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FULL SCALE EXPERIMENTAL ASSESSMENT OF CONCENTRICALLY BRACED STEEL FRAMES DESIGNED FOR MODERATE SEISMICITY

A. Kanyilmaz (1), C.A. Castiglioni (2), H. Degee (3)

(1) PhD Candidate, Politecnico di Milano, alper.kanyilmaz@polimi.it
(2) Full Professor, Politecnico di Milano, carlo.castiglioni@polimi.it
(3) Full Professor, Hasselt University, herve.degee@uhasselt.be

Abstract

Concentrically braced frames (CBF) represent a very effective structural form against horizontal loading, providing high lateral resistance at the same time limiting lateral displacements. Global cyclic behavior of these structures is determined by several phenomena acting together such as yielding of tension bracings, buckling and post-buckling of compression bracings, slip of bolts, and frame action provided by semi-rigid joints. A large amount of research has been conducted for CBF systems in order to maximize their performance in regions exhibiting a very significant seismicity level. Indeed, current code previsions are quite advanced for high-ductility design of CBF structures. However, although these systems are also very popular in low-to-moderate seismic regions, there is not a clear distinction for their detailing requirements between high-seismic and moderate-seismic design. Since the strict application of the high-seismic design principles in regions of low to moderate seismicity leads to solutions with a significant increase of the building costs, designers usually choose “non-dissipative” design, neglecting any detailing provisions that enhance the seismic performance. This approach may lead to unsafe solutions with significant life-safety and economic consequences.

This situation gives rise to the need of an optimized design (both in terms of safety and economy), with specific design rules more compatible with the buildings located in areas susceptible to low-to-moderate earthquakes. Ongoing research project MEAKADO (RFSR-CT-2013-00022) aims to develop specific design methodologies for steel and steel-concrete composite structures in regions characterized by a low to moderate seismic activity, with an appropriate reliability level. The present paper presents the preliminary results of the full scale testing program realized in this research project. Tests focus on the contribution of the compression diagonal, assessment of the parts of the horizontal loads that are effectively resisted by the bracing system and the part that is actually taken by the frame, and investigate the inherent ductility provided by “non-dissipative” bracing connections. Thanks to the observations obtained from these tests, possibilities to improve seismic performance of concentrically braced frames built in moderate seismic have been discussed.

Keywords: Concentrically braced frames, moderate seismicity, full scale tests, cyclic tests

1. Introduction

The general philosophy of seismic design requires providing the structure with global and fully developed plasticity during an earthquake event. In case of high seismicity, this can be achieved applying rigorously the capacity design rules, aiming to protect of critical structural components from failing (e.g. connections), and provide a homogeneous distribution of inelastic deformations throughout the structure. Earthquake design procedures recommended by most building codes [1][2] are appropriately advanced for the design in high seismic zones (magnitudes higher than 6.5), as well as engineers and other professionals with high seismicity experience. However, in these building codes, there is not a clear distinction between high and moderate seismic zones in terms of application of the seismic design rules. Yet, it is very well known that seismic demand of buildings located in areas of moderate seismicity (magnitudes between 4.5 and 6.5) are in many ways different than in areas of high seismicity [3].

Concentrically braced frame (CBF) structures are commonly adopted in moderate seismic zones, and represent a very effective structural form against horizontal loading. They provide high lateral resistance at the same time limiting lateral displacements, and seismic forces are mainly carried by axial loads produced in their members (Fig. 1). They are economic alternatives to the costly moment resisting frames thanks to their simple connection details and smaller beam and column cross sections as the bending moment demands in the frame is widely replaced by axial forces.

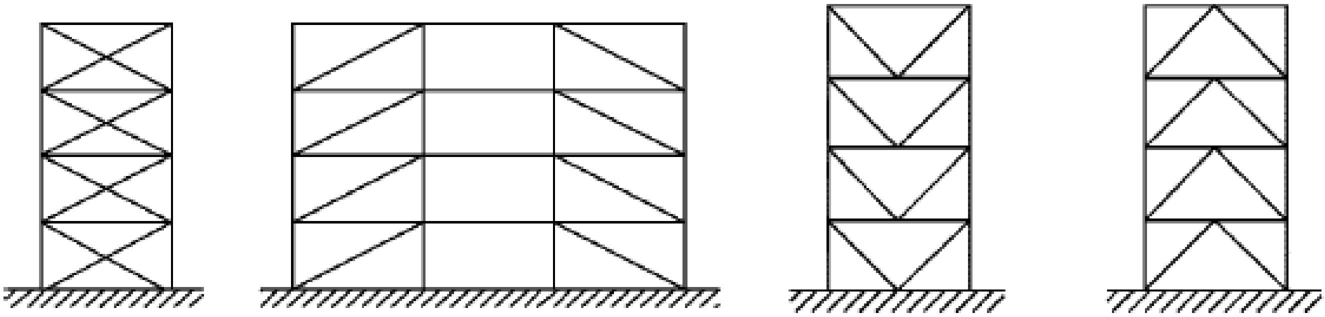


Fig. 1 Concentrically braced frame configurations classified by Eurocode 8.

Several seismic design practices are adopted around the world for CBF structures. In US, CBFs are classified in two categories as special concentrically braced frames (SCBF) for dissipative design, and ordinary concentrically braced frames (OCBF) for non-dissipative design [2]. Mainly, SCBFs are designed with high response modification factors and strict detailing requirements, and OCBFs are designed with small response modification factors and simpler detailing requirements. Eurocode approach is similar to these, classifying CBF structures in two categories, namely “Ductility class medium” and “Ductility Class High”. However, there is not a distinction for the detailing requirements between these two approaches; the only difference is the value of the behavior factor allowed. Therefore, in moderate seismic regions, designers usually choose low dissipative design, and neglect any further provisions aiming at enhancing the seismic performance. From a safety point of view, this approach can lead to poor solutions, which can endanger the life safety of the people and can have significant economic consequences.

Fig. 2 shows the total European steel production for construction sector for the countries belonging to ECCS organization [3]. As it can be seen, most of the steel is used in low and moderate seismic zones. This highlights the need for a design philosophy that will provide an optimal balance between effective risk, safety and economy for the steel structures located in low-moderate seismic regions.

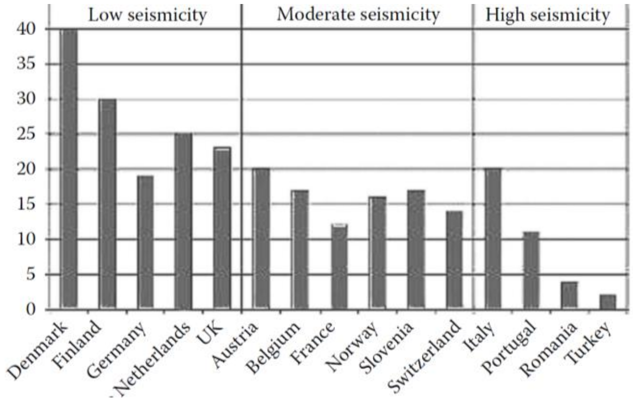


Fig. 2 European steel production for constructions (kton/million inhabitants) for ECCS countries

Extensive literature review published elsewhere [4] showed that very few experimental evidences have been developed to characterize various resistance, stiffness, and ductility resources of braced frames designed for moderate seismicity [5–9]. At the same time, several researchers pointed out how the capacity of this type of structures is under-estimated, and also numerically and analytically shown the potential benefits of the frame reserve action, compression diagonal contribution, and inherent ductility of non-dissipative connections. Some experiments have been performed, mostly at component level, yet there is not still enough evidence to quantify the above mentioned benefits and draw general conclusions.

Ongoing research project MEAKADO [10,11] investigates the possibilities to develop specific design methodologies for steel and steel-concrete composite structures in regions characterized by a low to moderate seismic activity, with an appropriate reliability level. It comprises a combination of experimental and numerical studies and should result in proposals formulated according to a pre-standard format in the perspective of further revisions of the design codes. This paper presents the preliminary results of full scale tests performed inside this research program, which characterize resistance, stiffness, and ductility resources of braced frames designed for moderate seismicity.

2. Experimental Program

Within MEAKADO research project, full scale tests have been conducted in order to quantify the abovementioned phenomena, and increase the limited experimental database. Tests mainly focused on:

i. Extra global stiffness and strength, and global reserve capacity provided by semi-rigid beam-column connections of CBF systems

ii. Contribution of the compression bracings to the initial global stiffness of X-braced systems, and their post-buckling resistance

iii. Ductility provided by non-dissipative bracing joints thanks to slip of bolts and ovalizations

The experimental program consists of 24 full scale cyclic tests performed on 1 level and 1 bay (2.6 m height and 4.3 m length) concentrically braced specimens with three different bracing profiles. The specimens represent a single storey frame extracted from of a multi-storey structure, with dimensions corresponding to realistic full sizes of a building frame, yet limited by the testing facilities (Fig. 3). All the test specimens have been designed according to EN1993 recommendations [12,13].

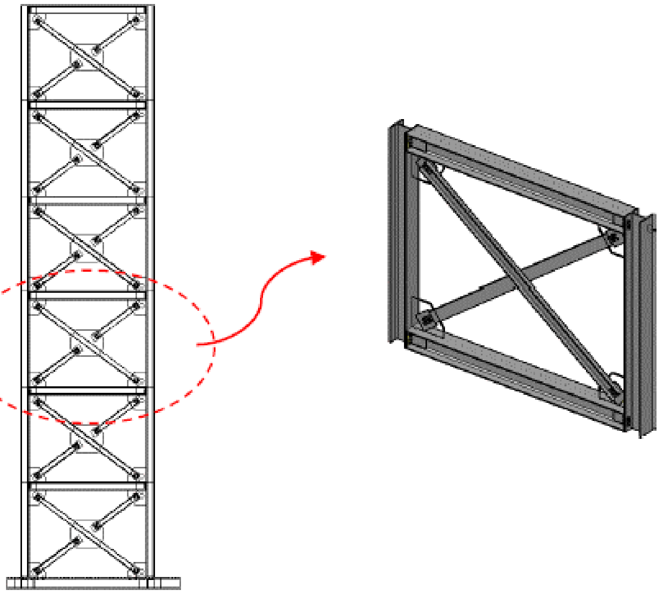


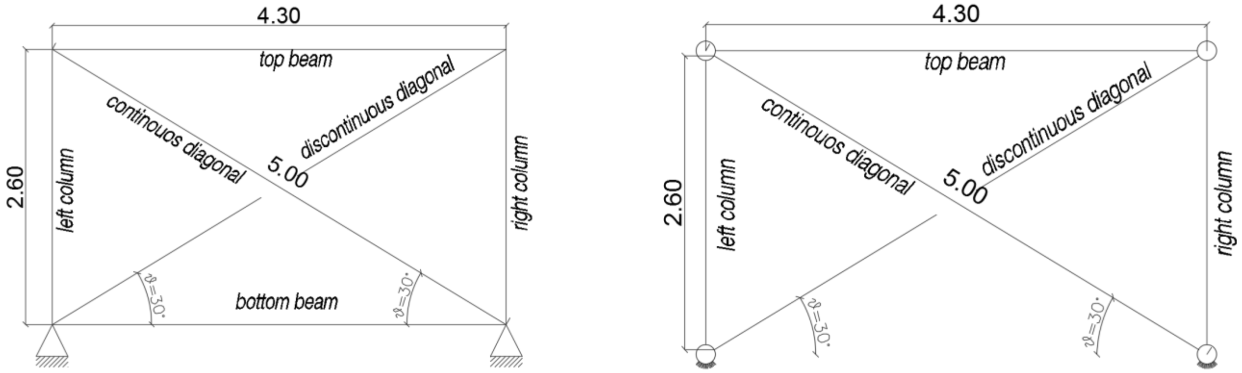
Fig. 3 Generic scheme of the frame

In order to characterize and quantify the frame action provided by braced frames, several bracing profiles have been tested. Bracings have been assembled inside two types of frames:

i. A moment resisting frame with semi-rigid beam-to-column connections (MRF) (Fig. 4.a)

ii. A frame with ideally pinned connections (PC) (Fig. 4.b)

In the first case (MRF), semi-rigid beam-column joints have been obtained by means of a gusset plate bolted both to the beams and columns. In the second case (PC), the beam-to-column connections of the frame have been realized by steel pins that introduce rotational degree of freedom in the loading plane.

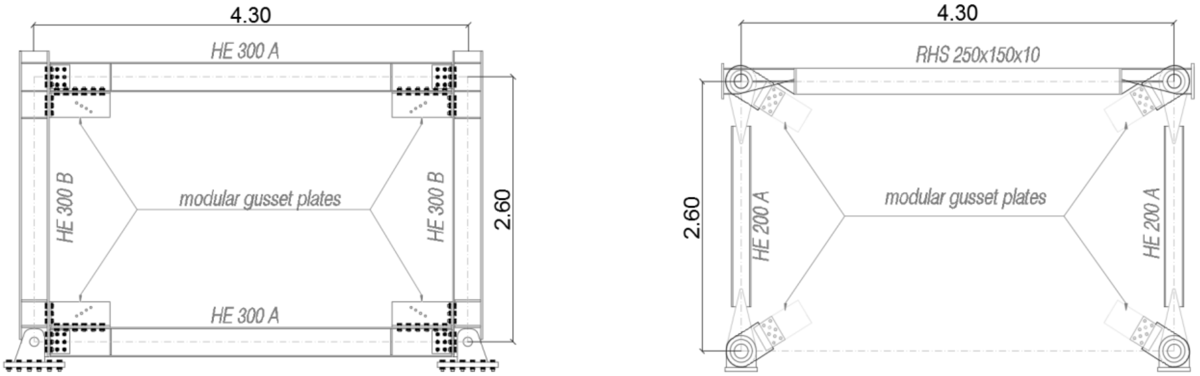


a. Frame with semi-rigid joints

b. Frame with ideally pinned joints

Fig. 4 Conceptual scheme of a) MRF and b) Frame with pinned connections (PC) (measures in meters)

Fig. 5 shows the construction drawings of the MRF and PC specimens. Beams and columns of these frames have been designed to remain elastic at maximum applicable load, and inelastic deformation is aimed only for the bracings and their connections. The overall MRF and PC frame dimensions are kept equal in reference to element inter-axes, so that comparison can be easily made between several tests. Gusset plates are designed in a way that they can be bolted to the beam and column members of the test frame to allow an easy installation and replacement. After each test, gusset plates and bracing elements have been renewed, keeping the beams and columns.



a. MRF test frame

b. PC test frame

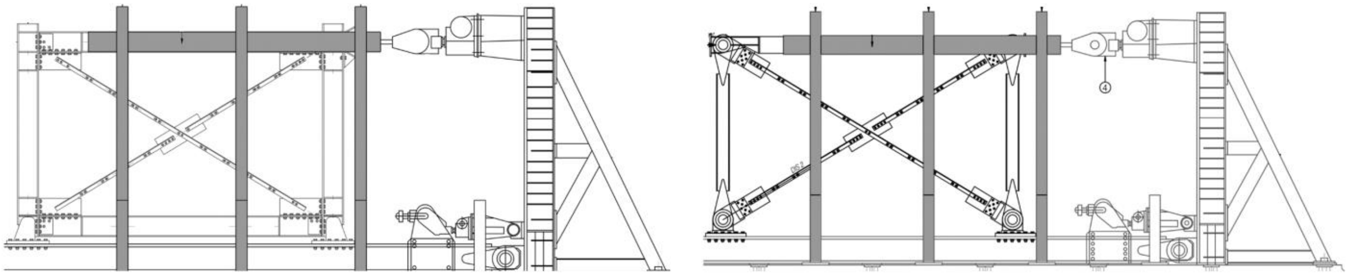
Fig. 5 Test frame drawings

Beam-to-column connections of MRF frame have been designed using double angle plates bolted both to the column flange and to the beam web. This connection type is not expected to have a significant flexural strength and stiffness, with a behavior close to ideal pin. Therefore, it has been verified against the limit states of shear failure, block shear and bearing strength at the bolt holes.

The bracings are made of double angles arranged back-to-back by means of steel interconnectors, which are typical bracing configurations frequently used in the building construction in moderate seismic regions. They are inclined by an angle θ=30° with respect to the horizontal axis, and have a theoretical length of 5.00 m. Bracing connections have been designed according to the EN1993 without taking into account any dissipative design concept of EN1998. The following profiles have been tested:

- 2L-profile 60x60x8 mm with 4M16 10.9 pre-stressed joints
- 2L-profile 70x70x7 mm with 4M20 10.9 pre-stressed joints
- 2L-profile 80x80x8 mm with 4M20 10.9 pre-stressed joints

Tests have been performed in “Laboratorio Prove Materiali” of Politecnico di Milano, from 11th February to 29th April of the year 2016. Fig. 6 shows the test set-up for MRF and PC test frames. Cyclic loading has been applied in correspondence to the top joint of right-side column by means of a short beam, transferring the force from the electromechanical actuator, which has a tension/compression capacity of 750 KN. A load cell attached to the actuator measures the applied load. Test specimens have been restrained out-of-plane. A displacement controlled loading protocol has been used. The tests have been performed in a quasi-static regime with an application of a displacement amount at 0.4 mm/s. ECCS loading protocol [14] has been modified in order to obtain information at small displacement amplitude increase. Gravity loads have not been applied in the tests.



a. MRF specimens

b. PC specimens

Fig. 6 General test set up for two test frame types

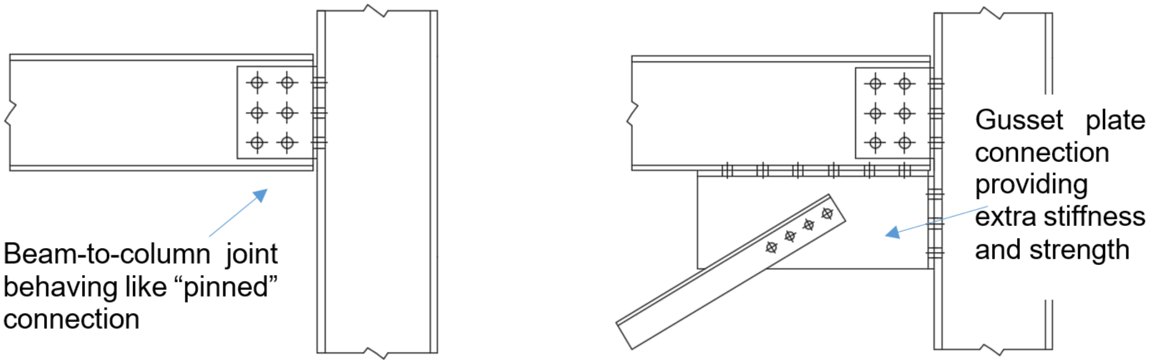
Displacements have been measured at various locations of the specimens by means of displacement transducers (LVDT). Axial deformations of steel elements have been measured by means of strain gauges. A thermal camera has been used to observe the bolt slip and ovalization at bracing connections.

3. Preliminary Test Results

All the tests have been completed, and elaborations are still under-way. Although deeper analysis is still required, some interesting first conclusions can already be drawn from the results achieved up to now. The results are interpreted to investigate the moment resisting frame action, the contribution of compression diagonal on global behavior, and ductility provided by non-dissipative bracing connections.

3.1 Moment resisting frame action

In concentrically braced frames, “frame action” naturally exists in the form of beam-to-column shear and gusset plate connections (Fig. 7). This may be a valuable resource as a secondary system to prevent collapse, providing a certain degree of stiffness and strength following the bracing failure. Despite even simple gusset plate connections may contribute to this “reserve” strength and stiffness capacity in CBF systems, in design practice these connections are normally designed as simple pinned joints.



a. Beam-to-column connection with gusset plate b. Beam-to-column connection without gusset plate

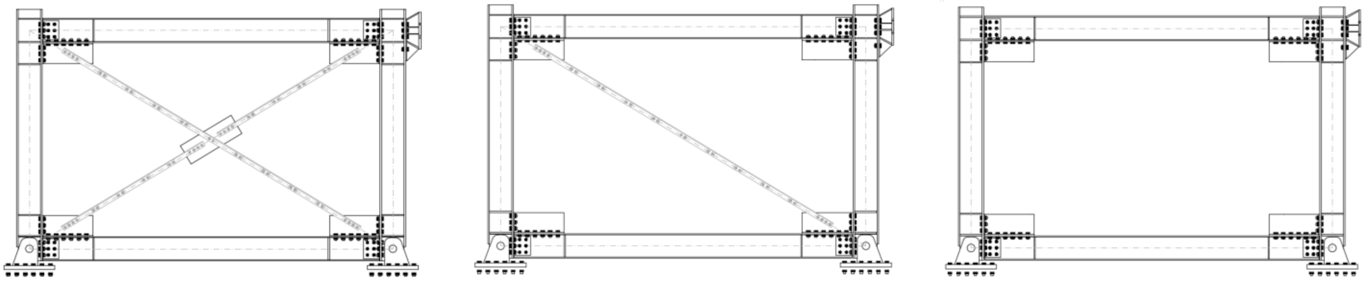
Fig. 7 Beam-to-column connections with and without bracing gusset plate

In this chapter, this reserve effect has been quantified by means of full scale tests performed with several configurations, and its potential to improve seismic performance of concentrically braced frames in moderate seismic actions has been presented. The tests specimens are classified in 3 types, and schematically described in Fig. 8:

a. Cross diagonal braced frames with semi rigid gusset plate joints

b. Single diagonal braced frames with semi rigid gusset plate joints

c. Frames with semi rigid gusset plate joints without diagonals

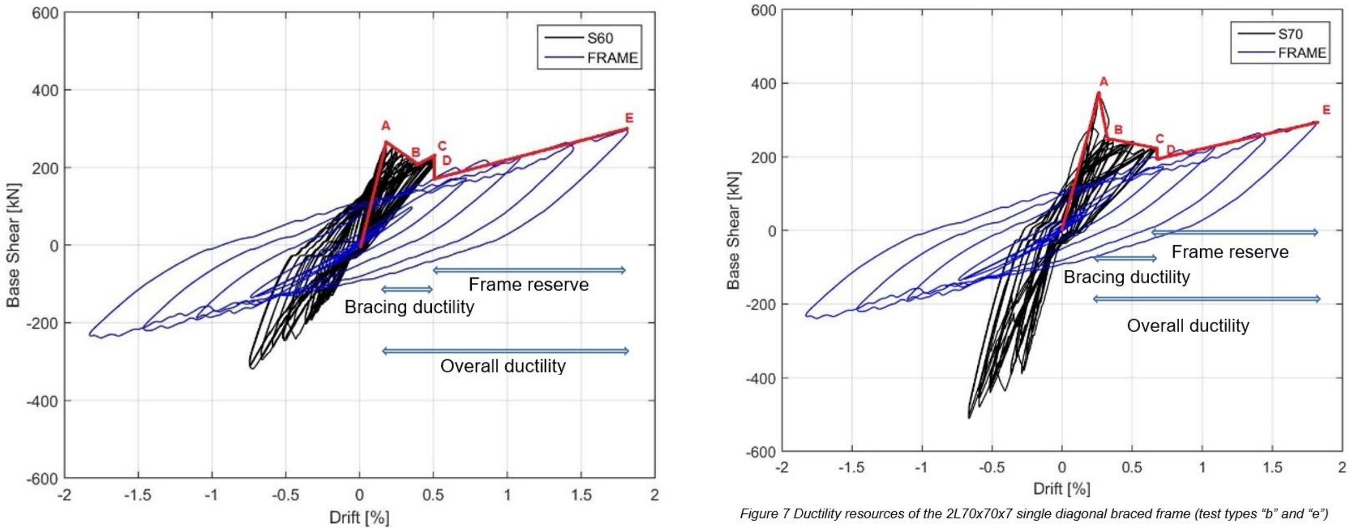


Type a Type b Type c

Fig. 8 Test specimens designed to investigate frame action

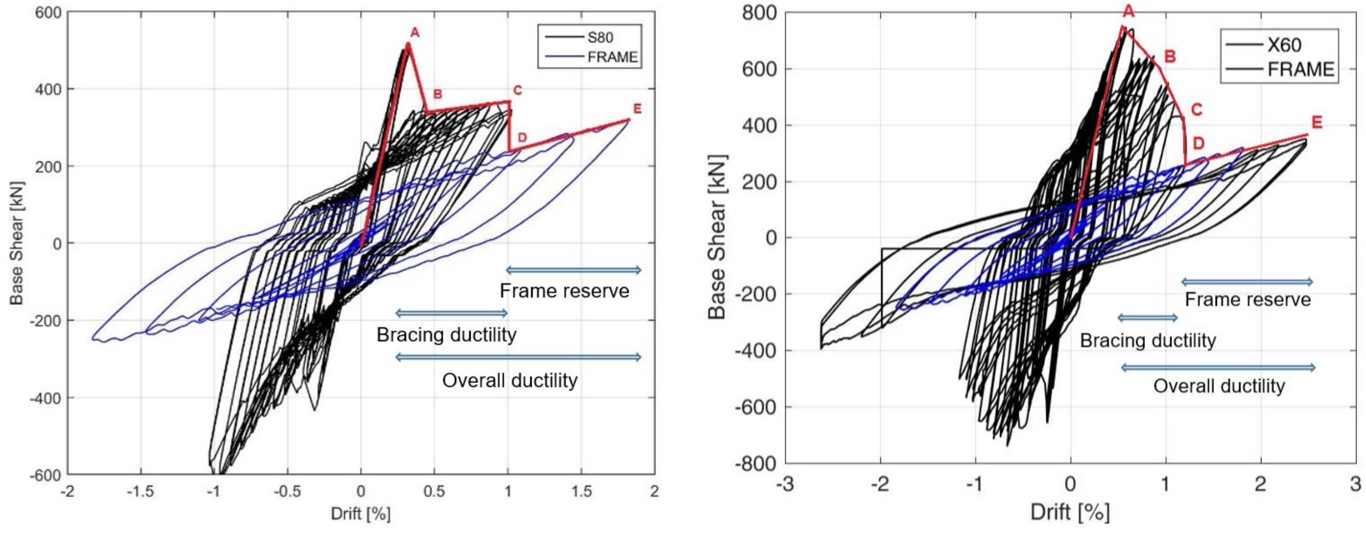
Fig. 9 compares the global behavior of four test specimens with different bracing elements. Black hysteresis curve shows the global force-displacement behavior of the braced frame with single diagonal, drawn until bracing failure, while the blue hysteresis curve shows the global force-displacement behavior of the MRF frame without bracings. The MRF frame without bracings has been pushed until large drifts to show how much the steel frame with no bracings would deform with increasing base shear.

After plastic buckling occurred, additional load cycles have been imposed to the specimens until failure of the bracing joint. During this post-buckling phase, both under tension and compression cycles, the specimens continued to have significant strength and stiffness. With reference to Fig. 9, first plastic buckling occurred at point A, then failure at the net section occurred in the bracing joint at point C (B for S60); the frame with fractured bracings has been pushed and pulled until point E. The values beyond point D on graphs show the base shear carried only by frame action with the corresponding drift value.



a. 2L60x60x8 single diagonal

b. 2L70x70x7 single diagonal



c. 2L80x80x8 single diagonal

d. 2L60x60x8 X-braced frame

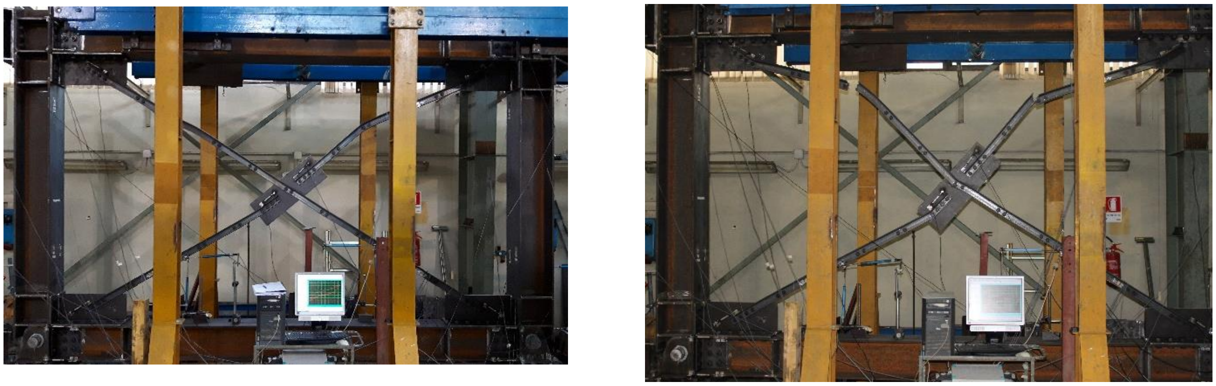
Fig. 9 Ductility resources of the test specimens

The extra ductility provided by the frame action is very significant in all cases. The calculated overall ductility of the test specimens is much higher when the frame ductility is taken into account. In Table 1, ductility provided by the braced frame and the overall ductility composed of bracing and frame actions are reported. Although the CBF systems are known to have limited ductility, when the frame action is able to provide sufficient strength and deformability, the overall ductility of the braced frame can arrive to important values.

Table 1 Ductility provided by braced frame and overall ductility including frame reserve

	Braced frame ductility (C/A drift ratio)	**Overall ductility (E/A drift ratio)**
S60	2,68	9,53
S70	2,58	6,96
S80	2,97	5,48
X60	4,46	9,77

In all cases, when the bracings were completely damaged due to connection fractures, the moment resisting frame with semi-rigid joints provided a reserve capacity. Thanks to this frame action, specimen continued to deform reaching large drifts (around 2%) with not too large but remarkable resistance and stiffness. Fig. 10 shows the specimen X60 before and after full bracing fracture.



a. During post-buckling b. After both bracings completely fractured

Fig. 10 Specimen X60 during post buckling and after bracings' complete failure

3.2 Contribution of Compression Diagonal

Current Eurocode 8 allows disregarding the compression diagonal, during the analysis stage of concentrically braced frames with X-type bracings (X-CBF). This may be a rational assumption for high-seismic situations, where the compression bracings undergo buckling at the early stages of the seismic event. On the other hand, in moderate seismicity, where the shear deformation demand for braced frames, and the number of high-amplitude cycles are very limited, it may be reasonable to consider both tension and compression diagonals in the analysis. Accounting for compression diagonals at the analysis stage, and exploiting their post-buckling resistance and dissipative contribution in design, may allow using a higher behavior factor, and increase the economic efficiency of X-CBF structures in moderate seismic regions. On the other side, post buckling resistance of compression bracing while the tensile bracing is under stress, may increase the design expectations of maximum base shear in X-braced frames. In order to understand the real seismic performance of compression bracings, a sound characterization of the cyclic behavior of these elements subjected to alternate tension and compression is needed.

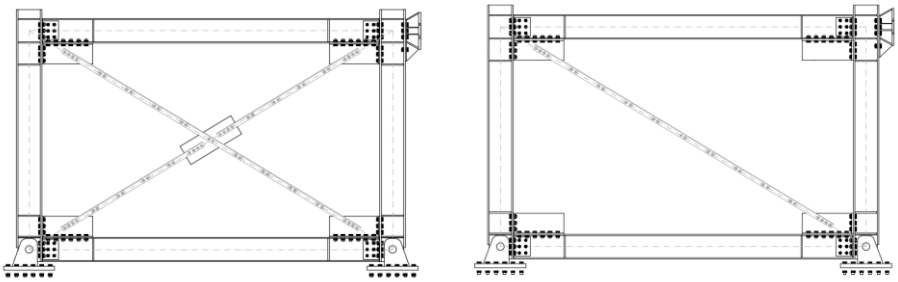
In this chapter, preliminary test results have been presented, which investigated stiffness and post-buckling performances of several real scale braced frame configurations. Thanks to the observations obtained from these tests, possibilities to improve seismic performance of concentrically braced frames built in moderate seismic have been discussed. Single and X bracings have been tested inside MRF and PC frames. The tests specimens are classified in 4 types, and schematically described in Fig. 11.:

a. Cross diagonal braced frames with semi rigid gusset plate joints

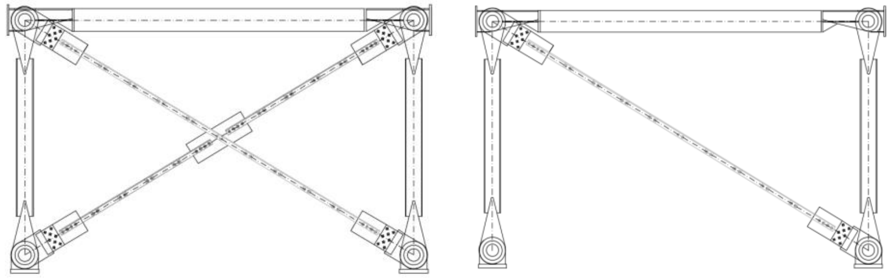
b. Single diagonal braced frames with semi rigid gusset plate joints

c. Ideally pinned frames with X-braced diagonal

d. Ideally pinned frames with single diagonal



Type a Type b



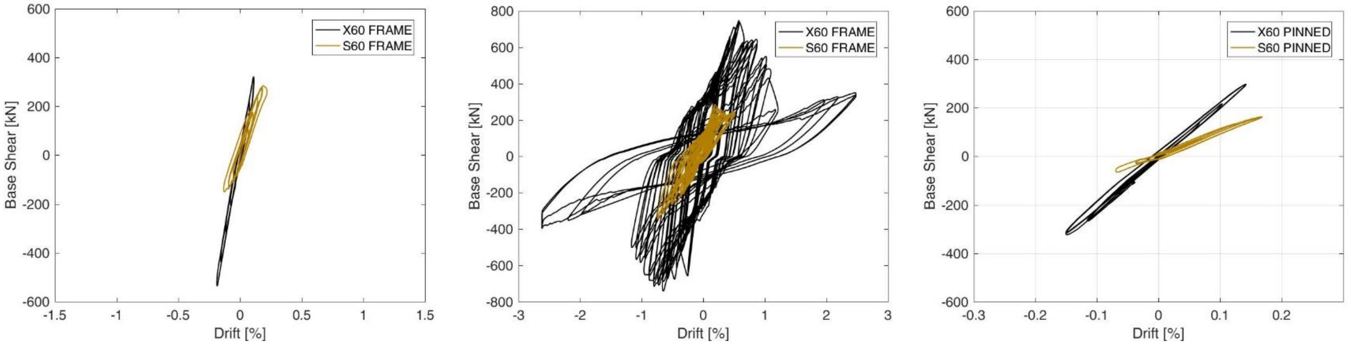
Type c Type d

Fig. 11 Test specimens designed to investigate the contribution of compression diagonal

With single bracing tests, post-buckling behaviour of bracings with different slenderness has been characterized. On the other hand, X-braced specimens provided information about the initial stiffness and energy dissipation due to slippage of bolts. One full scale test with X-bracing also provides information about the post-buckling resistance of compression diagonals. Fig. 12 shows comparisons between the frames with and without compression diagonals for three profile type S60. Two major observations can be made from these comparisons:

i. Compression bracing significantly influences the initial stiffness of X-braced frames, which is an aspect that is normally neglected during the analysis stage in current design practice.

ii. Overall behavior of the frames with and without compression diagonal is significantly different.



a. X-braced vs Single diagonal inside semi-rigid frame - initial stiffness

b. X-braced vs Single diagonal inside semi-rigid frame - global behaviour

c. X-braced vs Single diagonal inside ideally pinned frame - initial stiffness

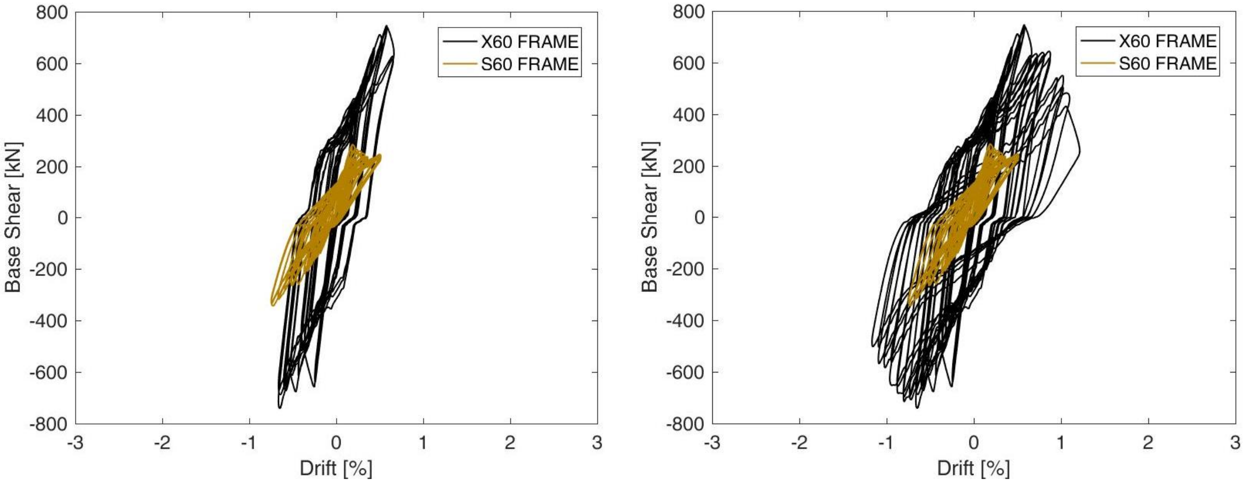
Fig. 12 Comparisons between the X-braced and single diagonal specimens (for 2L60x60x8 bracings)

This observation was valid for all other specimens. Table 2 quantifies the initial stiffness of each test specimen and the contribution of the compression diagonal. With less slender diagonals, the change is even more significant. This implies that at the analysis stage, neglecting the compression diagonal would result in natural modes that are very different than the actual values. The contribution of compressional diagonal in all cases is around 50 % regardless of the change in the bracing slenderness.

Table 2 Initial stiffness properties of test specimens

	2L60x60x8			**2L70x70x7**			**2L80x80x8**		
	X-Bracing (KN/% drift)	**Single bracing (KN/% drift)**	**Compression diagonal contribution (%)**	**X-Bracing (KN/% drift)**	**Single bracing (KN/% drift)**	**Compression diagonal contribution (%)**	**X-Bracing (KN/% drift)**	**Single bracing (KN/% drift)**	**Compression diagonal contribution (%)**
Semi-rigid Frame	2796	1404	**50,2**	3505	1775	**50,6**	3680	1993	**54,2**
Pinned Frame	2189	999	**45,6**	2505	963	**38,4**	2698	1081	**40,1**
Frame action subtracted	2515	1124	**44,7**	3224	1494	**46,3**	3399	1712	**50,4**

Contribution of the compression diagonal is not limited only to the initial stiffness of the structure. The global resistance of the braced frame is also completely different when the compression diagonal is taken into account (Fig. 13). For instance, the single diagonal specimen completely fails at a 0.7% drift. At the same drift, X-braced specimen only enters the plastic buckling phase (Fig. 13.a). Global energy dissipation of the X-braced specimen is also much higher thanks to extra post-buckling and bolt-slip dissipations (Fig. 13.b). During post-buckling phase, even after joints were fractured, compression bracings provided a moderate amount of strength both under tensile and compression forces.



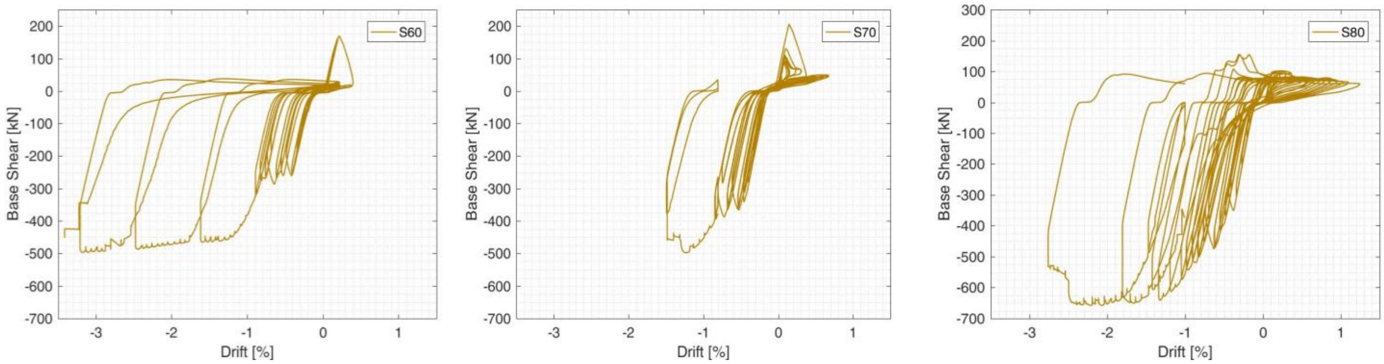
a. Until 0.7% Drift

b. Complete behaviour

Fig. 13 Contribution of compression diagonal on global behaviour for X-braced specimen 2L60x60x8

3.3 Ductility provided by “non-dissipative” bracing connections

Three specimens (S60, S70, S80) have been tested until collapse under tension forces. None of them fully reached full tensile yielding of their gross section due to the fact that their connections have not been designed according to capacity design rules. Fig. 14 shows the global base shear vs floor drift behavior of the single diagonal specimens (S60, S70, S80), when they have been pushed until the joint fracture. An inelastic deformation in beams and columns has not been observed either (the beams and columns are designed to remain elastic). Therefore, the global ductility in these cases, is provided mainly by slip and ovalization of bracing joint bolts (Fig. 14). The obtained ductility values are between 2.50-2.87, as shown in Table 3.



a. 2L60x60x8 single diagonal b. 2L70x70x7 single diagonal c. 2L80x80x8 single diagonal

Fig. 14 Global base shear-drift behaviour of single diagonal specimens tested until global collapse

Table 3 Ductility values for three test specimens with single diagonal

	Drift at tensile yielding	**Drift at tensile collapse**	**Ductility**
60S	1,12	3,21	**2,87**
70S	0,52	1,22	**2,35**
80S	0,95	2,40	**2,53**

4. Conclusions

This paper presents the preliminary results of the full scale tests performed on concentrically braced frame specimens designed for moderate seismicity. The tests investigated the moment resisting frame action and the contribution of compression diagonal on global behavior of the CBF systems, and inherent ductility provided by bracing connections designed according to non-dissipative approach. The preliminary conclusions are:

- Current design procedure with simple pinned beam-end assumption does not reflect the realistic behavior of concentrically braced frames. This may lead to wrong estimations both at analysis and design stages in terms of global stiffness and strength characteristics of these type of structures.
- In moderate seismic regions, seismic performance of concentrically braced frames can be improved designing them accounting for the frame reserve capacity. This can be done engaging the beam and column by means of a gusset plate connection which results in an increased global stiffness and strength. In this way, when the bracings completely fail, global collapse can be prevented thanks to this flexible reserve system.
- Compression bracing significantly influences the initial stiffness of X-braced systems, which is an aspect that is normally neglected during the analysis stage in current design practice.
- Overall resistance of the frames with and without compression diagonal is significantly different.
- Non-dissipative bracing connections may provide a significant amount of ductility

Detailed investigation of the test results is still under-way, and the final results and conclusions are planned to be published in the next future.

5. Acknowledgements

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