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The Seismic Performance of Reinforced Sustainable Concrete Low-Rise Structures

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Abstract

The utilization of sustainable concrete in producing reinforced concrete structures subjected to seismic actions is one of the leading research topics of recent years. With the technical exhibition that this concrete may be used in conventional reinforced concrete structures, a significant threshold for this sustainable material is accomplished. In the scope of this study, the seismic behavior of five different reinforced concrete structures under seismic actions, which are considered to be produced from sustainable concrete and conventional concrete, was investigated in detail. The geometrical, cross-section, and longitudinal section dimensions of these reinforced concrete structures are convenient for the equivalent seismic load method to use effectively. Furthermore, the Turkish Building Seismic Code limits were considered for the numerical simulation of reinforced concrete structures. Based on this detailed seismic simulation, the equivalent seismic load method may be used in earthquake simulation of reinforced concrete structures incorporating sustainable concrete. Furthermore, the numerical simulation results obtained from the sustainable concrete structures were extensively compared with the conventional concrete structures results. It may be concluded from these results that there are negligible differences between the seismic performance indicators of reinforced sustainable concrete structures and conventional concrete structures.

Keywords: Equivalent seismic load method, Natural aggregate, Recycled concrete aggregate, Reinforced Concrete, Seismic, Sustainable concrete.

1. Introduction

Reinforced concrete is a structural material that allows concrete and steel to work together under external loads without bonding problems. Therefore, reinforced concrete (*RC*), which has a wide utilization area, is used to construct many different types of structures: high-rise buildings and factory structural systems, floors, roofs, arches, retaining walls, water reservoirs, silos, and various kinds of shell systems, large span bridges, etc. The basic materials of reinforced concrete structures are concrete and steel. Steel is a sustainable material. Thanks to these extensive numerical and experimental studies, concrete, another important reinforced concrete material, is now considered a sustainable product [1-8]. It is well known that most of the structures in the world are built from reinforced concrete material. When sustainable concrete (*SC*) is used to produce these structures, the construction sector in developed and developing countries obtains significant advantages in both environmental and economic activities. Sustainable concrete is defined as concrete containing one recycled waste material. Recycled

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concrete aggregate (*RCA*), obtained by recycling waste concrete, is one of the materials used in sustainable concrete production. Therefore, many comprehensive experimental and numerical studies are carried out to investigate the potential utilization of sustainable concrete in producing reinforced concrete structures. Based on these studies, the structural performances of reinforced concrete members constructed from sustainable concrete incorporating *RCA* under simulated seismic actions reveal that this concrete is suitable for producing structural members and reinforced concrete structures [1-8]. Therefore, the seismic performance of sustainable concrete structures is one of the critical research topics of recent years. In addition, through the utilization of sustainable concrete in the production of reinforced concrete structures, these structures will be designed effectively and efficiently in the scope of the future green idea. Thus, the recycling of demolishing old structures (non-code complying or inadequate for seismic conditions) and replacing them with new ones is established.

The seismic behavior of a structure depends on the magnitude of an earthquake and the quality of the structure. The structure quality may be defined depending on parameters such as choosing the structural system, proper cross-section sizing of the structural members, and controlling the workmanship [9]. Therefore, a structural system of a building resisting seismic loads and each structural member of the system may be provided with sufficient stiffness, stability, and strength to ensure an uninterrupted and safe transfer of seismic loads down to the foundation soil [9]. In the literature, many detailed experimental and numerical studies on sufficient strength, ductility, and stiffness parameters are conducted to ensure effective seismic performance in reinforced concrete structures. These studies are generally exhibited on structures and structural elements made of conventional concrete (*CC*). The use of sustainable concrete in the production of reinforced concrete structures raises the question of whether the existing seismic design and assessment procedures and the concepts of sufficient strength, ductility, and stiffness are valid for these reinforced sustainable concrete structures. Therefore, experimental and numerical studies on the seismic performance of reinforced sustainable concrete structures within the mentioned issues are important research topics.

In the scope of this comprehensive study, the seismic performance of reinforced concrete structures, which are considered to be produced from sustainable concrete, has been extensively investigated. In the numerical simulation study, the seismic performances of the sustainable concrete incorporation of *25%*, *50%*, *75%*, and *100% RCA* (*SC25*, *SC50*, *SC75*, and *SC100*) structures were compared with the seismic performance indicators of the reinforced *CC* structure. The obtained results of these detailed comparisons are given in detail in the following sections.

2. Materials and Method

2.1. Material properties of the numerical simulation study

The seismic numerical simulations were executed on full-scale *RC* structures, one of the representative low-rise structures in real, incorporated *SC* and *CC*. Five concrete properties, sustainable and conventional concrete, were considered in the numerical simulations. The stress-strain relationships of this concrete were obtained using Equations 1-5 with the modified Hognestad [10] model proposed by Saribas [11]. The stress-strain relationships obtained for sustainable and conventional concrete are given in Figure 1a. It may be noted that these concrete properties were used in labeling the structures. For example, in the specimen of *CC*, *CC* represents the conventional concrete and conventional concrete structure, and S*C100* indicates sustainable concrete and sustainable concrete structures containing *100% RCA*.

$$f_c = s \times 0.85 f_{ck} \tag{1}$$

$$E_c = 12680 + i \times 460 f_c \tag{2}$$

$$\varepsilon_{co} = \frac{2 f_c}{E_c} \tag{3}$$

$$\sigma_c = f_c \left(\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}} \right)^2 \right) \tag{4}$$

$$f_{cu} = 0.85 f_c \tag{5}$$

In these Equations 1-5, f_c is the concrete compressive strength, f_{ck} is the characteristic concrete compressive strength, s is the recycled concrete aggregate coefficient, E_c is the modulus of elasticity of concrete, i is the recycled concrete aggregate coefficient, ε_{co} is the strain value corresponding to the maximum concrete compressive strength, ε_c is the concrete compressive strain, ε_{cu} is the ultimate concrete compressive strain, f_{cu} is the ultimate concrete compressive strength [11].

The stress-strain relationship of B420C reinforcing steel considered for longitudinal and transverse reinforcement is obtained with Equations 6-8 defined in TSDC-2018 [9]. The stress-strain relationship of this reinforcing bar is given in Figure 1b.

$$f_s = E_s \varepsilon_s \quad \text{for} \quad (\varepsilon_s < \varepsilon_{sy}) \tag{6}$$

$$f_s = f_{sy} \quad \text{for} \quad (\varepsilon_{sy} < \varepsilon_s < \varepsilon_{sh}) \tag{7}$$

$$f_s = f_{su} - \left(f_{su} - f_{sy} \right) \frac{\left(\varepsilon_{su} - \varepsilon_s \right)^2}{\left(\varepsilon_{su} - \varepsilon_{sh} \right)^2} \quad \text{for} \quad (\varepsilon_{sh} < \varepsilon_s < \varepsilon_{su}) \tag{8}$$

In these Equations 6-8, f_s is the tensile strength in reinforcement steel, E_s is the elasticity module of reinforcement steel, ε_s is the strain of reinforcement steel, f_{sy} is the yield strength of the reinforcement steel, ε_{sy} is the yield strain of reinforcement steel, ε_{sh} is the strain hardening of reinforcement steel, ε_{su} is the ultimate strain of reinforcement steel, f_{su} is the ultimate strength of the reinforcement steel [9].

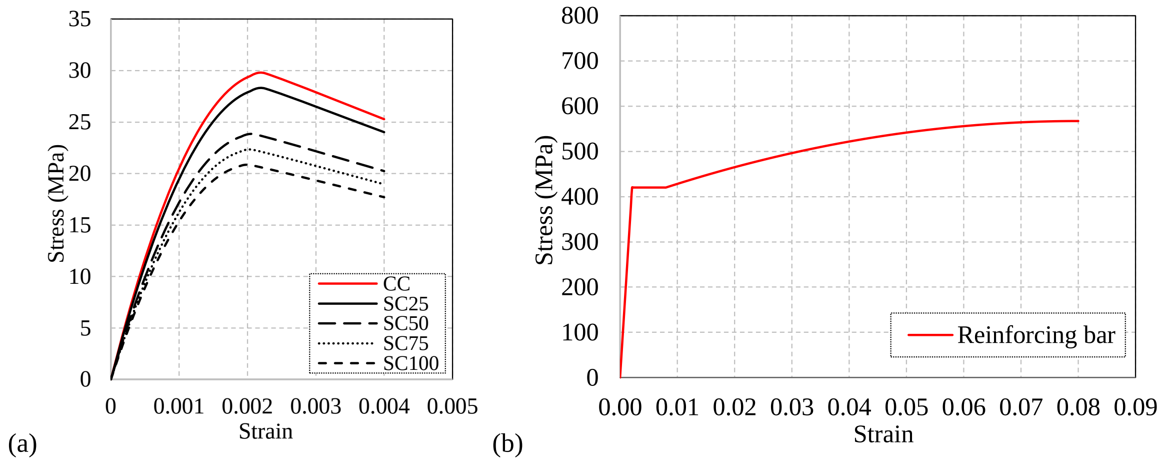

Figure 1. Stress-strain relationships (a) concretes, (b) reinforcing bar

2.2. Details of numerical simulation

The main factor that causes inertial forces in a structure is earthquakes that occur on the ground depending on time. The magnitude of these inertial forces changes depending on the characteristics of the structure and structural system, the magnitude of the earthquake, the distance of the structure to the fault, and the ground conditions where the structure is located [12-15]. Therefore, this is necessary to determine the inertial forces that occur with the earthquake to design a structure that meets the effects of the seismic actions. However, since each earthquake may cause different acceleration in the same area, a realistic estimation of earthquake effects is crucial for structure safety and cost. While there is more than one method to calculate the inertial forces that an earthquake creates, the simplest is the equivalent seismic load method for low-rise structures. Furthermore, the equivalent seismic load method is used to convert the dynamic load effect of a possible earthquake to the static load used in earthquake-resistant structure design and applied horizontally to each storey level of the structures. In addition, this dynamic force applied to the structure as a base shear force is regarded in both directions of the structure's plan (*x* and *y*-direction). It may be noted that the equivalent seismic load method should be implied to low-rise structures, the structure should be as symmetrical as possible to avoid torsional irregularity, and the structure should have similar rigidity in both directions. The geometrical properties of the structures considered in the scope of the study are given in Figure 2. The seismic code limitations that are effective in choosing the design method for the structures are shown in Table 1. It should also be highlighted that the dead and live loads were considered at 1.5 kN/m^2 and 2 kN/m^2 at each storey level [9]. Furthermore, the self-weight of the structural members was regarded for the simulation of these *RC* structures. In addition, wall loads on the edge beams were considered as 6 kN/m.

Table 1. Structural variables of reinforced conventional and sustainable concrete structures

Structural parameters	*value*	*Description*	*Analysis Method*
S_S *(Short-period map spectral acceleration coefficient)*	0.542	Latitude: 37.039107°	**Equivalent Seismic Load Method**
S_1 *(1.0 second period map spectral acceleration coefficient)*	0.134	Longitude: 35.385142°	
Soil type	ZC	TSDC-2018 Table 16.1	
F_S *(Local Ground Effect Coefficient for a short period)*	1.28	TSDC-2018 Table 2.1	
F_1 *(Local Ground Effect Coefficient for 1.0 second period)*	1.50	TSDC-2018 Table 2.2	
Earthquake ground motion level	DD-2	TSDC-2018 Table 3.4	
H_N *(Total heigh of structures)*	13	TSDC-2018 Table 3.3	
I (Importance coefficient of structures)	1	TSDC-2018 Table 3.1	
BKS (Building use class)	3	TSDC-2018 Table 3.1	
DTS (Earthquake design class)	2	TSDC-2018 Table 3.2	
BYS (Building height class)	6	TSDC-2018 Table 3.3	
Structural System x and y-direction	A.11	TSDC-2018 Table 4.1	
R (Structural behavior factor)	8	TSDC-2018 Table 4.1	
D (Overstrength Factor)	3	TSDC-2018 Table 4.1	
Torsional irregularity	No	TSDC-2018 Table 4.4	
Soft Storey	No	TSDC-2018 Table 4.4	
Modulus of soil reaction (K_s)	50000 kN/m^3		

*: Please see the TSDC-2018 for more information.

On the other hand, the total equivalent seismic load (base shear), V_{tE}, acting on the entire structure in the considered earthquake direction may be determined by Equation (9) [9].

$$V_{tE} = m_t S_{aR}(T_p) \geq 0.04 m_t \times I \times S_{DS} \times g \tag{9}$$

The total equivalent seismic load determined by Equation (9) is expressed by Equation (10) as the sum of equivalent seismic loads acting at storey levels [9].

$$V_{tE} = \Delta F_{NE} + \sum F_{iE} \tag{10}$$

Excluding ΔF_{NE}, the remaining part of the total equivalent seismic load may be distributed to storey levels of the structure (including *N'th* storey) in accordance with Equation (11) [9].

$$F_{iE} = [V_{tE} - \Delta F_{NE}]\ [m_i H_i / \sum m_i H_i] \tag{11}$$

In these Equations 9-11, V_{tE} is the total equivalent seismic load acting on the building (base shear) in the earthquake direction considered, m_t is the total mass of a building, $S_{aR}(T_p)$ is the reduced design spectral acceleration, I is the importance coefficient of structures, S_{DS} is the short period design spectral acceleration coefficient, g is the acceleration of gravity, ΔF_{NE} is the additional equivalent seismic load acting on the *N'th* storey (top) of building, F_{iE} is the design seismic load acting at *i'th* storey, m_i is the *i'th* storey mass of a building, H_i is the height of *i'th* storey of a building measured from the top foundation level [9].

Flat slab type raft foundations are considered in these sustainable and conventional concrete reinforced concrete structures (Figure 2). Considering these features of these structures, the seismic behavior of these structures may be determined by the equivalent seismic load method (Table 1, Figure 2). The seismic numerical simulation of conventional and sustainable reinforced concrete structures under seismic loads was carried out through the SAP2000 [16]. It is stated in the literature that performance indicators of RC columns, beams, and slab members incorporating sustainable concrete proved well accurate with structural counterparts containing conventional concrete [1-8]. Therefore, in the numerical simulations, the cross-section stiffness of the columns, beams, and slab members in the reinforced concrete structures was regarded as the effective section stiffness defined in TSDC-2018 [9]. The moment-curvature relationships of beams, columns, and axial load-bending moment relationships diagrams of columns were obtained with XTRACT 3.0.8 [17].

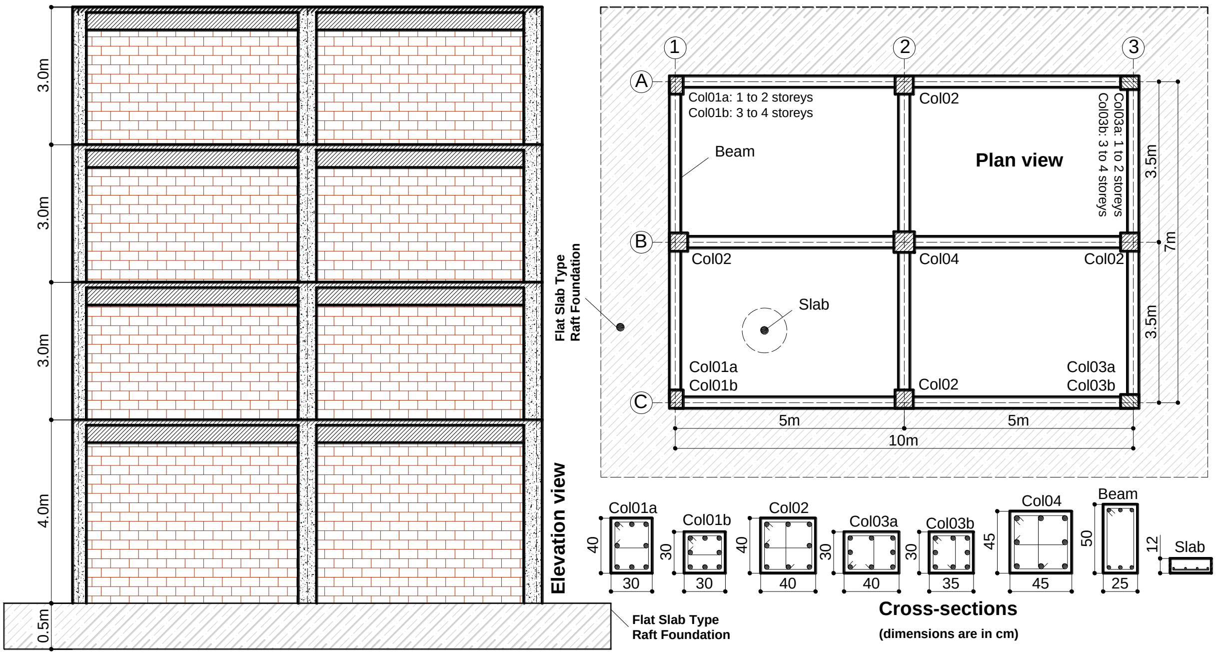

Figure 2. The geometrical properties of reinforced concrete structures

3. Numerical simulation results

3.1. Moment-curvature and axial load-bending moment relationship of RC Members

The moment-curvature and axial load-bending moment relationships of the columns and beam members in reinforced concrete structures in which seismic simulations were conducted thanks to the equivalent seismic load method were obtained through a fiber-analysis approach using the XTRACT 3.0.8 [17]. Furthermore, the confined concrete behavior was regarded by the Mander Model [18] based on the characteristics of the reinforcing bar, the cross-section dimensions, and unconfined concrete properties. The reinforcing bars in tension were assumed to behave in an elastic-plastic manner with strain hardening based on the B420C (Fig. 1b). The geometric ratio of longitudinal reinforcement is 1.34%. And the thickness of the concrete cover is 48 mm. In addition, the number of fibers of RC columns cross-section is about 580. As a result of the cross-section analysis, the obtained moment-curvature relationships of RC columns are presented in Figure 3.

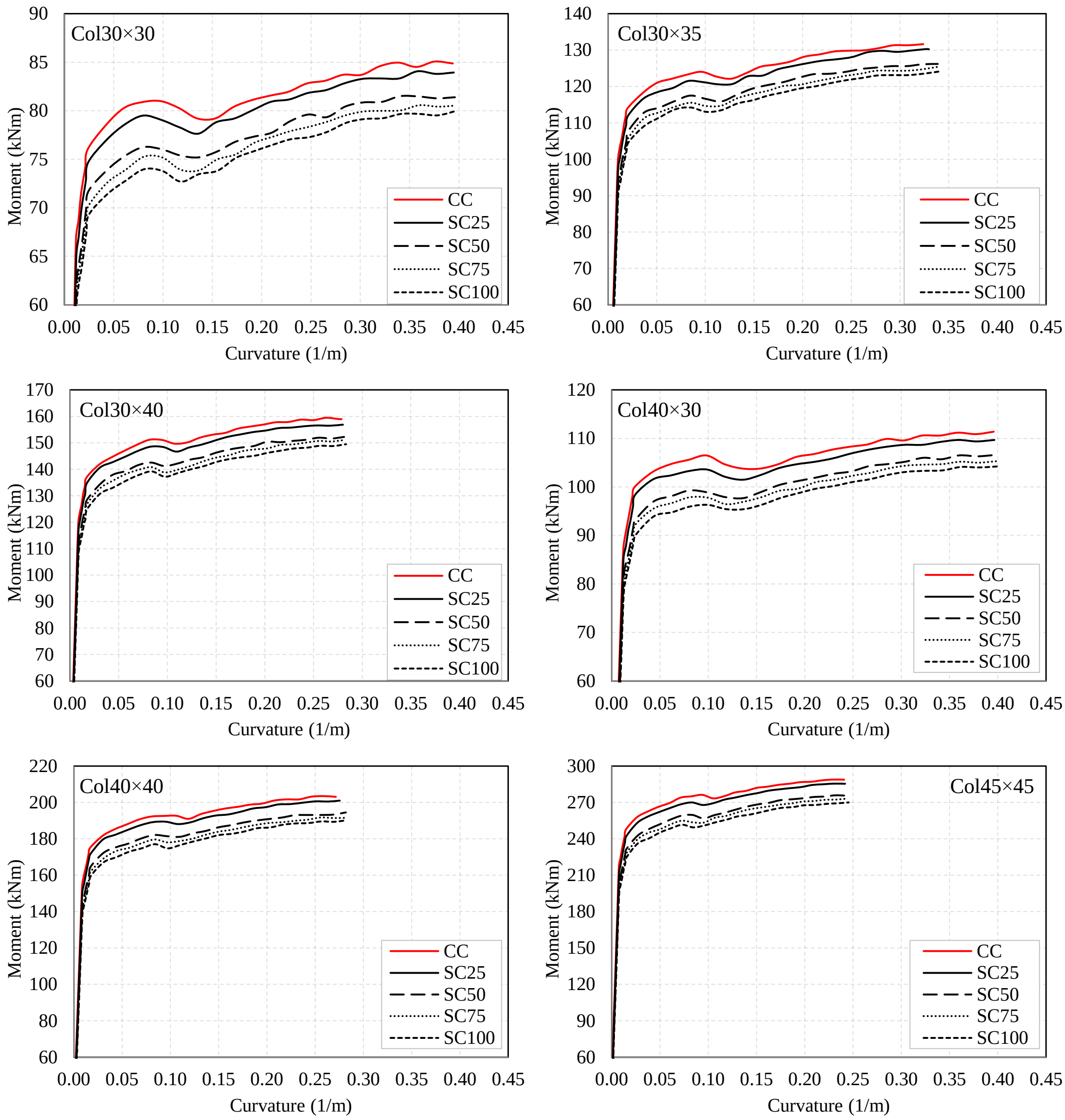

Figure 3. Moment-curvature relationships of reinforced conventional and sustainable concrete columns

The moment-curvature relationships of beams are shown in Figure 4. The axial load-bending moment diagrams for different types of concrete in columns for the same cross-section are presented in Figure 5. When the moment-curvature and axial load-bending moment diagrams of these columns are evaluated comprehensively, it is seen that the axial load and bending moment capacities of columns decrease as the RCA ratio in sustainable concrete increases (Figures 3-5). In addition, it was observed from Figure 4 that the moment-curvature capacities of beams were not affected by the RCA ratio since the bending reinforcement governs the flexural behavior of the members [5].

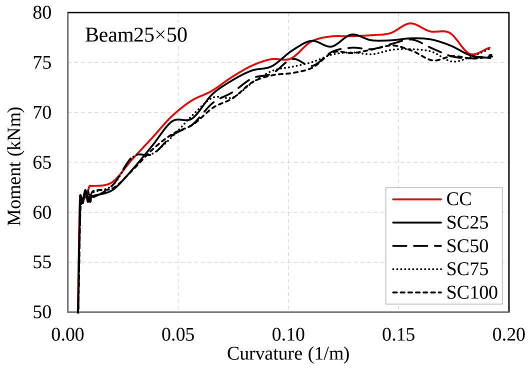

Figure 4. Moment-curvature relationships of reinforced conventional and sustainable concrete beams

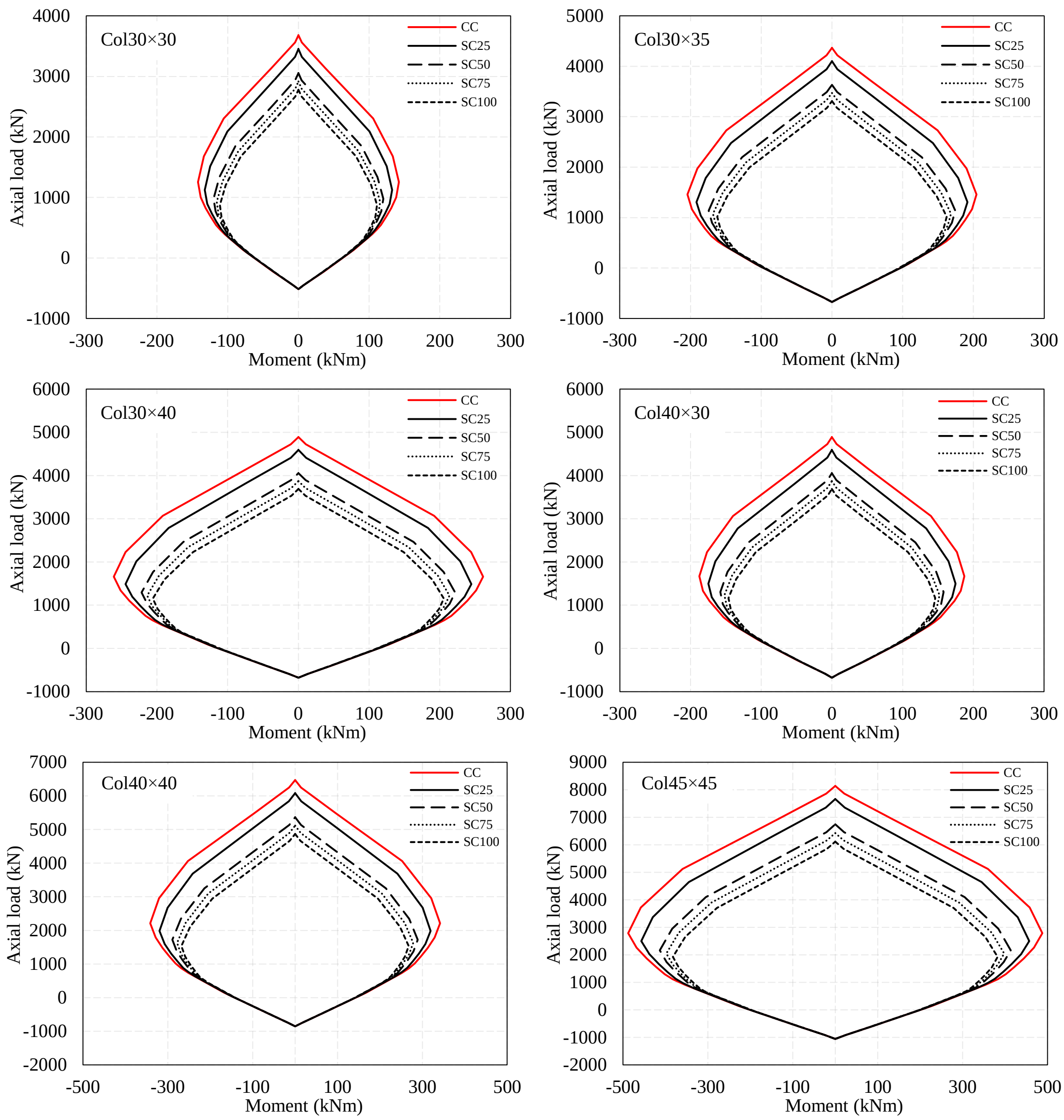

Figure 5. Axial load-bending moment relationships of reinforced conventional and sustainable concrete columns

3.2. Seismic simulation results of reinforced sustainable concrete structures

The equivalent seismic load method is a simple earthquake simulation procedure. In this method, the seismic behavior of a structure may be simulated considering the dominant natural vibration period, where the mass participation rate is the highest [9, 12-15]. Therefore, storey weights or masses are essential parameters in the dynamic behavior of structures. The storey weights of the reinforced concrete structures, whose numerical simulation was performed according to the equivalent earthquake load method, are given in Figure 6. While the storey weights are similar for the basement, first, and second storeys, the weight of the top storey is less than that of these storeys. The stiffness of the columns plays a critical role in the seismic behavior of reinforced concrete structures.

The simulation results of reinforced concrete structures with sustainable concrete under earthquake loads are presented in Figures 7-10. When the numerical simulation results are evaluated comprehensively, the natural vibration period of the reinforced sustainable concrete structures is higher than that of the natural vibration period of the reinforced conventional concrete structure. For example, the natural vibration period of the *CC* structure is 0.79s, while the natural vibration period of the *SC100* structure is 0.99s (Figure 7).

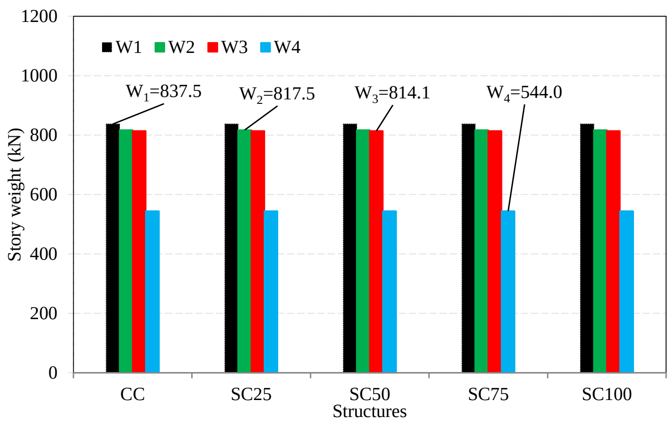

Figure 6. Storey weights of conventional and sustainable concrete structures

The difference between the natural vibration periods of the structures may be explained by the modulus of elasticity of SC (Figure 1a) since the low modulus of elasticity causes the lower lateral stiffness of RC columns. Therefore, this situation primarily causes a decrease at the moment carrying capacity of the RC columns (Figures 3, 5). In addition, the reduction in the stiffness of reinforced concrete structures causes the natural vibration periods of the structures to increase (Figure 7).

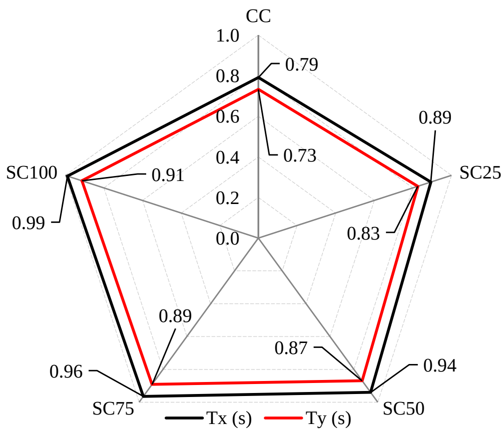

Figure 7. Natural vibration period in x and y-direction of conventional and sustainable concrete structures

Furthermore, the reduction in the stiffnesses of the main load-bearing structural members (columns) causes an increase in the storey and top displacements of the reinforced concrete structures (Figure 8). It should also be noted that as the RCA ratio in sustainable concrete increases, both the storey shear forces and the basement shear forces of the structures decrease in x and y-direction (Figure 9).

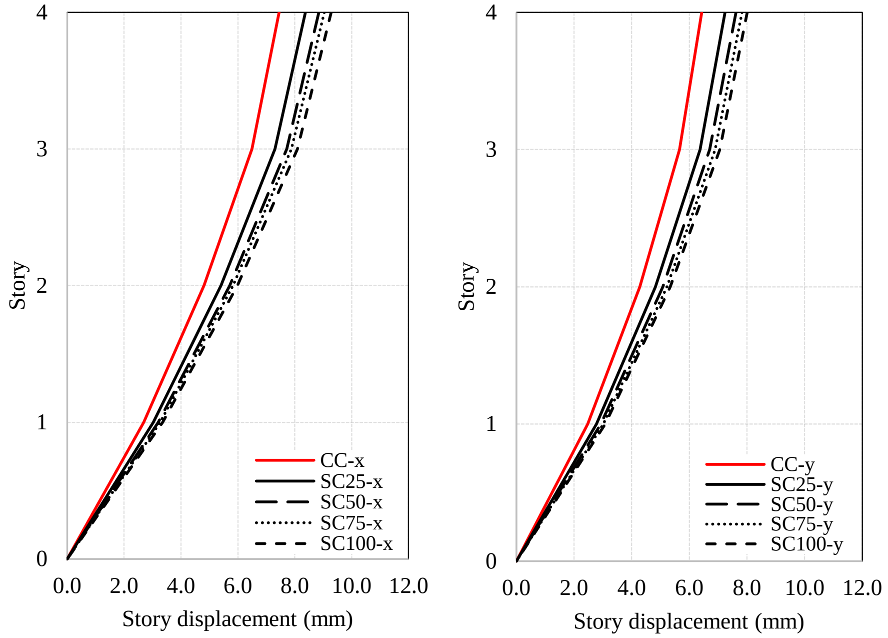

Figure 8. Storey displacement in the x and y-direction of conventional and sustainable concrete structures

The interaction results of the flat slab type raft foundation and the superstructure in reinforced concrete structures under seismic actions are provided in Figure 10. This figure shows that different deflection values were obtained in raft foundations where different concrete properties were regarded. It is worth noting that the main factor causing the difference in deflection is the RCA ratio in sustainable concrete (Figure 10).

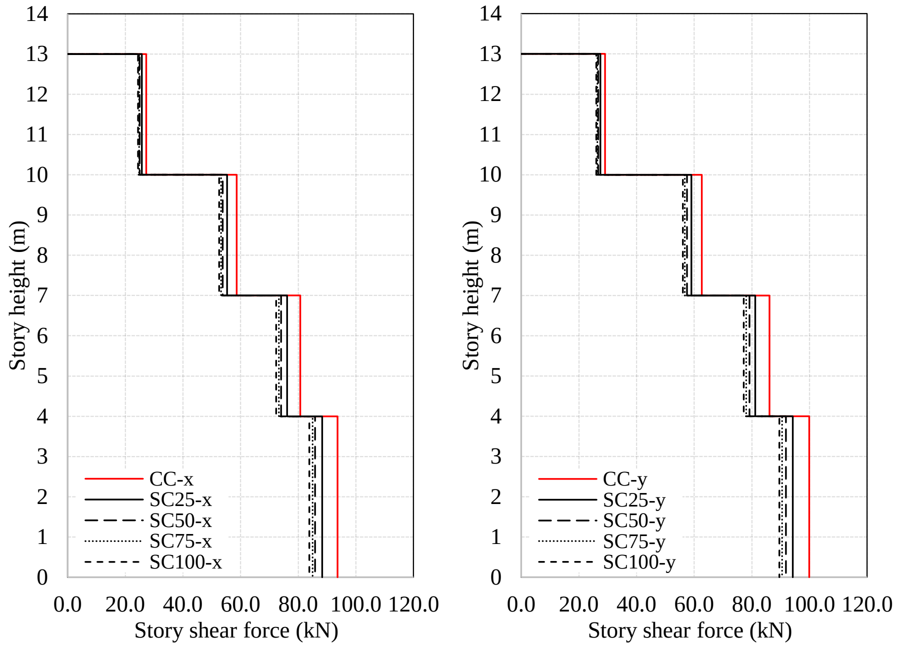

Figure 9. Storey Shear force in x and y-direction of conventional and sustainable concrete structures

When the results obtained in this simulation study to determine the seismic behavior of reinforced concrete structures incorporating sustainable concrete are evaluated in general, the dynamic behavior of reinforced concrete structures is significantly affected by the RCA ratio. The natural vibration periods, storey displacement, top displacements, storey shear forces, basement shear forces, and deflections in raft foundation of the reinforced concrete structures with sustainable concrete under earthquake loads were negligible differences from reinforced conventional concrete structures. The main parameter that causes this difference is the RCA ratio and sustainable concrete properties (Figure 1a).

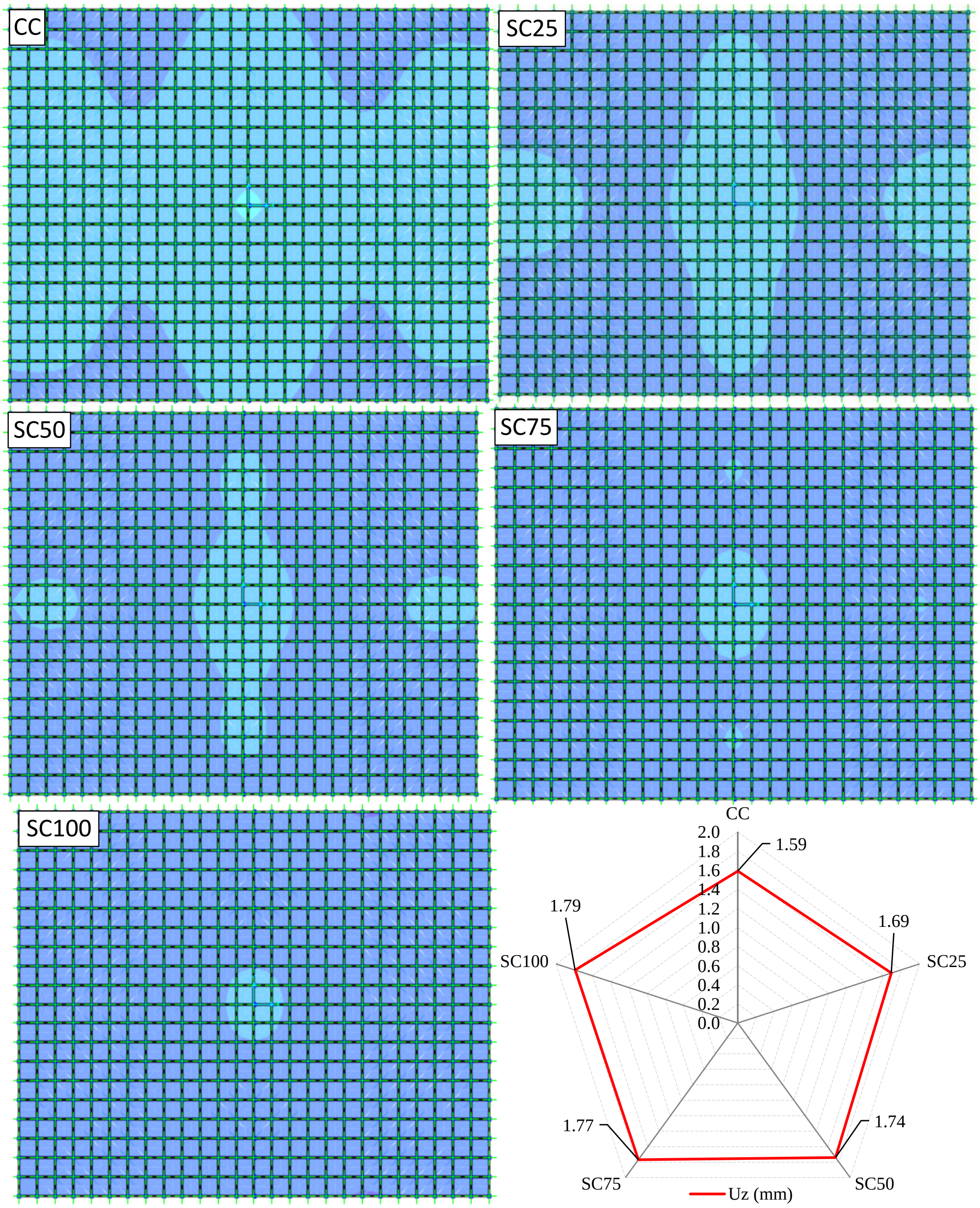

Figure 10. Deflection in flat slab raft foundation of conventional and sustainable concrete structures

4. Conclusions

This paper presents the results of a comprehensive numerical seismic simulation study executed on full-scale low-rise reinforced concrete structures incorporating sustainable concrete. And particular attention was paid to comparing the conventional concrete simulation results with the sustainable concrete results. The main conclusions can be derived from the global performance of the reinforced concrete structures:

- The equivalent seismic load method may reasonably simulate the seismic behavior of reinforced sustainable concrete low-rise structures.
- The numerical simulation highlighted that the RCA ratio is the dominant effective parameter for the seismic performance indicators of the reinforced sustainable concrete structures.
- The seismic simulation results revealed that the optimal RCA ratio in sustainable concrete might be between 25-50 % to make a proper seismic design in reinforced sustainable concrete structures.
- The modulus elasticity of sustainable concrete is the governing variable that affects the stiffness of reinforced sustainable concrete columns under seismic loading. Furthermore, a significant harmony is provided between the stress-strain behavior of sustainable concrete and storey shear force, storey displacement, base shear force, and roof displacement of these reinforced concrete structures.
- The seismic indicators of sustainable concrete reinforced concrete structures proved enough accuracy with the reinforced conventional concrete structures. This result mentions that the equivalent seismic load method is also valid for structures incorporating sustainable concrete.

Although this seismic simulation study contains enough research variables, there is an obvious need for further studies to obtain more applicable results on using sustainable concrete in constructing reinforced concrete structures.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Author Contribution

- I.S. Conceptualization, Methodology, Writing-Original draft preparation, Visualization, Investigation, Resources, Data curation, Reviewing and Editing, Project administration.
- M.A. Data curation, Investigation.

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