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Standardised friction damper bolt assemblies time-related relaxation and installed tension variability

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ABSTRACT

The sliding hinge joint is a type of low-damage seismic resistant connection equipped with a bolted friction damper at the bottom beam flange. To accurately control its flexural resistance, it is critical to govern the bolts' preload which depends on complex issues related to the installation procedure, and the short- and long-term phenomena. Despite the influence of these factors on the initial and life-time behaviour of bolts, currently, little information exists. Nevertheless, a statistical characterisation of the variability of the preloading force (initial and during the life-time) would be needed, in order to develop reliable design guidelines for these connections.

Within this framework, this paper examines experimentally, the variability of the preloading force of European bolt assemblies applied in friction dampers, through continuously monitoring the preloading at installation over a period of time. This was done to analyse the accuracy of the standardised installation procedures and the rate of loss of the initial tension over time. The tests have evidenced a higher accuracy of the torque method, highlighting some criticisms of the combined method which, conversely, proved to be inaccurate as currently codified. The short- and mid-term tests have shown that the estimated loss after 50 years, in case of assemblies with normal washers or with European standardised disc springs is, on average, equal to 10% and 27%, respectively. Additionally, in all the cases, the greatest part of the total loss (≅70%) occurred in just 30 days, highlighting that time-dependent phenomena are mainly concentrated in the first days after tightening.

1. Introduction

Eurocodes provide to design structures to guarantee minimum performance levels under a set of design load combinations [1,2]. Typically, design procedures are based on checks for Serviceability Limit States (SLS) (related to the most frequent load combinations occurring during the life-time of the structure) and Ultimate Limit States (ULS) where, the structure, in case of the occurrence of rare load combinations (such as those related to seismic events with high return period), can be designed to dissipate energy in selected zones.

In case of steel Moment Resisting Frames (MRFs), according to the design procedures suggested by EC8 [3], the energy dissipation can be concentrated both in beams ends or in joints. In the former case, the design is aimed at promoting the formation of plastic zones in beams through the adoption of full-strength joints and over-strength columns while [4–7], conversely, in the latter case, the joints are designed to transfer to the columns only a part of the bending moment through the adoption of partial-strength joints [3,8,9]. Independently from the adoption of one or another design strategy, the main drawback of the traditional approaches is the need for the development of structural damage which, even though on one hand is used to preserve structural economy and human life, on the other hand represents also the main source of direct and indirect losses occurring in case of rare seismic events. Over the past decades, several strategies have been proposed in order to solve this issue. Among these, supplemental energy dissipation systems have been suggested, attempting to reduce structural damage, and proposing to concentrate energy dissipation in replaceable devices [10]. Nevertheless, even though supplementary energy dissipation design strategies can concentrate the greatest part of damage in specific fuses, the structural damage cannot be completely avoided because, to activate the seismic devices, adequate sway displacements, typically leading to the plastic engagement of the structure, are still needed.

In order to overcome these issues, recently, alternative low-damage strategies, based on the inclusion of friction dampers in the connections of MRFs, have been proposed. One of the first connections applying these principles was initially developed by Grigorian et al. in 1993 [11], providing pioneering studies on slotted bolted connections with friction interfaces made of mill scale steel or mill scale steel and brass. Following these initial works, many other studies have been carried out, especially in New Zealand, developing a further generation of

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friction connections, the so-called Sliding Hinge Joints (SHJ) which also help to keep any additional costs of the innovative solution to a minimum. These are characterised by extremely simple details based on the inclusion of Asymmetric Friction Connections (AFC) at the beam bottom flange, with shims made of mild steel, aluminium, brass or – in the most recent versions – abrasion-resistant steel (e.g. [12–18]). Similar solutions have also been recently patented in Japan [19], extending a previous concept of a friction-bolted slotted anti-seismic damper [20]. More recently, also in the European framework, similar solutions have been proposed suggesting new layouts, in which the friction damper is realised with steel angles and an additional haunch, welded or bolted to the beam bottom flange [21,22]. This layout, although probably not as simple as the SHJ, provides the possibility to realise the whole damper as a separate element in the shop (the haunch is represented in Fig. 1, which can be produced and bolted on site to the beam), allowing, in this way, a better control on the materials' quality (e.g. higher control of the surface conditions, continuous factory controls on the production, control on the employed bolts' quality), and on the application of rigorous bolts installation procedures complying with the relevant European standards. The typical beam-to-column joint, recently proposed in Europe for application in semi-continuous steel Moment Resisting Frames (MRFs), represents an alternative to the classical bolted connections, consisting in a modification of the detail of a Double Split Tee joint (DST) where, in place of the bottom Tee, a bolted friction connection is realised with a slotted haunch slipping on friction shims pre-stressed with high strength bolts (Fig. 1). All these elements, practically, realise at the bottom beam flange a Symmetrical Friction Connection (SFC). Adopting such a type of detail, under seismic actions, the beam is forced to rotate around the pin located at the base of the upper T-stub web and the energy dissipation is provided by the alternate slippage of the lower beam flange on friction shims (Fig. 1). This detail is beneficial in isolating floor slab contribution and preventing frame elongation.

This connection, similarly to the SHJ, is intended to behave as rigid under SLS, and to allow beam-to-column inelastic rotation at the ULS. Additionally, through the application of proper hierarchy criteria, both at the global and local level, it can be easily designed to be the only source of energy dissipation of the whole structure. The typical design of these connections should follow these conceptual steps:

1) ***Design of the friction damper*** for the actions deriving from the ULS load combinations. The dampers, in order to avoid the plastic engagement of the beam, should be designed in order to develop a flexural resistance of the connection corresponding at most to the plastic resistance of the beam;
2) ***Design of the non-dissipative parts of the connection***, accounting for the maximum over-strength due to random variability of the friction material. It is worth noting that the component of the over-strength related to the material strain-hardening is negligible, because the friction damper is characterised by a rigid-plastic response. Additionally, in terms of stiffness, being the slip resistance of the friction damper uncoupled from the stiffness of the connection, the joints elements can be designed to achieve a full rigidity, with a clear advantage with respect to the classical semi-continuous design for the serviceability limit state checks [3,8];
3) ***Design of columns*** by means of the adoption of the classical standardised procedures (e.g. EC8) or even by means of more advanced design procedures, such as the Theory of Plastic Mechanism Control (TPMC) [23]. Accurate procedures, such as the TPMC, are able to assure the development of a failure mechanism of global type and the reduction of structural damage occurring in steel members, to zero.

Within this framework, it is clear that the capacity design of all the structural parts depends on the definition of the sliding resistance of the damper. In order to govern the bending strength of the joint and to control the resistance hierarchy of the whole structure, it is critical to characterise two main parameters: the friction coefficient of the interface, and the bolts forces at installation and during the life-time of the connection. Clearly, the friction coefficients – static (to be used in serviceability limit state design) or dynamic (to be used in ultimate limit state design) – of the friction devices depend on the materials employed to realise the dissipative interface and, specifically, they depend on the tribological properties of the shims (micro and macro hardness, shear resistance, roughness, superficial finishing, etc.) used in the damper. This topic has already been subject of studies by several research groups worldwide [24–27] and it is currently in phase of study by the authors, who are providing a statistical characterisation of the friction coefficient values for several possible materials, defining upper and lower bound regression models able to provide the friction coefficient as a variable dependent on the cumulative travel [28,29]. These models can be used to define to design values of the friction coefficient under different load combinations (Serviceability (SLS) and Ultimate Limit State (ULS) design). A possibility for the friction sliding design could be to adopt the lower bound value of the dynamic CoF (Coefficient of Friction) to design the damper at ULS, the upper bound value of the static CoF to design the non-dissipative parts of the structure and the lower bound of the static CoF to design the joint under SLS load conditions. Alternatively, the nominal capacity of the damper could be designed adopting the average CoF using lower bound and upper bound values of the static CoF to determine strength reduction and overstrength factors.

Conversely, the bolt preloading force, after installation and during the life-time of the connection, aside from the procedure applied to tighten, depends on many complex phenomena involving: i) embedment relaxation, ii) bolt creep, iii) vibrations, iv) elastic

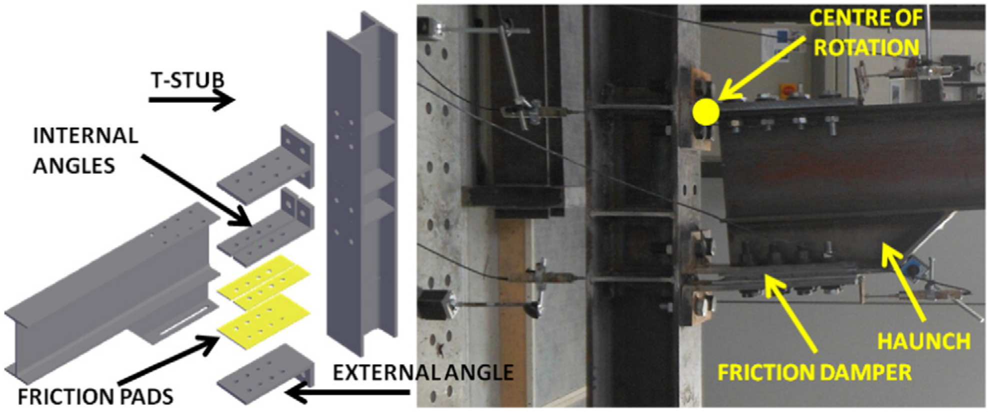

Fig. 1. – Typical layout of the connection studied in [21,22].