LESSONS FROM THE 2023 SOUTHEAST TÜRKIYE EARTHQUAKES: A STUDY ON DAMAGED RC BUILDINGS CONSIDERING THE HASSAN INDEX

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Abstract: *A survey was conducted across 10 cities in Southeast Türkiye to classify damage in 242 reinforced concrete (RC) buildings constructed in the last 15 years, ranging from 2 to 16 stories. The 'robustness' of these buildings was quantified using ratios of cross-sectional areas of vertical elements (walls and columns) to floor-plan areas. The results are compared with similar measures obtained for buildings in Erzincan and Duzce (Türkiye) and buildings in Chile and Japan as well. These comparisons suggest that excessive drift was one of the primary causes of the widespread damage in RC buildings across the cities surveyed, from Antakya to Malatya. Drift a) exposed a myriad of defects in structural layouts and reinforcing detailing, b) caused nearly destruction of partitions and other non-structural building components (leading to disruptions of functionality even in the absence of structural damage), and c) induced instability even in structures with better detailing. In contrast, stiff (albeit uncommon) structures with abundant and well-distributed structural walls had lower drifts and performed well. Except for sporadic failures in details placed at critical locations, those structures are still in use and should serve as models for reconstruction.*

1. Introduction

The earthquake sequence in the southeast of Türkiye in February 2023 caused extensive damage in 11 provinces (with a surface area roughly the size of Bulgaria) and a population of 14 million. The population of the most severely affected provinces was 6.5 million (Adıyaman, Kahramanmaras, Gaziantep, Hatay, and Malatya). The number of buildings in the area is reported to have been 2.7 million (Presidency of Strategy and Budget, 2023). After the event, 1.7 million of these structures were rapidly inspected, and around 230,000 buildings were classified as severely damaged, to be demolished, or already collapsed. In specific cities such as Antakya and Nurdağı, approximately half of the building inventory was classified as having severe or worse damage. High shaking intensity (with values of PGV exceeding 100 cm/s in 10 stations) and lack of robustness in the built environment contributed to the mentioned high frequency of damage.

The earthquake sequence started at the Pazarcık segment of the South Anatolian Fault with a moment magnitude (M_w) of 7.7 (AFAD) (M_w=7.8, USGS) on February 6, 2023. Nine hours later, a nearby fault in Elbistan fractured with a M_w=7.6 (AFAD), (M_w=7.5, USGS) motion. Tens of thousands of aftershocks followed, with the largest having a magnitude Mw= 6.6 (AFAD), (M_w=6.7, USGS). A third event happened 14 days later in Antakya on February 20, 2023, with M_w=6.4 (AFAD), (M_w=6.3, USGS). Locations of the epicentres of the main shocks are presented in Fig. 1.

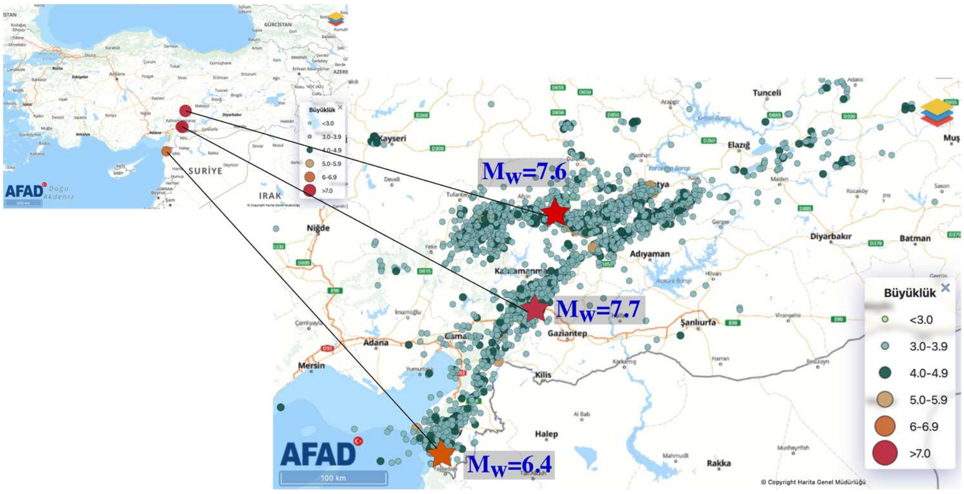


Figure 1. Epicentres of the earthquake sequence main and aftershocks.

The peak ground accelerations (PGA) and velocities (PGV) of selected sites are presented in Table 1. The values are from the station with the largest amplitudes, except for Antakya, Kahramanmaras-Central, and Hassa. Values for these cities are weighted averages from the multiple stations. Typical PGV values for the design spectra defined in seismic regulations in high seismicity areas are around 50-60 cm/s. It can be observed from the table that the demand levels were significantly above the design targets at many sites. Since peak ground velocity (PGV) is correlated with drift demand (Sozen, 2003), the high intensity of these motions (and the fact that the intensity was much more significant than suggested by the design spectra) is likely an essential contributor to the widespread damage observed in RC frame structures.

Table 1. PGA and PGV values from some selected sites.

Province/ City	**Gaziantep/ Nurdagi**	**Kahramanmaras/ Turkoglu**	**Hatay/ Hassa**	**Hatay/ Kirikhan**	**Hatay/ Antakya**	**Kahramanmaras/ Central**	**Malatya/ Yesilyurt**	**Kahramanmaras/ Elbistan**	**Gaziantep/ Islahiye**
PGA (g)	0.6	0.68	0.59	0.75	0.99	0.41	0.45	0.4	0.66
PGV (cm/s)	109	96	129	86	133	61	35	93	110

The earthquake sequence provided an opportunity to evaluate Turkish seismic design and practice. The event's extent, severity, and rarity attracted many reconnaissance teams around the globe. The general trend in reconnaissance studies is to collect qualitative data before the evidence gets lost due to the difficulties and complexities of the data collection. Not surprisingly, though necessary, qualitative data has limitations (e.g., subjective and lacking detailed measurements). Hassan and Sozen (1997) provided a straightforward and manageable method for collecting quantitative data in reconnaissance studies.

Shiga et al. (1968) originally proposed an index value based on vertical structural member areas in reinforced concrete buildings for comparing earthquake damage. Hassan and Sozen (1997) improved upon this idea by defining an index as a measure of structural robustness to estimate the seismic risk of existing reinforced concrete (RC) structures. The fundamental idea was to create a sorting tool to identify high-risk structures for inventory and possible intervention purposes.

Hassan and Sozen introduced the column index (CI) and wall index (WI). The sum of these indices is also defined and named the priority index (PI). The column index is half the sum of column cross-sectional areas in the critical floor divided by the total floor area above. Wall indices are calculated separately for each direction of the structural frame as the ratio of the sum of the cross-sectional areas of RC shear walls and 10% of masonry infill walls (without voids and bounded by the frame on all edges) to the total floor area above. The smaller of the wall indices, which are calculated in each direction, is the WI of the building. Buildings are defined through (CI, WI) coordinates in a cartesian coordinate system to combine the data in a single graph. The damage to the building is designated as “severe,” which means either severe damage or collapse, and “other,” which means it is either moderate, light or no damage. Severe damage refers to disintegration of the concrete core and/or bar buckling, shear failures, or bond failures in any member. The critical floor is typically the ground floor or the next level up. These levels typically get most of the damage in an earthquake. The floor that gives the lowest indices values controls. The information necessary to calculate Hassan Indices includes the building floor areas, critical levels, vertical member sizes, and the damage level. Hence, depending on the complexity of the structures, the time necessary to complete the survey varies from about half an hour to a couple of hours.

Based on Hassan and Sozen’s original idea, a broad group of researchers mobilized a considerable effort, and the concept was evaluated by gathering data from 15 earthquakes in 12 different countries over the last quarter century (Hassan and Sozen 1997, Donmez and Pujol 2005, Shiga et al. 1968, Riddell et al. 1987, Gur et al. 2009, O’Brien et al. 2011, Cuadra et al. 2013, Zhou et al. 2013, Shah et al. 2017, Sim et al. 2015, Villalobos et al. 2018, Pujol et al. 2020, Alcocer et al. 2020, Pledger et al 2023). Including the recent efforts following the 2023 Türkiye earthquakes, the total number of buildings assessed worldwide for this purpose is about 1700. The general tendency of the data up to 2023 earthquakes could be defined as the probability of severe damage drops substantially if the PI is above 0.25%. The following section details the data collection methodology and the context of similar data collected after the 2023 Türkiye earthquake sequence.

2. Reconnaissance Study

1.1. Site visit

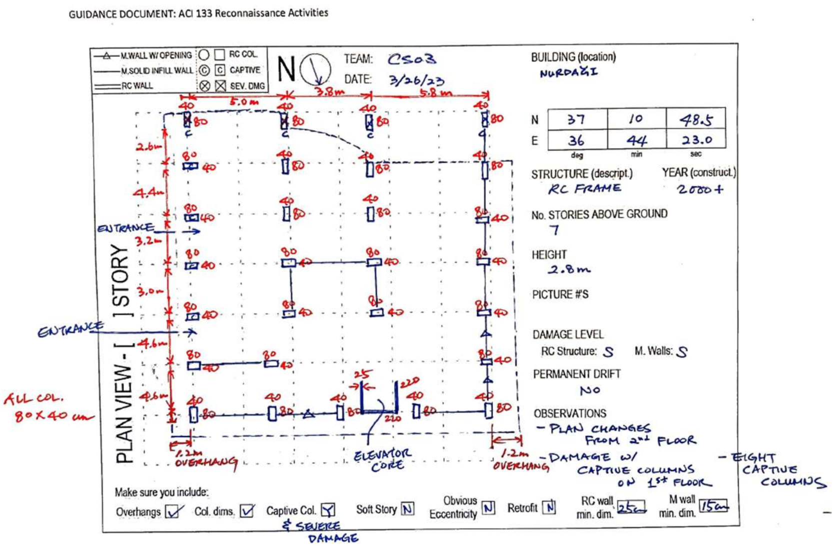
After the February 2023 earthquake sequence, a team of faculty, students, practicing engineers, architects, and researchers was deployed to the area led by the American Concrete Institute (ACI) 133 Disaster Reconnaissance Committee. The entire team was made up of 41 members. Given the size, smaller groups of 3-4 people were formed each day, each with at least one member with previous earthquake damage identification experience. Nine districts were visited following the cities with heavy damages along the fault line (see Fig. 2).

Figure 2. Locations of the investigated ACI buildings.

1.2. Collected data

Approximately 320 buildings were surveyed for 13 days starting March 25, 2023. Eliminating buildings with incomplete data resulted in a dataset representing 242 buildings used in this study. The data is public and can be reached at https://www.dropbox.com/sh/6cmdgdn82n9ufxr/AACt-1rberSKM4fFFaDeL3_5a?dl=0.

The result of the site visits is a dataset that facilitates the evaluation of the structural conditions of the surveyed buildings. Data were collected in the field using a standard survey form (Fig. 3). The collected data include the layout of the building, measurements of vertical element sizes, location of the building (geographical coordinates), classification of the structural frame, construction year (when available), number of stories and total building height, and annotations highlighting apparent vulnerabilities such as eccentricity, soft stories, and captive columns. Furthermore, any discernible earthquake-induced damage was documented, focusing on recording the damage's location, its characteristics and severity, and any potentially related details about the member type and reinforcement detailing. Prior studies have reported on damage to older structures in cities in Türkiye: Erzincan (Hassan and Sozen, 1997), Bolu-Düzce (Donmez and Pujol, 2005), and Bingöl (Gur et al., 2009)—the current study aimed to collect data from structures built after the 2000's. Hence, buildings surveyed in this study were subject to the Turkish Seismic Regulations of 1998, 2007, or 2018. The 1998 and 2007 regulations were similar, whereas the 2018 regulations included significant changes to the seismic demand and drift limit definitions.


GUIDANCE DOCUMENT: ACI 133 Reconnaissance Activities

M.WALL W/ OPENING
M.SOLID INFILL WALL
RC WALL
○ ☐ RC COL.
Ⓒ [C] CAPTIVE
⊗ ☒ SEV. DMG

TEAM: CS03
DATE: 3/26/23

BUILDING (location)
NURDAĞI

N	37	10	48.5
E	36	44	23.0
	deg	min	sec

STRUCTURE (descript.) RC FRAME
YEAR (construct.) 2000+

No. STORIES ABOVE GROUND
7

HEIGHT
2.8m

PICTURE #S

DAMAGE LEVEL
RC Structure: S M. Walls: S

PERMANENT DRIFT
NO

OBSERVATIONS
- PLAN CHANGES FROM 2nd FLOOR
- DAMAGE W/ CAPTIVE COLUMNS ON 1st FLOOR
- EIGHT CAPTIVE COLUMNS

Make sure you include:
Overhangs ☑ Col. dims. ☑ Captive Col. ☑ & SEVERE DAMAGE Soft Story [N] Obvious Eccentricity [N] Retrofit [N] RC wall min. dim. [25cm] M wall min. dim. [15cm]

Figure 3. Example of a field survey form.

3. Observed Damage

The purpose of the reconnaissance study was to gather data without targeting any particular type of structural failure. Nonetheless, due to practical considerations, it was impossible to gather data from buildings that had collapsed or were judged unsafe to enter due to the severity of damage.

Figure 4 shows the distribution of observed damage across the surveyed buildings. Figure 5 shows the damage rating assigned to individual buildings, building height, and estimated PGV. It appears from Fig. 5 that there was no correlation between the number of stories and the damage experienced by these buildings.

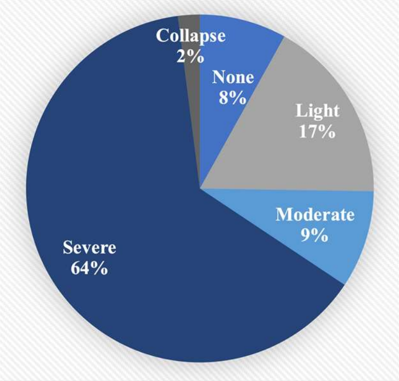


Figure 4. The damage percentage of the surveyed buildings by the ACI reconnaissance team.

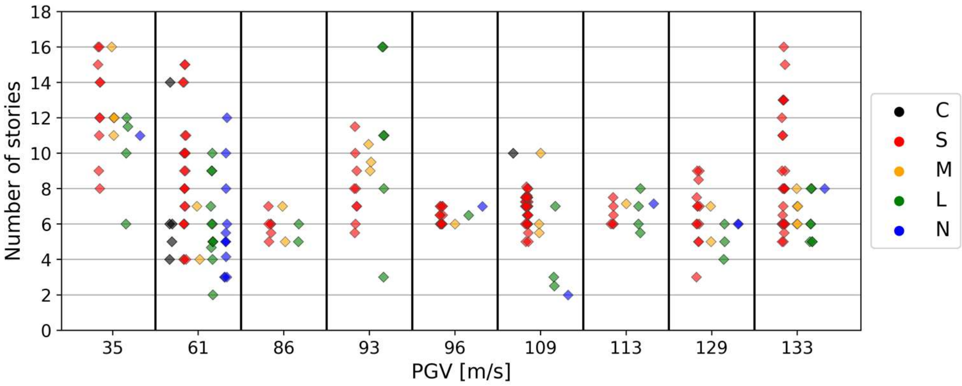


Figure 5. Damage of the surveyed buildings by PGV and Number of Stories.

Seventeen percent of the investigated buildings were identified as having soft stories (Fig. 6). Eighty-five percent of buildings with a soft story had severe damage compared to 61% of buildings with no soft story.

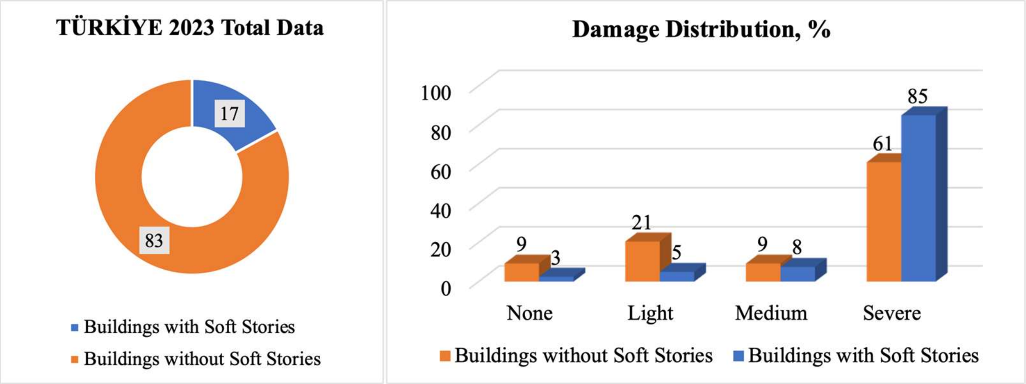


Figure 6. Percentage of the surveyed buildings with and w/o soft stories and damage distributions.

Structural frames with shallow beams (ribbed slab systems) are common in Türkiye. This system is called an “asmolen” slab, but even though the referral is to the slab, the frame behaviour is dictated by the shallow beams, which are forced to have the same thickness as the joist beams. Typical beam depth is 30-35 cm, and the width varies as needed. Shallow beams produce more flexible frames with larger periods than conventional (deeper) beams. Further information about this structural type can be obtained from Donmez (2015). Hence, the seismic drift demands from these structures are expected to be higher. Twenty-two percent of the investigated buildings are RC frames with shallow beams (Fig. 7).

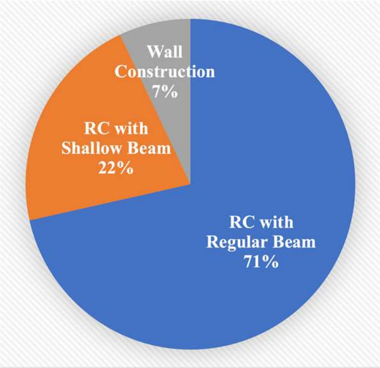


Figure 7. Types of structural systems of the surveyed buildings.

4. Hassan Index

As mentioned above, the Hassan Index defined by Hassan and Sozen (1997) includes two main parameters: CI and WI. These parameters are presented in Eq. 1 and 2.

$$CI = \left(A_{ce}/A_{ft}\right) \times 100, A_{ce} = A_{col}/2 \quad (1)$$

$$WI = \left(A_{wt}/A_{ft}\right) \times 100, A_{wt} = A_{cw} + A_{mw}/10 \quad (2)$$

Table 2 shows a drop in the average Priority Index between the current and prior surveys conducted in Türkiye. It was also observed that the size and height of the affected structures had increased considerably: the average number of stories, floor area, and total floor area of buildings in the Bolu-Düzce data were about 3 stories, 175 m^2, and 600 m^2. These values increased to 8 stories, 500 m^2, and 4000 m^2 for the current set. So, relative to earlier surveys conducted in Türkiye, the newer structures in this dataset are taller and more extensive but have a drop to half in “robustness.”

Table 2. Variation of Averages and Standard Deviation of Hassan Indices for the Türkiye Data.

	1992 Erzincan	1999 Bolu-Düzce	2003 Bingöl	2013 Türkiye
CI-AVG %	0.25	0.28	0.19	0.1
WI-AVG %	0.12	0.04	0.12	0.07
PI-AVG %	0.37	0.32	0.31	0.17
CI-STD %	0.16	0.16	0.07	0.06
WI-STD %	0.15	0.05	0.22	0.09
PI-STD %	0.16	0.17	0.19	0.09

The collected data are presented in Hassan coordinates in Fig. 8. It could be seen that a large majority of the severely damaged buildings had PI≤0.25%. A subgroup of “critically” damaged buildings was selected from those categorized as having “severe” damage based on whether the survey team would expect the buildings to have a high risk of collapse in their existing condition. Figure 8 presents that “critically” damaged buildings clustered near the origin, and all but one “critically” damaged building had PI<0.25%. Buildings with moderate or less damage exist under the PI=0.25% threshold. The distribution of both identifications below and above the threshold are presented in Fig. 9. Similar percentages considering structural and non-structural damages are also presented.

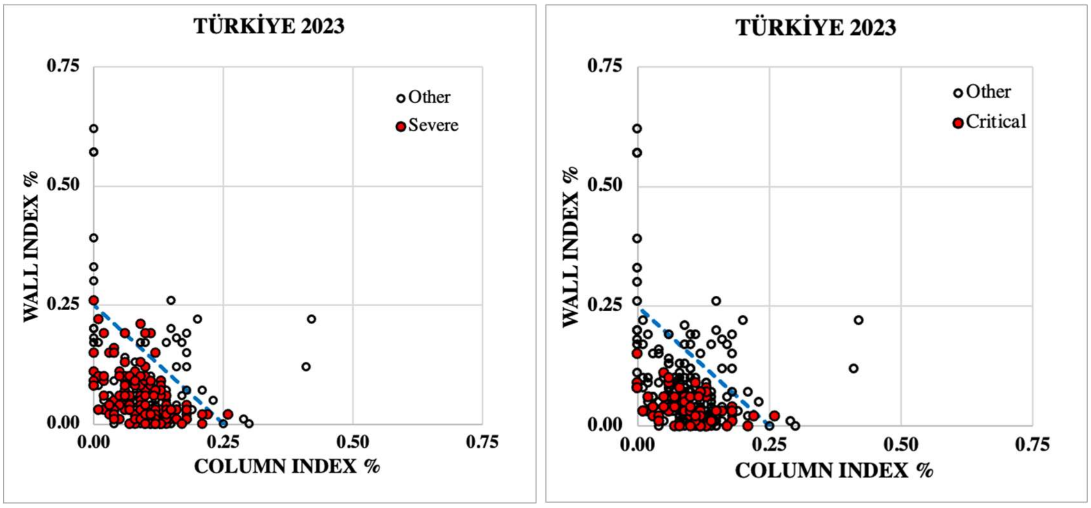


Figure 8. Distribution of data with Hassan Indices.

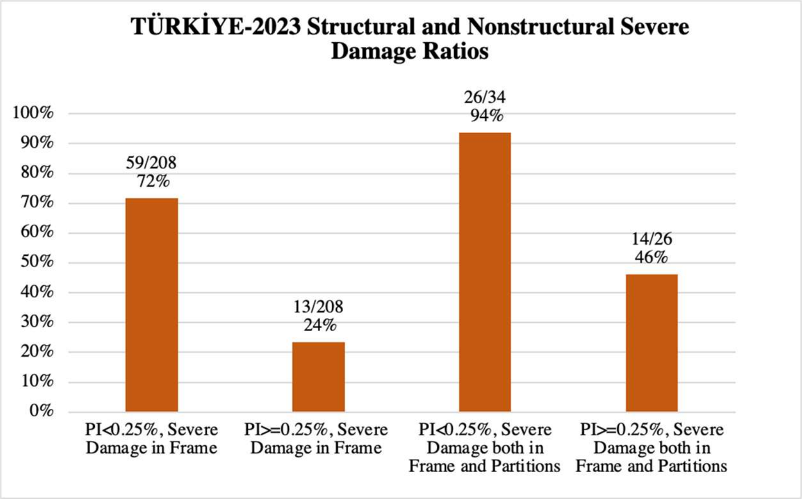


Figure 9. Percentages of each damage class below and above the 0.25% threshold.

Seventeen percent of surveyed buildings had soft stories (Fig. 6). The percentages of damaged structures with a soft story in comparison with the complete set is presented in Fig. 10. As expected, damaged percentages increased for the cases with soft stories either severe damage or “critical” damage considered. Interestingly, if only 0.1% WI existed, almost no damage was observed for soft-story buildings.

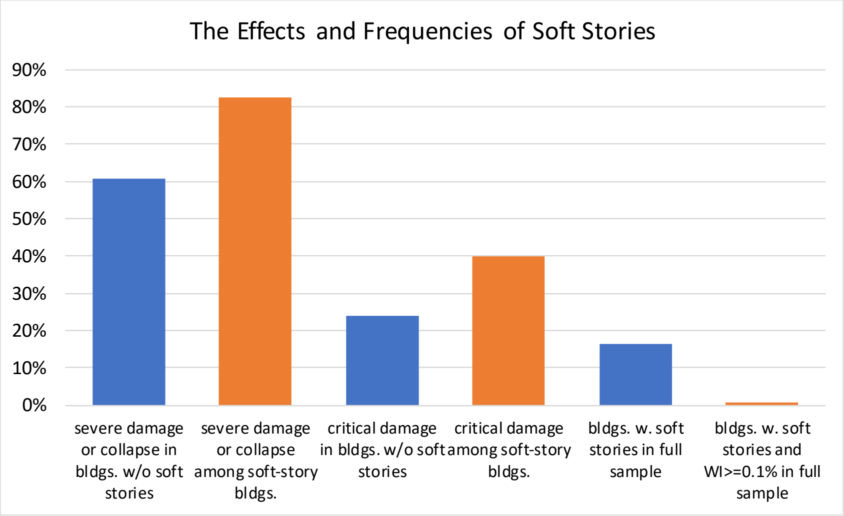


Figure 10. Effect of the soft story on damage percentages.

The damage percentages of the shallow beam frames are also investigated and presented in Fig. 11. There is a clear trend of increase in severe damage for shallow beam structures.

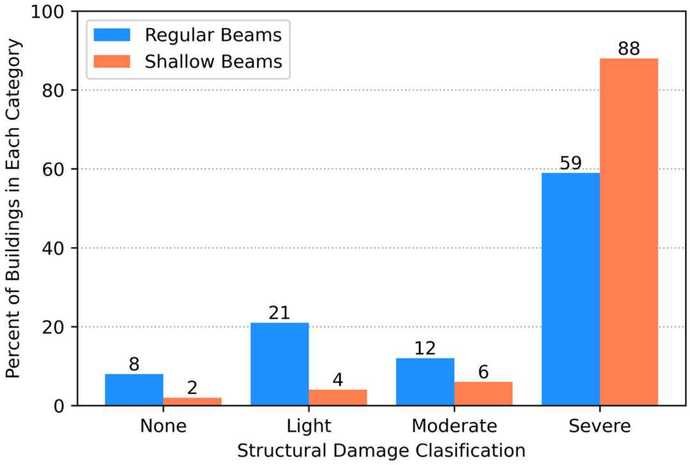


Figure 11. Damage distributions in shallow beam frames.

The significant difference in earthquake intensities among the cities necessitates a separate investigation of the data based on the demand level. Hence, demand levels are organized according to PGV levels. Antakya, Hassa, Kirikhan, Nurdagi, Turkoglu, and Islahiye districts are taken as high-intensity regions with PGV values exceeding 50-60 cm/sec. Elbistan, Gaziantep, Malatya, and Kahramanmaras are low-intensity regions with PGV values less than 50-60 cm/sec. The results are presented in Fig. 12. It could be observed that even though it gets more severe under the high demands (two to three times the design value), the 0.25% threshold still holds. A similar separation is done considering the “critical” damage in Fig. 13.

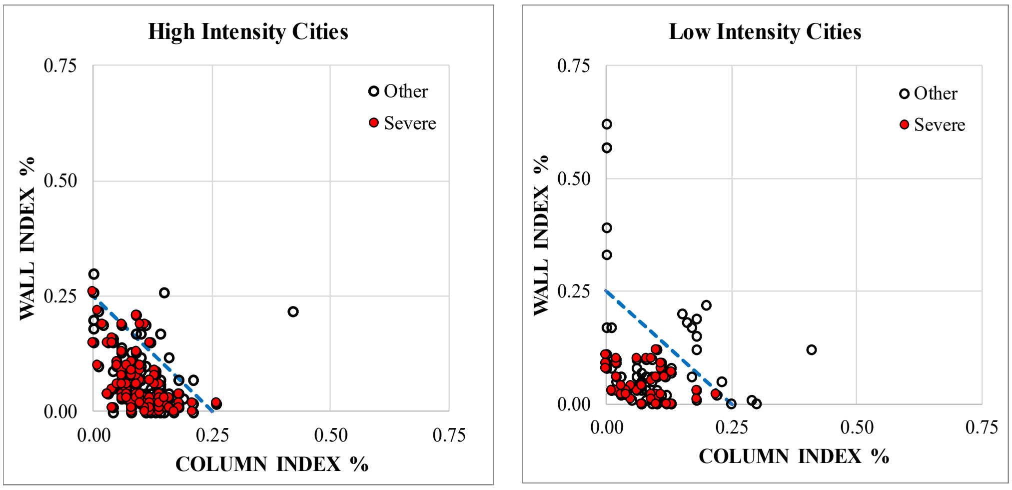


Figure 12. Damage distributions in high and low-intensity regions.

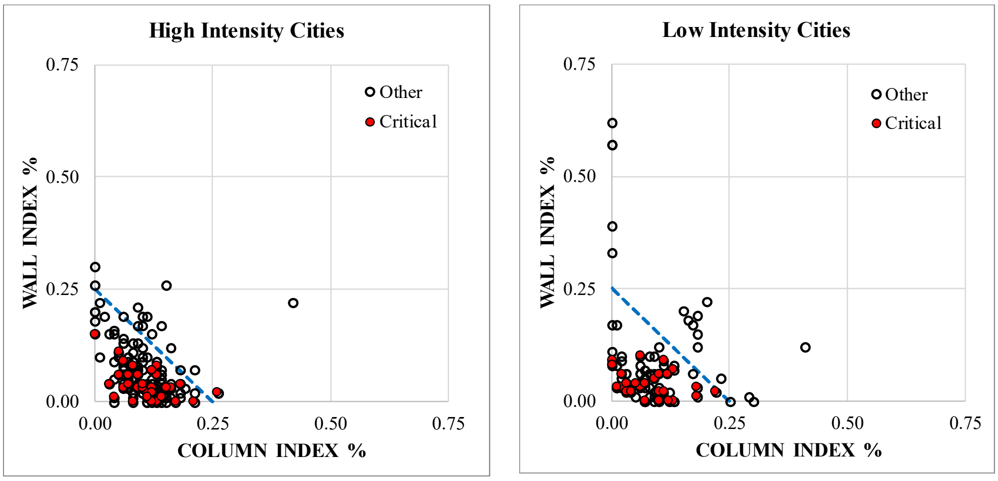


Figure 13. Damage distributions in high and low-intensity regions with the "critical" definition.

The data is organized to see which index is more effective in identifying the vulnerability of the buildings, Fig. 14. It could be observed that the wall index is more effective than the priority index (or column index). The risk of severe damage decreases to low levels with a Wall Index larger or equal to 0.1%.

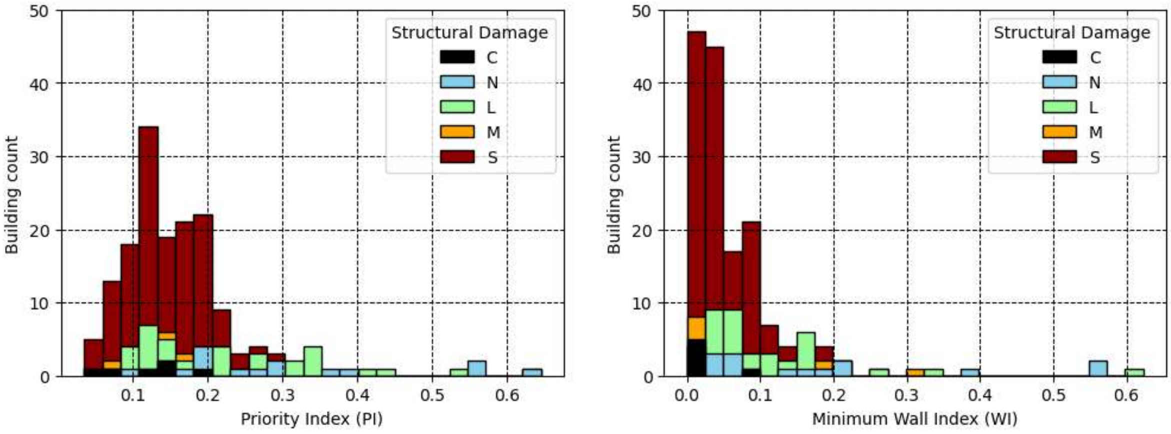


Figure 14. Damage histograms for the Priority Index (left) and Min Wall Index (right).

The Hassan data from Erzincan (Hassan and Sozen, 1997) and Bolu-Düzce (Donmez and Pujol, 2005) earthquakes are presented in Fig. 15. Also, Chile (Riddell et al., 1987) and Japan (Shiga et al., 1968) data are adopted for Hassan representation and presented in Fig. 16. Chilean and Japanese approach to seismic design is clearly toward more robust structures specifically with heavy usage of shear walls in the buildings. Note that the vertical axes of Figures 15 and 16 are different.

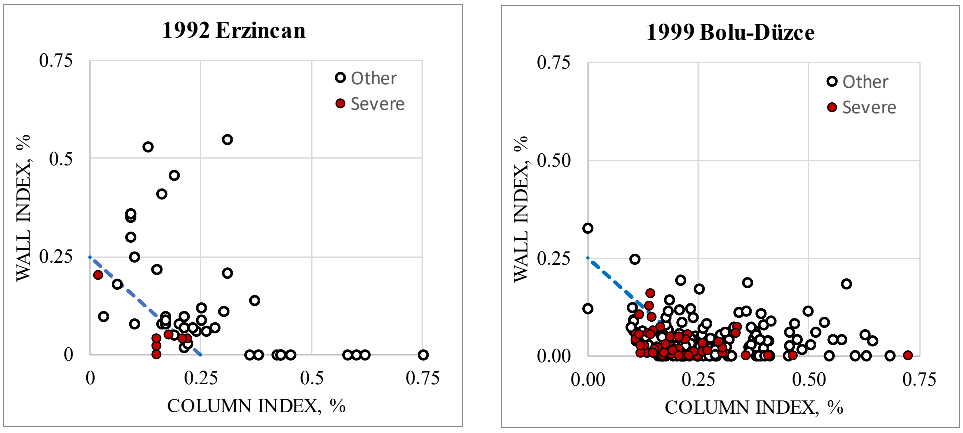


Figure 15. Hassan's data representation of the data from previous earthquakes.

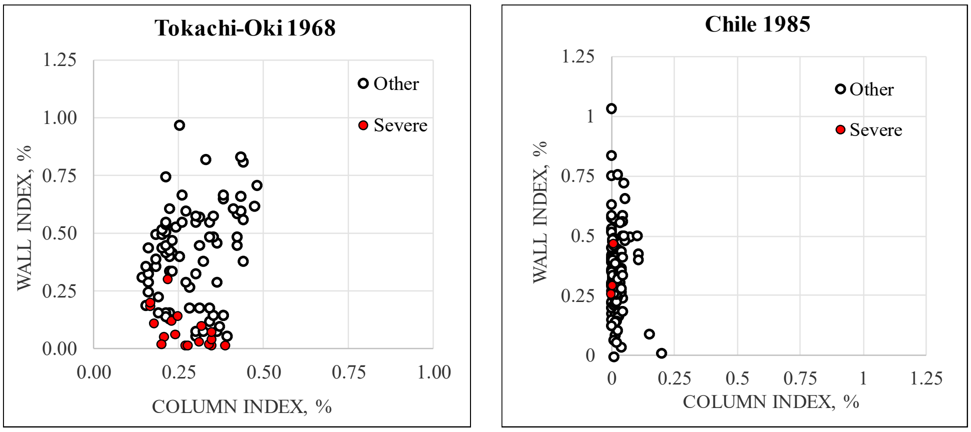


Figure 16. Hassan's data representation of Chile and Japan Data.

All the data collected from the events in Türkiye are presented in Figure 17. It is a representation of the Turkish approach to the level of robustness and corresponding damage accumulation.

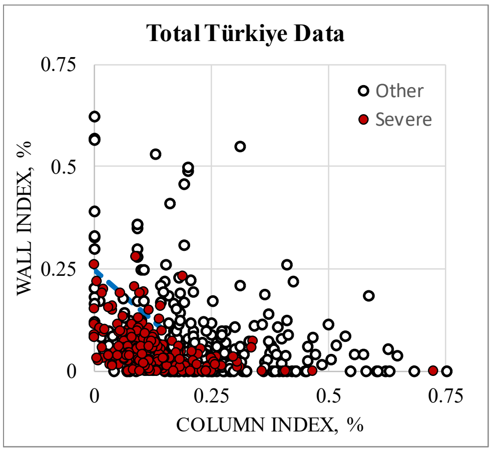


Figure 17. Hassan data representation of the data from all data from Türkiye.

5. Discussion of Results and Conclusion

The collected data show that the criterion proposed by Hassan and Sozen (1997) can help identify severe damage risk. Noting the changes that have occurred in construction practices, earthquake regulation, and building size and height as time has passed, it is remarkable that the criterion by Hassan and Sozen is still reliable. The probability of severe structural damage among buildings below the threshold CI+WI=0.25% is nearly three times larger than that of buildings above it, and severe partition damage is almost inevitable in the same domain. More than half the buildings surveyed did not have partition damage above the threshold, Fig. 9.

Structures with soft stories were identified to have a higher risk of severe structural damage and collapse, but providing a minimum WI of 0.1% seems to nullify this risk, Fig. 10. Frames with shallow beams sustained higher severe damage percentages, Fig. 11. It is recommended to provide sufficient robustness with shear walls in this type of framing.

The separation of high- and low-intensity cities, Fig. 12, indicates that the potential for severe damage increases for high-intensity cases. Still, the criterion holds in the face of high demands unknown until the Türkiye 2023 events. On the other hand, damage potential drops for low-intensity cases. The data from high-intensity regions data is also investigated considering the “critical” damage definition, Fig. 12. It is clear that structures with lower robustness have higher risk. The wall index, hence, shear wall usage, seems more effective overall in controlling the damage.

Evaluating the collected data in comparison with the previous Türkiye events, Fig. 15, it could be seen that dispersion is lower for the 2023 Türkiye data. Specifically, Bolu-Düzce 1999 data had a more extensive spread. It is known that the level of structural deficiencies was worse for Bolu-Düzce structures, which might have caused the excess. However, the combined Türkiye data, Fig. 16, indicates that the Hassan approach is very valuable in identifying the damage potential.

If the Turkish data is compared with the Chilean and Japanese data, it is clear that Turkish design practice prefers “less robust” structures, Fig. 17. Also, severe damage is extensive compared to Chile and Japan.

The evidence supports that limiting drift through increased “robustness” is paramount for the survival of the structures. Identifying severe damage in reference to “robustness” is successful even under the high uncertainty involved in the discussed surveys. The reason for the success is simple: robust structures develop lower displacement demands in earthquakes. Lower displacement demands prevent the triggering of damages due to structural deficiencies and, at the same time, protect the lives and property. The lack of control and inspection in Türkiye needs an approach that results in the design of structures not sensitive to probable deficiencies. The data collected in the last quarter century indicates that implementing “robustness” could be a key for such a purpose.

The performed study suggests that the index proposed by Hassan and Sozen can be used as a design criterion as well as a rapid seismic risk assessment tool. Hence, considering the ease of application and control, CI+WI>0.25% (at least WI>0.1%, Fig. 14) could be set as a design goal. In this approach, it is recommended to provide the detailing for ductility to have a backup for possible extreme events in the face of ground motion uncertainty.

6. References

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