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Experimental and numerical assessment of beam-column connection in steel moment-resisting frames with built-up double-I column

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Abstract. Built-up Double-I (BD-I) columns consist of two hot rolled IPE sections and two cover plates which are welded by fillet welds. In Iran, this type of column is commonly used in braced frames with simple connections and sometimes in low-rise Moment Resisting Frames (MRF) with Welded Flange Plate (WFP) beam-column detailing. To evaluate the seismic performance of WFP connection of I-beam to BD-I column, traditional and modified exterior MRF connections were tested subjected to cyclic prescribed loading of AISC. Test results indicate that the traditional connection does not achieve the intended behavior while the modified connection can moderately meet the requirements of MRF connection. The numerical models of the connections were developed in ABAQUS finite element software and validated with the test results. For this purpose, moment-rotation curves and failure modes of the tested connections were compared with the simulation results. Moreover to avoid improper failure modes, some improvements of the connections were evaluated through a numerical study.

Keywords: built-up double-I column; cyclic test; finite element; seismic behavior; steel moment resisting frame

1. Introduction

In steel moment resisting frames (MRF), beam-columns connections have a crucial role in the global behavior of steel frames. Therefore, design, construction and quality control of MRF connections are of great importance. The observed seismic performance of the MRF connections confirmed various undesirable failure modes can adversely affected the intended ductile behavior of steel frames (Mahin 1998, FEMA 355-E 2000).

A wide range of experimental and numerical studies have been done on the behavior of steel MRF connections or improvement of the vulnerable existing connections. Numerous studies have been conducted on evaluating the behavior of connections which were common before 1994 Northridge earthquake (Whittaker *et al*. 1998, Righiniotis and Imam 2004, Kim *et al*. 2008, Ramirez *et al*. 2012). Following the lessons from the earthquakes, a series of studies were carried out which resulted in some modifications on the conventional practice of MRF constructions (Popov *et al*. 1998, Ricles *et al*. 2002). Some techniques were also proposed for retrofitting and improvement of the behavior of existing steel MRFs (Uang *et al*. 1998, Civjan *et al*. 2000, Chi *et al*. 2006). Some experimental investigations were performed on small scale specimens to assess the behavior of welding and detailing, moreover various tests were carried out on different aspects of full scale interior and exterior joint assemblages. Thereby, FEMA has released some documents on the evaluation and upgrading of existing welded MRF connections (FEMA 351 2000) and some criteria for new MRF joints (FEMA 350 2000). A series of studies are still devoted to the performance investigation of conventional MRF bolted and welded connections with different detailings through finite elements modeling approaches or experimental studies (Engelhardt and Husain 1993, Shanmugam and Ting 1995, Dubina and Stratan 2002, Coelho and Bijlaard 2007, Gholami *et al*. 2013a, b, Lee *et al*. 2014, Morrison *et al*. 2016, Jahanbakhti *et al*. 2017). Some modifications in the seismic design of conventional MR beam-column joints have also been suggested in some recent researches (Lee and Kim 2007, Bai *et al*. 2015, D'Aniello *et al*. 2017). New connections for bolted and welded MRF connections that ensure the global ductile behavior of steel structures have been developed (Goswami and Murty 2010, Mirghaderi *et al*. 2010, Ataollahi *et al*. 2016, Tong *et al*. 2016, Erfani *et al*. 2016).

In Iran, steel mills commonly produce narrow European I sections such as IPE and INP, therefore, rolled steel wide flange sections are not available for construction of low-rise steel frames. Recently, steel structures fabricators have produced built-up wide flange or box sections for major projects. However, in many existing steel buildings or even a few new low-rise buildings built-up double-I columns are utilized. As illustrated in Fig. 1, this type of built-up column section consists of two IPE sections and two cover plates which are welded with continuous or intermittent fillet welds.

The Built-up Double-I (BD-I) columns are commonly

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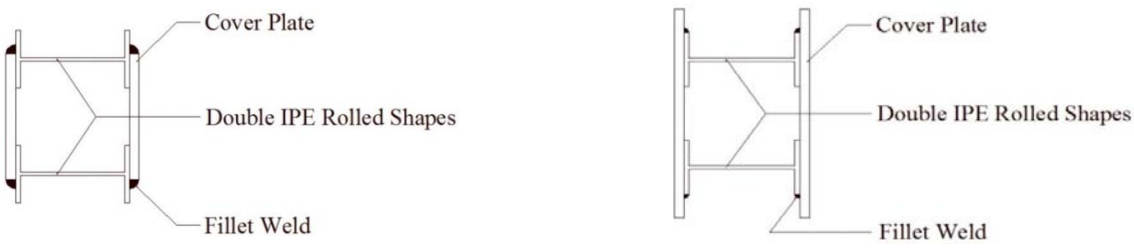


Fig. 1 Typical sections of built-up double-I columns

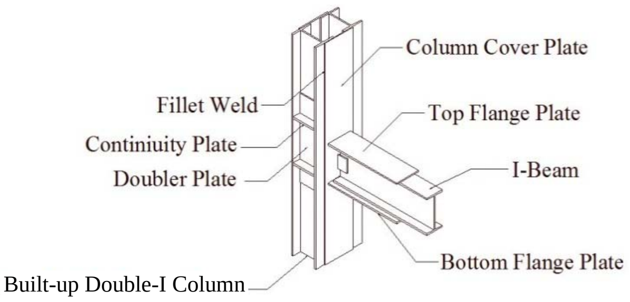
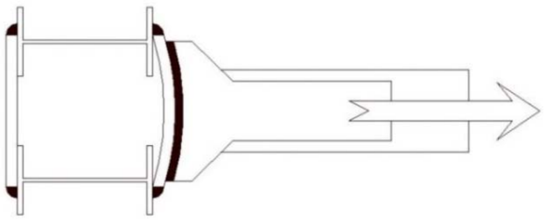
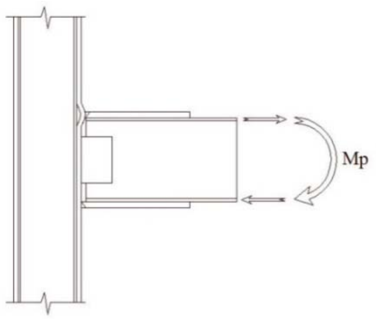


Fig. 2 WFP beam-column connection in steel intermediate MRFs with BD-I column section



(a) Stress concentration in welds



(b) Reduction of connection's rigidity

Fig. 3 Undesirable behavior of conventional moment resisting connections

used in braced frames with simple connections and sometimes in low-rise MRFs which have not been prohibited in Iranian National Building Code (INBC-10 2008) yet. In this regard, INBC-10 permitted employing BD-I columns with continuous weld in intermediate steel MRFs up to 2012 where the beam-column connection was Welded Flange Plate (WFP) as shown in Fig. 2. In the latest version of INBC-10, this type of connection is not accepted as a prequalified connection (INBC-10 2013).

This recommended WFP detailing, which is basically suitable for connecting I beam to box column, is not practical for BD-I columns. In practice, some components of this welded connection are omitted. For instance, internal or external continuity plates or doubler plates are not properly fabricated. These defects may lead to undesirable failure modes of the joint that may adversely influence the intended ductile behavior of MRFs. For example, in the absence of internal continuity plate in the past conventional practice, the cover plate of the BD-I section is only welded to the flanges of IPE and stress concentration occurs in the fillet weld of the cover plate to IPE section as well as groove weld of flange plates to the column cover plate. Moreover, flexural deformation of the column cover plate can reduce the rigidity of the MRF connection (Fig. 3). Finally, the webs of IPE sections are relatively thin and in the absence of doubler plates, the WFP connection is vulnerable to weak panel zone behavior.

Although WFP connections to BD-I columns have been widely used in the past decades in a significant number of buildings, few experimental researches have been conducted on the seismic behavior of these MRF connections. For example, Mazrooei *et al*. (2005) carried out an experimental study on 7 full scale conventional moment resisting connections in Iran. In the test specimens, BD-I columns were made up of IPE180 sections. The loading was applied monotonically up to the failure of the connection. It was concluded that the conventional connection is not fully restrained and to achieve a rigid connection, the cover plate of the column should be welded by slot weld to the flange of IPE section. No result has been reported for plastic rotation capacity of the connections. Deylami and Shiravand (2010) proposed a side plate connection detail for I-beam to BD-I columns where full depth side plates were utilized to transfer shear and moment actions to the column. They employed ANSYS software to simulate the cyclic performance of the connections and concluded that the beam reaches the ultimate flexural strength and the connection can provide 4% rotation requirement of special steel MRFs. This technique was further studied numerically by Deylami and Salami (2011) through using a trapezoidal side plate connection detail for I-beam to box and BD-I columns. The results showed that this connection has a proper behavior under cyclic loadings. In an experimental study, Mazrooei *et al*. (2011) conducted a series of full scale tests to investigate some retrofitting techniques (such as T-stiffeners or ribbed stiffeners) on MRF connections of I-beam to box columns (8 samples) and to BD-I columns (1 sample). They concluded that T-stiffeners can adequately enhance the performance of MRF connections. Through an experimental and numerical study, Deylami and Gholipour (2011) evaluated a modified conventional connection that could be used in special MRFs.

In this study, two MRF connections with BD-I column section were fabricated and tested under cyclic loading. The first one was a Traditional Moment-resisting Connection (TMC) which did not have doubler and continuity plates as required by seismic design provisions. Although these defects should be considered in a proper seismic design, the TMC represents a pre-seismic code connection (before 1998 revision of INBC-10) or a connection in which some components are missed due to improper design, detailing or fabrication. The Modified Moment-resisting Connection (MMC) was designed according to seismic provisions of INBC-10 to satisfy intermediate MRF requirements and was tested to evaluate its seismic performance based on provisions of ANSI/AISC 341 (2010). Moreover, the MMC satisfies strong column-weak beam requirement. It should be noted that all components of test specimens were connected with high quality welding, particularly CJP groove welds, to eliminate adverse local effects of welding on the global behavior of the connections. The results of the tests were used for validation of the numerical finite element modeling in ABAQUS software. A further numerical simulation was performed to improve the detailing of the MMC to meet the seismic requirements of MRF connections.

2. Experimental program

The description of test setup, specimen design and fabrication, and material properties are presented in this section.

2.1 Design and details of test specimens

The main goal of this study is to evaluate the seismic performance and vulnerability of conventional steel MRF connections which were widely used in past decades in Iran especially for midrise buildings. In this regard, beam-to-column connection detail, as depicted in Fig. 2, is a WFP connection in which flange plates are connected through CJP groove weld to the column face and connected by means of fillet weld along beam axis to the beam flange. Welded shear tab plate transfers shear force. For flange plate connection as shown in Fig. 4, design forces of connection (V_u and M_u) as prescribed in FEMA 350 (2000) and ANSI/AISC 358 (2010) depend on probable plastic moment (M_{pr}) as follows

$$M_{pr} = C_{pr} R_y M_p \tag{1}$$

$$V_u = M_{pr}/L_h \tag{2}$$

$$M_u = M_{pr} + (S_h/L_h) M_{pr} \tag{3}$$

where C_{pr} is a factor to account for the peak connection strength (for most connection given as $C_{pr} = (F_y + F_u)/2F_y$), R_y ratio of the expected yield stress to the specified minimum yield stress, M_p is nominal plastic flexural strength, L_h is distance between plastic hinge locations, and S_h is distance from face of column to the plastic hinge.

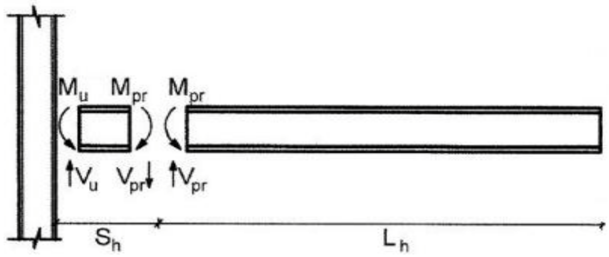


Fig. 4 Free body diagram of exterior MRF connection

Table 1 Geometrical properties of the specimens

Specimen TMC	
Beam section	IPE270
Column section	2IPE180
Spacing of I-sections	180
Column cover plate	PL 220×12
Bottom & top-flange plate	PL 350×220×20
Shear plate	PL 150×100×10
Specimen MMC	
Beam section	IPE270
Column section	2IPE180
Spacing of I-sections	180
Vertical Internal Stiffener	IPE180 (L = 810)
Column cover plate	PL 220×12
Bottom & top-flange plate	PL 350×220×20
Shear plate	PL 150×100×10
Continuity plate	PL 164×43×10
Doubler plate	PL 500×150×10

*All dimensions are in mm

All sections were selected from available rolled steel profiles to fabricate specimens similar to the traditional MRF connections. The beam section is IPE270, and the Double-I column section includes two IPE180 and two 220×12 mm cover plates which are connected by means of continuous fillet weld. Geometrical properties of the two test specimens (TMC and MMC) are listed in Table 1. Details and geometry of the two specimens are illustrated in Figs. 5 and 6.

In a traditional connection specimen, no continuity plates and vertical stiffeners were used as shown in Fig. 5. The traditional connection specimen TMC was improved in the modified connection specimen MMC by providing a vertical stiffener and a pair of continuity plates on the exterior flange of each IPE section. To facilitate connecting this vertical stiffener to the cover plates of BD-I column, an IPE180 section reinforced with doubler plate on the web and two pairs of continuity plates was added. The cover plates of the column were connected to flanges of the vertical stiffener by slot weld. The vertical stiffener in the BD-I column extended one beam depth from the flange plate.

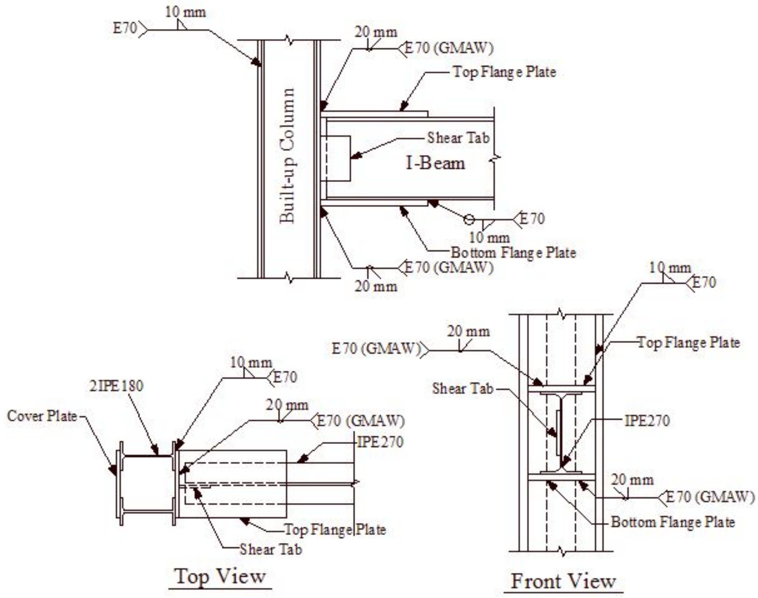


Fig. 5 Details of TMC specimen

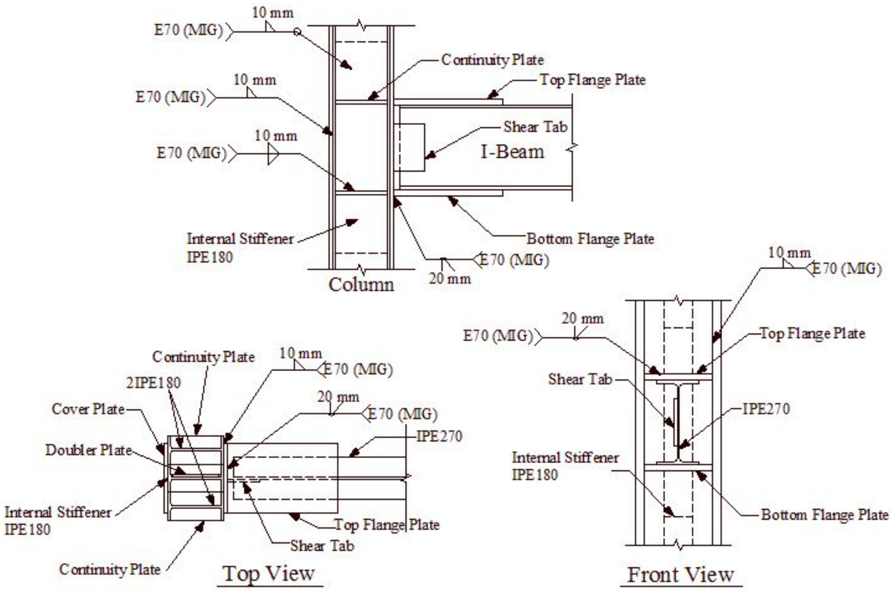


Fig. 6 Details of MMC specimen

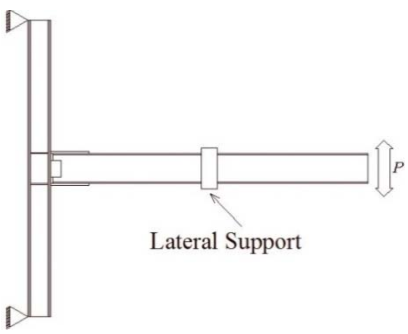


Fig. 7 Schematic diagram of exterior beam-column connection test setup

Fig. 8 Photo of test setup and loading frame

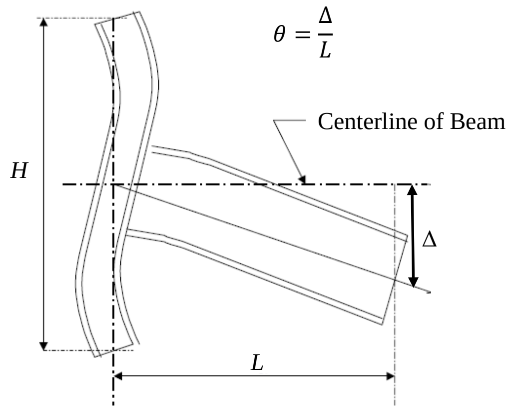


Fig. 9 Deformation of the exterior beam-column connection

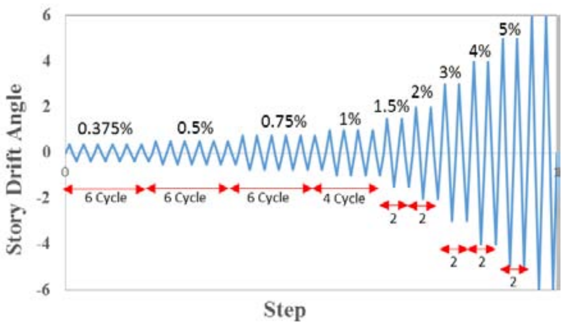


Fig. 10 Cyclic loading protocol of AISC 341

2.2 Test setup

Considering the elastic deformed shape of MRFs, points of inflection are generally located at the midspan of beams and mid-height of columns. Therefore, the exterior beam-column assemblage consists of one half-span beam and two half-height columns. Figs. 7 and 8 respectively present the schematic diagram and photo of the test setup, where top and bottom of the column are pinned to the loading frame and a lateral support is provided for the beam. In this test setup, for both specimens, story height is 2.7 m and full beam span is 6 m. A semi-automatic 250 kN hydraulic actuator was mounted on the loading frame to apply a vertical load at the end of the half-span beam. The maximum stroke of the actuator is 300 mm, thus the maximum drift in the test setup is limited to 4% which satisfies the intended performance requirements of AISC 341 provisions.

The actuator load and vertical displacement of the beam end relative to loading frame were recorded by load cell and LVDT, respectively. These data were monitored by a control unit to follow the cyclic loading protocol. The vertical displacement of the beam end as depicted in Fig. 9 is proportional to the drift angle of the story. The cyclic loading protocol as prescribed by AISC 341 is plotted in Fig. 10 in terms of story drift ratio.

2.3 Material properties

The tensile properties of steel and weld are necessary for numerical simulation of test specimens. For this purpose, based on ASTM A6 (2012) and ASTM A 370 (2014), standard samples form plates as well as web and flange of IPE sections were prepared and tested. The yield strength and ultimate strength steel samples determined from stress-strain curves have been tabulated in Table 2.

Table 2 Mechanical properties of steel

Type of specimen	Yield strength (MPa)	Ultimate strength (MPa)
IPE270 - Flange	350	460
IPE270 - Web	335	451
IPE180 - Flange	350	477
IPE180 - Web	275	436
Plate 20 *mm*	300	452
Plate 12 *mm*	310	448
Groove Weld	490	565

Table 3 Required properties of weld per AWS D1.8

Type of weld	Test temp. (°*C*)	CVN toughness (*J*)	Required CVN toughness (*J*)
GMAW	21	142	54

In addition, using high quality welding process and qualified welders for fabrication of specimens can minimize possible welding defects in the specimens. It should be noted that the welding defects can adversely influence cyclic behavior of the specimens. The CJP welds were made by gas-shielded welding process and were ultrasonically tested by a certified inspector. Furthermore, the quality of the groove welds was confirmed, as reported in Table 3, in accordance with AWS D1.8 (2009) requirements.

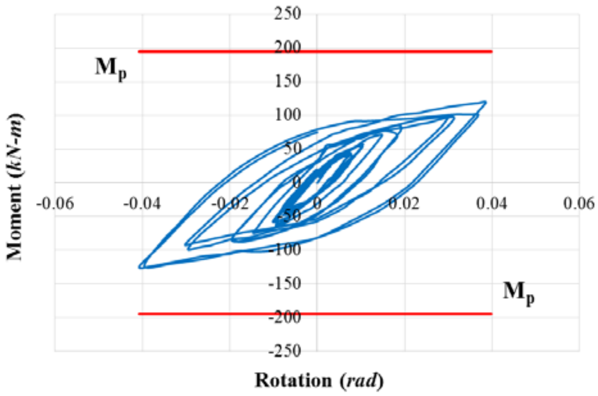
3. Test results

To meet the requirements of special MRF connections based on AISC 341 provisions, the connection should be capable of accommodating a story drift angle of at least 0.04 rad, and the measured flexural resistance shall equal at least $0.8M_p$ of the connected beam at a drift angle of 0.04 rad. For intermediate MRF connection the aforementioned requirements should be satisfied at story drift angle of 0.02 rad.

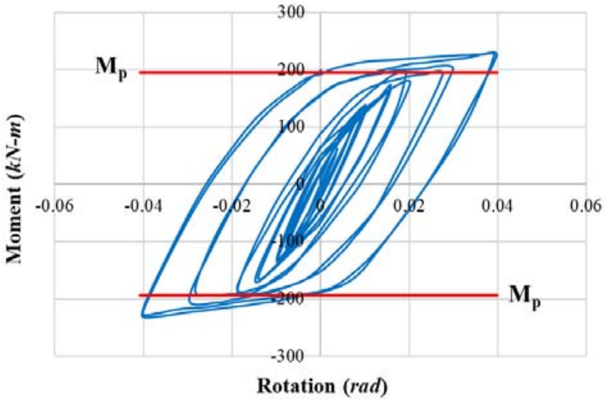
3.1 Hysteresis response

Actuator load and vertical displacement of beam end are recoded for both specimens. Considering beam length, bending moment at the centerline of the column and lateral drift ratio of story are computed. Fig. 11 shows the cyclic moment-rotation curves of both specimens.

To achieve the intended performance of MRF, flexural hinge should be formed in the beam next to the welded flange plate. The corresponding equivalent plastic moment M_p of the beam is marked in Fig. 11. It should be noted that the plastic moment of beam occurs at the end of the flange plate while the moment is calculated at the centerline of the



(a) TMC



(b) MMC

Fig. 11 Bending moment versus rotation of connection

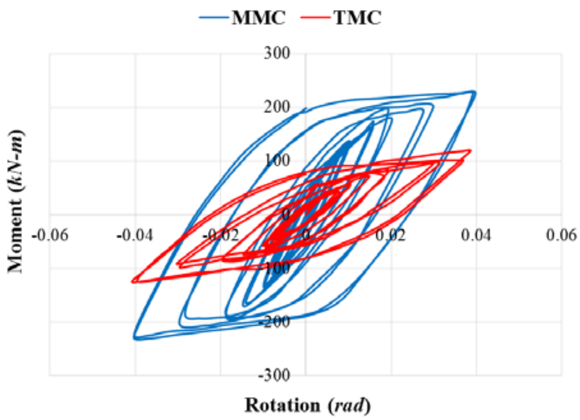


Fig. 12 Comparing hysteresis moment-rotation behavior of TMC and MMC samples

column. To find the equivalent plastic moment at the centerline of the column, the plastic moment of beam is multiplied by L/L_h. The hysteresis curves of TMC and MMC are compared in Fig. 12. The moment-rotation curve of TMC indicates that the beam could not reach its plastic strength due to early yielding of the panel zone in the connection. However, in MMC, the beam can meet its plastic capacity and can accommodate the drift of 0.04 radian without any degradation of moment strength. In other words, the TMC can be used as a MRF connection

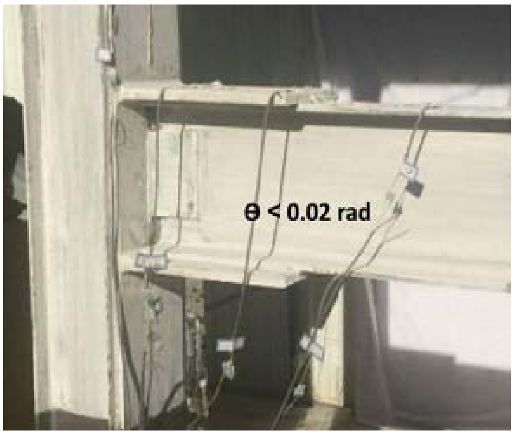


Fig. 13 Linear behavior of the TMC up to 1.5% drift angle

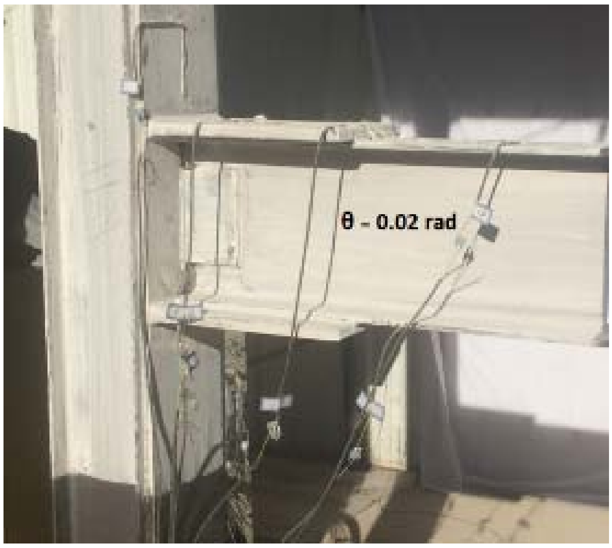


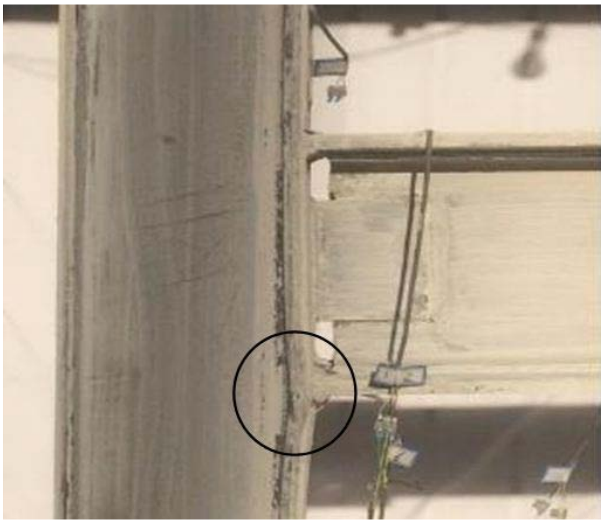
Fig. 14 Initiating nonlinear behavior of the panel zone in the TMC at 2% drift angle

only in ordinary MRFs, while the moment-rotation curve of the MMC conforms to the requirements of AISC special MRF connections.

3.2 Test observation

Potential yield zones of the specimens were painted with whitewash prior to testing. As steel yields, light color brittle whitewash flakes and detaches from the surfaces of the specimens which reveals bare steel. The responses of the TMC and MMC specimens subjected to cyclic loading in a qualitative sense are as follows.

Up to 1.5% drift angle, the TMC specimen remained elastic without any sign of yielding (see Fig. 13). At drift angle of 2% as shown in Fig. 14, at few points of the panel zone whitewash flakes formed and the nonlinear behavior of the panel zone commenced. A considerable out-of-plane deformation of the column's cover plate was observed at 3% story drift angle, which gradually resulted in tearing of the flange of the IPE profile in the BD-I adjacent to the fillet weld of the cover plate. This kink deformation of the cover plate next to the flange plate of the connection has



(a) Large kink deformation of the column's cover plate

(b) Tearing in the column's flange

Fig. 15 Behavior of the TMC at 3% drift angle

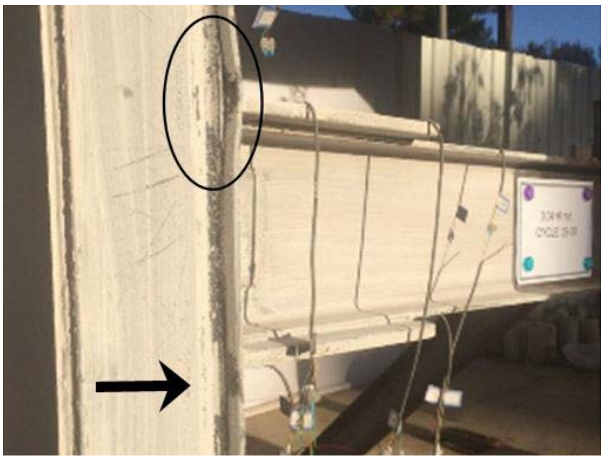


Fig. 16 Complete tearing of IPE's flange and formation of plastic zone in back of the column's flange in the TMC specimen at 4% drift angle

been presented in Fig. 15.

At 4% story drift angle, a considerable separation of whitewash flakes was observed in the panel zone. Tearing of the IPE's flange plate propagated and as a result limited the flexural capacity of the TMC. Moreover, the formation of a plastic zone in back of the column's flange was recognized (see Fig. 16). No defect or failure was detected in the fillet and groove welds, which confirmed the high quality of the welds.

Similarly, no whitewash flakes were detected in testing of the MMC specimen up to 1.5% story drift angle and the connection remained almost linear (Fig. 17). At 2% drift angle as shown in Fig. 18, some whitewash detachment in flange and web of the beam was observed next to end of the flange plate, which represents initiating flexural yielding of the beam. Following loading protocol to 3% drift angle results in considerable whitewash flakes in the flange and web of the beam as presented in Fig. 19, thus yielding of the beam is obvious. At the end of 0.03 rad cycle, little nonlinear behavior of the panel zone was also recognized.

Higher amount of fall of whitewash flakes in the beam (next to end of flange plate as shown in Fig. 20) and the panel zone (Fig. 21) was observed. At the end of cyclic

Fig. 17 Linear behavior of the MMC up to 1.5% drift angle

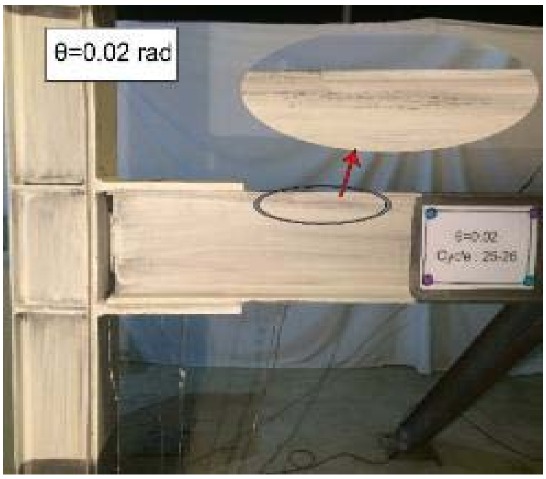


Fig. 18 Initiating yielding of the beam in the MMC at 2% drift angle

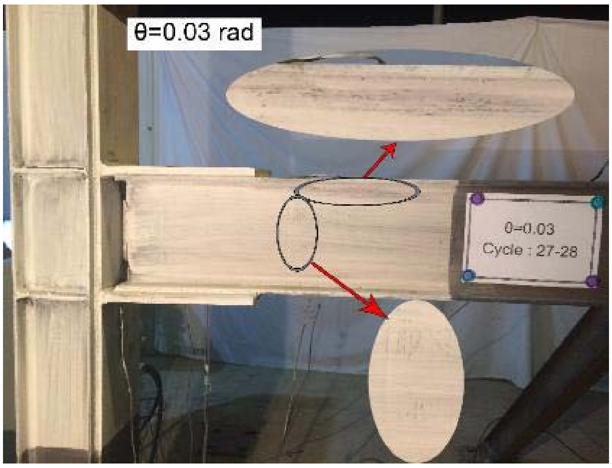


Fig. 19 Considerable nonlinear behavior in flange and web of the MMC at 3% drift angle

Fig. 20 Yielding of the beam in the MMC at 4% drift angle

loading, no failure was detected in the connection and welds.

In summary, the nonlinear behavior of the TMC was shear yielding of the panel zone followed by kink deformation of the cover plate of the BD-I column and finally tearing of the flange of IPE section. This type of failure confirms that the TMC is not suitable as an MRF connection in any ductility level. The dominant nonlinear behavior of the MMC was flexural yielding of the beam next to the end of the flange plate followed by limited panel zone yielding. This behavior indicates that MMC behaves somewhat properly which can be improved with some modifications that will be evaluated numerically in the next section.

Fig. 21 Nonlinear behavior of the panel zone in the MMC at 4% drift angle

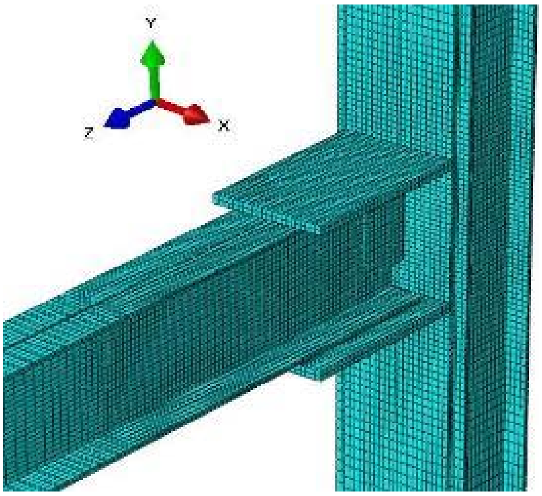
4. Numerical modeling

To gain insight into the behavior of beam-column connections with BD-I column sections and to evaluate the effects of some influential parameters on them, a numerical study was performed in Finite Element (FE) ABAQUS software in addition to the experimental program. For this purpose, firstly the accuracy of the numerical modeling method was verified by the test results. The validity of the numerical modeling approach was established by a nonlinear analysis of both TMC and MMC joints under cyclic loading. The hysteresis moment-rotation curves and the plastic zones in the connections obtained from numerical modeling were compared with the test results. Then, further improvements of the MMC were evaluated by proper detailing through numerical simulation.

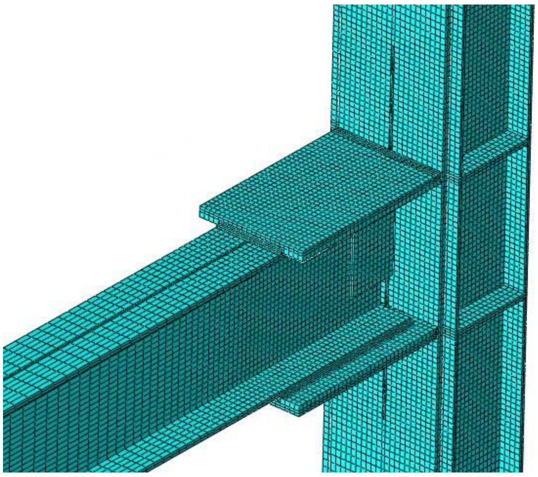
4.1 Modeling details

4.1.1 Geometry

For modeling and analysis of different parts of the connections such as beam and column sections as well as steel plates, 3D solid elements with 8 and 20 nodes (referred to as C3D8R and C3D20R elements in ABAQUS) were utilized. To joint different parts of the models such as cover plates, IPE sections, top and bottom flange plates etc., proper edge or surface tie constraints were utilized in the models. Mesh size of 10 to 50 mm which was obtained by a mesh sensitivity analysis was used. A finer mesh size was

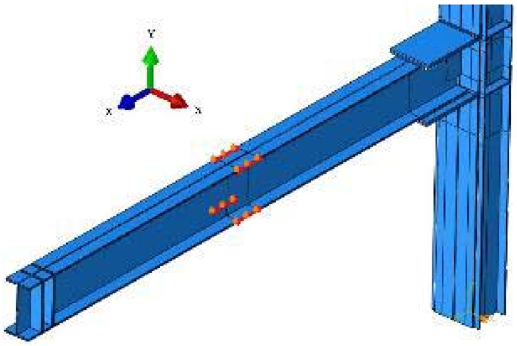


(a) TMC

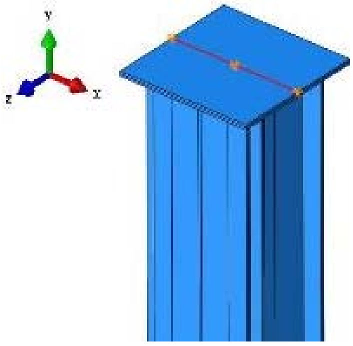


(b) MMC

Fig. 22 3D view of the test specimens modeled in ABAQUS



(a) Lateral support of beam



(b) Column ends

Fig. 23 Boundary conditions of the connection specimens

utilized for zones near the joint region and a coarser size was chosen to simulate the beam and column far from the joint region where no stress concentration and nonlinear behavior were anticipated. Around 9448 and 13136 elements were used for modeling and analysis of the TMC and MMC joints, respectively. Fig. 22 illustrates a 3D view of both connections discretized with solid elements.

4.1.2 Boundary conditions

According to the test setup shown in Fig. 7, top and bottom of the column were connected to the reaction frame by means of two pins. Therefore, in the numerical models top and bottom of the column were restrained on the centerline along three orthogonal directions. In this way, the column ends can rotate freely about the rotation axis of the pin. Moreover, the lateral supports, which were provided in the test setup to prevent any possible lateral movement of the beam, were simulated with appropriate lateral restrains on the beam. Fig. 23 shows the boundary conditions that were applied to the models to simulate the test setup.

4.1.3 Material model

In this study, tensile tests were conducted on specimens cut from web and flange of hot rolled sections and plates. Based on tensile testing results as reported in Table, elasto-plastic bilinear uniaxial stress-strain model with a kinematic hardening in post yield branch accompanied with Von Mises failure surface are utilized for modeling steel material in elastic and inelastic phases for each part. The yield and ultimate stresses of different parts of the test specimens used in the FE models are listed in Table 2.

4.1.4 Loading and analysis

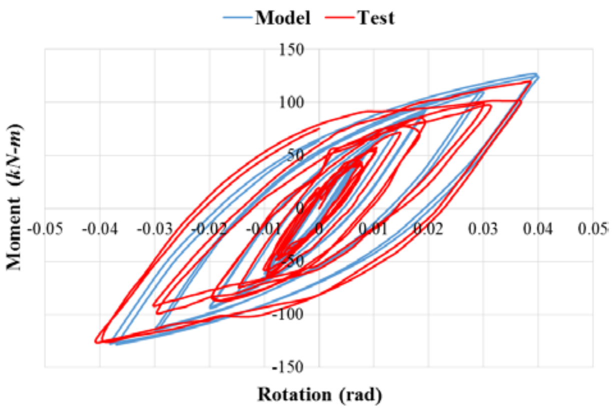
Nonlinear static analysis was conducted on the models subjected to the aforementioned cyclic displacement history applied at the beam end (Fig. 10). The load corresponding to each displacement step was computed as sum of the nodal forces on reference plane normal to the axis of the beam.

4.2 Verification of the numerical model

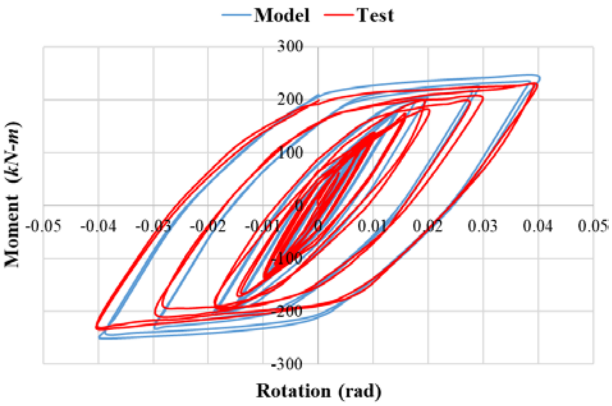
Analysis results including plastic regions and moment-rotation curves were obtained and compared with the failure mode and response curves reported in the test results.

Moment-rotation curves of the TMC and MMC specimens obtained from numerical and experimental studies are plotted in Fig. 24. The comparison of the hysteresis curves confirms a good agreement between the numerical and experimental results. At key points of hysteresis curves the amounts of relative error between the numerical and experimental curves are compared in Table 4.

To demonstrate that the numerical model is capable of detecting the nonlinear behavior and failure mode of the tested connections, a few failure modes are presented. Fig.



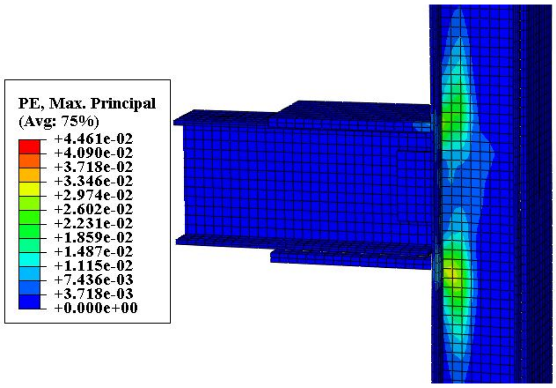
(a) TMC



(b) MMC

Fig. 24 Moment-rotation curves of the connections

(a) Test



(b) Model

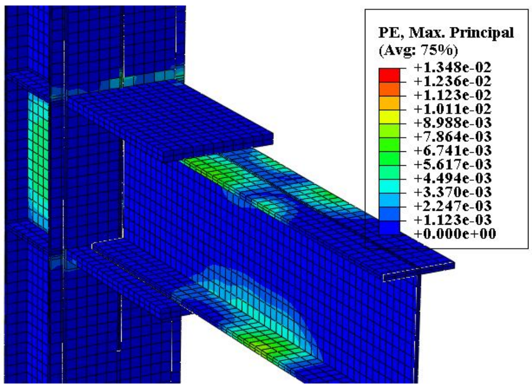
Fig. 25 Failure mode of TMC

Table 4 Comparing numerical simulation results with test results

Connection	Rotation (*rad*)	Maximum moment Test (*kN-m*)	Maximum moment Model (*kN-m*)	Error (%)
TMC	0.0075	43.6	48.2	9.5
	0.01	54.8	58.6	6.5
	0.015	71.1	78.2	9.0
	0.02	83.4	92.1	9.4
	0.03	98.2	109.9	10.7
	0.04	118.2	124.6	5.1
MMC	0.0075	110.1	105.8	4.1
	0.01	135.7	136.9	0.9
	0.015	171.6	183.7	6.6
	0.02	193.6	204.0	5.1
	0.03	206.1	224.5	8.1
	0.04	227.2	244.5	7.1

25 illustrates the plastic strains developed in TMC and the local failure observed in the test corresponding to the rotation of 0.04 radian. In the absence of proper continuity plates in TMC specimen, the formation of plastic regions in the model and failure mode in the test indicates that in both cases the failure is concentrated at flange-web intersection

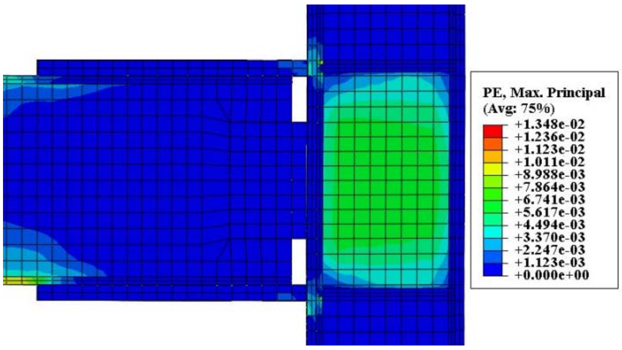
(a) Test



(b) Model

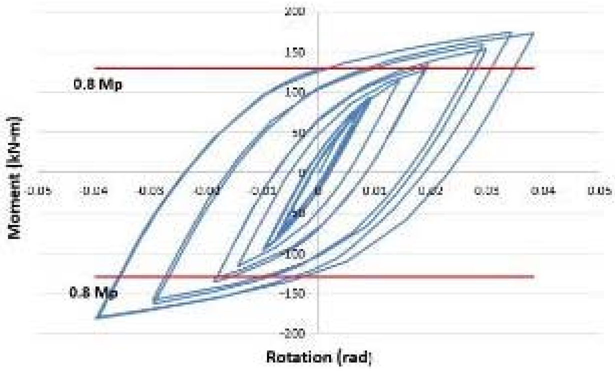
Fig. 26 Flexural yielding of beam in MMC at 0.04 radian

(a) Test

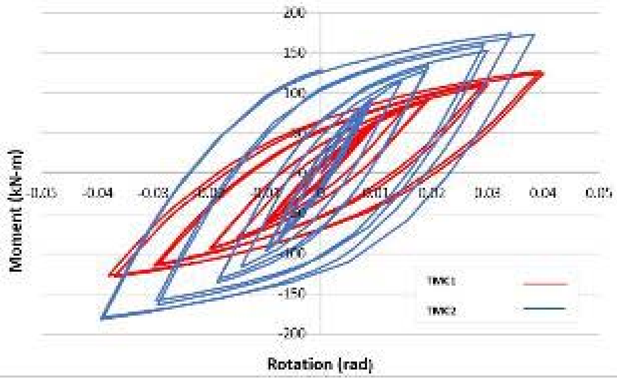


(b) Model

Fig. 27 Shear yielding of beam in MMC at 0.04 radian



(a) ITMC



(b) Comparing ITMC with TMC

Fig. 28 Moment-rotation curves of the ITMC connection

of IPE sections in the BD-I column next to the top and bottom flange plates (this failure was observed starting from 0.02 radian in the test). This failure mode confirms that the missing continuity plate which was common practice in old buildings leads to the local failure of the column section and can endanger load bearing capacity of the column. This phenomenon is totally against the seismic design objective of columns in MRF systems and consequently prevents flexural yielding of beam and even shear yielding of panel zone.

Fig. 26 presents the plastic strains developed in the flange and web of the beam in MMC specimen at the drift angle of 0.04 radian. Test and analysis results indicate that adding the vertical stiffener (middle IPE reinforced with doubler plate) and continuity plates to MMC leads to the formation of a flexural plastic hinge in the beam immediately next to the top and bottom flange plates (starting from 0.02 radian). As reported in test observations, shear plastic strain follows beam yielding in the panel zone (starting from 0.03 radian) which is also detected in the results of the numerical modeling (see Fig. 27). This shear yielding occurs in the web on IPE sections since the doubler plates were only used in the middle vertical stiffener. Adding doubler plate to the web of IPEs can eliminate this panel zone yielding and will be addressed later through numerical modeling.

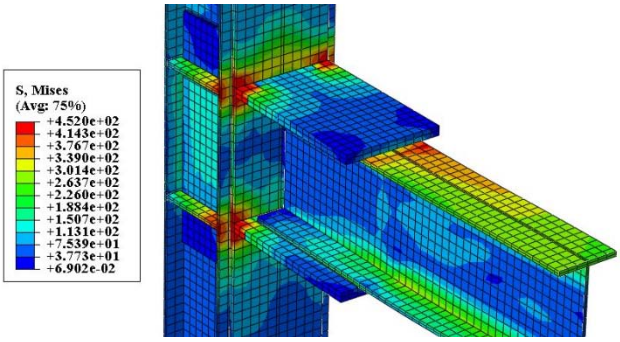
4.3 Evaluation of the improved connections

Regarding the observed behavior of both connections, in this section and based on the verified numerical simulation, the effects of some required improvements on the behavior of the connections are discussed.

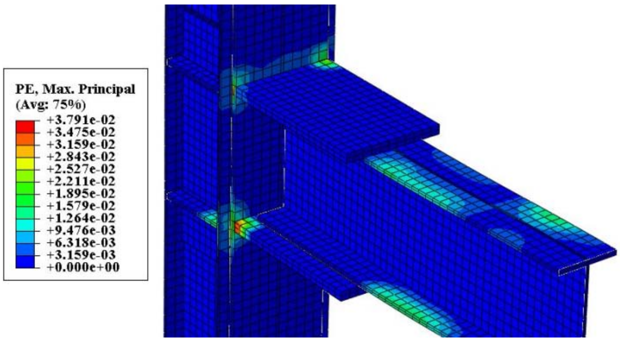
4.3.1 Adding doubler plate and continuity plates to the TMC

Test results of TMC confirmed the deficiency of panel zone in this connection. Moreover, premature local failure of column precedes the expected flexural yielding of the beam. Therefore, the behavior of the connection after adding doubler plates to the web of each IPE of BD-I section and two pairs of continuity plates for each IPE as shown in Fig. 2 is evaluated. Moment-rotation curves of improved TMC (ITMC) model under specified cyclic load protocol specified in AISC, are plotted in Fig. 28.

Analysis results indicate that improvements performed on TMC connection, result in considerable increase of strength of the ITMC connection. For instance, in similar rotation of 0.04 radian, the capacity of ITMC connection is 174.5 kN, which is around 40% more that of TMC connection. Moment rotation curves also show that the ITMC connection has higher rotational stiffness. However, the plastic strain in the ITMC connection which is presented in Fig. 29, indicates that the nonlinear behavior of the connection is still concentrated in the column, which is not suitable for intermediate and special steel moment connections. Apparently this connection satisfies the requirements of Intermediate MRF connections, but due to yielding mechanism the ITMC can be accepted as an ordinary MRF connection which can be used in low rise buildings in low to moderate seismic hazard zones.

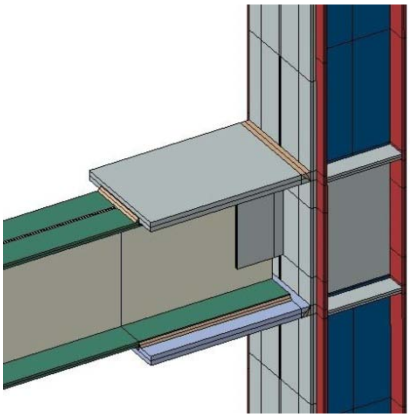


(a) Von Mises stress distribution

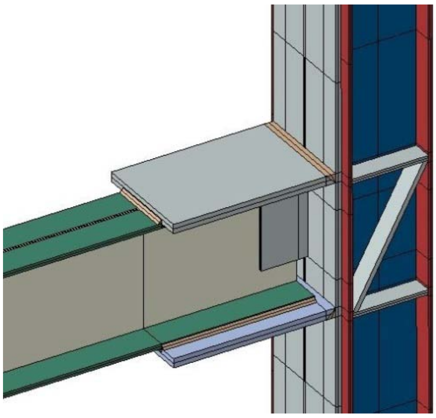


(b) Plastic strain

Fig. 29 The results of FE analysis in ITMC in the rotation of 0.04 radian

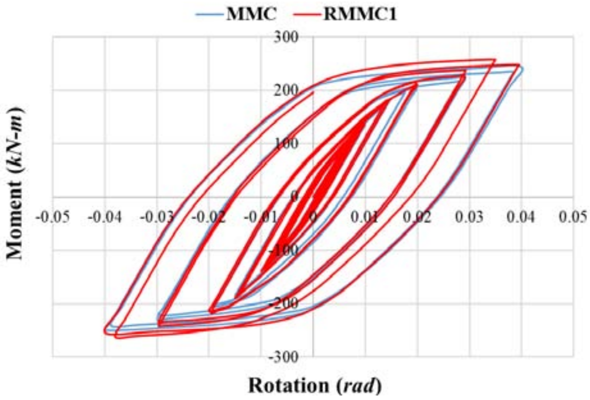


(a) Doubler plates

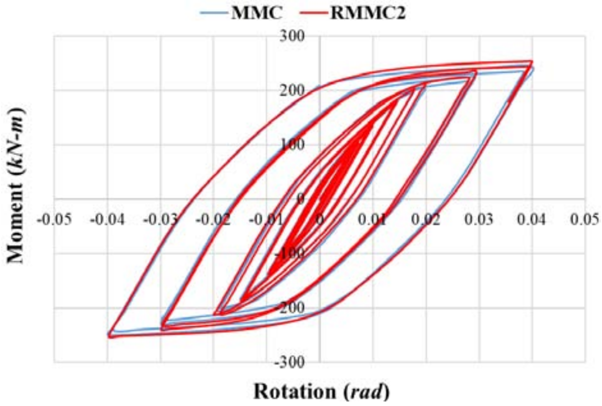


(b) Diagonal stiffeners

Fig. 30 Reinforcing schemes of MMC panel zone

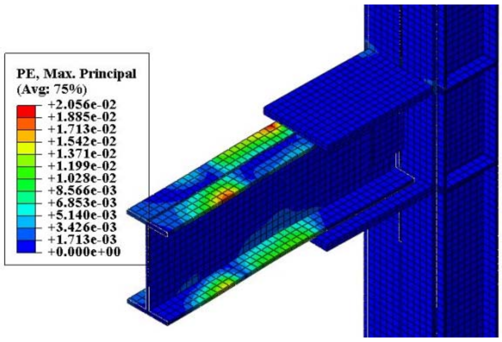


(a) Doubler plates

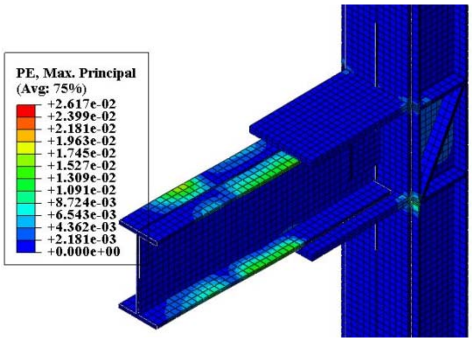


(b) Diagonal stiffeners

Fig. 31 Comparison of the moment-rotation curves of the MMC with the reinforced connection



(a) Doubler plates in RMMC1



(b) Diagonal stiffeners in RMMC2

Fig. 32 Comparison of the plastic strain distribution in reinforced MMC with the reinforced connection

4.3.2 Reinforcing the panel zone of MMC

Test and numerical analysis results indicated that the behavior of the MMC complies with the requirements of seismic design codes for MRF connections except the occurrence of some plastic shear strain in the panel zone of IPEs in BD-I column. To improve this weak point, the panel zone of the connection may be reinforced appropriately against shear actions to reach limited panel zone yielding as prescribed by AISC 341. For this purpose, two schemes were considered for column web reinforcement as depicted in Fig. 30. One scheme was to add two doubler plates of 10 mm thick to the webs of the IPEs (denoted as RMMC1) and the second was to use two diagonal stiffeners of 10 mm thick on the panel zone (denoted as RMMC2).

Analysis results of the reinforced MMCs including moment-rotation and plastic strain distributions are presented in Figs. 31 and 32, respectively. The comparison of the moment-rotation curves of the reinforced connections using the two schemes with MMC shows that reinforcement of the panel zone increases the strength of the connections slightly (around 5%). In addition, the curves show that the reinforced connections can reach the plastic moment of the beam and that the strength of the connection at drift rotation of 0.04 radian is more than 80% of the beam plastic flexural capacity. Moreover, the plastic strain distribution in both reinforced connections indicates that these improvements can eliminate plastic shear strain in the panel zone and consequently lead to the formation of a plastic hinge in the beam. In other words, the flexural plastic hinge occurs in the beam immediately next to the top and bottom flange plates. This behavior adequately conforms to the seismic code provisions specified for ductile steel MRF connections. Strictly speaking, the RMMC specimen can conservatively be evaluated as an intermediate MRF connection. In practice, using doubler plates is preferred. This improvement might be necessary for MMC with stronger beam section or interior connections where panel zone is subjected to higher nonlinear behavior.

5. Conclusions

An experimental and numerical study was performed on WFP connection of I beams to BD-I columns. Two exterior connection specimens, one traditional which exists in old steel moment resisting frames in Iran and the other a modified connection, were designed, fabricated, and tested under cyclic loading. Then, finite element modeling of the connection in ABAQUS software was carried out and validated with the test results. Finally, by considering some modifications, the seismic performance of the connection was evaluated through numerical modeling. The major findings of the research are as follows:

(1) Test results show that Traditional Moment Connection (TMC) does not conform to the seismic requirements of the MRF connections according to AISC. In this connection, the beam cannot reach its plastic capacity due to premature failure of connection in IPEs of the BD-I column. In addition, the major nonlinear behavior of this connection occurs in the panel zone which is not suitable in seismic design.

(2) Test results indicate that in Modified Moment Connection (MMC), the connection can properly accommodate 4% interstory drift angle without any degradation in moment capacity. Also, the plastic hinge occurred in the beam next to the top and bottom flange plates accompanied with a slight plastic strain in the panel zone. Therefore, with some modifications to eliminate the plastic strain in the panel zone, the connection can be used as a MRF connection with moderate ductility in seismic design.

(3) Numerical modeling of the test specimens and analysis results show that the model can properly simulate the behavior and capture the nonlinear modes of the steel MRF connection.

(4) Although the modifications performed on TMC specimen were able to enhance the moment capacity of the connection, some plastic strains still concentrated on the column. This behavior is not suitable in seismic design, therefore, this connection could be used in ordinary MRFs.

(5) Adding doubler plates to the panel zone of IPEs in MMC eliminated the plastic strains from the panel zone of BD-I. Therefore, this connection can be used at least in intermediate moment resisting frames.

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