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Two novel shear fuses in moment resting frames

P. Rezazadeh Kalehbasti [a], Kiarash M. Dolatshahi [b,*]

[a] Department of Civil and Environmental Engineering, Stanford University, Stanford, United States
[b] Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

Based on the code specifications, in moment-resisting frames the span-to-depth ratio has to be larger than a minimum value to make sure of adequate plastic hinging at beam-ends. This provision poses a restriction on the use of deep beams with short spans, especially for the framed-tube system in tall buildings. In this paper, a new energy dissipation method is introduced for moment-resisting frames by modifying the mid-span of the beam by two different methods, resulting in: (i) Perforated Shear Links (PSLs) and (ii) Slit Shear Links (SSLs). The links dissipate energy through shear yielding of the web, weakened by perforation or slitting, respectively. A thorough study is conducted on the behavior of the proposed shear links through finite element models verified by test results. The rupture propensity of the models is evaluated by calculating and comparing Damage Index (DI) in various link rotations by post-processing the results of the finite element simulations. In this regard, the results show that the proposed systems can be employed in moment resisting frames with short spans to decrease rupture propensity by 43%. The suggested links can also be designed to be replaceable, making them ideal for repair and retrofit purposes which adds to the resiliency of structures and brings about a more sustainable construction.

1. Introduction

One of the most favorable lateral load resisting systems is special moment-resisting frame (SMRF) due to the high ductility and energy dissipation capacity it provides. A drawback of this system concerns the related provisions imposed by the recent seismic codes: they require that the energy be dissipated through plastic-hinging at beam-ends, and for this to happen, a minimum span-to-depth ratio of seven in SMRFs and five in intermediate moment-resisting frames (IMRFs) [1] must be satisfied. In framed-tube structures, highly sought-after structural systems especially for high-rise buildings, the span-to-depth ratio is about 3.4–4 which is less than the aforementioned limit [2]. Beside this negative point, the drift and strength of moment-resisting frames (MRFs) are interrelated; hence, in the cases that drift limits control the design of the structure, fortifying the structural elements results in a rise in force demands on other structural parts due to an increased capacity of the plastic hinges [3]. As a result, a higher force demand leads to an overdesigned structure. Another disadvantage of MRFs is the uphill, expensive, and troublesome repair of the beams after earthquakes due to the harsh levels of incurred damage [4].

Many alternative structural systems have been proposed for application in MRFs to alleviate the mentioned drawbacks, including self-centering post-tensioned connections [5,6], damage-free frictional beam-to-column connections [7–10], compressed elastic dampers [11], steel sliding-controlled coupled beam [12], and linked column frames (LCF) [13]. Recent studies on replaceable structural components have been conducted in EBFs [14], MRFs [3], LCFs [13], and Coupled Concrete Shear Walls (CCSW) [15].

In this paper, two structural shear fuses, namely Slit Shear Link (SSL) and Perforated Shear Link (PSL), are introduced and studied in detail in order to surmount the deficiencies of the existing options for MRFs with short spans. The mentioned deficiencies comprise problems such as lacking the suitability for being utilized in short-spanned beams, interdependence of drift and strength design, the complexity of implementation and repair, and lacking the feasibility of being replaced following an earthquake. These shear links are implemented through decreasing the shear strength of the beam in the mid-span by modifying the web. Consequently, these fuses employ the shear force in the mid-beam as the deformation-controlled action of the system and dissipate the seismic energy via shear yielding (PSLs) and plastic hinging (SSLs). Additionally, the links decouple drift and strength design of the structure, since through the application of shear links in the mid-beam, the modifications to any of the two designs can be done independently. This energy dissipation mechanism is partly similar to that of the Eccentrically Braced Frames (EBFs) and coupled shear walls, in which short links are employed. Short links, generally, have the advantage of having higher energy dissipation capacity under severe cyclic loadings compared to long links [16]. Another merit of the proposed link configurations is suitability for being implemented in new constructions as well

* Corresponding author.
E-mail address: dolatshahi@sharif.edu (K.M. Dolatshahi).

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as retrofitting existing structures, for they can be designed to be easily replaceable enhancing the resiliency of the structure.

Regarding the stress concentration rooted in modifying the web of the beam, the resulting damage can be an essential factor in evaluating the stability and ductility of the suggested links under cyclic loadings. Many attempts have been made to develop cogent damage indices (DIs) for predicting the amount and location of potential rupture in structural steel components (see the works by El-Tawil, Vidarsson, Mikesell and Kunnath [17], Ricles [18], Chao, Khandelwal and El-Tawil [19], and Prinz and Richards [20]). In this paper, DI was employed to inspect the potential of proposed models for ductile fracture. The links have also been studied and compared regarding other essential factors such as the energy dissipation capacity in addition to shear strength and stiffness under monotonic and cyclic loadings. It must be noted that experimental studies are required to inspect the relation between DI and rupture initiation as well as to study the actual performance of the proposed links.

2. Concept establishment

A beam with a low span-to-depth ratio is not a good candidate for the formation of flexural hinges, since the moment diagram has a relatively steep gradient. Such a gradient does not allow for the formation of flexural hinges with sufficient length [21] and occurrence of reasonable levels of strain in the beam [1]. Shear force demand (V_p) in the beam is a function of nominal plastic flexural strength (M_p) of the beam:

$$V_p = \frac{2M_p}{L} \tag{1}$$

It can be seen from this formula that decreasing the length of the beam (L) results in an increased shear demand - Fig. 1. In traditional design procedures, this shear capacity is provided by increasing the web thickness, which results in a higher M_p leading to an increase in force demands on the other structural components, e.g. the diaphragms and foundation.

Considering this flawed procedure, the shear in the beam - a force-controlled action in recent codes - seems to be a much better alternative to the moment at the beam-ends for dissipating seismic energy in short beams. Hence, a shear link can be placed at the mid-span of the beam to act as a yielding shear fuse, as shown in Fig. 2(a). General illustrations of the Perforated Shear Link and the Slit Shear Link are shown in Fig. 2(b) and (c), respectively. SSL dissipates seismic energy via the formation of plastic hinges at both ends of the strips; however, energy dissipation in PSL is realized through formation of inclined tension strips.

These links can be fabricated to be non-replaceable whenever required, i.e. the suggested links and the beam can be shop-fabricated together in which the end plates of the link can be replaced by stiffeners welded to the web. Alternatively, as depicted in Fig. 2(a), the links can be assembeled at the work-site by means of bolting the end-plates - the grey part is shop-fabricated and is set up on-site. Moreover, the designed links can be employed for retrofit purposes in structures where plastic hinges have formed in the beam-ends following an earthquake, but significant residual drifts have not occured. In such a situation, application of a shear link in the mid-section of the beam can increase the capacity of the structure significantly rendering the building functional again. Such applications can make the restoration of damaged buildings more economically viable and improve the sustainabiliy of the structure.

The suggested links are especially suitable for application in framed-tube tall buildings to provide a sustainable solution for short-spanned beams used in such structures. Furthermore, although flexural demand in the mid-span is much lower than the capacity of the beam (Fig. 1), implementing these shear links negligibly affects the lateral stiffness of the frame and the capacity of the beam for gravity loads. The reason is that the applied modifications keep the flanges untouched providing a segment with a lower shear capacity than the original beam (Fig. 2). Hence, both PSLs and SSLs are applicable in MRFs with a variety of span lengths to act as the deformation-controlled component.

3. Design concept and recommended details

The mid-section of the beam needs to be weakened in terms of shear strength to fulfil the goal of designing the recommended shear links - replacement of the plastic hinging mechanism in MRFs. Sufficient reduction in the shear strength of the mid-beam results in the occurrence of shear yielding in advance of the plastic hinging at beam-ends. In other words, fulfilment of the following formula leads to assured performance of the link as described previously [22]:

$$V_L \leq \varphi V_P \tag{2}$$

where, V_L = the design shear strength of the shear link, φ = coefficient concerning the link overstrength in shear yielding, and V_p is found using Eq. (1). An amount of 1.5 is generally suggested for the coefficient accounting for the link overstrength which originally corresponds to the strain-hardening of the diagonal braces and beams connected to the link in an EBF based on the capacity design principles [23]. The authors have proven the reliability of this concept in a previous work where Shear Slotted Bolted Connection (SSBC) was studied as a new type of shear fuse in the middle of the beam through nonlinear static and dynamic analyses in a multi-degree of freedom structure [24,25]. SSBCs consistently uniformed the drift of the stories of a 9-story 9-span structure and decreased the maximum drift in that structure. Besides, in another work by the authors, the application of a reduced section shear link in the mid-beam has yielded promising results in terms of stable hysteresis behavior and decoupling the stiffness and strength design of the structure [26]. The main characteristics,

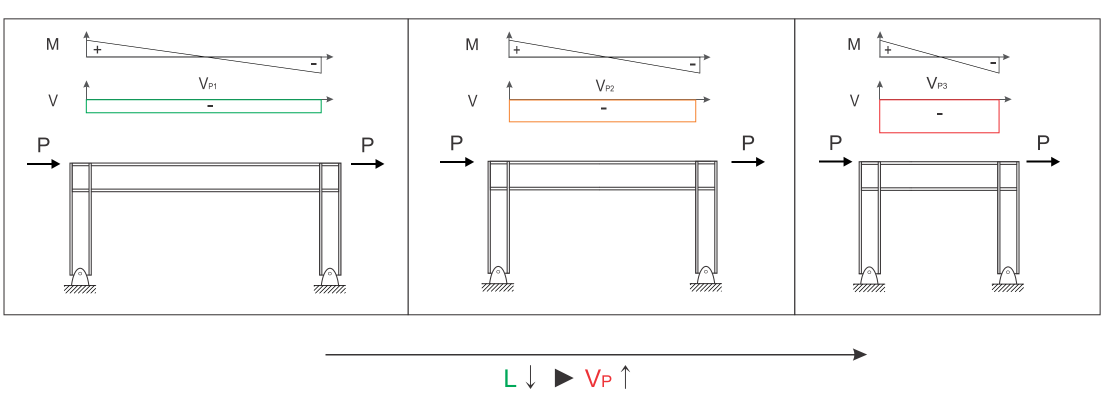

Fig. 1. Variation of shear demand with span length in MRFs.