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BEAM-TO-COLUMN CONNECTIONS WITH HISTERETIC DAMPERS

BY

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Abstract. Steel structures are widespread in areas with high seismic activity due to their good performance, although, in some cases the energy dissipation capacity is not sufficient and the connection can fail or it can suffer large degradations. Their repair can be very costly and in some cases the degradation needs to be avoided due to the destination of the building. In order to increase the connection dissipation capacity, ductility and stiffness a series of hysteretic dampers is introduced in the construction of the connection. These dampers can be repaired or replaced with low costs, low difficulty and in a short period of time.

Keywords: ductility; yielding dampers; energy dissipation; visco-elastic dampers; friction dampers.

1. Introduction

Steel connections should be capable of ensuring the strength and ductility of the entire structure. The main issue of classic steel connections is the reduced plastic rotational capacity. This leads to a premature and brittle failure

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of the connection before the formation of the plastic hinge in the beam, which contradicts the "weak beam-strong column" principle. The premature and brittle failure causes of steel connections were studied by many researchers (Mahin, 1998; Miller, 1998; Hedayat & Celikag, 2009).

The 1994 Northridge and 1995 Kobe earthquakes and the major degradations caused by these events triggered research for optimizing the behaviour of connections regarding the ductility and rotational capacity in order to increase their energy dissipation capacity under cyclic loading. Researchers focused their attention on concentrating the stresses outside of the connection and on ensuring a global behaviour of the structure to satisfy the "weak beam-strong column" concept. In order to fulfil this requirement two methods were proposed: stiffening the connection with additional elements: end plate, stiffeners, haunches (Engelhardt & Husain, 1993) and reducing the beam section (RBS – reduced beam section) (Engelhardt *et al.*, 1996).

These solutions have both advantages and disadvantages, but these methods imply that the main dissipative element is the end plate and/or the end of the beam. However, increasing the joint ductility can be realised by introducing additional energy dissipative elements. Several alternative versions of connections were proposed, optimized in order to have a better behaviour. Beam-to-column connections with hysteretic dampers can be classified as:

- connections with metallic yielding dampers;
- connections with visco-elastic dampers;
- connections with friction dampers.

2. Connections with Metallic Yielding Dampers

This is the most widespread class of dampers used in beam-to-column connections for steel structures due to their relatively low fabrication cost, low maintenance, simple and easy replacement of degraded elements. Several advantages of this type of seismic damper are the large energy dissipation capacity, stable and predictable behaviour.

One example is the PI damper connection designed by Koetaka in 2004 (Koetaka *et al.*, 2005). It consists of attaching steel plates to the top and bottom flanges of the beam (Figs. 1 and 2). The top plates are designed to take over the bending moment and the shear force. The bottom plates are designed to dissipate the energy, the main criteria for design are ductility, fatigue resistance and the possibility of repairing the connection by replacing the damaged element. The rotational centre of the connection is at the top of the beam ensured by the two gusset plates.

The PI dissipative element is fabricated by casting which reduces production costs. The failure mechanism assumes the formation of three plastic hinges: one at the top/middle of the curved part and two at the ends of the curved part of the element. The location of the last two plastic hinges is conditioned by the fact that the top two gusset plates have a larger thickness and stiffness. The ultimate capable force of the PI element can be calculated :

$$P = \frac{w \cdot \sigma_y \cdot t_r^2}{2h_p} \quad (1)$$

where: w is the width of the PI damper; σ_y – yielding strength of the material; t – thickness of the curved segment of the dissipative element; h_p – vertical distance between the plastic hinges.

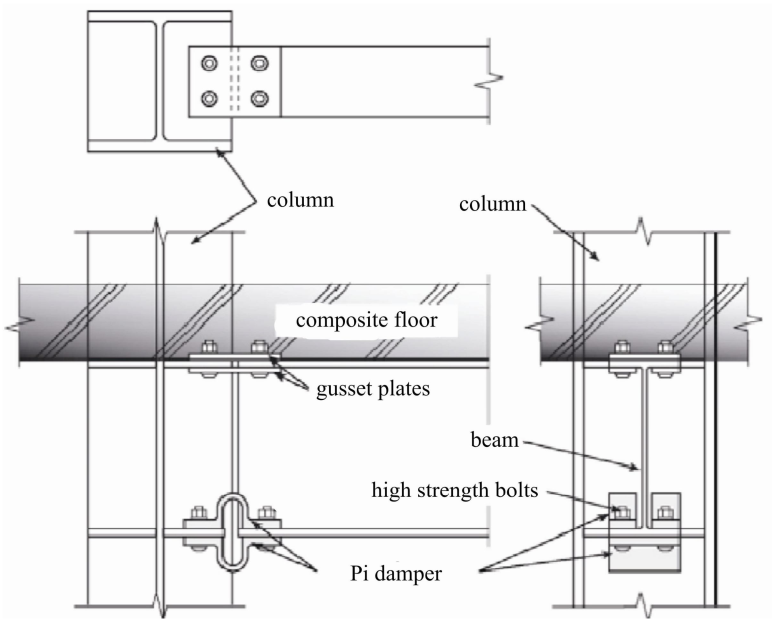

Fig. 1 – Connection with PI damper (Koetaka *et al.*, 2005).

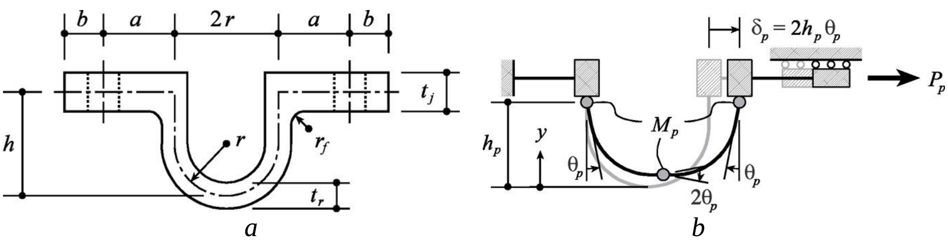

Fig. 2 – PI dissipative element: a. geometric characteristics, b. failure mechanism (Koetaka *et al.*, 2005).

In Fig. 3 the slit damper connection proposed by Sang Hoon Oh in 2008 is shown (Oh *et al.*, 2009). The connection consists of a cantilever as support for the beam by the means of a “slit damper” made of two rows of metallic plates which are designed to yield before the main elements of the connection. The dissipative element can be replaced after a major earthquake. The top flange of the beam is attached to the column by the means of a smaller “split-T” cantilever which creates the centre of rotation of the connection.

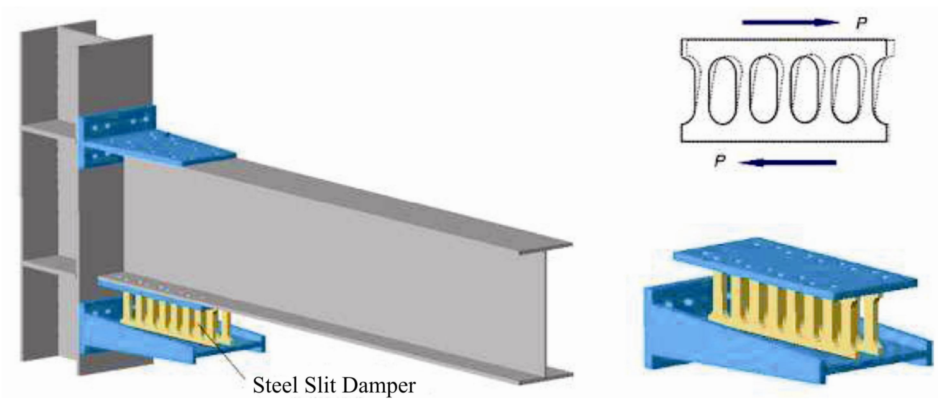

Fig. 3 – Steel slit damper connection (Oh *et al.*, 2009).

The lateral displacement allows two types of failure/yielding of the slit damper: shear and flexural failure. The failure type depends on the geometric characteristics of the dissipative element. Chan and Albermani defined the formula for the failure force, *P*, of the dissipative element for: shear – equation 2 and flexure – equation 3:

$$P = \frac{n \cdot \sigma_y \cdot t \cdot B}{3\sqrt{3}} \tag{2}$$

$$P = \frac{n \cdot \sigma_y \cdot t \cdot B^2}{2 \cdot H'} \tag{3}$$

where: n is the number of vertical plates of the damper; σ_y – yielding strength of the material; t – thickness of the dissipative plate; B – width of the dissipative plate; H' – equivalent depth of the dissipative plate.

In 2012 Saffari proposed an improved version of the slit damper (Fig. 4) namely by replacing the superior “split-T” element with a slit damper. At the same time the shape of the dissipative element was improved. However, the dissipative elements are welded on the beam flange and column which makes them almost impossible to be replaced.

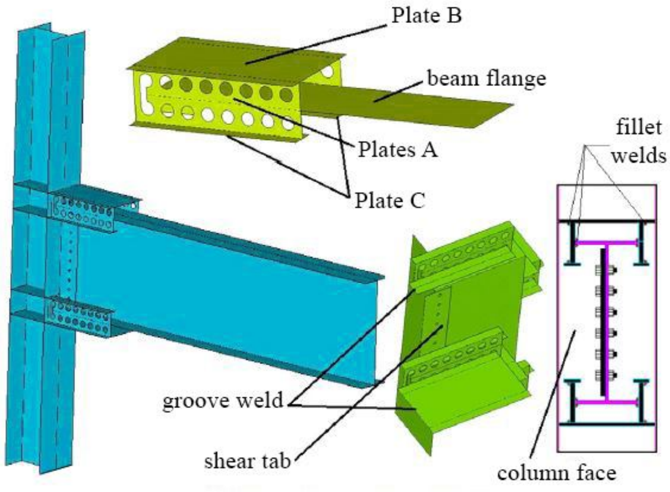

Fig. 4 – Steel slit damper proposed by Saffari (Saffari *et al.*, 2013).

The double split tee (DST) connection, shown in Fig. 5, was proposed in FEMA 350 (FEMA 350, 2005) as a consequence of modifying the AISC seismic provisions (AISC, 2010) and due to the requirement of increasing the ductility of the connections. The rotational centre of these connections is in the middle of the beam.

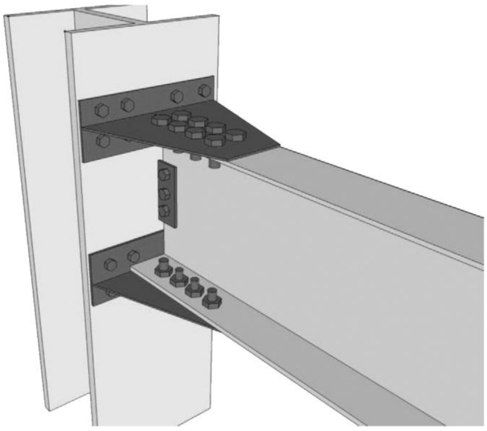

Fig. 5 – DST connection (Herrera *et al.*, 2013).

The DST element is made of an end plate and a cantilever welded in controlled conditions and placed at the top and bottom of the beam where the connection is made with bolts. The shear force is taken over by a gusset plate attached with bolts to the beam web. The energy is dissipated through plastic hinges in the end plate and through friction between the cantilever and the beam flange, however the friction dissipation is a secondary effect. Many studies (Herrera *et al.*, 2013; Bravo *et al.*, 2014) proved that in most cases the connection fails prematurely due to the fracture of the bolts at the column flange. Also, the major degradations found at the weld location make this type of connection susceptible to failure in case of weld defects.

In 2014 Latour and Rizzano (Latour & Rizzano, 2015) proposed an improved version of the DST connections (Fig. 6). The authors proposed the implementation of the ADAS (Added Damping and Stiffness) concept in order to direct the stresses away from the weld and to reduce the bolt failure probability. In order to achieve these facts the end plate was shaped as a double hourglass which follows the distribution of normal stresses under bending.

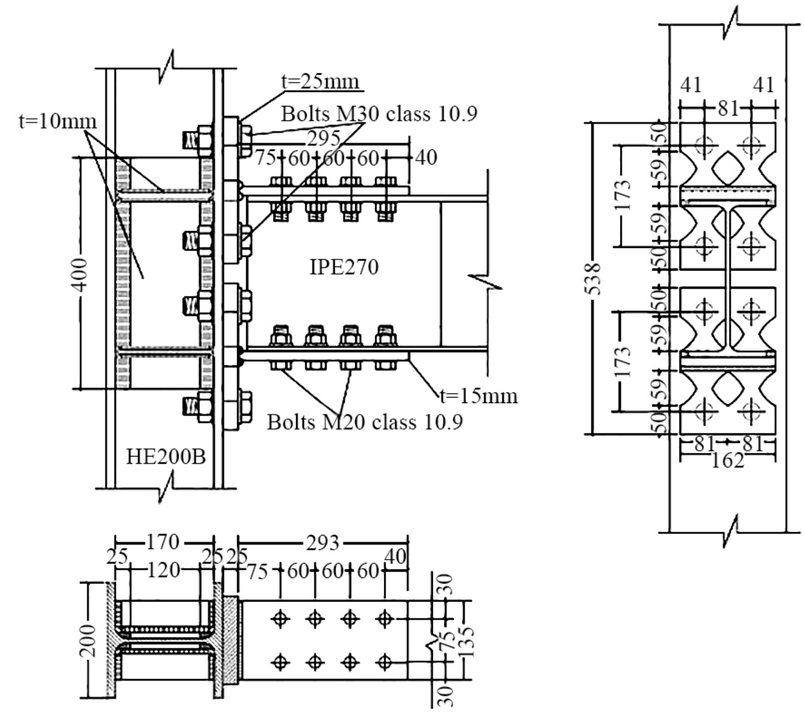

Fig. 6 – DST connection with hourglass shaped end plate (Latour & Rizzano, 2015).

Another optimization method was proposed by Lewei Tong (Tong, L. *et al.*, 2016) in 2015 who was inspired by the slit damper connection. He proposed two versions for the DST elements (Fig. 7) the main difference is that the dissipative element is cast thus excluding the welding of the two elements. Another difference is that the bottom DST element is distanced from the face of the column. In order to ensure the adequate behaviour the splice on the web of the beam is provided with oval holes.

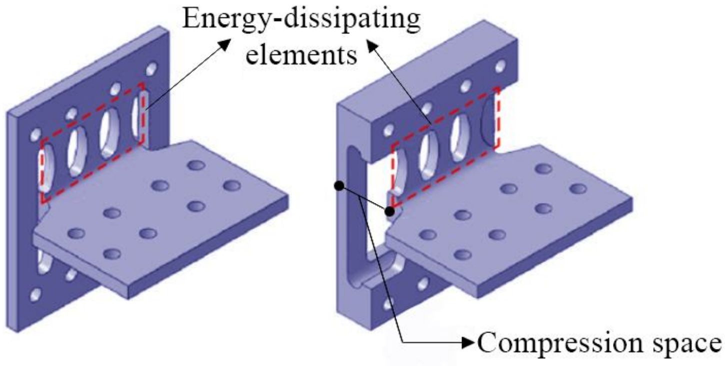

Fig. 7 – Cast DST elements (Tong, L. *et al.*, 2016).

Another connection is the dissipative bolted fuse connection proposed by Luis Calado in 2011 (Fig. 8) (Calado *et al.*, 2013; Valente *et al.*, 2017). This connection assumes keeping the welded connection between the beam and column, but the plastic hinge is shifted in the beam end by introducing a weakened section.

Weakening the section is done by interrupting the continuity of the beam and connecting it with splices. The reinforced concrete slab is also provided with a gap in order to avoid the concrete degradation and in order to allow larger splice rotations. It is important for the longitudinal bars of slab reinforcement to be continuous in order to transmit the internal forces in the slab. The reinforcement bars cannot be replaced and in order to avoid their yielding the neutral axis is required to appear within the slab between the top and bottom reinforcement. In this case the maximum stresses will be applied on the bottom splice of the beam which allows their yielding and the efficient dissipation energy. Researchers also studied the possibility of welding the splices (Valente *et al.*, 2017).

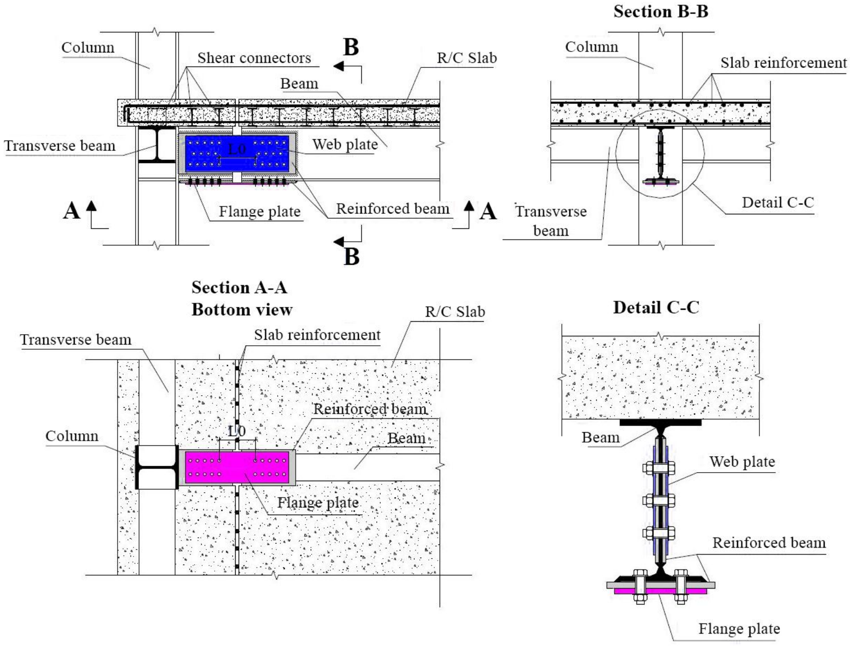

Fig. 8 – Dissipative bolted fuse connection (Calado *et al.*, 2013).

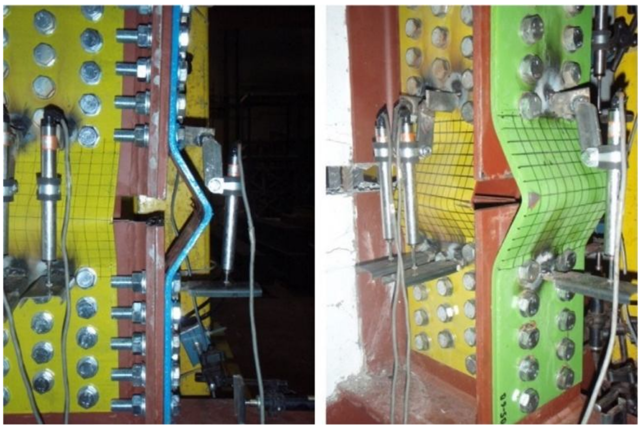

Fig. 9 – Damaged dissipative bolted fuse connection (Calado *et al.*, 2013).

In comparison to all connections presented so far, the memory alloy bolt connections do not have a specific configuration and do not follow the energy dissipation by yielding elements which can be replaced. This type of connection assumes using bolts or NiTi alloy tendons (Shape Memory Alloys – SMA) a high end material. This material presents shape memory properties and super elastic properties. The super elastic properties are manifested by recovering the initial shape after unloading even after very large deformations of the element. The shape memory properties are manifested when after unloading the remnant deformations can be eliminated by heating the material. In the last decade a series of studies were carried out on this material. Several solutions for bolted connections with this material were proposed by Yam (Figs. 10 and 11) (Yam *et al.*, 2015) and Wang in Fig. 12 (Wang *et al.*, 2015). The energy dissipation in these connections takes place during the bolts yielding.

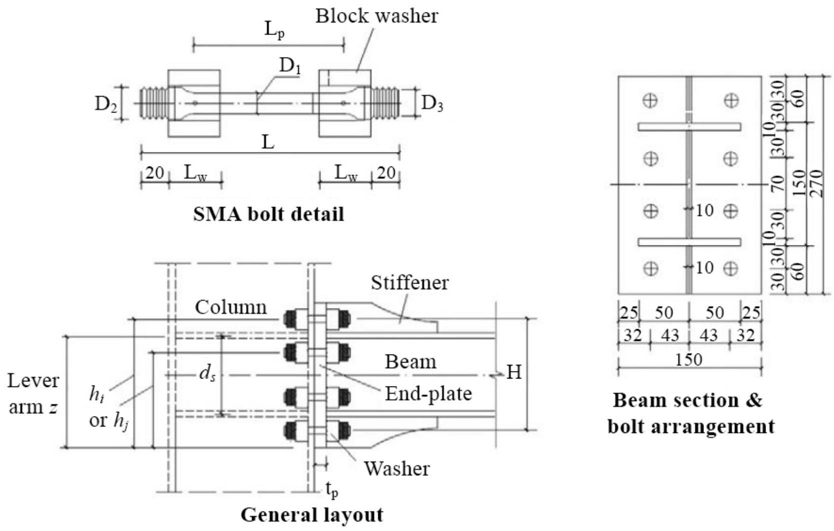

Fig. 10 – SMA bolt connection (Yam *et al.*, 2015).

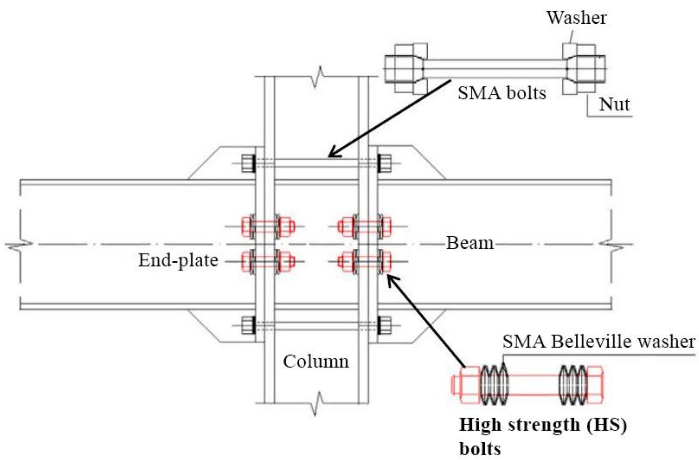

Fig. 11 – SMA tendon connection (Yam *et al.*, 2015).

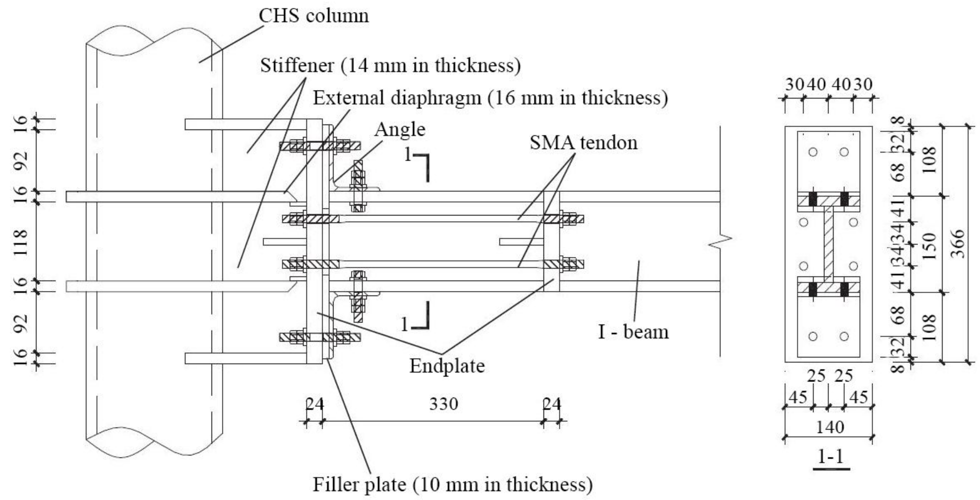

Fig. 12 – SMA tendon connection for circular columns (Wang *et al.*, 2015).

3. Connections with Visco-Elastic Dampers

A relevant example is the connection proposed by Banisheikholeslami (Banisheikholeslami *et al.*, 2016). The connection is a combination of visco-elastic and metallic yielding dampers. This combination was made to increase the efficiency of the connection. The damper is made of a metallic cantilever, a rubber visco-elastic layer, a special support for the beam and bolts. The connection is presented in Fig. 13 (Banisheikholeslami *et al.*, 2016).

The metallic cantilever ensures the transmission of the shear force from the beam to the column and is the support for the visco-elastic layer. The visco-elastic layer has the purpose of dissipating the energy and also restoring the ensemble to its initial position. Its thickness can vary in accordance to the energy dissipation requirement. The double T beam support besides supporting the beam is designed to ensure the beam rotation. For this purpose, the holes on the bottom of the support are rectangular, as seen in Fig. 13 *b*. In case of large displacements, when the dissipation capacity of the visco-elastic layer is exceeded, in order to avoid the failure of the connection, hysteretic damper bolts are provided. According to their length yielding can occur due to shear or bending. The special shape – reduced section in the middle of the shaft – ensures yielding and allows the replacement of the damaged elements.

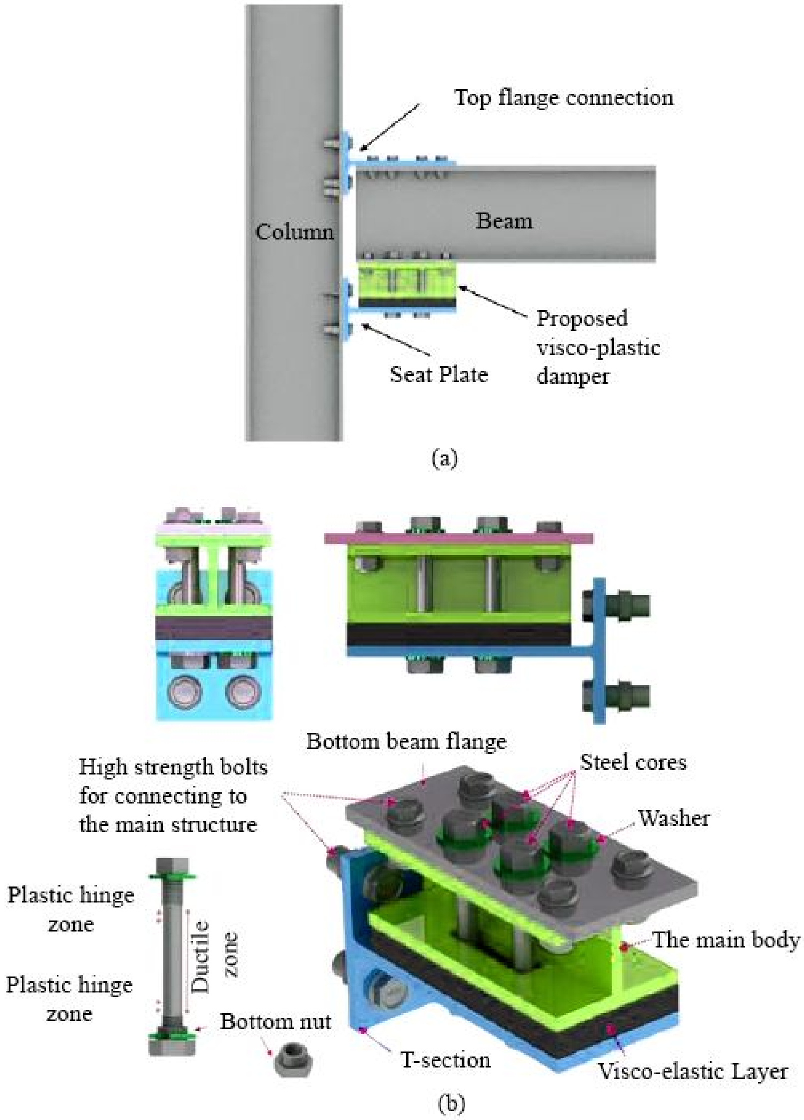

Fig. 13 – Visco-elastic and hysteretic dampers connection: *a* – overall view; *b* – detail (Banisheikholeslami *et al.*, 2016).

4. Connections with Friction Dampers

The same as the visco-elastic damper connection the friction damper connection proposed by Latour (Latour *et al.*, 2015) is an optimized version of the DST connection (Fig. 14). The main difference is friction layer introduced between the beam flanges and the DST elements and the bolt holes are one single slit in order to allow the translation of the beam and the friction energy dissipation.

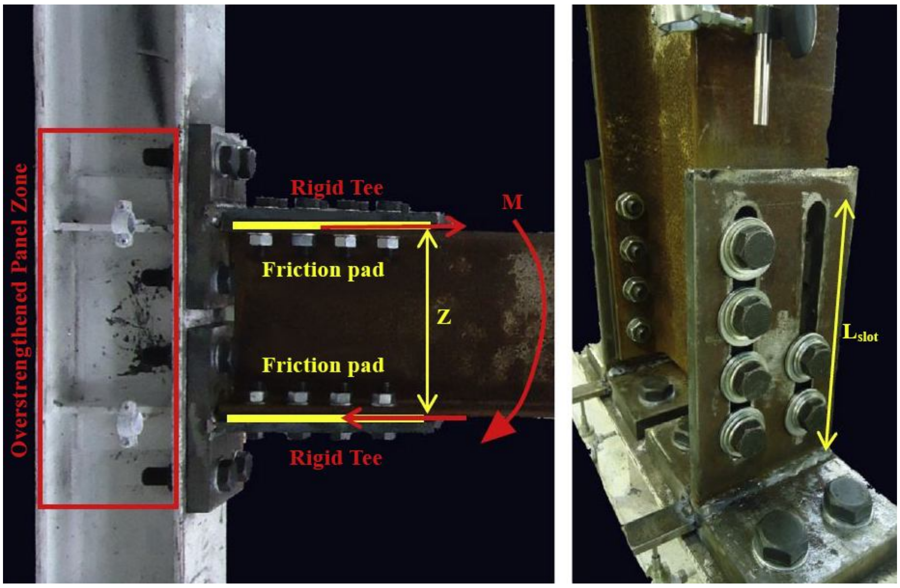

Fig. 14 – Friction damper connection (Latour *et al.*, 2015).

5. Conclusions

Seismic design codes impose energy dissipation through plastic deformations, without major degradations of the structure which lead to the maximum use of the bearing capacity of columns and beams. It is evident that the repair of primary structural elements is very difficult and costly.

In recent years, many researchers proposed different beam-to-column connections which allow the function of the building to remain active after major earthquakes by dissipating the seismic energy through additional elements and devices which can be easily and cheaply replaced.

Steel beam-to-column connections with dampers are passive degradation control devices for buildings subjected to seismic actions. These devices are usually dependent of displacements.

The most spread dissipative connection type is the metallic yielding damper connection. The behaviour of these dampers is constant and the energy dissipation capacity can be designed easily, but these devices need replacement if they suffer major degradations. The SMA tendon connections do not require replacement due to the shape memory properties of the material. However, the super elastic properties of this material can lead to excessive storey drifts which leads to expensive costs for implementation.

Visco-elastic damper connections and friction damper connections are not as spread as the previous examples due to the complex evaluation of the energy dissipation capacity. Although, there is no requirement for replacing the dissipative elements these connections have some disadvantages, such as: friction damper connections require interventions for restoring the initial position of the connection and after a number of cycles the friction material needs replacement; visco-elastic connections have a self-centring characteristic but the visco-elastic material ages and needs replacement at certain intervals of time because the material properties are lost even if there is no seismic action.

Each of these types of beam-to-column connections with hysteretic dampers, disregarding their disadvantages and larger cost than classic connections, posses a long-term advantage of keeping the primary structural elements undamaged. Therefore, the entire structure can be used safely after a major earthquake, without the need of major repair works.

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ÎMBINĂRI GRINDĂ-STÂLP CU DISIPATORI HISTERETICI

(Rezumat)

Structurile metalice sunt foarte răspândite în zonele cu activitate seismică ridicată, datorita performanței sporie, însă în unele situații capacitatea de disipare a energiei, nu este suficientă şi îmbinarea poate ceda, sau suferi degradări majore. Repararea şi repunerea în funcțiune a acestor îmbinări poate fi destul de costisitoare, dificilă, sau există cazuri când datorită funcționalului clădirii, degradările nu sunt permise. Pentru a spori capacitatea de disipare, implicit ductilitatea şi rigiditatea îmbinărilor acestea sunt dotate cu o serie de disipatori histeretici, care pot fi reparați sau înlocuiți fără a implica costuri exagerate, cu dificultate redusă şi în intervale scurte de timp.