SEISMIC EVALUATION AND UPGRADING OF TYPICAL IRANIAN STEEL BUILDINGS

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ABSTRACT:
The construction of a wide range of typical Iranian steel buildings a large number of which were built before 1990 was based on no seismic code. According to the experiences of past earthquakes, especially Manjil Earthquake (1990) and Bam Earthquake (2003), it has been confirmed that many of these steel buildings may suffer extensive damage while earthquakes. Considering that some of these buildings are critical facilities that must remain operational following earthquakes, serious concerns are raised about their performance in future earthquakes. Observation of damaged Iranian steel buildings shows that most of them have failed due to their joint failure. The beam-to-column connections of these buildings follow the practice of Iranian typical connection named as “Khorjini connection”. In this study, following the evaluation of existing Khorjini connections, a connection upgrading method which significantly improves the seismic performance of these connections is proposed. In order to demonstrate the effectiveness of the proposed method, three Iranian common steel buildings that can be representative of low-, medium-, and high-rise buildings have been analyzed by linear static, nonlinear static (pushover), and nonlinear dynamic (time history) methods. Results obtained from these analyses also approve the success of suggested method in upgrading the seismic behavior of Iranian common steel buildings.

KEYWORDS:
Khorjini connection, steel building, seismic evaluation, connection upgrading

1. INTRODUCTION

The construction of a wide range of Iranian steel buildings a large number of which were built before 1990 was based on no seismic code. These buildings can be seen from faraway rural areas to large cities of Iran, and are used widely as residential, commercial, and also administrative buildings. Based on the experiences of past earthquakes such as Manjil Earthquake (1990) and Bam Earthquake (2003), it has been confirmed that many of these steel buildings may suffer extensive damage while earthquakes. Considering that some of these buildings are critical facilities like hospitals and schools that must remain operational following earthquakes, serious concerns are raised about their performance in future earthquakes.
This category of Iranian steel buildings has obvious similarities in construction practices, and most of these common buildings suffer from the same deficiencies in their lateral load bearing systems. These buildings usually have the framing system in only one direction, and this framing system can just carry gravity loads. The beam-to-column connections of these frames often follow the practice of typical Iranian connection named as “Khorjini connections” that can be categorized as non-seismic semi-rigid connections. Because of non-rigidity of connections as well as non-existence of bracing systems in existing frames, typical Iranian steel buildings which belong to the study category show limited strength against lateral loads, and they are not capable of resisting moderate or large earthquakes.

2. SEISMIC PERFORMANCE OF TYPICAL IRANIAN CONNECTIONS

Based on diverse research projects which have been conducted by Iranian authorities and academics [1,4,7,10,15], the main weak point of typical Iranian steel structures is located in their connections. These connections usually suffer from execution problems plus glaring mistakes in design and calculation. If the connection deficiencies are found out, and suitable strengthening methods are proposed, the seismic performance of these common buildings will be upgraded significantly. The typical Iranian steel connection named as "Khorjini Connection" is considered carefully in this section, and its seismic deficiencies are discussed comprehensively. Then the authors' proposed method of improving the seismic performance of this category of connections is discussed.

Beam-to-column connections in majority of typical Iranian steel buildings built before 1990 are Khorjini connections. Figure 1 depicts two schemes of this type of connection. Steel frames with Khorjini connections are one of the most common structural systems in Iran. In this system, a pair of continuous beams passes along two sides of several columns, and each beam is placed on a seat angle welded to the column. Another angle connects the top flange of beam to the side of column. In some cases, vertical brackets may also be used inside the top and bottom angle sections in order to increase the load bearing capacity. The columns often consist of double rolled profiles joined together by tie plates. At the beam-to-column connection, a long plate is welded to the face of column, and both top and bottom angles are placed on this plate. The top angle is usually smaller than the bottom angle in size, and is also shorter. All Khorjini connections used in Iranian steel buildings are the same in configuration. The only difference that can be observed in different frames is the length and the size of angle sections which vary according to connection design loads.

Khorjini connections which have been developed in the past 50 years by practicing engineers of Iran are used extensively because of their simplicity and economic advantages. Construction using this type of connections saves on erection time and labor cost. Furthermore, because of limitations on the availability and the cost of deep rolled sections, Khorjini connections provide the possibility of using two parallel beams instead of one deeper beam [16]. In structural analyses, beams connected to columns by Khorjini connections are assumed as continuous beams, and if they satisfy the section compactness requirements, their design moment can be reduced by 10 percent.

Figure 1: Two common details of typical Iranian Khorjini connections [4, Photo: B.Shafei]

In the absence of the bracing system in subject buildings, the seismic performance of existing frames could be satisfying only if the beam-to-column connections were able to provide required rigidity, but common Khorjini connections show low rigidity. The configuration of this type of connections is such that only two angle sections are located on the top and bottom flanges of crossing beams. Theoretical and experimental researches [1,4,10,11,15] demonstrate that these two angles are not capable of providing the expected strength and stiffness requirements of a rigid connection. As a result, the behavior of connection under cyclic loads is poor and vulnerable. The poor behavior of connections is emphatically contrary to the seismic code regulations that accept no failure in connections during seismic behavior [2].

The typical Khorjini connection should be categorized as a non-seismic semi-rigid connection, and its moment capacity is far less than the connected frame elements. The major reason of weak performance of this type of connections is the premature failure of welds. Hence, frames with Khorjini connections have extremely low ductility, and they often show undesirable brittle behavior during earthquakes. For the purpose of seismic upgrading of existing frames, the connections should be strengthened such that in addition to satisfy the rigidity requirements, they can provide the possibility of plastic deformations in connected beams by their stable elastic behavior. Furthermore, connections should be detailed in a manner that they provide a safe load path for transferring the loads from beams to columns. An essential point regarding the reliable load path is that all connection components should participate properly in the load transfer with no interruption [2]. But in Khorjini connections, just two angle sections welded to beams and columns (with poor quality welds in most cases) have the role of load transferring. Poor behavior of connection components which are not able to provide a reliable load path causes the failure of connection in first few cycles of loading. In order to obviate this important structural fault, the connection should be upgraded such that it can provide the reliable load path as well as desirable strength and stiffness.

3. PROPOSED METHOD FOR UPGRADING THE CONNECTIONS

By the method proposed in the current research study, the Khorjini connection is upgraded in a manner that the load path changes from existing angle sections to new additional connection elements further to provide a rigid connection. Subsequently, the stress level in angle sections decreases significantly, and this results in preventing the brittle failure of the connection. In order to provide the expected seismic behavior, the connection is retrofitted by adding two vertical plates hereafter called R-plates perpendicular to the frame direction. These plates are placed between two beam profiles, and their edges are welded to beam and column flanges. Figure 2 shows the shape of an R-plate plus its installation on an upgraded Khorjini connection. Both horizontal and vertical loads as well as flexural moments are transferred from beams to columns through these added plates instead of existing angle sections. R-plates lock the rotation of connection, and satisfy required strength and stiffness by connecting to beams by fully penetration welds, and to columns by fillet welds.

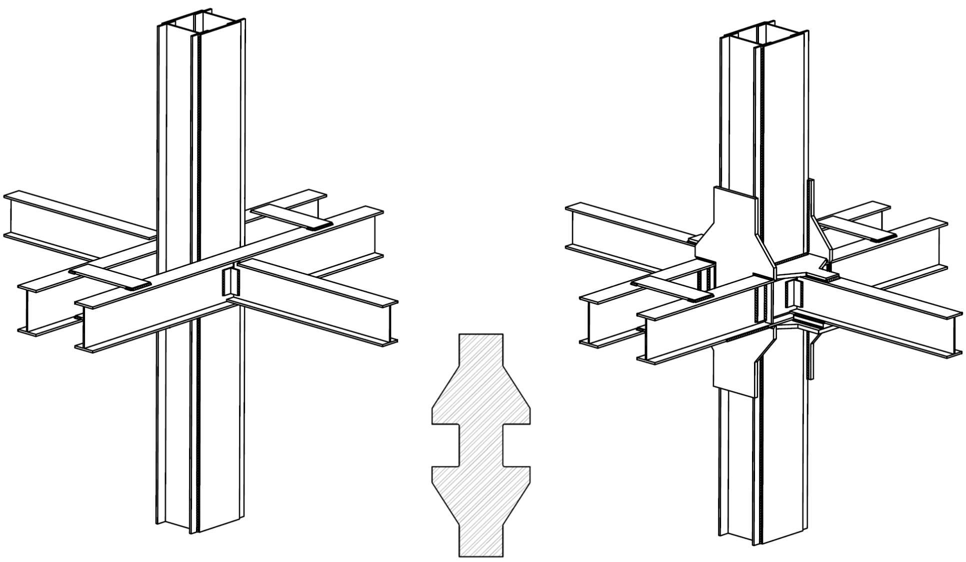

Figure 2: Typical existing Khorjini connection before upgrading (Left), proposed vertical plate (R-plate) to be added to both sides of the connection (Middle), and the upgraded Khorjini connection (Right)

According to a comprehensive experimental and analytical research conducted on structural behavior of both upgraded Khorjini connections and new seismic-rigid connections of continuous beams to the column [9], the proposed connections have demonstrated the acceptable behavior while cyclic loading. It can be inferred from experimental results that all experimented specimens sustained the interstory drift angle greater than 0.08rad without any significant loss of strength, which is far in excess of the requirements for a beam-to-column connection given by the latest seismic codes. The experimental and analytical results show that moment capacity of these connections is more than bending resistance of connected beams. Therefore, the structural ductility is controlled by the flexural behavior of beam ends; and the total behavior of connections and also of column might remain reasonably elastic. Hence, the upgraded frame can be categorized as a ductile system which has high energy dissipating capacity as well as stable hysteretic loops. Showing expected seismic performance, the frame can safely be used as a special or ordinary moment resisting frame. For the purpose of getting detailed information regarding the structural behavior of upgraded connection, authors would recommend that the reader refer to a related paper published by the first co-author of this paper in the Journal of Constructional Steel Research (Mirghaderi 2008) [9].

4. CASE STUDY BUILDINGS

For the purpose of seismic evaluation of typical Iranian steel buildings which have Khorjini connections, three categories of them have been studied before and after upgrading their connections. These buildings include 3-, 6-, and 9-Floor existing buildings that can be representative of low-, medium-, and high-rise buildings respectively. These selected buildings have been modeled and analyzed by static and dynamic methods comprehensively in order to understand their seismic performance. Each of aforementioned buildings has been studied in three different stages: At the first stage, the existing building with its typical Khorjini connections has been considered. Then at the second stage, connections of the study building have been upgraded to rigid connections using the proposed method. Finally at the third stage, the frame elements including beams and columns have been strengthened in addition to the upgraded connections. Comparison of these three stages can give a clear view toward the seismic behavior of study buildings.

The structural system of all study buildings follows the common practice of construction of steel buildings in Iran. These buildings have no bracing system, and their connections are Khorjini connections. According to DIN Standard, columns consist of double IPE-profiles joined together by tie plates, and beams consist of a pair of continuous IPE-profiles. It should be mentioned that the connections of columns to the foundation have been assumed to be hinged connections based on typical details of study buildings. For the purpose of modeling and seismic analyses of study buildings, a 2-D frame has been extracted from each of aforementioned buildings. Figure 3 shows the general dimensions of selected 3-, 6-, and 9-Floor frames. It should be noted that the comparisons between 2-D and 3-D models have been confirmed that the 2-D models adequately capture the major static and dynamic behavior characteristics of study buildings.

All of case study buildings have been chosen from buildings which are capable of resisting gravity loads with no problem. This fact has been confirmed by analyzing the selected buildings under gravity loads. The gravity load values used in structural analyses of selected buildings are defined based on design load criteria suggested by Iranian national building code. In all selected buildings, the dead load values are 450, 600, and 450 kg/m^2, while the live load values are 150, 200, and 500 kg/m^2 for the roof (last floor), middle floors, and the parking (first floor) respectively. The study buildings have been modeled in the first stage assuming to have Khorjini connections, and in the second stage assuming to have upgraded connections. It should be emphasized that the beam and column section properties are the same in first two stages. But in the third stage, the frame elements have been strengthened by adding plates. These plates are added to increase the frame load bearing capacity as well as to provide desirable proportioning for satisfying the strong column-weak beam regulation. After some iteration, the suggested method for strengthening of beams and columns includes adding two plates to the top and bottom flanges of Khorjini beams located at the first floor, as well as adding two plates to sides of all frame columns. The added column plates can be considered as the continuation of R-plates upward and downward.

In order to ease the comparison of seismic performance of 3-, 6-, and 9-Floor buildings, the proposed strengthening method at the third stage has been assumed to be the same for all study frames. It is obvious that in real retrofitting projects, the best and optimum frame sections can be found by more iteration based on existing conditions of the building.

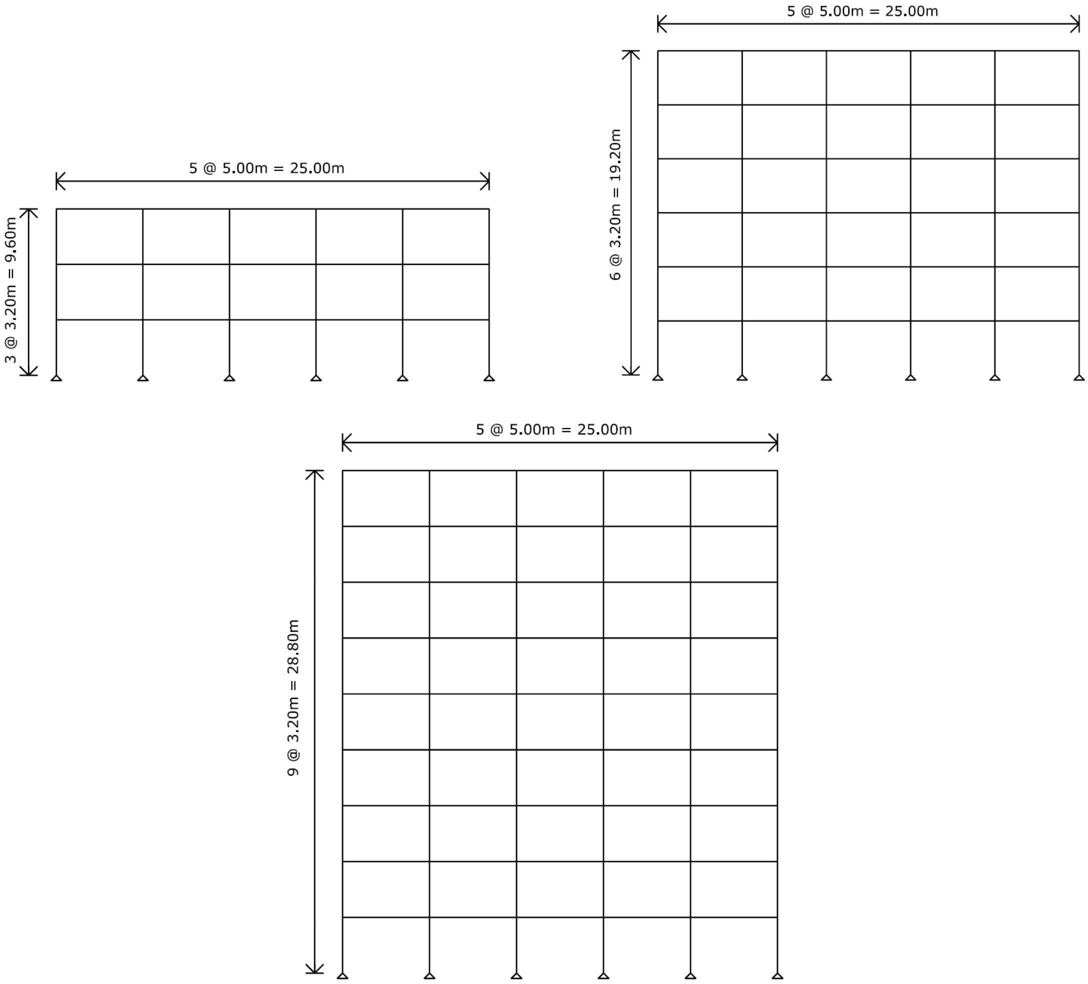

Figure 3: Dimensions of selected 2-D frames including 3-, 6-, and 9-Floor frames subjected to seismic evaluation

5. MODELING, ANALYSES, and RESULTS

One of important cases in modeling of typical Iranian buildings is the proper definition of existing Khorjini connections. Khorjini connections in contrast to the regular connections should be modeled in a manner that the continuous behavior of beams is preserved in connections. In other words, the rotation angle of beams should be essentially equal at both sides of connections. In order to satisfy the mentioned behavior, an element called "Panel Zone" has been assigned to connections while modeling. Assigning this element provides the possibility of different or even independent rotation of beams and columns. This element adds two rotational springs around the major and minor axes of connections, and specific stiffness can be defined for each of them. In the case of assuming zero stiffness, the rotation of beams and columns will be totally independent, but on the other hand, in the case of assuming considerable stiffness, the rotation of beams and columns will be the same, similar to rigid connections. It should be noted that the displacement of beams and columns at the joints will be essentially the same in all cases.

5.1. Modal Analysis

Modal analysis is used to determine the fundamental vibration periods as well as mode shapes of structural systems. Table 1 shows the fundamental vibration periods of 3-, 6-, and 9-Floor frames in three aforementioned stages. As it can be inferred from Table 1, typical Iranian steel frames with Khorjini connections have the large fundamental vibration periods, and consequently low stiffness. Upgrading the existing Khorjini connections decreases the fundamental vibration periods to the regular range. According to Table 1, strengthening of the frame elements in addition to upgrade of connections reduces the fundamental vibration periods by about 20 percent in average. This improvement is achieved because of providing more stiffness in frames.

Table 1: Fundamental vibration periods (seconds)

Model Type	3-Floor	6-Floor	9-Floor
Khorjini Connections	2.367	4.438	6.565
Connections Upgraded	0.584	1.047	1.518
Fully Upgraded	0.421	0.844	1.312

5.2. Nonlinear Static Analyses

The objective of the nonlinear static analysis is to determine the lateral capacity of the structural frame, the failure mechanism, and the sequence of inelastic response events leading to near collapse. In the current study, both material and geometric nonlinearities have been applied to structural models. Material nonlinearity is added by defining appropriate plastic hinges on frame elements based on criteria mentioned in FEMA-273 and -274. Moreover, geometric nonlinearity is applied to the models by activating both P-Delta and large displacement effects. It should be declared that because the modeling of premature brittle failure of Khorjini connection prior to upgrading was not possible in SAP2000, the used software, related pushover curves (Figure 4) could continue infinitely. Hence, in the first stage of analyses, the pushover curves have been cut based on related experimental and analytical researches on the seismic behavior of Khorjini connections [7,10,15].

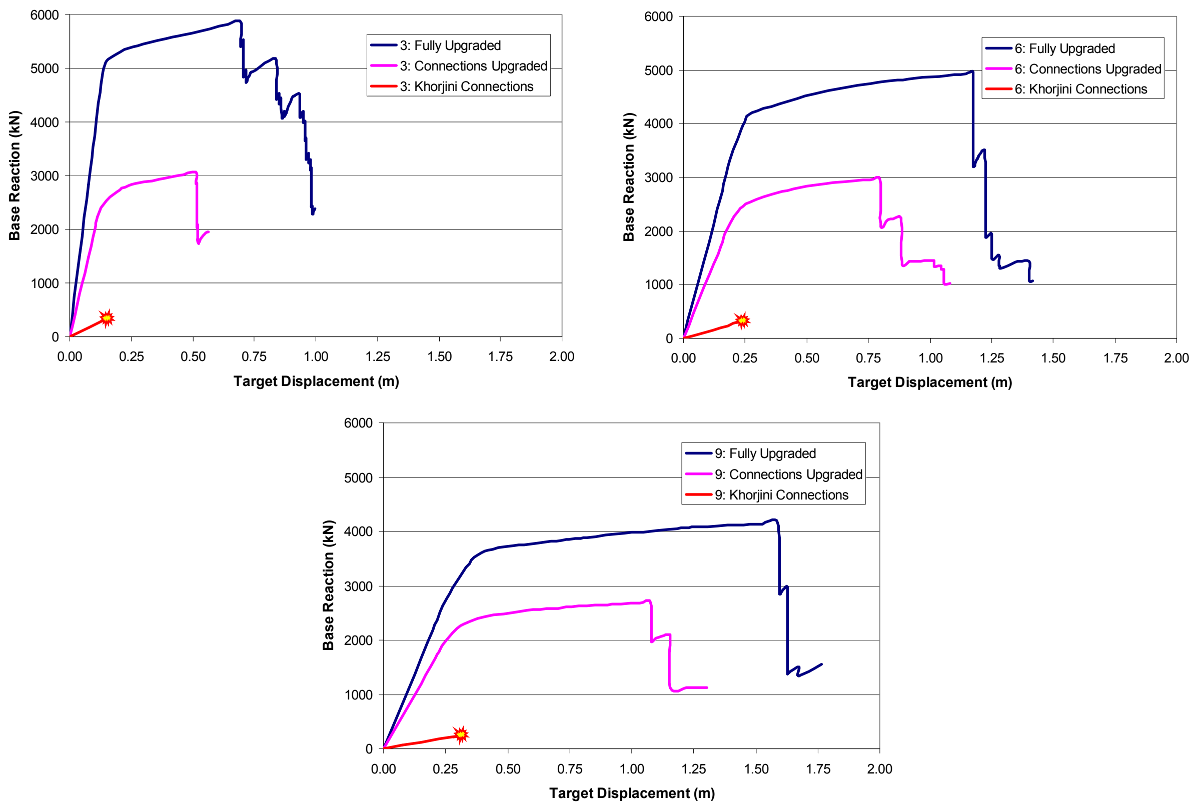

Figure 4: Pushover curves of 3-, 6-, and 9-Floor frames

Figure 4 shows the base shear-roof displacement curves obtained from nonlinear static analyses of 3-, 6-, and 9-Floor frames. Results of study frames approve that existing frames with Khorjini connections have low load bearing capacity, and they experience large displacements while earthquakes. On the other hand, by upgrading the connections using the proposed method, the load bearing capacity of frames increases significantly, and they can be expected to resist design earthquake loads with acceptable lateral displacements. Furthermore, if more increase in load bearing capacity is required, strengthening of the frame elements plus upgrading the connections results in an improvement of about 70 percent in lateral load bearing capacity of frames.

5.3. Nonlinear Time History Analyses

In order to evaluate the response of study buildings, seven different earthquakes including Bam (2003), Manjil (1990), Tabas (1978), Naghan (1977), El-Centro (1940), Northridge (1994), and Kobe (1995) have been selected. These earthquakes time histories are widely used in the profession to represent typical earthquakes, and have different peak ground accelerations, strong motion durations, and frequency contents. While the selected earthquake time histories should be representative of the real ground motion at the building site, all chosen time histories have been scaled to 0.5g based on a method suggested by Iranian Code of Practice for Seismic Resistant Design of Buildings [3]. This method is almost similar to the proposed method of FEMA-356 [6]. Ultimate responses of study frames obtained from nonlinear time history analyses have been assumed equal to the average of results calculated by each of seven time histories. The maximum values of average responses have been shown in term of maximum lateral displacement of floors (Figure 5). It should be noted again that results for the first stage of analyses are based on assuming proper connection behavior during all earthquakes, while in real cases existing connections fail after just few cycles because of premature brittle failure [7,10,15]. Considering the maximum lateral displacements of floors shown in Figure 5 demonstrates that upgrading the connections decreases lateral displacements significantly. Additionally, by strengthening of the frame elements plus upgrading the connections, the lateral displacements can be reduced by about 45, 25, and 15 percent in 3-, 6-, and 9-Floor frames respectively.

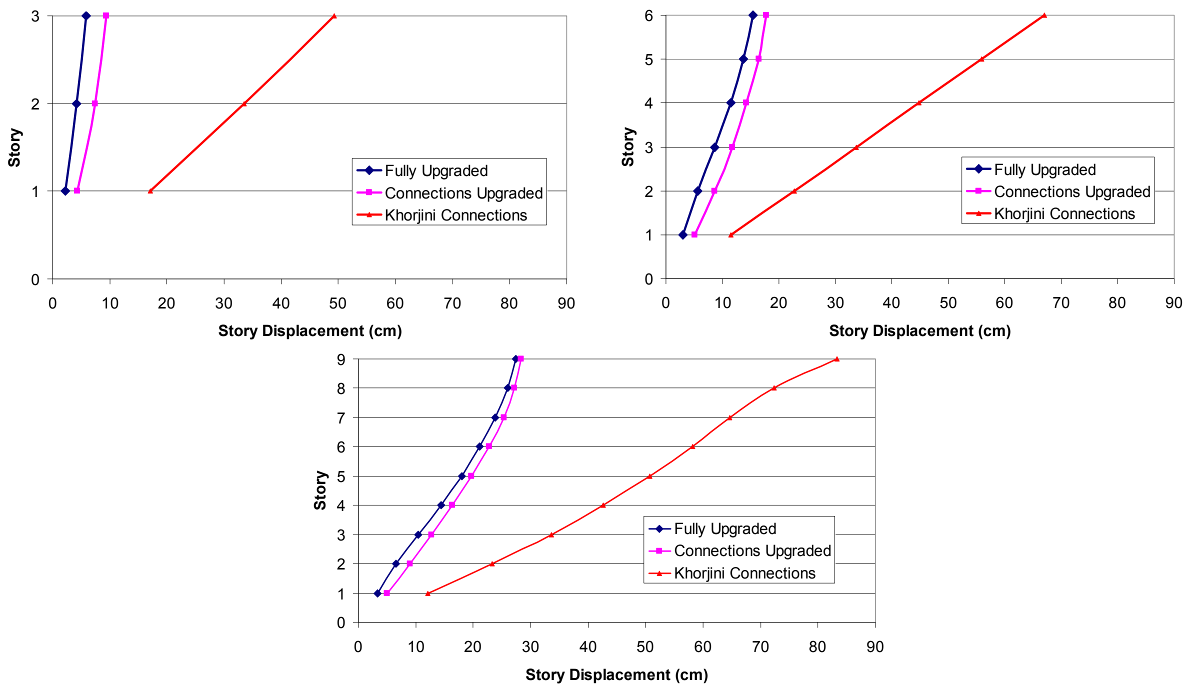

Figure 5: Maximum lateral displacement of floors for 3-, 6-, and 9-Floor frames

6. CONCLUSIONS

This paper studies the seismic performance of typical Iranian steel buildings. Since a large number of these buildings have been constructed based on no seismic code, there are serious concerns about their performance in future earthquakes. Observation of damaged buildings approves that most of them have failed due to their joint failure. The beam-to-column connections of these buildings follow the practice of Iranian typical connection named as "Khorjini connection". This connection should be categorized as a non-seismic semi-rigid connection, and its moment capacity is far less than the connected frame elements. The major reason of weak performance of this type of connections is the premature failure of welds. Hence, frames with Khorjini connections have extremely low ductility, and they often show undesirable brittle behavior during earthquakes.

In order to improve the seismic performance of this common Iranian connection, the authors' proposed method has been described. The upgrading method uses two vertical plates called R-plates for the purpose of satisfying strength and stiffness requirements as well as providing a reliable load path. Theoretical and experimental researches confirm that this upgraded connection coincides well with the seismic regulations established for connections of buildings in high seismic areas. Upgrading the existing Khorjini connection can provide the rigidity in both Khorjini frames and perpendicular frame. Additionally, this pattern of strengthening prevents from undesirable weak column-strong beam mechanism by formation of plastic hinges in beams instead of columns. In short, it can be concluded that the proposed upgrading method is an applicable cost-saving method which considers all possible deficiencies, and improves the seismic behavior of typical Iranian steel buildings significantly.

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