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# The structural behavior of lightweight concrete buildings under seismic effects

Yasser A.S Gamal*[1,2] and Mostafa Abd Elrazek**[1]

[1]*Department of Civil Engineering, High Institute of Engineering Technology, EL-MINA, Egypt*
[2]*Department of Civil Engineering, Faculty of Engineering, NUB University, Egypt*

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**Abstract.** The building sector has seen a huge increase in the use of lightweight concrete recently, which might result in saving in both cost and time. As a result, the study has been done on various types of concrete, including lightweight (LC), heavyweight (HC), and ordinary concrete (OC), to understand how they react to earthquake loads. The comparisons between their responses have also been taken into account in order to acquire the optimal reaction for various materials in building work. The findings demonstrate that LWC building models are more earthquake-resistant than the other varieties due to the reduction in building weight which can be a curial factor in the resistance of earthquake forces. Another crucial factor that was taken into study is the combination of various types of concrete [HC, LC, and OC] in the structural components. On the other hand, the bending moments and shear forces of LC had reduced to 17% and 19%, respectively, when compared to OC. Otherwise, the bending moment and shear force demand responses in the HC model reach their maximum values by more than 34% compared to the reference model OC. In addition, the results show that the LCC-OCR (light concrete column and ordinary concrete roof) and OCC-LCR (ordinary concrete for the column and light concrete for the roof) models' responses have fewer values than the other types.

**Keywords:** dense concrete; heavyweight concrete; lightweight concrete; response spectrum analysis; seismic load

## 1. Introduction

Since ancient times, the lightweight aggregate (LWA) was used to create the LC. And the Romans also built the Pantheon by using pumice as a lightweight aggregate (LWA). In addition, the LWA has been working in the building sector since 1928. And, one well-known material that has been used in place of ordinary concrete in the construction industry is a lightweight aggregate. In addition, the LWA has built numerous multistory structures, massive buildings, and offshore platforms (Mindess *et al*. 2003). Therefore, they have been widely used in recent decades all across the world, notably in the UK, Sweden, and the USA.

The LC is used to build numerous buildings and bridges in the USA. Also, the LC was used in

*Corresponding author, Lecturer, E-mail: Yasser.gamal2310@mhiet.edu.eg
**Corresponding author, Ph.D., E-mail: yasser.abdelshafy@nub.edu.eg


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construction of the American Bridge, Missouri Building, Kingston Bridge, Dubai International Airport, and Dubai Cooper River Bridge.

Since a very long time ago, there have been numerous attempts to build structures with different properties using a variety of concrete types instead of ordinary concrete to gain significant advantages in the construction industry. Due to their mass, the concrete constructions are susceptible to earthquakes. Consequently, the primary goal of lightweight concrete (LC) is to lower the dead load of a concrete structure, allowing structural designers to minimize the size of structural components such as beams, columns, and footings. And, in order to obtain the optimal behavior, it is necessary to analyze how it responds to seismic effects.

The Heart of America Bridge in Missouri, the Dubai Cooper River Bridge in South Carolina, and the Terminal 3 Concourse at Dubai International Airport were just a few examples of the numerous structures and bridges built using lightweight concrete (LC).

Additionally, the designers aim to use LWC materials to lower building costs. And, it is also possible to accomplish this by reducing the weight of the materials used to construct structural components. Therefore, the LC was used to reduce the mass of the floor slab which can lead to reduce the expensive cost than OWC and HC construction.

Although there has been a lot of research examining various LC types with a range of attributes (Kilic *et al.* 2003, American Concrete and Committee 1977, Kan and Demirboga 2009, Vandanapu and Krishnamurthy 2018, Wang *et al.* 2020, Nadh *et al.* 2021, Poursadrollah *et al.* 2023, Mohamed *et al.* 2023, Ali *et al.* 2023, Nasimi *et al.* 2023), less study has been done on the investigation of how these LC types affect seismic behavior. The behavior of the LC during seismic action has also received little attention in research. So, it would be very intriguing to investigate the LC's seismic performance. And, in-depth research is generally required to compare the seismic performance of the LC building to that of other types (OC and HC). On the other hand, the study also takes into account how they (LC, HC, and OC) interact with one another in the structural aspects.

## 2. The characteristic of lightweight concrete

There are many different ways to produce lightweight concrete, from pumice aggregate to man-made sintered aggregate (Fly ash), and each one has its advantages that can help increase the volume of the mixture, reduce dead weight, and also have low density and thermal conductivity (Mindess *et al.* 2003). The mechanism of its creation can be prepared either by different methods such as injecting air into its composition, omitting the finer sizes of the aggregate, or even replacing them with a hollow, cellular, or porous aggregate.

Also, the components of the LC are defined by ACI Committee 213 (Committee and American Concrete 2014). It can be produced with LWA or by a mixture of ordinary fine aggregates and lightweight fine aggregates. ACI Committee 213 also uses the LC to categorize materials according to their densities, which range from 320 to 1920 kg/m$^3$ (Committee and American Concrete 2014).

As a result of economic and technological advancement, there is a tendency to use low-cost materials that are lightweight in the construction of structural elements. The load on the column has been reduced by lowering the dead load of the roof slab, which is caused by self-weight and flooring loads. Therefore, employing LC in the slab can help reduce the load on columns and, subsequently, the structural elements. Overall, the LC can lower building costs compared to other types like (OC and DC), and hence, it is considered crucial for developing the lowest-cost, fastest-growing construction projects.

Although there is a lot of research studying different types of lightweight concrete with a variety of characteristics, there is a shortage of research on the effects of seismic behavior (Kilic *et al.* 2003, American Concrete and Committee 1977, Kan and Demirboga 2009, Majhi *et al.* 2021, Rustamov *et al.* 2021, Yang *et al.* 2019, Yang *et al.* 2021, Pakizeh *et al.* 2023, Aflakisamani *et al.* 2023, Di Nunzio, *et al.* 2023). So, extensive research is essentially needed to study the seismic performance of lightweight concrete buildings and compare it with other types (ordinary concrete and heavyweight concrete).

Adel A. Al-Azzawi revealed that lowering the shear span to effective depth ratio from 2.9 to 1.9 for lightweight aggregate solid slabs resulted in a 29.06 percent increase in ultimate load and a 29.06 percent increase in ultimate deflection value (17.79 percent) (Al-Azzawi and Al-Aziz 2018). In addition, E G Badogiannis revealed that beam behavior is largely independent of the design method used, with the use of lightweight aggregate concrete due to the improving post-peak structural performance marginally (Badogiannis and Kotsovos 2014).

In contrast, there are fourteen classes of lightweight concrete, ranging from LC8/9 to LC80/88. Lightweight concrete exhibits homogeneity in its constituent parts as a result of the similar elastic modulus of the light aggregate and the concrete matrix (Szydlowki and Mieszcak 2017). Furthermore, LC behaves differently under loading, resulting in a different type of failure than conventional concrete.

According to the strength range, LC can be divided into three main categories: low-density concrete with a strength between 0.7 and 2.0 MPa, moderate strength concrete with a strength between 7 and 14 MPa, and structure concrete with a strength between 17 and 63 MPa. Additionally, this concrete has densities ranging from 300 to 800 kilograms per square meter, 800 to 1350 kilograms per square meter, and 1350 to 1920 kilograms per square meter, respectively (Torgal *et al.* 2016). According to BS EN 206-1 (British Standards 2020), lightweight aggregates can be used to achieve an oven-dry density of the LC that is not less than 800 kg/m$^3$ and not more than 2000 kg/m$^3$, which can be created by replacing dense natural aggregates by lightweight aggregates.

Several researchers have confirmed that LC has increased shrinkage due to its low modulus of elasticity, which rises by up to 50% (Kahn and Lopez 2005, Domagala 2020, Tian *et al.* 2015). Different factors (such as time dependence, outdoor temperature, and humidity levels) can help lower shrinking rates. Additionally, all varieties of aggregate can be identified by their shrinkage rate. Furthermore, the aggregate sintered at a high temperature has less shrinkage compared to other varieties. Otherwise, the LC has a higher rate of creep than the OC. However, the rate of creep is higher in the LC than in ordinary concrete, and it is also similar for higher classes and dense concrete (Domagala 2020, Tian *et al.* 2015). Furthermore, low density of lightweight concrete typically results in less desirable mechanical properties than dense concrete.

Compared to ordinary concrete, which develops the first crack when tensile stress reaches 85–90% of its strength, lightweight aggregate concrete has three stages of crack development. Furthermore, the LC can be used in elements that have uncracked conditions under high-tension loads. And, the comparison between ordinary concrete and the LC's disintegration mechanism can be seen in Fig. 1. Also, in the uniaxial compression test, the stress-strain relationship has produced a rectilinear pattern (Szydlowki and Mieszcak 2017).

LC has a different cracking pattern, location, and destruction mechanism than ordinary concrete. Typically, the destruction in DC happens in the contact zone between the cement and the

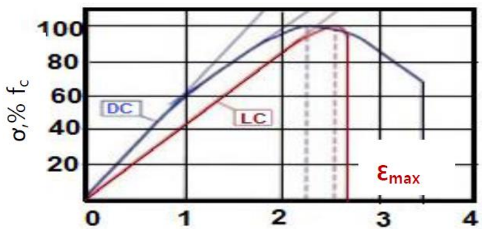
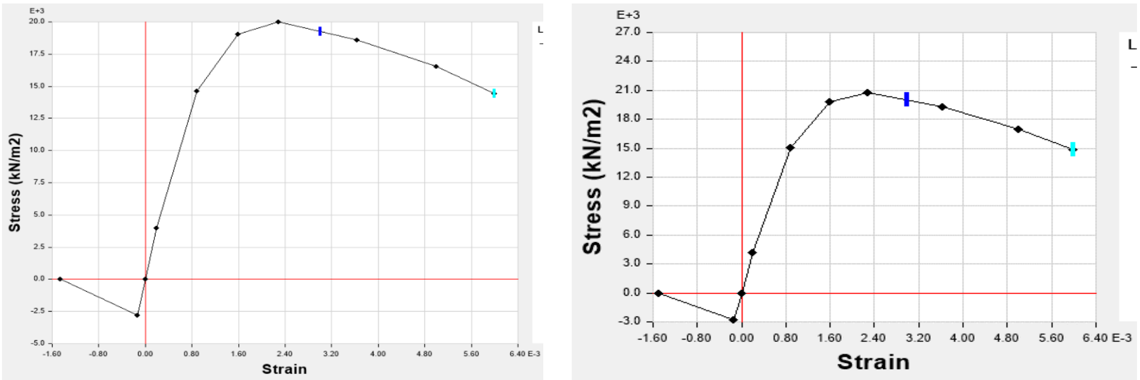



Fig. 1 Stress-strain dependence in compression test for DC and LC with the same strength (Szydlowki and Mieszcak 2017)




Lightweight concrete Heavy concrete

Fig. 2 Stress-strain curve for (LC, OC, and HC)

aggregate, which is regarded as their weak point while also being most loaded due to the stress concentration caused by the significant differences in elastic modulus of the matrix and aggregates. On the other hand, the destruction sites of lightweight concrete appear in the cement matrix as a result of an increase in the contact zone's high strength and higher elastic modulus. Additionally, two of lightweight aggregate concrete's main drawbacks are its reduced rigidity and the rapid spread of cracks (Szydlowki and Mieszcak 2017).

In contrast, the building's construction heavily relied on the use of dense concrete, which played a crucial role in creating its robust structure. This type of concrete, known as heavyweight concrete, is available in 15 different compositions that vary based on the concentration of barytes. It boasts remarkable physical and mechanical properties, with a specific gravity ranging from 2600 $Kg/m^3$ to 3000 $Kg/m^3$.

Incorporating material nonlinearity and inelastic behavior through a nonlinear force-deformation relation could provide insights into the limit-state behavior and ductility. As shown in Fig. 2, the LC, and HC constitutive models were utilized in the study. To model the concrete, a bi-linear model (LC, OC, and HC) was employed in the finite element (FE) model, which can also account for the strain-hardening effect.

## 3. Objectives of research

The focus of this study is to investigate the seismic response demand of LC by comparing it

Table 1 The characteristic of the LC, HC, and OC

| Ser | Type of RC | Self-weight Kg/m$^3$ | Modulus of elasticity kg/cm$^2$ | $f_{cu}$ kg/cm$^2$ |
|---|---|---|---|---|
| LC (Deifalla 2020) | LC | 1700 | 1.2*10$^6$ | 250 |
| HC (Topçu 2003) | HC | 3203 | 4.3x10$^6$ | 260 |
| OC | OC | 2200 | 2.1x10$^6$ | 250 |

with other types of concrete, namely HC and OC. The study also considers the interaction between these concrete types in the structural elements. The outcomes of the study include lateral displacement, story drift, story shear force, and overturning moment.

Table 1 presents the models that were employed in the study, with Model 1 being LC, Model 2 being OC, and Model 3 being HC.

## 4. Response spectrum method (RES)

In the past, calculating the full response of a structure using the basic mode superposition method as a linear elastic analysis was a challenging task. This method had certain drawbacks because it required generating a large amount of data and computational effort to obtain a complete analysis of joint displacement and forces over time. However, this issue can now be resolved by using the response spectrum method. This method relies on the maximum values for each mode to determine how the structure will behave when subjected to seismic loading, thus making the analysis more efficient and less computationally intensive.

The concept of the earthquake response spectrum, developed by M.A. Biot in 1932 as a way to predict the response of the ground motion and its consequences on the structures, was effectively propagated and accepted by (Housner 1947).

In the last century, the response spectrum has offered a traditional method for obtaining the peak response of every possible linear SDF system, which is thought to be the main idea in earthquake engineering. It offers a practical way to summarize the peak response of every possible linear SDF system, it can assist in providing structural dynamics knowledge for design, and it also incorporates the response spectrum concept into design codes.

Eq. (3) can be used to obtain the seismic equation of motion for three-dimensional seismic motion.

$$\ddot{y}\,(t)_n + 2\,\zeta_n\, w_n \dot{y}\,(t)_n + w_n^2\, y\,(t)_n = p_{nx}\ddot{u}\,(t)_{gx} + p_{ny}\ddot{u}\,(t)_{gy} + p_{nz}\,\ddot{u}\,(t)_{gz} \tag{3}$$

where *pni*=- *ϕnT Mi* the three Mode Participation Factors are defined by in which $i$ is equal to $x$, $y$ or $z$.

The first step is to determine the highest peak forces and displacements for each direction. The second step is to identify the responses for three orthogonal directions, which is necessary to get the maximum response from the three simultaneous components of earthquake motion.

The peak response of the response spectrum equation can get from the following Eq. (4)

$$\begin{aligned} u_o\,(T_n\,,\zeta) &= \max_t\,|u(t,T_n,\zeta)| \\ \dot{u}\,(T_n\,,\zeta) &= \max_t\,|\dot{u}(t,T_n,\zeta)| \\ \ddot{u}\,(T_n\,,\zeta) &= \max_t\,|\ddot{u}\,(t,T_n,\zeta)| \end{aligned} \tag{4}$$

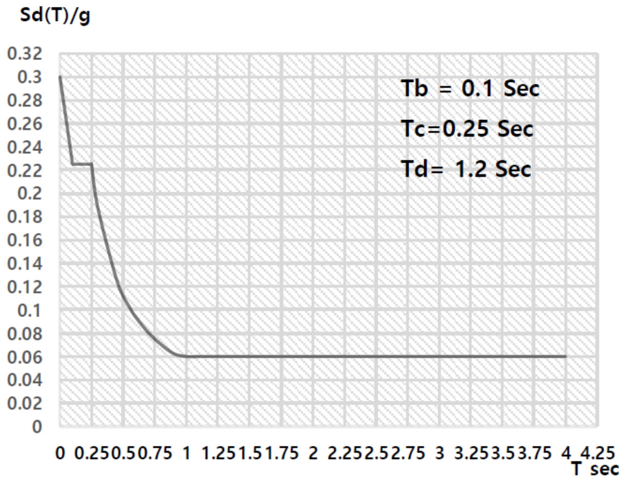


Fig. 3 Response spectrum curve (RES)

The deformation response spectrum is a plot of $u_o$ against Tn for fixed $\zeta$. A similar plot for $\dot{u}_o$ is the relative velocity response spectrum, and $\ddot{u}$ to is the acceleration response spectrum.

The maximum seismic response for each natural mode can be calculated using response-spectrum analysis (RSA), a linear-dynamic statistical analysis method. It can also measure pseudo-spectral acceleration, velocity, or displacement as a function of the structural period for a given time history and level of damping.

Indeed, all types of structures where the modal involvement doesn’t go below 90% of the structure’s mass in each orthogonal direction can use the response spectrum notion. The square root of the sum of squares (SSRS) is utilized as a directional combination method for the response spectrum approach, while complete quadratic combination (CQC) is used as a modal combination method. Finite element modeling states that the prerequisite for the number of vibration modes is to obtain more than 90% mass involvement.

The seismic zone is decided to be Zone 5-B, and its features are adopted using the seismic regions of Egypt. In addition, the spectrum shape is type 2. Additionally, the importance factor is 1, and the seismic region factor is 0.3 g. The type of soil class is also “*C*”, which indicates dense soil. The value of *R*, which is equal to five, indicates that the shear wall construction completely handles the resistance of the whole base shear. According to ((ECP) 2008), “Dead Load (DL)+ 0.25 LL+FL (flooring load)” constitute the entire seismic mass. And, *Tb*=0.1 sec, *Tc*=0.25 sec, and *Td*=1.2 sec. The RES curve for the investigated cases is shown in Fig. 3.

The study is conducted on a 20-story building with a total height of 60 meters, as illustrated in Fig. 3. The typical floor height is 3 meters, and the structure mainly consists of a flat slab with external, interior, and shear wall systems. For modeling purposes, it is assumed that all column and core section sizes remain constant, irrespective of the building’s height.

According to ECP-201, all elements have been seismically designed with the following parameters: importance factor=1, earthquake zone (5B) based on the Egyptian zoning system, peak ground acceleration PGA=0.3 g.

Although most of the structure has been built on basement levels, the modeling of the building has disregarded the basement floor and viewed it as an ordinary floor. Additionally, as shown in Fig. 4, the building’s configuration and height are the same, and the plot’s dimensions are

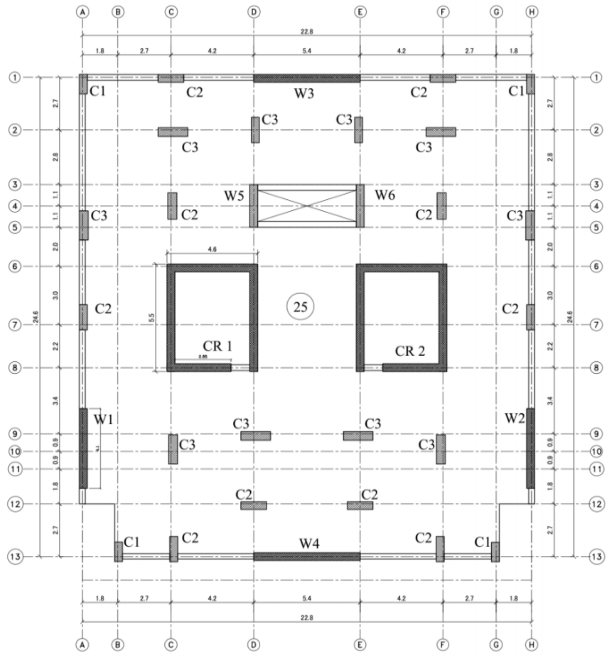



Fig. 4 The configuration plan

Table 2 The dimension of cross sections for beams and columns in 20-story building

| Element | *L* (Length cm) | *B* (width cm) |
|---|---|---|
| The interior columns, cm | | |
| C2 | 130 | 40 |
| C3 | 150 | 45 |
| The Exterior columns, cm | | |
| C1 | 100 | 40 |
| C2 | 130 | 40 |
| C3 | 150 | 45 |
| Wall thickness, cm | | |
| Thickness of shear wall [SW] | 40 | |

31.85×35.10 m.

The concrete's compressive strength ($f_{cu}$) has identified to be 25 MPa. The yield stress for steel bars $f_y$ is equal to 400 MPa, and the modulus of elasticity $E$ of the $R_c$ concrete is equal to 200,000 MPa.

The cross-sectional elements are carefully chosen to ensure accuracy and sufficiency in obtaining a satisfactory response from the structure. The sizes of the cross-sectional elements have been determined using a preliminary design approach. The construction of all elements follows the guidelines outlined in the ECP (2008) code. Each flat slab has a uniform thickness of 25 cm. The thickness of the walls between axes 1-4, 5-10, and 11-20 is 40 cm, as shown in Table 2.

Table 3 Dimension and reinforcement of columns and shear walls

| Ser 1 | Load | Size of column | % of Reinforcement |
|---|---|---|---|
| | | Lightweight Concrete [LC] | |
| C1 | 2750 | 40×100 | 0.7% |
| C2 | 4387 | 40×130 | 0.85% |
| C3 | 5439 | 45×150 | 0.83% |
| | | Ordinary Concrete [OC] | |
| C1 | 3265 | 40×100 | 0.8% |
| C2 | 5354 | 40×130 | 1% |
| C3 | 6431 | 45×150 | 0.93% |
| | | Heavy Concrete [HC] | |
| C1 | 4288 | 40×100 | 1.1% |
| C2 | 7053 | 40×130 | 1.3% |
| C3 | 8491 | 45×150 | 1.26% |

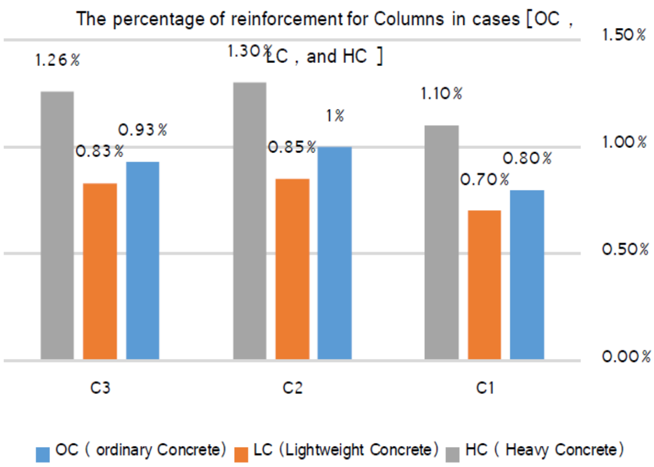



Fig. 5 The percentage of reinforcement for Columns in cases (OC, LC, and HC)

The Egyptian Code for Loads and Forces has been used to analyze these sections for conformity with its requirements while considering the impact of seismic loads. Furthermore, the interior columns' dimensions are C2 (40 cm×130 cm) and C3 (45 cm×150 cm). And the exterior columns are C1 (40 cm×100 cm), C2 (40 cm×130 cm), and C3 (45 cm×150 cm). Also, Table 3 and Fig. 5 provide dimensions and detailed designs of cross-sections for columns and beams for LC, OC and HC.

Live loads are taken at 2.5 Kn/$m^2$ for each floor, while the dead loads are made up of both the self-weight and the flooring load (1.5 Kn/$m^2$). Moreover, the reinforcement steel is ST40/60, and its elastic modulus is $E$=2.0×$10^8$ kN/$m^2$. Furthermore, the Poisson ratio is 0.3.

Table 4 shows the various formulas to calculate the thickness of slabs that depend on the type of construction elements and the column slenderness ratio according to the guidelines of the Egyptian Code (ECP) (ECP 2008), while the depth of solid slabs is typically governed by the deflection rather than the flexural strength requirements. The structural design components have been carefully considered and designed according to the guidelines outlined in the ECP code. The

Table 4 The values of *Ln/t* in case of member span with length less than 10 m (ECP 2008)

| Element | Simply support | One End continuous | Two End continuous | Cantilever |
|---|---|---|---|---|
| Solid Slabs | 25 | 30 | 36 | 10 |
| Hollow Block | 20 | 25 | 28 | 8 |
| Paneled Beam | $T$=short length $Ls$/(12-16) | | | |
| Flat slab | $Ts$ is the bigger of $= \begin{cases} 150\text{ mm} \\ \frac{L}{32}\text{ without drop} \\ \frac{L}{36}\text{ with drop} \end{cases}$ | | | |

value of *Ln/t* for member spans less than 10 meters has been taken into account during the creation of the structural model. Ln refers to the clear span, and t refers to the slab thickness which must be at least 120 mm, as per the (ECP 2008) guidelines.

In the structural model, the flat slab has a thickness of 25 cm, and the cross-sectional size of the edge beam is (30×80) cm. The building's vertical components are made up of columns and shear walls. The concrete properties for each element (slabs, columns, and beams) vary depending on the type of concrete used, as presented in Table 1. Fig. 8 illustrates that the study also investigates the seismic response demands of the structure's elements for various concrete types (LC, HC, and OC).

A range of three-dimensional (3D) modeling approaches has been used to perfect building structure geometry, from the method for one-dimensional elements to detailed 3D solid modeling of all structural components. Additionally, a FE model is needed to incorporate all the structural components and imitate their actual behavior to predict a building's seismic response. However, it should be noted that creating these simulations typically requires more effort and resources compared to simplistic models. It is generally acknowledged that this type of research leads to more accurate conclusions than overly simplified models. The outcomes of this type of analysis have often been better than those of simplified models. Various analytical approaches and models of varying complexity have been established to evaluate the different models' ability to predict the performance of LC elements and the impact of analysis assumptions on demand forecasts.

The dynamic response of the structure's critical elements was simulated using a three-dimensional mathematical model of the structure. This model represents the mass and stiffness of the structural components. The structure is represented as a 3D frame structure, with frame elements for the columns, longitudinal beams, transverse beams, and shell elements for the slabs.

The mathematical models for the structure models for twenty stories are developed using ETABS software (Inc 2018) to determine the seismic response demands. The measured responses involve story displacement, story drift, story shear force, and an overturning moment.

## 5. Numerical analysis

### *5.1 Lateral displacement and story drift*

Horizontal displacement is a critical factor to consider in the design of high-rise buildings, as it affects the building's behavior both during and after an earthquake. Amplified lateral deformation can significantly impact the behavior of the building. Deflection and story drift with high values

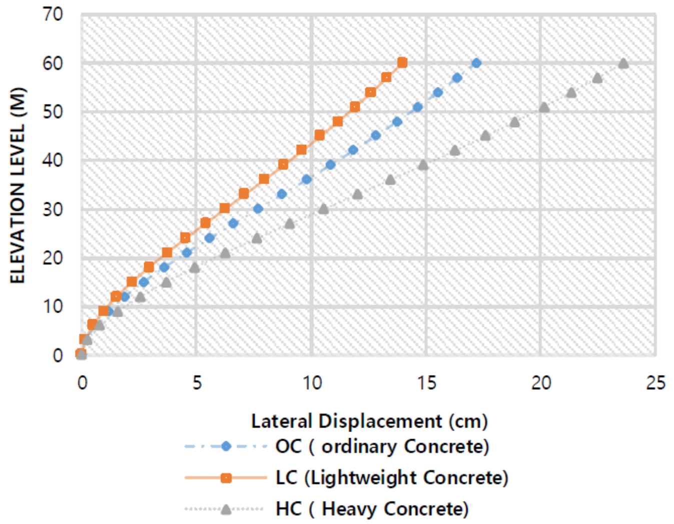



Fig. 6 Story displacement, cm

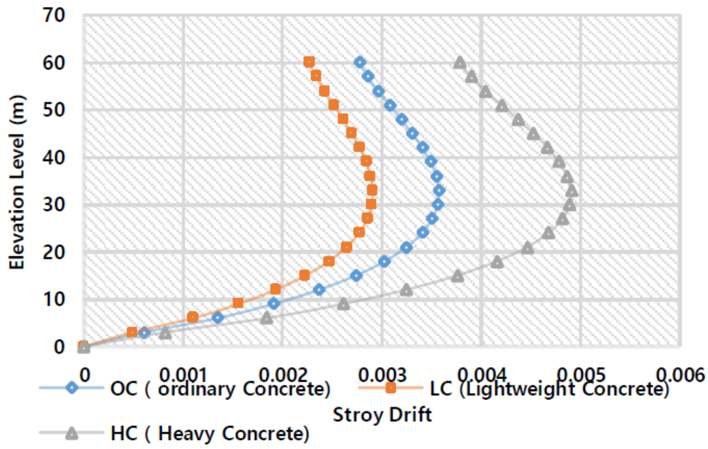



Fig. 7 Story drift

can have a negative impact on the structural and non-structural elements of the building. Therefore, it is crucial to accurately consider these factors during the design stage (Abdel Raheem *et al*. 2015).

Despite the increasing use of LC in the building sector, to the best of our knowledge, no previous research has investigated the seismic response of lightweight concrete and the impact of variations in concrete type. In other words, variations in concrete types (LC, OC, and HC) can affect the seismic performance of high-rise buildings. Thus, the study examines various concrete types, including LC, HC, and OC, to understand how they respond to seismic loads. Additionally, the study considers the cracked section in the design to obtain the deformation response demand.

Fig. 6 shows the distribution of story displacement over the height of the model. Model HC exhibits the highest top displacement response, with a value of 0.236 m, which is greater than 37.4% of OC. On the other hand, the maximum story displacement of the LC model is 18.64%

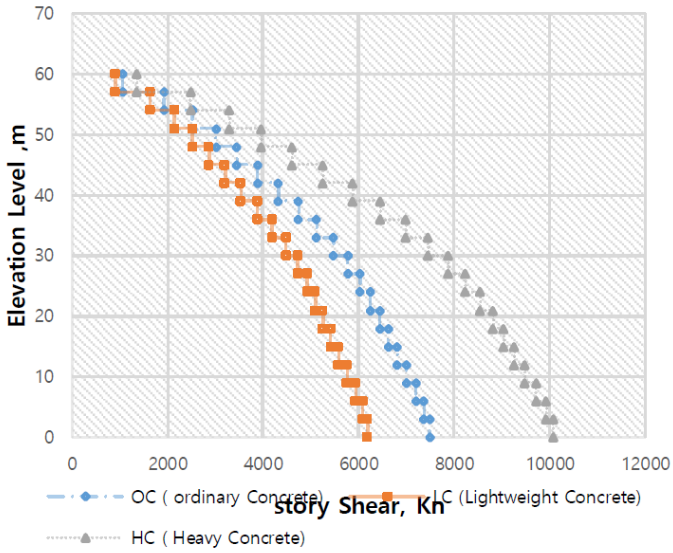



Fig. 8 Story shear, kn

lower than that of the OC models.

In previous models, the story drift response demand was examined. As well, all models have been compared with the reference OC (REF). Fig. 7 shows the story drift over the modeling's height in various cases. The story drift ratios for the models (OC, HC, and LC) rise progressively throughout the building's height, peaking at the 11th story. Hence, it declines at increasing levels. Furthermore, the HC model has a higher story drift ratio than the OC model, and its maximum story drift value exceeds 37.33 percent of the RF model. Otherwise, the LC model's declining percentage when compared to the RF model is 18.62%.

### *5.2 Shear force response*

It sounds like the study you are referring to is comparing different types of models (OC, LC, and HC) in terms of their ability to simulate shear force in response to seismic activity. The study is likely trying to determine which type of model is best suited for predicting the behavior of buildings during earthquakes.

The weight of a building can affect its response to seismic activity, particularly in terms of distribution and shear. Therefore, it is important to study how different models respond to seismic loading in order to identify the best modeling approach for ensuring seismic resistance.

Fig. 8 likely displays the shear response of each model in the x-direction, which is the direction of seismic loading being studied. By comparing the shear responses of each model, the study can determine which model is most accurate and reliable for predicting the behavior of buildings during earthquakes.

The LC model displays the lowest shear force demand of 17.29% compared to the reference model (OC). In the HC model, the shear force demand response gets its maximum value and reaches more than 34.58 % compared to the reference model OC. Hence, the additional shear force response demand developed could violate the safe design for resisting elements.

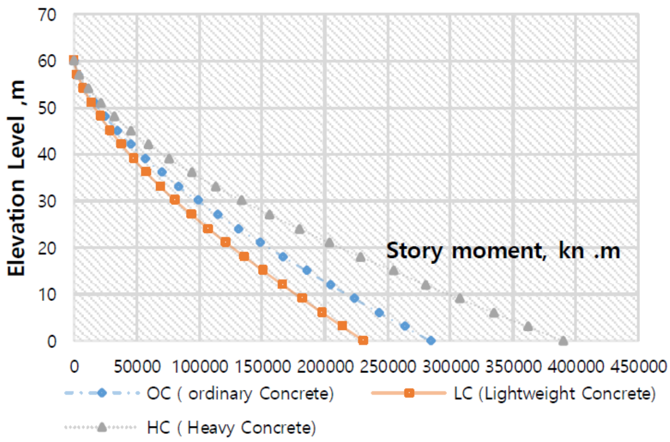



Fig. 9 Storey moment, kn.m

Table 5 load cases for design

| Ser | Case No | Load combination for design |
|---|---|---|
| 1 | Case 1 | 1.4 DL+1.6LL |
| 2 | Case 2 | DL+LL+0.25 $E_{qx}$ |
| 3 | Case 3 | DL+LL-0.25$E_{qx}$ |

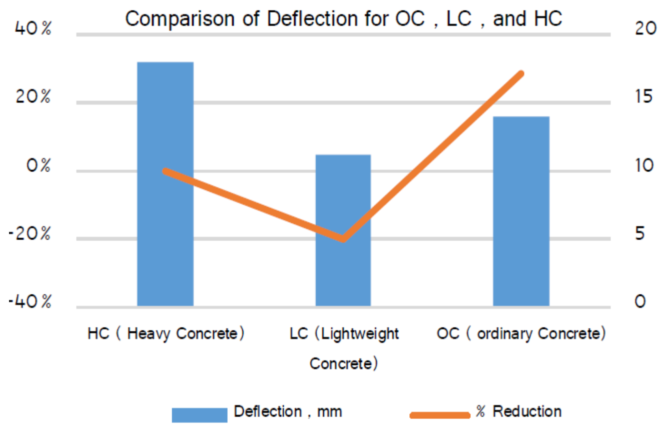



Fig. 10 Deflections for slabs (OC, LC, and HC)

### *5.3 Overturning moment response*

The overturning moment for each model (LC, OC, and HC) is shown in Fig. 9. The HC model's overturning moment exceeds 37.37% that of the REF. Otherwise, the LC model's declining percentage as compared to the RF model can reach 18.63%.

### *5.4 Bending moment and stress for slabs*

The structure was examined for the load cases indicated in Table 5. Based on the results of the

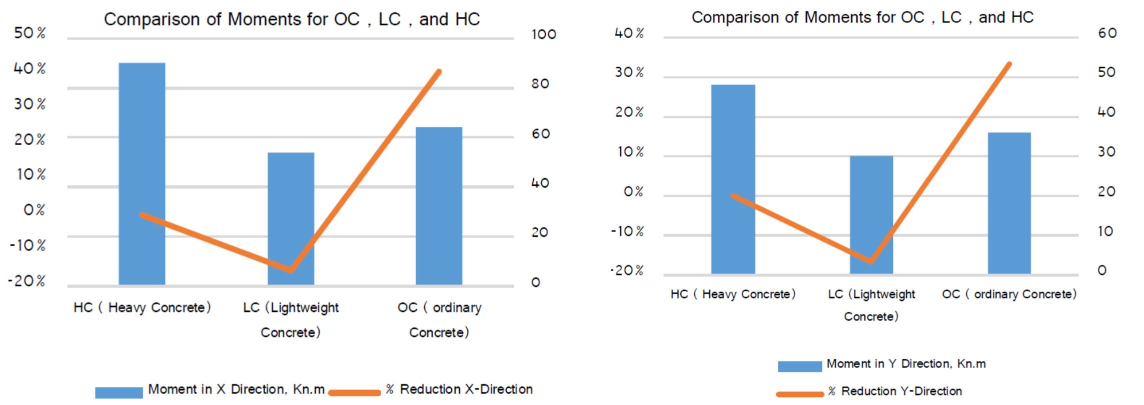



Fig. 11 Bending moment for slabs (OC, LC, and HC)

analytical model, the bending moment and deflection of the slab elements are compared for OC, LC, and HC.

Fig. 10 appears to display the maximum deflection of a slab caused by its own weight for three different types of concrete: OC, LC, and HC. The study likely conducted this analysis to examine how different types of concrete affect the deflection of a slab and to identify which type of concrete is best suited for minimizing deflection.

The results of the analysis indicate that the deflection caused by self-weight is smaller for LC compared to OC. Specifically, the slab deflections for OC, LC, and HC are 14 mm, 11.2 mm, and 18 mm, respectively. This means that the LC slab has the smallest deflection, while the HC slab has the largest deflection.

It is also worth noting that the deflection of the HC slab exceeds 29% of the reference (OC) model, indicating that HC may not be the best choice for minimizing deflection. On the other hand, the deflection of the LC slab declined to 20% of the reference model, suggesting that LC is a good choice for reducing deflection in slabs.

On the other hand, the study has investigated the effects of changing the type of concrete on the lateral direction of the stress values for OC, LC, and HC slabs. These are +4 MPa (compression) at the top layer and 6.4 MPa at the bottom layer for OC. And, the values are 5.4 MPa (compression) and -2.4 (tension) for LC. Otherwise, the values are 10 (compression) and -3.0 (tension) in HC.

Fig. 11 displays the maximum values of moments for the OC, LC, and HC slabs in both the x-direction and y-direction. The moments refer to the bending moments experienced by the slabs, which are important for assessing their structural stability.

The results indicate that the maximum moments in the x-direction for OC, LC, and HC are 64 Kn.m, 54 Kn.m, and 90 Kn.m, respectively. This means that the bending moment of the HC slab is the largest, exceeding 41% of the reference (OC) model. On the other hand, the bending moment of the LC slab is the smallest, declining to 16% with respect to the reference model. This suggests that LC is a good choice for reducing bending moments in slabs.

Similarly, the maximum moments in the y-direction for OC, LC, and HC are 36 Kn.m, 30 Kn.m, and 48 Kn.m, respectively. Here, the bending moment of the HC slab exceeds 33% of the reference model, while the bending moment of the LC slab declines to 17% of the reference model. Once again, these results suggest that LC is a good choice for reducing bending moments in slabs.

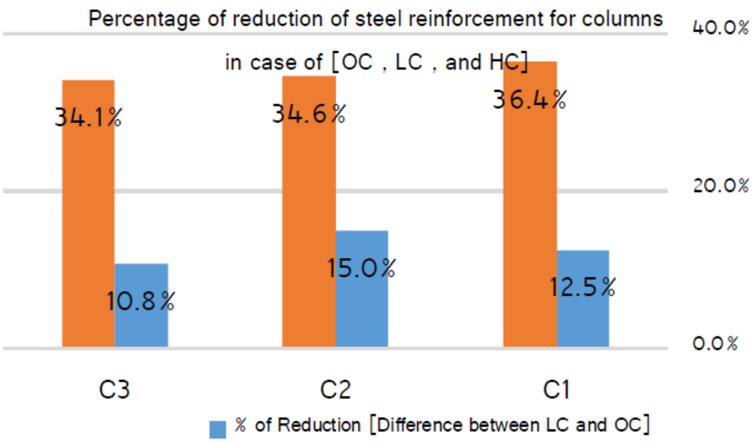



Fig. 12 Percentage of reduction of steel reinforcement for columns in case of (OC, LC , and HC)

Table 6 The reduction of as for LC

| Ser | OC | LC | HC | % for LC (Difference between LC and OC) | % for LC (Difference between LC and HC) |
|---|---|---|---|---|---|
| C1 | 0.8% | 0.7% | 1.1% | 12.5% | 36.4% |
| C2 | 1% | 0.85% | 1.3% | 15.0% | 34.6% |
| C3 | 0.93% | 0.83% | 1.26% | 10.8% | 34.1% |

### *5.5 Feasibility study of using LC*

It appears that the study involved creating and analyzing twenty-story structures according to the ECP-201 code. The bending moments and shear forces of these structures were then examined and used to modify the sectional characteristics of lightweight structures.

Using design software (Etabs), the study found that the area of steel in lightweight concrete could be reduced by approximately 10% to 15% with respect to OC (ordinary concrete), as shown in Table 6 and Fig. 12. This indicates that lightweight concrete can be used to achieve similar structural performance while using less steel reinforcement compared to ordinary concrete.

Furthermore, the study found that the percentage of reduction in steel area is even greater when comparing lightweight concrete to HC (heavyweight concrete), with a reduction of about 34% to 36%. This suggests that lightweight concrete may be more cost-effective and efficient choice for construction projects compared to heavyweight concrete.

It seems that the study’s findings suggest that using lightweight concrete can be a cost-effective option for construction projects. The steel ratio of lightweight concrete was found to be lower compared to ordinary or heavyweight concrete, which means that less steel reinforcement is needed to achieve similar structural performance. This can lead to cost savings in construction projects, which is an important consideration in the industry.

Furthermore, the study suggests that using lightweight concrete can still maintain good lateral seismic performance, even with a lower steel ratio. This means that lightweight concrete can be an effective and efficient choice for construction projects, especially in areas prone to seismic activity where lateral seismic performance is a critical factor.

Overall, the study’s findings demonstrate the benefits of using lightweight concrete in

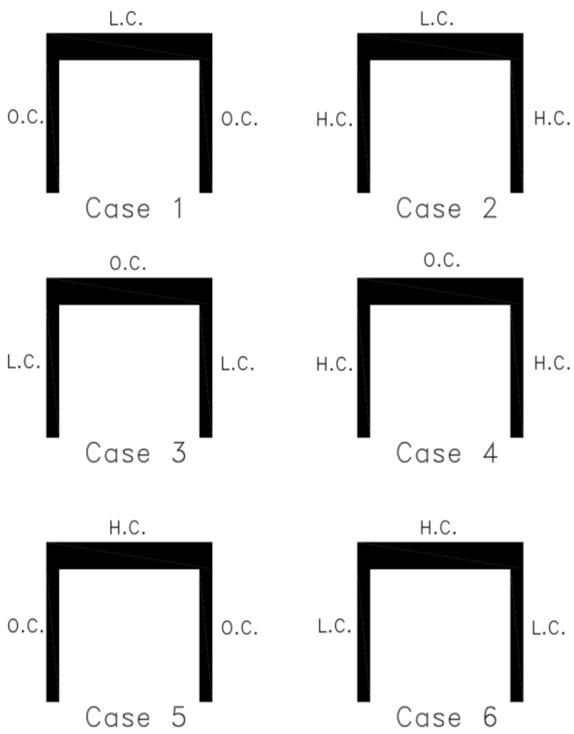



Fig. 13 The modeling cases

Table 7 The studied cases

| Ser | Case | Description | Model Code |
|---|---|---|---|
| 1 | Case No 1 | OC column LC Roof | OCC-LCR |
| 2 | Case No 2 | HC column LC Roof | HCC-LCR |
| 3 | Case No 3 | LC column OC Roof | LCC-OCR |
| 4 | Case No 4 | HC column OC Roof | HCC-OCR |
| 5 | Case No 5 | OC column HC Roof | OCC-HCR |
| 6 | Case No 6 | LC column HC Roof | LCC-HCR |
| 7 | REM [Reference Model] | OC column OC Roof | OCC-OCR |

construction projects, including potential cost savings and good lateral seismic performance, making it a viable and attractive option for the construction industry.

### *5.6 The variation of concrete type in the structure elements*

It appears that the study examined the performance of different types of concrete (LC, OC, and HC) in structural elements in terms of their response to lateral displacement, story drift, story shear, and overturning moment. Based on the study's findings, the following key conclusions can be drawn:

**First: the lateral displacement response**: The distribution of the maximum story displacement over model heights for the studied cases is shown in Fig. 14. Model OCC-HCR has

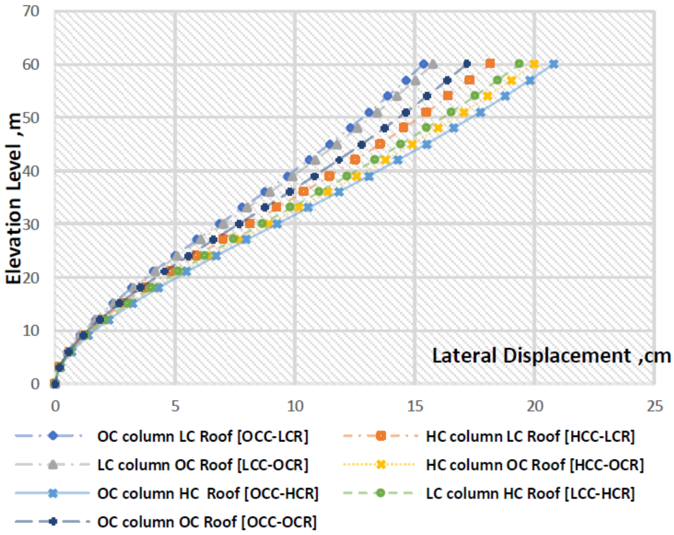



Fig .14 Lateral displacement, cm

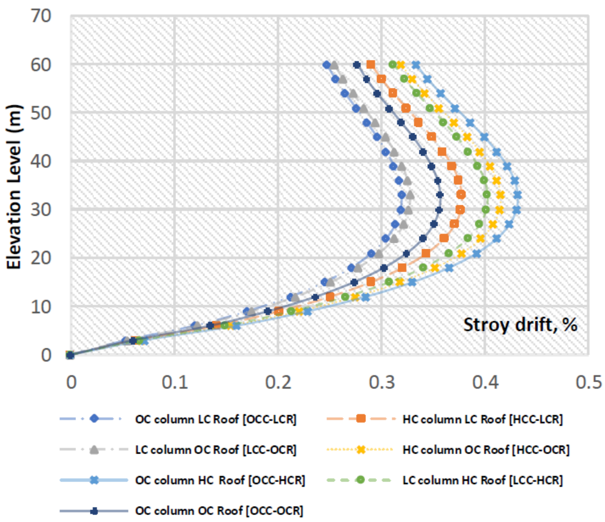



Fig. 15 Story drift

the highest top displacement response with respect to other varieties. In addition, their value is 0.2079 m, which is greater than 21.03% of OCC-OCR. On the other hand, the peak displacements for OCC-LCR and LCC-OCR are less than 8% to 10% of those for OCC-OCR.

**Second: the story drift response:** Fig. 15 shows the story drift over the height of the structure for the studied cases. The maximum story drift of the OCC-HCR model is 20.95% higher than that of the RF (OCC-OCR). In contrast, the maximum story drift values of the OCC-LCR and LCC-OCR models are less than 8% to 10% of the OCC-OCR model.

**Third: the story shear response**: The highest base shear value of the OCC-HCR model is 19.09% higher than the RF. However, both the OCC-LCR and LCC-OCR models exhibit values that are between 7.5 and 9.5% less than those for the OCC-OCR model. Fig. 16 displays the base

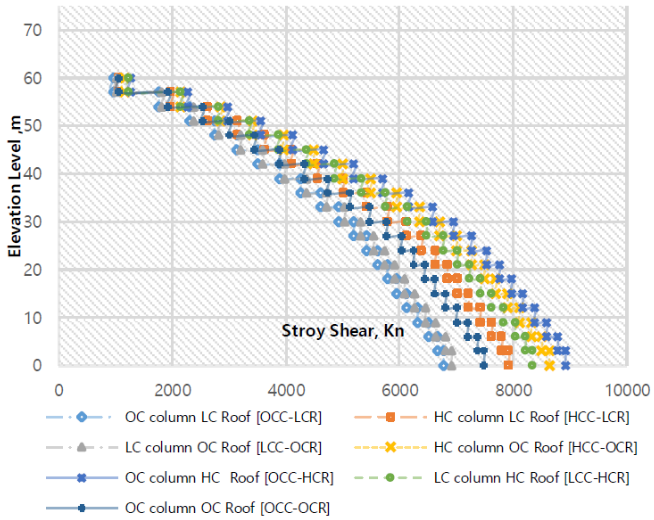



Fig. 16 Story shear, kn

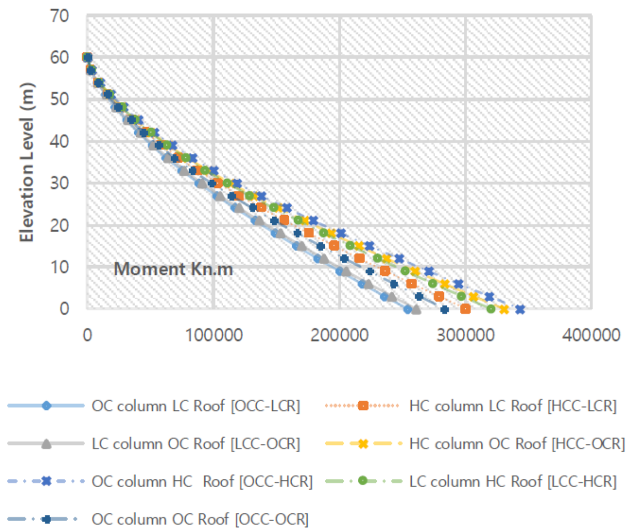



Fig. 17 The overturning moment

shear force for each model.

**Fourth: the overturning moment response**: The overturning moment response for each model is shown in Fig. 17. The OCC-HCR's maximum overturning moment is 20.96% more than the OCC-OCR's. Furthermore, the decreasing percentage in the OCC-LCR and LCC-OCR models is between 8 and 10% with respect to OCC-OCR.

## 6. Conclusions

It appears that the study aimed to investigate the effects of different types of concrete (LC, HC, and OC) on the seismic response of buildings. The choice of concrete type can have significant impacts on the seismic performance of a building due to factors such as rigidity, stiffness, and weight. It is important to consider both the economic aspect and safe design when selecting the type of concrete to use in construction. The study found that using lightweight concrete (LC) can result in a more effective seismic response compared to other types of concrete such as HC and OC. This is due to the lower weight of LC, which can affect the forces that cause earthquakes. Additionally, the design of the structure for story drift and story displacement is safer when using LC because its Young's modulus is lower than other types of concrete.

Overall, the study's findings suggest that using LC in structural elements can be an effective method for enhancing a building's seismic performance while potentially reducing costs. Structural designers who prioritize the use of low-cost materials can consider using LC as a cost-effective option for construction projects, especially in areas prone to seismic activity.

It seems that the study also investigated the combination of different types of concrete (LC, OC, and HC) in structural elements of modeled structures. Despite using several concrete types, the study showed that constructing buildings with the same type of concrete can result in optimal behavior. The study compared the seismic response of different combinations of concrete types in the modeled structures, including OCC-LCR (case 1), HCC-LCR (case 2), LCC-OCR (case 3), HCC-OCR (case 4), OCC-HCR (case 5), and LCC-HCR (case 6). As shown in Figs. 14, 15, 16, and 17, The results showed that OCC-LCR (case 1) and LCC-OCR (case 3) models had the lowest response compared to other types.

The seismic analysis also revealed lower bending moments and shear forces for lightweight concrete structures, which could allow for a smaller cross-section of members. This is because of the lower Young's modulus of lightweight concrete. The study indicated that the seismic analysis of the structure depends on the dead load and forces generated by an earthquake. Using lightweight concrete can result in less bending moments and shear forces, which, in turn, can reduce the cross-section of members or the amount of steel used in moment and shear-resistant sections.

Overall, the study's findings suggest that lightweight concrete can offer various advantages in construction buildings, such as reducing the size of cross-section elements, and reinforcement requirements, which can contribute to reducing time and cost. The study indicates that using lightweight concrete in structural elements can be an effective method for enhancing a building's seismic performance while potentially reducing costs. Structural designers can consider using lightweight concrete in building construction projects, especially in areas prone to seismic activity. By using lightweight concrete, designers can potentially reduce the size of cross-section elements and reinforcement requirements, resulting in a more efficient and cost-effective construction process.

In general, the advantages of lightweight concrete in construction buildings are various, such as reducing the size of cross-section elements, and reinforcement requirements, which can contribute to reducing time and cost.

It appears that increasing the structural stiffness along the floors can help mitigate the risk of story drift in buildings. Additionally, improving the shear reinforcement and increasing the ductility of the structure can help improve its seismic performance. The use of lightweight concrete can be advantageous in construction projects because it provides adequate strength with low density and can help avoid shrinkage cracks by maintaining low drying shrinkage.

In addition to building construction, lightweight concrete has also been successfully used in the construction of long-span bridges and offshore platforms. The use of lightweight concrete in these applications can help reduce the overall weight of the structure, making it more efficient and cost-effective.

Overall, the use of lightweight concrete in construction projects can offer various advantages, such as reducing the risk of story drift, improving shear reinforcement, and providing adequate strength with low density. The successful application of lightweight concrete in various construction projects, including long-span bridges and offshore platforms, further supports its effectiveness and potential for use in a wide range of construction applications. (Concrete Centre, 2006).

It seems that the study found that the use of lightweight concrete in construction projects can lead to a reduction in the area of steel needed, with a reduction of about 10% to 15% compared to ordinary concrete and about 34% to 36% compared to heavyweight concrete. This reduction in steel requirements can help reduce costs, which is a critical criterion in the construction industry.

Additionally, the study found that the use of lightweight concrete can provide good lateral seismic performance, although further research is needed under seismic loading to fully understand its characteristics in building construction.

Overall, the study's findings suggest that using lightweight concrete in construction projects can be an effective method for reducing steel requirements and lowering costs while still maintaining good lateral seismic performance. However, additional research is necessary to fully understand the behavior of lightweight concrete under seismic loading and its potential applications in building construction.

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