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SEISMIC PERFORMANCE OF RC BUILDINGS AND HIGHWAY BRIDGES DURING THE KAHRAMANMARAS EARTHQUAKES

Y. Demirtaş[1,2*], E. Sülev[3], O. Tunaboyu[1], A. Bozer[1] & Ö. Avşar[1]

[1] Department of Civil Engineering, Engineering Faculty, Eskişehir Technical University, Eskişehir, Türkiye, *yunus_demirtas@eskisehir.edu.tr

[2] Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Uşak University, Uşak, Türkiye

[3] Department of Civil Engineering, Engineering Faculty, Nuh Naci Yazgan University, Kayseri, Türkiye

Abstract: *On February 6, 2023, two sequential severe earthquakes with magnitudes of Mw 7.7 and 7.6, occurred in the southern region of Türkiye with the focal depths of 8.6km and 7.0km, respectively causing an excessive loss of lives and property. The spectral acceleration values recorded in these earthquakes far exceeded those expected for the design-based earthquake with a return period of 475 years. Even there are several period ranges where the spectral acceleration values exceeded those anticipated for the maximum credible earthquake (2475-year return period). Governmental officials indicated that more than 50,000 citizens lost their lives and declared a monetary direct loss of more than 100 billion dollars. Because of the large area affected by the earthquake, the structural damage inspection concentrated on a specific region. Hatay was selected to conduct a reconnaissance survey on damaged structures not only due to the large extent of damaged buildings and losses but also the high intensity ground motions recorded in this province. Given the substantial size of the affected building stock, particular emphasis was placed on inspecting the structural damage in relatively new constructions of reinforced concrete (RC) buildings, which were constructed after 2000. Investigations were conducted based on the damage resulting from the irregularities in structural system, deficiencies in detailing at the member level, and the inadequacy of construction materials. Additionally, the structural damage and seismic performance of highway bridges were examined. The deviation from a simple and regular design approach, the inability to establish a structural system compliant with earthquake-resistant design principles due to deficiencies in the dimensions and layout of structural elements are the main causes of observed damage in buildings. Moreover, during both design and construction stages, building inspections and audit were not properly and sufficiently employed. Therefore, the inspected damaged buildings have several irregularities in their structural systems, improper detailing in RC components and inadequacies in the concrete and reinforcement steel. In contrast to past earthquakes, structural damage was observed in the examined highway bridges, with a concentration of damage in superstructure beams and shear keys due to the pounding effect between the superstructure and substructure.*

Keywords: RC Buildings, Detail Faults, Bridge Damages, Field Observation

1. Introduction

According to the records of the Earthquake Department of the Disaster and Emergency Management Presidency (AFAD), first earthquake occurred on 06.02.2023 at 04:17 local time. The instrumental magnitude was Mw 7.7 and the epicenter was in the Pazarcık District of Kahramanmaraş Province of Türkiye. The focal depth of this earthquake was determined as 8.6 km. In the same day, another earthquake with a magnitude of Mw 7.6 occurred at 13:24 local time in the Elbistan District of Kahramanmaraş Province. The focal depth of the second earthquake is calculated as 7.0 km (Avşar *et al.*, 2023). After this date, a large number of aftershocks with magnitudes up to Mw 6.4 have been recorded. According to the intensity map produced using the Earthquake Preliminary Damage Estimation System (AFAD-RED), the intensity of the earthquake in the nearest center of population to the epicenter of the Mw 7.7 earthquake was calculated as MMI XI, and the intensity of the Mw 7.6 earthquake was calculated as MMI X (AFAD).

Although the Pazarcık and Elbistan earthquakes did not occur on the same fault, the affected area was not limited to the province of Kahramanmaraş due to the fact that they ruptured close to each other and the focal depth was close to the ground in the range of 7-9 km. The disaster has affected an area of 108,812 km², encompassing the provinces of Hatay, Adıyaman, Gaziantep, Malatya, Kilis, Diyarbakır, Adana, Osmaniye, Şanlıurfa, and Elazığ, which are located in the eastern part of the Mediterranean, Eastern Anatolia, and Southeastern Anatolia regions. After the Mw 7.7 and Mw 7.6 magnitude earthquakes, more than 7,500 aftershocks and two independent earthquakes were occurred. This disaster caused great destruction and damage in 11 provinces in the south and east of Türkiye and was recorded as the biggest disaster that the country has experienced since the last century. More than fifty thousand people lost their lives as a result of the devastating effects of these earthquakes. According to the statement made by the Ministry of Environment, Urbanization and Climate Change on 07.03.2023, 232,632 buildings consisting of 651.416 independent sections were reported to be demolished, to be demolished immediately or severely damaged (Avşar *et al.*, 2023).

Within the scope of the study, because the earthquake affected a vast area, the structural damage inspection conducted by the authors focused on a specific location. Hatay was chosen to undertake a reconnaissance assessment on damaged structures because of the significant number of damaged buildings and losses, as well as the high intensity shaking reported in this region. Given the significant magnitude of the impacted building stock, special attention was made on investigating structural damage in relatively recent reinforced concrete (RC) structures built after 2000.One of the reasons for considering such a milestone is the relative increase in the awareness for earthquake resistant design and construction of the engineering and construction community after the 1999 Marmara Earthquakes. Additionally, In Türkiye a new seismic design code was enacted in the year 1998. TEC, (1998) is a modern regulation in which Earthquake Zoning Map was revised, capacity design principles and both structural and member ductility requirements were introduced. In 2000, the "Design and Construction Rules of Reinforced Concrete Structures" (TS500, 2000)standard was published by the Turkish Standards Institute. Subsequently, the Building Inspection Law dated 29/6/2001 and numbered 4708 was enacted. Furthermore, the structural damage and seismic performance of highway bridges were investigated.

2. Damages observed in reinforced concrete buildings constructed after 2000

The official results of the damage assessment studies were announced on the the Ministry of Environment, Urbanization and Climate Change's official website on 19.02.2023 for the 11 provinces most affected by the earthquake (Avşar *et al.*, 2023). As a result of the damage assessment, the buildings that are decided to be heavily damaged/collapsed should be demolished. Moderately damaged buildings are only allowed to be used after necessary repairs and strengthening. Therefore, since it is not possible to use heavily damaged/collapsed and moderately damaged buildings, it is important to determine the distribution of these two groups for temporary shelter works for post-earthquake studies. According to the number of heavily damaged/collapsed and moderately damaged buildings, the provinces of Hatay, Kahramanmaraş, Gaziantep, Adıyaman and Malatya are the most affected ones among the 11 provinces.

2.1. Improperly arranged structural systems

According to Turkish Building Earthquake Code (TBEC), 2018 controlled damage (CD) performance level should be expected in ordinary buildings designed under design based earthquake level (DD-2) with a recurrence period of 475 years. This performance level corresponds to the level of damage, which is not too severe and mostly repairable, in the structural elements of the building in order to ensure life safety. Under the maximum acceptable earthquake level (DD-1) with a recurrence period of 2475 years, severe damage can be occurred to the structural system and its components but partial or total collapse of the building is prevented (CP). As a result of the field observations made specifically for the buildings built after 2000, component damage was observed beyond the CD performance level, especially in the buildings that did not possess appropriate seismic design, and even a considerable amount of buildings were inspected to be well beyond the CP performance level.

The direct transmission of the story level inertial forces to the foundation through the shortest path during strong ground motion is essential for the sake of the earthquake performance of buildings. Non-orthogonal (Figure 1) and discontinuous moment-resisting frame axes (Figure 2) of cause irregularities in the transfer of inertial forces through the structural system. One of the most common examples for the discontinuous frame was observed at the exterior axes of the RC buildings. The vertical members at the exterior axes are not directly connected with a beam. As the ground story plan area is mostly less than the above story plan areas, the beams are generally applied under the surrounding infill walls without connecting to the vertical members directly. Therefore, a moment resisting frame, at which the vertical and horizontal structural components were connected directly, cannot be achieved in a designed way. The main reason for not connecting the vertical components with beams mainly arises from the architectural concerns because of preventing those directly supported beams to achieve a flat ceiling at the architectural volumes.

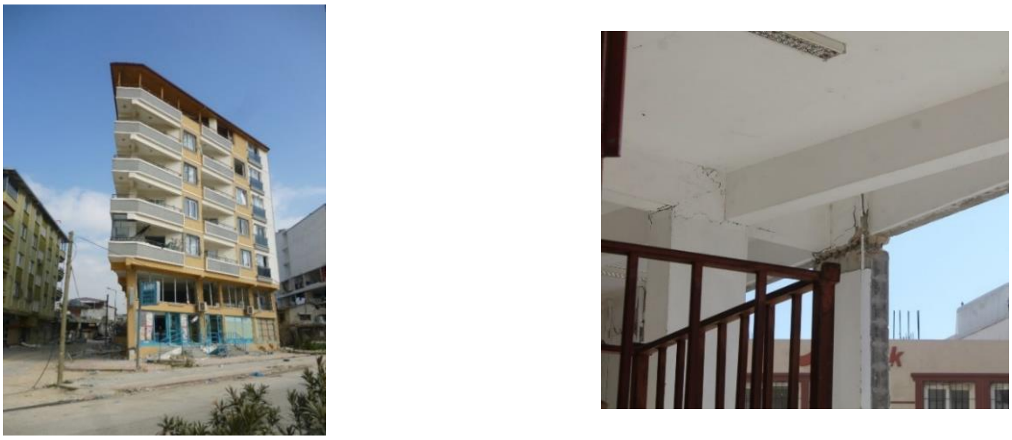

Figure 1. Non-orthogonal axis systems

Figure 2. Discontinuities in the axis system

2.2. Structural irregularities

According to TBEC (2018), weak-story irregularity is a type of vertical irregularity in buildings where the behavior factor of the structure is reduced up to a certain limit value, resulting in increased seismic forces in the seismic design of buildings. However, when the limit value is exceeded, the effective shear area of the weak-story needs to be increased, making it necessary to address this irregularity, which arises from the improper distribution of story strength between successive stories. In the case that the vertical load-bearing elements are not discontinuous, the weak-story irregularity is due to the lack of infill walls mostly in the ground story. Observations made in the field (Figure 3) show that the stiffness irregularity between successive stories, which is also commonly termed as soft story is also affected by a similar mechanism. TBEC (2018) controls the formation of soft story irregularity by limiting the ratio of the drift ratios of the successive stories. Therefore, it is the responsibility of the design engineer to consider the contribution of each structural and non-structural component in the story stiffness. Therefore the stiffness contribution of the infill walls should be included in the structural model in order to calculate the story displacements more precisely. In the field observations, beam damages were observed, which is estimated to be due to the sudden stiffness change that occurs when the slabs are continuous in one part of the beam length and not in the other part (Figure 4).

Figure 3. Weak/soft story mechanisms

Figure 4. Slab discontinuities

2.3. Insufficient strength and stiffness

It has been observed that the shear walls are exposed to excessive shear forces and lose their structural integrity as a result of insufficient use of the shear walls in both directions (Figure 5). According to TBEC (2018), shear forces on shear walls are obtained by proportioning the shear plastic moment capacity to the moment demand, taking into account the overstrength coefficient and dynamic amplification coefficient according to the capacity design principle. On the other hand, in field observations, brittle shear damages were observed in the shear walls by reaching their shear capacities before they reach their plastic moment capacities (Figure 5).

Buildings that lack sufficient stiff elements in both directions and have irregularities in the stiffness between adjacent floors are exposed to significant relative lateral displacements when using ribbed slab, leading to increased seismic damage in structural components. Additionally, non-structural elements such as infill partition walls and cladding panels are observed to topple out of their planes due to these large lateral movements. Ribbed slab, in such cases, exacerbates the damage to both structural and non-structural elements, necessitating careful consideration in the design of RC buildings having ribbed slabs Figure 6.

Figure 5. Shear failure of shear walls

Figure 6. Out-of-plane tipping of exterior infill walls in ribbed slab systems

2.5. Brittle beam damages

As can be seen in Figure 7, shear damage was observed close to the mid span of the beam. The shearing demands in the transition region should be taken into account when determining the stirrup spacing from the end regions to the mid region. Generally, large shearing demands occur in the short beams between the stiff vertical members (e.g. Beam between the strong axis of two shear walls.). If it is not equipped properly and cross reinforcement bundles are not used in the design, severe shear damages are inevitable (Figure 8).

Figure 7. Shear damage near the mid span of the beam

Figure 8. Shear damage of short beams

2.6. Captive column damages

Captive column damages were frequently encountered (Figure 9). According to TBEC (2018), in cases where captive column formation cannot be prevented, the shear forces obtained by dividing the total plastic moment capacities at the lower and upper ends of the column section by the column net height should be taken into account in design. Otherwise, if the column shear demands are larger, which is the case in short and captive columns, than the column shear capacity consistent with the flexural capacity of the columns, brittle type of column shear failure is inevitable before the formation of plastic hinges at the column ends.

Figure 9. Shear damage on the captive columns

2.7. Improper detailing in RC members

A significant part of the building stock in Türkiye consists of substandard reinforced concrete structures. In recent years, a certain level of improvement has been achieved in the building stock due to the updates made in seismic design codes as well as the new regulations in the construction audit. Moreover, there is a considerable improvement in the construction materials especially after the 1999 Marmara Eathquakes. However, improper detailing in RC components and incorrect applications made during the structural system selection stage as well as the construction stages are still remain the main problems observed in the severely damaged and recently constructed RC buildings. Often poor workmanship and unsupervised construction lead to detailing errors during construction. Although some of the improper detailing in RC components originates from the design stage, the majority of the detailing problems were observed to take place during the construction stage due to poor workmanship and inadequate supervision or even in some cases lack of supervision during the construction of residential buildings.

Even if the distance between the stirrup arms is sufficient to meet the column shear demands, the horizontal distance between the stirrup arms and/or crossties should not more than 25 times the stirrup diameter, according to TBEC 2018. In Figure 10, it is seen that the longitudinal rebars are confined with only single stirrup, which can only restrain the corner rebars. As required by most of the previous and current seismic design codes in Türkiye, internal rebars should be confined by additional crossties or stirrups other than the outer single stirrup. Otherwise, upon the crushing of cover concrete, internal bars can deform and buckle causing loss of integrity for the column cross section.

Figure 10. Large spacing between stirrups

According to TBEC (2018), the transverse reinforcements used in column confinement zones should be continued in the foundation or overhead beam along a height not smaller than the minimum size of the column. The transverse reinforcements in the shear wall end regions must be continued inside the foundation for a height not less than 300 mm and shear wall thickness. However, incorrect applications were observed in the application of the transverse reinforcements in the vertical structural members through the foundation due to the difficulty of implementation, lack of knowledge and most likely due to lack of audit. As can be seen in Figure 11, transverse reinforcements were not properly and adequately applied and it was observed that the longitudinal reinforcements buckled both at the lower end of the column and at the foundation level. This situation was observed especially at the lower points of the exterior and corner columns. Such columns become critical since there is no transverse reinforcement to hold the longitudinal reinforcements in this region when the cover concrete of the foundation under the column or the beam above the column is crushed and disintegrated.

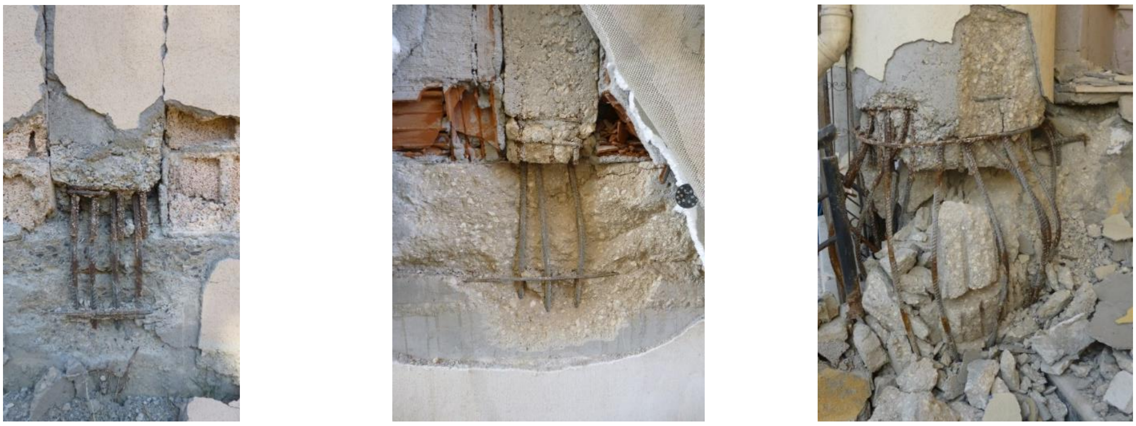

Figure 11. Discontinuity of transverse reinforcement within the foundation

The use of transverse reinforcement with minimum required diameter, spacing and detailing should be applied in the confinement regions to satisfy the high ductility requirement for columns. The spacing between the transverse reinforcement directly affects the ductility of the section and the compressive strength of the concrete. Special confinement zones should be created at the lower and upper ends of the columns. Thus, it is aimed that the concrete in the core region of the column will show a more ductile behavior with the confining effect. In Figure 12, it is seen that a suitable confining zone is not provided by the transverse reinforcement as described in TBEC (2018). As a result, it is seen that the core concrete is crushed followed by the buckling of the longitudinal reinforcements in the confinement regions at the lower and upper ends of the column.

Figure 12. Lack of stirrups or crossties in the confinement zones

The longitudinal reinforcements should be confined by using closed stirrups and crossties at the end confined regions of the shear walls as in the case of columns. In addition, in order to preserve the integrity of the shear wall section, there must be a certain number of special earthquake crossties per square meter depending on whether it is at the critical shear wall height or not. As can be seen in Figure 13, the horizontal and vertical reinforcements in the shear wall have been disintegrated and buckled due to the application of insufficient number of crossties or not applying at all, thus losing the integrity of the shear wall section. As a result, the most critical structural component that resists the seismic demands caused by the earthquake is exposed to severe damage, which can lead to unrecoverable damage or total collapse of the structural system.

Figure 13. Lack of crossties in the shear wall

According to TBEC (2018), a certain amount of the transverse reinforcement calculated for the confinement zone of the column ends should be applied to the beam-column joints as well, depending on the confinement of the joint region by the beams. This requirement has been present not only in the current earthquake code, but also in previous earthquake regulations since 1975 (TEC, 1975). Even in newly constructed RC buildings, severe joint shear damage was observed due to lack of transverse reinforcement in the joint panel (Figure 14). It is seen that only stirrups are used as transverse reinforcement in the beam-column joints of the newly built RC buildings. As also observed in the column end regions, if additional stirrups or crossties are not used in the joint region, the longitudinal rebars buckle upon the crushing of joint cover concrete (Figure 15). Because buckling of internal rebars cannot be prevented by a single exterior stirrup (mostly 8mm diameter bars) with its flexural stiffness. Therefore, adequate amount of transverse reinforcement should be placed in the joint regions, just as in the column confinement regions, by applying additional stirrups and crossties, taking into account the maximum spacing limit of $25\varnothing_{stirrup}$ between the confined longitudinal rebars.

Figure 14. Not using transverse reinforcement in beam-column joints

Figure 15. Lack of crossties in beam-column joints

Ductility of the reinforcing steel is one of the most important parameters in obtaining a ductile response for RC buildings. However, in the field inspections made in the damaged buildings, it was observed that the reinforcements fractured in a brittle manner in the critical sections of many reinforced concrete elements (Figure 16). A horizontal or inclined fracture surface was observed in such brittle reinforcement rebars. It is thought that brittle fracture occurs as a result of buckling of the reinforcement under pressure and low cycle fatigue effects due to the reverse cyclic nature of the earthquakes. The reason for such response is due to the combined effect of high gravity loads with the high vertical component of ground motions. Another reason for brittle reinforcement fractures is thought to be the deficiency in material properties such a high carbon content of reinforcement bars.

Figure 16. Fracture of reinforcement rebars

3. Damages observed on highway bridges

It is known that in the field investigations conducted after the severe earthquakes in Türkiye in the past, the bridges generally performed well and preserved the functionality of the highway and railway network, which are the lifelines of transportation network (Caner *et al.*, 2021). In the devastating earthquakes experienced in February 2023, the bridges generally performed well and were able to fulfill their main duties. On the other hand, although some damages were observed in the bridges examined, heavy damage and destruction were not encountered as in the residential buildings.

Shear keys restrain the displacement of the bridge superstructure in both longitudinal and transverse directions at the abutments and piers during seismic events. Most of the shear keys were damaged up to failure as a result of pounding induced effects between superstructure and shear keys. Shear keys are considered to be the fuse elements for the bridge and it is acceptable for them to be damaged to protect the substructure components. It is important to carry out the structural repair of the damaged shear keys after the earthquake or to remove them completely and to make new ones in order to restrain the transverse displacement of the bridge superstructure in the future earthquakes. Figure 17 shows different levels of damage in shear keys.

Figure 17. Damaged shear keys

Due to the displacements of the bridge superstructure in the longitudinal direction, pounding takes place between the superstructure and abutment back wall, which can expose to severe shear damage during the seismic events (Figure 18). Although the seismic damage imposed on the shear keys or abutment back walls can impair the functionality of the bridge and result closure of the bridge to traffic, the seismic repair or replacement of such fuse elements can be conducted to recover the functionality of the bridges.

Figure 18. Back wall damages caused by pounding between the abutment and superstructure in the longitudinal direction

In the highway bridge application practice in Türkiye, the elastomer bearings that separate the superstructure and the substructure are placed directly in between without using any connections. Therefore, friction force between the elastomer bearings and the concrete surfaces is the only resisting force to hold the elastomer bearings at their locations. However, during the lateral movement of the superstructure as well as the uplift of the superstructure due to vertical component of ground motions, dislodgement of elastomer bearing took place during this earthquake event (Figure 19).


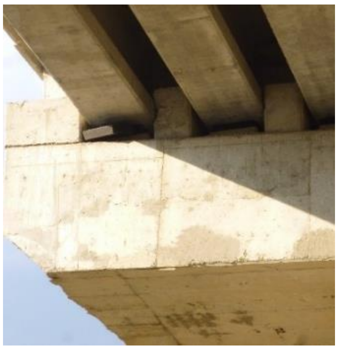

Figure 19. Displacement of elastomer bearings

One of the highway bridges, which is already out-of-service before the earthquake, was failed due to deck unseating as a result of insufficient seat length(Figure 20). The original condition of the bridge before the earthquake is unknown. The insufficient seat length at the abutments and piers is the main cause for the bridge failure.

Figure 20. The unseating of superstructure of a bridge, which is out-of-service on the Hatay Hospital road, Coord: 36.27212, 36.20774

4. Conclusion

Two sequential severe earthquakes with magnitudes of Mw 7.7 and Mw 7.6, occurred in the southern region of Türkiye, caused great destruction with a tremendous amount of loss of life and property. The fact that the earthquakes were very severe, that they occurred one after another after 9 hours, and that the area affected by the earthquake, including 11 provinces, was very large, increased the destruction and losses even more. The earthquake damages in the reinforced concrete buildings and highway bridges built after the year 2000, which were affected by the earthquake in and around Hatay province, were examined. The earthquake performances of the examined structures, the observed damage types and their causes are explained below for each type of structure.

- The most common damages observed in RC buildings during the field observations were due to weak/soft storey mechanism. It is thought that the contribution of infill walls in the story stiffness should be considered in the numerical models in order to calculate the displacement demands more accurately.
- The structural system should be as simple and regular as possible to prevent damage localization. Vertical structural components should be directly connected by beams to satisfy frame continuity. Shear walls should be placed symmetrically in sufficient numbers in both directions in order to provide adequate stiffness and strength in both principal axis of the building in an equal manner. Columns are generally designed to be placed such that their weak axis are mostly along the long plan direction of the building to hide the columns inside the infill walls. Most of the improper structural configurations are formed as a result of architectural design. Therefore, it is believed that the architectural discipline should also take responsibility in the seismic safety of the structural system, whose earthquake resistant design is mostly dominated by the architectural constraints.
- Field observations have shown that detailing problems in RC sections mainly arise from the poor workmanship during the construction phase and the fact that these errors could not be corrected due to

lack of supervision. Transverse reinforcements whose hooks are not bent at the correct angle, insufficient stirrup spacing, lack of transverse reinforcements at the critical sections such as column ends, beam-column joints and foundations are commonly observed detailing problems in columns. Other than the exterior stirrup, lack of additional stirrups or crossties caused buckling of longitudinal bars and hence disintegration of RC section.

- It has been observed that the deficiencies in the transverse reinforcement details in the shear wall end zones and web region caused damage to the shear walls that prevents to be effective to resist large seismic demands. Especially lack of crossties both in the end region and in the web region resulted in buckling of the longitudinal reinforcements and loss of section integrity. On the other hand, many examples have been encountered where the shear wall web reinforcement was not placed inside the confined end regions or the ends were not hooked, so it was opened and detached from the reinforcement cage. The shearing capacity of the shear walls, with deactivated web reinforcement, decreased significantly, causing brittle shear damage.
- In the observations made in damaged buildings, it was observed that the reinforcing steel, which is one of the most important construction material to obtain a ductile behaviour in RC structures, did not exhibit ductile response and fractured in a brittle manner.
- The inspected highway bridges responded such a devastating earthquake in a much better way when compared with the residential RC buildings. Seismic damages have been mostly observed in the sacrificial elements of the bridges such as shear keys and back walls as a result of pounding between the superstructure and the shear keys and back walls. Such pounding also caused considerable damage in superstructure precast pre-stressed beams. Dislodgement of elastomer bearings is also a very common type of bridge damage, where they are not connected to the bridge structure in any form of connection detail.

5. Acknowledgement

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