Performance of RC Structures and Associated Lessons to be Learned from November 12, 2017, Sarpol-e Zahab - Ezgeleh Earthquake (M_W 7.3)

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ABSTRACT

Sarpol-e Zahab - Ezgeleh earthquake (M_W 7.3) occurred in Iran and Iraq border region on November 12, 2017 at 21:48 local time. This earthquake is the most devastating event in Iran after the 2003 Bam earthquake (M_W 6.6) in terms of damages. According to findings arising from the visit to the earthquake affected area between November 25 and 30, 2017, heavy structural and non-structural damages were occurred in all types of RC buildings, including structures built in national Iranian mass housing project, called Mehr housing scheme. In many cases, new structures, experienced severe damages or collapse during the earthquake, even in regions with low recorded PGA like Sharafabad town in Eslamabad-e Gharb city. Post-earthquake studies showed that damages in RC structures were mostly due to the poor construction quality including low concrete strength and non-seismic detailing as well as false structural design and local site effects. According to Iran construction laws, the "Iran Construction Engineering Organization" (IRCEO) is the prime responsible for the effective supervision in structural design and construction process in urban areas. Considerable number of damaged buildings that are constructed in recent years, is probably because of the lack of enough supervision by IRCEO and other responsible organizations. In this paper, observed damages to RC structures were examined and explained in detail.

Keywords:
Sarpol-e Zahab - Ezgeleh Earthquake; RC structures; Failure types; Seismic code

1. Introduction

On November 12, 2017, a strong earthquake of M_W 7.3 hit Kermanshah province and neighboring areas at 21:48 local time. The epicenter was located around 10 km from Ezgeleh village of Salas-e Babajani district and around 37 km NW from the Sarpol-e Zahab city, quite close to the Iraq and Iran border with the focal depth of 18 km. Out of 14 administrative districts in Kermanshah province, nine were affected by Sarpol-e Zahab - Ezgeleh earthquake in terms of victims, infrastructural failures and lifeline damages. Earthquake records and response spectra corresponding to the main shock event, recorded in Sarpol-e Zahab city, are plotted in Figure (1). As shown in Figure (1a), the maximum PGA in case of N-S component was 0.68 g. The maximum recorded PGA in Kerend-e

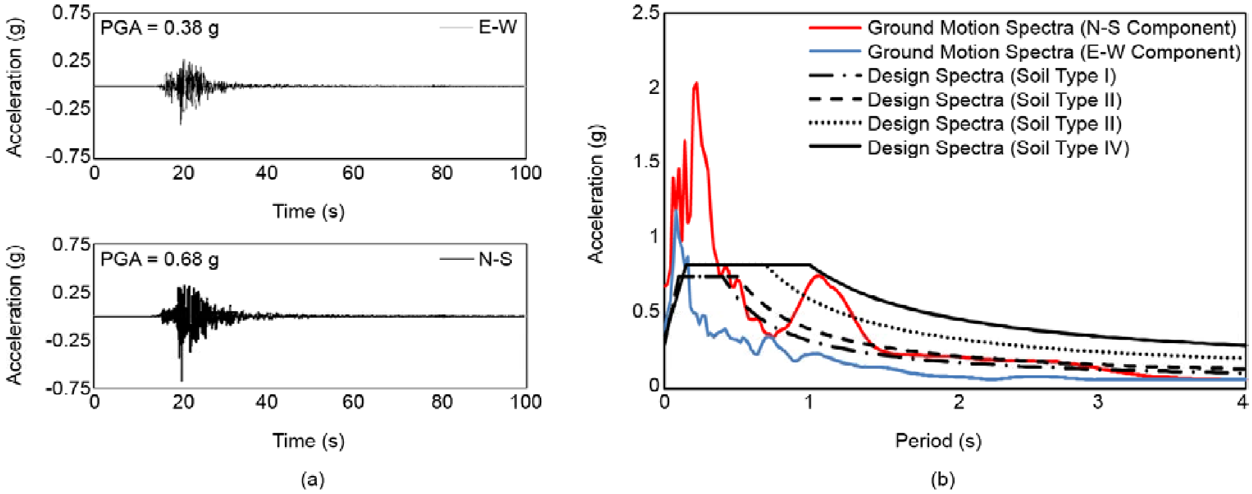


Figure 1. (a): Acceleration time histories recorded for the main shock event in Sarpol-e Zahab station (b): Elastic response spectra for the main shock and design spectra for various types of soils according to Iranian code of practice for seismic resistant design of buildings.

Gharb and Eslamabad-e Gharb cities were 0.28 g and 0.12 g, respectively. In Figure (1b), earthquake response spectra are compared with recommended design spectra for various soil conditions as is mentioned in Iranian seismic code [1].

A field reconnaissance was carried out by the authors between November 25 and 30, 2017, and the observations were reported in the present paper. The goal of the field reconnaissance was to study the damage patterns and their causes in the buildings, mainly in Sarpol-e Zahab city and other urban and rural regions. The location of investigation sites are shown in Figure (2).

The paper discusses the performance of reinforcement concrete (RC) buildings during the earthquake main shock and aftershocks.

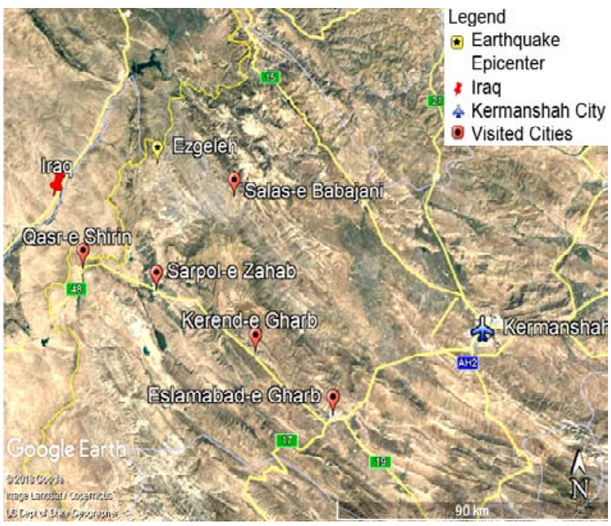


Figure 2. Locations of investigation sites that are referred in this paper.

2. Damages to Reinforced Concrete Buildings

A classification of the substantial damages occurred to RC structures in earthquake affected areas are provided in this section. Moment resisting frame structures with one-way slabs are the most common type of construction in urban areas especially for buildings with less than five floors. However, other types of damaged lateral-force-resisting systems (LFRS) especially in buildings built in Mehr housing scheme towns, observed during the visit. For the residential, engineered RC buildings, like in many other small cities in Iran, the owner or the shareholder of the land is also the constructor of the building. The constructor, personally, is not required to have specific knowledge or experience on construction. While, the structural designs are conducted by civil engineers, the construction is generally carried out by an uneducated person, without proper inspection. The non-engineered buildings, on rural areas, are designed and constructed entirely by uneducated workers.

According to the observations, properly engineered, inspected buildings make up only a small portion of the existing buildings in earthquake affected cities of Kermanshah province in Iran. In villages, almost all of buildings are unreinforced masonry built with adobe, hollow concrete blocks or stones. The infill walls of RC frames are either constructed using clay bricks without any proper anchorage system. According to the current Iranian code for the seismic design of structures [1], construction of RC buildings with "ordinary" shear walls or moment frames, with low ductility, was not allowed in the earthquake affected regions; therefore, it seems that RC structures should pass at least "intermediate" moment frame and shear walls detailing specifications. As mentioned before, a major part of the existing buildings in affected areas are low-rise reinforced concrete frame buildings that were not properly constructed, because of the lack of an effective inspection mechanism. Consequently, most of the existing buildings have a range of deficiencies. Therefore, it is not possible to define the large majority of existing buildings as properly engineered construction, even if they have been approved legally. Structural and construction deficiencies and associated damages to RC buildings observed during field visit are presented as follows based on the number of occurrences in the region. It is worth noting that the failure modes and damage causes, listed below, are largely interdependent, and some of them including low quality of concrete, insufficient stirrups, etc. can exacerbate other failure modes.

2.1. Poor Quality of Concrete

Poor quality of concrete is one of the most important causes of structural damages and building failures. The damages caused by poor quality concrete in earthquakes, has been reported by many researchers in recent decades [2-3]. Based on the observations, the quality of the concrete used in the damaged buildings was considerably poor. Examples of the use of low-quality concrete are shown in Figure (3). In earthquake affected region, utilization of hand-mixed concrete especially for residential buildings is the common construction practice. According to the observations, lack of sieve analysis resulted in oversized aggregates and poor gradation concrete mixture, high water to cement ratio, insufficient concrete curing and lack of vibration after concrete placement are the most important mistakes in mixture of concrete material.

2.2. Strong Beam-Weak Column

As expected, given the fact that meeting the strong-column / weak-beam requirement is not mandatory in intermediate or ordinary RC buildings, based on ACI-318 [4] and Iranian seismic code [1], strong beam / weak column connections were observed in the RC buildings in the earthquake affected region. Examples are presented in Figure (4). In general, the ductility capacity of structures, with weak columns compared to the beams, is significantly reduced and in the worst case of weak columns, flexural yielding can occur at both ends of all columns in a given story, resulting in a column failure mechanism that can lead to collapse [4]. Figure (5) shows the case study of a new 3-story residential building in Sarpol-e Zahab city. Severe damage occurred at both ends of columns in first stories, while no considerable damage was observed at the beam ends.

2.3. Stiffness Irregularity (Soft Story)

Soft first story is a common failure mode in damaged RC buildings in earthquake affected

(a) (b) (c)

Figure 3. Use of low quality concrete.

(a) (b)

Figure 4. Damages due to strong beam-weak column.

(a) (b)

Figure 5. Case study: A 3-story RC building, damages due to strong beam-weak column.

region because the first story of the buildings have been often used as car parking or commercial areas with no partition walls. As well as removing the infills, ground floors with high ceilings considered as a main cause of soft story phenomenon in field observation. By decreasing the lateral stiffness of first story in comparison with upper stories, the first story suffer more lateral deformation in earthquake with a tendency to the early formation of plastic hinges at column ends in first story. The soft story phenomenon, which can be amplified by ignoring the strong column-weak beam Criterion, significantly reduce the lateral strength and dissipation capacity of the structure. The Iranian seismic code [1] has not provided any mandatory regulations to avoid "soft story" in regular buildings with the height less than 50 meters, or all structures (regular or irregular) with three story or less. While, according to the observations, low-rise RC moment frame buildings, are also significantly vulnerable to soft story-related damages (Figure 6).

2.4. Short Column Effect

Short column collapse were widely observed during the field observations, such as the cases shown in Figure (7). The short columns have much higher lateral stiffness in comparison with normal columns and higher seismic loads can develop in

Figure 6. Soft story phenomenon.

Figure 7. Short column effect.

such columns and may result in double diagonal cracking failure. Figure (7a) shows the formation of a short column due to the intermediate staircase landing between two floors, Figure (7b) shows the short column effect due to the partial infilled frames to attain architectural requirements and finally, Figures (7c) and (7d) indicates the generation of a short column due to the partial collapse of infill walls. Proper seismic detailing, with closer stirrup spacing specially for columns prone to shear failure due to the short column effect, is required to prevent short column failures.

2.5. Shear Wall Collapse

Shear wall collapse, particularly in Sharafabad town, close to Eslamabad-e Gharb city, was observed. As mentioned before, the maximum recorded PGA for the earthquake in Eslamabad-e Gharb city was negligible (0.12 g) and the damage to the shear walls was concentrated to only two adjacent buildings while the other buildings in this town, did not experience severe structural damage due to earthquake (Figure 8)

According to Figures (9) and (10), the top of shear walls in first story was considered as the probable location, corresponding to onset of shear wall damage, influenced by poor concrete quality at the top of walls. As well as poor quality of concrete, other deficiencies can be considered as the cause of shear wall collapse as follows:

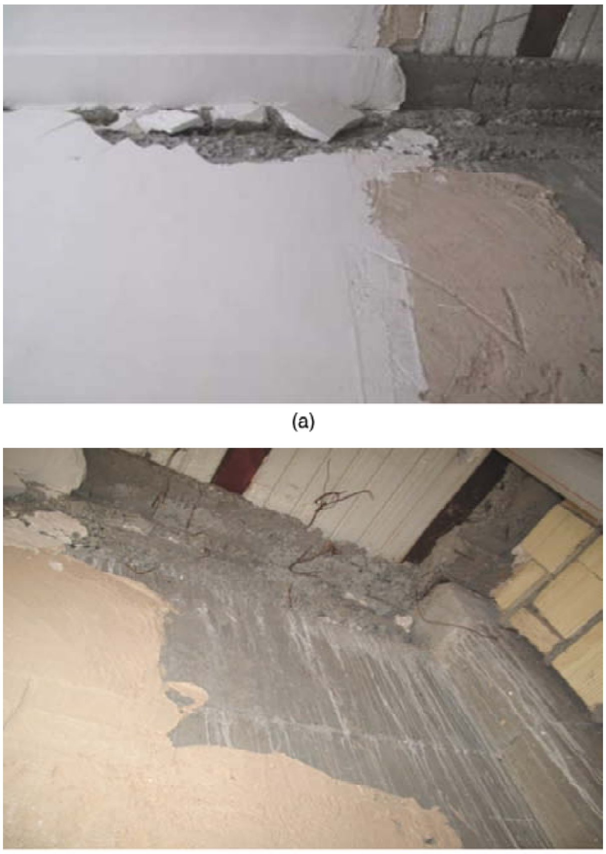
- According to ACI-318, the shear horizontal reinforcement requires to extend to the edge of the wall to be anchored to develop yield stress in tension within the confined core of the boundary element using standard hooks or heads. As shown in Figure (11), significant deficiencies observed in anchorage of horizontal reinforcements in the boundary elements. The diameter of anchorage segments in boundary zones, was much less than diameter of horizontal reinforcement in the wall web, with insufficient splice length and was placed out of the boundary element core. As a result of deficiencies in anchorage of horizontal reinforcements, severe detachment between boundary elements and the shear wall web observed in collapsed blocks.
- According to ACI-318, if longitudinal

Figure 8. Collapse of structures with dual LFRS (moment frame and Shear wall) in Eslamabad-e Gharb.

(a)

(b)

Figure 9. Collapsed shear walls.



(a)

(b)

Figure 10. Poor concrete qulity at the top of shear walls.

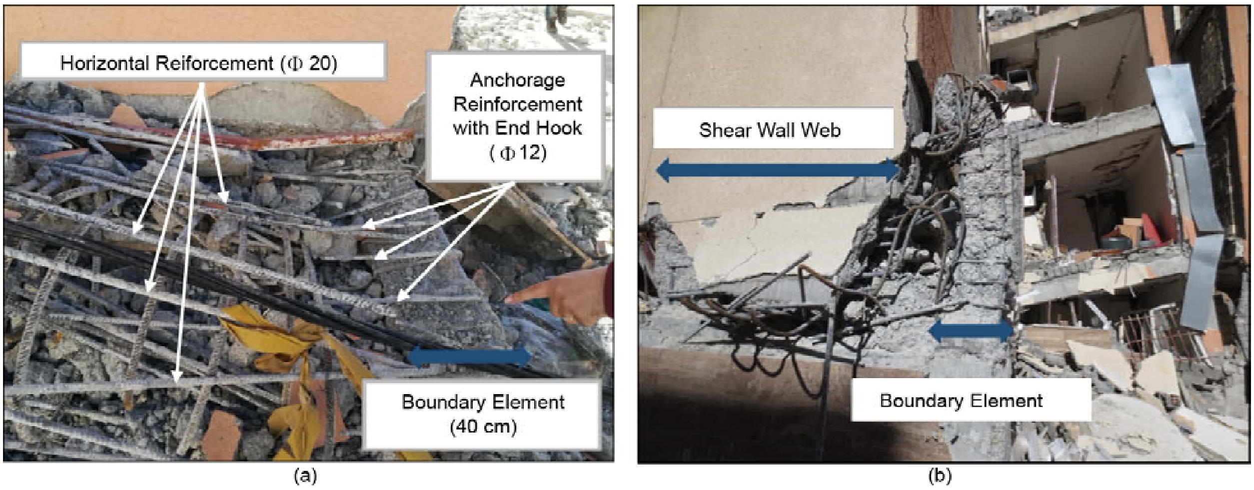


Figure 11. Detachment of boundray element and shear wall web due to the deficiencies in anchorage of horizontal reinforcements.

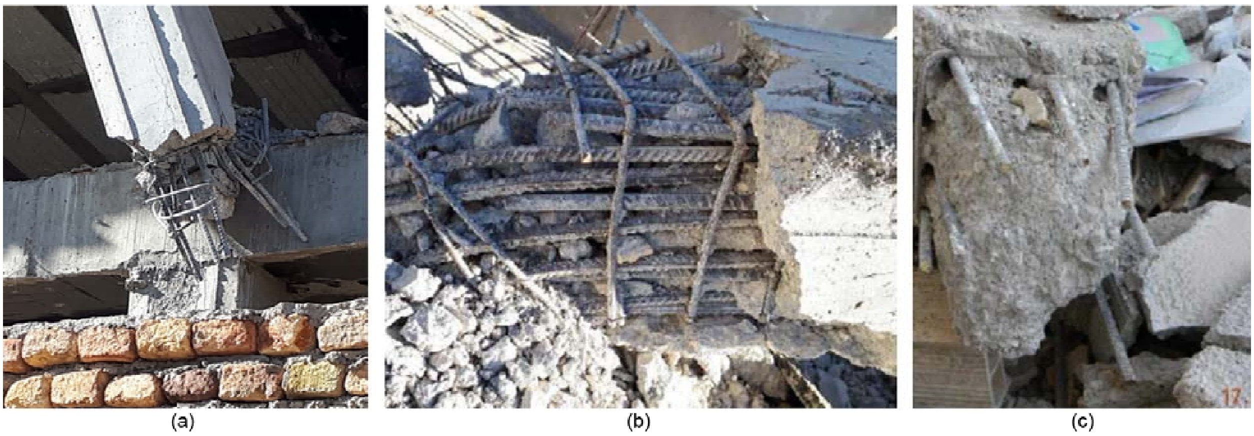


Figure 12. Short splice length and splices near joints.

reinforcement is required for axial strength in structural walls or if the ratio of longitudinal reinforcement to gross wall section area exceeds 0.001, longitudinal reinforcements shall be laterally supported by transverse ties. As shown in Figure (9a), widespread buckling of longitudinal reinforcement observed, due to the lack of transverse ties. Large spacing and inappropriate anchorage of transverse reinforcement, ignoring the lateral support of longitudinal reinforcement by transverse ties, impaired the efficiency of the shear walls, remarkably.

2.6. Short Splice Length and Splices Near Joints in Columns

A widespread failure mode observed in RC buildings was the inadequate splice length of longitudinal reinforcements especially near beam-column joints, which is an undesirable location for splicing, as shown in Figure (12). Short lap splices at plastic hinge regions, lack of end hook angle, and widely spaced stirrups increased the severity of the damage.

2.7. Insufficient Stirrups

As is shown in Figure (13), the stirrup arrangements in the columns of damaged RC buildings were poorly detailed. The length of the hook provided in stirrups was short and had inappropriate 90° - end hooks. Excessive spacing of transverse reinforcement throughout the column, even in hospital building with the highest design importance factor as shown in Figure (13c). The maximum spacing according to confinement requirements of ACI 318 [4], for a column with characteristics shown in Figure (13c) is about 70 mm while the stirrups spacing is more than 400 mm as shown in Figure (13c). This caused shear failures, buckling of longitudinal rebar and poor confinement of the core concrete.

(a) (b) (c)

Figure 13. Insufficient and inappropriate stirrups detailing.

2.8. Failure of Beam-Column Joints

Beam-column joint failure is one of the most critical damages in RC structures and can notably increase the possibility of the collapse of the structure. Due to the small size and significant forces generated within the joints, the joints must properly confined by stirrups to avoid brittle failure under seismic loads. As well, joint confinement, proper anchorage of the beam and column reinforcement in the interior of the joint play a significant role in the performance of RC structures (Figure 14a). Intensive damages to beam-column joints were observed frequently during the visit. A lack of transverse reinforcement or insufficient stirrup spacing in the beam-column joints, as well as the lack of standard end hooks at the end of column longitudinal rebars was observed in the majority of the damaged beam-column joints, as shown in Figure (14).

2.9. Failure and Cracks on Infill Wall

Numerous earthquakes and studies have already shown that the presence of infill masonry panels can significantly change structural response. Although for low/medium seismic loadings, the masonry can protect the structure in some cases, but for medium/high levels, due to their fragile behavior, a severe strength reduction at peak-strength may be attained resulting in an actual loss of global capacity [5]. Participation of walls in

(a) (b) (c)

Figure 14. Failure of beam-column joints.

seismic-induced forces can cause damage to the buildings in many cases. Masonry infills irregularly distributed in elevation may potentiate "soft-story" mechanisms and unwanted dynamic tendencies, like torsions (Figure 6). As well as "soft-story" phenomenon, partial damages to the panels may also attract forces to structural parts that were not designed to resist, like "short column" phenomenon (Figure 7). Another important influence is the decrease of the natural period of the structure, due to high initial stiffness of infill walls, which can result in an increase of induced seismic acceleration. The observed damages, suffered by the infill walls, are clearly the result of the low construction quality of the infill walls, their inability in accommodating the large drifts experienced by the building and finally, deficiencies in anchorage of the infill wall and proper connection between infill walls and the structure. According to the in situ observations, undesirable seismic response of infill walls can be organized in three general categories as mentioned in Noorifard et al. [6]. At the first category, only the infill walls are damaged by in plane failure (Figure 15). At the second category, there is the possibility of other non-structural elements damage and human injury as well as the wall damage by the out of plane failure of infill walls (Figure 16). At the third category, the arrangement of walls in plan and

(a) (b)

Figure 15. In-plane failure modes of infill walls. (a): Cracking in wall piers, induced by the location and size of openings. (b): In-plane failure due to diagonal cracking induced by weak components and joints.

(a) (b)

Figure 16. Out of plane failure of infill walls induced by weak components and joints.

elevation cause severe structural damage. Damages such as short column, soft story and torsion of structure are classified in this group as shown in Figures (6), (7) and (13c).

3. Performance of RC Structures Built in Mehr Housing Scheme

The large-scale, Mehr housing project, designed in 2007, aimed to cover a part of house shortage through building of around two million housing units within five years specially for low-income people with housing units through free land and cheap credits all around Iran. All Mehr housing towns with damaged building caused by earthquake, in Kermanshah province, visited by the authors. As summarized in Table (1), buildings in Shahid Shiroodi (Sarpol-e Zahab city) and Sharafabad (Eslamabad-e Gharb city) Mehr housing towns, experienced severe structural and nonstructural damages while buildings in Dalahoo town (Kerend-e Gharb) although did not experience severe damages due to the negligible earthquake acceleration, are abandoned because of very poor construction quality. In this section, observed structural and nonstructural damages of RC buildings of Mehr housing are summarized in Figures (17) to (19) and Table (1). The percentage next to the lateral-force resisting system (LFRS) or observed damages for each town, indicates the percentage of the specific type of failure or LFRSs among the buildings in the town. For example, "IMF (50%)" in lateral resisting system column, indicates that about 50% of structures in this town had RC, Intermediate Moment frame (IMF) lateral resisting system or "Short Column (100%)" indicates that in 100% of blocks in a specified town, at least one short column failure mode, observed.

4. Conclusion and Lessons Learned That Should be Taken into Consideration in the Future

Sarpol-e Zahab - Ezgeleh earthquake (M_W 7.3) occurred in Iran - Iraq border region on November 12, 2017 at 21:48 local time. According to the findings arising from visit to the area between 25 and 30 November 2017, heavy structural and non-structural

Table 1. RC buildings of Mehr towns.

Town	City	Location	Year Built	Number of Blocks	Number of Floors	Lateral-Force Resisting System (LFRS)	Observed Damages		Related Figures
							Structural	Nonstructural	
Shahid Shiroodi	Sarpol-e Zahab	34.46° N 45.84° E	2012	24	7	IMF* in N-S Direction & DUAL** in E-W (100%)	Short Column (100%) Column Overall Buckling (20%)	Extensive, Out-of-Plane Failure of Infill Walls (100%)	Figure 7a Figure 16a Figure 17
Sharafabad	Eslamabad-e Gharb	34.07° N 46.30° E	2017	99	5	DUAL (50%) IMF (50%)	Complete Structural Collapse in Two Adjacent Blocks with DUAL LFRS as Discussed in Detail in Section 2.5 (2%) No Significant Damage Observed for Other Buildings (98%)	Out-of-Plane Failure of Infill Walls (10%) Minor In-Plane Cracks (10%)	Figure 8 Figure 9 Figure 10 Figure 11 Figure 18
Dalahoo	Kerend-e Gharb	34.27° N 46.25° E	Under Construction	23	5	Tunnel Form*** (100%)	Due to Negligible Acceleration of Earthquake in This Area, no Obvious Damages Due to the Earthquake Observed. Although Significant Construction Deficiencies Observed During the Visit as Shown in Figure (19) (100%)		Figure 19

*IMF: Intermediate Moment Frame
**DUAL: IMF + Intermediate Shear Wall
***Tunnel Form: Bearing Walls + Two Way Slab

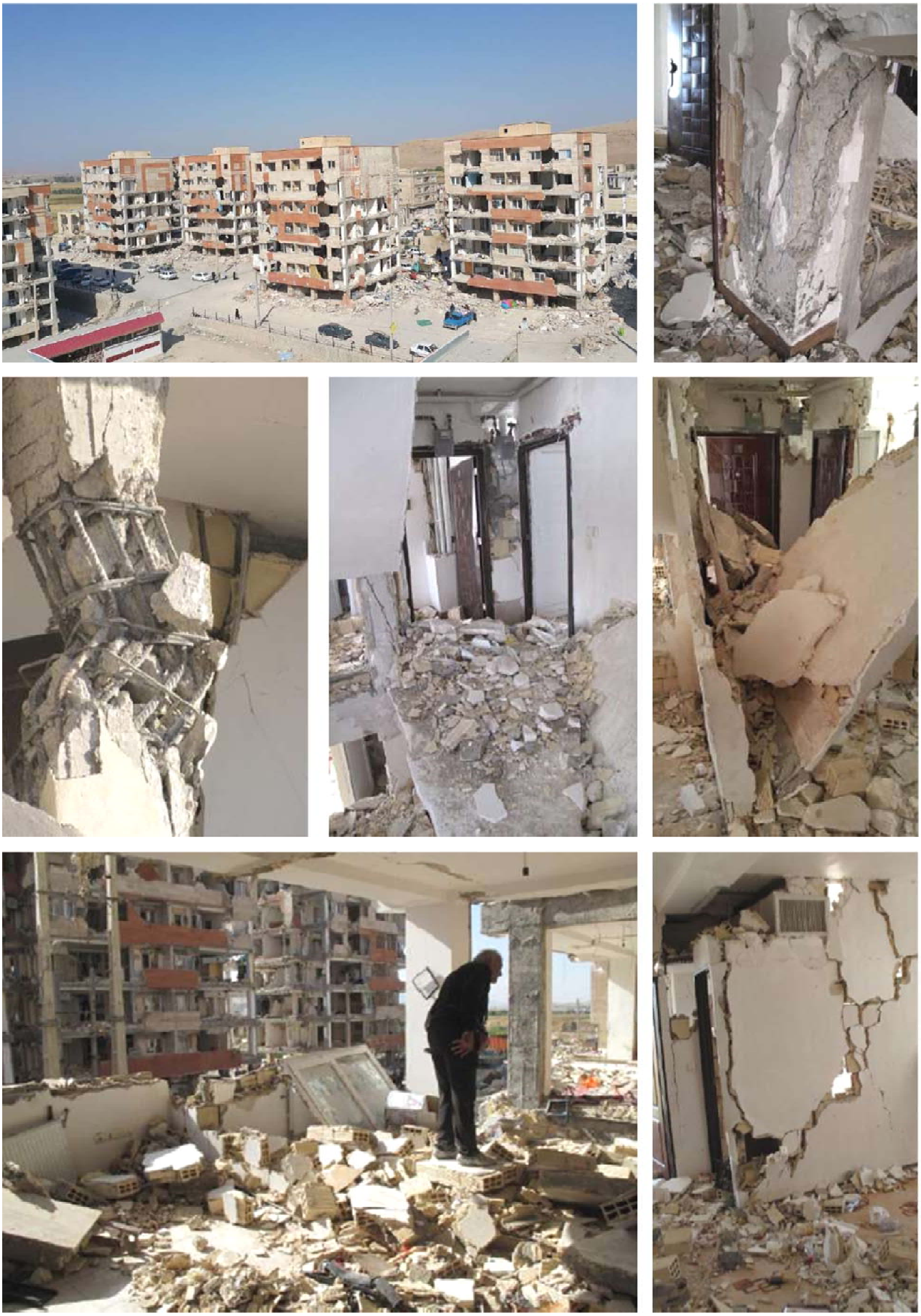


Figure 17. Observed structural and non-structural damages in Shahid Shiroodi town.

Figure 18. Observed structural and non-structural damages in Sharafabad town structures.

Figure 19. Observed structural damages in Dalahoo town structures.

damages were occurred in all types of prevalent structural systems including structures built in national, Iranian mass housing project, called Mehr housing scheme. Post-earthquake studies showed that damages in structures were mostly due to the poor construction quality including low concrete strength and non-seismic detailing, as well as false structural design and local site effects.

According to I.R. Iran construction laws, the Iran Construction Engineering Organization (IRCEO) is the prime responsible for the effective supervision in structural design and construction process in urban areas and Mehr housing towns. Large number of damaged buildings that are built in recent years is mainly because of the lack of enough supervision by IRCEO and other responsible organizations.

In spite of the previous strong earthquakes happened in undeveloped cities or rural areas of Iran like Buin Zahra earthquake (2002), Bam earthquake (2003) or East Azerbaijan earthquakes (2012), which almost all of structures were unreinforced masonry buildings, in Sarpol-e Zahab - Ezgeleh earthquake, many so called, "engineered" structures that are built in recent decade, severely damaged that could have been avoided by using appropriate structural concepts. This earthquake had no new lesson, while the same failure mode of RC structures had been reported in many other reconnaissance earthquake reports from all over the world [3, 7, 5]. However, the main lessons to be learnt from this event, in order of importance are as follows:

- The need for more effective supervision on the design and construction process by qualified engineers.
- Poor quality of constructions was the most important cause of the widespread destruction in the region.
- The need for reconsideration of the design acceleration spectra provided in [1].
- The providing proper isolation between infill walls and the structure, and at the same time, using proper infill walls anchorage systems to avoid in-plane and out-of-plane infill collapse respectively, considering widespread human and economic losses caused by undesirable collapse of infill walls.
- Providing mandatory regulations to avoid "soft story" even in low rise, RC moment frame structures.

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