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Numerical Investigation of the Influence of Nonuniform Floor Diaphragm Stiffness on Torsional Mode Formation in Reinforced Concrete Buildings

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Abstract

This study numerically investigates the influence of non-uniform diaphragm stiffness distribution across different stories on the formation of torsional vibration modes in reinforced concrete buildings. Although floor diaphragms are commonly idealized as rigid in conventional structural analysis, their actual in-plane stiffness and deformation characteristics may influence the dynamic properties and seismic response of a structure. To investigate this issue, eight three-dimensional four-story reinforced concrete building models were developed and analyzed using ETABS. The models were divided into two groups. The first group examined different combinations of rigid and semi-rigid diaphragm assumptions across the stories, while the second group investigated the effects of varying slab thicknesses, considering 15 cm and 20 cm slabs in different story arrangements. The dynamic behavior of the models was evaluated by comparing their natural periods, modal shapes, modal mass participation ratios, and displacement responses. The results indicated that the third vibration mode was predominantly torsional in the analyzed models, with a reported rotational mass participation ratio of approximately 0.82. The vibration period was approximately 0.75 s. For the structural configurations and parameter ranges considered, variations in diaphragm modeling assumptions and slab thickness distribution did not substantially change the formation of torsional modes. These findings suggest that, for the investigated low-rise reinforced concrete buildings, the examined variations in diaphragm stiffness were not sufficient to produce a notable change in the identified torsional mode. However, the results should be interpreted within the limitations of the building configurations and modeling assumptions considered.

Keywords: Reinforced concrete buildings, Floor diaphragm, Diaphragm stiffness, Rigid diaphragm, Semi-rigid diaphragm, Torsional vibration modes, Modal analysis, ETABS.

1 | Introduction

Floor diaphragms play an important role in the structural behavior of buildings by transferring horizontal loads to vertical lateral-force-resisting elements. Their in-plane stiffness and deformation characteristics can influence how lateral forces are distributed throughout a structural system. In conventional structural analysis,

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floor diaphragms are frequently idealized as rigid in their own plane. However, actual diaphragm behavior may differ from this assumption, depending on the floor system, structural configuration, and stiffness characteristics. Previous studies have investigated diaphragm flexibility and its implications for the dynamic response and seismic performance of buildings [1–5].

The assumption of a rigid diaphragm can simplify structural modeling, but it may not adequately represent every building configuration. Research on the modeling of floor flexibility in existing reinforced concrete buildings highlights the importance of representing diaphragm behavior appropriately when evaluating structural response [6]. Similarly, Ruggieri et al. [7] examined methods for estimating floor deformability in existing reinforced concrete buildings and considered its implications for structural response and seismic fragility. These studies provide a basis for investigating how different diaphragm stiffness assumptions may influence the predicted dynamic characteristics of a building.

Diaphragm behavior is particularly relevant to seismic analysis because the distribution of lateral forces and the resulting structural response depend on the interaction between the floor system and the vertical resisting elements. Moehle et al. [8] addressed the seismic design of cast-in-place concrete diaphragms, including chords and collectors, emphasizing the structural functions associated with the transfer of seismic forces. Tena-Colunga and Sabanero-García [9] investigated the impact of diaphragm flexibility on the dynamic properties and seismic design parameters of buildings with plan irregularities. In addition, Savnik et al. [10] studied the influence of diaphragm modeling on the dynamic performance of a reinforced concrete high-rise building. Collectively, these studies demonstrate why diaphragm assumptions should be considered when interpreting the results of structural and seismic analyses.

The stiffness of a floor diaphragm is also related to the mechanical properties and configuration of the slab. Changes in slab thickness or in the distribution of slab properties among stories may affect the stiffness characteristics of individual floors. Research on reinforced concrete stiffening diaphragms has examined their stress–strain behavior in the presence of cross-reinforcement [11], while Pisapia et al. [12] addressed the evaluation of floor diaphragm stiffness. Studies of hollow and voided slab systems have also examined their flexural capacity and stiffness, providing additional context for understanding the mechanical behavior of different floor configurations [13], [14]. Nevertheless, findings concerning the flexural behavior of individual slab systems should not automatically be interpreted as direct evidence of their influence on the global torsional modes of an entire building.

The broader structural context is also important. The interaction between vertical resisting systems and supporting conditions can affect structural response, as illustrated by Singh and Chowdhury's [15] work on shear-wall–frame interaction considering foundation compliance. Research on precast reinforced concrete industrial buildings has further examined the influence of horizontal diaphragms and cladding wall panels on seismic behavior [16]. Although these studies consider different structural systems and research questions, they reinforce the need to assess floor diaphragms in relation to the overall structural system rather than as isolated components.

The design and analysis of reinforced concrete buildings must also be considered within the framework of applicable structural standards. ACI 318-14 provides requirements for structural concrete design [17], while ASCE/SEI 7-10 specifies minimum design loads for buildings and other structures [18]. These standards establish relevant design and loading frameworks for reinforced concrete building analysis. They do not, by themselves, establish whether a particular distribution of diaphragm stiffness will alter the formation of torsional vibration modes; this question requires examination of the structural configuration and analytical results.

Despite the existing research on diaphragm flexibility, seismic response, and diaphragm modeling, the specific effect of distributing different diaphragm stiffness assumptions across the height of a low-rise reinforced concrete building remains worthy of further numerical investigation. In particular, it is important to determine whether assigning rigid and semi-rigid diaphragm behavior to different stories, or varying slab thickness

between floors, produces observable changes in the modal characteristics and torsional mode formation of the building.

Accordingly, the present study investigates the effect of non-uniform diaphragm stiffness distribution across different stories in four-story reinforced concrete buildings. Eight three-dimensional models were developed and analyzed using ETABS. The first group of models examined different combinations of rigid and semi-rigid diaphragms across the stories. The second group investigated variations in slab thickness, considering 15 cm and 20 cm slabs in different story arrangements. The resulting natural periods, modal shapes, mass participation ratios, and displacement responses were compared to determine whether the investigated changes affected the formation of torsional vibration modes.

2 | Literature Review

The effects of diaphragm flexibility on the seismic response of buildings have been investigated in different structural systems. Fleischman and Farrow [2] studied the dynamic behavior of structures with flexible diaphragms and perimeter lateral-force-resisting systems. Their research is directly relevant to understanding how diaphragm flexibility may affect the dynamic behavior of a building. Cohen et al. [1] investigated the seismic evaluation of low-rise reinforced masonry buildings with flexible diaphragms, providing a related perspective on diaphragm flexibility in low-rise structures. Although masonry buildings differ from the reinforced concrete buildings examined in the present study, the research addresses the broader structural implications of flexible floor systems.

Moeini and Rafezy [3] investigated floor diaphragm flexibility in reinforced concrete structures and considered relevant code provisions. Their work is particularly pertinent because it addresses diaphragm flexibility in the same general material and building category as the present study. Mortazavi [4] examined the effects of diaphragm flexibility on the seismic response of one-story steel buildings. While the structural material and building height differ from those considered here, this study provides additional context for examining the role of diaphragm flexibility in seismic response.

Nakashima et al. [5] also addressed the effect of diaphragm flexibility on the seismic response of building structures. More recently, Tena-Colunga and Sabanero-García [9] examined the influence of diaphragm flexibility on dynamic properties and seismic design parameters in buildings with plan irregularities. Their focus on dynamic properties is particularly relevant to research that evaluates modal behavior and the potential influence of diaphragm assumptions on torsional response.

These studies establish diaphragm flexibility as a relevant consideration in structural analysis. However, the extent to which diaphragm flexibility affects a building depends on the characteristics of the structure under investigation. The results obtained for masonry, steel, irregular, or other building systems cannot be transferred directly to every reinforced concrete building without considering differences in structural configuration and modeling assumptions.

Diaphragm modeling is an important decision in numerical structural analysis because the selected representation determines how floor behavior is idealized. Ruggieri et al. [7] proposed a practical approach for estimating floor deformability in existing reinforced concrete buildings and examined its effects on structural response and seismic fragility. This work is relevant to the evaluation of whether floor flexibility should be explicitly considered when assessing an existing structure.

Savnik et al. [10] investigated how diaphragm modeling influences the dynamic performance of a reinforced concrete high-rise building. This research directly relates to the modeling choices considered in the present study, although the building height differs. Baldassi et al. [6] examined the modeling of in-plane floor flexibility in existing reinforced concrete buildings, further demonstrating the relevance of floor flexibility in numerical assessments of reinforced concrete structures.

The structural analysis framework also matters when evaluating dynamic behavior. Wilson [19] presented a three-dimensional approach to static and dynamic structural analysis, providing a general analytical foundation for investigating the response of structural systems. Within this context, modal analysis can be used to examine vibration periods, mode shapes, and mass participation ratios, thereby enabling comparisons between alternative structural models.

The work of Moehle et al. [8] is also relevant because it addresses the seismic design of cast-in-place concrete diaphragms, including chords and collectors. These components form part of the diaphragm's force-transfer system and should be considered when evaluating the structural role of concrete floors. Taken together, these studies provide a basis for comparing rigid and semi-rigid diaphragm idealizations and examining their implications for the dynamic properties of a building.

The mechanical properties of floor systems are relevant to diaphragm stiffness, but different measures of stiffness should be distinguished. The flexural stiffness of a slab, its in-plane diaphragm stiffness, and the effective stiffness of a floor within the complete structural system are related concepts, but they are not interchangeable.

Hud et al. [11] investigated the stress–strain state of a reinforced concrete stiffening diaphragm in the presence of cross-reinforcement. Their work provides context for understanding the mechanical behavior of reinforced concrete diaphragm components and the potential relevance of reinforcement arrangements. Pisapia et al. [12] addressed the evaluation of floor diaphragm stiffness, making their research directly relevant to the characterization of diaphragm stiffness.

Additional studies have examined the mechanical behavior of hollow and voided concrete slabs. Kim et al. [13] investigated the flexural capacity of one-way hollow slabs with donut-type hollow spheres. Teja et al. [20] studied the structural behavior of Bubble Deck slabs, while Kim [21] examined the flexural behavior of reinforced concrete and prestressed concrete void slabs incorporating polystyrene forms. Valivonis et al. [14] investigated the flexural capacity and stiffness of monolithic biaxial hollow slabs.

These studies contribute to the broader understanding of how slab configuration and material arrangement relate to mechanical behavior. However, their principal focus is on the flexural or structural performance of particular slab systems, rather than directly establishing the influence of slab thickness variation on the formation of torsional modes in a multi-story reinforced concrete building. Accordingly, they provide background for considering floor-system properties but should not be treated as direct proof of the global modal effects investigated in the present study.

Research on diaphragm behavior also includes structures that differ from conventional multi-story reinforced concrete buildings. Hojat Jalali and Maleki [22] investigated the nonlinear behavior of concrete end diaphragms in straight slab-girder bridges. Because bridge end diaphragms serve a different structural configuration and loading environment from building floor diaphragms, their findings should be interpreted within the bridge context. Nevertheless, the study provides related background on the nonlinear behavior of concrete diaphragm components.

Ostetto et al. [16] examined the influence and effectiveness of horizontal diaphragms and cladding wall panels on the seismic behavior of precast reinforced concrete industrial buildings. Their work addresses the interaction between horizontal diaphragm systems and other building components in a particular structural typology. This is relevant to the broader understanding that diaphragm performance should be considered in relation to the complete structural system.

Singh and Chowdhury [15] studied shear-wall–frame interaction while considering foundation compliance. Although their research does not specifically investigate the distribution of diaphragm stiffness across stories, it illustrates the importance of considering interactions among structural components and supporting conditions when interpreting structural response. Such considerations are relevant when distinguishing the influence of diaphragm modeling from other factors that may affect a building's dynamic behavior.

The modeling and design of reinforced concrete structures are undertaken within established design and loading frameworks. ACI Committee's ACI 318-14 provides requirements for structural concrete design and associated commentary [17]. ASCE/SEI 7-10 addresses minimum design loads for buildings and other structures [18]. These documents provide the relevant regulatory context for designing and analyzing reinforced concrete buildings subjected to structural loads.

The studies reviewed above address complementary aspects of diaphragm behavior, including seismic response, in-plane flexibility, diaphragm modeling, concrete diaphragm mechanics, and the stiffness and flexural behavior of different floor systems [1–10], [11–16], [20–22]. Wilson [19] provides a broader foundation for three-dimensional structural analysis. However, design standards and previous studies do not remove the need to examine the specific effects of the modeling assumptions adopted for a particular building configuration.

The reviewed literature demonstrates that diaphragm flexibility and modeling are relevant to the analysis of building dynamics and seismic response. Previous research has examined flexible diaphragms in different building systems [1–5], diaphragm modeling in reinforced concrete structures [6], [7], [10], the design and behavior of concrete diaphragms [8], [11], [12], and the role of diaphragms in other structural systems [15], [16], [22]. Related research has also examined the mechanical behavior of different hollow and voided slab systems [13], [14], [20], [21], while general three-dimensional structural analysis provides the analytical context for evaluating dynamic properties [19]. Tena-Colunga and Sabanero-García [9] further connect diaphragm flexibility with dynamic properties and seismic design parameters in plan-irregular buildings.

Nevertheless, the specific effect of non-uniform diaphragm stiffness distribution across the height of a low-rise reinforced concrete building, particularly its relationship with torsional mode formation, is not established by the titles and scope of these references alone. This issue therefore requires a targeted numerical investigation using a clearly defined structural model and controlled variations in diaphragm properties.

The present study addresses this issue through the analysis of eight three-dimensional four-story reinforced concrete building models using ETABS. Two groups of models are considered. The first group examines different combinations of rigid and semi-rigid diaphragm assumptions across the stories. The second group evaluates slab thickness variations, considering 15 cm and 20 cm slabs in different arrangements. The modal shapes, vibration periods, mass participation ratios, and displacement responses are compared to determine whether the examined changes in diaphragm modeling and slab thickness influence torsional mode formation in the investigated buildings.

The objective is not to assume that diaphragm stiffness has the same effect in every structure, but to evaluate the effects of the specific modeling variations considered and to identify the extent to which the findings can be applied to the investigated low-rise reinforced concrete building configuration.

3 | Research Methodology

3.1 | Structural Models and Their Specifications

The models investigated in this study are regular three-dimensional four-story frames in plan. The structures are assumed to be residential buildings with an ordinary importance level. The buildings are located in Ramsar, an area classified as having a high relative seismic hazard. The structural systems considered in this study include reinforced concrete moment-resisting frames with intermediate ductility and dual systems consisting of reinforced concrete moment-resisting frames with intermediate ductility combined with reinforced concrete shear walls with intermediate ductility. The soil at the site is classified as Type II. The story height is 3.2 m, and the floor system consists of reinforced concrete slabs. The structural grid plan is illustrated in *Fig. 1*, while the elevation of the frames along one of the principal directions is presented in *Fig. 2*.

This study will be conducted by modeling eight reinforced concrete buildings in ETABS, divided into two groups, as described below:

Group 1: The parameter under investigation is the diaphragm rigidity, considering the following configurations:

- I. All four stories with rigid diaphragms.
- II. All four stories with semi-rigid diaphragms.
- III. Two stories with rigid diaphragms and two stories with semi-rigid diaphragms.

Group 2: The parameter under investigation is the diaphragm thickness in reinforced concrete moment-resisting frames, considering the following configurations:

- I. All four stories with a slab thickness of 12 cm.
- II. All four stories with a slab thickness of 18 cm.
- III. Two stories with a slab thickness of 12 cm and two stories with a slab thickness of 18 cm.

Based on the aforementioned groups, the specimens are designated according to *Table 1*.

Table 1. Designation of the specimens investigated in this study.

Specimen ID	Lateral Load-Resisting System	Shear Wall Thickness	Diaphragm Thickness	Diaphragm Rigidity
G1-S1	Four-story reinforced concrete moment-resisting frame	—	20 cm on all four stories	Rigid on all four stories
G1-S2	Four-story reinforced concrete moment-resisting frame	—	20 cm on all four stories	Semi-rigid on all four stories
G1-S3	Four-story reinforced concrete moment-resisting frame	—	20 cm on all four stories	Rigid on the two lower stories and semi-rigid on the two upper stories
G1-S4	Four-story reinforced concrete moment-resisting frame	—	20 cm on all four stories	Rigid on the two upper stories and semi-rigid on the two lower stories
G2-S1	Four-story reinforced concrete moment-resisting frame	—	20 cm on all four stories	Rigid on all four stories
G2-S2	Four-story reinforced concrete moment-resisting frame	—	15 cm on all four stories	Rigid on all four stories
G2-S3	Four-story reinforced concrete moment-resisting frame	—	20 cm on the two lower stories and 15 cm on the two upper stories	Rigid on all four stories
G2-S4	Four-story reinforced concrete moment-resisting frame	—	20 cm on the two upper stories and 15 cm on the two lower stories	Rigid on all four stories

The following assumptions are adopted for the gravity loading of the initial frame model:

- I. The self-weight of the reinforced concrete slab is assumed to be 400 kg/m² for a slab thickness of 15 cm and 550 kg/m² for a slab thickness of 20 cm.
- II. The live load on the floors is taken as 200 kg/m², while the roof live load is assumed to be 150 kg/m².
- III. The partition load on the floors is taken as an equivalent uniformly distributed load of 100 kg/m²

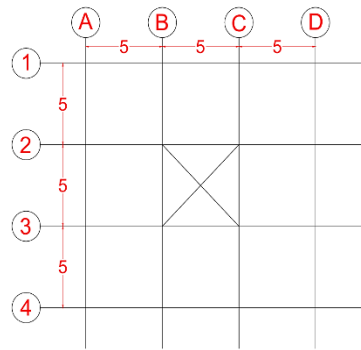


Fig. 1. Plan view of the structures under investigation.

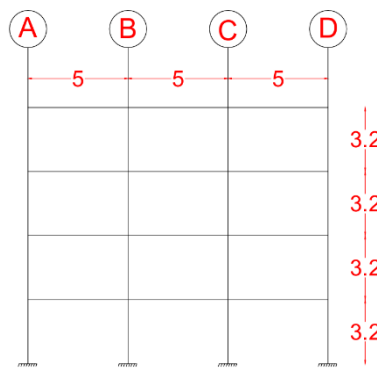


Fig. 2. Elevation view of the frames in one of the principal directions.

4 | Analysis and Conclusions

As discussed in the previous chapter, this study investigates the effect of varying diaphragm rigidity at different stories of reinforced concrete buildings on the development of torsional modes. To this end, four-story reinforced concrete moment-resisting frames with intermediate ductility were designed by varying the diaphragm rigidity and floor slab thickness. Their performance was evaluated using the absolute story displacement, interstory drift, and mass participation ratios in torsional modes as the assessment criteria.

4.1 | Effect of Story Diaphragm Rigidity on the Development of Torsional Modes

To investigate the effect of diaphragm rigidity on the behavior of reinforced concrete moment-resisting frames, four four-story frames were examined. In one model, the diaphragms of all four stories were assumed to be rigid, whereas in another model, the diaphragms of all four stories were assumed to be semi-rigid. In the remaining two models, the diaphragms of two stories were assumed to be rigid, while those of the other two stories were considered semi-rigid.

Table 2 presents the modal mass participation ratios and the natural period of each mode for specimen G1-S1. As can be observed, the third mode is the torsional mode of the structure, with a mass participation ratio of 0.8247 and a natural period of 0.755 seconds.

Table 2. Modal mass participation ratios and natural periods for specimen G1-S1.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z Axis
1	0.842	0.8199	0.0042	0
2	0.842	0.0042	0.8199	0
3	0.755	0	0	0.8247

Fig. 3 illustrates the third mode (torsional mode) developed at the fourth story of specimen G1-S1. Figs. 4 and 5 also present the absolute displacements and interstory drifts of specimen G1-S1 in the X and Y directions, respectively.

Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 1.44 mm, the maximum interstory drift in the X and Y directions is 0.004, and the torsional rotation about the Z axis is 0.000007 radians.

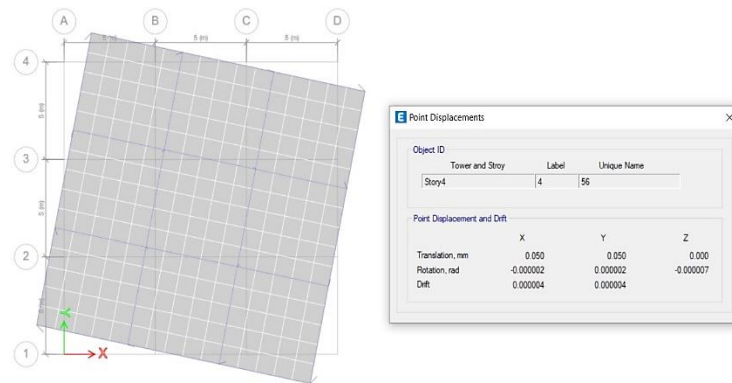
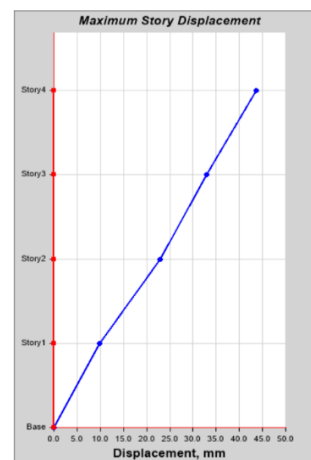
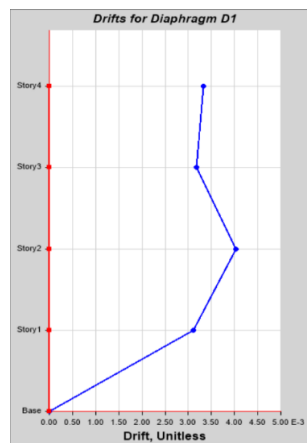


Fig. 3. Torsional mode shape at the fourth floor of specimen G1-S1.

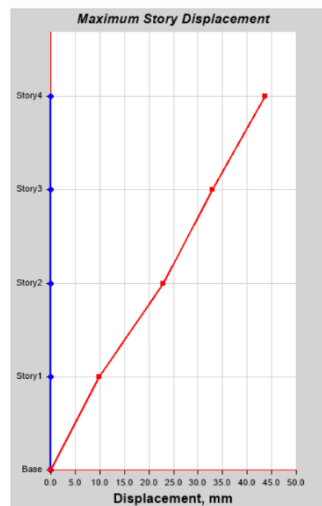


a.

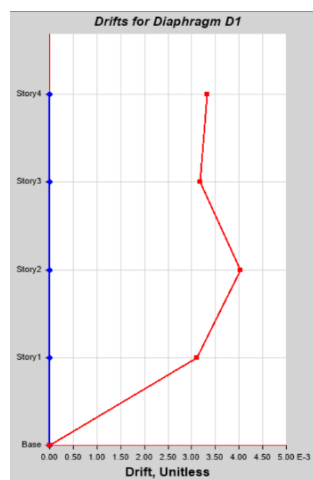


b.

Fig. 4. Evaluation of the behavior of specimen G1-S1 in the X Direction: a. Absolute displacement, b. Relative displacement.



a.



b.

Fig. 5. Evaluation of the behavior of specimen G1-S1 in the Y direction; a. Absolute displacement, and b. Relative displacement.

Table 2 presents the mass participation ratios and natural periods of each mode of the structure under investigation for specimen G1-S2. As can be observed, the third mode is the torsional mode of the structure, with a mass participation ratio of 0.8245 and a natural period of 0.756 seconds.

Fig. 6 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G1-S2. Figs. 7 and 8 also show the absolute and relative displacements of specimen G1-S2 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 44.6 mm, the maximum interstory drift ratio in the X and Y directions is 0.004, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 2. Modal mass participation ratios and natural periods of the modes of specimen G1-S2.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.842	0.8211	0.003	0
2	0.842	0.003	0.8211	0
3	0.756	0	0	0.8245

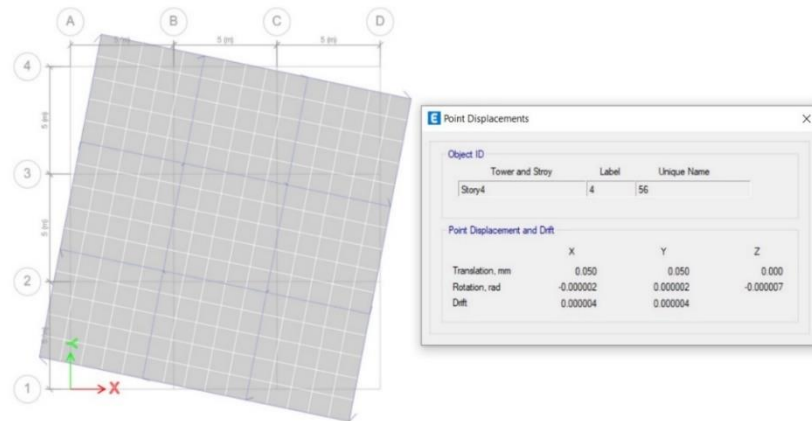
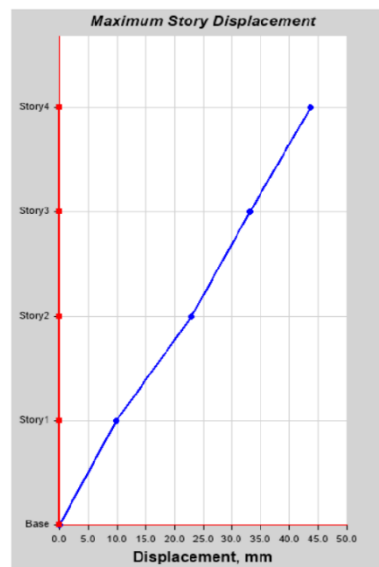
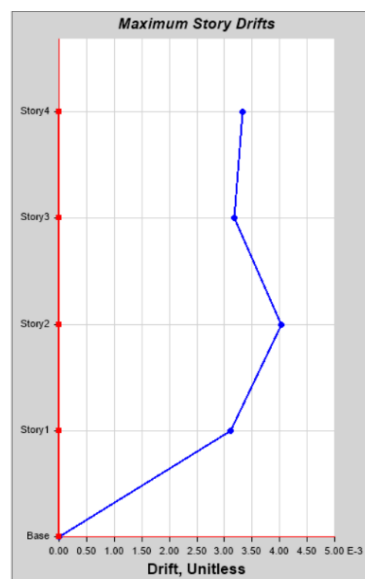


Fig. 6. Torsional mode shape at the fourth floor of specimen G1-S2.

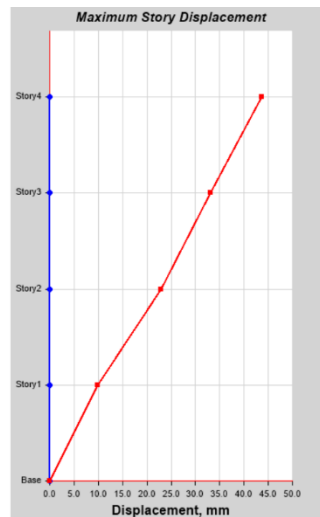


a.

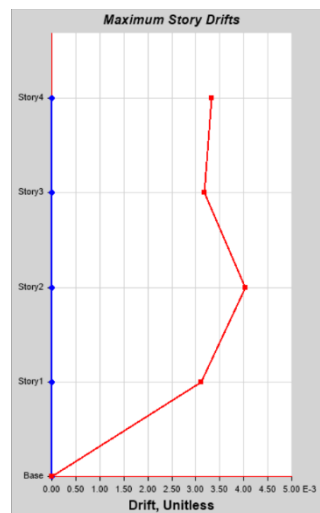


b.

Fig. 7. Evaluation of the behavior of specimen G1-S2 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 8. Evaluation of the behavior of specimen G1-S2 in the Y direction; a. Absolute displacement, and b. Relative displacement.

Table 3 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G1-S3. As can be observed, the third mode is the torsional mode of the structure, with a mass participation ratio of 0.8245 and a natural period of 0.756 seconds.

Fig. 9 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G1-S3. Figs. 10 and 11 also show the absolute and relative displacements of specimen G1-S3 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 44.6 mm, the maximum interstory drift ratio in the X and Y directions is 0.004, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 3. Modal mass participation ratios and natural periods of the modes of specimen G1-S3.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.842	0.8214	0.0042	0
2	0.842	0.0042	0.8214	0
3	0.756	0	0	0.8245

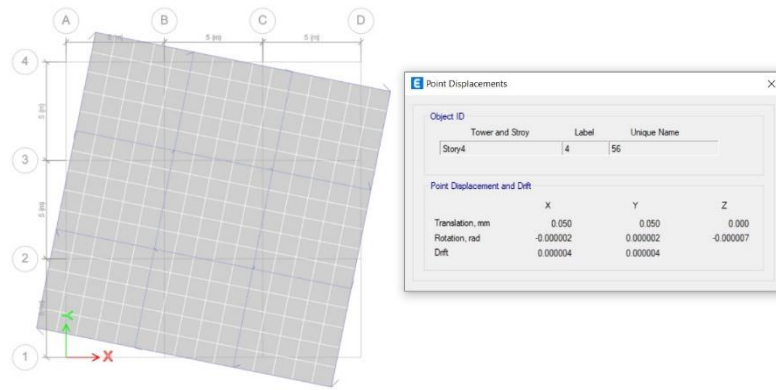
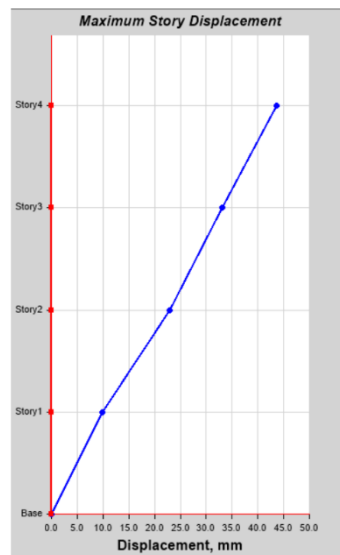
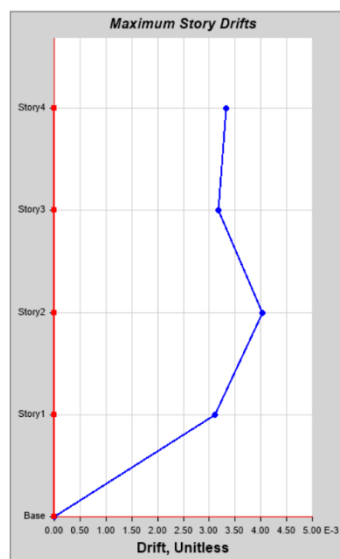


Fig. 9. Torsional mode shape at the fourth floor of specimen G1-S3.

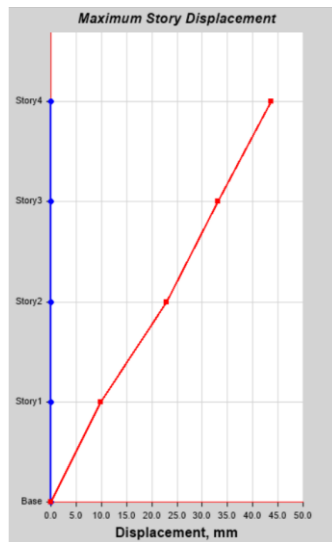


a.

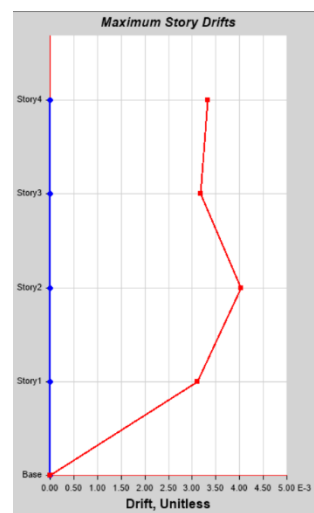


b.

Fig. 10. Evaluation of the behavior of specimen G1-S3 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 11. Evaluation of the behavior of specimen G1-S3 in the Y direction; a. Absolute displacement, and b. Relative displacement.

Table 4 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G1-S4. As can be observed, the third mode is the torsional mode of the structure, with a mass participation ratio of 0.8247 and a natural period of 0.755 seconds.

Fig. 12 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G1-S4. Figs. 13 and 14 also show the absolute and relative displacements of specimen G1-S4 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 44.6 mm, the maximum interstory drift ratio in the X and Y directions is 0.004, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 4. Modal mass participation ratios and natural periods of the modes of specimen G1-S4.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.842	0.8208	0.003	0
2	0.842	0.003	0.8208	0
3	0.755	0	0	0.8247

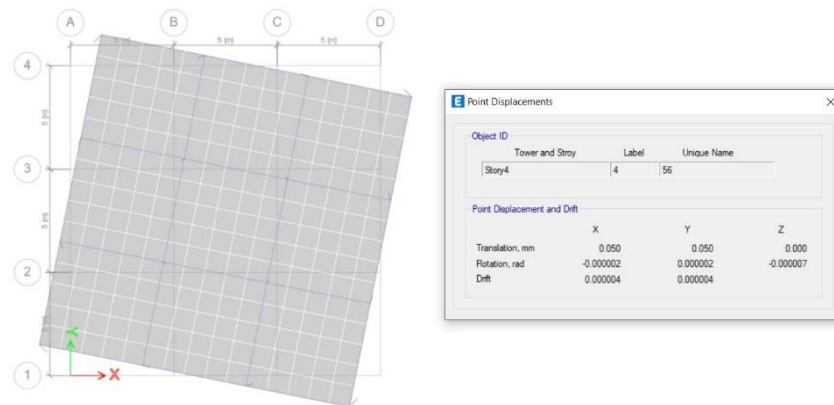
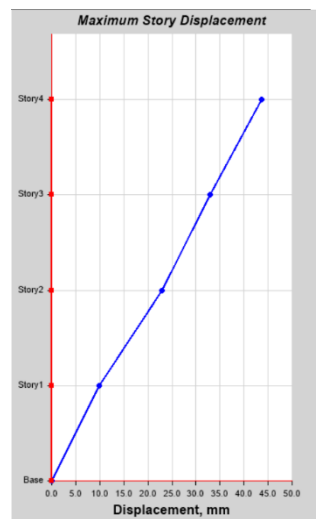
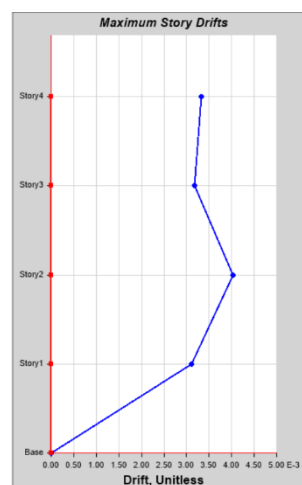


Fig. 12. Torsional mode shape at the fourth floor of specimen G1-S4.

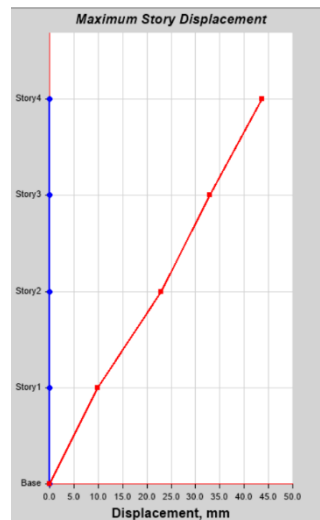


a.

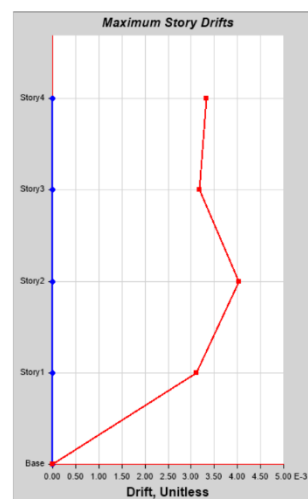


b.

Fig. 13. Evaluation of the behavior of specimen G1-S4 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 14. Evaluation of the behavior of specimen G1-S4 in the Y direction;
a. Absolute displacement, and b. Relative displacement.

The results obtained from examining the behavior of the specimens in Group G1 indicate that changes in floor diaphragm stiffness do not affect the formation of the torsional mode in low-rise reinforced concrete structures. In the specimens belonging to Group G1, the cross-sectional properties of the beams and columns were kept constant, while floor diaphragm stiffness was considered the variable parameter. The results show that the natural periods of the specimens are approximately 0.75 seconds and that the modal mass participation ratio of the third mode (torsional mode) is approximately 0.82 in all specimens.

Furthermore, the investigations indicate that, in the low-rise reinforced concrete frames examined, changes in slab thickness and diaphragm stiffness do not affect the maximum absolute displacement or the maximum relative displacement (interstory drift) of the structure. Accordingly, the maximum interstory drift ratio in the structures under investigation is 0.004, while the maximum absolute displacement is approximately 45 mm.

4.2 | Effect of Floor Slab Thickness on the Formation of Torsional Modes

To investigate the effect of slab thickness on the behavior of reinforced concrete moment-resisting frames, four four-story frames were examined. In one specimen, the slab thickness was set to 20 cm on all four floors, while in another specimen, the slab thickness was set to 15 cm on all four floors. In the remaining two specimens, the slab thickness was set to 15 cm on two floors and 20 cm on the other two floors.

Table 5 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G2-S1. As can be observed, the third mode is the torsional mode of the structure, with a modal mass participation ratio of 0.8247 and a natural period of 0.755 seconds.

Table 5. Modal mass participation ratios and natural periods of the modes of specimen G2-S1.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.842	0.8199	0.0042	0
2	0.842	0.0042	0.8199	0
3	0.755	0	0	0.8247

Fig. 15 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G2-S1. Figs. 16 and 17 also show the absolute and relative displacements of specimen G2-S1 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 44.8 mm, the maximum interstory drift ratio in the X and Y directions is 0.004, and the torsional rotation about the Z-axis is 0.000007 radians.

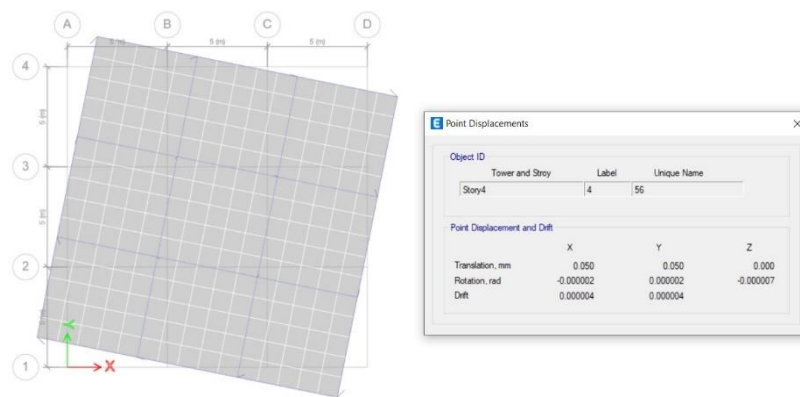
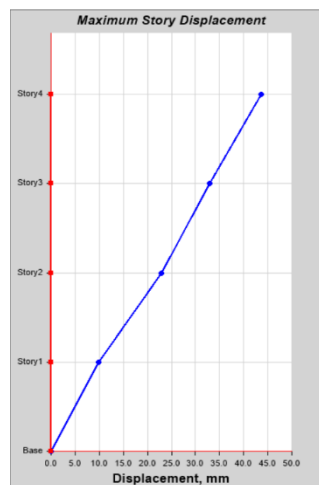
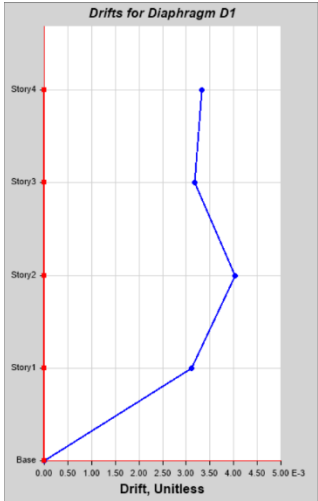


Fig. 15. Torsional mode shape at the fourth floor of specimen G2-S1.

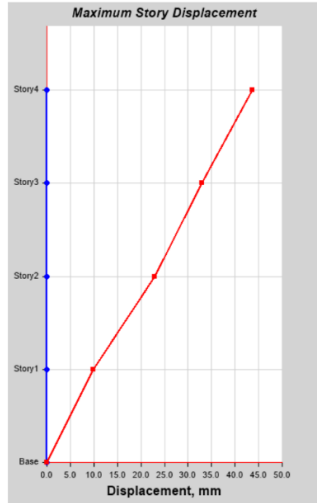


a.

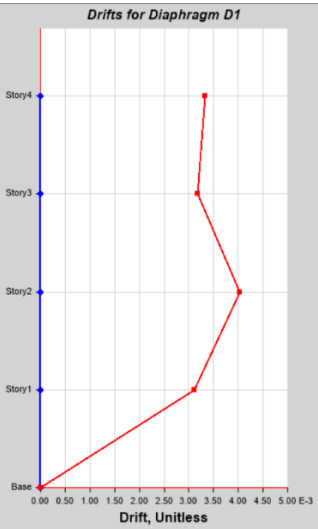


b.

Fig. 16. Evaluation of the behavior of specimen G2-S1 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 17. Evaluation of the behavior of specimen G2-S1 in the X direction; a. Absolute displacement, and b. Relative displacement.

Table 6 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G2-S2. As can be observed, the third mode is the torsional mode of the structure, with a modal mass participation ratio of 0.8223 and a natural period of 0.772 seconds.

Fig. 18 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G2-S2. Figs. 19 and 20 also show the absolute and relative displacements of specimen G2-S2 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 45.8 mm, the maximum interstory drift ratio in the X and Y directions is 0.0045, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 6. Modal mass participation ratios and natural periods of the modes of specimen G2-S2.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.872	0.8234	0.0037	0
2	0.872	0.0037	0.8234	0
3	0.772	0	0	0.8223

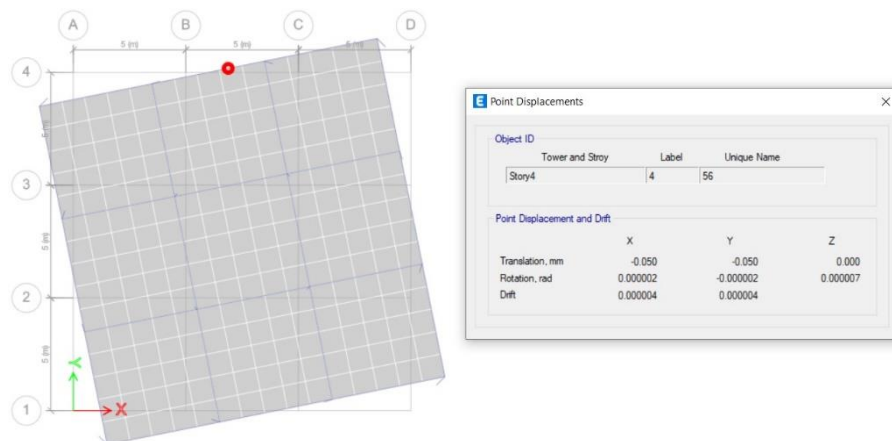
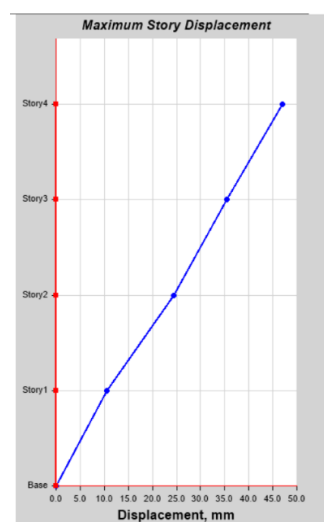
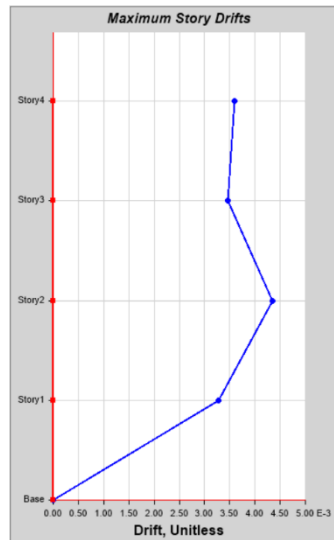


Fig. 18. Torsional mode shape at the fourth floor of specimen G2-S2.

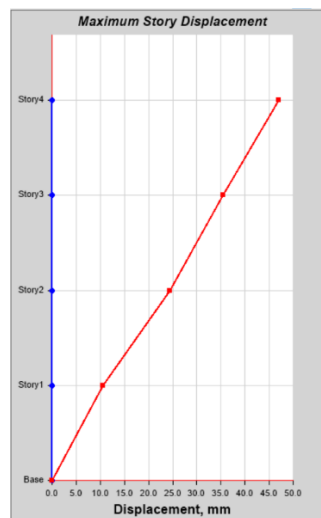


a.

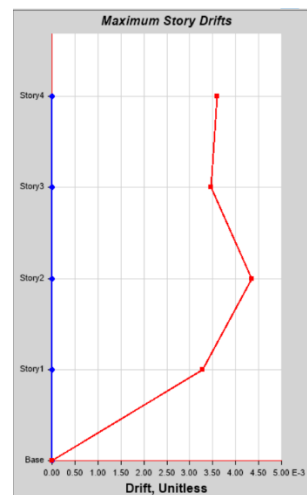


b.

Fig. 19. Evaluation of the behavior of specimen G2-S2 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 20. Evaluation of the behavior of specimen G2-S2 in the X direction; a. Absolute displacement, and b. Relative displacement.

Table 7 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G2-S3. As can be observed, the third mode is the torsional mode of the structure, with a modal mass participation ratio of 0.8203 and a natural period of 0.759 seconds.

Fig. 21 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G2-S3. Figs. 22 and 23 also show the absolute and relative displacements of specimen G2-S3 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 45 mm, the maximum interstory drift ratio in the X and Y directions is 0.004, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 7. Modal mass participation ratios and natural periods of the modes of specimen G2-S3.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.849	0.8099	0.004	0
2	0.849	0.004	0.8099	0
3	0.759	0	0	0.8203

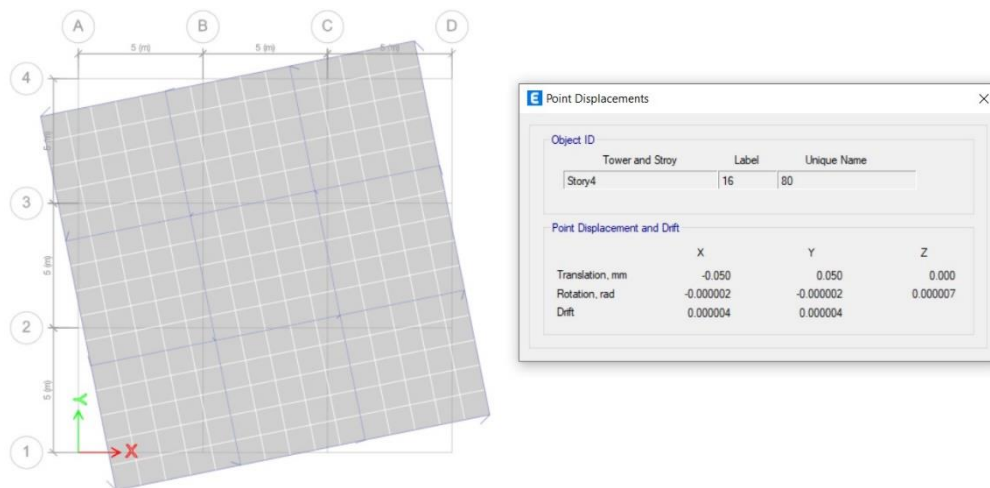
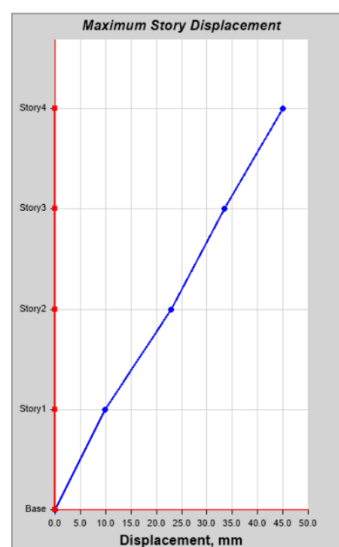
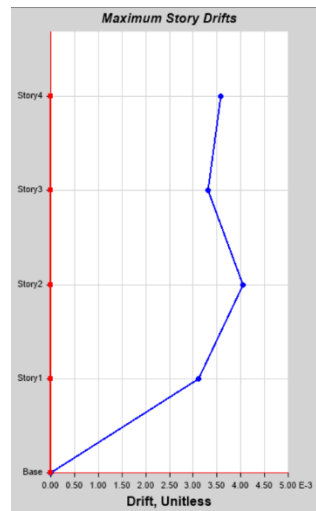


Fig. 21. Torsional mode shape at the fourth floor of specimen G2-S3.

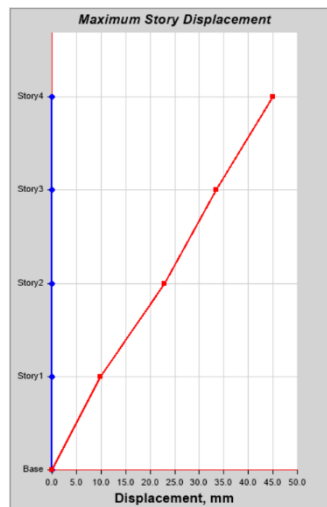


a.

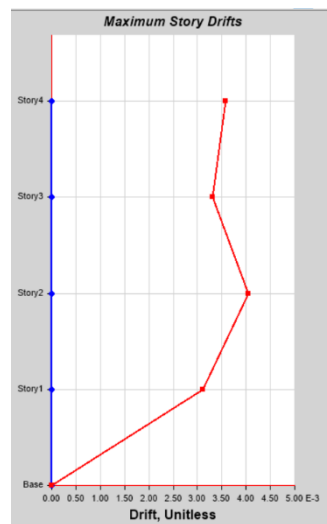


b.

Fig. 22. Evaluation of the behavior of specimen G2-S3 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.



b.

Fig. 23. Evaluation of the behavior of specimen G2-S3 in the X direction; a. Absolute displacement, and b. Relative displacement.

Table 8 presents the modal mass participation ratios and natural periods of each mode of the structure under investigation for specimen G2-S3. As can be observed, the third mode is the torsional mode of the structure, with a modal mass participation ratio of 0.8266 and a natural period of 0.768 seconds.

Fig. 24 illustrates the third mode shape (torsional mode) occurring at the fourth floor of specimen G2-S3. Figs. 25 and 26 also show the absolute and relative displacements of specimen G2-S3 in the X and Y directions, respectively. Examination of these figures indicates that the maximum absolute displacement of the frame in the X and Y directions is 45.2 mm, the maximum interstory drift ratio in the X and Y directions is 0.0045, and the torsional rotation about the Z-axis is 0.000007 radians.

Table 8. Modal mass participation ratios and natural periods of the modes of specimen G2-S4.

Mode Number	Natural Period (s)	Modal Mass Participation in the X Direction	Modal Mass Participation in the Y Direction	Modal Mass Participation About the Z-Axis
1	0.865	0.8233	0.0038	0
2	0.865	0.0038	0.8233	0
3	0.768	0	0	0.8266

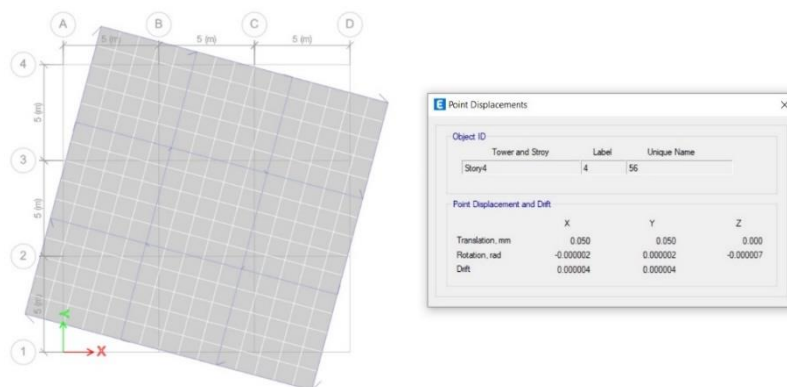
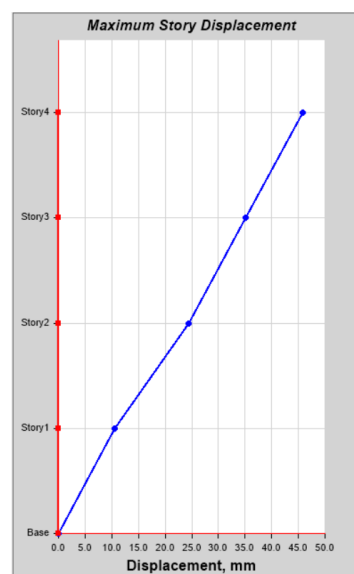
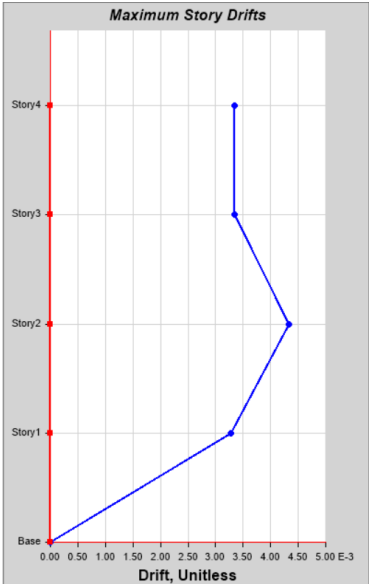


Fig. 24. Torsional mode shape at the fourth floor of specimen G2-S4.

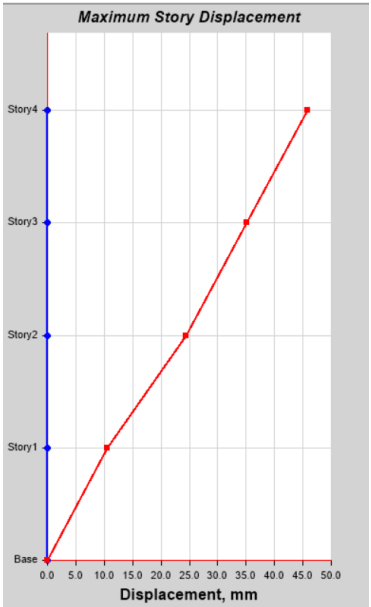


a.



b.

Fig. 25. Evaluation of the behavior of specimen G2-S4 in the X direction; a. Absolute displacement, and b. Relative displacement.



a.

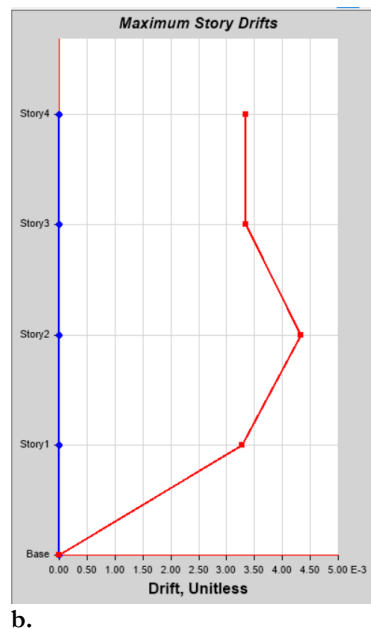


Fig. 26. Evaluation of the behavior of specimen G2-S4 in the X direction; a. Absolute displacement, and b. Relative displacement.

The results obtained from examining the behavior of the specimens in Group G2 indicate that changes in floor slab thickness do not affect the formation of the torsional mode in low-rise reinforced concrete structures. In the specimens belonging to Group G2, the cross-sectional properties of the beams and columns were kept constant, while floor slab thickness was considered the variable parameter. The results show that the natural periods of the specimens are approximately 0.75 seconds and that the modal mass participation ratio of the third mode (torsional mode) is approximately 0.82 in all specimens.

Furthermore, the investigations indicate that, in the low-rise reinforced concrete frames examined, changes in slab thickness do not affect the maximum absolute displacement or the maximum relative displacement (interstory drift) of the structure. Accordingly, the maximum interstory drift ratio in the structures under investigation is 0.004, while the maximum absolute displacement is approximately 45 mm.

5 | Conclusion

This study investigated the effect of the nonuniform distribution of diaphragm stiffness across different floors of reinforced concrete buildings on the formation of torsional modes. Specifically, the study sought, where possible, to develop a method for predicting changes in the behavior of reinforced concrete frames resulting from variations in diaphragm stiffness across different stories, based on the findings of this research.

The research methodology used to investigate the parameters of interest consisted of the following steps:

- I. Three-dimensional modeling of reinforced concrete frames in ETABS: The structures under investigation were designed as four-story buildings, with three 5 m bays in each principal direction.
- II. Investigation of diaphragm behavior and thickness: The effects of diaphragm behavior and slab thickness at different stories on diaphragm stiffness and the formation of torsional modes were investigated. For this purpose, eight four-story reinforced concrete frames were modeled in ETABS and divided into two groups, as described below. It should be noted that only one parameter was varied within each group, while all other parameters were kept constant. The floors were modeled as flat reinforced concrete slabs. Accordingly, the study involved modeling eight reinforced concrete buildings in two groups using ETABS:
 - *Group 1, Diaphragm stiffness: The investigated parameter was whether the floor diaphragms behaved as rigid or semi-rigid diaphragms. The configurations included all four floors with rigid diaphragms, all*

four floors with semi-rigid diaphragms, and two floors with rigid diaphragms and two floors with semi-rigid diaphragms.

- Group 2, Slab thickness in reinforced concrete moment-resisting frames: The investigated parameter was diaphragm thickness. The configurations included a slab thickness of 15 cm on all four floors, a slab thickness of 20 cm on all four floors, and a combination of 15 cm slabs on two floors and 20 cm slabs on the other two floors.

III. Evaluation of the effects of the investigated parameters: The effects of each parameter on diaphragm stiffness and the formation of torsional modes in the modeled buildings were examined within each group. Ultimately, the study aimed, where possible, to establish a method for predicting changes in reinforced concrete frame behavior resulting from variations in diaphragm stiffness across different stories.

The main findings of the study are summarized as follows:

In Group 1, where diaphragm stiffness across the floors was the variable parameter, the natural periods of the specimens were approximately 0.75 seconds, and the modal mass participation ratio of the third mode (torsional mode) was approximately 0.82 in all specimens.

The results indicate that changes in floor diaphragm stiffness do not affect the formation of the torsional mode in low-rise reinforced concrete structures.

In Group 2, where floor slab thickness was the variable parameter, the natural periods of the specimens were approximately 0.75 seconds, and the modal mass participation ratio of the third mode (torsional mode) was approximately 0.82 in all specimens.

The results indicate that changes in floor slab thickness do not affect the formation of the torsional mode in low-rise reinforced concrete structures.

The investigations indicate that, in the low-rise reinforced concrete frames examined, changes in slab thickness and diaphragm stiffness do not affect the maximum absolute displacement or the maximum relative displacement (interstory drift) of the structure. The maximum interstory drift ratio in the investigated structures was 0.004, while the maximum absolute displacement was approximately 45 mm.

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