SUMMARY OF THESIS

Design and assessment of MRFs and Dual-CBFs equipped with “FREEDAM” connections

Candidate: Maglio Maria

Supervisors: Prof. Vincenzo Piluso, Prof.ssa Elide Nastri, Prof. Rosario Montuori

1. PROJECT OBJECTIVES AND GOALS

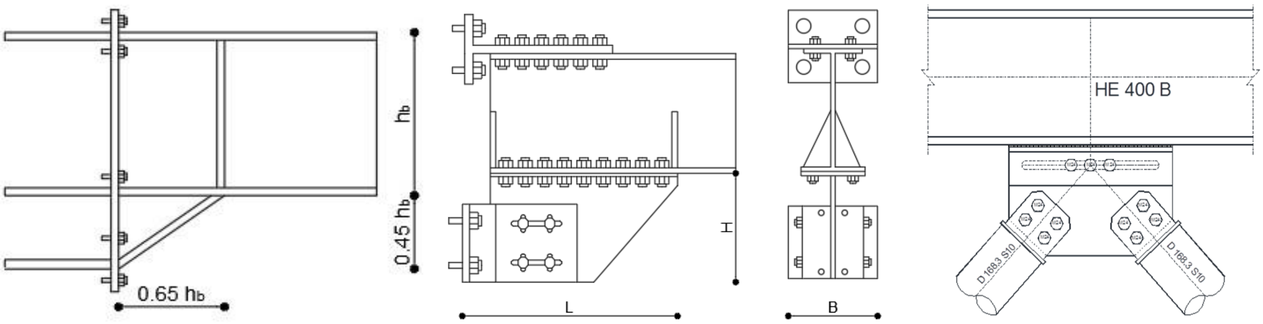
The thesis work was carried out within the European research project FREEDAM Plus, in particular, it concerns the Task 3 of WP3, that aims at the valorisation and knowledge for FREE from DAMage steel connections developed in the recently completed RFCS project FREEDAM (RFSR-CT-2015-00022). This project involves the design of connections able to withstand without any damage not only after frequent and occasional seismic events, but also destructive earthquakes such as those corresponding to rare and very rare events, it is named with the acronym FREEDAM to underline the "FREE From DAMage Connections" aim. The main novelty concerns beam to column connections equipped with friction devices manufactured in shop and bolted to the structural elements (beam and column) directly on site. Then the device is chosen from the catalogue according to the beams size. From the design point of view, the approach is based only on few steps design of FREEDAM friction dampers for the actions deriving from the ULS and SLS load combinations, to assure the transmission of the beam bending moment required to fulfil serviceability limit state requirements and to withstand without slippage the gravity loads; design of the non-dissipative parts of the connections, accounting for the maximum overstrength due to random material variability of the friction material and to the random variability of the bolts preload force.

In addition to the evaluation of the seismic performance of innovative joints, one of the main goals was to study the steel structures behavior in the medium ductility class (DC2) which is proposed in the draft of the future Eurocode 8 (currently not yet in force) [1] applying a seismic design methodology already known but suitably adapted to meet the requirements of the structures in seismic areas of medium intensity. In fact, steel represents the future both in the seismic and environmental fields and the objective is to encourage the use of steel in construction, demonstrating the reliability of this material and the ability to adapt to the performance required by new seismic codes [1-2].

The select structural typologies investigates are Moment Resisting Frames (MRFs) and Dual Concentrically Braced Frames (D-CBFs) with chevron braces. First typologies mentioned are the most common seismic-resistant structures, they are characterized by high dissipation capacity, because of the large number of dissipative zones under cyclic bending represented by the beam end sections; but they could be not able to provide sufficient lateral stiffness, as required to fulfil serviceability limit states [3-4]. D-CBFs constitute a rational solution leading to a design able to satisfy both the requirement for the ultimate limit state and the serviceability limit state. In fact, the exploitation of the dissipative capacity of the beam ends, of the lateral stiffness provided by the diagonals of the braced part and of the dissipation capacity of link elements allow to obtain high global ductility and limited interstorey drifts [5-6]. In this structural typology the moment resisting frames should contribute with at least 25% to the total resistance [2].

Low-rise (4-storey) and medium-rise structures (8-storey), in two directions of application of the seismic force (X and Y) and in two ductility classes, are designed.

First, 16 structures with traditional haunched connections (Fig. 1a) [7] are designed, consequently the same structures are designed considering FREEDAM connections (Fig. 1b), for a total number of 32 examined structures. FREEDAM devices are located at the beam-to-column connections for MRFs and dual systems, while an additional device located at the brace intersection is also introduced in the case of dual frames (Fig. 1c). It is important observing that, while for traditional dual systems, diagonal braces are involved in the dissipative behaviour both in tension and compression, in case of FREEDAM structures, diagonals are designed to remain in elastic range. Beams and diagonals are also checked against local hierarchy criterion. The design of the structures with traditional connections helped clarifying the role of FREEDAM connections on the design and performance of seismic resistant structures.



a) b) c)

Fig. 1. Beam-to-column Haunched connection (a), beam-to-column FREEDAM connection (b), FREEDAM device at the diagonals intersection (c)

2. DESCRIPTION OF METHOD AND RESULTS

To design earthquake resistant steel structures in the new Eurocode 8 draft [1] three ductility classes are proposed: DC1 in which the overstrength capacity is considered, while the deformation capacity and energy dissipation capacity are disregarded; DC2 in which the local overstrength capacity, the local deformation capacity and the local energy dissipation capacity are considered with the purpose of avoiding the soft storey mechanism only; DC3 in which the ability of the structure to form a global plastic mechanism at SD limit state and its local overstrength capacity, local deformation capacity and local energy dissipation capacity are considered.

The structures were designed by adopting the Theory of Plastic Mechanism Control' (TPMC), an advanced seismic design strategy initially proposed by Mazzolani and Piluso [8] and subsequently update by Piluso et al. [9], is based on the kinematic theorem of plastic collapse extended to the concept of equilibrium curve of mechanism. The kinematic theorem of plastic collapse asserts that the collapse multiplier is the minimum between all kinematically admissible multipliers. Starting from the assumption of a rigid-plastic behaviour, the attention is focused on the structure collapse state. Moreover, according to the TPMC design procedure second order effects are directly accounted for by the concept of the equilibrium curve of the mechanism. The unknowns of the design are the sections of the columns, on each floor, assuring the desired collapse mechanism while beam sections and/or other dissipative zones are assumed as known quantities and designed to withstand the worst condition between the fundamental load combination (ULS) and the seismic combination (SD). The aim was to develop Design Guidelines regarding the TPMC that has been specialized to be used for the two ductility classes that allow energy dissipation, namely DC2 and DC3.

For DC3 ductility class the complete theory (3-TPMC) is adopted because we are considering very dissipative structures wishing to provide a collapse mechanism of global type (Fig. 2a) To fulfil the philosophy adopted by the new draft of EC8 [1], a simplified theory (2-TPMC) is adopted for DC2 ductility class where the condition to avoid only the soft-storey mechanism is set up (Fig. 2b).

In particular, the development of the TPMC for DC2 ductility class is a complete novelty of the thesis work as this kind of design approach providing shallower sections if compared to the traditional TPMC approach (herein called TPMC for DC3), could be helpful for the implementation in the code perspective and for the promotion of the use of the steel for seismic designed structures. In fact, the TPMC approach for DC2 avoid the soft storey mechanism which is the main goal of the seismic design in moderate seismic zones.

It is important observing that in DC1 ductility class, the TPMC is not adopted because the structures must be designed to remain in the elastic range, so it makes no sense to apply a plastic control design method.

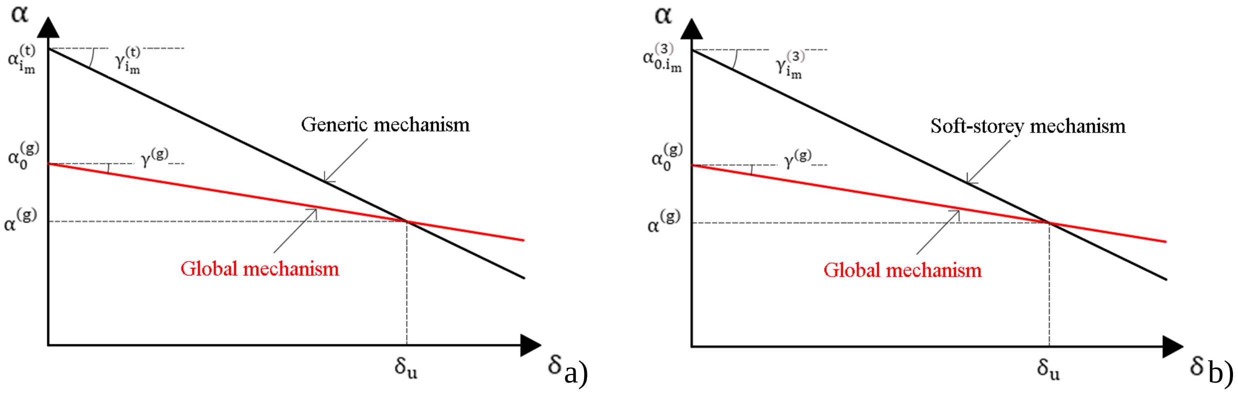


Fig. 2. TPMC statement for 3-TPMC (a) and 2-TPMC (b)

TPMC was properly applied both to structures with traditional connections and structures equipped whit FREEDAM connections. The accuracy of the proposed guidelines has been carried out, by means of push-over analyses (by means of SAP 2000 computer program [10]) to check the development of the collapse mechanism. Pushover analyses produce capacity curves, which expresses the relationship between the shear force and the displacements. The seismic performance has been assessed in terms of system overstrength and global ductility. In addition, non-linear dynamic analyses [11] have been carried out using Sap2000 computer program again [10]. The scope of this analyses is the comparison between the seismic performance of the structures with haunched connections and the same structures equipped with FREEDAM connections.

The design results have been reported and compared in terms of sections, structural weight, dynamic characteristics and seismic performance. It can be concluded that FREEDAM structures are cheaper than traditional ones and have a higher global ductility.

About the System overstrength, it can be observed that in traditional structures is greater than the FREEDAM ones; however, it is higher than that suggested by the Eurocode [1]. From a comparison given in terms of Maximum Interstorey Drift, it is possible to observe that the structure equipped with FREEDAM connections at beam-to-column joint show, on average, better performances if compared with full strength joint ones. It is due to the high dissipative capacity of FREEDAM connections which do not present relevant degradation under cyclic loading. In addition, it is important observing that the performances of the structures equipped with FREEDAM connections can be higher if the involvement of bolt in shear is considered after the achievement of the ultimate stoke of dampers; however, the maximum stroke is never achieved even at Near Collapse limit state.

In the DC2 ductility class the design requirement is always satisfied, in fact the soft storey mechanism has never developed. So, the reliability of the proposed guidelines was verified.

3. POTENTIAL FOR APPLICATION OF RESULTS

Application of haunched connections (Fig. 2a) assures that plastic hinges form in the beams which increases the global seismic performance of steel moment resisting frames, but a greater beam plastic rotation is needed to achieve an equivalent seismic energy dissipation. FREEDAM connections (Fig. 2b), have a wide-ranging use because they can be used both in the construction of new buildings and for the seismic rehabilitation of existing buildings. Structures equipped with FREEDAM connections have better seismic performance than structures equipped with traditional ones, they own additional resources of ductility given by bolt in shear. In addition, they assure that non-dissipative zones, such as beams and columns, are prevented from damage.

The TPMC has proved to be an excellent design tool for both traditional and FREEDAM structures and in both the ductility classes assuring that columns sections are not involved in plastic range.

In the light of the results obtained, it is possible to observe that the steel buildings, equipped with FREEDAM connections and designed using the TPMC, represent an excellent solution for building both in areas subjected to strong and medium seismic events, in addition they are very advantageous economically.

In particular, the TPMC for DC2 design approach, presented for the first time in this thesis work could have an immediate implementation in the codes for its simplicity of application, the reliable result, i.e. avoiding the formation of soft storey collapse mechanism, and the promotion of the steel market for the seismic resistant structures in moderate seismic risk zones.

Buildings have an important influence on the quality of our life and steel is a material that offers a wide range of solutions to meet these needs. The future challenge will be to use these results by developing an integrated project, in which not only the structural aspects but also those related to the building envelope will be investigated to create an anti-seismic building, capable of satisfying people's needs and limiting the environmental impact.

4. REFERENCES

[1] CEN, Eurocode 8, draft. "Design of structures for earthquake resistance - Part 1-1: General rules and seismic action", 2020a.

[2] CEN, Eurocode 8 draft:"Design of structures for earthquake resistance - Part 1-2: Rules for new buildings", 2020.

[3] F. Mazzolani and V. Piluso, "Theory and Design of Seismic Resistant Steel Frames", London: E & FN Spoon, an Imprint of Chapman & Hall, 1996.

[4] F. Mazzolani, "Moment Resistant Connections of Steel Frames in Seismic Areas, Design and Reliability", E&FN Spoon, 2000.

[5] A. Longo, R. Montuori and V. Piluso, "Plastic design of seismic resistant V-Braced frames," Journal of Earthquake Engineering, vol. 12, pp. 1246-66, 2008.

[6] V. Piluso, R. Montuori, E. Nastri and A. Paciello, "Seismic response of MRF-CBF dual systems equipped with low damage friction connections," Journal of Constructional Steel Research, no. 154, pp. 263-277, 2018.

[7] "EQUALJOINTS RFCS Project (RFSR-CT-2013-00021), final report," 2015.

[8] F. Mazzolani and V. Piluso, "Plastic Design of Seismic Resistant Steel Frames," Earthquake Engineering and Structural Dynamics, pp. Vol. 26, pp. 167-191, 1997.

[9] R. Montuori, E. Nastri and V. Piluso, "Advances in theory of plastic mechanism control: Closed form solution for MR-Frames," Earthquake Engineering and Structural Dynamics, vol. 44, no. 7, pp. 1035-1054, 2015.

[10] CSI 2007. SAP 2000, "Integrated Finite Element Analysis and Design of Structures. Analysis Reference.," Computer and Structure Inc. University of California, Bekerley.

[11] D. Vamvatsikos and C. Cornell, "Incremental dynamic analysis," Earthquake Engineering and Structural Dynamics, 2002.