced lateral forces are applied based on the AISC. All stories are 4 meters height. The yield strength of the walls reinforcement is 454 MPa. The concrete cylindrical compressive strength

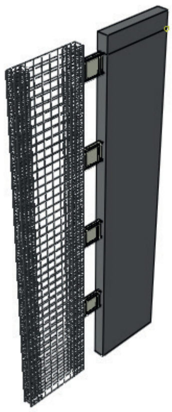


Fig. 6 Experimental model of coupled reinforced concrete shear walls Cheng in the ABAQUS software

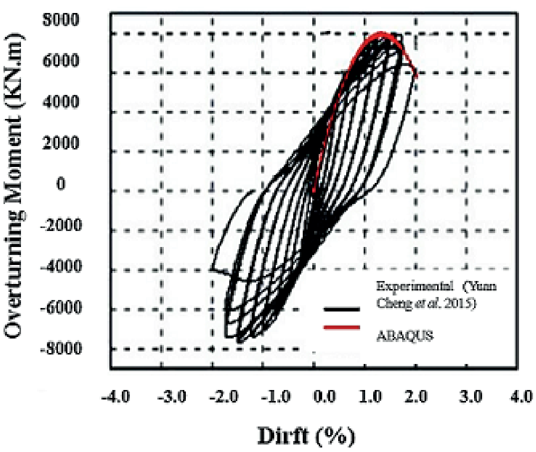


Fig. 7 The matching of the push-over curve obtained by the ABAQUS software and the hysteresis curve obtained by the laboratory

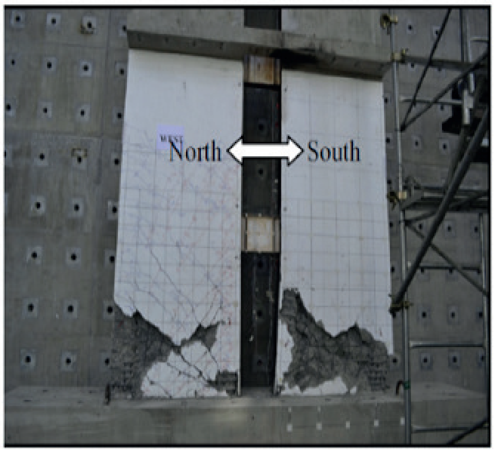


Fig. 8 Deformations generated after testing Cheng et al. [25]

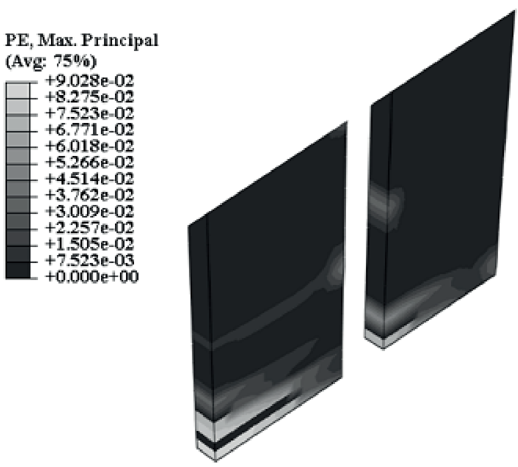


Fig. 9 Contour of the maximum plastic strains in the final loading

is considered to be 30 MPa. Given the fact that the steel coupling beams convey considerable shear forces as well as bending moment to the walls, their connections are considered to be highly important. For this purpose, according to research, buried depth of steel coupling beams in concrete walls is suggested. However, the purpose of this study is not to investigate this issue. Moreover, to simplify this model in the software, 345 MPa yield strength steel boundary columns are used. Therefore, the connection between coupling beams and steel boundary columns is considered to be rigid. Fig. 10 shows the cross-section of the desired structure.

The dimensions obtained from the analysis and elastic design of the desired structure are set out in Table 1.

According to Section 2, the proposed formula is dependent on the continuous analytical method. All the equations of this method are valid for concrete shear walls. In the present model, these relationships cannot be used due to the presence of the steel boundary columns. Therefore, to calculate the cross-sectional dimensions of the ideal coupling beams in the present model, we must equate the elastic behavior of this structure with a similar concrete wall and then apply the proposed formula. To solve this problem, one can equate the flexural and shear rigidity of the wall with the similar concrete shear wall by using the strength of material. To simplify this method, the rigidity of the reinforcements inside the concrete walls is neglected. Eq. (13), calculates the cross-section dimensions of similar concrete wall.

$$W_l = \frac{3.167}{q_2}$$
$$W_t = 0.379 q_1 . q_2$$
$$q_1 = \frac{\left[4A_{IPB}\right]G_s + \left[0.833 t_c h_c\right]G_c}{G_c} \quad (13)$$
$$q_2 = \sqrt{\frac{\left[4A_{IPB}\right]G_s + \left[0.833 t_c h_c\right]G_c}{\left[4I_{x,IPB} + A_{IPB}(h_w + h_c)^2\right]E_s + \left[0.0833 t_c h_c^3\right]E_c} \frac{E_c}{G_c}}$$

In Eq. (13), $I_{x,IPB}$ ad A_{IPB} represent the moment of inertia and the cross-sectional area of the boundary columns, respectively. The parameter h_w is the height of web of the boundary columns. The parameters h_c and t_c stand for respectively the dimensions of the cross-sectional area of the concrete wall. In the present section, the parameters E_s, G_s, E_c and G_c are considered as 2.1 × 10^8, 0.807 × 10^8, 0.257 × 10^8 and 0.108 × 10^8 KPa, respectively.

According to Eq. (13), the cross-sectional dimensions of each of the similar walls in the first and second stories are 2.864 × 0.357 meters and for the third to fifth stories are 2.719 × 0.340 meters, respectively. According to the studies using software and strength of material, this method yields an error of less than 1%. According to the previous section, the equations of the continuous analytical method include assumptions. One of these assumptions is the uniformity of the geometrical properties of the walls at the height of the structure. In the present model, due to the different geometrical properties of the structure in the height, the only solution is the average stiffness of the shear walls. Accordingly, the cross-section dimensions of each shear wall are considered to be 2.777 m and 0.346 m.

As the cross-sectional dimensions of the separate shear walls are determined, the calculations for the ideal coupling beams are set out in Table 2. It is noteworthy that the length of the coupling beams is assumed to be 2 meters. In addition, the coupling beams are considered to be type ASTM A572 Gr.50 steel having 345 MPa yield strength.

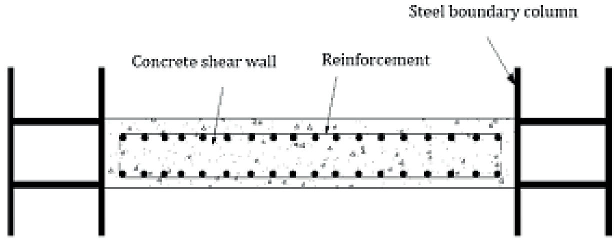


Fig. 10 The cross-section of the desired structure

Table 1 Cross-sectional dimensions of reinforced concrete shear wall

Parameters	The first and second stories	Third to fifth stories
Dimensions of concrete shear wall cross- section (cm)	200 × 30	200 × 30
Number and diameter of reinforcements	H: 36Φ20 & V: 36Φ16	H: 36Φ16 & V: 36Φ16
Steel boundary column	2IPB260	2IPB220

Table 2 Ideal coupled beam cross- section calculations

	5-Story	
$A_1 = A_2 = 0.961$ m^2	$k = 1.0547$	Eq. (2)
$A = 1.922$ m^2	$n = 0.6$	Eq. (6)
$I = 1.234$ m^4	$K_s = 1.0869 \times 10^5$ KN/m	Eq. (8)
$L = 4.777$ m	$I_{e_{Ideal}} = 0.01518$ m^4	Eq. (9)
$b = 2$ m	$D = 0.954$ m	Eq. (11)
$t = 0.346$ m	$t_f \cong 0.032$ m	
$I_s = 12.428$ m^4	$b_f \cong 0.48$ m	
$A_g = 2.613$ m^2	$h_w \cong 0.48$ m	Eq. (12)
$h = 4$ m	$t_w \cong 0.010$ m	
$H = 20$ m		

According to Section 2, if the walls are affected by the wide triangular load, the highest shear force is created in the lower beams. However, if the walls are affected by the concentrated load, the lower and upper coupling beams experience the least shear force and the other beams of the stories exert the greatest shear force. In the present model, the shear force distribution in the beams is similar to the concentrated load. In this model, the lateral loading pattern is considered based on the first mode frequency of the system. Therefore, the cross-sections of the first and fifth stories beams of this structure are approximately 20% less than the ideal coupling beam. The coupling beams enter nonlinear behavior sooner than all the structural members which is due to the considerable stiffness of the shear walls. Given the importance of coupling beams, it is imperative to use stiffener along with it. The presence of stiffeners does not affect the elastic behavior of the coupling beams. In the present model, the design of the stiffeners is based on the AISC. Fig. 11 illustrates the lateral stiffness curve obtained from the nonlinear static analysis of ideal coupled shear walls and separate shear walls.

Based on the static nonlinear analysis, shear capacity, lateral elastic stiffness and energy absorption of the systems are calculated by the software. The ductility of these systems is currently being examined. The reason for such a parameter is the presence of severe earthquakes and the acceptance of some structural damage. It is not possible to control the elastic behavior of structures in moderate earthquakes. Experience shows that structures have nonlinear behavior when an earthquake strikes. Therefore, a significant amount of earthquake energy is lost as damping energy [30, 31]. Given the static nonlinear behavior of structures, their ductility is calculated by Eq. (14).

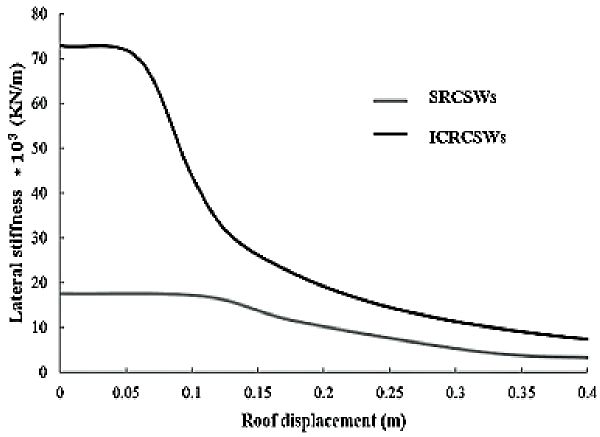


Fig. 11 The lateral stiffness curve of ideal coupled reinforced concrete shear walls (ICRCSWs) and separate reinforced concrete shear walls (SRCSWs)

$$\mu = \frac{1}{1-\sqrt{1-\left(\frac{2E_{abs}}{K_y\delta_{Max}^2}\right)}} > 1 \tag{14}$$

In Eq. (14), the parameters K_y, E_{abs} and δ_{Max} represent the lateral elastic stiffness, energy absorption and the maximum displacement of the roof, respectively.

Based on the static nonlinear analysis of the desired structures, lateral elastic stiffness and energy absorption for separate shear walls are equal to 17600.37 kN/m and 598.53 kN.m and for ideal coupled shear walls are equal to 73000.85 kN/m and 1473.64 kN.m. In addition, the maximum displacement of the both models roof is 0.4 meters. Therefore, according to Eq. (14), the ductility of the separate shear walls and the ideal coupled shear walls are 4.137 and 7.4, respectively.

According to Fig. 11, the coupled shear walls significantly changes the behavior of the structure. The rigidity of the coupling beams is a major factor in the nonlinear behavior of the structure. By increasing the roof displacement to 0.05 meters, the behavior of the coupling beams becomes elastic. As the roof displacement increases, the behavior of the coupling beams becomes nonlinear and the lateral stiffness of the system begins to decline. By increasing the roof displacement by 0.4 meters, the rigidity of the coupling beams gradually disappears, and the system behaves similar to separate shear walls. This theme increases the ductility of the structure.

At the beginning of the present section, the static nonlinear behavior of separate reinforced concrete shear walls as well as ideal coupled are investigated. In the remainder of this section, the nonlinear behavior of the ideal coupled shear walls is controlled. To accomplish this objective, according to Table 3, we modify the rigidity of the coupling beams of the system under investigation and analyze each of these models. It is noteworthy that the cross-section dimensions of the beams are arbitrarily selected and only their local buckling criteria are compiled according to the AISC. The purpose of this method is to evaluate the effects of rigidity of steel beams on the behavior of coupled shear walls.

Based on the aforementioned discussions, using the shear walls inter coupled, and the linear and nonlinear behavior of the system changes significantly. In fact, the seismic parameters such as the response modification factor and the ductility of this structure depend on the rigidity of the coupling beams. According to the research done recently, the behavior of coupling beams in shear walls is

Table 3 Cross-sectional dimensions and behavior of coupling beams in the desired systems

	Cross-sectional dimensions of coupling beams (cm)				Behavior of coupling beams
	Second to fourth stories		First and fifth story		All stories
CRCSWs$_1$	$h_w = 30$, $t_w = 0.8$	$b_f = 20$, $t_f = 1.2$	$h_w = 25$, $t_w = 0.6$	$b_f = 18$, $t_f = 1.0$	Bending
CRCSWs$_2$	$h_w = 50$, $t_w = 0.8$	$b_f = 30$, $t_f = 1.6$	$h_w = 40$, $t_w = 0.6$	$b_f = 26$, $t_f = 1.4$	Interaction
ICRCSWs	$h_w = 62$, $t_w = 1.0$	$b_f = 48$, $t_f = 3.2$	$h_w = 50$, $t_w = 0.8$	$b_f = 38$, $t_f = 2.4$	Shear
CRCSWs$_3$	$h_w = 70$, $t_w = 1.2$	$b_f = 50$, $t_f = 3.2$	$h_w = 60$, $t_w = 1.0$	$b_f = 48$, $t_f = 3.2$	Shear
CRCSWs$_4$	$h_w = 80$, $t_w = 1.4$	$b_f = 50$, $t_f = 3.2$	$h_w = 70$, $t_w = 1.2$	$b_f = 50$, $t_f = 3.2$	Shear
CRCSWs$_5$	$h_w = 90$, $t_w = 1.6$	$b_f = 50$, $t_f = 3.2$	$h_w = 80$, $t_w = 1.4$	$b_f = 50$, $t_f = 3.2$	Shear

similar to the 'Eccentrically Braced Frames'. For example, according to the AISC, response modification factor of eccentrically braced frames is proposed for coupling beams having bending behavior equal to 6 and shear behavior equal to 7. Flexural behavior means yielding the flanges of coupling beams occurs before the web. By increasing the rigidity of the coupling beams, their behavior tends to shear. Shear behavior means yielding the web of coupling beams occurs before flanges. The AISC has proposed the behavior of coupling beams in the eccentrically braced frames based on Eq. (15).

$$\begin{cases} b \le 1.6\dfrac{M_p}{V_p} \Rightarrow \textit{Shear behavior} \\ 1.6\dfrac{M_p}{V_p} < b < 2.6\dfrac{M_p}{V_p} \Rightarrow \textit{Interaction behavior} \\ b \ge 2.6\dfrac{M_p}{V_p} \Rightarrow \textit{Bending behavior} \end{cases} \quad (15)$$

$$\frac{M_p}{V_p} = \frac{zf_y}{0.6A_{web}f_y} = \frac{b_f t_f\left(h_w + t_f\right) + 0.25 t_w h_w^2}{0.6 h_w t_w}$$

In the Eq. (15), M_p and V_p represent the bending and shear strength of plastic of the coupling beams, respectively. In addition, the parameter b stands for the length of the coupling beams. Other parameters have already been introduced.

Fig. 12 shows the push-over curve of the systems as considered in Table 3. According to Fig. 12, by increasing rigidity of the coupling beams, resistive parameters such as final shear capacity, lateral elastic stiffness and energy absorption of the structure are constantly increased as well. In fact, changes to these parameters up to the ICRCSWs model are significant; however, they decrease by increasing beams rigidity. This theme is similar to the elastic behavior of the structures discussed in Section 2. According to the figure on page 13, by increasing the rigidity of coupled beams, the system ductility is decreased based on the models. This issue is perfectly logical.

The coupling beams are the first line of defense against lateral forces, and their behavior becomes nonlinear sooner than other members of the structure [32]. Hence, in this system, the fuse elements are the coupling beams which are most vulnerable to earthquakes. Increasing the rigidity of the coupling beams increases their shear capacity; however, the shear force is created as displayed in Fig. 13 based on the ICRCSWs model which does not change significantly. Therefore, the coupling beams experience less plastic stress, which reduces the ductility of the system.

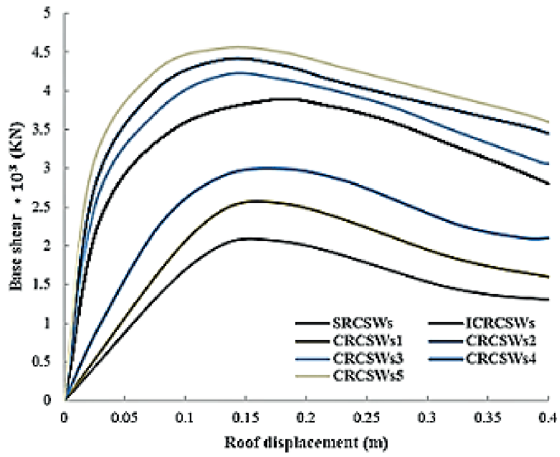


Fig. 12 Push-over curve of the systems desired in Table 3

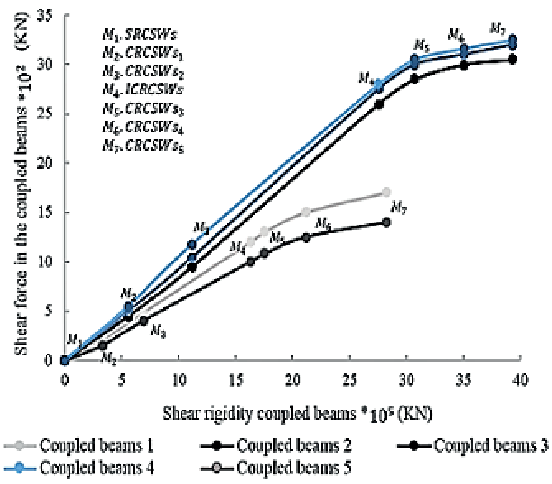


Fig. 13 Shear force of coupling beams of the desired models in Table 3

Fig. 14 shows the second-story beam von Mises stress contour of the models ICRCSW*s*, CRCSWs_3, CRCSWs_4 and CRCSWs_5 at final loading. In this contour, the yielding points of the beam are shown in dark color.

According to Fig. 14, by the increase in coupled beams rigidity, the yield points of CRCSWs_3, CRCSWs_4 and CRCSWs_5 models are decreased. Therefore, the cross-sectional dimensions of the ideal beams predicts the nonlinear behavior of this structure accurately.

3.3 Original 10 and 15-story models

In Section 3.2, the static nonlinear behavior of the ideal reinforced concrete shear walls of 5-story is investigated. Analyzing the results of this section, it is quite clear that the proposed formula accurately predicts the nonlinear behavior of this system. Next, considering the research process in the previous section, we examine the accuracy of this formula for shear walls of 10 and 15-story. The dimensions of the elastic design of these structures are shown in Table 4.

According to Eq. (13), the cross-section dimensions of each of the wall is determined as follows: In 10-story, in the first to sixth stories: 5.349 m × 0.52 m (being similar to each other); and for the seventh to tenth stories: 5.192 m × 0.514 m; in addition, in 15-story, in the first to ninth stories: 6.992 m × 0.665 m and for the tenth to fifteenth stories: 6.799 m × 0.663 m. Next, according to the previous section, the average cross- sectional dimensions of the shear walls of 10-story are determined as follows: 5.286 m × 0.517 m and for 15-story: 6.914 m × 0.664 meters. The calculations for the ideal coupling beam of these systems are presented in Table 5.

Based on the calculations in Tables 2 and 5, it is quite clear that as the number of stories of the shear walls increases, the rigidity of the coupling beams is increased. This issue is examined in Section 2. The nonlinear behavior of these systems is examined in the remainder of this study. For this purpose, according to the previous procedure, we modify the rigidity of the coupling beams of the desired systems and analyze each of these structures. It is noteworthy that this process is very time consuming. Fig. 15, shows the ductility obtained from the static nonlinear analysis of these structures.

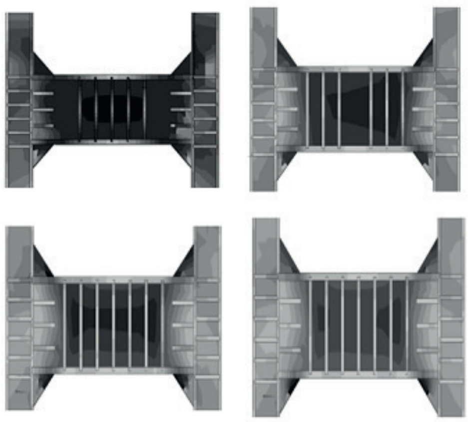


Fig. 14 Second-story beam von Mises stress contour at final loading

Table 5 Ideal coupled beam cross- section calculations

10-Story		
$A_1 = A_2 = 2.732$ m^2 $A = 5.465$ m^2 $I = 12.726$ m^4 $L = 7.286$ m $b = 2$ m $t = 0.517$ m	$k = 1.0842$	Eq. (2)
	$n = 0.8$	Eq. (6)
	$K_s = 0.9633 \times 10^5$ KN/m	Eq. (8)
	$I_{e_{Ideal}} = 0.0366$ m^4	Eq. (9)
	$D = 1.198$ m	Eq. (11)
	$t_f \cong 0.045$ m	Eq. (12)
	$b_f \cong 0.67$ m	
	$h_w \cong 0.70$ m	
	$t_w \cong 0.0115$ m	
15-Story		
$A_1 = A_2 = 4.59$ m^2 $A = 9.181$ m^2 $I = 36.576$ m^4 $L = 8.914$ m $b = 2$ m $t = 0.664$ m	$k = 1.0957$	Eq. (2)
	$n = 1$	Eq. (6)
	$K_s = 0.7461 \times 10^5$ KN/m	Eq. (8)
	$I_{e_{Ideal}} = 0.0476$ m^4	Eq. (9)
	$D = 1.205$ m	Eq. (11)
	$t_f \cong 0.052$ m	Eq. (12)
	$b_f \cong 0.77$ m	
	$h_w \cong 0.76$ m	
	$t_w \cong 0.0125$ m	

Table 4 Cross- sectional dimensions of reinforced concrete shear wall

Parameters	10-Story		15-Story	
	First to sixth stories	The seventh to tenth stories	First to ninth stories	Tenth to fifteenth stories
Dimensions of concrete shear wall cross- section (cm)	450 × 50	450 × 50	600 × 65	600 × 65
Number and diameter of reinforcements	H: 36 Φ 25 & V: 36 Φ 18	H: 36 Φ 20 & V: 36 Φ 18	H: 36 Φ 30 & V: 36 Φ 20	H: 36 Φ 25 & V: 36 Φ 20
Steel boundary column	2IPB300	2IPB260	2IPB400	2IPB340

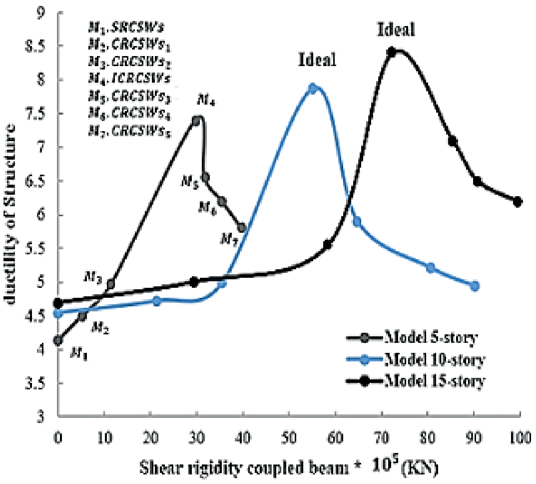


Fig. 15 Ductility of 5, 10 and 15-story structures

Based on Fig. 15, it is evident that by increasing the rigidity of the coupling beams, the ductility of the systems under investigation is increased. In fact, the excessive rigidity of the beams reduces this parameter. The root cause of this issue is fully explored in the 5-story model. This section does not provide details on this issue. Therefore, based on the Fig. 15, the proposed formula accurately predicts the nonlinear behavior of the systems under investigation (10 and 15-story).

4 Conclusions

In the present study, the behavior of coupled shear walls was investigated based on the continuous analytical method and ABAQUS software. Based on the methods proposed, the research results are divided into two main sections. In the first section, the linear static behavior (elastic behavior) of coupled shear walls is studied and in the second section, the effects of steel beams on the nonlinear static behavior of coupled reinforced concrete shear walls are considered. The important results from these two sections are as follows:

- The stresses caused by external loading in the coupled shear walls are determined to be nearly 400% less compared to the separate shear walls. In addition, with increasing rigidity of the coupling beams, the lateral stiffness of the system increases nearly 800% which is considered as a significant increase. As the number of stories in this system increases, the rigidity of the coupling beams should increase as well. However, the excessive rigidity of the coupling beams does not significantly affect the elastic behavior of these structures. Therefore, using the help of the continuous analytical method and the software, a formula is proposed to calculate the dimensions of the ideal coupling beams cross-section. The difference between the present study and previous studies is the presentation of this formula. These two topics were examined in the 10-story model.
- Examination of the static nonlinear behavior of the systems in question indicates a significant increase in ideal coupled shear walls ductility compared to separate shear walls. However, increasing the rigidity of the coupling beams compared to the ideal beams has minimal effect on the resistive parameters of the system and even decreases the structure ductility. This is due to the decrease in plastic stresses in the coupling beams. Therefore, the cross-sectional dimensions of the ideal beams correctly predict the nonlinear behavior of the systems in question. The behavior of coupled shear walls depends on the beams ductility. This issue was examined by comparing the behavior of separate elastic shear walls versus coupled and continuous shear walls. Furthermore, by increasing the rigidity of the coupled beams, the behavior of this system is improved.
- With respect to the results obtained from the behavior of elastic coupling shear walls, a formula is proposed to calculate the cross-sectional dimensions of ideal coupling beams. This formula is obtained by using a continuous analytical method as well as software. Based on the presented method, changing the stiffness of separate shear walls has no effect on the behavior of the ideal coupling shear walls. The behavior of these walls having different number of stories varies with one another. If the number of stories of this structure is higher than 15, the behavior of ideal coupling shear walls is similar to homogeneous shear walls. Therefore, the stiffness ratio of ideal coupling shear walls and the stiffness of homogeneous shear walls is considered to be nearly 0.6 in 5-story structure, 0.8 in 10-story structures, and 1 in structures having more than 15 stories, respectively.
- Examination of the static nonlinear behavior of the systems in question indicates a significant increase ideal coupling shear walls ductility compared to separate shear walls. This issue was examined in 5, 10 and 15-story structures. The ductility ratio of ideal coupling shear walls and separate shear walls is increased by 78.87% in 5-story structure, 72.22% in 10-story structure and 67.45% in 15-story structure.
- However, increasing the rigidity of the coupling beams compared to the ideal beams has little effect on the resistive parameters of the system and even decreases the structure ductility. This is due to the increase in the shear capacity of coupled beams; meanwhile, the shear

force generated does not change considerably in beams. Therefore, the coupled beams experience less beyond the yielding stresses. This issue leads to reduction of system ductility. Therefore, the cross-sectional dimensions of the ideal beams correctly predict the nonlinear behavior of the systems under investigation.

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Conflicts of interest

The authors declare no conflict of interest.

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