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Research Article

Effect of outrigger system in high-rise buildings on structural behavior and cost

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Abstract: Due to the advantages it provides, the outrigger system is widely used as a load-bearing system element in high-rise buildings around the world. In this study, the design parameters and structure morphology of high-rise buildings were examined, and it was aimed to investigate the performance and cost effects of load-bearing system preferences by designing two types of high-rise buildings in line with the obtained data. The Sta4Cad program, in which the finite element model is applied, was used to perform integrated static, earthquake, and wind analyses of multi-storey reinforced concrete structures. Because of the finite element analysis of the models, when the construction costs were examined, it was found that the outrigger system has a cost rate of 7.2% lower than the frame system. Considering the design trends, the study will create a focal point for researchers and designers and contribute to significant resource savings.

Keywords: High-rise building, outrigger system, structural design, frame, cost.

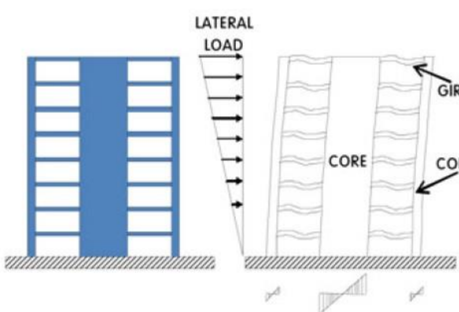
1. Introduction

The rapid development of materials, construction technologies, and structural systems has led to a significant increase in high-rise buildings recently (Arriagada, 2019). The reduction of upper displacements and basic core overturning moments under lateral loads such as earthquake and wind loads has received increasing attention in the structural design of super-high-rise buildings (Zhou et al., 2018). The race to build the tallest building in the sky has been associated mainly with the development of innovative, advanced, and lateral force-resistant systems. Engineers have developed various new structural system schemes as structural systems over the past fifty years (e.g., outrigger system, bundled tube system, diagrid system) (Amoussou et al., 2021; Arunachalam et al., 2020). The construction sector, together with its sub-sectors, undertakes the locomotive role in economic growth (Takva et al., 2023a). With the land costs, limited housing areas, and increasing population, high-rise buildings remain up-to-date and have become more popular today. However, many developed modern cities are located in active earthquake zones (Forcael et al., 2017). The effects of lateral forces such as earthquakes and winds are gaining more and more importance in the structural design of high-rise buildings due to their higher height. In addition to gravitational loads, special methods should be developed to protect the structure against lateral forces in high-rise buildings. The outrigger system is useful for lateral forces in structural design withstanding lateral load (Vellaichamy and Chakkaravarthi, 2022).

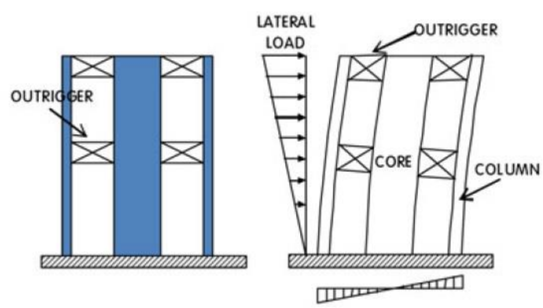
It is stated that the outrigger system, which is widely used to improve structural lateral rigidity and general stability in high-rise buildings, is accepted as one of the most effective load-bearing systems (Wu and Li, 2003). It is important to effectively reduce the seismic losses of high-rise buildings (Lu et al., 2022). Even if the outrigger system is damaged in an earthquake, it does not cause collapse and has little effect on the vertical bearing capacity of the building (Lu et al., 2011). Therefore, this system can be used as a potential energy dissipation component to reduce the vibration and damage of high-rise buildings (Lu et al., 2014; Zhou and Li, 2014; Tan et al., 2015; Jiang et al., 2017). The outrigger system is widely used as a common load-bearing system in most of the world's high-rise buildings such as Burj Khalifa (828 meter) and Shanghai Tower (632 meter) (Günel and Ilgin, 2014; Choi et al., 2017; Chen and Zhang, 2018).

The outrigger system is an existing alternative to reduce the dynamic response of high-rise buildings (Zhou et al., 2019). The most important factor affecting the design of high-rise buildings is their sensitivity to lateral loads. The use of the core-wall system is a very effective and efficient structural system used to reduce the drift caused by lateral loads (wind and earthquake loads). However, as the building height increases, the core does not have sufficient rigidity to keep the wind oscillation within acceptable limits. For such high-rise structures, a structural system known as an external outrigger system can be introduced. Outriggers are deep, rigid beams that connect the central core to most of the outer columns, helping hold the columns in their position, and reducing sway. The limitation caused by this system reduces the lateral slip at the top. With the introduction of the outrigger structural system, the stiffness of the structural system is increased by 20 to 30 percent (Kamath et al., 2012).

Considering that the central core is generally reinforced concrete, it is seen that this section is the only main structural element that resists lateral loading for medium high-rise buildings. This core system is sometimes used along with moment-connected frames or trusses in the core to increase the lateral resistance capacity. When the building is higher than 150 m, the supported core system cannot provide sufficient lateral stiffness for the building to keep wind drift within acceptable limits. For this reason, the outrigger load-bearing system is one of the efficient building systems resistant to lateral loading for high-rise buildings. Figure 1 shows the outrigger structural system combining the core and perimeter columns, allowing the full width of the building and the use of the traditional core system (Park et al., 2010).



(a)



(b)

Figure 1. Structure behavior according to loads: (a) building without outrigger, (b) building with outrigger (Park et al., 2010).

One of the first applications of the outrigger load-bearing system for high-rise buildings occurred at the First Wisconsin Center, a 42-story commercial building completed in 1974 in Milwaukee, United States (Taranath, 2011). Subsequently, extensive studies were conducted to optimize the location of outrigger systems and improve system performance, to investigate the effect on high-rise building load-bearing systems, and to develop new alternatives in this context. Smith and Salim (1981) studied the behavior of high-rise building structures supported by outriggers using a simplified model and taken into account the flexibility, number and location of outriggers. Hoenderkamp and Bakker (2003) proposed a graphical analysis method for the preliminary design of high-rise building structures consisting of outrigger trusses and braced frames subjected to horizontal loading. Lee et al. (2013) analyzed the geometric nonlinear behavior of wall-frame high-rise building structures and found that their proposed analytical model is simple and efficient. Zhou et al. (2016) investigated the theoretical method of inter-story drift-based optimal location of outriggers. Fang et al. (2018) proposed a simple optimal method for optimizing the construction order of the outrigger system, which considers structural stability and overall stiffness. Kamgar and Rahgozar (2017) presented a methodology for determining the optimum position of a flexible outrigger system based on maximizing the strain energy of the outrigger-belt truss system. Tavakoli et al. (2019) investigated the seismic behavior of the outrigger supported building structure by considering the soil-structure interaction based on finding the best location of the outrigger and belt truss system. Balling and Lee (2015) developed a simplified high-rise model based on the dominant degrees of freedom and super elements. It was applied in a spreadsheet to be used in the preliminary design of high-rise structures with outriggers and belt trusses. The simplified high-rise model was used to analyze and optimize the response of the four configurations of the 100-story building to gravity, wind and seismic loading.

As a result of the data obtained from the literature review and the studies examined, cost research and evaluation on outrigger systems in high-rise buildings emerge as an issue that needs to be improved. The difference between this study and existing studies is the cost analysis and evaluation. Buildings with a height of 150 m and above were examined and proportional distributions and design parameters were explained. In this study, two high-rise buildings were designed. Based on the data obtained, it is aimed to investigate the performance and cost effects of the different load-bearing system preferences, which are the least and most applied, on two different 60-storey high-rise buildings, where only the outrigger system is used as a variable.

2. Materials and methods

The behavior of high-rise buildings can be compared to the behavior of a cantilever fixed to the ground under possible lateral loads. In this cantilever, while moment and shear effects occur in the support area under lateral effects, high displacements occur at the free end. To limit these displacements, sufficient lateral stiffness against lateral loads must be provided. To provide this stiffness, instead of increasing the dimensions of the structural elements, increasing the efficiency of the load-bearing system will be the most appropriate solution.

Based on the structural behavior of the system, two different models are discussed in the Sta4Cad environment. Preliminary analyses of the structural elements were performed under the same loading condition. Vibration periods, structure weight findings, maximum displacements, and relative storey drifts are the parameters examined to show the behavior of the models to control lateral loads. A basic flow chart of this study is presented in Figure 2.

The Sta4Cad V14.1 version is a package program that enables 3D analysis and integrated drawings of multi-storey reinforced concrete structures. For the whole structure, the global stiffness matrix is established immediately and displacements are found. Shear deformations and torsional effects in the beam and column elements are considered. The set of equations; In order for the solution to be fast, the endpoint numbers are arranged by the program in a way that solves them in minimum memory with point optimization. Structure + foundation can be solved together, and foundation stiffness matrices are established (Sta4Cad V14.1, 2015).

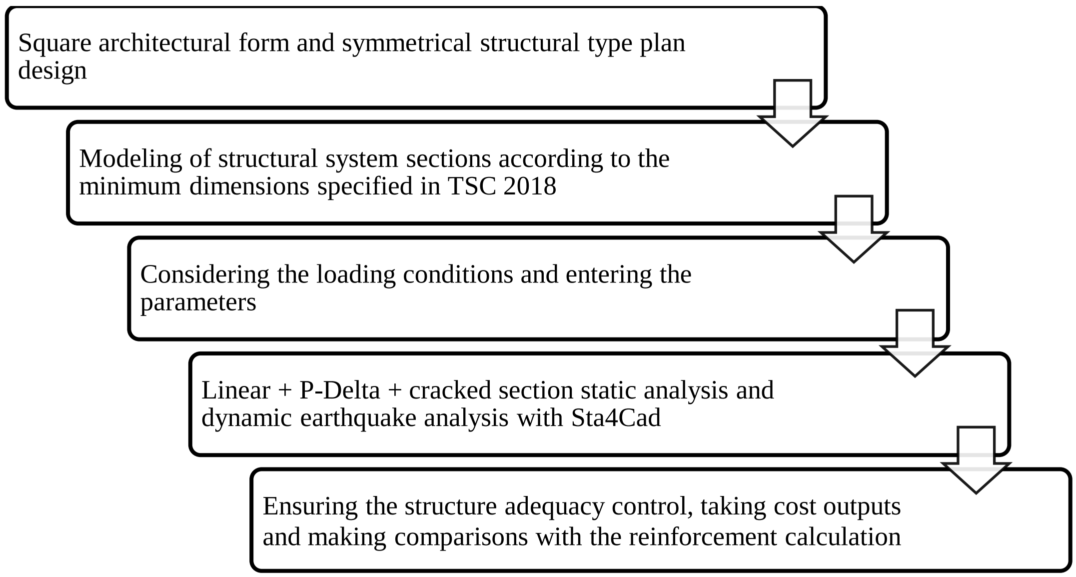
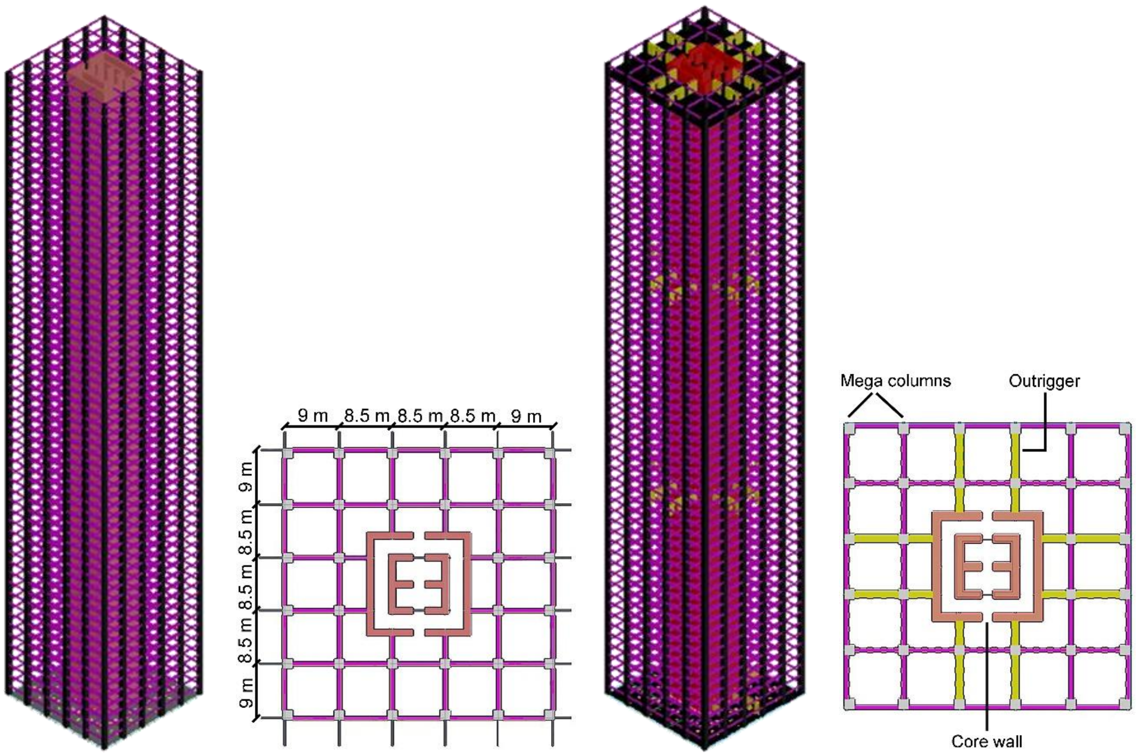


Figure 2. Flow chart for the analysis.

Building geometry plays an important role in the construction industry and architectural design (Takva and İlerisoy, 2023a; Takva and İlerisoy, 2023b; Takva et al., 2023b; Takva et al., 2023c). Designs created with rational decisions in building production processes, which progress in many scopes, from the scale of a single building to the formation of urban textures, are among the basic assumptions of efficient and optimum production practice. In this direction, within the scope of the study, efficiency output and cost analysis in buildings, where many parameters play an important role in terms of architectural design, such as high-rise buildings, are discussed. In this context, two types of models, which are the focus of the analysis of the outrigger system, were designed and the results were compared. Figure 3(a) shows a model with a shear wall and mega columns without the outrigger system. Figure 3(b) shows a simplified model of a high-rise building using the outrigger system. The model shows a central shear wall, mega columns, and an outrigger system element extending to the outer columns. Columns and shear walls with the outrigger system will resist the rotational effect against horizontal forces and lateral deformation and bending moments will decrease. The criteria considered in the architectural formation and structural design of the type models are listed below.

- Since the square form is used a lot in existing structures and the external support shear systems are intended to be the only variable in the study, the plan geometry of the structure was considered to be square.
- The prismatic form was chosen since it will reduce the variables as it continues on the same floors as the form.
- The design was developed with a central core plan scheme.
- The ratio of the core area to the total floor area was set as approximately 14.3%.
- In the models to be applied, the slenderness ratio was taken as an average value of 5.5.
- A symmetrical and regular axis system was defined in the plan.
- Optimum conditions are obtained by modeling the load-bearing elements in the minimum cross-section dimensions determined by the standards. In the design process, the number of sections was increased by making interventions when there was an insufficiency in the load-bearing elements.
- All the structural elements were made of reinforced concrete. In the material selection, concrete class C50 (fck= 50 MPa) and reinforcement steel B500C (fyk= 500 MPa) were used.
- The ground-superstructure interaction of the buildings was modeled separately and their foundation solutions were excluded.
- In this study, which is planned as a single variable, the other design components were kept the same in order for the analyses to be efficient.



(a) (b)

Figure 3. Type models were designed within the scope of the analysis: (a) Model 1 (frame) view and layout, (b) Model 2 (frame with outrigger) view and layout.

Since the purpose of the comparison is to show the difference of the outrigger systems in terms of both structural performance and cost comparison, only outrigger system elements were added to the same plan. In the analysis method, type models were linear elastic and only axial force acted on the columns. The outrigger system was rigidly connected to the core. The core was firmly supported on the foundation. The characteristics of the type high-rise building are given in Table 1.

Table 1. Specification of building.

Number of stories	Story height	Building height	Dimension (length × width)
60	4 meter	240 meter	43.5 meter × 43.5 meter

The working logic of outrigger systems is to create rigid floors at some points along the height of a building. In this context, the outrigger system was located on the 20th, 40th, and 60th floors to examine the lateral stability of the building. Figure 4 shows the view of the designed building and the details of the floors with outriggers.

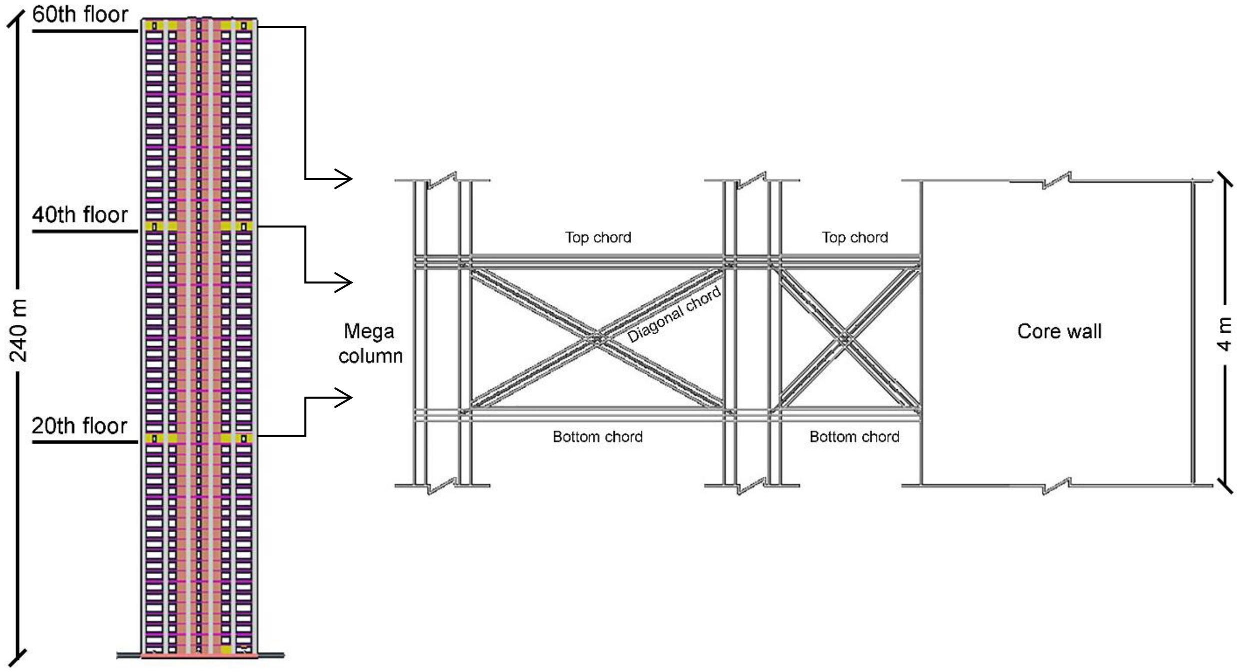


Figure 4. Floors with outriggers and details.

In the models made, the diaphragm is rigid in the plane. Therefore, the displacements of the frame and shear wall are the same for a given floor level. The same earthquake zone is considered, structural models are subjected to the same loading conditions. The loading criteria are given in Table 2.

Table 2. Load values accepted as constant in models (TS 498, 1997; TS 500, 2000; TSC, 2018).

Dead load	Calculated using Sta4Cad
Live load	350 kg/m^2
Coating load	154 kg/m^2
Snow load	200 kg/m^2
Wind load	80 kg/m^2 110 kg/m^2
Ground class	Medium-fine sand
Ground safety tension	25 t/m^2
Wind speed	46 m/s

As the building height increased, changes were made in the cross-sectional dimensions based on the economic efficiency of the load-bearing system elements. All structural elements were designed in the most economical range and a cost comparison was created by considering optimum solutions. Table 3 lists the changes in the structural member dimensions.

Table 3. Cross-section changes in structural elements.

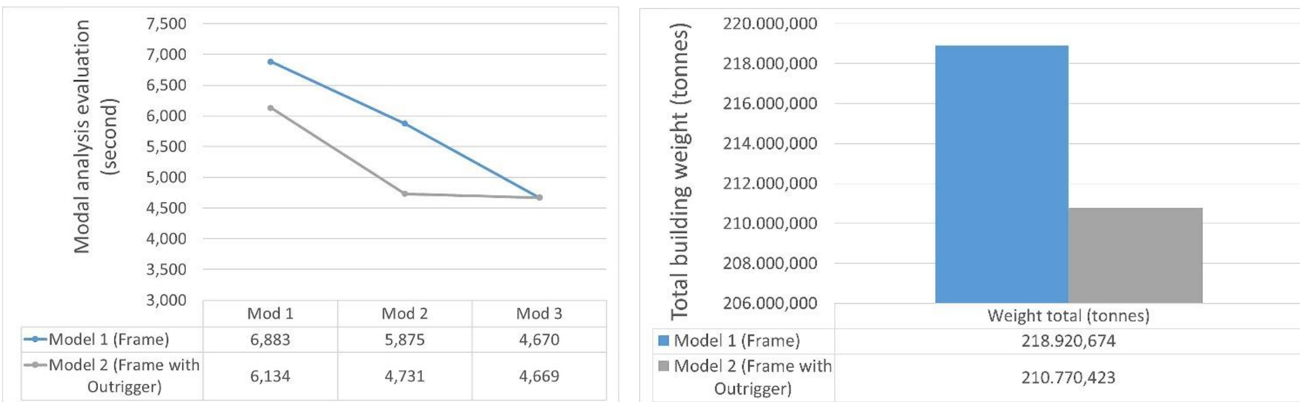
Structural member	Type 1	Type 2
Column	200 cm × 200 cm-level 1st- 20th 185 cm × 185 cm-level 21th- 40th 150 cm × 150 cm-level 41th- 60th	200 cm × 200 cm-level 1st- 20th 175 cm × 175 cm-level 21th- 40th 140 cm × 140 cm-level 41th- 60th
Outer beam	65 cm × 80 cm (overall)	50 cm × 80 cm (overall)
Center beam	75 cm × 80 cm (overall)	Hinged Joint
Shear wall	100 cm thick (overall)	100 cm thick (overall)

3. Findings and results

Because of the finite element analysis of the two high-rise building models, structural performance and cost comparisons were made in line with the summarized parameters.

3.1. Structural behavior assessment

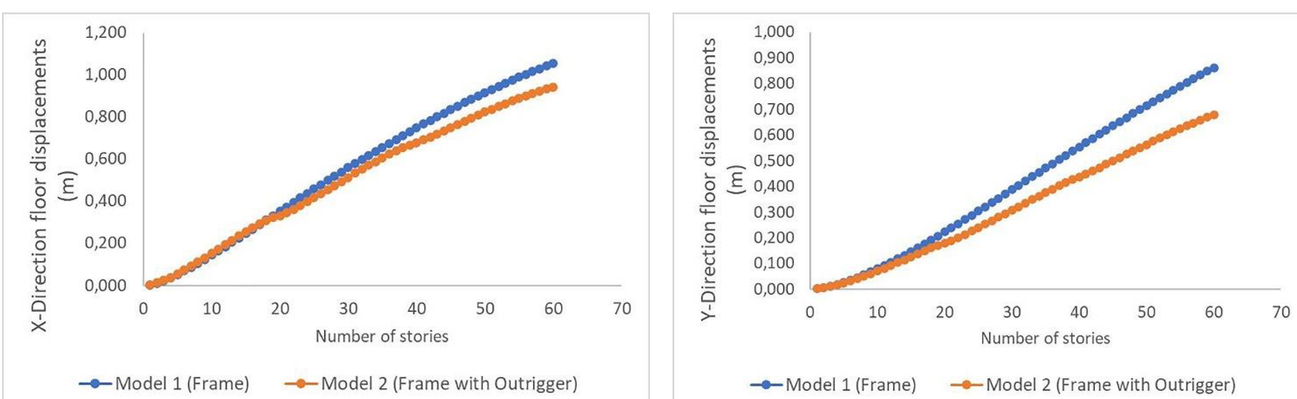
When the periods expressing one full oscillation period of the structure under the horizontal load are examined, the outrigger system period values are lower than those of the frame system. The Mod-1 value of Model 1 is 6.883 seconds, while the Mod-1 value of Model 2 is 6.134 seconds, and it is seen that it decreases by 10.8% compared to the Mod-1 value (Figure 5). The Mod-2 value of Model 2 was similarly reduced by 19.5% compared to the Mod-2 value of Model 1. It was observed that the total building weight of Model 2 decreased by 3.8% despite the use of additional structural elements on 3 floors.



(a) (b)

Figure 5. Analysis data: (a) free vibration periods, (b) structure weight data.

The displacement demands obtained by the linear analysis are an indicator of the damage that may occur in the building due to the earthquake. In the X direction, the maximum displacement for Model 1 is 1,045 meters, while for Model 2 this value is 0.94 meters, with displacements reduced by 11.9% (Figure 6). The maximum displacement in the Y direction is 0.87 meters for Model 1 and 0.68 meters for Model 2, with a reduction of 27.9%.

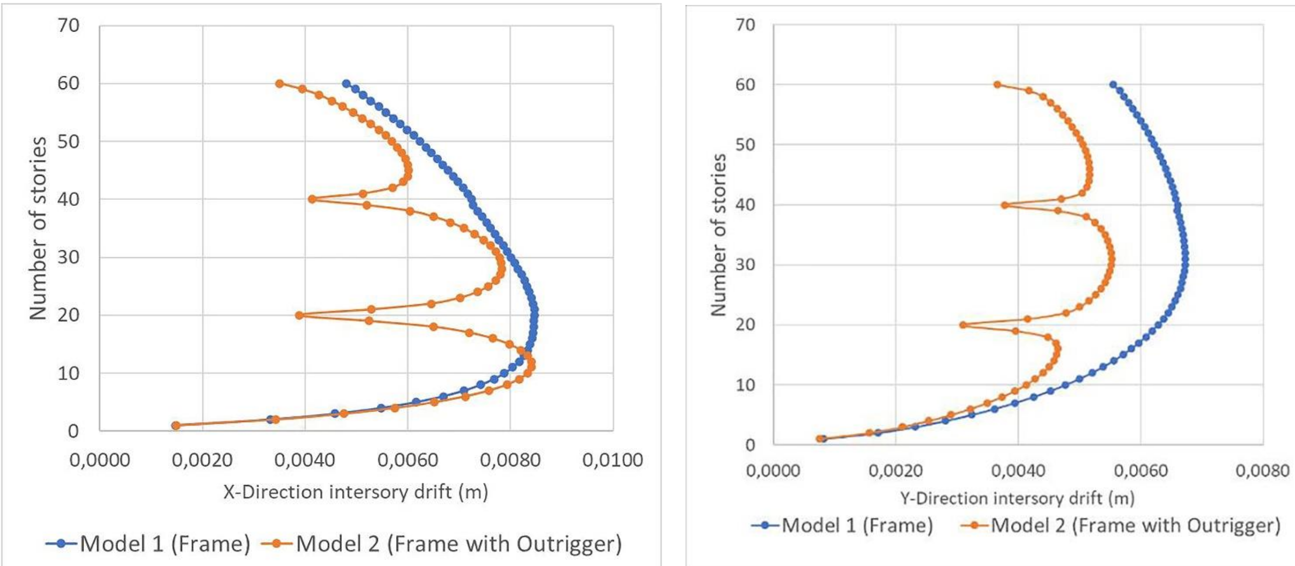


(a) (b)

Figure 6. Displacement data: (a) X direction, (b) Y direction.

The drift amount of reinforced concrete structures is important in terms of earthquake safety. This is mostly a feature that needs to be controlled in the frame system and is solved by the use of shear elements. In the X direction, the maximum relative drift amount for Model 1 is 0.00393 meters, while for Model 2 it is 0.00439 meters, and a decrease of 11.9% was found in

Model 1 compared to Model 2 (Figure 7). In the Y direction, the maximum relative drift amount for Model 1 is 0.00282 meters, while for Model 2 it is 0.00359 meters, and a 27.3% reduction was found in Model 1 compared to Model 2.



(a) (b)

Figure 7. Relative drift amounts: (a) X direction, (b) Y direction.

3.2. Cost assessment

Looking at total rough construction costs, Model 2 was found to have a 7.2% lower cost ratio (Figure 8). This situation is also understood from the positive building behavior.

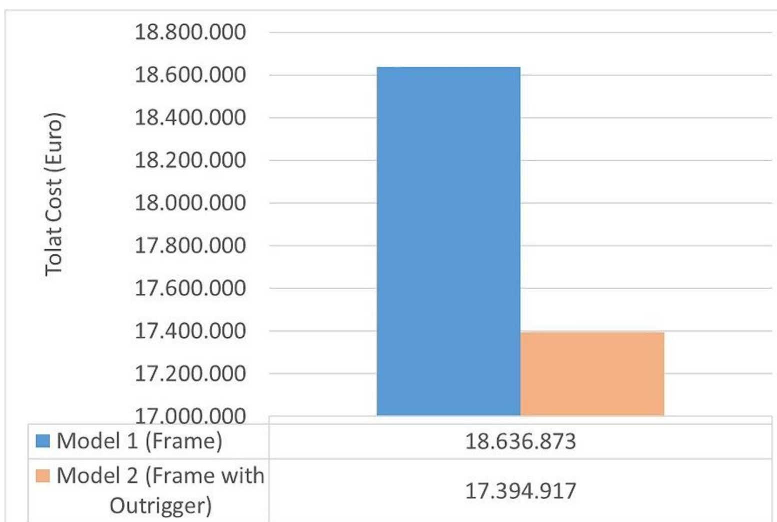


Figure 8. Total costs of the models.

When the items that cause changes in rough costs are examined, it is revealed that the biggest difference is in the use of reinforcement, and Model 1 needs more reinforcement at a rate of 9.7% (Figure 9). Compared to Model 1, it is seen that 4.4% less concrete is used due to the smaller cross-sections.

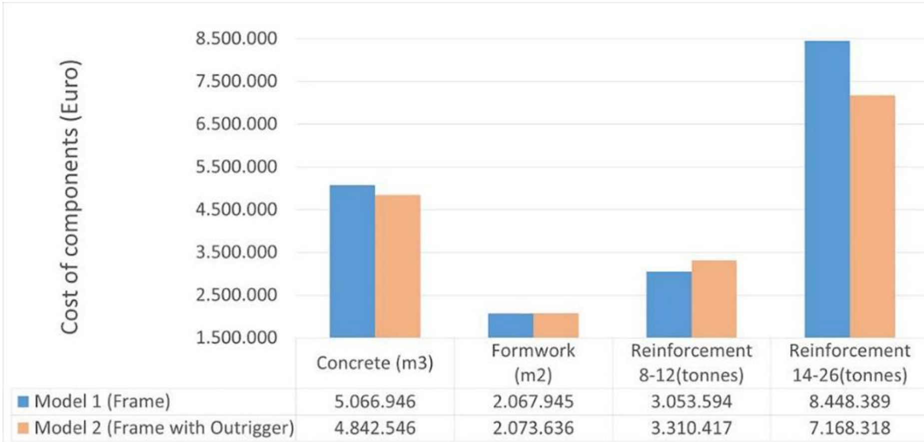


Figure 9. Making comparisons for cost items.

4. Conclusions and comments

In the field of structural engineering, it has been understood because of the literature review that the effects on the cost are not considered, while many studies have been carried out on the performance analysis of the load-bearing systems used in high-rise buildings. Because the finite element analysis was carried out with the aim of revealing the performance and cost relationship of the structural system, it was observed that the rigidity of the structure increased in the model using the outrigger system. Accordingly, it has been determined that the displacements, relative storey drifts decrease, and there is a remarkable decrease in cost with the improvement of the system behaviors. Because of the analysis, the structural behavior findings of the models were listed as items.

1. Outrigger systems increase lateral rigidity by limiting the displacements of the structure, especially under lateral loads, which in the design philosophy, increases the frequency of the structure and decreases the natural vibration period.
2. With the increase in lateral rigidity and decrease in the vibration period, the capacities of the bearing elements gain importance, and the cross-sections are less strained with the changing system properties, however, the smaller the sections, the weight of the structure and thus the loads transferred to the foundation tend to decrease. Although additional building elements were used on 3 floors for creating the outrigger system, the decrease in the total weight of the building is a clear indicator of the mentioned effect.
3. In addition to vertical loads, the effect of horizontal loads such as earthquakes and wind causes large displacements. For this reason, second-order effects are formed. It can be said that the rigidity increases with the use of the outrigger system and the maximum displacements decrease.

4. As a result of the comparison of these two models with the same architectural design, rising in the same location, the only difference between them, is the outrigger system added to 3 installation floors as a load-bearing system component, in terms of rough construction cost;

5. Along with the advantage that the outrigger system brings to the structural design of the load-bearing system, the reduction of cross-sections also has a positive effect on construction costs.
6. The cost outputs revealed with the calculations will contribute to significant resource savings, considering the design trends.

It is thought that the result of the study will shed light on the load-bearing system decisions by helping designers and practitioners in reducing costs, especially in the preliminary design phase. Knowing the cost effect of the load-bearing system change and acting considering this information will be beneficial.

Nomenclature

cm = Centimeter
fck = The characteristic strength of concrete
fyk = The characteristic yield strength
kg = Kilogram
m = Meter
m^2 = Square meter
s = Second
t = Tonne

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