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Seismic Structural Failure Potentialities of Newly Constructed Buildings in Iran

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ABSTRACT: As Iran is located at high seismic risk region and future ground motions are predicated by seismologist, thus, A Case study was conducted to investigate the major seismic structural failure potentialities due to design and constructional flaws in two province of Iran, Tehran and Esfahan, the former with high seismic risk and the latter with an intermediate risk. More than forty buildings were inspected to find the four major failure potentialities in these two provinces. Two imperfections were found in steel structures and two in reinforced concrete buildings. Design and constructional imperfections in protected zone in steel structures and latticed column details are two main points threaten newly constructed steel structures. In reinforced concrete structures, stairway constructional flaws and wrong pipe passing constructional details are the two main defects covered in this study for this type of structures. This paper also presents solutions for each failure potentiality and recommends some constructional and design hints to increase the safety of structure and make them ready for future seismic excitations.

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INTRODUCTION

There are many researchers who investigate the behaviour of structures under seismic forces. In addition, through the decades, numerous institutes and organizations published valuable specifications to help designers and structural inspectors to build safely and effectively. Seismic resistance of structures is one of most recent subjects that many research groups are recently working on and spend a huge amount of money and time to reach this goal. Our familiarity with the seismic theory is well improved but still many structural failures are reported from different parts of the world. Precise structural design and correct constructional details are two main factors which could control these types of reports and would lead to reduction in number of building failures.

In December of 2003, Bam, a city located 1000 kilometres southeast of Tehran, faced with an earthquake with magnitude of 6.6 (Mw). 31,000 people killed, 30,000 injured and 75,600 people became homeless during this earthquake (USGS, 2003). Bam earthquake proved that constructional imperfection could lead to historical disaster. Poor welding design flaws and constructional imperfections were reported as three main reasons of Bam earthquake seismic failures. For instance, structural irregularities and poor welding were two factors which were responsible for the steel structure building in Figure 1.

250,000 Reinforced Concrete (RC) buildings out of 780,000 damaged buildings have destroyed in Balakot city of Pakistan in 2005 earthquake (Nienhuys, 2010). In 2010 Haiti earthquake, history was repeated and design and constructional defects were responsible again for that high death toll (Fierro and Perry, 2010).

There are some design and constructional imperfections which are similar in newly constructed buildings in Iran. Hence, this paper presents the four major common constructional and designing mistakes in Iran, especially in Tehran and Esfahan provinces. By detailed structural inspection of buildings in these two populated cities, two main failure factors are introduced and analysed for steel structures and two for reinforced concrete buildings.

Figure 1. Steel structure failure in Bam (Manafpour, 2008)

MATERIAL AND METHODS

Study zone

This Study has done based on critical structural inspection in Iran. Tehran as the capital province of Iran and Esfahan as one of the most populated cities in Iran are two study zones which are covered in this study. Tehran with geographical coordinate of (35.6° N, 51.4° E) and Esfahan with (32.6° N, 51.6° E) are located at Eurasian tectonic plate. As it is shown in Figure 2, Tehran is located at the high seismic zone. Two-thirds area of Esfahan province is in an intermediate seismic hazard risk and the rest has shown high seismic risk in global seismic hazard studies. Tehran as the capital province of Iran has the population of 12,183,391 and Esfahan has 4,879,312 based on the survey of 2011.

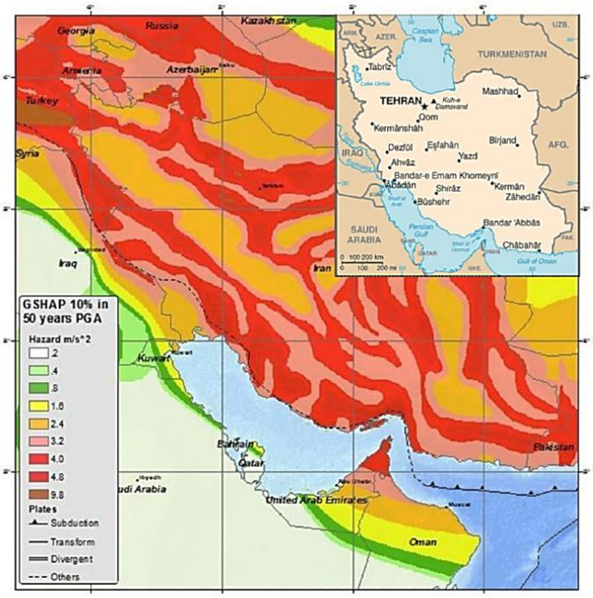

Figure 2. GSHAP hazard map, Iran. (By USGS)

Protected zone in steel structures

As defined in AISC, 341 Seismic Provisions for Structural Steel Buildings, there is a specific area in steel moment frame structures which should be clear of any fabrication and erection attachments. This area could be located at the member or connections of members. This specification also noted that in the intermediate and special moment frame, protected zone requirements should be satisfied completely due to inelastic straining which may occur in these types of frames during seismic excitations (AISC, 2010b).

The 2010 version of AISC 358 specified protected zone requirements for several types of connections. For other connections, based on inelastic behaviour of structure, engineers should define this zone and follow AISC 341 recommendations. Section rapid change, welding discontinuities and constructional imperfection could affect the inelastic behaviour of members and connections seriously. There are other operations which are not permitted by AISC 341 (article I2. 1) in protected zones to reduce any unpredictable behaviour of steel frame under earthquake lateral displacements.

Figure 3 shows that for full-welded moment resisting beam-column connections, the protected zone will start from the face of the column to one half of the beam depth beyond the plastic hinge point. Experimental studies have shown that hinge point in unreinforced connections will occur somewhere between column face and one beam-depth length on the beam. Thus, for unreinforced full-welded moment connection in intermediate and special moment frames, the protected zone will extend from the column face to the three-halves of the beam depth.

Note that in the case of using bottom erecting cover plate, the area of protected zone would be increased due to the bending strength of cover plate.

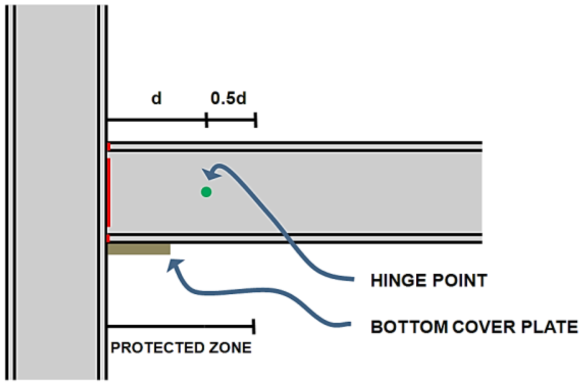

Figure 3. Protected zone for Full welded moment connection (d= beam depth)

Latticed column tie plates

There are two main reasons to use latticed columns in steel structures. Lacing two separate steel profiles help constructor to hold two columns parallel and install them with the correct distance apart (McCormac and Csernak, 2011). Another purpose of lacings is to equalize the stress distribution between two steel profiles.

The most important fact about latticed column is that designers make the two components act as a unit profile by using lacing plates. Note that bending in compression member will cause shearing forces. Shearing effect reduces the column strength (Salmon et al., 2009). Equation 1 is related to Euler critical load of single column under compression force without shearing effect. Equation 2 estimates the Euler critical load as follows:

$$p_{cr} = \frac{\pi^2 E I}{L^2} \qquad (1)$$

$$P_{cr} = \frac{\pi^2 E I}{L^2} \times \frac{1}{\left[1+\frac{\beta}{AG}\frac{\pi^2 E I}{L^2}\right]} \qquad (2)$$

Where:

P_{cr}: the Euler critical load for column with both end pins

E: modulus of elasticity

I: moment of inertia of column section

L: length of the column

β: non-uniform stress correction factor

A: section area

G: shear modulus

Based on equation 2, the lacing plates should be designed to resist shearing effect (Salmon et al., 2009). Therefore, size, distance and connection of lacing plates could play an important role in overall behaviour of these types of columns. Besides, end tie plate has to be designed to reduce the shearing effect and make two components of built-up latticed column act as a unit column (McCormac and Csernak, 2011). The 2010 AISC Specification for Structural Steel Buildings requires that

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in latticed columns, intermediate tie plates have to be designed if lacing arrangement interrupted. The length of the tie plate should be long enough to let beam or brace gusset plate be attached correctly to joint zone (AISC, 2010b).

The regular space between lacing plates and correct connections of tie plates (i.e. intermediate and end tie plates) are two other factors which can control the compressive and bending capacity of latticed columns.

RC Beam Sleeve and pipe passing

A large number of buildings in the Iran are short or mid-rise. These types of buildings often do not have full detail and complete mechanical drawings in comparison with high-rise buildings. In most cases, especially in rural areas, constructors decide how to pass sleeves through the reinforced concrete members. Constructor decision is not always accepted by international codes. Note that the 2011 ACI 318 code only permits RC members sleeve passing in the case of approval of the licensed design professional, not by constructors (ACI 318, 2011).

ACI 318 also states that pipes and sleeve passing through the RC members shall not reduce the strength of members significantly. In addition, sleeve outside dimension shall not be larger than one-third of beam width. Sleeves shall not be installed closer than three diameters on center based on this code (Figure 4).

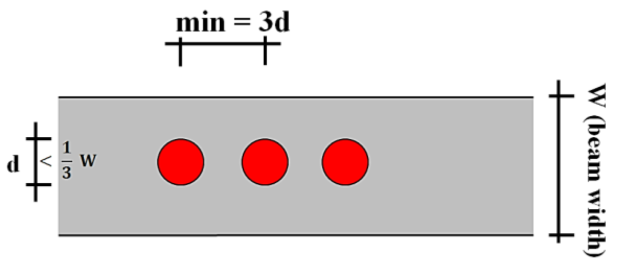

Figure 4. ACI 318-11 pipe and sleeve placing requirements (top RC beam view)

The sufficient cover of pipes should be checked base on this code. More than 0.002 times of concrete section area, reinforcement shall be provided normal to the pipes or sleeves (ACI 318, 2011).

Beam, as one most effective member which contribute with the large proportion to system ductility, needs more constructional precision in the case of sleeve passing conditions.

Stairway-Frame Interactions

Stairway is the only way which helps people to evacuate buildings safely and quickly in emergency situations such as earthquakes or hurricanes. Therefore, any design or constructional imperfections could lead to a big disaster.

Designers have two approaches for designing of stairways. The first design concept is to assume that stairway structural system act as a lateral resistance system during earthquake. The other approach is to neglect the existence of stairway structural system. In the second approach, the stairway structure connects to main building frame in the way which no force will apply on it during seismic movements.

The problem starts from the point that designer assumes the stairway separated from the main building frame but due to incorrect connection between stairway system and main building frame, it acts with main building frame during an earthquake. Thus, unpredictable structural behaviour is expected due to stiffness alteration. The 2010 ASCE 7 Minimum Design Loads for Buildings and Other Structures states that egress stairways should function for life-safety purposes after an earthquake and the components' (stairway members) importance factors shall be taken as 1.5.

Different inter-story drifts of adjacent floor slabs would apply a load on stairway and make them act as a bracing member between two floors, the same with the situation theoretically happens in steel braced structures. Bracings are designed to transfer lateral forces from each floor to the bottom one while absorb seismic energy by passing these forces. But the thin and fragile stairway slab between two floors could not pass the lateral forces unless it has been designed as a bracing member in design procedure (Figures 5 and 6).

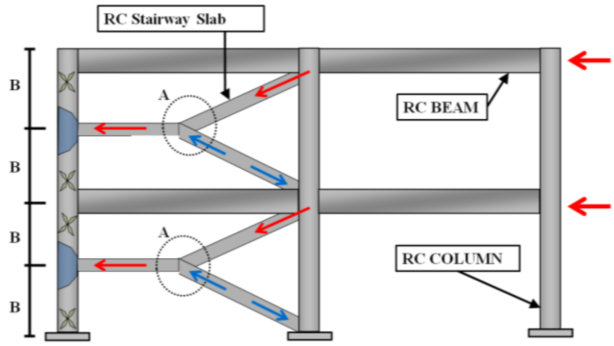

Figure 5. Stairway-Frame interaction failure potentialities

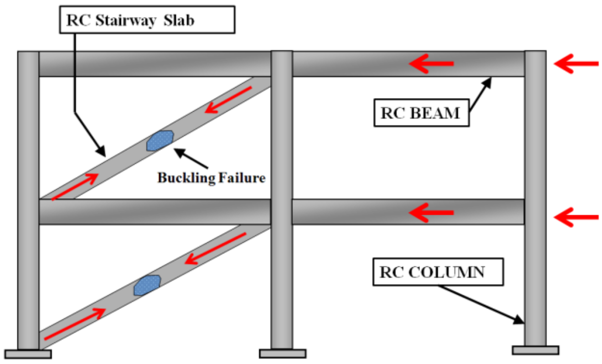

Figure 6. Stairway-Frame interaction failure potentialities

Another result of interaction between stairway and building main frame is related to short column phenomenon, when the lateral force apply on a floor slab and transfer to bottom floor via stairway. As Figure 5 shows, the transferred load act at the middle part of story column. Hence, that column will act as two short separate columns (zone B in Figure 5) with enormous shear forces which will be applied due to that separation and transference. Note that designers mostly assumed that stairway act separately from the building frame, but due to incorrect construction of connection between stairway and building frame, these two structures (i.e. stairway structure and main frame) will act together and short column action could easily make a shear failure on separated short columns (Figure 5).

FEMA E-74 recommended that stairs shall be detailed with a fixed connection at one end and a sliding connection at the other. This could remove the interaction between stairway and main moment frame of building (Figure 7).

Therefore, there are two main failures possibility which may occur due to stairway-frame interaction defects. The first occurs where the main frame columns are stiff enough to handle the short column shear forces. Thus, in this case bracing action of stairway could fail the stairway fragile members (Figure 8a). The second risk about the interaction refers to column shear failure because of short column action and insufficient confinement of RC columns (Figure 8b).

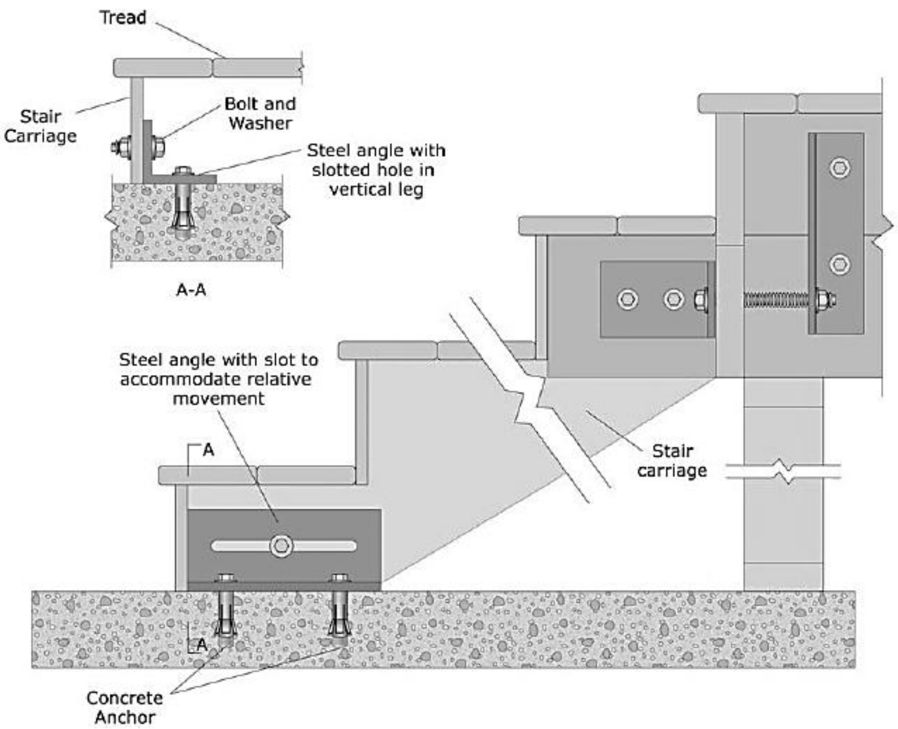

Figure 7. Stairway with landing with single run between (FEMA E-74, 2011)

Figure 8. Stairway-Frame interaction failure in past earthquakes; (a) 2010 Chile Earthquake stairway bracing action failure (FEMA E-74, 2011), (b) 2003 Bam Earthquake stairway short column failure (Vaseghi, 2003).

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RESULTS AND DISCUSSION

Protected zone in steel structures

As mentioned in article (I2. 1) in ASIC 341-10, any holes, tack welds and erection aids are not permitted in protected zones. Tehran with high risk of seismic excitation and Esfahan with intermediate risk are two cities which engineers should design steel structures with at least intermediate ductility to reduce the risk of brittle failures (ASCE 7, 2010). The critical structural inspection in these two cities showed that protected zone requirements are not satisfied and this structural imperfection put these cities on high risk of seismic failures.

Figure 9a shows a steel moment frame structure with ten stories above ground level. This building is located in Tehran and the photo has taken in 2013. Figure 9b clearly illustrates that the exterior wall erection aid has been welded to the beam and the protected zone requirements have not been considered in this structure. As engineers expect inelastic behaviour of steel structures in high risk zone, such as Tehran, these types of constructional incorrect details could lead to a rapid fracture in protected zone and energy dissipation will stop in first cycles of seismic loading.

It is apparent from Figure 10 that the same defects threaten structures in Esfahan province, too. Design engineer restrained cantilever beam with high end bending moments to zone which expected to behave in elastically during ground motions. Thus, the early fracture at beam end web plate is expected to happen in future earthquakes. Note that beam splice could make failure condition worse in these three-stories building in Esfahan.

Latticed Column Tie Plates

Recent investigations have shown that regular lacing bar spacing, sufficient size of tie plates and correct connection of other structural members (e. g. Beams and Brace members) to latticed column could guarantee appropriate unit behaviour of column.

As indicated in Figure 11a, a two-story building in Esfahan has constructed in 2013. The Figure 11b shows that the gusset plate interrupts the lacing and based on AISC 360, an intermediate tie plate is required. There are two main constructional imperfections in this specific case study. The first refers to the length of intermediate tie plate along the length of column. As it is shown, the constructor used two different sizes of intermediate plate (Figure 11b) and the length of the plates is not sufficient for gusset plate-column connection. The second significant defect is the incorrect connection between the gusset plate and lacing plate. Theoretically, lacing plates are design to resist a large shear forces between two components of built-up column, not for flexural forces. Figure 11c clearly shows that the bracing member would apply tensile or compressive load to the gusset plate as a result of lateral displacement of frame. Then the gusset plate transfer this load to middle part of lacing plate (via welded connection) and force this small shearing-resistance element to resist large flexural force.

Figure 12a and 12b are two other constructional details with incorrect use of intermediate tie plate and inappropriate lacing arrangement, irregular lacing plate spaces in Esfahan, respectively. All of these details could cause unpredictable deflection and irregular stress distribution between two components of built-up column.

RC Beam Sleeve and Pipe Passing

An intermediate reinforced concrete moment frame is shown in Figure 13a this building has four stories above ground level and one story beneath it. The east elevation of this newly built structure is shown in Figure 13b. The cantilevered RC beam with sleeve passing is also existed. The cantilever beams are the most sensitive member of moment frames which can absorb enormous vertical seismic load and show an enormous upward-downward deflections during earthquakes. Theoretically, cantilevers should resist a large flexural moment at their fully restrained ends. Based on the 2011 ACI 318, sleeve passing shall not reduce the strength of the member significantly. Thus, passing three sleeves through the region close to the high bending stress zone in this building is structurally incorrect and could increase the failure risk of this building even in lower seismic excitations (Figure 13).

On the basis of the precise structural inspection of the beam-column joint and sleeve passing constructional detail, it is observed that top and bottom longitudinal reinforcements in second floor cantilever beam of this building have been cut because of non-existence of mechanical detail drawings (Figure 13c). This structure is so brittle. Therefore, the cantilever beams end connections prone to fail in first cycles of seismic load application. This fact should be considered that horizontal structural irregularity of this building could increase the failure risk of this building, too.

The top beam of three-story RC intermediate moment frame building is shown in Figure 14. The number of sleeves and spaces between them are incorrect, based on ACI 318 requirements, at left and right ends of the beam. The high bending moments are expected to occur at two ends of structural frame beam. Thus, passing mechanical sleeves through this location could impair the strength of beam significantly and could put this building at high risk of failure in future ground motions.

A five-story building with a dual system (moment frame plus RC shear wall) is the next case. This building is located in Esfahan and under construction. There are eight pipe vacant spaces in beam next to shear wall. These holes are placed next to each other. About two-thirds of beam length contains holes for pipe and sleeve passing which could greatly reduce the total strength of this member (Figure 15). Passing pipes and sleeves close to structural joints are incorrect due to high bending and shear forces existence in these zones.

Stairway-Frame Interactions

An enormous number of reinforced concrete structures are at high risk of failure because of incorrect constructional details of stairways. Short column shear

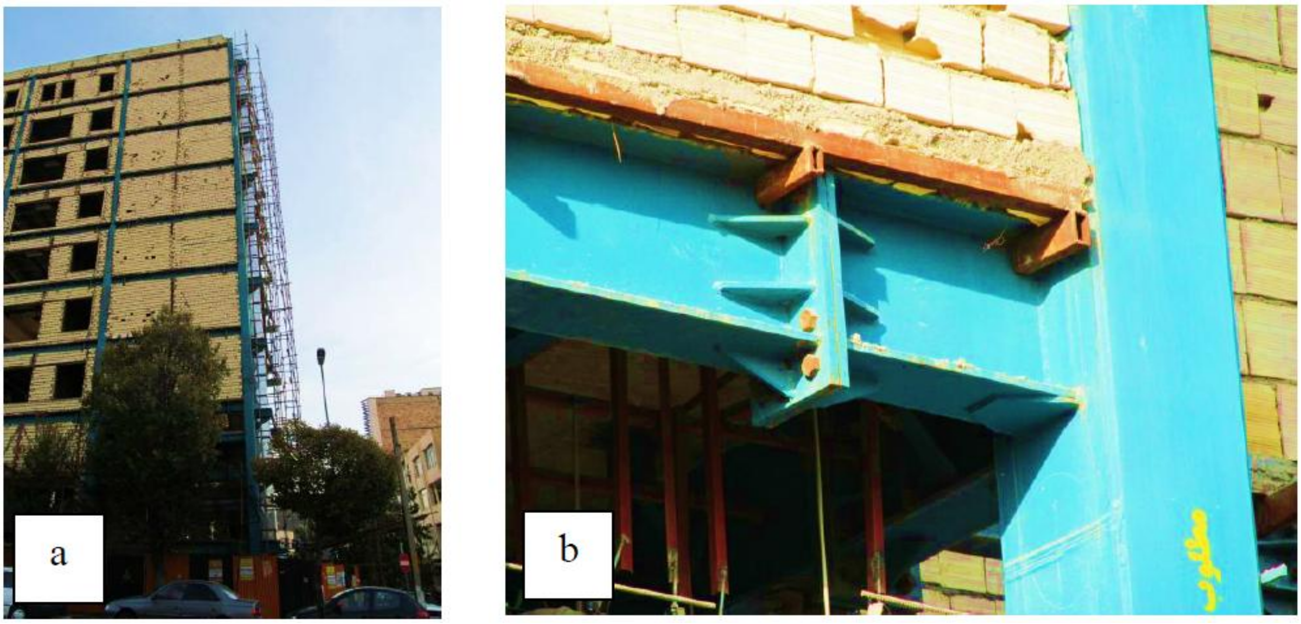

Figure 9. Ten-story Steel structural with protected zone imperfection; (a) building elevation, (b) beam-column view

Figure 10. Three-story Steel structural with protected zone imperfection; (a) building elevation, (b) beam-column view

Figure 11. Two-story Steel structural with tie plate imperfection; (a) building elevation, (b) beam-column view, (c) detail view of connection

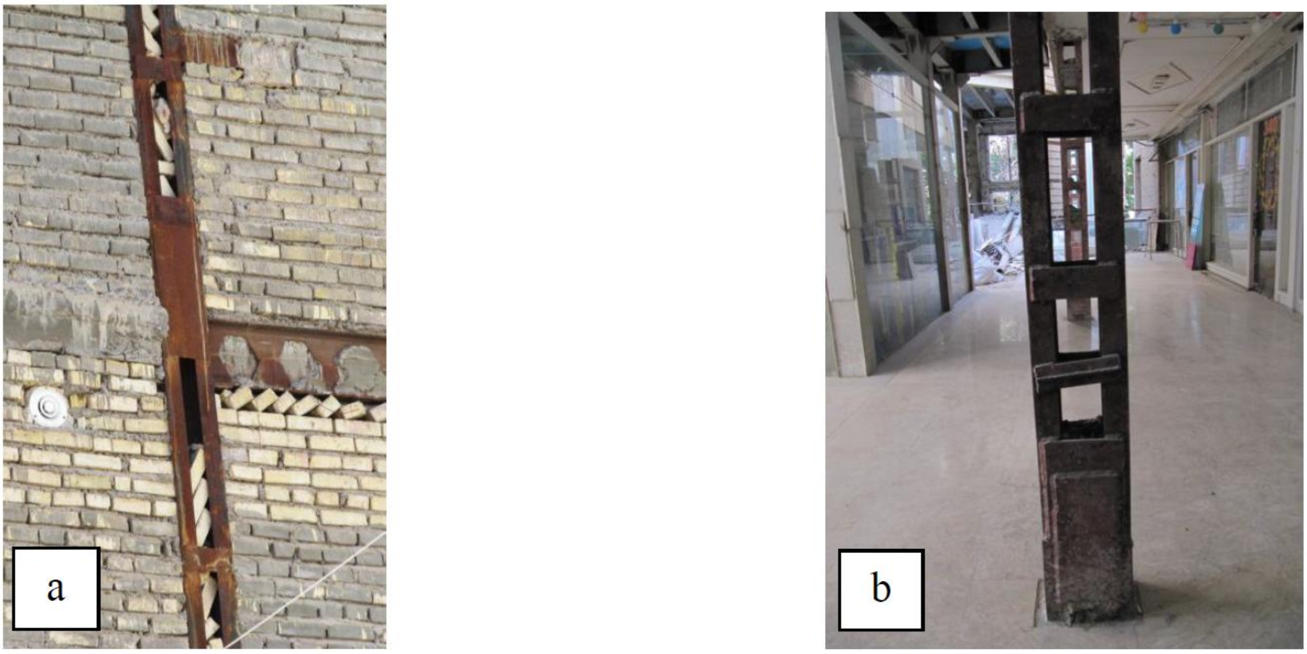

Figure 12. Two buildings with constructional defects; (a) Incorrect usages of tie plates, (b) irregular arrangement of lacing plates

Figure 13. Wrong pipe and sleeve passing through cantilever beam; (a) Building North elevation, (b) Building East elevation, (c) detail A- Beam to column connection detail

Figure 14. Wrong pipe and sleeve passing through high bending moment zones

Figure 15. Five-story building with unacceptable pipe passing detail; (a) overall view, (b) beam-shear wall connection detail

Failure is one of the most critical issues which threaten the safety of buildings in these two particular cities. The first failure potentiality is stairway failure due to bracing action. As it is shown in Figure 16, the connections of stairway to main frame are fixed and brace action of stairway under lateral seismic forces is predicted. In addition, because of fixed-end connection of stairway, the C1 column is at high risk of brittle shear failure due to short column occurrence. It has to be mentioned that because of mid-height floor slab existence, the column C2 is at very high risk of failure under severe short column action between two adjacent floor slabs. This could increase the risk of stairway bracing action failure and column C2 shear failure, too. The two other buildings in Figure 17a, and 17b show the failure potentialities in Iran, particularly Esfahan and Tehran. In both buildings, fixed-end stairway connections to building frame put these structures in high risk of failure.

There is another alternative that could be helpful to reduce the interaction and it is reinforced concrete corbel design for stairway columns. The stairway could slide on corbel on one end and fixed on the other end to the column. Hence, the brittle shear failure of column and bracing action of stairway will be removed (Figure 18).

Figure 16. Stairway-Frame interaction failure potentialities; (a) building view, (b) detail view

Figure 17. Two buildings in Esfahan with high risk of brittle stairway and short column failure

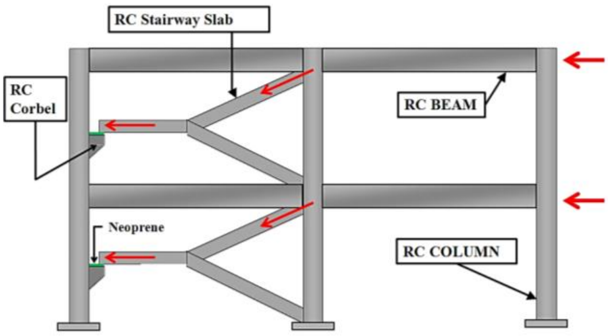

Figure18. RC sliding corbel connection for interaction removal

CONCLUSION

This paper investigates the four major design and constructional imperfections which could lead to higher seismic failure risk in Iran in future earthquakes. Two main factors are introduced and analysed for steel structures and two factors for reinforced concrete structures.

By structural technical inspection of more than forty buildings in Esfahan and Tehran, it was shown that dissatisfaction of code protected zone requirements and wrong constructional detail of latticed column are two serious factors that threaten steel structures in Iran. On the other hand, incorrect stairway construction and wrong sleeve passing techniques are two significant defects which could lead to severe structural failures in future earthquakes in this part of the world.

By increasing constructional controls and providing additional code guidelines, the incorrect details in high strain protected zone could be controlled. More technical meeting between structural designers and architectures would end up with safer buildings and could remove any future architectural-structural intersection.

Based on widely use of latticed columns in Iran, the best solution for incorrect design and constructional imperfection in these types of column is controlling these columns by using international specifications and codes. Building constructors have to decrease any constructional irregularities and non-technical labour decision when some details are missed in drawings. Regular and exact structural inspection by a certified structural inspector and skilled labour could help us to tackle these types of constructional defects.

The detail mechanical drawings are necessary before the start of building construction. Structural designers should design buildings based on mechanical and architectural needs. Sleeve and pipes should be mentioned before any constructional process. However, international codes, such as ACI 318, have some minimum requirements in the case that no mechanical drawings are provided.

Based on FEMA E-74 and findings of this study, stairway-frame interaction is in critical condition. This study shows that 8 out of 10 RC buildings are susceptible to fail due to stairway-frame interaction. Thus, a very exact structural inspection is needed to control this constructional imperfection in RC structures based on updated building codes and modern structural engineering knowledge. RC corbel is one of the most effective techniques that could remove this interaction and isolate stairway from main building frame displacements.

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