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Effect of the diaphragm conditions on the structural response of tunnel-form buildings

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Abstract. Tunnel-Form Buildings (TFBs) offer a rapid and cost-effective construction method for mass housing projects, particularly in low- to medium-rise structures. Despite their widespread use and favorable seismic performance, a lack of specific seismic design standards for TFBs persists. Moreover, the impact of diaphragm flexibility on their seismic behavior remains under-investigated, leading to uncertainties in structural design. The structural engineers often rely on general methods for reinforced concrete structures, which have proven inadequate. Given the substantial computation costs of TFBs, engineers are often tempted to consider the slabs as rigid diaphragms, whether rightly or wrongly. This study investigates the influence of diaphragm flexibility on the seismic response of two typical six-story TFB configurations employed in a large-scale housing project in Algeria. Utilizing validated finite element models, the structural behavior of these configurations under seismic loading was compared, taking into account both rigid and realistically modeled diaphragms. Linear and non-linear analyses are conducted to assess the impact of diaphragm flexibility on key performance parameters, including displacements, member forces, and energy dissipation mechanisms. The findings of this study contribute valuable insights for the seismic design and analysis of TFBs, providing a more accurate representation of their structural behavior and informing the development of improved design guidelines.

Keywords: diaphragms (concrete); flexibility; rigidity; shear walls; structural design; tunnel-form buildings

1. Introduction

The Tunnel-Form System (TFS) is a widely recognized modern construction method and industrialized building system. TFS utilizes prefabricated modules, to form concrete walls and floors (Fig. 1). These modules are designed for easy installation and removal, enabling a continuous construction process. This technology is especially beneficial for residential, commercial, and infrastructure projects where speed and cost-effectiveness are essential.

Tunnel-Form Buildings (TFBs) are reinforced concrete structures that use modular steel forms to cast walls and slabs in a single operation (Fig. 2). The TFBs are frequently employed for mass housing projects because of their advantages, which include quicker building times, reduced construction costs, and seismic performance, particularly for low- to mid-rise structures (Balkaya and Kalkan 2003, Deger and Wallace 2015, Shamilah *et al.* 2023, Yakut and Gulkan 2003). However, TFBs have some limitations such as high sensitivity to near-fault ground motions. Existing research has demonstrated that high-rise tunnel-form structures can sustain significant damage (Deger and Wallace 2015, Gallardo *et al.* 2021, Guler *et al.* 2018, Ugalde *et al.* 2019). TFB have demonstrated notable seismic performance during the February 6, 2023 earthquake (Figs. 3 and 4). This earthquake, with a magnitude of 7.8, struck near the Turkey-Syria border,

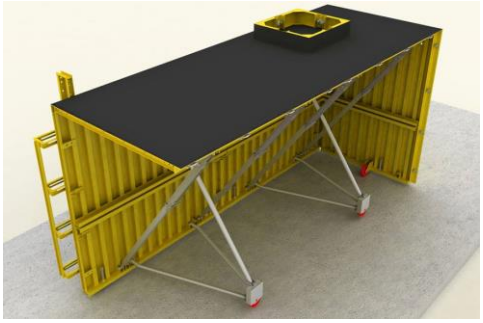

Fig. 1 Modular steel forms used in tunnel-form buildings

Fig. 2 Modular steel forms used for mass housing projects

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Fig. 3 Kahramanmaras tunnel-form buildings: Robust and resistant to damage after the February 6, 2023 earthquake

causing extensive damage and loss of life (Celik *et al.* 2024).

The issue with TFBs is the absence of dedicated design codes and standards. Current seismic codes do not fully address their unique requirements. Consequently, designers often rely on standard seismic design methods for reinforced concrete structures. However, subsequent research has demonstrated that these methods are inadequate for TFBs (Yuksel and Kalkan 2007). Studies have revealed that empirical formulas provided by seismic codes often give an inaccurate estimate of the fundamental period of vibration of the TFBs. Because these formulas are derived from approximate methods, based on the base and height of the building, which are not sufficient to completely describe the dynamic properties of the TFBs. As a result, there are large differences between predicted and observed fundamental periods (Balkaya and Kalkan 2003, 2004, Hadzima-Nyarko *et al.* 2022, Lee *et al.* 2000). Furthermore, the structural properties of TFBs, which derive from their construction type, frequently result in the first mode being torsional due to their configuration and stiffness distribution (Hamid and Shahbudin 2021, Tozlu and Borekci 2024).

Recent studies have greatly enhanced the understanding of the seismic performance and reliability of tunnel-form concrete structures. Beheshti and Asayesh (2017) found that asymmetric TFBs, despite their susceptibility to torsional vibrations, exhibit excellent seismic performance due to their high lateral stiffness and strength. Mohsenian *et al.* (2019) proposed new response modification factors and fragility curves for irregular TFBs, demonstrating that these buildings can meet immediate occupancy performance requirements under design-basis earthquakes. Further research by Mohsenian *et al.* (2020) suggested that these structures perform adequately despite geometric irregularities, indicating that current design codes might be overly conservative. In 2021, Mohsenian *et al.* (2021) showed that tunnel-form concrete structures maintain performance under sequential earthquakes, proving their

Fig. 4 Osmaniye's tunnel-form buildings: Minimal damage after the February 6, 2023 earthquake

robustness. Sadeghi *et al.* (2023) compared these buildings to traditional ones in Iran, finding that tunnel-formwork RC shear walls are more economical and perform better in seismic conditions. Mohsenian and Di-Sarno (2024a) emphasized the need for refined predictive models, as traditional methods often misestimate the performance point during seismic events. Their subsequent study (Mohsenian and Di-Sarno 2024b) identified that shear failure in tunnel-form concrete systems is deformation-controlled, while bending failure is force-controlled.

Despite extensive research, the role of diaphragm flexibility in these structures remains underexplored. Diaphragms are crucial for distributing seismic forces, and their rigidity or flexibility can significantly impact the overall seismic response. A flexible diaphragm may increase lateral displacements and torsional effects, while a rigid diaphragm can enhance force distribution and structural integrity.

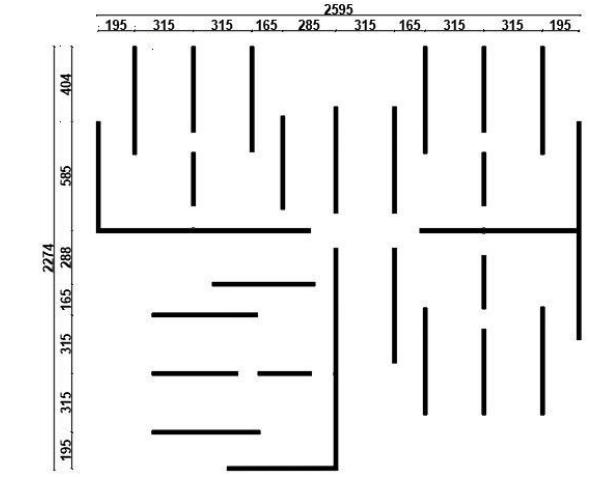
Finite element analyses were conducted on six-story TFBs with both rigid and realistically modeled diaphragms to assess the impact of diaphragm flexibility on their structural behavior under lateral loading. Model validation was performed prior to analysis. A thorough nonlinear analysis of diaphragm conditions is crucial for developing accurate predictive models and design guidelines that ensure the performance of tunnel-form buildings in seismic regions. This research aims to address this critical knowledge gap and provide valuable insights for structural engineers in the design and analysis of these structures.

2. Overview and numerical modeling of two TFB case studies

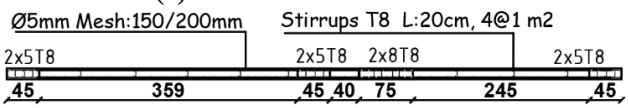
2.1 Description of the two TFBs

For this study, following common practices for this type of construction in various projects, a large-scale construction project involving 1500 housing units in Algeria, which utilized the tunnel-formwork system, was selected for the study. Two structural configurations were employed: one for corner buildings (Fig. 5) and another for interior buildings (Fig. 6). These TFBs consist of six stories with one underground level, each story having a height of three meters.

(a) Plan view of a typical floor

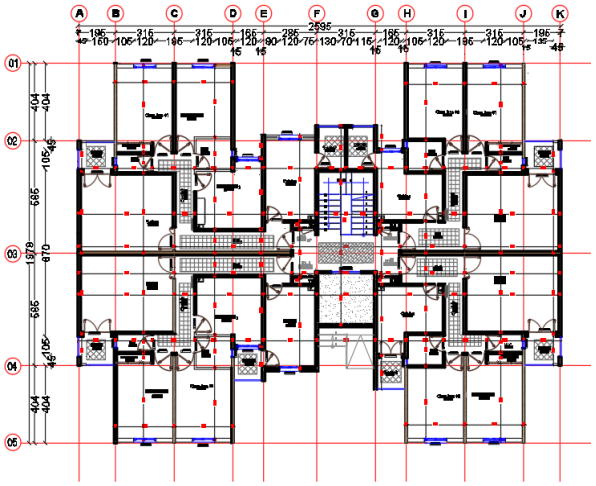


(b) Distribution of shear walls

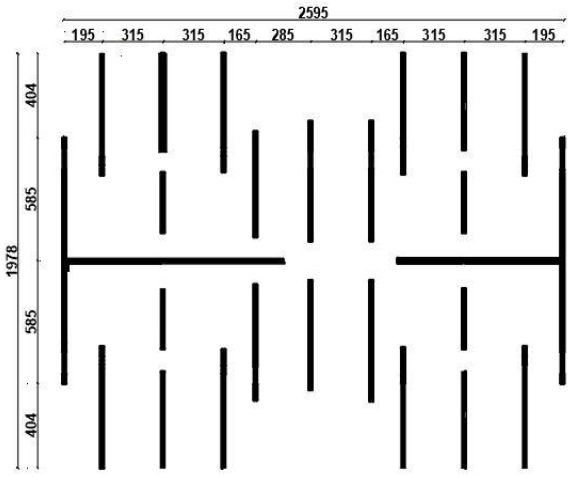


(c) Reinforcement for a typical shear wall

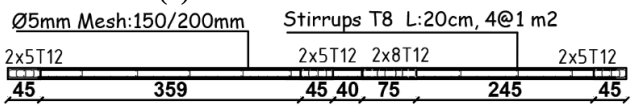
Fig. 5 Case study of the investigated TFB (Configuration 1: corner building)



(a) Plan view of a typical floor



(b) Distribution of shear walls



(c) Reinforcement for a typical shear wall

Fig. 6 Case study of the investigated TFB (Configuration 2: interior building)

Table 1 Mechanical properties of steel

Linear material properties	
Young's modulus	210000 MPa
Poisson's ratio	0.3
Mass density	7850 kg/m^3
Plasticity properties	
Yield stress	400 MPa
Ultimate stress	

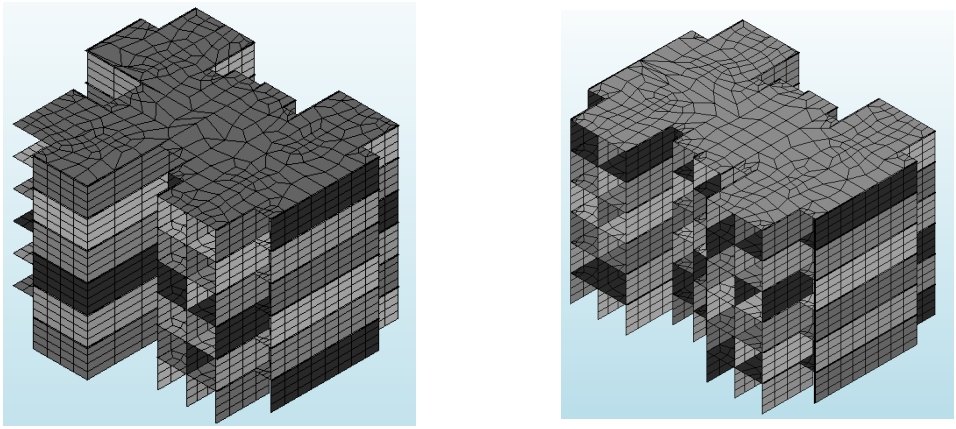
Table 2 Mechanical properties of concrete

Linear material properties	
Young's modulus	26071.6 MPa
Poisson's ratio	0.2
Mass density	2500 kg/m^3
Compression behavior	
Compression curve	CEB-FIP Model code 1990
Compression strength	30 MPa
Tensile behavior (Hordijk curve)	
Tensile strength	Mode-I tensile fracture energy
1.8 MPa	50 N/m

The TFBs are subjected to gravity loads, including a superimposed dead load of 2.5 kN/m² and a live load of 1.5 kN/m². they were designed for a moderate seismic zone according to the Algerian seismic code (RPA99-V2003 2003) and the Algerian concrete code (CBA 93 1993). Details of the reinforcement of a typical shear wall are shown in Fig. 5(c) and 6(c). The slabs have a thickness of 14 cm and are reinforced with a welded mesh of 5 mm diameter, with a grid spacing of 150 mm×200 mm.

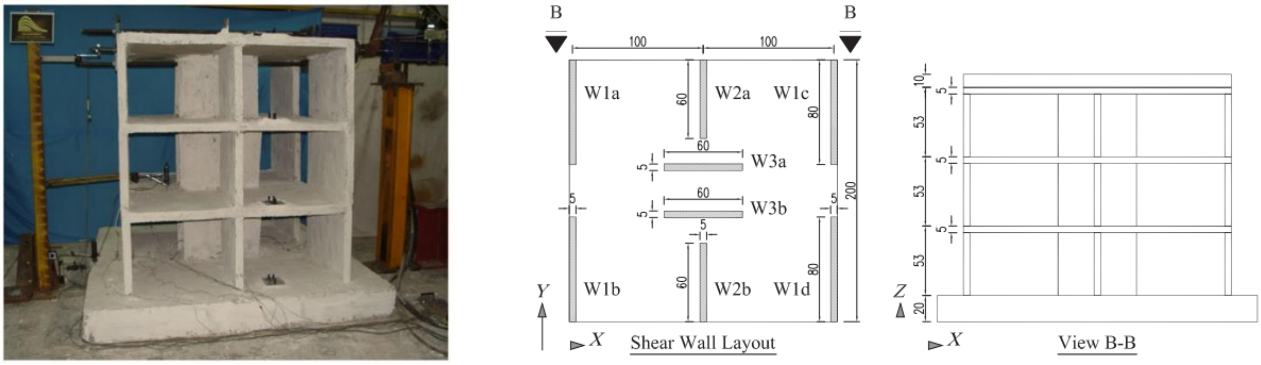
2.2 Material properties and finite elements models

The nonlinear physical properties of materials are



(a) Case study 1: Corner building (b) Case study 2: Interior building

Fig. 7 Numerical models of the investigated TFB



(a) 1/5 scale representation of TFB (b) Scaled dimensions (centimeters)

Fig. 8 Numerical models of the investigated TFB

characterized by an elastic-plastic stress-strain relationship for steel (see Table 1) and a total strain-based rotating crack model for concrete available in Diana FEA library (DIANA FEA BV 2019). The tensile behavior follows the Hordijk curve, while the compressive behavior adheres to the CEB-FIP Model Code 1990 curve, as detailed in Table 2.

For the numerical analysis, DIANA-FEA finite element software was used (DIANA FEA BV 2019). DIANA-FEA has improved capabilities for nonlinear analysis, material modeling, and dynamic simulations, making it an effective tool for complicated structural analysis. Its powerful solver and large material library ensure accurate and efficient modeling of real-world engineering problems.

Detailed finite element models of a six-story building were created, incorporating both rigid and realistic diaphragms. The realistic diaphragms aimed to accurately represent structural components such as reinforced concrete (RC) slabs and shear walls. The concrete slabs and shear walls were modeled using regular curved shell elements with 20 nodes and quadratic displacement interpolation. Each node of a curved shell element usually has 6 Degrees of Freedom (3 translational and 3 rotational DOF). These elements are suitable for capturing bending, membrane, and shear behaviors in thin to moderately thick shell structures. Embedded grid elements, with 3 DOF per node (translational DOF in the x, y, and z directions), were employed to simulate the reinforcing steel bars. These elements are fully bonded to the concrete elements, ensuring compatibility between the reinforcement and the surrounding concrete. A total strain-based rotating crack model is used for the concrete elements, which accounts for cracking in tension (using the Hordijk curve) and crushing in compression (following the CEB-FIP Model Code 1990 curve).

The rigid diaphragm was simulated by defining master DOF at the center of mass of each floor, which effectively constrained the in-plane motion of all nodes within the diaphragm to act as a rigid body. For the "realistic" diaphragm, the slab was modeled explicitly using shell elements to capture its semi-rigid behavior, allowing for both in-plane and out-of-plane deformations. This approach ensures that the diaphragm's behavior aligns with real-world structural response, accounting for both rigidity and flexibility as appropriate.

Geometric nonlinearity is incorporated into the analysis and is accounted for using the capabilities provided by Diana FEA. This will ensure that P-Delta effects and potential changes in stiffness are accurately captured.

A uniformly distributed lateral load of 100 kN/m was applied incrementally at each floor until structural failure occurred. Load steps and sub-steps were utilized to ensure numerical stability and accuracy in capturing the structure's non-linear behavior. In the Diana FEA analysis, the target load level of 100 kN/m was achieved by defining 20

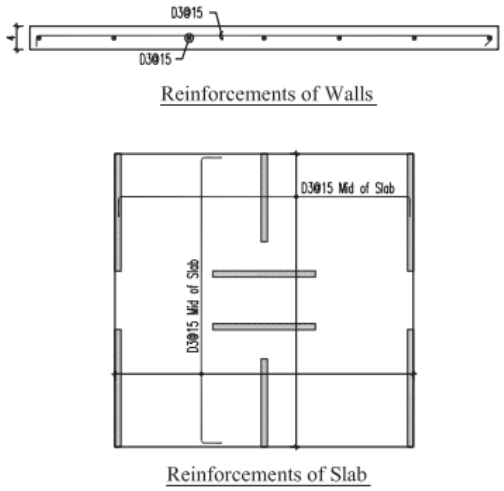


Fig. 9 Reinforcement details for the slab and walls of the Experimental model

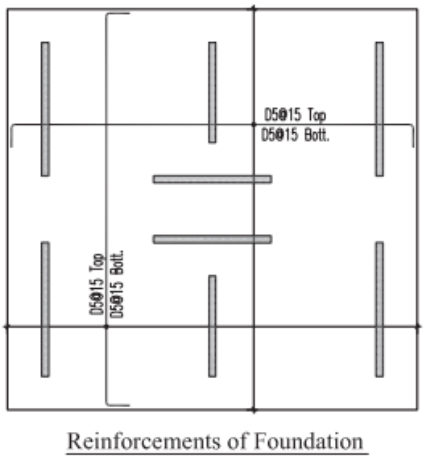
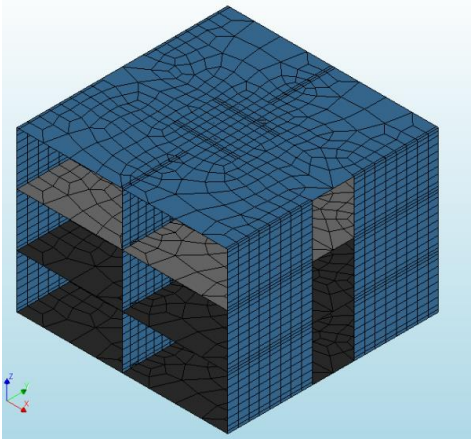
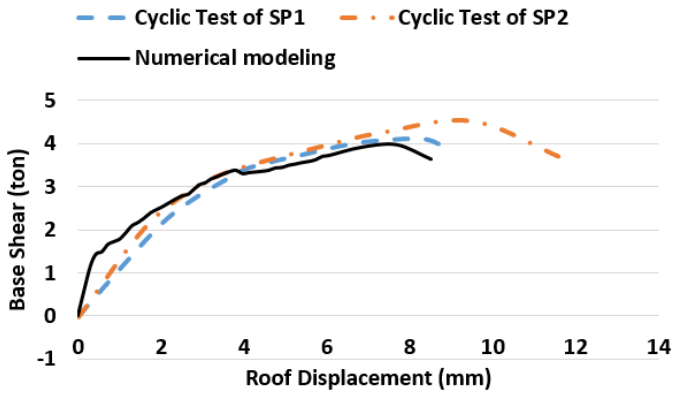


Fig. 10 Reinforcement details for the foundation of the Experimental model



(a) Finite element model of experimental TBF



(b) Base shear vs. top displacement curves: close agreement with minor discrepancies

Fig. 11 Comparison of numerical model and test specimen

increments of 5 kN/m each. In combination with the arc-length control method, the size of the increments could adapt within each step, although the initial increment value remained fixed. This approach allowed for precise tracking of the structural response throughout the loading process.

2.3 Verification of the finite element model

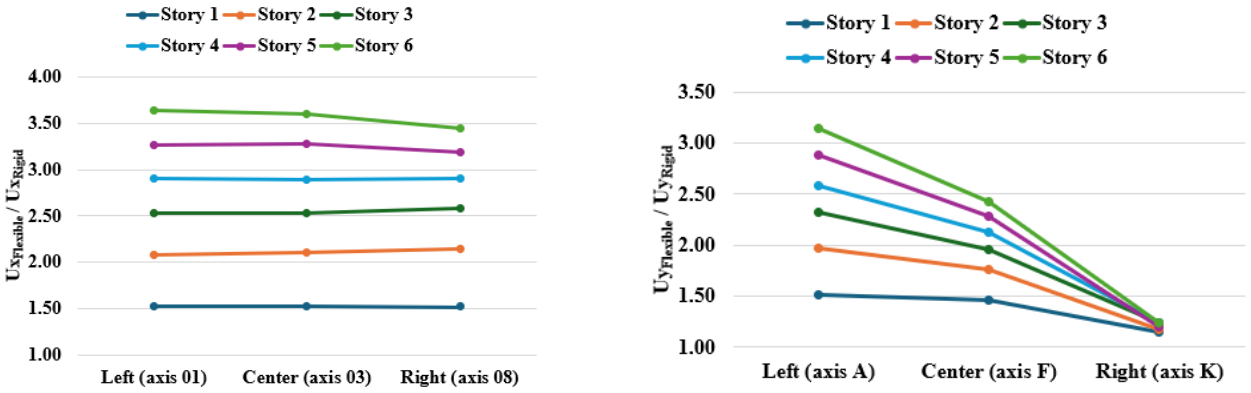
To validate the finite element model, an experimental model from specialized literature was utilized (Tavafoghi and Eshghi 2013). This model is a three-story, 1/5 scale representation of TFB (Fig. 8). The specimen represents typical tunnel-form buildings. The three-story structure was designed to support a permanent and a variable loads of 1.5 kN/m² and 2.0 kN/m², respectively. Additionally, it was designed to transfer lateral loads to the shear walls. The reinforcement details of various structural elements are depicted in Figs. 9 and 10. The specimen was subjected to quasi-static cyclic lateral loading.

From Fig. 11, both cyclic tests show some variability and fluctuations compared to the numerical model. The finite elements (FE) models exhibit a response that is slightly stiffer and stronger than the experimental results: “the initial differences in stiffness are likely due to the contrast between monotonically increasing loading and cyclic loading” (Tavafoghi and Eshghi 2013). Additionally, assumptions made during modeling, such as the perfect bond for reinforcements, may contribute to these discrepancies. Despite these differences, the comparison shows that the numerical model matches the test specimen.

2.4 Comparative analysis of diaphragm conditions: rigid vs. real flexibility

This study aims to understand and quantify the differences between two models of the same RC tunnel-form building: one with realistic diaphragm flexibility and the other with the assumption of a rigid diaphragm. The comparative analysis focuses on three key aspects:

• Understanding structural dynamics through modal analysis comparison: A comparative analysis reveals the impact of different diaphragm assumptions (rigid vs. real flexibility) on the natural frequencies and mode shapes of the structure.



(a) X direction (b) Y direction

Fig. 12 Normalized displacement ratios (real flexibility vs. rigid diaphragm) for each story in the corner Building (configuration 1)

Table 3 Comparison of modal characteristics of corner building (configuration 1)

	Real diaphragm			Rigid diaphragm		
Mode	Frequency	*Eff.* Mass *Tx* Percentage	*Eff.* Mass *Ty* Percentage	Frequency	*Eff.* Mass *Tx* Percentage	*Eff.* Mass *Ty* Percentage
1	4.73	33.1750	8.8656	5.66	70.9390	0.0924
2	5.89	35.0020	21.2460	6.84	0.1101	68.1030
3	7.41	2.7190	37.3370	19.60	17.3720	0.0053
4	15.55	3.0454	0.1252	23.70	0.0054	0.0703
5	15.66	9.4672	0.2033	24.10	0.0041	0.0009

Table 4 Comparison of modal characteristics of interior building (configuration 2)

	Real diaphragm			Rigid diaphragm		
Mode	Frequency	*Eff.* Mass *Tx* Percentage	*Eff.* Mass *Ty* Percentage	Frequency	*Eff.* Mass *Tx* Percentage	*Eff.* Mass *Ty* Percentage
1	3.35	74.81	0.00	4.71	82.75	0.00
2	5.55	0.00	6.71	9.35	0.00	74.20
3	6.39	0.00	62.63	11.12	0.00	0.42
4	10.98	15.56	0.00	13.83	9.62	0.00
5	19.64	3.63	0.00	22.27	3.03	0.00

• Evaluating the lateral displacement across six stories to understand the structural behavior under different diaphragm conditions.

• Evaluating the distribution of base shear in the shear-walls to assess how the different diaphragm assumptions affect the overall structural behavior.

3. Results and discussion

3.1 Modal analysis

As shown in Tables 3 and 4, the rigid diaphragm results in higher frequencies and more concentrated effective mass participation in the primary modes, indicating a stiffer and more constrained system. In contrast, the real diaphragm allows for more distributed mass participation across multiple modes, suggesting a more flexible and less constrained system. The natural frequencies vary significantly between the two diaphragm conditions for building configurations 1 and 2: 20% and 40% respectively for the first mode, 16% and 68% respectively for the second mode, and 164% and 74% respectively for the third mode. These differences will undoubtedly affect the structural response.

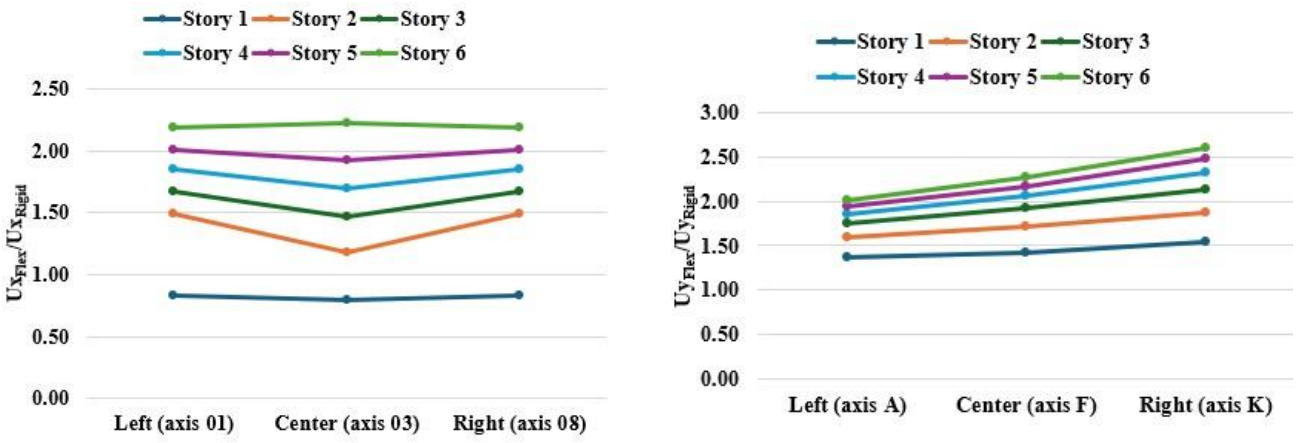
3.2 Comparing horizontal displacements in the investigated TFB using real and rigid diaphragm assumptions

3.2.1 Corner building (configuration 1)

Based on Fig. 12(a), it appears that all the reinforced concrete (RC) slabs move as rigid bodies in the X direction. However, noteworthy peak lateral displacements occur: they are 1.5 to 3.6 times higher for the bottom and top floors, respectively, compared to those observed in rigid diaphragm buildings.

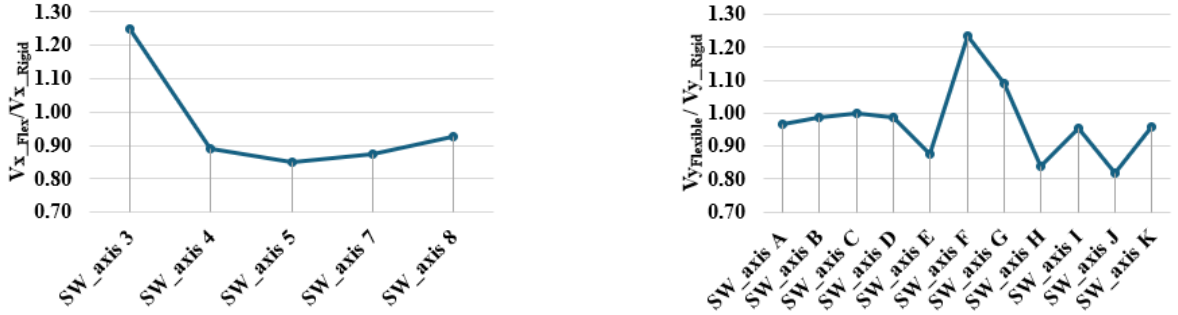
From Fig. 12(b), the behavior in the Y-direction demonstrates the characteristics of a semi-rigid diaphragm, with notable variations in displacement across different regions of horizontal diaphragms:

• On the right side, the normalized displacement ratio of 1.2 indicates that the real diaphragm experiences a 20% increase in displacement compared to the rigid diaphragm. This suggests that the right side is relatively less influenced by flexibility, likely due to the presence of more shear walls



(a) X direction (b) Y direction

Fig. 13 Normalized displacement ratios (real flexibility vs. rigid diaphragm) for each story in the interior Building (configuration 2)



(a) X direction (b) Y direction

Fig. 14 Normalized distribution of base shear in the corner TFB (configuration 1) using real and rigid diaphragm assumptions

on this side, which provide additional stiffness and restrict displacements.

• At the center, the displacement ratio rises to 2.5, reflecting a 150% increase in displacement compared to the rigid diaphragm. This significant increase highlights that the center of the diaphragm is highly sensitive to flexibility, as it lacks the restraining effect of shear walls and is more prone to deformation under lateral loads.

• The left side shows the highest displacement ratio of 3.52, corresponding to a 252% increase in displacement. This indicates that the left side is the most flexible region of the diaphragm. The pronounced displacement is likely due to a combination of torsional effects and the absence of sufficient shear walls compared to the right side, resulting in reduced stiffness and greater susceptibility to deformation.

3.2.2 Interior building (configuration 2)

Fig. 13(b) suggests that all reinforced concrete RC slabs behave as rigid bodies in the Y direction. However, noteworthy peak lateral displacements are observed: they are 1.37 to 2.61 times greater for the bottom and top floors, respectively, compared to those observed in rigid diaphragm buildings.

From Fig. 13(a), it can be observed that the diaphragm exhibits typical semi-rigid behavior in the Y direction. Indeed, a relative deformation of the slab is evident between the center (axis 03) and the ends (axes 01 and 08). This difference can reach 26% and 15% on the second and third floors, respectively. This significant difference suggests that the ends of the diaphragm are much more sensitive to flexibility.

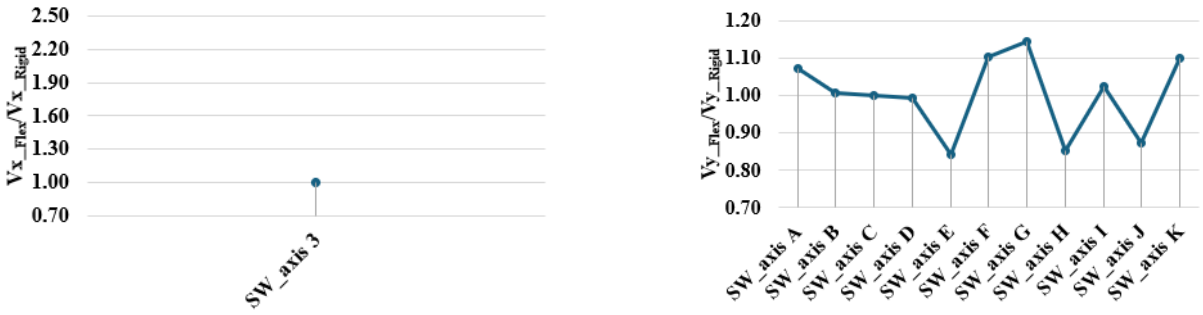
3.3 Comparing horizontal displacements in the investigated TFB using real and rigid diaphragm assumptions

To comprehensively assess the lateral flexibility of diaphragms in tunnel-formwork buildings, the distribution of lateral forces to the shear walls was also studied.

3.2.1 Corner building (configuration 1)

From Fig. 14(a), in the X direction, the difference in base shear when comparing a real diaphragm to the rigid diaphragm assumption can reach up to 25% in the shear wall located in the central diaphragm axis (#03). For the remaining walls, this difference does not exceed 10%. This is due to the asymmetrical distribution of shear walls: there are no shear walls on the left side, while there are five shear walls on the right side, suggesting lateral flexibility of this diaphragm.

From Fig. 14(b), in the Y direction, the results indicate that the shear forces in the walls differ by no more than 15% when comparing realistically modelled diaphragms to



(a) X direction (b) Y direction

Fig. 15 Normalized distribution of base shear in the interior TFB (configuration 2) using real and rigid diaphragm assumptions

those assumed to be rigid, except for the central wall (axis F), where the difference reaches approximately 25%. It is confirmed that the diaphragms in the Y direction are neither very rigid nor very flexible but somewhat in between.

3.2.2 Interior building (configuration 2)

Fig. 15(a) shows that there is no difference in the base shear wall in the X direction, as there is only one shear wall along axis (03).

Fig. 15(b) indicates that the shear forces in the walls differ by no more than 15% when comparing realistically modelled diaphragms to those assumed to be rigid. This confirms that the diaphragms in the Y direction exhibit intermediate behavior, neither very rigid nor very flexible.

4. Conclusions

This study investigated the influence of diaphragm behavior on the structural response of two representative tunnel-form building configurations subjected to lateral loads. By developing numerical models that explicitly accounted for the in-plane stiffness and nonlinear behavior of diaphragms, and comparing them to conventional rigid-diaphragm assumptions, the following conclusions are drawn for the analyzed cases:

- Rigid diaphragm assumptions led to overestimated natural frequencies (e.g., higher fundamental frequencies) and simplified modal mass participation, concentrating vibration energy in fewer modes. In contrast, models incorporating realistic diaphragm flexibility distributed mass participation across numerous modes, significantly altering both natural frequencies and mode shapes. This demonstrates that diaphragm flexibility critically influences dynamic behavior in tunnel-form systems, even for the limited cases examined.
- Horizontal displacements under lateral loads differed by up to 252% between rigid and flexible diaphragm models. Similarly, the distribution of base shear among shear walls varied by as much as 25%, revealing that rigid diaphragm assumptions can misrepresent load-sharing mechanisms in tunnel-form systems. These findings underscore the necessity of modeling diaphragm flexibility to achieve accurate predictions of displacements and force distribution in similar configurations.

The conclusions above are derived from the two case studies examined and may not fully represent all tunnel-form building typologies. However, the observed trends emphasize that diaphragm flexibility is a critical factor for structures with similar configurations, warranting further investigation to refine seismic design practices for this unique structural system.

Acknowledgments

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