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Research Article

AN INVESTIGATION ON RC HIGH-RISE STRUCTURES WITH AND WITHOUT OUTRIGGERS UNDER LATERAL STATIC LOADS

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ABSTRACT

Today, the need of high-rise structures is rising throughout the world day by day. The package programs used in the modelling and analyzing of high structures are being renewed and improved every day. However, analytical solutions are still to be very helpful in the preliminary design of the building model. In this study, the analytical solution approach has assessed for the horizontal displacement determinations of the shear wall-framed systems and shear wall-framed systems with outrigger systems under the static horizontal loads. For this purpose, two building models with 45 floors have been considered. The shear wall-framed system with outriggers has created by adding outrigger system to the shear wall -framed system in two levels. As the horizontal loads to the building models, the triangular distributed load representing the earthquake load and the uniformly distributed load representing the wind load have been applied. Displacement solutions of both models under horizontal loads have been performed using the analytical approach and ETABS program. The results of both models have been compared with each other and the validity of analytical solutions have been evaluated. Internal forces occurred in the both models under horizontal loads have been also assessed. The internal force solutions were obtained by using ETABS program. In addition, the effectiveness of the outrigger system has been examined.
Keywords: RC high-rise structures, shear wall-framed system, outriggers, horizontal displacements, internal forces.

1. INTRODUCTION

The vertical loads are the primary factor in the design of structures. However, they leave this priority to the horizontal loads depending on increasing building height. Lateral stiffness of the structure is main factor to resist the horizontal loads that are wind and earthquake loads. Therefore, the selection and modeling of horizontal load bearing system has become extremely important. Nowadays, multi-storey structures have generally constructed by using shear wall-framed systems and shear wall-framed systems with outriggers.

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1.1. Shear Wall-Framed System

As the building height i ncreases, moment-framed systems cannot provide alone the required conditions for resisting horizontal loads without the support of shear walls. Especially when the number of storey exceeds a certain level, horizontal loads start to create unacceptable lateral drifts in the frame systems. In this case, the moment-framed systems consisting of column-beams can no longer provide adequate lateral stiffness under lateral loads. This situation can be achieved with the use of shear wall systems. A typical floor plan of the shear wall- framed system has shown in Figure 1[1].

Behaviors of shear walls and frames under horizontal loads are different. Moment-framed systems under horizontal forces have shown shear beam displacement behavior model, while shear wall systems have shown bending beam displacement behavior model. Here, there is a benefit to draw attention to a very important feature. According to the surface to which the load is applied, the shear beam model creates a convex displacement profile while the bending beam model has a concave displacement profile [2]. In shear wall-frame systems, frame and shear wall cooperate closely in height of structure and in the horizontal planes of the storey. Thanks to this cooperation, the resistance of the structure to horizontal loads is increasing effectively.

In Figure 2, the interaction between the moment-frame and the shear wall has shown [1]. Storey shear forces are effective on the horizontal displacements of the frame. At the upper floors, the storey shear force is small and the horizontal displacement stiffness is small too. However, in the lower floors, while the shear force is increasing, the horizontal displacement stiffness does not increase in the same rate. Therefore, the inter story horizontal displacement of the lower floors is greater than that of the upper floors. On the other hand, the shear wall subjected to the horizontal loads makes a horizontal displacement increasing towards the upper floors starting from zero. In the case of using shear wall and moment-frame system with together, if the height of the structure is high enough, the shear wall restricts the lateral displacements of the frame in the lower floors, while the frame is limited the horizontal displacements of the shear wall in the upper floors [3].

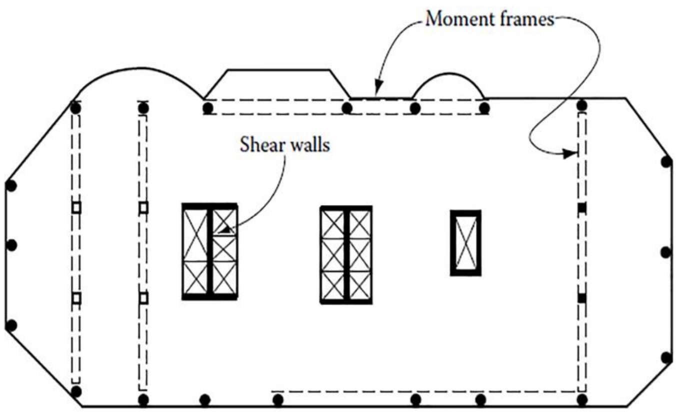


Figure 1. Shear wall-framed system

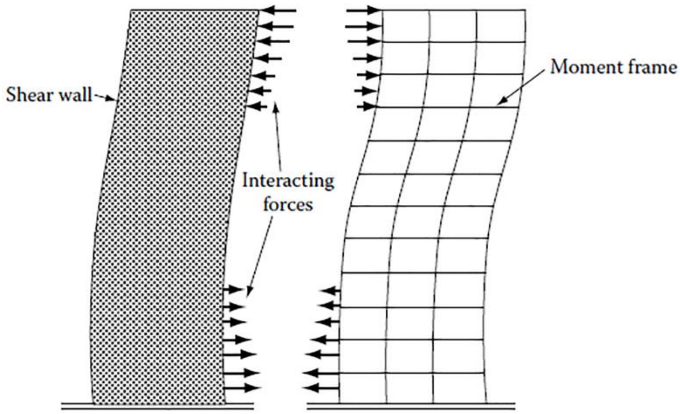


Figure 2. Shear wall-frame interaction

Because of this, as shown in Figure 2, negative shear forces can occur in the shear wall in the upper floors. This situation has especially seen in multi-storey structures depending on the stiffness of the shear wall and frame. In structures with a lower number of floors, if the shear wall is very rigid, the shear wall limits the horizontal displacement of the frame, and the shear wall carries most of the horizontal load. On the other hand, the size of the effective area on the floor plan is determinative in the normal force of the shear wall rather than its stiffness. For this reason, the effect of normal force at the shear walls is lower than that of the columns, but the bending moment is much more effective [3].

1.2. Shear Wall-Framed System with Outrigger System

In recent years, while load bearing system of high-rise structures have been creating, systems which have core (shear) wall system at the center of the structure plan and columns at the outsides of the structure plan are preferred. Beams and floors provide interaction between the core wall and the outside moment-frame columns. However, for providing stronger cooperation and interaction between the core wall and the outside columns, rigid horizontal members that are usually formed from truss steel bars are placed between these two systems in certain levels of the structure height.

The basic function of these rigid horizontal members, called the outrigger system, is to strengthen the mutual interaction between the shear wall and the moment-frame columns, and in particular to increase the bending rigidity of structure against horizontal loads. The outrigger system can be applied in one or several levels in the structure [1]. Typical plan view of this system has given in Figure 3. The outrigger system is generally applied bilaterally (Figure 4.a), and can be also applied unilaterally depending on position of the core wall (Figure 4.b) [4]. This system is usually placed at 15 or 20-floors with homogeneous intervals in high-rise structures. The floors in which this system is located are usually used as mechanical floors.

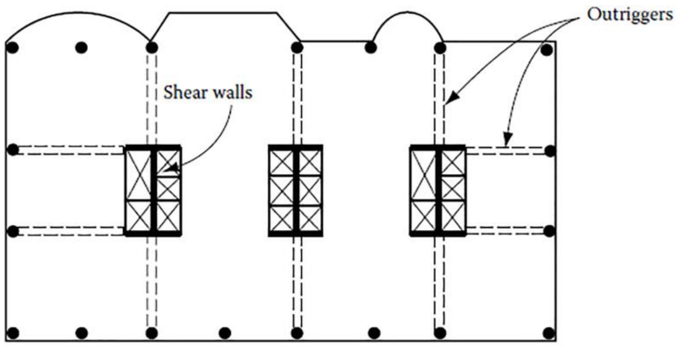


Figure 3. The plan view of outriggers

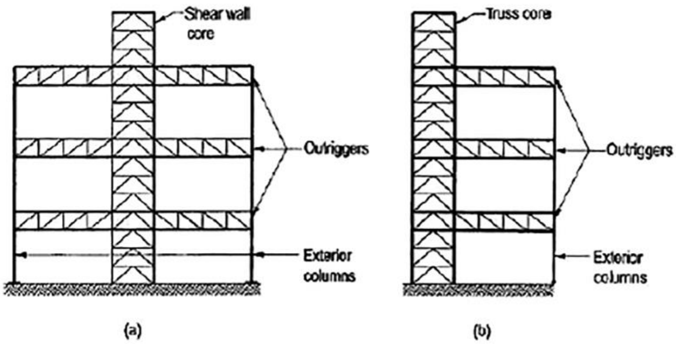


Figure 4. The outriggers applied a) bilaterally applied of outriggers b) unilaterally applied outriggers

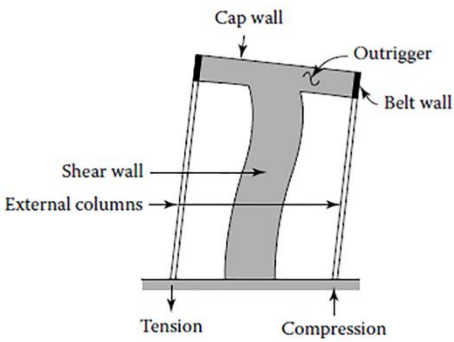


Figure 5. Reducing rotation and displacement of core wall

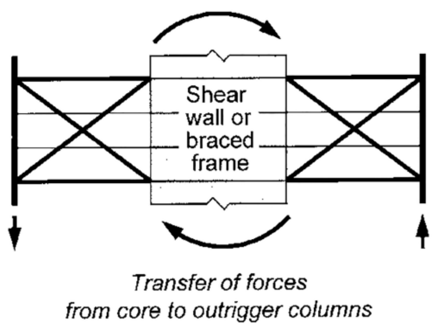


Figure 6. Force transfer from core to outrigger column

The behavior of the outrigger system is quite simple and effective in the structure subjected to horizontal loads. When horizontal loads act on the structure, the outrigger will provide a strong cooperation between the core wall and outside columns, so that the rotation and displacement of the core will decrease. In other words, the core wall with outrigger systems will show less rotation and lateral displacement than one without the outrigger systems (Figure 5) [1]. In addition, the overturning moment occurred in the structure under the horizontal loads will be not only resisted by the bending moment in the core wall but also by the moment which is occurred by tension and compression force pairs in the outside columns. These force pairs occur depending on strong interaction between the outside columns and the core wall with outrigger systems. The operating principle of this system has shown in Figure 6 [5].

1.3. Literature Review

Simplified analytical and graphical method solutions for high-rise structures with the Outrigger systems began nearly 40 years ago. Taranath [6, 7], when belt trusses were assumed to have infinite bending stiffness and located up the height of the structure were considered to be the most significant factor influencing the reduction in horizontal drift. McNabb and Muvdi [8, 9] showed that the structural properties of the shear wall and the columns are significant design parameters in reducing lateral deflections and suggested a solution for a structure system with two outriggers. Stafford Smith and Salim [10] were presented a graphical method including the flexibility of the outrigger structures.

Nair [5] investigated the efficiency of the belt trusses, which are also called as "virtual outriggers" system and placed between the outside columns. In that study, belt trusses are not connected with the shear wall directly and they have used instead of the traditional outrigger system under lateral loads. Hoenderkamp and Snijder [11] have analytically investigated the behavior of high-rise structures under horizontal loads using the belt trusses, which are not directly connected by shear walls, placed between columns and called as facade riggers. Hoenderkamp and Bakker [12] was investigated analytically the behavior of the structure with outrigger system subjected to horizontal loads. In the analytical solution of the outrigger system, shear deformations were taken into account besides the bending deformations. Hoenderkamp [13] conducted an analytical study in which two-level outrigger system were considered and kept constant the position of the outrigger system located on the top of the structure. He investigated optimum position of the second one by considering the peak displacement and shear wall base moment.

Kamath et al. [14] investigated the effect of bending stiffness of outrigger system to the structure. They studied the effects of the positional changing and bending stiffness of the outrigger system on the lateral displacements, shear forces and moments of the shear wall. Nanduri et al. [4] conducted a numerical study on the high-rise structure with outrigger system. They were examined the behaviors of shear wall-framed systems with conventional outriggers and shear wall-framed systems with conventional outriggers and belt trusses under vertical and lateral loads. Calayır and Dedeoğlu [15] investigated the earthquake responses of shear wall-framed systems with and without outriggers by using linear analysis method in time-domain. Two structural systems had same storey plan and same structural members that are core, columns and beams. They evaluated effectiveness of the outrigger system by comparing the earthquake responses of both structural systems with each other.

2. ANALYTICAL DETERMINATION OF HORIZONTAL DISPLACEMENTS OF STRUCTURES UNDER LATERAL LOADING

2.1. Shear Wall-Framed System

The lateral displacement determination of the shear wall-framed system subjected to horizontal loading will not be presented in this study. Detailed information on this subject can be obtained from references in [16-17].

2.2. Shear Wall-Framed System with Outriggers

In this study, the analytical solution of the shear wall-framed system with outrigger will be given under the lateral loads. Solutions of analytical approach provide brief and concise information about the behavior of building systems. It also allows faster and more reliable approximate solutions for preliminary design.

The assumptions have given below for the analytical determination of the horizontal displacements of the shear wall-framed system with outriggers.

1. Structure models behave linearly elastic.
2. Only axial forces are occurred in the columns.
3. The outrigger system is rigidly connected to the shear wall.
4. The shear wall is assumed to be deformed only due to the bending moment.
5. The sectional properties of the shear wall, outrigger system and columns are kept constant throughout their height.

2.2.1. Shear Wall-Framed System with Outriggers Under Uniformly Distributed Lateral Loading

In the shear wall-framed system with outriggers, the rotation angles of the core and the outriggers should be consistent as shown in Figure 7. The bending stiffness of the core is an important factor for its rotation. On the other side, the bending and shear stiffness of outrigger system and overturning stiffness of the outside columns are important factors for the rotation of outrigger system [11].

The shear wall-framed system with two level outriggers subjected to uniformly distributed lateral loading and the rotation angles of occurred in the shear wall at outrigger levels due to this loading are shown in Figure 7.a.

The bending moment diagram of the core (Figure 7.e) consists of the external load moment diagram (Figure 7.b) reduced by the outrigger restraining moments that, for each outrigger, are started the outrigger level and extend uniformly down to the base (Figure 7.c and d) [18].

2.2.1.1. Determination of Rotation Angles of Shear Wall at Outrigger Levels

The rotations of the first and second outrigger levels of the core shown in Figure 7. a. are expressed as follows by using the moment area method [19]

$$\Theta_{1;s} = \frac{1}{EI_p}\int_{x_1}^{x_2}\left(\frac{wx^2}{2} - M_1\right)dx + \frac{1}{EI_p}\int_{x_2}^{H}(wx^2 - M_1 - M_2)\,dx \tag{2.1}$$

$$\Theta_{2;s} = \frac{1}{EI_p}\int_{x_2}^{H}\left(\frac{wx^2}{2} - M_1 - M_2\right)dx \tag{2.2}$$

Here EI_p and H indicate the bending stiffness and total height of the core, respectively, and w is intensity of uniformly distributed load, x_1 and x_2 indicate the distances of 1 and 2 outriggers from the top of the core, M_1 and M_2 are the restraining moments occurred by the effect of the outriggers on the core.

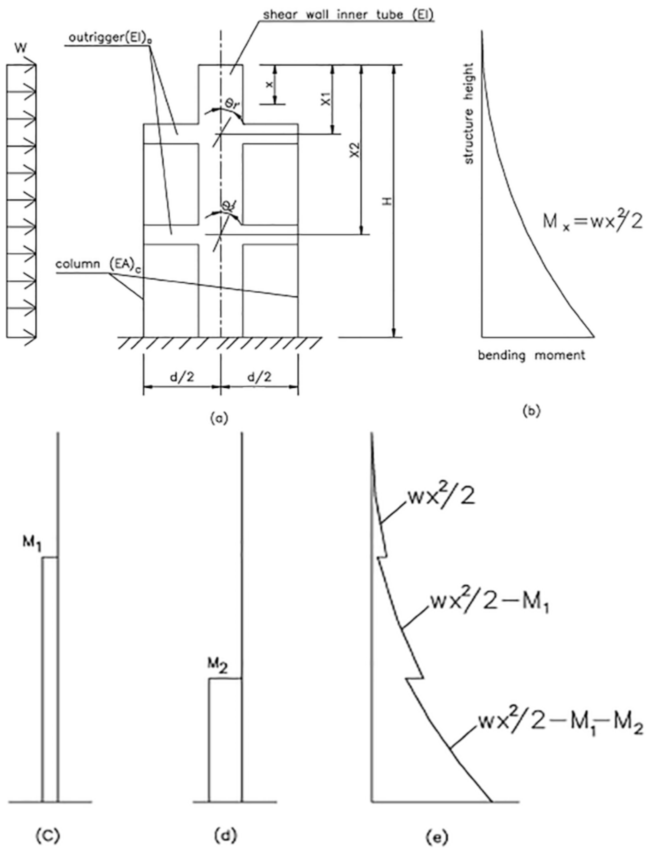


Figure 7. The shear wall-framed system with two level outriggers a) *subjected to uniformly distributed horizontal loading*; b) external load moment diagram; c) $\boldsymbol{M_1}$ *moment diagram;* d) $\boldsymbol{M_2}$ *moment diagram;* e) core resultant moment diagram

2.2.1.2. Compatibility Equations for Core and Outriggers

Total rotation angles of the outriggers can be written as

$$\Theta_{1;o} = \Theta_{1;o;b} + \Theta_{1;o;s} + \Theta_{1;c} \tag{2.3}$$

$$\Theta_{2;o} = \Theta_{2;o;b} + \Theta_{2;o;s} + \Theta_{2;c} \tag{2.4}$$

$\Theta_{1;o}$ and $\Theta_{2;o}$ are the total rotation angles of the first and second outriggers, respectively. $\Theta_{1;o;b}$, $\Theta_{1;o;s}$ and $\Theta_{1;c}$ are rotation angles of the first outrigger due to the bending, shear deformation and axial deformation of outside columns, respectively. $\Theta_{2;o;b}$, $\Theta_{2;o;s}$ and $\Theta_{2;c}$ are also rotation angles of the second outrigger due to the bending, shear deformation and axial deformation of outside columns, respectively.

Equations of 2.3 and 2.4 can be expressed as more clearly [11-14]

$$\Theta_{1;o} = \frac{M_1 b}{24\,\alpha^2 EI_o} + \frac{M_1}{2\,\alpha^2 hGA_o} + \frac{M_1 (H-x_1)}{EI_c} + \frac{M_2 (H-x_2)}{EI_c} \tag{2.5}$$

$$\Theta_{2;o} = \frac{M_2 b}{24\,\alpha^2 EI_o} + \frac{M_2}{2\alpha^2 hGA_o} + \frac{M_1 (H-x_2)}{EI_c} + \frac{M_2 (H-x_2)}{EI_c} \tag{2.6}$$

where b is the length of the outrigger measured from the outside column to the outrigger-core interface, α is dimensionless parameter defined by $\frac{2b}{d}$ and d is twice of the horizontal distance between the outside column and the center of the core and also h is the vertical dimension of the outrigger. EI_o is the bending stiffness of the outrigger and also GA_o is the racking shear stiffness of all segments in the outrigger truss. EI_c is the rotational stiffness parameter representing the axial stiffness of both outside columns.

At the intersection of the neutral lines of the shear wall and outriggers, the compatibility equations of the rotation angles can be expressed as

$$\Theta_{1;s} = \Theta_{1;o} \qquad (2.7)$$

$$\Theta_{2;s} = \Theta_{2;o} \qquad (2.8)$$

If equations (2.1 and 2.5) and equations (2.2 and 2.6) are substituted into equation (2.7) and equation (2.8), respectively, and obtained new two equations are rewritten for M_1 and M_2, the following equations can be obtained

$$M_1 = \frac{w}{6EI_p}\left\{\frac{S_2.(H^3-x_1^3)+S_1.\ (H-x_2).(x_2^3-x_1^3)}{S_1S_2.(2H-x_1-x_2)+S_2^2+S_1^2.(H-x_2).(x_2-x_1)}\right\} \qquad (2.9)$$

$$M_2 = \frac{w}{6EI_p}\left\{\frac{S_2.(H^3-x_2^3)+S_1.\ \left[(H^3-x_1^3).(x_2-x_1)-(x_2^3-x_1^3).(H-x_1)\right]}{S_1S_2.(2H-x_1-x_2)+S_2^2+S_1^2.(H-x_2).(x_2-x_1)}\right\} \qquad (2.10)$$

S_1 and S_2 parameters in these equations are defined as $S_1 = \frac{1}{EI_p}+\frac{1}{EI_C}$ and $S_2 = \frac{b}{24\,\alpha^2 EI_o} + \frac{1}{2\alpha^2 hGA_o}$.

For the shear wall-framed system with two-level outriggers subjected to uniformly distributed lateral loading, the horizontal displacement at any x level can be found by following the steps below.

• The elastic curve equation of the cantilever beam is solved under a uniformly distributed lateral loading with intensity of w,

• The elastic curve equation of the cantilever beam is solved under M_1 moment applied at the level of x_1 ,

• The elastic curve equation of the cantilever beam is solved under M_2 moment applied at the level of x_2 ,

• Horizontal displacement of the structure system is determined by superposing the solutions obtained in above three steps.

In this case, the top horizontal displacement of the structure can be given as

$$y_{max} = \left[\frac{wH^4}{8EI_p} - \frac{M_1.(H^2-x_1^2)}{2EI_p} - \frac{M_2.(H^2-x_2^2)}{2EI_p}\right] \qquad (2.11)$$

If the structure has a symmetrical plan and there is shear wall and outrigger system on each axle, the top horizontal displacement of the structure can be written as

$$y_{max} = \frac{R-1}{R}\left[\frac{wH^4}{8EI_p} - \frac{M_1.(H^2-x_1^2)}{2EI_p} - \frac{M_2.(H^2-x_2^2)}{2EI_p}\right] \qquad (2.12)$$

where R is the total number of axles in one direction of the structure.

2.2.2. Shear Wall-Framed System with Outriggers Under Triangularly Distributed Horizontal Loading

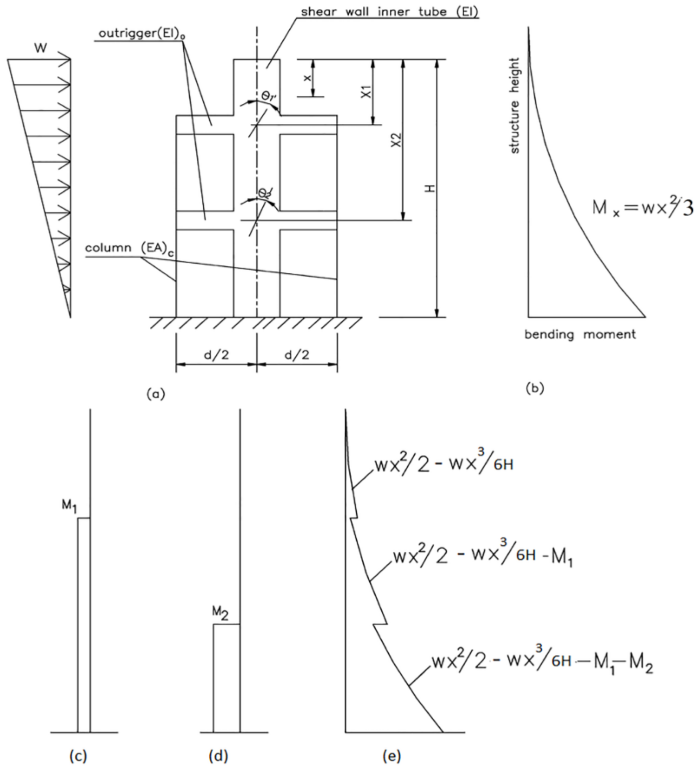


Figure 8. The shear wall-framed system with two level outriggers a) *subjected to triangularly distributed horizontal loading*; b) external load moment diagram; c) $\boldsymbol{M_1}$ *moment diagram;* d) $\boldsymbol{M_2}$ *moment diagram;* e) core resultant moment diagram

A typical shear wall-framed system with two outriggers under triangularly distributed lateral loading is given in Figure 8 [18]. In this system, the rotation angles of the core and the outriggers should be consistent as shown in Figure 8.a. In order to find the horizontal displacement of the structure, firstly the rotation angles at the outrigger levels of the core are obtained. Using the moment area method, the rotations at 1st and 2nd outrigger levels can be expressed as

$$\overline{\Theta}_{1;s} = \frac{1}{\mathrm{EI_p}}\int_{x_1}^{x_2}\left(\frac{w\ x^2}{3}-\frac{w\ x^3}{6\,H}-M_1\right)dx+\frac{1}{\mathrm{EI_p}}\int_{x_2}^{H}\left(\frac{w\ x^2}{3}-\frac{w\ x^3}{6\,H}-M_1-M_2\right)dx \qquad (2.13)$$

$$\overline{\Theta}_{2;s} = \frac{1}{\mathrm{EI_p}}\int_{x_2}^{H}\left(\frac{w\ x^2}{3}-\frac{w\ x^3}{6\,H}-M_1-M_2\right)dx \qquad (2.14)$$

where $\mathrm{EI_p}$ and H indicate the bending stiffness and total height of the core, respectively, and w is maximum intensity of triangularly distributed load, x_1 and x_2 indicate the distances of 1 and 2 outriggers from the top of the core, M_1 and M_2 are the restraining moments occurred by the effect of the outriggers on the core.

The calculation of the rotation angles of the outriggers in case of the triangularly distributed lateral loading is similar to that obtained for the uniformly distributed lateral loading.

At the intersection of the neutral lines of the shear wall and outriggers, the compatibility equations of the rotation angles can be expressed as

$$\overline{\Theta}_{1;s} = \Theta_{1;o} \qquad (2.15)$$

$$\overline{\Theta}_{2;s} = \Theta_{2;o} \tag{2.16}$$

If equations (2.13 and 2.5) and equations (2.14 and 2.6) are substituted into equation (2.15) and equation (2.16), respectively, and obtained new two equations are rewritten for M_1 and M_2, the following equations can be obtained

$$M_1 = \frac{w}{24.H.EI_p}\left\{\frac{[(3H^3-4x_1^3).S_2.H+S_2.x_1^4+(x_2^4-x_1^4).(H-x_2)+4.S_1(H-x_2).(x_2^3-x_1^3)]}{S_1S_2.(2H-x_1-x_2)+S_2^2+S_1^2.(H-x_2).(x_2-x_1)}\right\} \tag{2.17}$$

$$M_2 = M_1 * \left(1+\left[\frac{(x_2-x_1).S_1}{S_2}\right]\right) + \frac{w(x_2^4-x_1^4)}{S_2.24.H.EI_p} - \frac{w(x_2^3-x_1^3)}{S_2.6.EI_p} \tag{2.18}$$

For the shear wall-framed system with two-level outriggers subjected to triangularly distributed lateral loading, the horizontal displacement at any x level can be found by following four steps below as similar to the case of uniformly distributed lateral loading.

In this case, the top horizontal displacement of the structure under triangularly distributed lateral loading can be given as

$$y_{max} = \left[\frac{11.wH^4}{120EI_p} - \frac{M_1.(H^2-x_1^2)}{2EI_p} - \frac{M_2.(H^2-x_2^2)}{2EI_p}\right] \tag{2.19}$$

If the structure has a symmetrical plan and there is shear wall and outrigger system on each axle, the top horizontal displacement of the structure can be written as

$$y_{max} = \frac{R-1}{R}\left[\frac{11.wH^4}{120EI_p} - \frac{M_1.(H^2-x_1^2)}{2EI_p} - \frac{M_2.(H^2-x_2^2)}{2EI_p}\right] \tag{2.20}$$

where R is the total number of axles in one direction of the structure.

3. NUMERICAL EXAMPLE AND RESULTS

In this study, the validity of the analytical solutions given in the previous sections have been studied for the horizontal displacement of the shear wall-framed system with outriggers subjected to lateral loading. In the scope of the study, two structure models have used. These models are the shear wall-framed system and the shear wall-framed system with outriggers that is formed by adding the outrigger system in two levels to the shear wall-framed system. All the structural features of the shear wall-framed system have been preserved while the shear wall-framed system with outriggers has been forming.

As the horizontal loads for the structure models, the triangularly distributed lateral loads representing the earthquake loading and the uniformly distributed loads representing the wind loading have been applied statically. Static displacement solutions for these models have obtained in two different ways as analytical approach and three dimensional finite element approach (ETABS program). The validity of analytical solutions has examined by comparing solutions of two approaches with each other. Internal forces occurred in the both models under horizontal loads have been also assessed. The internal force solutions were obtained by using ETABS program. In addition, the effectiveness of the outrigger system has been evaluated.

3.1. Model Introduction

Two 45-storey structure models, load-bearing systems of which are shear wall-framed system and shear wall-framed system with outriggers have formed as the same floor plans. These models are named as Model 1 and Model 2, respectively, and they have 7 axles in both directions in the plane. In the models, there is only one shear wall at each axle in x direction. In the shear wall-framed system with outriggers, the outriggers have placed on the cores in two levels at each axle in x direction. While first level of these levels corresponds to 15 and 16 storey, second level corresponds to 30 and 31 storey. The structural element properties (shear wall, column, beam and slab) of the two bearing system models are identical. Storey plan of the two models has shown in

Figure 9. The plan has 6 spans in the x and y directions. The lengths of all spans are equal and they are 6 m.

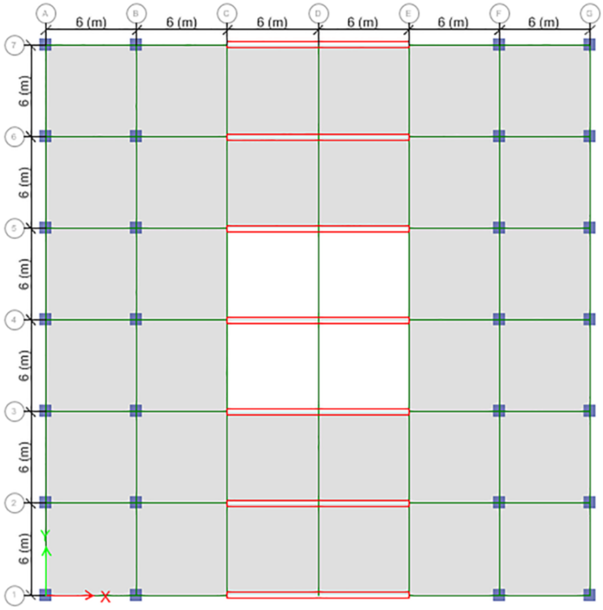
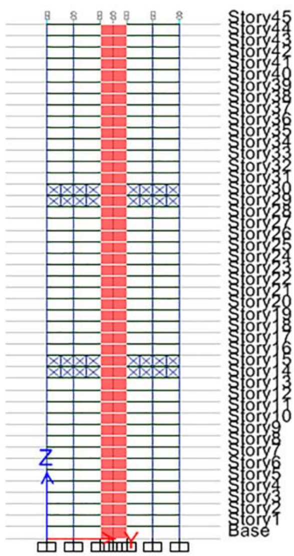


Figure 9. Plan view for the structure models

(a)

a) Model 1



(b)

b) Model 2

Figure 10. Elevation views of the structure models

The outriggers have designed as steel truss system and other members of the structure system have designed as reinforced concrete. Elevation views of the structure models have given in Figure 10. In both structure models, the structural element properties have kept constant throughout the structure height. Storey heights and floor thicknesses in the models have taken as 3.00 m and 0.12 m, respectively. The structural element properties of the models have given in Table 1. The sections of the structural elements of the outriggers have selected in the form of box / circle.

Table 1. Structural properties of Models

Structural Members	Shear walls	Columns	Beams	Outrigger diagonal cords	Outrigger diagonal cords	E_c	E_s
Model 1	0.4x12 m^2	0.8x0.8 m^2	0.4x0.6 m^2	--	--	34 000 000 kN/m^2	--
Model 2	0.4x12 m^2	0.8x0.8 m^2	0.4x0.6 m^2	0.4m x0.6 m t=0.017 m	D=0.3m t=0.012 m	34 000 000 kN/m^2	210 000 000 kN/m^2

3.2. Analysis of Structure Models Under Lateral Loads

The structure models that their structural properties have been given at the previous section have been analyzed under two different lateral distributed loadings effecting along the structure height statically. One of two loadings is a uniformly distributed horizontal load which it's intensity of 10 kN/m^2. The intensity of the uniformly distributed horizontal load was chosen according to the researches [12-13]. The other loading is a triangularly distributed horizontal load. The intensity of this loading was determined as 20 kN/m2 according to equality of the resultants of the horizontal uniformly and triangularly distributed loads.

4. RESULTS AND DISCUSSION

4.1 Shear Wall-Framed System

Horizontal displacement graphs of the shear wall-framed system under uniformly distributed and triangular distributed lateral loads have given in Figure 11 and Figure 12, respectively. Analytical solutions are relatively larger than finite element solutions. The difference between the two solutions has increased from the bottom of the structure to the top.

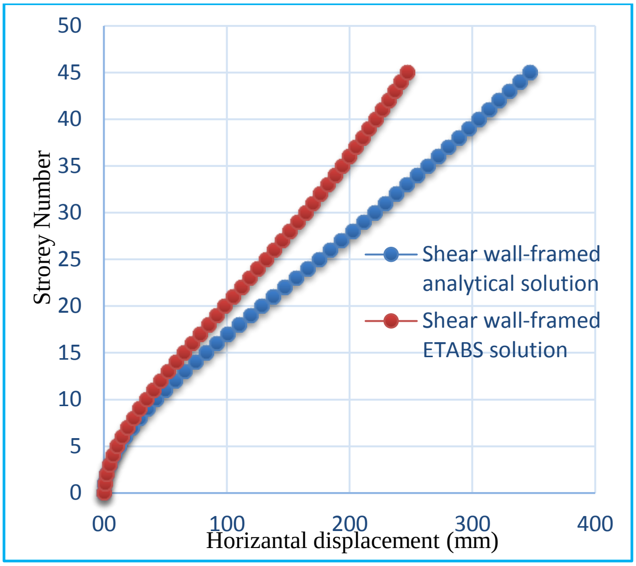


Figure 11. Displacement response of the shear wall-framed system under uniformly distributed load

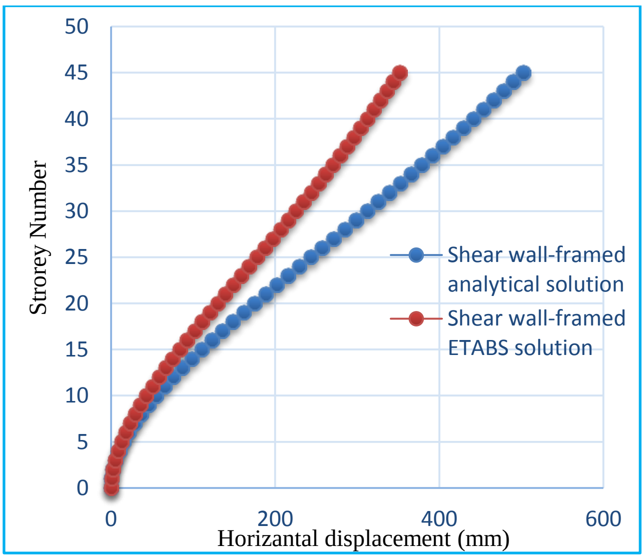


Figure 12. Displacement response of the shear wall-framed system under triangularly distributed load

The peak displacement of the shear wall-framed system under uniformly distributed load for analytical and finite element approaches was found 347 mm and 246,8 mm, respectively. In the case of triangularly distributed load, this displacement for analytical and finite element approaches was 502,7 mm and 351,8 mm, respectively.

When the peak displacements of analytical and finite element approaches are compared with each other, the results of the analytical approach for uniformly distributed and triangular distributed loads has been larger 71% and 70% with according to those of finite element approach, respectively. Depending on these results, it can be said that the analytical approach does not give sufficiently reliable solutions for horizontal displacement of the shear wall-framed system under lateral loads.

4.2 Shear Wall-Framed System with Outriggers

Horizontal displacement graphs of the shear wall-framed system with outriggers under uniformly distributed and triangular distributed lateral loads have shown in Figure 13 and Figure 14, respectively. The displacement profiles obtained from two approaches are quite close to each other along the structure height, as seen in the figures.

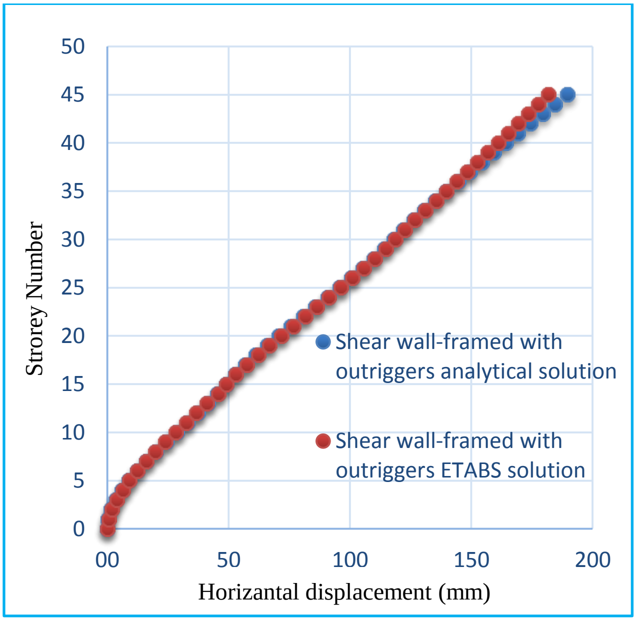


Figure 13. Displacement response of the shear wall-framed system with outriggers under uniformly distributed load

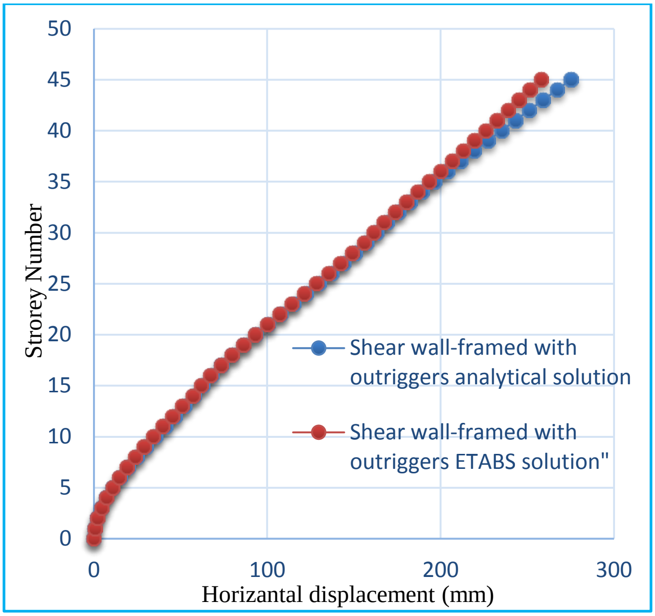


Figure 14. Displacement response of the shear wall-framed system with outriggers under triangularly distributed load

The peak displacement of the structural system under uniformly distributed lateral load for analytical and finite element approaches was found 189,5 mm and 181,7 mm, respectively. In the case of triangularly distributed lateral load, this displacement for analytical and finite element approaches was 275,3 mm and 258 mm, respectively. When the peak displacements of analytical and finite element approaches have compared with each other, the results of the analytical approach for uniformly distributed and triangular distributed lateral loads has been larger 4.3% and 6.7% with according to those of finite element approach, respectively. From these results, it can be said that the analytical approach gives reliable solutions for horizontal displacement of the shear wall-framed system with outriggers under lateral loads.

4.3. Evaluation Of Shear Wall-Framed System with and without Outriggers

In this part, the results obtained in sections 4.1 and 4.2 have evaluated together. Horizontal displacements of the shear wall-framed system and the shear wall-framed system with outriggers have given in Figure 15 and Figure 16 for two different lateral loadings. It has been observed from these figures that the shear wall-framed system with outriggers shows less displacement with respect to the shear wall-framed system under lateral loads. Depending on these results, it can be said that the outrigger system increases the lateral stiffness of the structure under lateral loads.

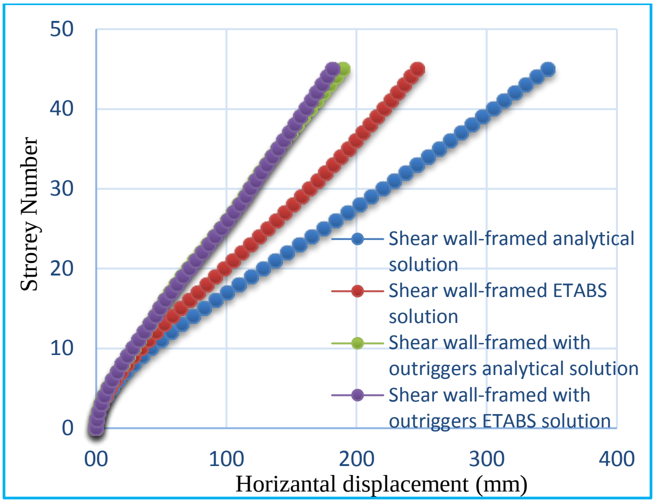


Figure 15. Displacement response of the shear wall-framed system with and without outriggers under uniformly distributed load

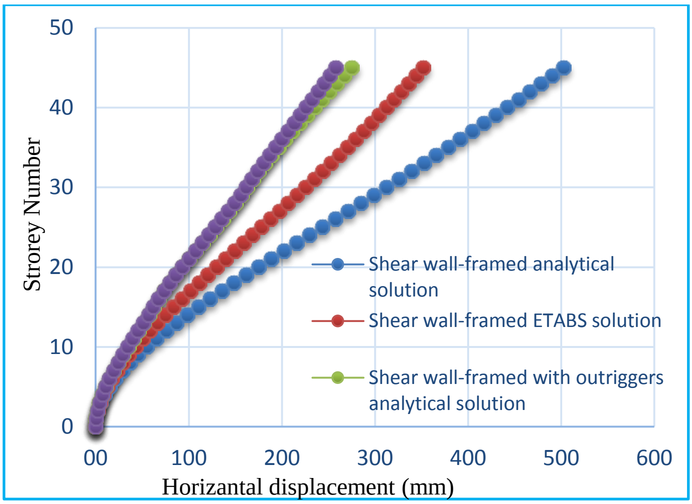


Figure 16. Displacement response of the shear wall-framed system with and without outriggers under triangularly distributed load

Lateral inter-storey drifts of the shear wall-framed system and the shear wall-framed system with outriggers have shown in Figure 17 and Figure 18 under uniformly and triangularly distributed lateral loads. In the shear wall-framed system with outriggers, the inter-storey drifts has been observed to be lower than those of the shear wall framed system in both load cases. For the shear wall-framed system with outriggers, the drift profile obtained from the analytical approach is generally close to ones of the finite element approach, as seen in the figures. This situation shows that the analytical method has given very compatible solutions in the shear wall-framed system with outriggers.

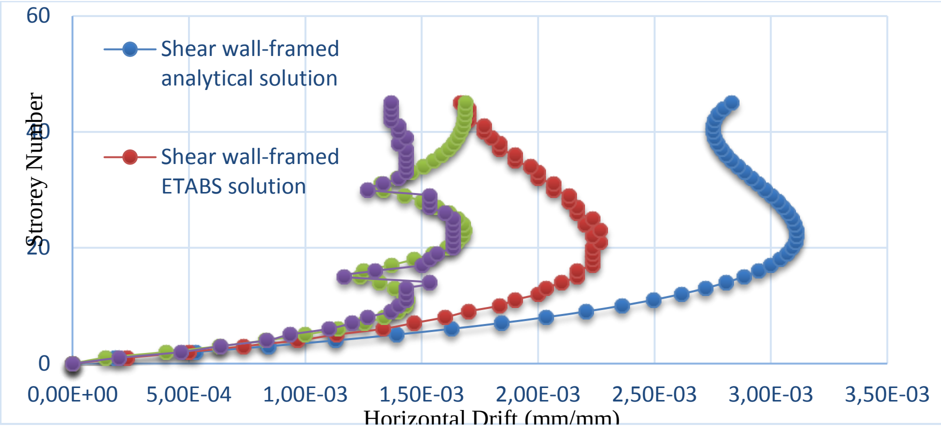


Figure 17. Drift response of the shear wall-framed system with and without outriggers under uniformly distributed load

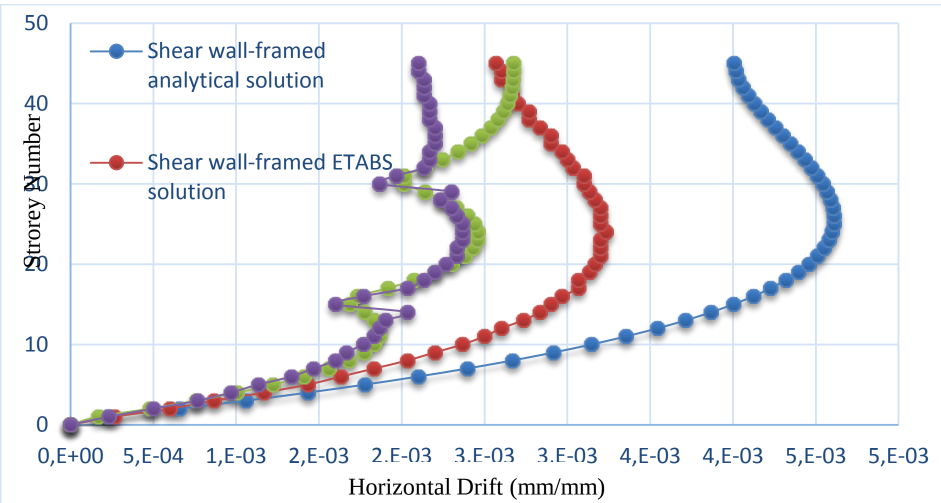


Figure 18. Drift response of the shear wall-framed system with and without outriggers under triangularly distributed load

In addition, the inter-storey drifts of storeys where the outrigger system is located have decreased compared to those of other storeys. According to this result, it can be said that the outrigger system increases the stiffness of the storey where it is located.

Internal forces of the shear wall-framed system with and without outriggers have also been evaluated under uniformly distributed and triangular distributed lateral loads. Similar changes were observed in the internal force solutions for both load cases. Therefore, internal force diagrams are presented and evaluated only for uniformly distributed load case.

It can be seen in Fig. 19 that when the outrigger is added to the shear wall-framed system subjected to uniformly distributed load, the bending moment of the core wall has changed direction at the outrigger level.

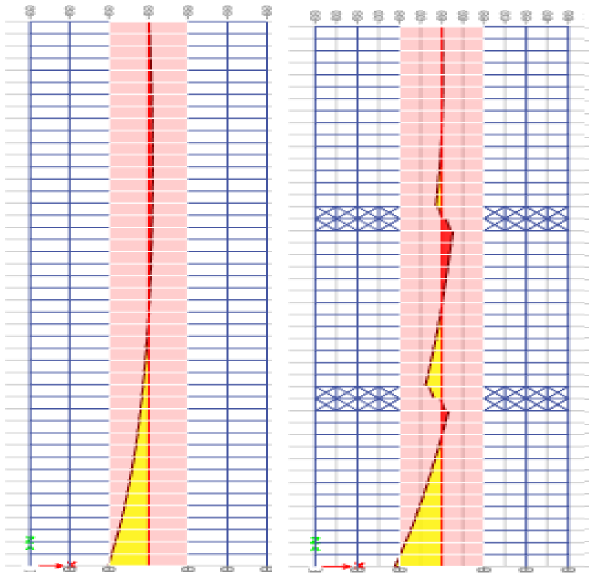


Figure 19. Bending moment diagrams of the core wall for the shear wall-framed system without and with outriggers under uniformly distributed load

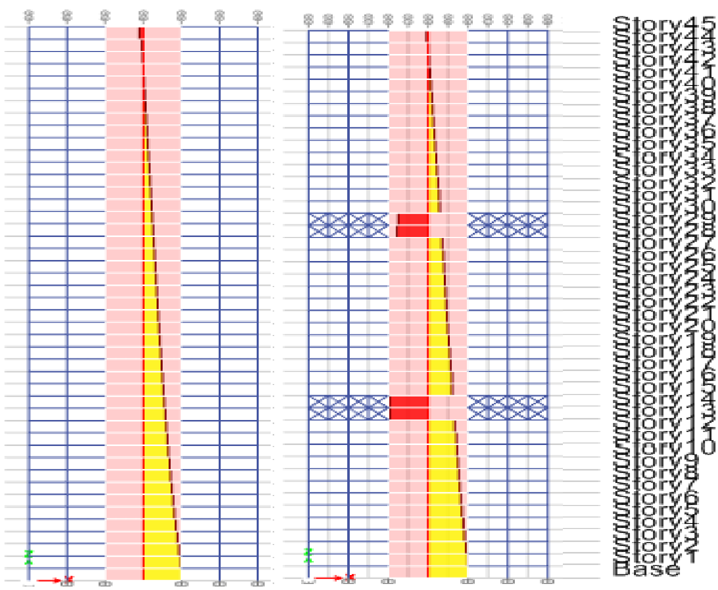


Figure 20. Shear force diagrams of the core wall for the shear wall-framed system without and with outriggers under uniformly distributed load

When the Fig. 20 is examined, it can be seen that the shear force of the core wall has changed direction at the outrigger levels. This situation has formed depending on the work principle of the outrigger system. The change of base shear force of core wall has remained at negligible level when the outriggers are added to the shear wall-framed system. Thanks to the outrigger, the interaction between the shear-wall and the outer columns has increased. As it was seen in the Fig. 21, the axial forces of the columns have considerably changed, especially those of the outer columns at the outrigger levels.

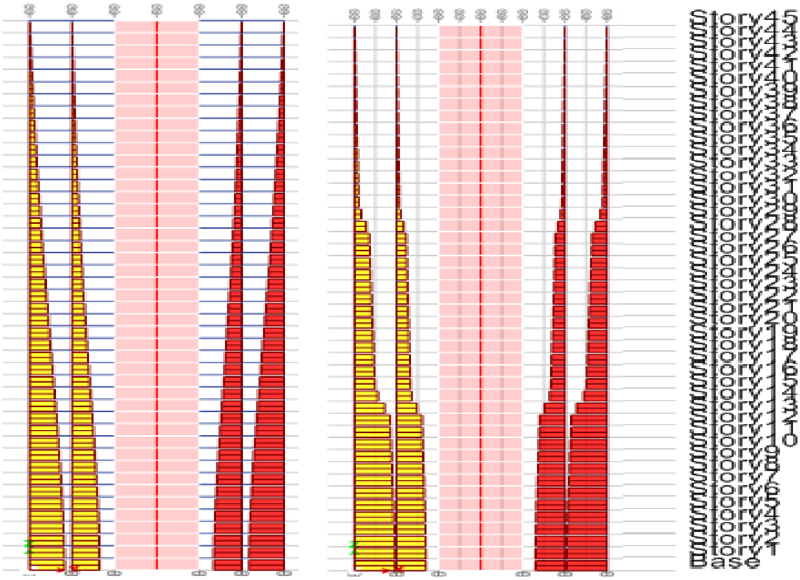


Figure 21. Axial force of the shear wall-framed system without and with outriggers under uniformly distributed load

Also the values of bending moment of the core wall and axial forces of the outer columns for the base level have been given in Tables 3 and 4 for uniformly and triangularly distributed loadings, respectively. When the internal forces of the shear wall-framed system with and without outriggers have compared with each other, the case of outrigger usage has reduced considerably the base bending moment of the core and increased the axial forces of the outer columns. The base bending moment reduction of the core has been 13.4% and 16% for uniformly distributed and triangular distributed lateral loads, respectively. This case will be a positive contribution to core wall design. The increments of base axial forces for the outer columns has been 16.2% and 16.4% for uniformly distributed and triangular distributed lateral loads, respectively.

Table 2. Bending moment of core wall and axial force of outer column values under uniformly distributed load

Axle	**The shear wall-framed system**	**The shear wall-framed system with outriggers**	**Reduction percentage**
	Base Bending Moment (kNm)	Base Bending Moment (kNm)	
4	201488	174426	%13,4
	Base Axial Force of Column (kN)	Base Axial Force of Column (kN)	**Increase percentage**
A-4	4985	5792	%16,2
B-4	3925	4204	%7,1

Table 3. Bending moment of core wall and axial force of outer column values under triangularly distributed load

Axle	The shear wall-framed system	The shear wall-framed system with outriggers	Reduction percentage
	Bending Moment (kNm)	Bending Moment (kNm)	
4	241013	202397	%16
	Axial Force of Column (kN)	Axial Force of Column (kN)	**Increase percentage**
A-4	7000	8145	%16,4
B-4	5472	5875	%7,3

5. CONCLUSIONS

In this study, analytical approaches used to determine linear elastic horizontal displacements of the shear wall-frame systems with and without outriggers subjected to horizontal loading were investigated. The validity of the displacement solutions obtained from these analytical approaches was evaluated by comparing with the results of the finite element approach. For numerical application, two structural models, which are the shear wall-framed system with and without outriggers, have formed. Using analytical and finite element approaches, horizontal displacements of these models have been obtained under uniformly distributed and triangularly distributed lateral loads. Internal forces occurred in the both models under horizontal loads have been also assessed. The internal force solutions were obtained by using ETABS program. In addition, the effectiveness of the outrigger system has been examined. The obtained results can be summarized as follows.

- For the shear wall-framed system, horizontal displacements obtained from analytical approach are relatively larger than those of finite element approach. The difference between the two solutions has increased from the bottom of the structure to the top. It can be said that the analytical approach has not given sufficiently reliable solutions for horizontal displacement of the shear wall-framed system under lateral loads.
- For the shear wall-framed system with outriggers, horizontal displacements have obtained from analytical approach are compatible with those of finite element approach. The displacement profiles obtained from two approaches are quite close to each other along the structure height for two loadings. It can be said that the analytical approach gives reliable solutions for horizontal displacement of the shear wall-framed system with outriggers under lateral loads.
- The shear wall-framed system with outriggers has shown less horizontal displacement than shear wall-framed system under the same lateral loads. Consequently, the outrigger system has increased the lateral stiffness of the structure. In addition, the inter-storey drifts of storeys where the outrigger system is located have decreased compared to those of other storeys. According to this result, the outrigger system increases the lateral stiffness of the storey where it is located.
- When the outrigger is added to the shear wall-framed system subjected to lateral loadings, the bending moment of the core wall has changed direction at the outrigger level and the base bending moment of the core wall has reduced considerably. This case will be a positive contribution to core wall design.
- The shear force of the core wall has changed direction at the outrigger levels. This situation has formed depending on the work principle of the outrigger system. The change of base shear force of core wall has remained at negligible level when the outriggers are added to the shear wall-framed system. Thanks to the outrigger, the interaction between the shear-wall and the

outer columns has increased. The axial forces of the columns have considerably increased, especially those of the outer columns.

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