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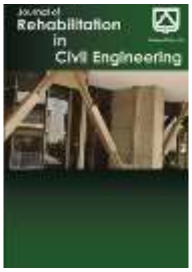

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A Technique for Seismic Rehabilitation of Damaged Steel Moment Resisting Frames

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ABSTRACT

Moment resisting frames (MRF) as one of the conventional lateral load resisting systems in buildings suffer from some limitations including code limitations on minimum span-to-depth ratio to warrant the formation of plastic hinges with adequate length at the ends of the beam. According to seismic codes, in ordinary steel MRFs the span-to-depth ratios should be larger than 5 and in special steel MRFs this ratio should not be less than 7, which is typically difficult to achieve in some cases. For instance, framed-tube structures typically have MRFs with span-to-depth ratios less than the above mentioned ranges. Therefore, existing buildings with small span-to-depth ratios may exhibit poor seismic performance when subjected to seismic excitation. In this paper, a method is presented to rehabilitate such MRFs. Although the idea of using shear link for design of new buildings has been investigated in recent years, this idea can also be used to rehabilitate existing MRFs. Moreover, the novelty of this proposed rehabilitation method in this paper is that it can be used for damaged MRFs after earthquakes to enhance their remaining strength and ductility capacity. While most of the available rehabilitation methods focus on improving the system strength and stiffness, the proposed rehabilitation in this paper is based on the weakening of the beam mid-span that causes the formation of the shear plastic hinge in middle of the beam instead of the two beam ends. Numerical evaluation is conducted to show the efficacy of this method, and the results show that the use of the proposed rehabilitation method considerably increases the ductility capacity of the system during subsequent earthquakes.

1. Introduction

The present study introduces a rehabilitation technique for short span-to-depth ratio steel moment resisting frames (MRF) that are partially damaged due to a previous earthquake. This rehabilitation method is

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based on the structural system proposed by Mahmoudi et al. [1], and Nikoukalam and K. M. Dolatshahi [2] that uses shear links in newly designed MRFs to increase their ductility and improve the overall seismic performance. Utilizing shear link in the beam mid-span, results in the formation of a plastic shear hinge mechanism in the beam mid-span rather than the formation of the flexural plastic hinges at beam ends. In this research this idea of using shear links is used to propose a new method for seismic rehabilitation of damaged MRFs. The seismic performance of the MRFs rehabilitated using the proposed method is investigated by means of numerical analyses.

After an earthquake it is important that the structure be rehabilitated in a short time and finally with a lower cost. However, the repair of the main beam after an earthquake is very difficult, destructive, and costly [3]. This study was conducted in an attempt to propose an economical rehabilitation technique for the damaged MRFs.

MRFs are extensively used because of their good performance [4], while providing freedom in architecture. MRFs exhibit a ductile behavior because of their ability to effectively dissipate the energy induced by ground shakings. The key to this energy dissipation is the development of plastic hinges at the two ends of the beam [5]. However, a number of limitations have led the researchers to pursue improved design concepts upon the current practice in MRF construction.

The first restriction is to make sure that plastic hinges develop with sufficient length near the beam ends. According to ANSI/AISC 358-10 [6] provisions, the span-to-depth ratio should be greater than 5 and 7 for intermediate and special MRFs, respectively. The rationale behind this limitation is explained here in reference to Fig. **1**. This figure shows two frames with identical cross sections for the beam and the columns under the same lateral load, F. The two frames, however, differ in their beam span length. Frame (a) has a clear span-to-depth ratio of L_1/D=7, which satisfies the code requirement, and Frame (b) has an L_2/D=4, which violates the code. This leads to two different lengths of plastic hinge for these frames, denoted by L_{p1} and L_{p2} in Fig. **1**a and b, respectively. Note that the plastic hinge in each plot is illustrated by the colored area. The hinge falls within the distance of a point with a moment of $M=SF_y$ and the beam end at which $M=ZF_y$, where S, F_y, and Z are elastic section modulus of the beam, stress of steel, and plastic section modulus of the beam, respectively. As seen, the length of the plastic hinge in Frame (a) is larger than that of Frame (b). The underlying reason is that the slope of the bending moment diagram of the beam for Frame (a) is less steep than that of Frame (b). Since the colored area in Frame (b) is smaller than that of Frame (a), the seismic input is dissipated in a smaller portion of the beam. This increases the cumulative induced plastic strain and thus, the probability of fracture for the short beam in Frame (b).

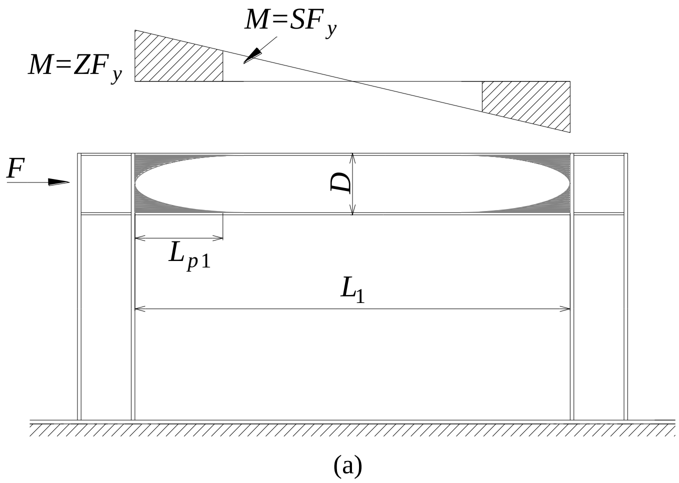


Fig. 1. Effect of span-to-depth rations on the plastic hinge length.

The code limitation on L/D is customarily disregarded in those moment resisting systems for which such a problem is commonplace, e.g., in tall buildings. One example of such systems are framed-tube structures in which the peripheral MRFs provide resistance against the lateral loads and the internal frames are designed to support the gravity loads [7]. In framed-tube structures, the columns are closely spaced while the beams have relatively deep cross sections. Such a structure, in fact, approximates a cantilevered tube with openings that are punched through the exterior walls. This combination usually leads to small span-to-depth ratios. Framed-tube structures typically have MRFs with span-to-depth ratios lower than the above mentioned ranges [7]. Such a building features a span-to-depth of roughly 4, which clearly violates the code regulations. Hence, it is expected that such a building exhibit an unsatisfactory performance because of a low energy dissipation due to insufficient length of the plastic hinges. For another example, in some cases, designers try to control the drift ratio by reducing the span lengths, which causes a lower span to depth ratio and accordingly violates the codes criteria.

The above mentioned limitation clarifies the importance of a rehabilitation method to enhance the seismic performance of existing MRFs with low span-to-depth ratios. This paper presents a new method to rehabilitate such MRFs with deep spandrel beams. In the proposed technique, by weakening the mid-span of an existing beam, the location of the plastic hinges shifts to the middle instead of the beam-ends. This method is applicable for the rehabilitation of either damaged or undamaged systems.

2. Literature Review

In recent years, several techniques have been used for seismic rehabilitation of steel MRF. Improving the strength and/or stiffness of the building is an efficient way to rehabilitate such systems [8]. Since, the bracing can improve the stiffness and strength of steel frames, some researchers have investigated the various implementation of braces for the rehabilitation of steel buildings. For example, buckling-restrained braces have been considered by Xie [9], a non-compression brace system have been studied by Tamai and Takamatsu [10] and Renzi et al [11] have examined an energy-dissipative bracing system. In addition, the application of braces for seismic retrofitting has been an important issue in recent years which have been investigated by various researchers [12], [13].

Some techniques have been recommended in FEMA guidelines [14] for seismic rehabilitation of welded beam-to-column connections [15]–[17]. Moreover, energy dissipating fuse elements have been considered by Leelataviwat et al. [18] to rehabilitate such systems. Self-centering systems [19], [20] and steel walls with reduced thickness that dissipate energy by shear buckling [21]–[24] are some examples of other techniques proposed for the rehabilitation of MRFs. Various passive energy dissipating dampers have also been used for the rehabilitation of steel buildings [25], [26]. Using replaceable fuses is also another way to ease rehabilitation after earthquakes. For instance, the use of steel rings made using steel plates not only increases the energy dissipation and the ductility capacity of the system during an earthquake, but also decreases time and cost of rehabilitation. In order to repair such systems, it is only needed to replace the rings without any need to rehabilitate the whole system [27-32].

It should be noted that while in the foresaid methods, the focus is on the rehabilitation of intact frames, the proposed method in this paper can also be applied for the rehabilitation of damaged steel MRF. This paper employs the replaceable fuse solution to reduce the repair time and cost, which can improve the resilience of the system [33], [34]. In the proposed system, the shear link is replaceable which ease the rehabilitation procedure. The shear link is welded to two end-plates, and these end-pates are bolted to the end-plates of the beam. Thus, if the shear link is damaged during an earthquake, the damaged link can be removed and replaced by an intact link.

3. Specimen Design

To achieve the idea of replacing the flexural plastic hinges at the two ends of the beam by a shear plastic hinge at the beam mid-span in a MRF the link beam is designed accordingly. To shift all plastic deformations to the shear link, the design shear strength the shear link, V_L, is predicted using Eq. (1):

$$V_L \le \varphi V_{pb} \tag{1}$$

where V_{pb} is the main beam shear force corresponding to the creation of flexural plastic hinges at ends of the beam, and φ is overstrength factor that represents the increase in strength because of the strain-hardening of the link with plastic shear hinge mechanism [2]. According to Nikoukalam and Dolatshahi [2] using φ=1/1.5, all plastic deformation take places in the shear link and the beam ends stay intact. However, using φ=1/1.35, the link yields in shear initially, followed by the formation of flexural plastic hinges at the two ends, because of the link overstrength, when drift ratio increases. The energy dissipation for the MRFs designed using this concept occurs through the beam ends as well as the shear link. The model used in the present study is constructed similar to Mahmoudi et al. [35] frame with a span width of 1.4m and a height of 1.5m which only the upper half of the column from the inflection point is built to conduct the test. The other parts of the frame is similar to that studied by Mamhoudi et al. [35].

Table 1 presents the geometric properties of the columns, the link , and the beam cross sections. The properties of associated components, such as double plates, stiffeners, and continuity plates are tabulated in Table 2.

Table 1. cross-sectional dimensions for different elements [1].

	d (mm)[a]	**b_f (mm)**	**t_w (mm)**	**t_f (mm)**
Column	280	280	12	**20**
Link	170	120	5	**12**
Beam	300	150	6	**8**

[a] **d is the depth of the section.**

Table 2. Associated components properties.

	d (mm)	b (mm)	t (mm)
Link Stiffener	146	57	10
Double Plate	276	240	10
Continuity Plate	240	134	12

4. Numerical Analysis

Nonlinear 3D finite element models (FEM) of a MRF tested by Mahmoudi et al. [35] are developed to validate the modelling approach. The strength degradation due to the the buckling of the frame parts is considered in the FEM of the frames. Link beams and columns are modeled using isoperimetric four-node doubly curved general-purpose conventional shell elements (S4R), that can capture the local buckling effects. The end-plates of the link, for their thickness, were modeled with the eight-node solid continuum elements with reduced integration (C3D8R). Initial imperfections were considered in the analyses, using the first five buckling modes of the FEM. A linear eigenvalue buckling analysis determines the buckling modes. In addition, to include the effects of large displacement, the geometric nonlinearity was enabled in ABAQUS. Therefore, the local buckling as well as the post buckling behavior of the elements are included in structural modelling. It is worth noting that the details of the welds are not modeled explicitly.

To ascertain the optimized rate of refinement which is essential to achieve accurate predictions in the connection region, mesh refinement study is conducted. The strain-hardening model utilized in the analyses includes both nonlinear isotropic and kinematic strain-hardening. For the steel material, Elastic modulus of 200,000 MPa and Poisson’s ratio of 0.3 are used. For the bottom of the columns simple support is assigned. For loading the specimen, displacements were imposed to the outer flange of the two columns at the beam centerline. The loading protocol applied to the specimen is the one given for the beam-to-column connection in AISC Seismic Provisions [36]. Table 3 reported the F_y and F_u for links, beams, and columns which resulted from coupon test [1]. Moreover, ST52 is used for the continuity plates, end-plates, doubler plates, and stiffeners. Material properties are modelled using Kaufmann's model [37] , which is based on cyclic coupon tests.

Fig. **2** compares the load versus drift hysteresis of tested MRF specimen and the corresponding predictions from the computer model. Figure 2 indicates that the computer model can predict the response obtained in the test with a good accuracy.

Table 3. Coupon test results for the steel material used in the specimens [1].

Section	Sample number	F_y (MPa)	F_u (MPa)
Beam	1	374	481
Beam	2	370	488
Link	1	301	403
Link	2	302	404

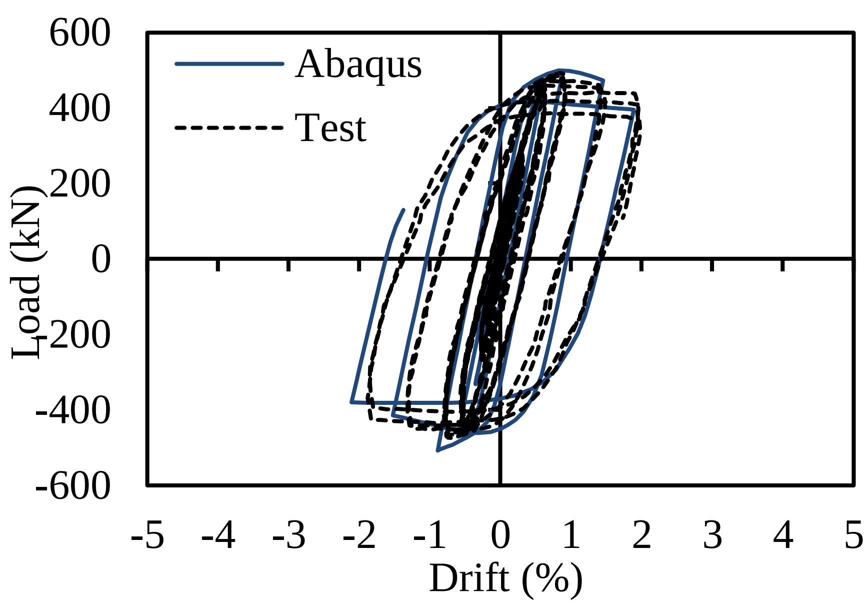
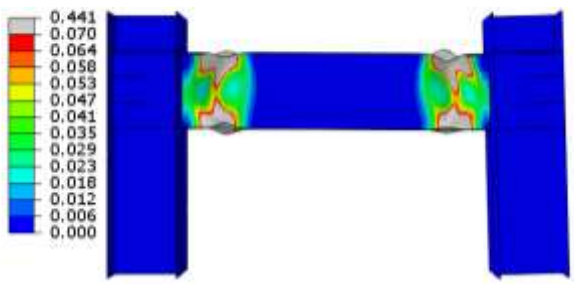


Fig. 2. Verification result, comparison of load versus drift hysteresis [1].

The peak strength and maximum drifts predicted using the ABAQUS model are only 2 and 6 percent different from those observed in the experimental study, respectively. Fig. **3** shows the equivalent plastic strain on the deformed shape of MRF at the 2% drift ratio obtained using the FEM that is in good agreement with the test specimen condition at the end of the test, as shown in the Figure.

Test photographs

(II) Finite element results



(a) Specimen MRF at 2% drift ratio

Fig. 3. Yielding pattern and deformed shape of the frames. The scale represents the equivalent plastic strain (PEEQ) [1].

For the seismic rehabilitation of the damaged MRFs, the frame has been initially loaded and after occurring the loss in peak strength, the mid span of the beam is weakened to evaluate the rehabilitation method. To achieve this objective, a shear link is placed in mid span of the beam which has a strong web thickness, at first. This frame is twice as thick as the shear link. In fact, the beam mid-span is strengthened to ensure that the plastic hinges will be formed at the both beam ends and this frame acts similar to a conventional MRF. For this purpose, with using Model Change property in ABAQUS, a plate has been tied to the web of the link to make sure the plastic hinges are developed at the two ends of the beam when the frame is initially loaded. When the original frame is reached to a target drift ratio (i.e., to represent damage due to a strong earthquake), the plate is deactivated and the frame behaves as a shear link frame.

This frame is subjected to cyclic loading. Fig. **4** presents the load versus the drift ratio for this specimen. It is clear from Fig. **4** that the 20% loss in peak strength is observed at a drift ratio of about 4.5%. To evaluate the shear link rehabilitation method, a link with an endplate connection was placed in the mid-span of this frame. This procedure is conducted for four different shear links with a web thickness of 3, 4, 5, and 6 millimeters, respectively. Fig. **5** demonstrates the hysteresis curves of the original frame and the rehabilitated frames simultaneously for the various web thicknesses considered. In this analytical procedure first the MRF reach 15% loss in its peak strength and then the frame is rehabilitated. In fact, after that the frame meets its 15% loss in peak strength the shear link is place in mid span for the rehabilitation. The 15% loss in peak strength can be representative of damage in the MRFdue to a severe earthquake. It should be noted, the stiffness of MRFs is 6-10% greater than the corresponding shear link frames models [2].

As demonstrated in Fig. **5**, the strength degradation of the rehabilitated frames take places at a significantly larger drift ratios compared to that of the original frame. It is worth mentioning that since this weakening occurred in mid span of the beam, it has a minimal affect on the stiffness. Fig. **5** also shows that the rehabilitated frames exhibit only around 5% loss in peak strength at 8.5% drift ratio. This indicates that the rehabilitated frames can undergo significantly larger plastic deformations with lower strength degradation. Therefore, it is clear that the suggested rehabilitation method has significantly improved the ductility capacity and seismic performance of the MRFs. It is worth noting that the maximum strength in both cases is very similar, though as predicted the peak strength of the main beam is a bit larger than that of the rehabilitated frames. The peak strength and the strength loss at 8.5% drift ratio for the rehabilitated frames with different shear link thicknesses, are presented in Table 4, based on the results shown in Fig. **5**. The results in Table 1 demonstrate that the thickness of the shear fuse did not significantly affect the seismic behavior. However, in Fig. **5** (d), for the rehabilitated frame with the web thickness of 3 mm, some pinching is evident in the graph that may be assigned to the local buckling of the plate. It appears that the optimum seismic response is observed when the frame is rehabilitated using a shear link with a web thickness of 4mm. Using the web thickness of larger than 4 mm did not have any noticeable effects, as shown in Fig. **5**. For all rehabilitated cases in Table 1, low strength loss (in order of 4% to 7%) is observed at a large drift ratio of 8.5%, indicating that the ductility capacity of the frame has been significantly increased using the proposed rehabilitation method. It is worth mentioning that rupture is the last source of strength degradation in large displacements if link has been designed according to codes [38]. But, to reach exact drift ratio it is necessary to include fracture in structural modelling which is beyond the scope of this study.

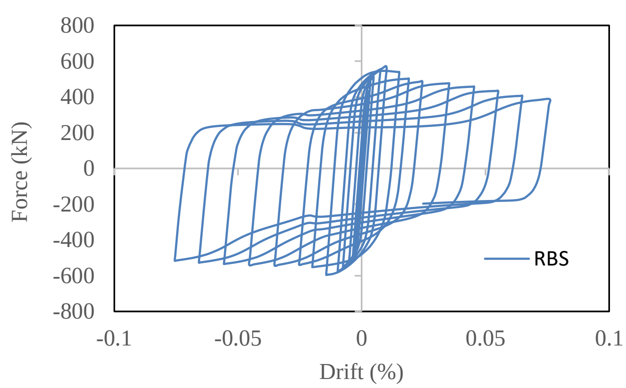


Fig. 4. Load versus drift ratio for strong shear link.

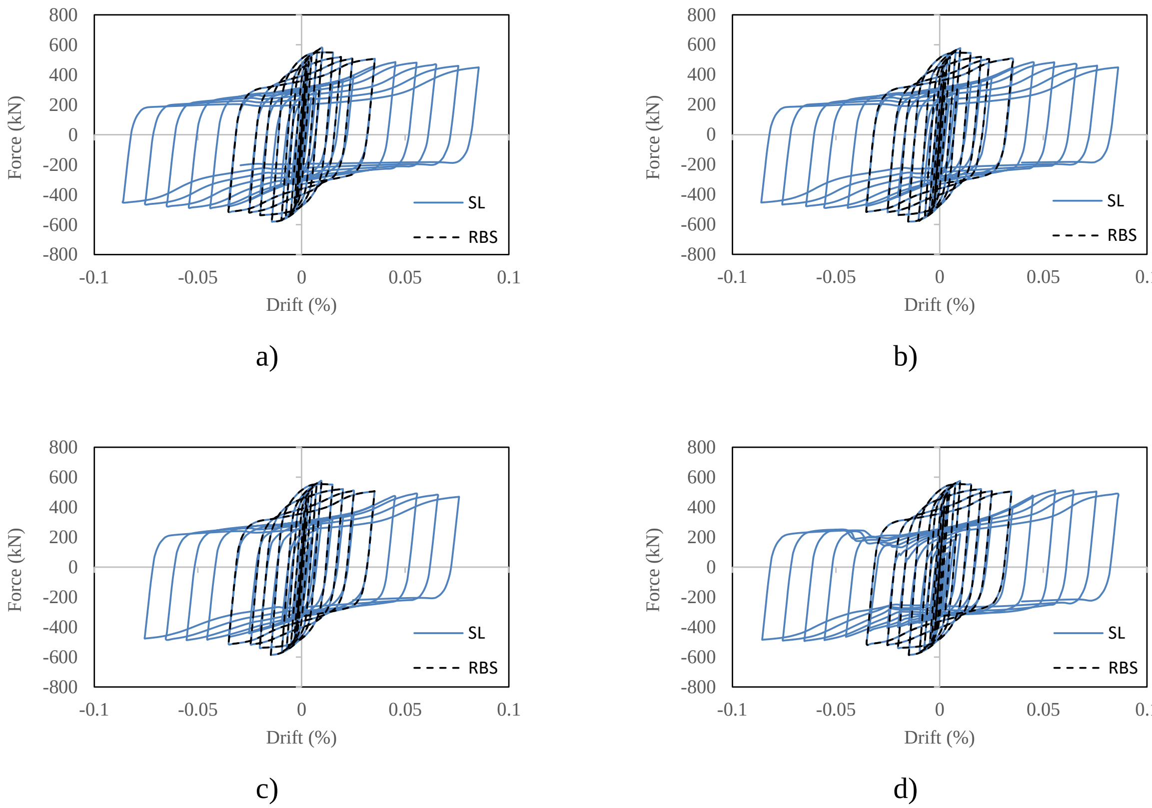
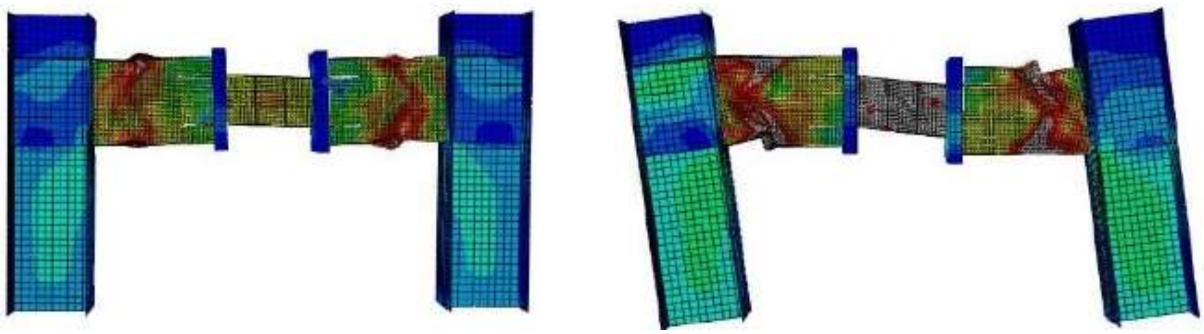


Fig. 5. Load versus drift ratio before and after rehabilitation. The thickness of the shear link web is a) 6 mm b) 5 mm c) 4 mm d) 3 mm.

Table 4. Comparison of the seismic capacities of rehabilitated frames with various thickness of the shear link web.

Thickness of the shear link web	Peak strength (KN)	Strength loss at 8.5% drift
6 mm	489	7%
5 mm	489	7%
4 mm	491	4%
3 mm	512	4%

In Fig. **6**, the equivalent plastic strain (PEEQ) is presented on the deformed shape of the main and the rehabilitated frame with 4 millimeters web link, at the end of the test. The spread of the plasticity and the buckling of the flanges and web are predicted by the FEM very well. As shown, while the link does not yield in the main specimen, it yields after the rehabilitation.



a) b)

Fig. 6. Yielding pattern and deformed shape of the finite element results. a) Before rehabilitation b) After rehabilitation.

5. Conclusions

In this study, a method is presented for the rehabilitation of either damaged or intact MRFs with low span-to-depth ratio. The idea entails weakening the mid-span of the beam using a shear link, such that the position of the plastic hinges moves from the ends of the beam to its middle, and consequently the frame can undergo much larger drift ratios before failure. It is worth noting that in conventional MRFs, energy dissipation is the consequence of development of plastic hinge in beam ends. This shift in the position of the plastic hinges from the ends to the mid-span can save the beam ends, which are previously damaged, from any further damage or deterioration.

The proposed rehabilitation technique is recommended mainly in MRFs with small span-to-depth ratios, which are typically used in framed-tube structures. To evaluate the seismic performance of the rehabilitated frames, a MRF is subjected to cyclic loadings, and after 15% strength loss in peak strength, four shear links with various web thicknesses are placed in mid-span of the beam. The results show that the rehabilitated frame can endure significantly larger drift ratios without significant strength degradation. Although the stiffness and the peak strength of the rehabilitated frame was very close to the initial frame, the drift corresponding to strength degradation in the rehabilitated frame was notably greater than that of the original frame.

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