Stability and Ductility of Steel Structures 2019 – Wald & Jandera (Eds)
© 2019 Czech Technical University in Prague, Czech Republic, *ISBN 978-0-367-33503-8*

U-shaped steel plate dissipative connection for concentrically braced frames

J. Henriques
Faculty of Engineering Technology, CERG, University Hasselt, Belgium

L. Calado
Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

C.A. Castiglioni
Department of Architecture, Built environment and Construction Engineering, Politecnico di Milano, Milano, Italy

H. Degée
Faculty of Engineering Technology, CERG, University Hasselt, Belgium

ABSTRACT: In concentrically braced frames, the use of dissipative connections allows to efficiently dissipate the seismic energy in earthquake scenarios and subsequently, to reduce the costs in the rehabilitation of the structure. To this end, U-shaped steel plates are simple and efficient connection components where significant dissipation of seismic energy can take place through the inelastic flexural deformation of the plate. This paper presents experimental results on the isolated U-shaped steel plate connections and on single-story concentrically braced frame (real scale) including the U-shaped steel plate to connect braces to adjacent members. The executed tests considered both monotonic and cyclic loading. The results highlight the efficiency of the U-shape steel plate to dissipate the energy input through inelastic deformations. On the other hand, the cyclic tests show potential fatigue behavior, as the deformation capacity is significantly reduced with repeated loading and increasing stress amplitude, requiring thus specific attention in practical design situations.

1 INTRODUCTION

Concentric braced frames (CBF) are commonly used in Europe as seismic resistant steel structures. Strong seismic activity has shown (Bertero V et al., 1994) significant damage in the building structure, namely in the braces usually designed as dissipative members. Subsequently, the repair of the structure involves the strengthening or replacement of damaged and buckled braces which requires considerable skill, material and labor cost (Morelli F et al., 2017). The most suitable solution to this problem consists in the protection of the braces through the use of anti-seismic devices, as dissipative connections.

In CBF with dissipative connections, the frame presents sufficient stiffness against lateral displacements and incorporates flexible connections between braces and structure. These connections provide ductility to the structure, increasing the dissipation of seismic energy, and protect the braces from buckling. Moreover, as damage is concentrated in the connections, the repair after strong seismic event becomes easier and less costly.

In the last decade, several seismic protection systems with innovative steel-based devices have been developed (Vayas I et al, 2017). Within the research project INERD (Plumier, A. et al, 2004) a dissipative connection consisting of a steel plate bent to a U shape was developed for application in CBF, connecting the braces to the adjacent members (Figure 1). The main geometric

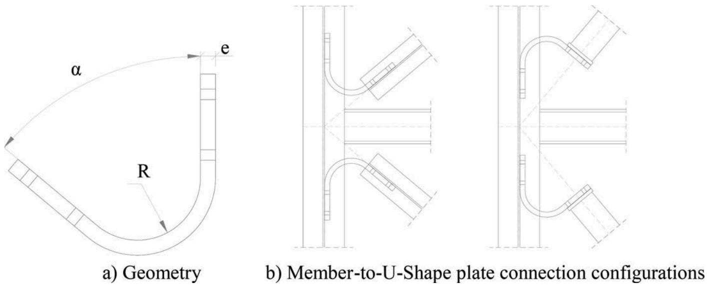


Figure 1. U-shape steel plate connection and its application.

variables of the U-shaped steel plate are: R – internal bend radius; e – thickness of the plate; α – inner angle of the U-shaped (defined by the angle between brace and adjacent member); width of the plate (out-of-plane dimension of the scheme in Figure 1-a); length of the straight parts; number of bolts to perform the connection between plate and member. In service, the loading of the U-shape steel plate connection varies according to the connection configuration. Accordingly, two loading positions are possible (Figure 1-b): perpendicular and parallel. In fact the loading position depends on the configuration of the connection between device and member which may consist of single or double overlap connection or end-plate connection (see Figure 1-b).

In the present paper the results of the two experimental programmes on the U-shaped plate connection, realized within the referred research project (Plumier, A. et al, 2004), are discussed. One experimental campaign had focus on the mechanical characterization of the U-shaped plate connection under monotonic and cyclic loading. These tests only considered tests on the isolated connection. The second experimental programme considered the testing of full-scale CBFs incorporating the referred connection. In the latter, only cyclic tests were performed.

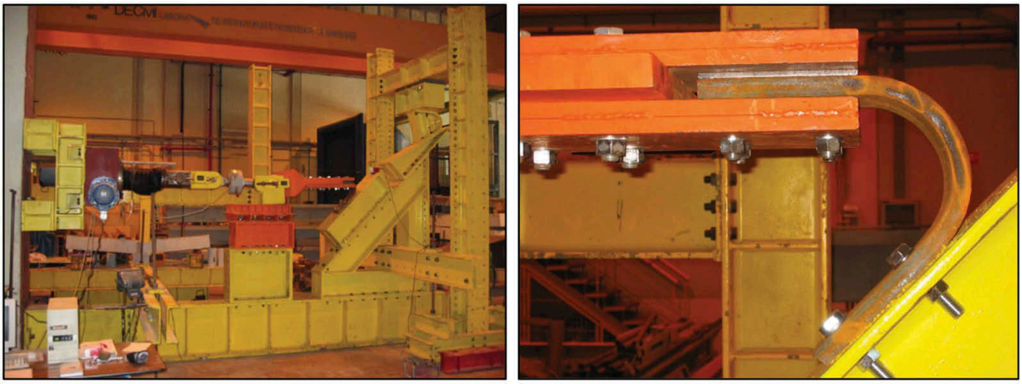
2 EXPERIMENTAL TESTS ON ISOLATED U-SHAPED STEEL PLATE CONNECTIONS

2.1 *Test specimens, testing layout and testing programme*

In order to experimentally assess the mechanical performance of the U-shaped steel plate connection, tests on the isolated connection device (Figure 2), at IST in Lisbon, Portugal, were performed. The U-shaped steel plate was design to be the governing component and consequently, the connected parts of the testing system were overdesigned. The tests considered the following types of loading: i) static monotonic pull; ii) static monotonic push; iii) cyclic loading following the ECCS cyclic loading protocol (ECCS, 1986); iv) cyclic loading with constant amplitude, where four different displacement amplitudes were tested. In total, for each test specimen, 7 tests were executed. In Table 1 is summarized the described testing programme. The testing variables consisted in the following: i) internal bend radius (R); ii) plate thickness (e); iii) angle between connected members (α) defining the angle between the U-shaped steel plate "legs"; iv) the loading position. The plate width was equal for all test specimens (b = 160 mm).

2.2 *Results*

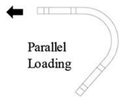
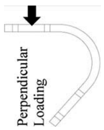
From the experimental tests on the isolated U-shaped steel plate, force deformation curves were obtained as illustrated in Figure 3-a). The chart includes the results of both static loading tests and of the cyclic loading test, following the ECCS cyclic loading protocol (ECCS, 1986), for test specimen Test 6. In Figure 3-b) are compared, for the same test specimen, the absorbed energy and the total number of cycles achieved in each cyclic loading test. These results highlight the following: i) the connection strength and stiffness is higher when the U-shaped steel plate is "compressed" between the connected members (Mon Push vs Mon Pull); ii) under cyclic loading, the



a) Test layout b) Test specimen

Figure 2. Experimental tests on isolated U-shaped connection (Plumier, A. et al, 2004).

Table 1. Summary of the experimental programme on isolated U-Shaped steel plate connection.

Test Specimen ID	R [mm]	e [mm]	α [º]	Load Position	Nº of Tests
Test 1	100	25	45		For all test specimens 2 tests with monotonic loading (1 Pull + 1 Push) and 5 tests with cyclic loading (1 ECCS, Δ = 20 mm, Δ = 40 mm, Δ = 60 mm, Δ = 80 mm)
Test 2	100	25	50		
Test 3	100	30	50		
Test 4	125	30	50		
Test 5	125	25	30		
Test 6	125	25	45		
Test 7	125	25	50		
Test 8	125	25	30		
Test 9	125	25	39		
Test 10	125	25	45		
Test 11	125	30	39		

deformation capacity of the connection is reduced; iii) under cyclic loading, the connection is sensible to fatigue, with the increase of the cycles amplitude, the absorbed energy and the number of completed load cycles decreases. These observations can be generalized for the other test specimens. The detailed results and conclusions on the full experimental programme can be accessed in (Plumier, A. et al, 2004) and (Henriques, J. et al, 2018).

3 EXPERIMENTAL TESTS ON CBF INCLUDING THE U-SHAPED STEEL PLATE CONNECTION

3.1 *Test specimens, testing layout and testing programme*

At Laboratorio di Prove e Materiali of Politecnico di Milano, Italy, tests on a single story CBF (Figure 4), incorporating the U-shaped steel plate to perform the connection between the diagonal braces and the adjacent members, in this case the columns, were executed. The U-shaped steel plate was design to be the governing component and consequently, connected devices and frame members were overdesign. In particular, the braces were designed as continuous and considering half-length of the diagonal in the computation of the buckling length (Constanzo S et al., 2019). The tests on the single story CBF consider only the cyclic loading protocol. A summary of the testing programme is given in Table 2. As for the tests on the isolated U-shaped steel plate, the testing variables are the bend radius (R), the plate thickness (e) and the angle between the connected members (α).

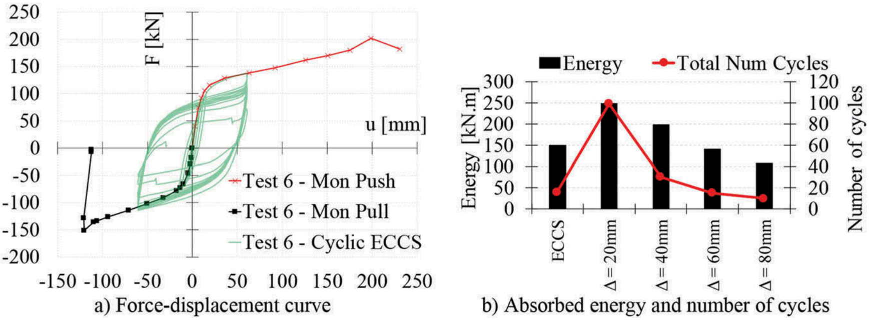


Figure 3. Results of the experimental tests on isolated U-Shaped steel connection.

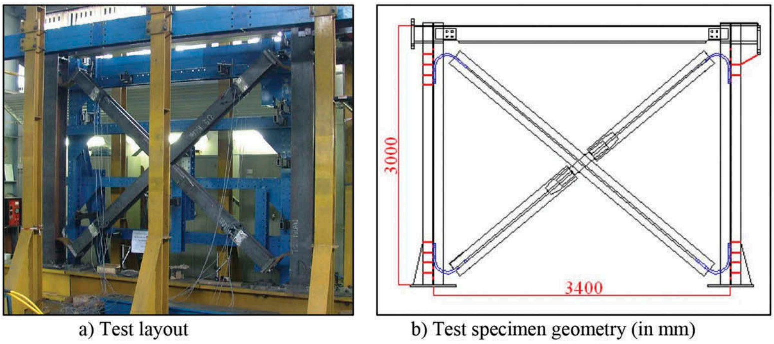
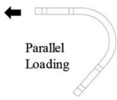
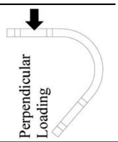


Figure 4. Experimental tests on CBFs incorporating U-Shaped steel plate connection.

Table 2. Summary of the experimental programme on CBFs incorporating U-Shaped plate connection.

Test Specimen ID	R [mm]	e [mm]	α [º]	Load Position	Nº of Tests
CBF 1	125	25	50		1 test using a cyclic quasi-static loading according to the ECCS cyclic loading protocol (ECCS, 1986)
CBF 2	100	25	50		
CBF 3	125	30	50		
CBF 4	100	30	50		
CBF 5	100	30	40		
CBF 6	100	25	40		
CBF 7	125	30	40		
CBF 8	125	25	40		

3.2 *Results*

The tests on CBFs allowed to obtain the force-interstory drift curves (cyclic loops) reflecting the behavior of the frame using the U-Shaped steel plate to connect bracings to adjacent members, in this case the columns. In Figure 5-a) are illustrated the results of two tests, namely CBF 2 and CBF 6. These test specimens are similar being the main difference the loading position of the U-shaped steel plate, and, because of limitation on the geometric dimensions of the frame due test layout, the angle between connected members (50º and 40º, respectively). The curve shows the global response is symmetric contrary to the behavior of the U-shaped steel plate connection (see Figure 3-a) under push or pull loading. This was expected has the CBF is symmetric, and therefore, under service, two connections work under push loading and the other two work under pull-loading. The curves show a very similar behavior, with a slightly stiffer response on the CBF frame with perpendicular loading on the U-shaped steel plate connection (CBF6). In Figure 5-b),

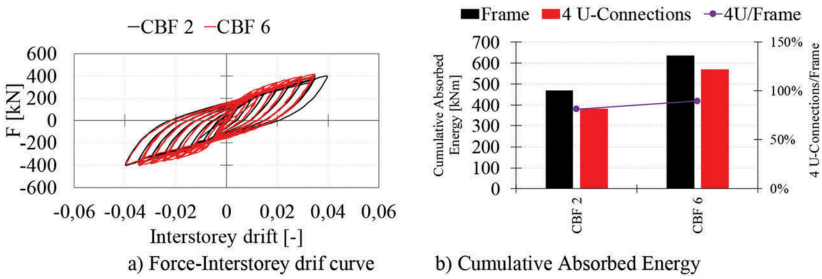


Figure 5. Results of the experimental tests on CBFs incorporating U-Shaped steel plate connection (CBF2 vs CBF6).

for the same test specimens, are shown the cumulative energy absorbed by the CBF and only by the 4 U-shaped steel plate connections. Though not all tests on the CBFs could be taken up to failure, due to the limitations on the experimental testing set-up, the referred test specimens achieved the same number of cycles (25). Hence, comparing the cumulative absorbed energy one can observe that the specimens with perpendicular loading absorb more energy. This is because of the higher strength and stiffness of the connection under these loading conditions. These results are in line with the results on isolated connections (Henriques, J. et al, 2018). In the same chart is also included the percentage of energy absorbed by these connections with respect to the total energy absorbed by the CBF. Here a difference is noticed. In CBF2, the referred connections absorbed approximately 82% of the total energy, while in CBF6 approximately 90% of the energy was absorbed by the connections. In any case, it is clear that the connections accomplish the foreseen function, and work as dissipative component of the CBFs.

4 ANALYSIS OF RESULTS

4.1 *Static vs cyclic tests*

In order to compare the performance of the U-shaped steel plate connection under monotonic and cyclic loading, the ratio between the deformation capacity obtained in both types of tests were computed. For the cyclic loading only the tests following the ECCS cyclic loading protocol was considered. In Figure 6 are plotted the computed ratios. For each test specimens, two ratios were determined, as the deformation capacity under push loading (compression) and pull loading (Tension) were, for some cases, remarkably different. It is clear that under cyclic loading the deformation capacity is significantly reduce. The average reduction is 50%. This indicates that under such load conditions, the connection is susceptible to experience low cyclic fatigue effect.

4.2 *Isolated vs CBF tests*

In order to compare the behavior of the U-shaped steel plate on the isolated tests and when incorporated in the CBF, an extrapolation of the frame behavior was performed using the results of the experimental tests on the isolated connection. To accomplish this task, an mechanical model was proposed to reproduce the CBF behavior. The model is described in (Henriques, J. et al, 2018). In Figure 7-a) are compared the force-lateral deformation curves of the CBF frame for both cases. It is clear that there is a stiffer response on the tests of the CBF in comparison to the extrapolated behavior. The difference is justified by the fact that in the referred mechanical model, the connections between columns and beam are assumed perfectly hinged and therefore neglecting the "frame effect". The latter has been identified and quantified in (Kanyilmaz A et al., 2018) comparing the cyclic performance of two CBFs with two different construction detailing: i) one frame constructed using actual (common) connections between the structural members (such as fin plates and gusset plates); ii) other frame constructed using perfectly hinged connection between members. The frame effect depends on the connection detailing (see Figure 4-b) therefore within the experimental programme on CBFs (Plumier, A. et al, 2004), an experimental test was

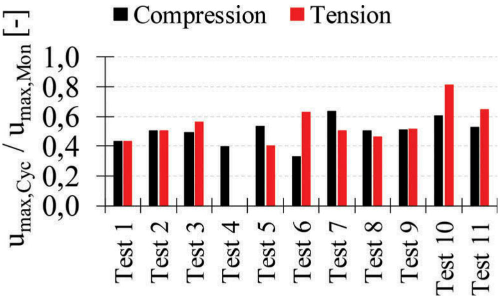


Figure 6. Comparison between the maximum deformation of the U-Shape steel plate connection under cyclic (ECCS cyclic loading protocol) and monotonic loading.

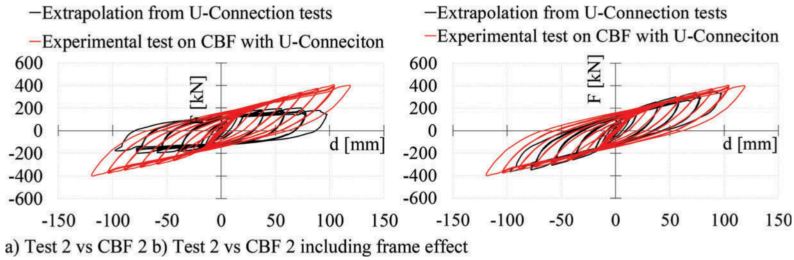


Figure 7. U-Shape steel plate response vs CBF response.

performed on a frame without any bracing allowing to determine the frame stiffness. The frame stiffness was then introduced in the above referred mechanical model, and the response of CBF extrapolated. In Figure 7-b) are given the results including the "frame effect". The agreement between tests and extrapolation is now excellent. Furthermore, comparing both charts, it is possible to observed that the U-shaped connection is the main source of deformation within the CBF, and therefore the dissipative component.

5 FATIGUE BEHAVIOR

The comparison between deformation capacity of the connection within the monotonic and cyclic loading tests highlighted the susceptibility of the U-shaped steel plate connection to low fatigue. Hence, using the test results fatigue design curves were derived and proposed following the S-N line approach prescribed in the EN 1993-1-9 (CEN, 2005). The detail of the used approach is given in (Henriques, J. et al, 2018). The proposed equations, best fit and design curve, are given in (1) and (2), respectively. In Figure 8 are compared the tests results with the proposed S-N lines. The results show a good agreement and highlight the susceptibility of the U-Shape steel plate connection to low cycle fatigue.

$$Log\ N = 12.00 - 3\ Log\ S \quad (1)$$

$$Log\ N = 11.53 - 3\ Log\ S \quad (2)$$

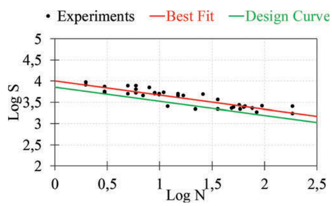


Figure 8. Best fit and low cycle fatigue design curves.

6 CONCLUSIONS

In this paper a dissipative connection, to be used between bracing and adjacent members in CBFs, has been presented. The connection consists of a steel plate bend in a U-shape, bolted to the connecting members, and is design to dissipate energy through inelastic deformation. The proposed connection is very practical given the simplicity to execute. In the paper, the mechanical behavior of the referred connection was investigated by means of experimental tests realized within the scope of the research project INERD. The experimental programme considered tests on the isolated connection under monotonic and cyclic loading, and test on full-scale CBF incorporating the connection. Besides the type of loading, several geometric parameters were varied within both experimental programmes, namely: i) the load direction with respect to the U-plate (parallel or perpendicular, in tension or compression) ii) the load type, i.e. monotonic or cyclic, iii) the thickness of the U-shaped steel plate, iv) the U-shaped steel plate bent radius and v) the angle formed by the U-shaped steel plate "legs"(which is directly related to the global geometry of the frame).

The main outcome of tests results can be summarized as follows:

- The connection can achieve high deformation capacity and therefore successfully dissipate significant seismic energy.
- Under cyclic loading, the connection demonstrates to be susceptible to low cyclic fatigue "effect".

Subsequently, S-N line curves for the fatigue design of the connection have been proposed in line the Eurocode approach. The comparison of the proposed equations with experimental results demonstrated their accuracy.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Research Fund for Coal and Steel (RFCS) research programme under CEC agreement N° 7210-PR-316 (The INERD project) and the grant agreement N° 709343 (INNOSEIS).

REFERENCES

Bertero V et al. (1994). *Performance of steel building structures during the Northridge earthquake*. University of California at Berkeley.

CEN. (2005). *EN 1993-1-9: Eurocode 3 – Design of steel structures - Part 1-9: Fatigue*. Brussels, Belgium: European Committee for Standardization.

Constanzo S et al. (2019). Proposal of design rules for ductile X-CBFS in the framework of Eurocode 8. *Earthquake Engineering and Structural Dynamics*, 48 (1): 124–151.

ECCS. (1986). *Recommended testing procedure for assessing the behaviour of structural steel elements under cyclic loads*. Brussels: ECCS – Technical Committee 1 – Structural Safety and Loadings – Technical Working Group 1.3 – Seismic Design.

Henriques, J. et al. (2018). Dissipative connections with U-shaped steel plate for breaces of concentrically braces frames. *Bulleting of Earthquake Engineering*, Submitted.

Kanyilmaz A et al. (2018). An adjusted design approach for concentrically braced frames in low-to-moderate seismicity areas. *Bulletin of Earthquake Engineering*, 16:4159–4189.

Morelli F et al. (2017). Seismic behaviour of an industrial steel structure retrofitted with self-centering hysteretic dampers. *Journal of Constructional Steel Research*, 157–175.

Plumier, A. et al. (2004). *TThe INERD project, Two innovations for Earthquake resistant design*. Brussels: European Commission.

Vayas I et al. (2017). *Innovative Anti-seismic Plates and systems*. Ioannis Vayas (Ed.), Research Fund for Coal and Steel, INNOSEIS Project RFCS-02-2015, ECCS press.