IMPROVEMENT OF X-CBF HYSTERESIS BEHAVIOR BY INTRODUCTION OF MCS

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1. ABSTRACT

An analysis of specificity in the hysteresis behavior of X-CBFs is presented. Attached is a brief overview of the undesirable modes of brittle fracture in the diagonals of such structures, often observed in the past earthquakes. A new approach for composition of frames with cross braces is developed by introduction of horizontal strut and by modification of the middle cross section of the diagonal. The aim of the proposal is to achieve predictable behavior and avoid the local buckling within the diagonal even in the stage of large inelastic strains. An experimental study of the proposed frame configuration and analysis of the hysteresis behavior was done. Based on the cyclic tests the frame response was studied and dissipated energy and behavior factor were obtained. Some conclusions and results of the study are presented.

2. INTRODUCTION

Bracing systems are among the most commonly used structures for construction in seismic areas. The configuration of the cross diagonals in the form of the letter "X" is one of the most commonly applied options in practice which for brevity we will refer to as the "X" CBFs. In the current seismic provisions as [1,2] bracing systems are required to be designed as energy dissipative structures by achieving ductile behaviour. The most common practice among engineers is to choose diagonals as dissipative elements. Therefore we can conclude that the hysteretic behaviour of the "X" CBFs depends on the proper hysteretic loop of the braces. Experience gained from past earthquakes is one of the main sources of knowledge concerning the actual behaviour of steel structures and in particular of CBFs. The analysis set out in [3, 4, 6 and 7] shows that very often the cause of the fracture of the bracings is the concentration of plastic strains in a limited area leading to low cyclic fatigue. The mode of fracture shown in Figure 1 is realized by the fact that the diagonals are of relatively low slenderness and they may not buckle but buckling with two hinge lines occurs within the gusset plate. Thus the gusset plate is subjected to cyclic bending experiencing plastic strains as a result of the tension and compression applied therein which inevitably leads to low cyclic fatigue. Another very typical and unacceptable brittle fracture, but common in the "X" CBFs, is rupture of the profile in the net section of the connection, Figure 1 - down too. Such fracture is extremely undesirable and contemporary design should avoid it.

***Fig. 1** – Concentration of hinge lines within the gusset plate (upper two). Brittle failure in the net section (down two).*

The experience on the seismic behaviour of the "X" CBFs known from past earthquakes is confirmed also by experimental studies like [10,11,12,13]. Figure 2 shows typical states related to the hysteretic behaviour of a single strut, published in the studies of *Gogging et all. (2004)* [5]. The test is conducted under cyclic axial load to a level causing the development of plastic strains in the member. As it can be seen from Figure 2 the areas that develop plastic hinges are the middle part of the member and the zones adjacent to the

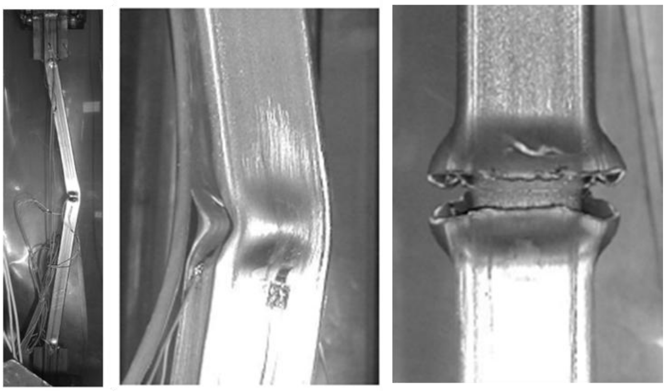


***Fig. 2** – Typical stages of inelastic behavior of a strut subjected to static cyclic loading during the experiments carried out by Elghazouli et al (2004) [11] - source. [5];*

connection. The tests prove that by cyclically increase of the axial displacements in the strut, particularly in cross-sections with concentration of plastic strains occurs, appear low cyclic fatigue and fracture of the member.

3. IMPROVEMENT OF THE HYSTERETIC BEHAVIOUR

Seeking to improve of the weaknesses referred to in item 2 (above) related to the hysteretic behaviour of the diagonal members of the "X" CBFs, during 2012 in the Laboratory of Steel and Timber Structures of the UACG has been developed a new advanced bracing system. The improvement is achieved by the introduction of two innovations. The first innovation requires introduction in the frame a horizontal intermediate member which aims to separate all diagonals from one another and thus making them of equal importance and non-interacting - Figure 3, left. The second innovation refers to the introduction of an "H"-shaped cross-section for the diagonals configured specifically therefor. A strengthening is provided in the end zones of the diagonals by widening the flanges. This prevents brittle fracture (see Figure 1) in the zones of net cross-sections due to the openings for bolts.

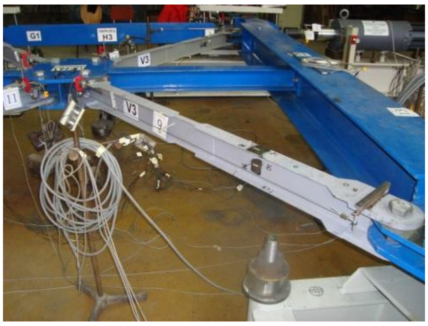


Fig. 3 *- General view of the proposed solution. Frame configuration - left. Connection solution with two gusset plates and two fitted bolts – right.*

Furthermore the connections are designed by fitted bolts so as to be achieved simple and unrestrained mechanism of rotation in the buckling state. In the middle part of the diagonals is introduced a modified cross-section (MCS) which is characterized by a reduced bending stiffness and increased cross-sectional area. Thus MCS is weakened in terms of bending and strengthened in terms of axial forces - Figure 4. The intention of the authors is to be achieved such effect so as under compression to be pre-defined the mode

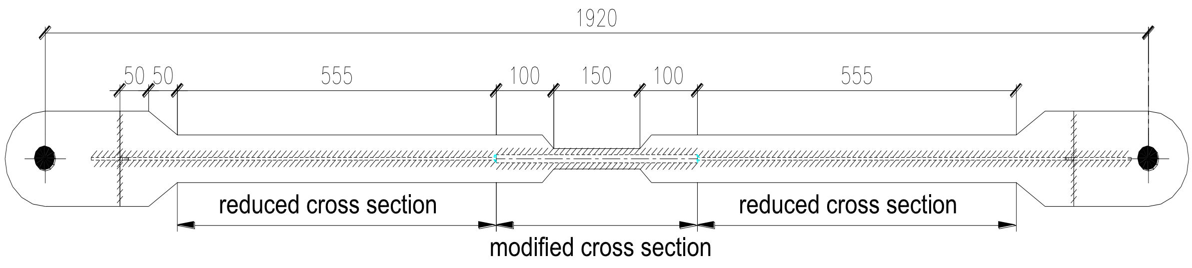


Fig. 4 *- Diagonal flange shaping and types of cross-sections in it*

of brace buckling and the plastic strains due to bending to be fully concentrated in the middle MCS. In reverse cycle, tensile force appear and the element becoming straight. Now plastic strains are directed to the reduced cross-section (RCS) and not in the MCS. Thus the diagonal is designed in such a manner that the plasticizing in tension and plasticizing in compression occur in different zones. This de-concentration of the zones for plasticization helps to eliminate the effects of low cycle fatigue and to avoid brittle fracture of the diagonals, leading to an overall improvement of the hysteresis behaviour.

4. EXPERIMENTAL STUDY

The proposed "X" CBFs were studied by laboratory test. The idea for the modified cross-section in the middle of the diagonal member arose during the implementation of the experimental program embedded in [9]. Since this idea was not included into the initial planning only one test specimen was manufactured and tested. It was a model in a geometrical scale of 1:2 - Figure 5. The frame (columns and beams) are designed following the principles of the capacity design according to [1] so that they shall remain elastic during the experiment. Basic information is described in Tables 1 and 2.

Slenderness of the diagonal		**Effective slenderness**	**Length of the RCS, mm**	**Degree of reduction**	**Class of cross-section** as per [1]
$\lambda_y = \frac{L_D}{i_y}$	$\lambda_Z = \frac{L_D}{i_Z}$	$\lambda_{y,eff} = \frac{L_D.\mu}{i_y}$	L_{RCS}	$k = \frac{A_{RCS}}{A_{MCS}}$	
123.2	**39.4**	**181.2**	**555**	**0.6782**	**class 1**

Table 1: Basic dimensions and slenderness

I_Z, mm^4	I_Y, mm^4	A_{RCS}, mm^2	A_{MCS}, mm^2	i_Z, mm	i_y, mm
2 791 975	286 473,3	1180	1740	48,64	15,58

Table 2: Inertial and geometric characteristics of the cross-sections

Pin connection between the braces and the frame was provided by fitted bolts M36 grade 10.9. Clearance between the bolt and the hole is 0.3 mm. The experimental set-up is shown in Figure 5. It was realized by a supporting stand, loading system - a hydraulic actuator, stabilising system and the experimental model. The experiment is implemented in a planar set-up and horizontal orientation of the model and of the loading system. Loading is realized by controlled displacement at the top of the frame. Displacement is applied quasi-statically and the loading protocol is symmetrical displacement history with stepwise incremented amplitudes. The as described loading protocol is consistent with the recommendations of the ECCS [8]. For obtaining information about the strains and displacements of the diagonals, strain gauges (SGs) and inductive displacement transducers (ITs) were installed. SGs are four per diagonal member and ITs are 12 for the whole set-up. ITs are arranged in specific places within the frame as it shown on Figure 5.

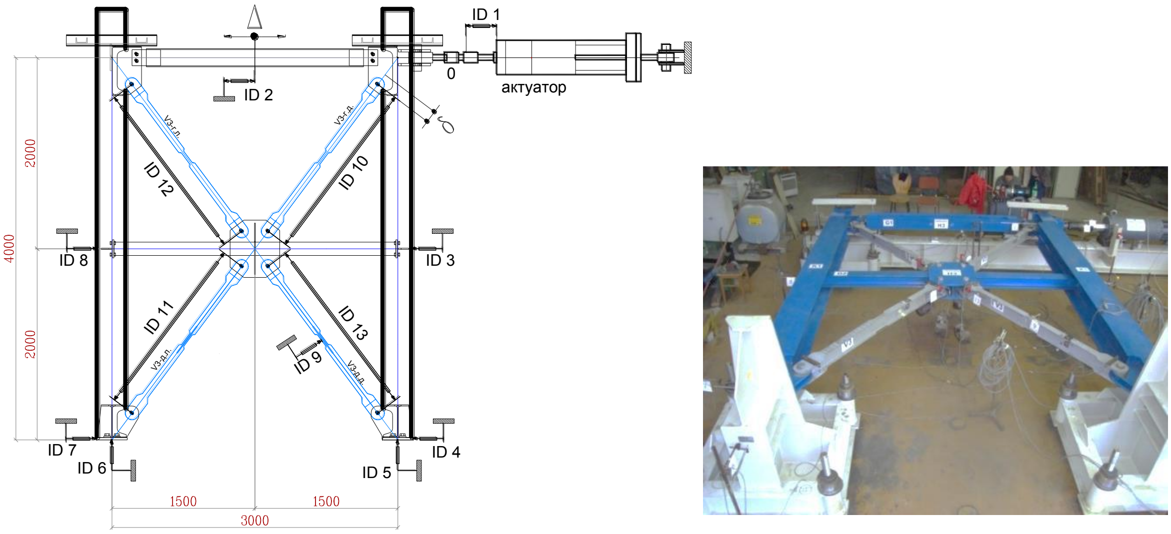


Fig. 5 *– Test set-up and arrangement of the inductive displacement transducers*

5. ANALYSIS OF THE RESULTS OF THE EXPERIMENTAL STUDY

Analysis of the experimental data was performed according to the recommendations of [8]. The results are illustrated in details and published in [9]. Typical feature of the hysteretic behaviour of this type of "X" CBFs is the occurrence of a pinching of the hysteresis loop and the lack of degradation of frame bearing capacity.

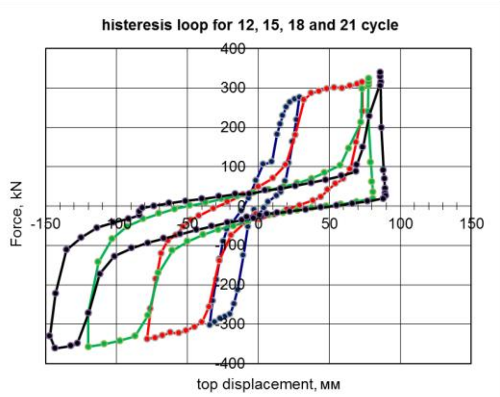


Fig. 6 *– Horizontal force versus lateral displacement for cycles 12,15, 18 and 21*

Based on the fact that the frame reached relatively large displacements part of inductive transducers have switched off after the realization of displacement of about 70 mm and the curves shown in the upper right quadrant of the hysteresis loop on Figure 6 are unreal. The same statement is true for the red line in Figure 7 which shows the cumulative dissipated energy by cycles. This curve is obtained after performance of calculations and summation of the areas enclosed by the hysteresis loops for each load cycle. It should be added that due to the exhaustion of the piston the test finished without fracture of that specimen.

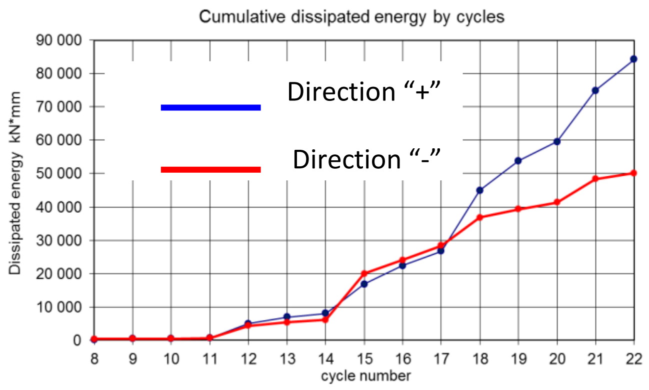


Fig. 7 *- Cumulative dissipated energy by cycles*

Figure 8 shows the resulting monotonic curves of relationship "force versus displacement" and the bi-linear approximation of it. It is noteworthy that in a best way the actual curve is approximated when the inclination of the second line is 1/30 of that of the line of the elastic behaviour.

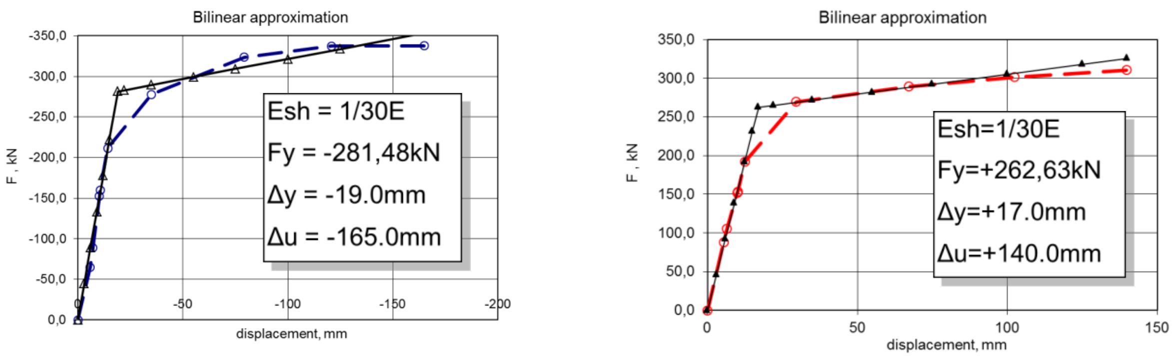
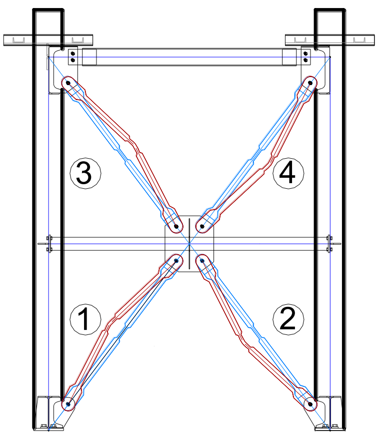


Fig. 8 *- Characteristic monotonic curve "force versus displacement"*

Figure 9 shows the sequence of buckling of the diagonals. The numbers put in circles next



Diagonal	**Cycle №**	**Δ [mm]**	**φ [rad]**	**as part of H**
Down left	2	5,385	φ=0,0013	$\frac{1}{742}H$
Down right	5	10,065	φ=0,0025	$\frac{1}{397}H$
Upper left	12	28,976	φ=0,0072	$\frac{1}{138}H$
Upper right	12	34,365	φ=0,0086	$\frac{1}{116}H$

Fig. 9 *– Sequence of buckling of compressed diagonals (at left). Table with corresponding displacements and storey drifts (right)*

to the diagonals on Figure 9 show the sequence of the occurrence of buckling and table in right provides information on the magnitude of displacements and drifts, when a particular diagonal has buckled for first time. The maximum value of the realized displacement is 149.2 mm which corresponds to the story drift $\varphi = 0,0373$ or $\Delta_{\max} = \frac{1}{26,8} H$. These maximal values are reached after implementing 22 cycles since the beginning of the test. Figure 10 shows the state of buckling of the diagonals during the last cycles of the experiment. Despite the large displacements (relative storey drift φ=37,3 mrad.) nowhere in the diagonals has appeared a mode of local buckling. Throughout the whole experiment it was not noticed local buckling or fracture of any cross-section. It is important to be supplemented that all 4 diagonal buckled in a way that corresponds to the original intention of the design.

Fig. 10 *- Buckling of compressed diagonal (left); MCS of buckled diagonal (right)*

6. CONCLUSIONS AND GENERALIZATIONS

Based on the presented results and the actual observed behaviour of the studied "X" CBF during the experiment carried out, can be made the following conclusions. The introduction of different cross-sections within the bracing, strengthen (for the area of the connections), two reduced cross-sections and one modified cross-section in the middle allow being achieved structural response corresponding to the design in a manner that all diagonals buckle under the presumed mode. Development of plastic strains due to tension and compression appear in different zones of the diagonal and it does not allow to be developed the mechanism for Low Cycle Fatigue (LCF). Delocalization of tension plastic strains from the compression ones leads to avoidance of the interaction between brittle fracture and concentrated flexural strains produced by local buckling. It was proved by the performed test, since during the reported experiment have not been recorded neither indications for LCF nor local buckling effects. Tension plastic strains appear only within reduced cross-sections and flexural strains due to brace buckling ale localized only within the modified cross-section. The achieved structural hysteresis is stable without degradation of strength. The effects of loop pinching are restarted, but they are compensated by ductility of the CBF. Finally an increase of the structural dissipativity is achieved, that could be seen from the figured up behaviour factors [9]. As a summary of the researches done and the analysis performed it can be concluded that the proposed variant of the shaping of the diagonals and the overall configuration of the "X" CBF leads to global improvement of the hysteretic behaviour.

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