PRELIMINARY FIELD OBSERVATIONS OF TUNNEL-FORM BUILDING DAMAGE FROM THE FEBRUARY 2023 TÜRKİYE EARTHQUAKES

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Abstract: *Tunnel-form buildings are a specific type of reinforced concrete (RC) structures constructed through the application of tunnel-formworks, which allow for the monolithic casting of a single story and repetitive use of the same formwork set for upper levels. Tunnel-form buildings are the predominant typology used in mass housing projects in Türkiye due to their relatively lower construction costs and shorter construction time, which stems from their construction technique. Furthermore, they are the primary choice of the public sector in the post-earthquake reconstruction process, as is the case with reconstruction efforts following the February 2023 Türkiye earthquakes. Turkish authorities have initiated mass housing projects adopting tunnel-form construction in earthquake-hit regions to address the high and urgent housing needs that emerged after the widespread devastation. Standardised designs are used for such structures considering different numbers of stories and seismicity levels. Such designs are typically based on force-based linear elastic procedures and rely on the behaviour factor and dominant vibration modes to estimate earthquake forces. The preliminary results from the post-earthquake field observations have shown that low- and mid-rise tunnel-form buildings exhibited better seismic performance than RC moment-resisting frame systems. While low- and mid-rise tunnel-form buildings have demonstrated high-seismic performance, some drawbacks and limitations may characterise the design of the high-rise ones. This paper describes and critically discusses the seismic damage in high-rise tunnel-form buildings resulting from the earthquake sequences of February 2023, and observed during a field investigation in June 2023. The fieldwork focused on mid- and high-rise tunnel-form buildings and covered the most severely affected provinces: Hatay, Kahramanmaraş, Adıyaman, Malatya, and Gaziantep. The present paper focuses on two case study structures from mass housing projects in Gaziantep and Hatay. Detailed field surveys were conducted to collect data on structural damage and failure modes. The findings contribute to understanding the seismic behaviour of high-rise tunnel-form buildings, shedding light on the shortcomings of their seismic design.*

1. Introduction

On February 6, 2023, a devastating earthquake with moment magnitude M_w=7.7 struck eastern Türkiye at 01:17 local time. The epicentre was in Pazarcik, Kahramanmaras, and the earthquake was generated by the Eastern Anatolian Fault with an estimated rupture length of 265 km (AFAD, 2023). Nine hours later, a second mainshock with magnitude M_w=7.6 occurred in Elbistan, Kahramanmaras, along the Cardak fault, impacting the northern part of the disaster region. Two weeks later, a strong aftershock with magnitude M_w=6.4 occurred in Dagduzu (KOERI, 2023) and struck the most severely affected area in the disaster region, Antakya. These series of large-magnitude mainshocks, along with many aftershocks, caused widespread devastation in the eastern part of the country, leading to the highest number of casualties in the country's history (AFAD, 2023). 518,009 houses were identified as requiring urgent demolition, collapsed, or were severely damaged, based on the comprehensive damage assessment study conducted by the Ministry of Environment, Urbanization and Climate Change. As shown by the Strategy and Budget Presidency of Türkiye report, most of the damaged structures were reinforced concrete (RC) moment-resisting frames.

Although RC frame is the dominant typology used in residential buildings, there is a distinct structural typology that is predominantly preferred in mass housing projects throughout Türkiye, including the disaster region, and is also the primary choice of the public sector in the post-earthquake reconstruction process: tunnel-form buildings. Unlike conventional construction practices, these buildings are cast utilising tunnel formworks tailored to specific projects' structural details. As illustrated in Figure 1, prefabricated steel formworks are assembled considering the project details and installed on the floor level to create a cellular structure. This specific formwork procedure allows the monolithic construction of a storey. Formworks are then removed and placed on the upper storey repetitively for the rest of the building. Using the same formworks leads to rapid construction and reduced cost, especially for multi-dwelling projects with identical layouts. Therefore, the tunnel-formwork construction technique is predominantly used for mass housing projects as a high number of repetitive work is required to construct multiple buildings with the same structural configuration.

Figure 1. Tunnel-formwork application.

Figure 1 also demonstrates the most salient characteristic of the typology: shear walls are almost the only vertical load-bearing elements, leading to significantly high ratios of shear wall-to-floor area. The high density of shear walls leads to a substantially stiffer structure compared to RC frame systems. The high ratios of shear wall-to-floor area enable the use of minimum section dimensions and reinforcement ratios. In Turkish Building Seismic Codes (TBSC), shear walls of tunnel-form buildings are allowed to have thinner sections compared to shear walls in dual frame-wall systems. However, having thin and lightly reinforced sections, shear walls can experience brittle failure modes (Pugh *et al.*, 2015). In such structures, the transfer and redistribution of lateral loads among the different shear walls are achieved through conventionally reinforced deep coupling beams, which may be susceptible to shear tension and compression failures. Nevertheless, observational data on low- and mid-rise tunnel-form buildings suggest they have very low vulnerability (Yaku and Gulkan, 2003).

The present paper provides some preliminary observations from a field reconnaissance mission after the February 2023 Türkiye earthquakes with a higher focus on the seismic performance of tunnel-form buildings. The fieldwork focused on the most severely affected provinces, Hatay, Kahramanmaraş, Adıyaman, Malatya, and Gaziantep, to observe this distinct typology's dominant structural and non-structural damage patterns.

This study presents only two sites: one in Nizip, Gaziantep, and the other in Antakya, Hatay. The buildings investigated from these two sites constitute two contrasting cases regarding damage level and experienced levels of ground motions. The observations allow for the identification of the main structural and non-structural damage patterns together with the probable causes and provide some insights for possible improvements in the design of such structures.

2. Damage observations on high-rise tunnel-form buildings

Figure 2 presents the two selected case study tunnel-form buildings. Both buildings were designed and constructed in compliance with TBSC 2007, in which capacity design principles are followed to ensure the location and type of failure. Specifically, TBSC 2007 employs a force-based, elastic design methodology, incorporating structural behaviour factors to design building structures. Additionally, the code prescribes the implementation of confined boundary zones at both ends of shear wall sections, and these zones occupy higher portions of the shear wall sections along the critical height of the building.

3.1 Nizip

Nizip is the largest district in the Gaziantep province and includes several mass housing sites. The selected case study site is preferred due to its proximity to a seismic monitoring station. The case study site is situated just 2.0 km away from Station 2704, operated by the Disaster and Emergency Management Presidency (AFAD) of the Ministry of Interior. Among all the mainshocks and large magnitude aftershocks, Station 2704 recorded only the M_w=7.7 earthquake of the February 6, 2023. As illustrated in Figure 3, the response spectra of the recorded horizontal accelerations are below the elastic design spectrum considering relevant soil conditions with average shear wave velocity at the first thirty meters $V_{s,30}$ = 721 m/s.

(a) (b)

Figure 2. Tunnel-form buildings in the investigated mass housing sites a) Building in Nizip, Gaziantep b) Building in Antakya, Hatay.

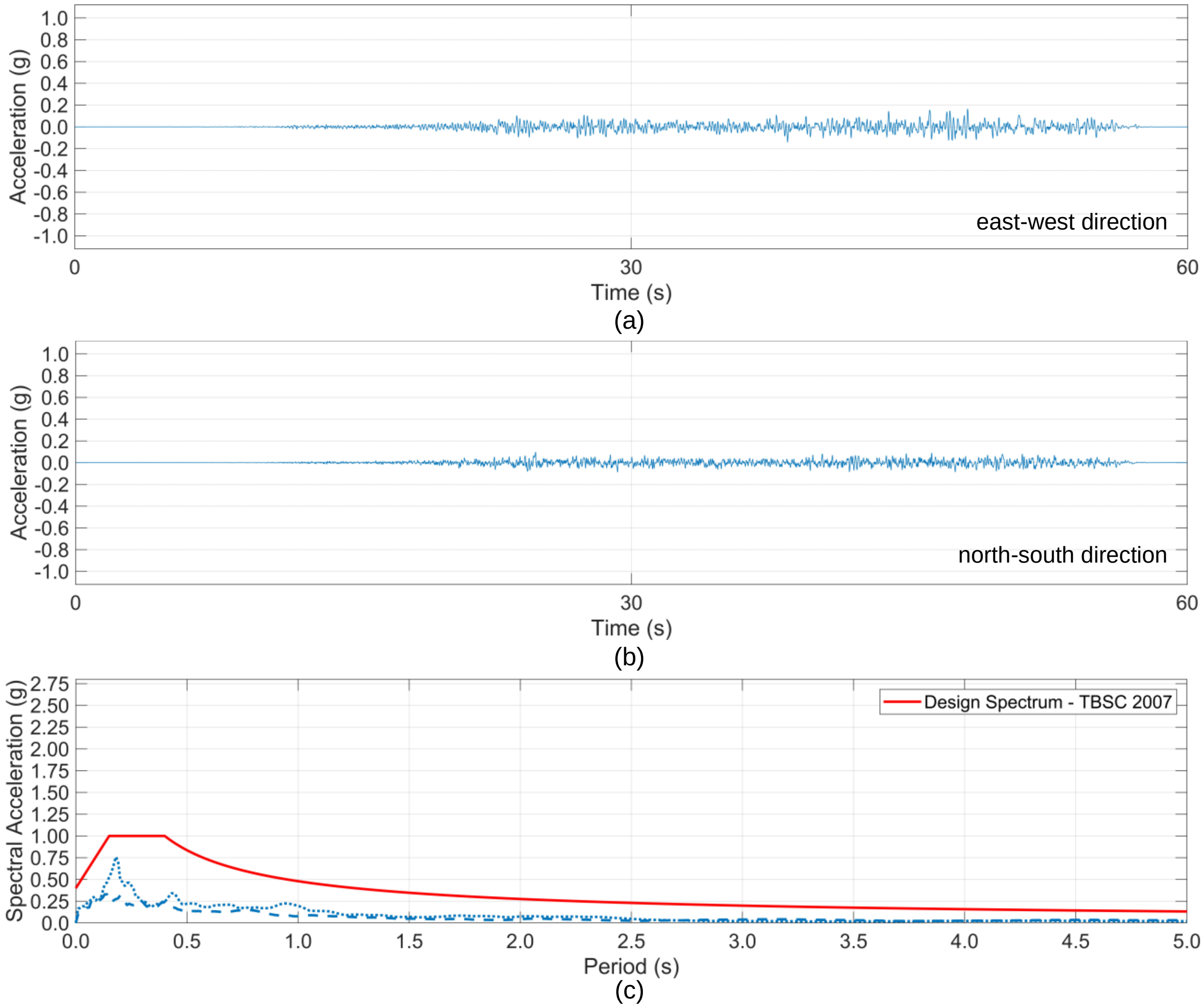


Figure 3. Recorded ground motions of M_w=7.7 of the February 6, 2023 by station 2704. a) Accelerations along east-west direction; b) Accelerations along north-south direction; c) Response spectra of the recorded acceleration series.

Tunnel-form buildings on this site are 13 storeys including basement floors surrounded with rigid basement walls. The case study site was constructed in 2014 and is located in the eastern part of Nizip. External observations revealed separations between the building and the surrounding ground. Figure 4(a) shows the impact of this separation and the damage to the façade elements, particularly at the ground level, causing breakages in decorative tile elements. Figure 4(c) shows the separations between the infill walls and structural elements. Additionally, spalling of plaster on the shear walls was noted as shown in Figure 4(b). This observation, however, was mainly limited to lower floors. Figure 4(d) shows the moisture observed in the basement floors. The penetration of the moisture into the shear walls could adversely affect the structural performance and is expected that the shear walls' reinforcements at this level were significantly compromised.

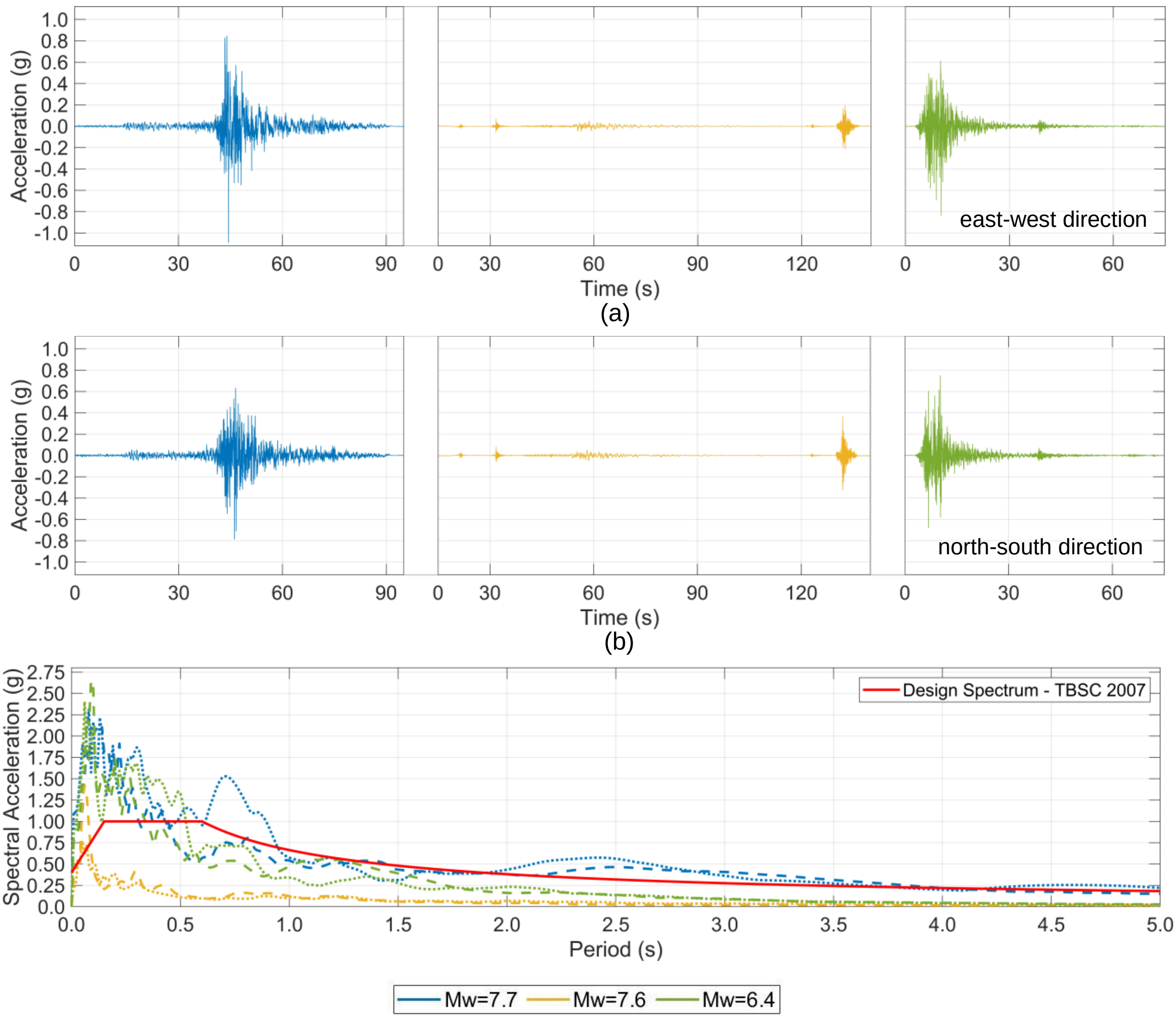
Coupling beams are key elements densely used in this structural typology. Figure 4(e) shows an example of the onset of diagonal cracks observed in coupling beams in Nizip. Nonetheless, such damage was predominantly found in coupling beams on the middle floors. No further damage to structural members was detected in Nizip.


(a)
(b) (c)
(d) (e)

Figure 4. Damage patterns of high-rise tunnel-form building in Nizip. a) Damage to the façade elements; b) Spalling of plaster; c) Separations between the infill walls and structural elements; d) Damp in the basement floors; e) Onset of diagonal cracks in a coupling beam.

3.2 Antakya

Antakya is the largest district and the center of Hatay province in terms of population. Central Antakya is one of the most severely affected places among all the regions affected by the earthquake sequences, with widespread devastations in residential buildings. Although the dominant typology of residential buildings is RC frame buildings, tunnel-form buildings mass housing projects are common as well. The case study mass housing site investigated herein this study is reffered to as Antakya to maintain brevity. The nearest ground motion recording station of AFAD, Station 3125, is 1.5 km away from this case study site. This station recorded the mainshock M_w=7.7 and aftershock M_w=6.6 of the February 6 earthquakes along with M_w=6.4 of the February 20 aftershock event. Figure 5 shows the accelerations history for the three events. The peak horizontal ground acceleration (PGA) among all records was almost 1.1g and was recorded during the M_w=7.7. It is worth mentioning that vertical PGA recorded during the same event was the same as the horizontal one, *i.e.,* 1.1g. Figure 5 also shows the response spectra of the recorded ground motions. It is noteworthy that the response spectra for short periods up to 0.5 sec, is significantly above the elastic design spectrum especially for the M_w=7.7 and M_w=6.4 earthquakes. Elastic spectral accelerations reaching up to 2.5g indicate that the stiffer structures were subjected to very high lateral forces. One of the reasons for this amplification at low periods can be attributed to the ground conditions in the region, where $V_{s,30}$ = 448 m/s.



(c)

Figure 5. Recorded ground motios of M_w=7.7, M_w=6.6, M_w=6.4 by station 3125. a) Accelerations along the east-west direction; b) Accelerations along the north-south direction; c) Response spectra of the recorded acceleration series.

Tunnel-form buildings in the investigated site are 17 storeys including basement floors surrounded with rigid basement walls. The case study site was constructed in 2012 and is located in the south of Antakya. Figure 6(a)-(b) presents the exterior view of the buildings showing the non-structural and structural damage suffered during the February earthquakes. It remains unclear which earthquake caused the specific portions of the damage. Extensive cracks were observed in the infill walls, particularly concentrated at the edges of the door and window openings. Furthermore, extensive cracks were also observed in the infill walls adjacent to the structural members that suffered significant structural damage. Figure 6(c) displays another common damage feature that is the separation of the infill walls from the structural system. Out-of-plane failure of infill walls was also observed although it was not widespread along the height of the building. Nevertheless, compared to the RC frame buildings in the nearest vicinity as depicted Figure 6(d), non-structural damage was less severe and limited in the distribution throughout the building height. Significant damage was observed in the shear walls at the ground level. Concrete crushing, reinforcement buckling, and fracture were evident in multiple shear wall sections. This damage, as presented in Figure 6(e)-(f), extended into the web of the some shear walls, coupled with observation of substantial concrete crushing. Figure 6(g)-(h) shows extensive diagonal cracks, that were mainly concentrated at the mid-levels. Additionally, as a flaw of the local construction practice, pipes passing through the coupling beams caused local weaknesses. In coupling beams with light damage, the damage was concentrated in this area, while in severely damaged ones, localisation of cracks were observed around the holes.


(a) (b)
(c) (d)
(e) (f)
(g) (h)

Figure 6. Damage patterns of high-rise tunnel-form building in Antakya. a) Front of the building; b)Rear of the building; c) Separation of the infill walls from the structural system; d) Damage to infill walls in a nearby tunnel-form building and an RC frame; e) Damage to shear wall, exterior view; f) Damage to shear wall, interior view; g) Diagonal cracks in a coupling beam; h) A commonly observed construction flaw.

3. Discussion

The tunnel-form buildings analysed in this study were designed in compliance with TBSC 2007. Both TBSC 2007 and its predecessor, TBSC 1999, were the guidelines used to design the majority of RC frame structures in the region. These two version of the seismic codes share the seismic design regulations, employing an elastic design approach based on capacity design principles for both RC frame and shear-walled structures. Despite this shared seismic design philosophy and regulations, field observations revealed a significant impact of the load-bearing system on seismic performance. Notably, the tunnel-form buildings in this study demonstrated superior seismic performance when compared to nearby RC frames, even though both were designed under the same regulatory framework and constructed around the same period. This observation holds true despite the recorded ground motions' response spectra significantly exceeding the design spectrum across a range of periods. The tunnel-form buildings maintained structural integrity in spite of sustaining considerable damage, due to their stiff and redundant structural systems. However, these characteristics alone may not fully account for their superior performance.

From the non-structural damage perspective, high-rise tunnel formwork buildings in Nizip have demonstrated 'good' performance. Even in Antakya, where significant structural damage was evident at different levels of the building, non-structural damage remained limited, except for specific locations. Rare observation of extensive infill wall failures suggests tunnel-form buildings exhibit stiffer behaviour compared to frame systems and is an indicator of the high stiffness of the typology emerging from the abundance of long-sectioned shear walls. Figure 6(c) and Figure 4(c) illustrates a prevalent occurrence of non-structural damage frequently observed also in other structures. Infill walls commonly detach from the load-bearing system, resulting in varying degrees of separation, ranging from hairline cracks to cracks with 1 centimeter width. Amongst the upper stories, diagonal cracks around the infill openings were common in high-rise tunnel-form buildings. Nevertheless, it is noteworthy that the extent of non-structural damage in tunnel-form buildings remains comparatively limited if compared with RC frames, primarily due to the limited flexibility of tunnel-form buildings. Even in the case of Antakya, where tunnel formwork buildings suffered extensive structural damage, the extent of non-structural damage was significantly better than that of RC frame buildings.

Tunnel-form buildings investigated in this study are composed of slender, thin-sectioned shear walls. Due to their thin profiles and long section lengths, the outermost layers of shear wall sections experience high strain demands under bending forces. Although the behaviour of slender shear walls is dominated by flexural forces, field observations in Antakya have shown that higher strain demands at the extremities of ground-story shear walls have resulted in concrete crushing in the boundary regions of the shear walls. In many instances, this concrete crushing was accompanied by reinforcement buckling. Such brittle failure mechanisms are consistent with research findings for slender, thin-sectioned shear walls and similar observations of damage were stated by Gurbuz *et al.* in the aftermath of the Aegean Sea Earthquake in 2020. In several structural elements, the damage propagated beyond the boundary regions, resulting in concrete crushing and bar buckling at the web, thereby exposing mesh reinforcements, as shown in Figure 6(e)-(f). This damage pattern was consistently accompanied by reinforcement fracture at the wall extremities. It is also noteworthy to emphasise again that the high-rise tunnel-form buildings in Antakya did not suffer from extensive non-structural damage.

Since tunnel-form buildings inherently exhibit a rigid behaviour due to their high shear wall ratios, coupling beams serve as the primary source for dissipating seismic energy through experiencing damage under load reversals. Their role in seismic energy dissipation was clearly observed during the field investigations. In the case of Antakya, coupling beams suffered varying levels of damage throughout the height of the buildings. Heavy damage is manifested, especially at the mid-height levels, through significant diagonal cracks along the beam length and concrete crushing around the coupling beam-wall connections. The widespread distribution of coupling beam damage throughout the building height suggests that these members heavily contributed to seismic energy dissipation. However, their efficiency raises questions as the observed damage patterns result solely from shear failure. Furthermore, their deep cross-sections, squat profiles, and the lack of diagonal reinforcement result in a considerably brittle response. Observations in Nizip, where no structural damage and only a limited level of non-structural damage was experienced, support this argument. The presence of diagonal hairline cracks in the coupling beams in Nizip at different floors suggests their inherent brittle response and potential inability to provide sufficient ductility. The onset of diagonal cracks in coupling beams in Nizip implies that these brittle members start to deform under low-amplitude ground motions.

4. Conclusion

Following the February earthquake series in Türkiye, the authors of this study conducted an extensive field trip solely focusing on mid- and high-rise tunnel-form buildings' seismic performance during the earthquake sequences. This paper presents the observations on the response of high-rise tunnel-form buildings from two sites: one in Nizip, Gaziantep and the other in Antakya, Hatay. These two sites deliver two contrasting cases regarding the experienced ground motion intensity and level of damage sustained by the buildings. The recorded ground motion levels by the nearest station to Nizip remained lower than the design spectrum, and the buildings in Nizip remained functional following the earthquakes with limited non-structural damage. In case of Antakya, the buildings were subjected to three strong events that had higher spectral values in short periods than that of the design spectrum. Significant levels of damage was observed within the shear walls emerging from brittle failure mechanisms. It was also observed that coupling beams were extensively damaged throughout the building height, showcasing that they significantly contributed to the dissipation of seismic energy. Nevertheless, the buildings retained their structural integrity even under the sequence of ground motion intensities significantly higher than the design considerations.

This study lays the groundwork for a more comprehensive investigation. Further research, presenting the field observations of the authors from the remaining provinces, will be published to comprehend the seismic performance of tunnel-form buildings at different ground motion intensities and the underlying mechanics of any damage, and provide recommendations to further improve their seismic performance.

5. Acknowledgments

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