Influence of splitting beam and column stiffness on CBFS ductile behaviour

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ABSTRACT

Concentrically braced frames with X-bracing configuration (X-CBFs) are one of the most popular systems for seismic resistant design. Their ductile behaviour is provided primarily by yielding of braces in tension and to a small extent by plastic rotation in buckled braces. An improved CBF configuration by introducing bracings with modified sections was developed in research program. In order to facilitate joint detailing, it is efficient that braces intersect into a horizontal member named ”splitting beam”. Experimental study has shown that braces, being above and below the splitting beam, often do not buckle simultaneously. This leads to concentration of inelastic deformations within one of the brace and causes unbalanced horizontal and vertical force. Finally, it might result in reduced storey ductility and premature brace fracture.

It was assessed through extensive parametric non-linear analysis that splitting beams in cooperation with columns have crucial impact on the brace buckling sequence and on the type of the global plastic mechanism. An analytical model and design procedure for determining the stiffness and strength demand of splitting beams and braced frame columns are proposed. The procedure ensures achievement of buckling of both halves of compression braces and formation of anticipated plastic mechanism. Some case studies based on static nonlinear analysis are presented.

Keywords: concentrically braced frame, plastic mechanisms, ductility, non-linear analysis

1 INTRODUCTION

Concentrically braced frames (CBFs) are traditional structural system for seismic load resistance. They may be approximated with a vertical truss system providing lateral stiffness and strength. They should possess adequate ductility and energy dissipation capacity as well. The intended ductile behaviour of CBF system is provided primarily by yielding of braces in tension and, to a small extent, by plastic rotation in the buckled braces. Provision of the structural ductilty demand is related to ensuring formation of the predefined plastic mechanism that exclude concentration of plastic deformations in a single storey. Eurocode 8 [1] limits the brace overstrength among all storeys and require capacity design for all non-dissipative elements so assuring formation of global plastic mechanism.

Yet in 1988 Khatib et al. [2] investigated the influence of brace intersecting beam stiffness in inverted V-CBFs. It is numerically observed that due to the formation of unbalanced vertical force after buckling of compression brace, the intersecting beam tends to deflect downwards proportionally to the beam flexural stiffness. This reflects in induction of additional shortening of both braces and holding off the yielding of the brace in tension. This mechanism leads to reduction of the intensity of the unbalanced force with increase of the storey drift. In case of eventual yielding of intersecting beam, storey plastic mechanism is formed and reduction of overall system ductility is observed. Authors propose an analytical expression for defining the necessary beam stiffness associated with the predefined stiff beam plastic mechanism. Deep research in the influence of beam stiffness on the seismic response of chevron concentric bracings is performed by Mario D’Aniello et al. [3]. Authors highlight the relation between the beam-to-bracing stiffness ratio and global and local performance parameters influencing the seismic response of inverted V-CBFs. As a result of the extensive numerical parametric study they propose analytical expressions for controlling the local brace ductility demand and the plastic mechanism at different performance levels. Further investigations spread to Split-X CBFs. In their work, Jay Shen et al. [4], [5] perform numerical study of six- and twelve-storey

CBFs with braces that split into a floor beam. They investigate the structural plastic mechanism and braces ductility demand in two cases: strong intersecting beam (designed including the unbalanced vertical force) and weak intersecting beam model (designed excluding the unbalanced force). Authors observe plastification and inelastic vertical deflections of the weak splitting beam leading to increased brace ductility demand that reflects into pinching of the hysteresis loops. Different mechanism of seismic energy dissipation and influence of higher natural modes were defined.
Eurocode 8 [1] covers the matter of intersecting beam stiffness and strength to the scope of chevron braced frames only. The formation of weak beam mechanism is avoided through capacity design of the brace intersecting beam by excluding intermediate support by the braces and introduction of unbalanced vertical force. US provisions AISC 341-10 [6] regulates the resistance of splitting beam to SCBFs through similar but not the same design rules. The codes [1] and [6] both cover the topic of intersecting beam design for chevron CBFs but they do not provide distinct guidelines for design of the intersecting beam in Split X-CBF. Moreover, Eurocode 8 [1] has no explicit instruction for Split X-CBF, which was highlighted by Landolfo R. in [7]. Experimental program conducted in UACEG, Bulgaria in 2014 [8] have shown that non-homogeneous plastic deformations may be inherent to single storey X-CBFs with diagonals that intersect into a horizontal splitting beam due to the non-concurrent buckling of the two halves of compressed brace.

2 CBF-MB AND EXPERIMENTAL OBSERVATIONS

The system concentrically braced frame with modified braces (CBF-MB) was developed based on traditional X-CBFs. Single storey frame of the proposed system consists of columns, diagonal braces, beam and splitting beam (*Fig. 1a*)). Columns and beams are non-dissipative elements while diagonals are the main dissipative members. Splitting beam separates the diagonals thus making them identical and non-interacting and allows avoidance of complicated detail of the crossed diagonals. Diagonals were developed as variable "H"-shaped welded built-up cross-section and named modified braces (MB). The behaviour of MB and the improvement of their low cycle fatigue endurance are reported in [8], [9] and stay beyond the scope off that paper. Testing programme for investigation of cyclic response of X-CBFs was performed in the Laboratory of Steel and Timber Structures in the UACEG. The tests were conducted by applying controlled displacement at the top of the frame. Displacement was applied statically and the loading cycles were fully reversal and symmetrical. The loading protocol used is consistent with the recommendations of the ECCS [10] and meets the test requirements for cyclic loading with increasing amplitudes of the applied displacement. Experimental observations of the study were reported in [8]. The test setup is shown in *Fig. 1 b).*

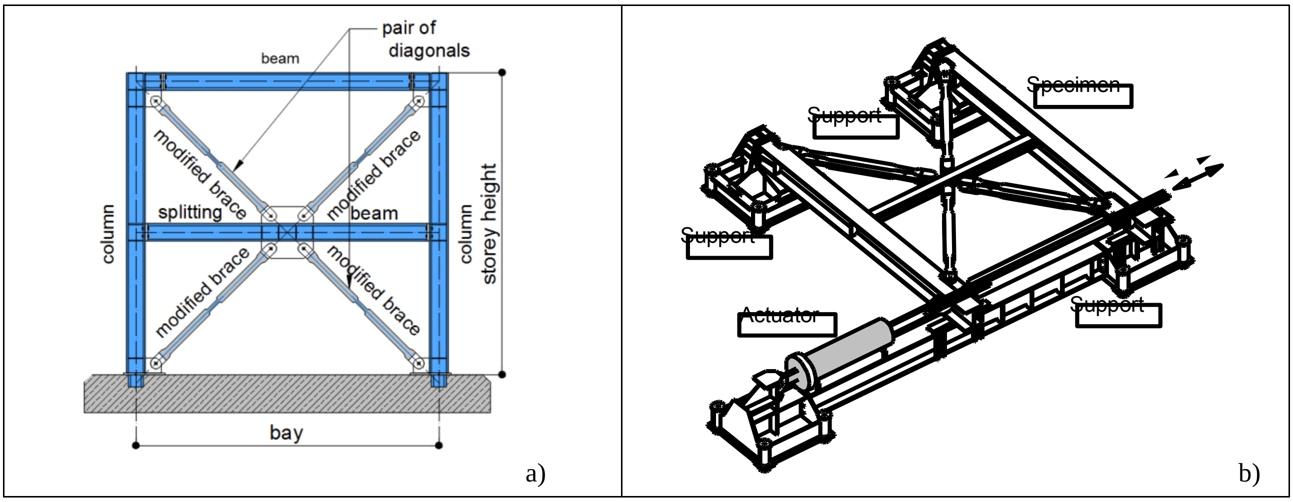

Fig. 1. a) Structural topology; b) Test setup;

In spite of the equivalence of all diagonals, it was registered that both compressed diagonals in a pair buckle at different value of the storey drift during the tests. Such effect may be addressed to braces initial imperfections, erection misalignment or combination of both. In the state when one diagonal has buckled and the other from the pair has not, unbalanced vertical and horizontal forces are induced, resulting in bending of the splitting beam and columns. Tests demonstrated that the lower the brace slenderness is, the more significant the splitting beam flexure is - *Fig. 2*.

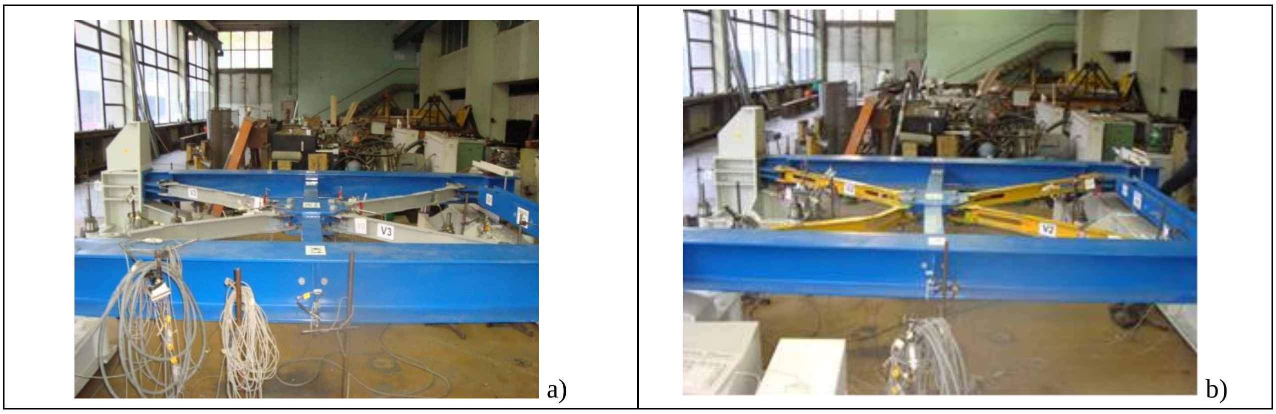

Fig. 2. a) X-CBF, brace slenderness 180; b) X-CBF, brace slenderness 120

3 NUMERICAL MODEL

3.1 Calibrated FE model

Calibrated fibre FE model is defined in SeismoStruct v7.0. [11]. The test specimen of CBF-MB is simulated mainly by inelastic force-based frame element type. The material hysteretic model used is the Menegotto-Pinto one with calibrated kinematic and isotropic hardening parameters to the experimental results. The diagonals material yield strength is 294,2 Mpa as derived from the performed standard tensile test. The single diagonal model is defined following the proposed modelling aspects in [12] by frame elements arranged to have bilinear initial camber Δo in the midspan of FE brace model. Camber is set to $(0.25\%)L_d$, where L_d is diagonal pin-to-pin distance. Joints between structural elements are modelled in accordance with the experimental set-up as partially fixed for the frame and pinned for the diagonals. Static time-history non-linear analysis in SeismoStruct is performed with the experimental loading history. Good agreement between the experiment and numerical test is achieved and illustrated in *Fig. 3 a)* for CBF-MB and in *Fig. 3 b* for the bare contour frame.

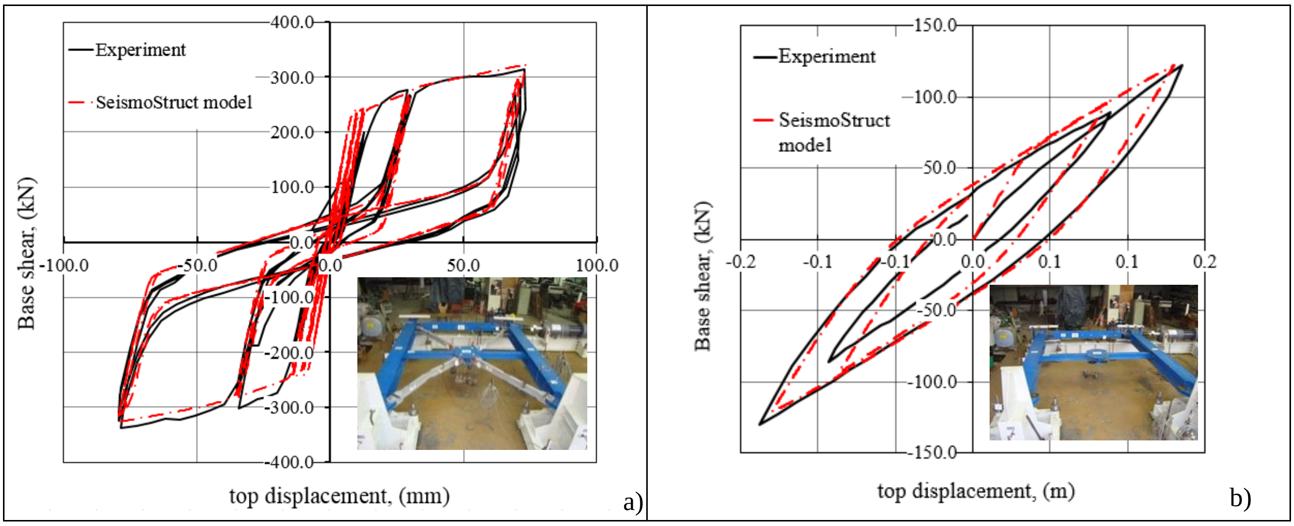

Fig. 3. Comparison between experimentally and numerically observed cyclic response of a) one-storey CBF-MB b) contour frame

Further numerical investigation is performed through series of static nonlinear analysis of the calibrated SeismoStruct model. In order to assess the influence of splitting beam and column stiffness on the global system behaviour, splitting beam cross section and column cross section are varied.

The numerical research was based on the assumption of different initial imperfection in braces midspan simulating non-simultaneous buckling of both braces in diagonal. Initial cambers of *(0.66%)*L_d is assumed for the lower brace and a sufficiently small camber *(0.125%)*L_d is assumed for the upper brace from a pair. Overall frame dimensions (column distance/storey height) are varied including cases with 3000mm / 4000mm, 4000mm / 6000mm and 6000mm / 4000mm.
It was investigated that both, column and splitting beam flexural stiffness influence the global plastic mechanism by acting as a storey H-shaped frame. Their bending elastic stiffness must be carefully proportioned in design. *Fig. 4* illustrates the global plastic mechanisms observed. The type shown on *Fig 4 a)* is characterized by uniform plastification of braces and may be defined as favorable one. Mechanisms shown on *Fig 4 b)* and *c)* are characterized with plastification of the splitting beam and columns respectively. The last two mechanisms are unfavorable and should be avoided by appropriate design. It was concluded that in case of unfavourable mechanism the storey H-shaped frame elastic stiffness is insufficient to provoke buckling of the unbuckled half of the compression brace and leads to concentration of flexural strains in the buckled brace.

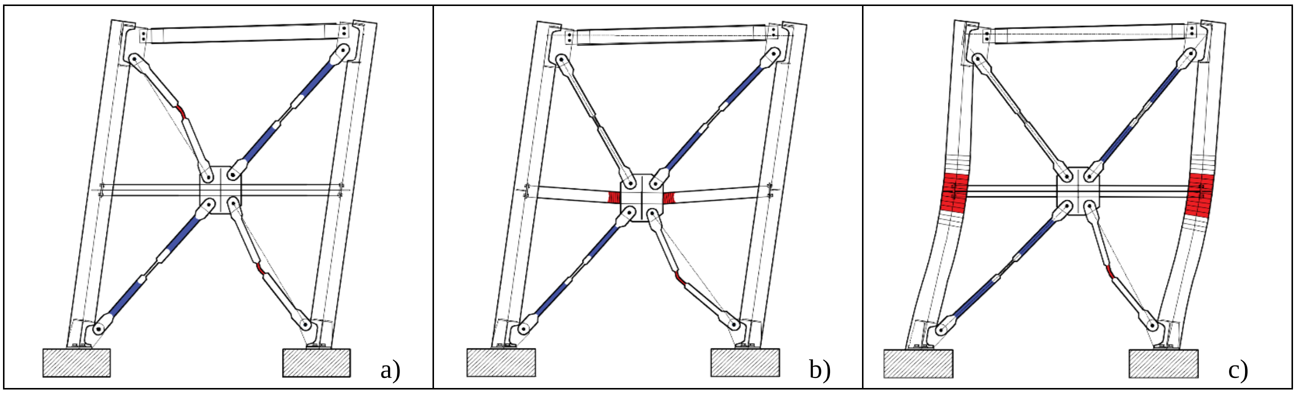

Fig. 4. Observed plastic mechanisms in CBF-MB: a) uniform plasticity b) weak splitting beam c) weak column

The influence of splitting beam stiffness on the sequence of buckling of compression braces in a pair is illustrated in *Fig. 5.* The figure presents the resultant capacity curves after performing a series of static pushover analysis of the calibrated model in SeismoStruct and varying the cross section of the splitting

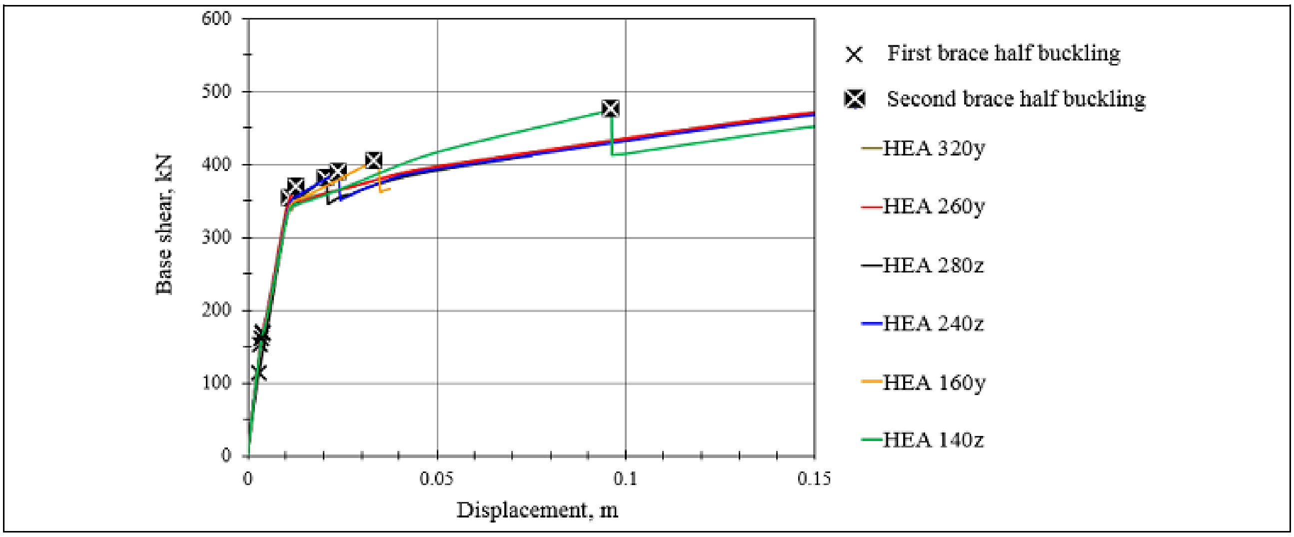

Fig. 5. Capacity curves of calibrated SeismoStruct models with different splitting beam cross section

beam. It is noticeable that as the splitting beam stiffness decrease, the second half of compression brace buckles at larger drifts. This is indicative for the ununiformity of braces elongations and shortenings which reflects in decreased endurance of braces life at cyclic reversal loads – plastic mechanisms illustrated in *(Fig. 4, b),c))*.

3.2 Simplified theoretical model

The influence of columns and splitting beam stiffness and strength was investigated in the former point. In order to define beam and column resultant stiffness demand a simplified theoretical model is proposed and illustrated in *Fig. 6*.

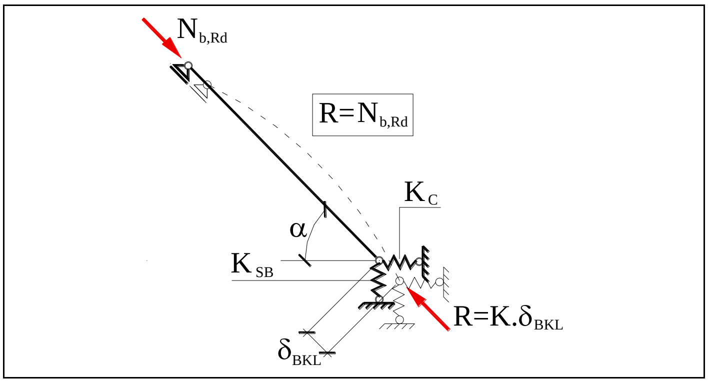

Fig. 6. Simplified spring model for defining cooperative beam and column stiffness

The proposed model represents half of the compression brace that hasn't buckled yet, supported by elastic springs representing columns and splitting beam stiffness. It is assumed that the axial force in the buckled half of the compression brace is equal to zero and the difference between axial forces in tension braces is negligible, therefore they are in equilibrium. Based on these conservative assumptions, these three braces are excluded from the theoretical model. Bending stiffness of columns is defined as for simple supported storey-to-storey elements and bending stiffness of splitting beam is defined as double-fixed element through the expressions:

$$K_C = \frac{2.48.EI_C}{H^3} \tag{1}$$

$$K_{SB} = \frac{\xi 48.EI_{SB}}{L_{SB}{}^3} \tag{2}$$

where I_C is the column cross section moment of inertia,
I_{SB} is the splitting beam cross section moment of inertia,
H is the storey height,
L_{SB} is the splitting beam length
ξ is a coefficient that takes into account the state of fixing of the splitting beam to the columns. Its values ranges from 1,0 (for pinned joints) to 4,0 (for fully fixed splitting beam). The determination of the actual value of ξ is accompanied by formation of supplementary elastic model of storey H-frame including two columns and one splitting beam.

According to the simplified spring model presented in *Fig.5*, it is easy to derive the resultant column and splitting beam stiffness K through *Eq. (3)*:

$$K = K_C \cos^2\alpha + K_{SB}\sin^2\alpha \tag{3}$$

It is well known that the reactive spring force R is a product of the spring stiffness K and the spring displacement δ. If we require that the spring force R is equal to the brace buckling resistence $N_{b,Rd}$, defined by [13] and if we define proper criteria for δ indicated as δ_{BKL}, then criteria for columns and splitting beam stiffness demand is easy to be formulated. Authors propose δ_{BKL} to be obtained through *Eq. (4)*:

$$\delta_{BKL} = 0,5.\left(0,004.H.\cos\alpha\right) \tag{4}$$

The physical criteria proposed for δ_{BKL} comes from the state at which buckling of both braces in a pair appears at frame storey drifts lower than 0,4%, which is less than the criteria defined in FEMA 356 [14] for Immediate Occupancy (IO) limit state. It is also assumed that the axial shortenings of the upper and lower compressed braces are equal, which requires certain stiffness of the splitting beam and columns.

Following the assumed stiffness criteria, some strength criteria should be defined as well. If we observe the state "just before buckling", corresponding to the assumptions of the theoretical model defined, the unbalanced forces may be derived and additional internal forces calculated. Their intensity is determined through static equilibrium in the intersection point between diagonals and splitting beam. This is illustrated in *Fig. 7* and the analytical expression of the resulting horizontal and vertical unbalanced forces is given by *Eq. (5-6).*

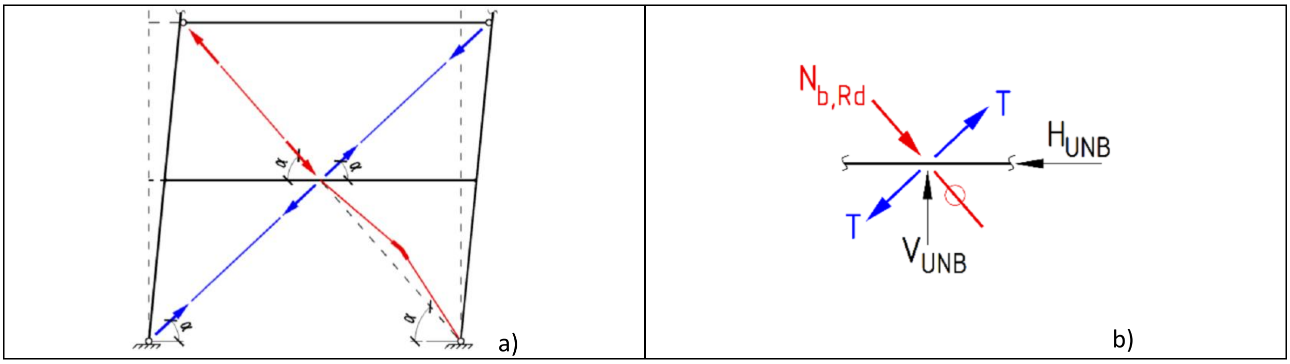

Fig. 7. a) Stage "just before buckling"; b) Unbalanced forces;

$$\mathrm{V}_{UNB} = N_{b,Rd}.\sin\alpha \tag{5}$$

$$\mathrm{H}_{UNB} = N_{b,Rd}.\cos\alpha \tag{6}$$

where $N_{\mathrm{b,Rd}}$ is the buckling resistance of the brace according to [13].

Numerical analysis through the software SeismoStruct have shown that fixing the splitting to columns and thus forming internal H-frame is advantageous. It provides enhanced self-centering capacity of the CBF-MB, minimizes the hysteresis pinching and leads to increased bending elastic stiffness of the splitting beam that is why splitting beam being fixed to columns is recommended by the authors.

3.3 Proposed design procedure

The guidelines proposed consider some specifities in design of non-dissipative elements (splitting beam and columns) in X-CBFs with braces that intersect into a beam. Dissipative elements (diagonals) and their connections should be designed in compliance with EN 1998-1 [1]. Splitting beam shall be fixed to the columns and shall be designed so as to avoid lateral-torsional buckling effects, having normalized slenderness $\bar{\lambda}_{LT}$ and satisfying *Eq. (7)*:

$$\bar{\lambda}_{LT} \leq 0,40 \tag{7}$$

Due to the constitution of internal H-frame it is also important that plastic hinge may appear in the splitting beam, not in column in all stages of structural performance - *Eq. (8).*

$$2.M_{Rc} \geq 1,3.M_{Rb} \tag{8}$$

where M_{Rc} and M_{Rb} are the design bending resistances of the column and the splitting beam respectively. It is not advisable to seek for economical design of the splitting beam, just the contrary. Due to their crucial impact on the overall inelastic behaviour of the system they must be designed with caution in accordance with the following principles. It is crucial that these elements are kept elastic and stiff enough in order to be able to supply the needed lateral stiffness in the state of zero lateral displacements and to prevent formation of unfavourable storey mechanism and brace buckling modes out of the frame plane.

Although CBFs are associated with truss systems and axial forces, authors recommend all joints being modelled adequately and the existence of bending moments and shear forces in columns and beams, being accounted for in the design. The internal forces including second order effects (M_E, V_E and N_E) in the seismic load case obtained through elastic analysis by tension-only diagonal model [1], shall be multiplied by capacity multiplier $1{,}1\gamma_{ov}.\Omega_{MIN}.\rho$. The first three parameters are strictly according to [1] and the parameter ρ=1,15 is proposed by the authors to account for the available overstrength of the system and the possible higher actual buckling resistance of the brace. That parameter may be adjusted for different ductility classes. Authors propose additional load case, named “UNB” (unbalanced) to be defined. It includes the unbalanced forces, formed in the considered “just before buckling” state defined and illustrated in *Fig. 6*. Unbalanced forces cause additional internal forces designated hereafter by the subscript “UNB”. These shall be added to the seismic internal forces and multiplied by the capacity amplifier to fulfill the principle “strong frame – weak diagonals” as expressed by the following *Eq. (9-11)*:

$$N_{Ed} = N_{Ed,G} + 1{,}1.\gamma_{OV}.\Omega_{\min}.\rho.(N_E + N_{UNB}) \tag{9}$$

$$M_{Ed} = M_{Ed,G} + 1{,}1.\gamma_{OV}.\Omega_{\min}.\rho.(M_E + M_{UNB}) \tag{10}$$

$$V_{Ed} = V_{Ed,G} + 1{,}1.\gamma_{OV}.\Omega_{\min}.\rho.(V_E + V_{UNB}) \tag{11}$$

4 CASE STUDY

In order to demonstrate the significance of the aformentioned factors and proposed design recommendations for the behaviour of CBF-MB a case study is presented. It is based on 2D analysis of CBF-MB extracted from a three-storey building with dimensions illustrated in *Fig.8.* Composite action with the concrete slab is not considered.

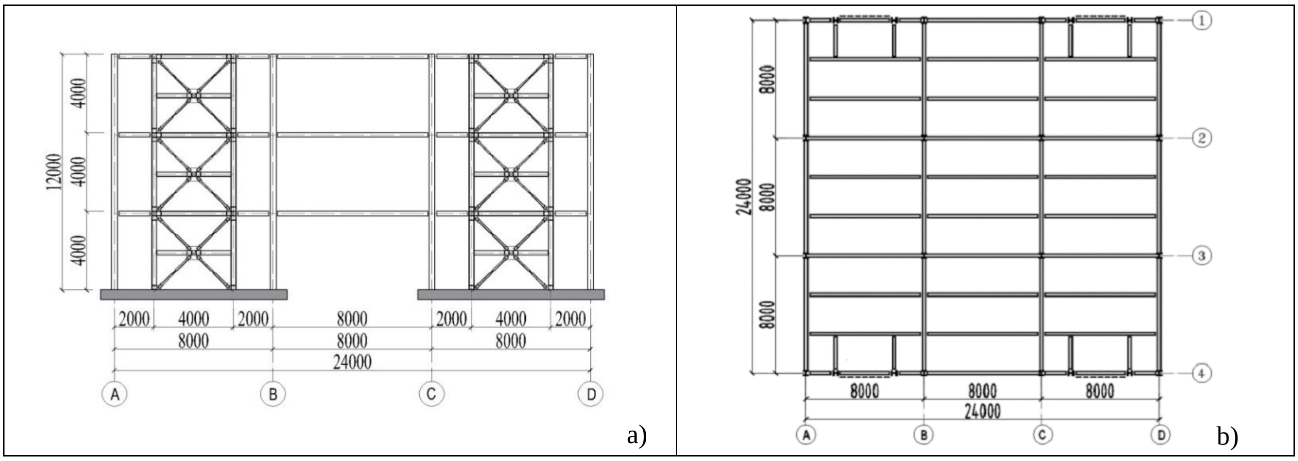

Fig. 8. 2D building frame and building plan

A preliminary design is conducted for vertical loads and hot-rolled sections are accepted for the main gravity loads elements. The assumptions for gravity loads are summarized in *Table 1*. Top floor loads are adopted as for occupied roof terrace. Seismic action is defined by design response spectrum for elastic analysis Type 1, the reference peak ground acceleration $a_{g,R}$ is taken as *0,32g* . It was considered ordinary office building requiring importance factor $\gamma_I = 1{,}0$ and correlated storey occupancies including roof terrace. The ground type is *B* ($T_B = 0{,}15$ *s*, $T_C = 0{,}50$ *s*) and behaviour factor $q=5{,}0$ was used as per results reported in [8].

Table 1. Building Loads

Vertical loads	
Structure self-weight	3,00 kN/m^2
Other permanent loads (ceiling, raised floor)	2,10 kN/m^2
Perimeter walls, storey height 4 meters	2,40 kN/m^2
Imposed loads:	
Intermediate floors / Roof floor (terrace)	3,00 kN/m^2 / 2,00 kN/m^2

It is assumed that total seismic mass is distributed equally between both CBF-MB in axes 1 and 4. Torsional effects from eccentricities of story masses are not taken in consideration in this example.

Beam FE element model in SAP2000 [15] with tension diagonal only is created for CBF-MB design. A multi-modal response spectrum analysis is performed. The results from the analysis are used for dimensioning of all diagonals. In order to assess the relevance of the proposed design guides for the non-dissipative elements (columns, beams and splitting beams) three cases through three models M1, M2 and M3 are analyzed. The cross section of the splitting beam is varied. Model M1 is based on design of non-dissipative elements according to the proposed design guidelines in section 3. Model M2 is based on design of non-dissipative elements according to the procedure in [1] but including capacity amplification for bending moments and shear forces for columns and beams. The last Model M3 is based on design of non-dissipative elements according to the procedure in [1] but including capacity amplification for columns and beams axial forces only. The resultant cross sections for splitting beams in the CBF-MB for the three design cases are summarized in *Table 2*. The resultant cross section and steel grade for floor beams is HEA 240 / S275 and for columns is HEA260 / S355.

Table 2. Cross sections of CBF-MB splitting beams

Model	**Splitting beam / Material**			**Utilization factor**		
	Storey 1	Storey 2	Storey 3	Storey 1	Storey 2	Storey 3
M1	HEA 260 /S355	HEA 260 /S355	HEA 240 /S275	0,73	0,54	0,50
M2	HEA 140y /S275	HEA 140y /S275	HEA 140 /S275	0,40	0,36	0,31
M3	HEA 140z /S275	HEA 140z /S275	HEA 140z /S275	0,57	0,50	0,43

A sophisticated finite element model of the examined three-storey CBF-MB is created in SeismoStruct [11] using inelastic force-based elements for braces, columns and beams and elastic frame elements for gusset plates. Material hysteretic model used is the Menegotto-Pinto one with adjustment of some parameters as described in point 3.1. The diagonals material yield strength is set to be 235 Mpa.
The diagonal is defined by inelastic frame elements with bilinear initial camber Δo assigned. In order to provoke non-concurrent buckling of compression braces different initial cambers are assigned for both braces in a pair. Initial camber of $\Delta o=0,66\%.L_d$ is assigned to lower brace halfs at each storey and initial camber of $\Delta o=0,125\%.L_d$ is assigned to upper ones. Joints between structural elements are modelled as pinned for diagonals, pinned for floor beams to column, pinned for column base and fixed for splitting beams to columns. Second order effects are taken into account by modelling a leaning column with initial inclination according to [13]. Non-linear pushover analysis is performed and the resultant capacity curves are obtained. *Fig. 9* summarizes the resultant capacity curves for the three models and indicates the limit states Damage Limitation (DL), Life Safety (LS) and Near Collapse (NC) with the storey drift limits according to [14].

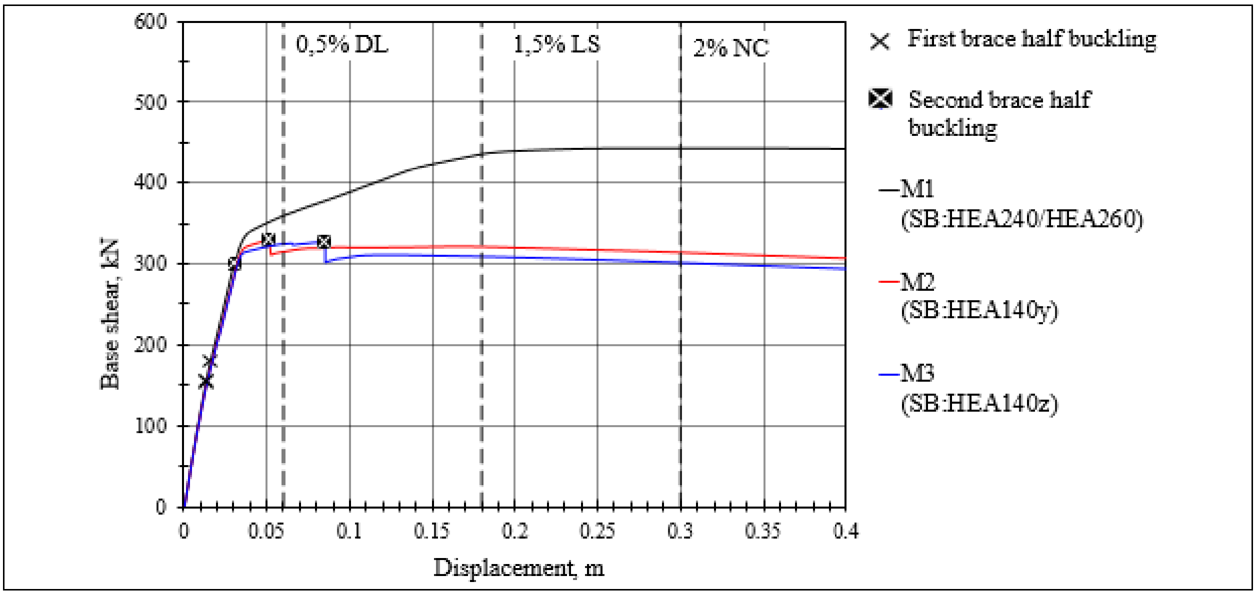

Fig. 9. Capacity curves for models M1, M2 and M3

It may be noticed that following the proposed design guidelines (M1) leads to proper structural overstrength and hardening. Models M2 and M3 demonstrate softening branch that is attributed to the dominating *P-Δ* effects after yielding of tension braces, prevailing the structural hardening. The former is result of insufficient horizontal stiffness of the H-frame formed by columns and splitting beams. The difference of buckling of braces halfs in time results in sharp drop in the capacity curve. It is evident that the proposed criteria for buckling of second brace half before drift 0,4% is verified and this results in improved non-linear behaviour.

The type of the plastic mechanisms for drifts 0,5%, 1,5% and 2% are illustrated in *Fig. 10.* They correspond to the limit states defined by [14]. It can be noticed that following the proposed design guidelines leads to uniform plastification of braces. Models M2 and M3 demonstrate non-uniformity of plastic strains in braces. This may significantly reduce the brace cyclic life and structural ductile behaviour.

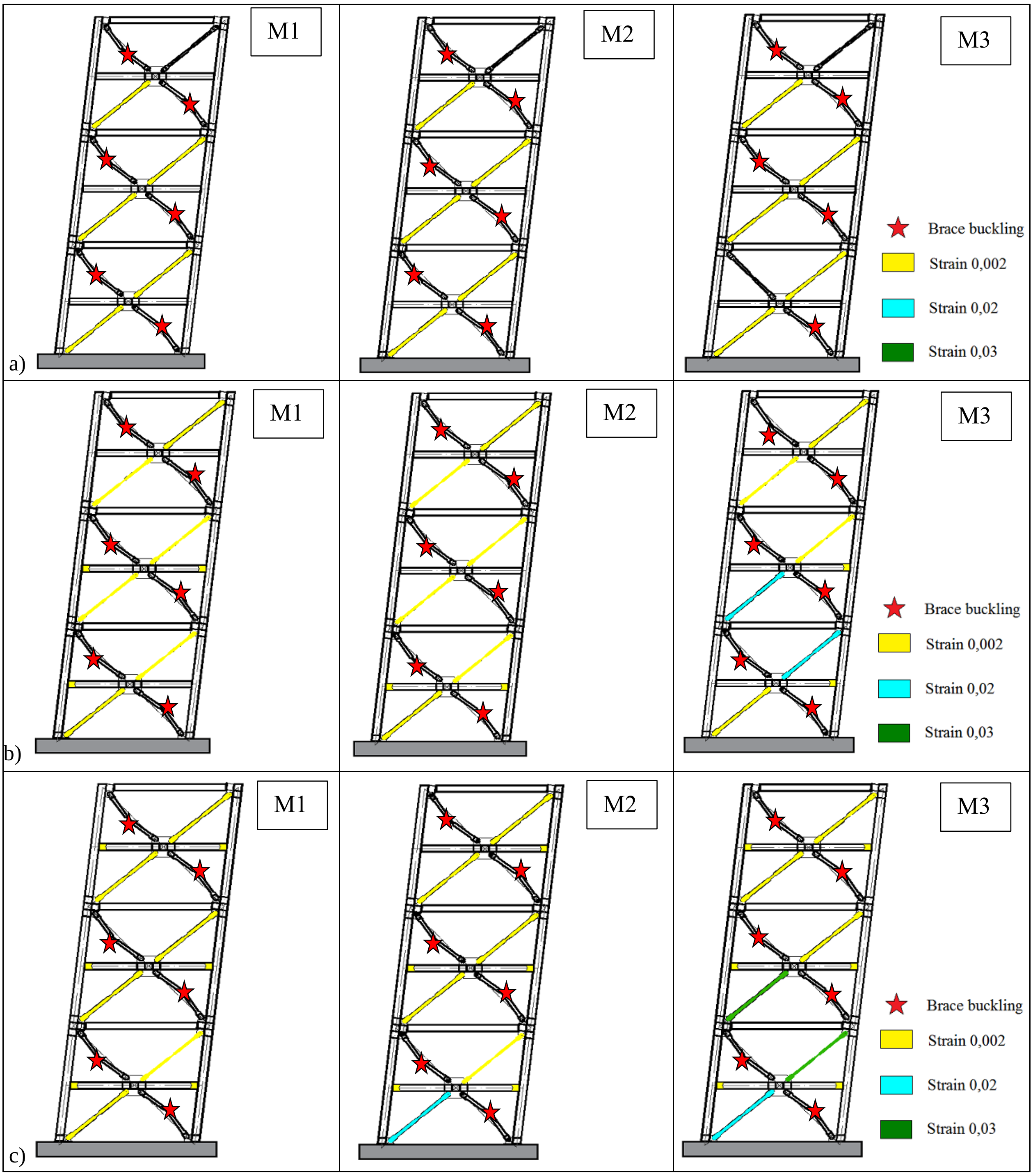

Fig. 10. Resultant deformed shapes for interstorey drift states: a) DL 0,5% b) LS 1,5% c) NC 2,0% (continued)

5 SUMMARY

The experimental and numerical tests discussed in the paper, have demonstrated that the stiffness of the splitting beam and columns directly affects the type of plastic mechanism that the CBF is going to perform. Depending on the splitting beam and column stiffness and strength, two types of mechanisms are identified: either both diagonals in a pair buckle or only one diagonal buckles – *Fig. 4*. The latter mechanism should be avoided, since it leads to plastic strains concentrations and premature exhausting of brace ductility or reduction of brace cyclic life.
As demonstrated in the paper, splitting beam stiffness has to be adjusted to the buckling resistance of the brace. The proposed analytical model and design procedure results in increase of the beam stiffness and establishes a source of H-frame stiffness that improves the inelastic CBF-MB behaviour and provides self-centering capacity of the system. The experience gained from the research of CBF-MB clearly indicates that splitting beams should be kept elastic with possible development of some flexural plastic hinges near LS performance level.

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