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EXPERIMENTAL STUDY AND POST-EARTHQUAKE DAMGE INSPECTION OF SCISSORS-TYPE OR SATCHEL (KHORJINI) CONNECTIONS FOR STEEL-FRAME BUILDINGS

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SUMMARY

Khorjini (satchel) connection is one of the beam-to-column connections in steel frame structures. It has become especially popular in Iran for conventional buildings, due to its speed and convenient in construction process and economic privileges in comparison to the other types of steel connections. Connecting two uncut beams to both side of a column by means of top and seat angles is a method for building a common type of Khorjini connection. In this study, experimental results of loading tests on six different types of mid-span Khorjini connections subjected to static cyclic unidirectional reverse lateral load and applied axial load were presented. The six specimens were design with different details of strengthening on the connection components in order to improve the bending moment capacities, stiffness and rigidity percentages and shear capacities of the satchel connections. Simplicity on installation and building of the connections are the other important parameters that have been taken into account in the design. In addition post-earthquake damage inspection results after Dec. 26, 2003 Bam-Iran earthquake on steel frame buildings with satchel connections are presented. The results of the inspection and the experimental study on Khorjini connections were discussed and some efficient improvements on Khorjini connections were suggested.

INTRODUCTION

Previous post-earthquake inspections and evaluation of damage in buildings in Iran have demonstrated that many steel frame buildings were suffered from high rate of damage due to lack of shear and moment capacities in the connections, especially those with common simple satchel connections. This is one of the most popular connections in Iran, which also called Khorjini or scissors-type connection. It is called scissors-type because the configuration and deformation of the connection are similar to those of a scissors. Two uncut beams are connected by means of top and bottom angles to both side of a column to configure a common simple satchel connection. In order to avoid overhead welding, the seat angle has commonly larger width and the top angle has smaller width than that of the beam flange. The characteristic that distinguishes this type of connection from the others is the beam-column eccentricity. The resulted eccentricity causes the connection to behave like scissors. Previews studies have shown that moment carrying capacity of Khorjini connections can be improved by applying efficient strengthening

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methods [1]. The objective of this study is to evaluate the capacity and failure mechanism of the common type of satchel connections subjected to lateral loading and to improve moment carrying capacity and rigidity percentage of the connection by applying efficient strengthening methods. To achieve the above goal, a post-earthquake inspection, theoretical and experimental studies were carried out and the results were concluded as some efficient suggestions for improvements of the common Khorjini connections.

RIGIDITY OF SATCHEL CONNECTIONS

In the tenth clause of the national building regulations of Iran [2], three types of structural frames have been identified, each with its own specific characteristics determines the dimensions of structure, and the type and strength of the related connection:

Group 1: frames with rigid enough beam-to-column connection (moment-resisting frames)

Group 2: frames with beam-to-column connection without rigidity (simple frames)

Group 3: frames with medium range rigidity, between that of group 1 and group 2 (semi-rigid frames).

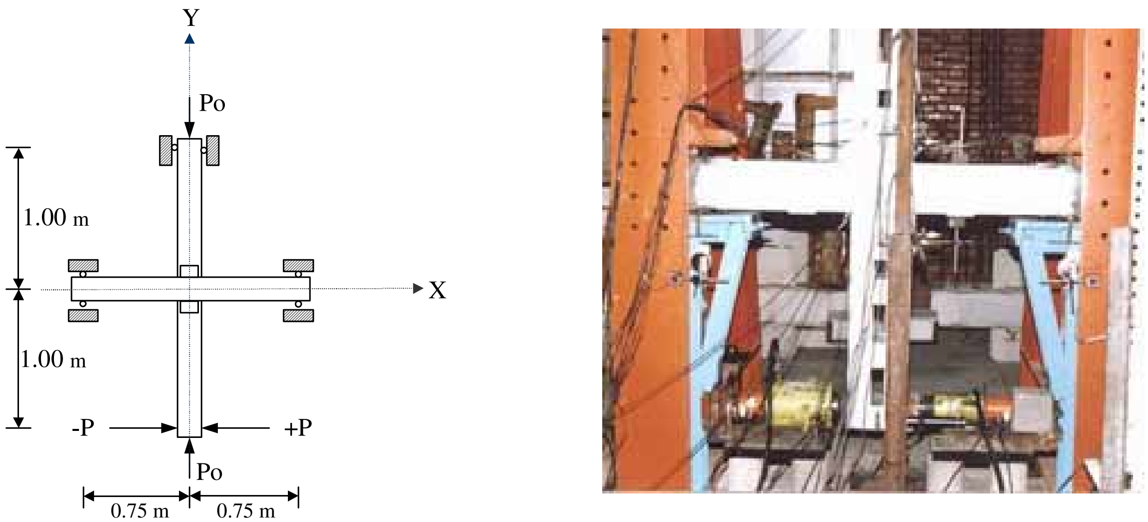
Connections with rigidity value greater than 90% belong to group (1), connections with rigidity value less than 20% belong to group (2), and connections with rigidity value between 20% and 90% are classified as group (3) [3]. In classification of connections on the basis of degree of rigidity, satchel connection with normal details is considered to belong to semi-rigid connections (group 3). One of the procedures to investigate the behavior of such connections is to make use of moment-rotation curve. This curve that can be obtained based on experimental or theoretical (mathematical model) evaluation, illustrates the relative rotations of beam and column versus moment variations of connections. In order to better understand and evaluate the rigidity rates of the connections, the beam-line concept was innovated by Bato Ravan and was applied for the first time by Surchinkov. This method is a graphical procedure to determine and to compare the rigidity degree of connections. The beam-line equation, which is derived on the basis of slope-deflection equations, considering symmetricity of loading over single span beam with the length L, has been defined as follows [3].

$$M_a = M_{Fa} + \frac{2EI}{L}\theta_a$$

To obtain rigidity percentage, the beam-line and the moment-rotation curve are plotted on the same coordinate system and the ratio of beam-line-to-moment-rotation curve intersection moment to the rigidity moment of the beam is defined to be the rigidity percentage for the connection. Investigations carried out concerning the effect of connection stiffness on distribution of building frame internal forces show that increase in the connection stiffness results in variations in the distribution of internal forces. However, beyond the limited range, called the threshold stiffness, such variations tend toward zero, and variations in the curve will not be noticeable. The threshold stiffness in the above studies is defined in the range of 500 to 1500 ton-meter/ radian, such that connections with stiffness greater than that of threshold are considered to belong to group (1), and those with stiffness less than threshold’s are taken to belong to the group (2) and (3). Rotational stiffness of the connection is equal to its moment-rotation curve slope gradient, and its value is derived from dividing the assumed bending moment in linear range by its corresponding rotation.

TEST SPECIMENS, EXPERIMENTAL SETTING

Six lateral loading tests have been carried out to determine stiffness and rigidity percentages of Khorjini connections. For this purpose, a conventional satchel connection specimen and those with different strengthening conditions in simple and rigid states have been subjected to lateral loading tests. Loading test setup has been designed so that the model under lateral loading is free to rotate or displace. Furthermore, the system is definite therefore, the measured support deformations, in the form of transferal displacements, are deducted from measured displacement values. Loading test setup with assumed support conditions has been selected as shown in Figure (1).



1.1) Loading setup configuration 1.2) A specimen under the cyclic loading

Figure 1 Test setup and experimental setting

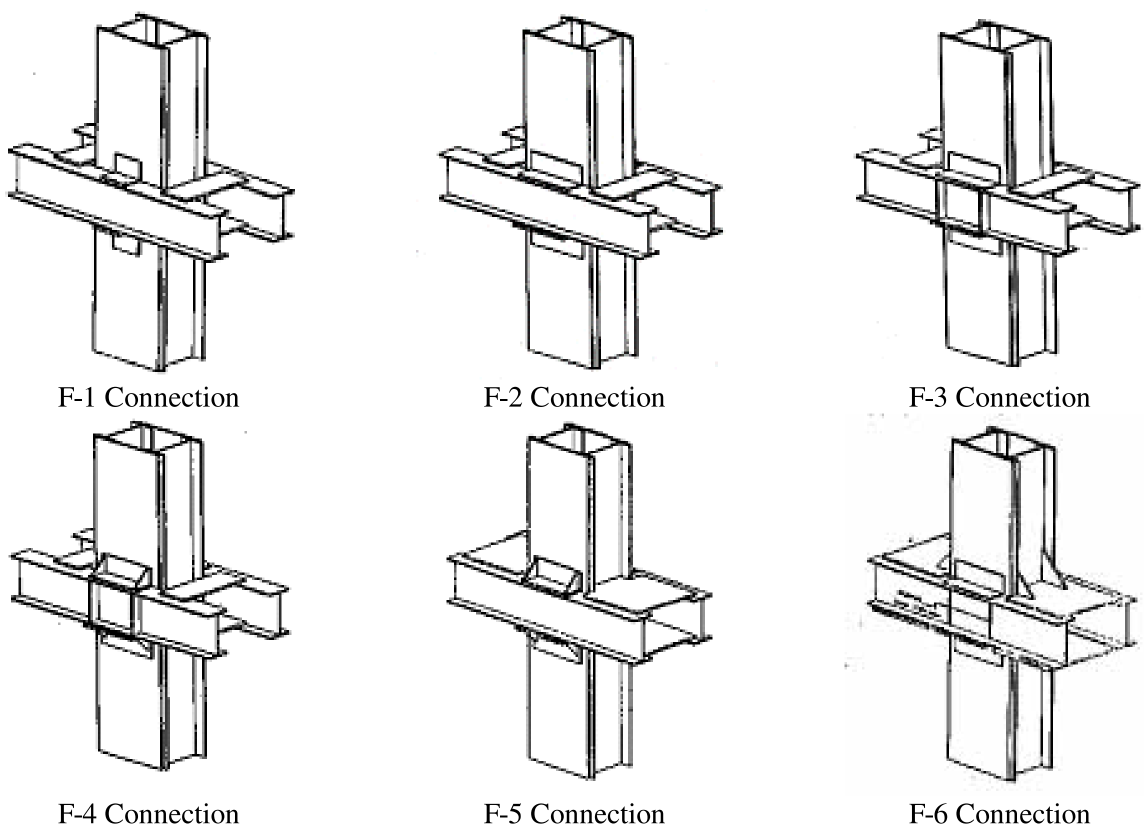


Figure 2 Details of the tested beam-column Khorjini connection specimens

The six specimens of satchel connections with or without strengthening elements have been subjected to lateral cyclic loading test. In the construction of each specimen, 2 steel beams of IPE14 section as the beam, 2 steel beams of IPE16 along with PL8 covering plates as the column, L8 angle as the lower seat, L6 angle as the upper angle and PL8 plate as strap (batten plate) have been used. Strengthening details of the tested specimens are given in Figure (2) and table (1).
Axial force in the columns during the test and in all specimens is constantly 20 tons (20 tons is chosen on the basis of dedicating 50% of the allowable stress capacity at the column section to the axial force). Cyclic lateral load, according to the setup shown in Fig. 1.1, is applied on the column lower end.

TEST RESULTS AND OBSERVED BEHAVIOR

Rotation of the central zone of the connection is measured in two ways and in each stage, the obtained average values are taken as rotation of the connection. Considering the load applied on the column end and the lever arm, the value of the connections carrying moments are calculated and the (M- θ) curve for the connections is plotted in accordance with Fig (3). The beam-line over the curves has been plotted as 0.75 m for the real span length of the beam (test specimen) and as 3 m for the conventional beam span, and the rigidity percentage of the connections has been calculated accordingly. In order to calculate the beam's fixing moment capacity (to determine the intersection point of beam-Line and vertical axis), yielding stress of the used steel is required. As such, a specimen was cut from the applied steel section for tensile test. The yielding stress was obtained equal to 3148 kg/cm^2 and the ultimate stress was derived equal to 4585 kg/cm^2. The (M-θ) curve gradient has been calculated as the connections' rotational stiffness. In table (1), rigidity percentage, ultimate flexural capacity and stiffness of the satchel connections specimens under lateral loading have been presented.

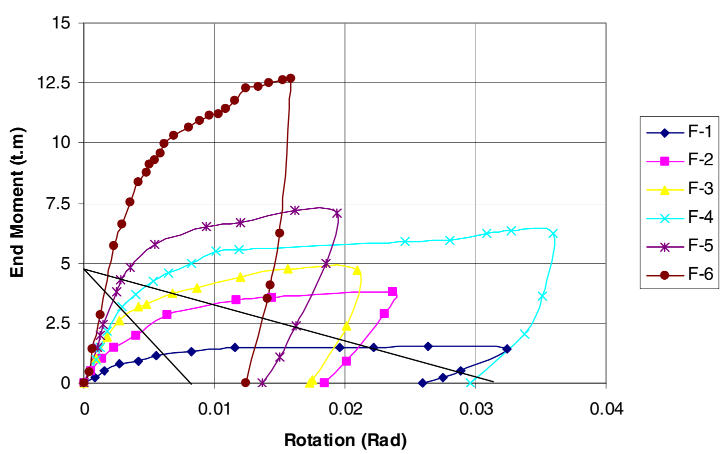


Figure 3 (M-θ) Envelope-Curve of the specimens under the lateral loading

Figure 3 shows that the maximum moment capacity is carried by F-6 Khorjini connection as well as maximum rigidity percentage value, which is almost equal to practical rigidity percentage value of a rigid connection. It is also clear that length variation in the connection angles causes an almost proportional rigidity percentage variation in the connection, so that specimen F-1 with angle length 10 cm has responded rigidity of 24% (in the range of simple connection), and stiffness of 310 t.m/rad, and the corresponding figures for the F-2 specimen are 45% and 700 t.m/rad respectively (the rigidity percentages are on the basis of real length of the beam 0.75 m). It was also observed in the results that applying stiffeners on both sides of web surface of each beam, along the angles two end-lines (F-3 connection) causes an increase in the bending stiffness of the connection and consequently in its bending capacity and rigidity percentage so that the connection F-3 with stiffeners, has produced 78% rigidity (based on beam length, 3m).

Table 1 Rigidity percentage and ultimate flexural capacity of specimens under lateral loading

Test No.	Length of upper and lower angles (cm)	Stiffener	Rotational stiffness of connection (t.m/ rad)	Ultimate flexural capacity (t.m)	Rigidity percentage	
					Beam length of the specimen 0.75m	Ordinary beam length 3.0m for IPE 14
F-1	10	-	310	1.72	24%	28%
F-2	20	-	700	3.84	45%	67%
F-3	20	Stiffener on both sides of the beam web	1100	4.74	61%	78%
F-4	20	Stiffener on the beam web and angles	1250	6.37	67%	86%
F-5	20	Upper and lower plates and the stiffener on angles	1600	7.18	75%	90%
F-6	20	Stiffener on the upper and lower plates and on the beam web	2500	12.77	84%	95%

It can be also concluded that using angles with triangular stiffeners and web stiffeners (specimen F-4), in comparison to the case of web stiffeners alone (specimen F-3), has achieved considerable increase in bending capacity and stiffness and in rigidity percentage but the amount of increase in the bending capacity is more effective (table 1). Providing upper and lower plates for the beam increases rigidity and bending capacity of the connection, efficiently (similar to that of the usual steel rigid connections). F-5 and F-6 connections with upper and lower plates produced 90% and 95% rigidity percentages, respectively, (based on standard beam length, 3 m), which are the highest rigidity percentages among the specimens. Since rotational stiffness values for the both specimens are greater than that of the threshold stiffness value, F-5 and F-6 connections may be used as fixed satchel connections. The batten plate connecting two steel beams on both sides of the column prevents an increase in eccentricity of the beam's vertical force component in large deformations condition; therefore, playing an effective role to increase the stability of the Khorjini connection.

KHORJINI CONNECTIONS RESPONSES IN THE RECENT BAM-EARTHQUAKE

On Dec. 26, 2003 at 01:56:56 (GMT) a devastating earthquake with magnitude Mw6.5, Ms6.7 reported by USGS, and 7 km depth announced by BHRC (Building and Housing Research Center of Iran), occurred in city of Bam in Kerman province, SE Iran. The earthquake caused more than 43000 deaths and 30000 injuries making it the deadliest earthquake in the world in the last 27 years. Maximum vertical peak ground acceleration, recorded by a SSA2 accelerograph (which was located in the center part of the city), was reported 988 gals by BHRC and the maximum horizontal peak ground acceleration was as high as

799 gals. Although the surface fault ruptures were observed between Bam and Baravat city (closer to Baravat), around the Bam fault, but the damage distribution map of the city showed that the most effected area was the east-central part of Bam city and less damages were observed in Baravat. Adobe and masonry buildings were the most types of structures in Bam city, which suffered from the highest level of damage. Reinforced concrete and steel frame (with moment resisting connections or with bracing) buildings were the other types of structures in the city but with considerable lower damage rates comparing to that of the masonry and adobe buildings. Many steel structures with simple type of Khorjini connections were observed in the city and some of them were inspected. Figure 4 illustrates a mid-span Khorjini connection in a building located in Bam city with steel frame system. Centric-steel-bracings were applied as the lateral resistant system of the building. The detail of the Khorjini connection is similar to that of the F-4 connection, illustrated in Figure 2, and as it is clear in the picture, the satchel connection shows no sign of crack or damage on its components.

Figure 4 An uncovered mid-span Khorjini connection in a building in Bam city after the earthquake

Figure 5 shows a steel frame building with a simple satchel connection, which is similar to F-2 connection in Figure 2. Since, this type of satchel connection is considered as a simple connection, group 2, in the practical designing of such structures, a proper system has to be designed for lateral resistant of such buildings. For this particular building, steel bracing was applied as the lateral resistant system. From the figure it can be indicated that the bracing system in the soft-story of the building had not enough lateral resistant capacity against the applied seismic load and failed, but the structure endured large deformations, and as it is shown the satchel connections had slight damages. In another word, the structural system in main direction, X-Y plane in Fig. 1.1, could behave as a ductile system even after failure of the bracing system. Therefore it might be concluded that the simple type Khorjini connections with sufficient lateral resisting capacity, guaranteed by an appropriate bracing system, could respond at the acceptable performance level with even ductile behavior after failure of the bracing system.

Figure 6 illustrates two single-beam or end-span Korjini connections in a steel structure located in the most damaged part of Bam city. As it is shown in the figure, the failure mechanism of the illustrated connections is in Z-Y Plane of Fig. 1.1 (perpendicular to X-Y plane), which is a different mechanism from that of which studied in the first part of this paper. As explained before, beams in Khorjini connections are connected from two sides of the columns. This results a configuration in which the transverse beams cannot be connected directly to the columns. After failure of the bracing elements, this become a serious problem, leading to a brittle failure, especially, when there is only one beam connected from one side of the column or in another word, when we have end-span Khorjini connection such as the connections shown in Figure 6. Figure 7 shows the shear and moment components applied on such end-span Khorjini connections. The top and bottom angles are subjected to shear forces and three components of moment, the end beam moment M1, the transverse beam moment M2, due to having practical semi-rigid connection, and a moment caused by the eccentricity of beam shear force V1 from the vertical axis of the column.

Figure 5 A building with conventional simple type of Khorjini connections in Bam city after the earthquake

Figure 6 Two end-span Khorjini connections in a 4-story building in Bam city after the earthquake

It can be recommended that in the preliminary steps of structural design procedures, configuration of the structures are defined as to have more spans available for installing the lateral resistant or bracing system in the transverse directions, (Z-Y) plane of the Khorjini connections. This may lead deformations of the structure to be dominated in the X-Y plane; in the direction that structural system can behave more ductile due to shear-moment resistant mechanism of Satchel connection in X-Y plane.

It is also suggested that in the performance design procedure, effects of the transverse stress components on the Khorjini connection should be taken into account. Further experimental and analytical study also is expected to evaluate the response of the end-span Khorjini connections under seismic loading, considering the effects of transverse elements. In case of a mid-span satchel connection, due to its symmetric configuration the effects of transverse stresses were reduced by installing the batten plates, but these ties for an end-span connection cannot be applied because of having a single beam in the connection.

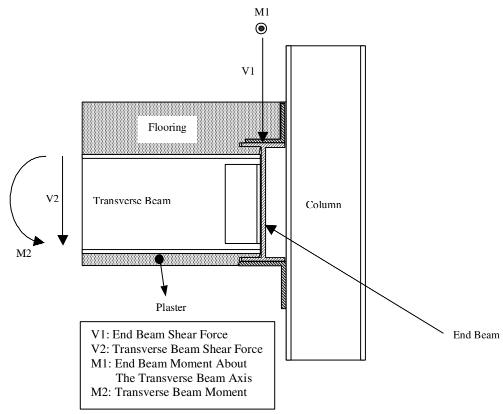


Figure 7 Forces components in an end-span Khorjini connection

CONCLUSION

Six specimens of Khorjini steel connections, with different strengthening details, were studied experimentally in order to evaluate the moment carrying capacities and rigidity percentages of the connections. Triangular stiffeners, beam web stiffeners, batten plates and beam top-bottom plates are the most effective means of strengthening applied in this study to increase the moment resisting capacity and rigidity percentage of a Khorjini connection. It is also suggested that a Khorjini connection with the top-bottom plates and sufficient angle stiffeners may perform as a moment resisting rigid Khorjini connection. It is recommended that in the design connections, F-1 through F-4 connections, be assumed as simple connections without moment resistance.

The post-earthquake inspection results indicate that further experimental studies are necessary to investigate the effects of transverse elements on Khorjini connections, especially on end-span satchel connections.

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