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Proposal to increase the ductility of steel structures

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ABSTRACT: The failure of a wide flange beam can be due to local plastic plate buckling of the flange and web in flexural compression, produced in-plane or in out-of-plane local buckling. In the same time the failure can occurs by coupling of these two local buckling. The out-of-plane plastic buckling presents a reduced ductility in comparison with the in-plane buckling. In order to study the plastic buckling of beams and to determinate the rotation capacity required by the plastic analysis or seismic design, the local collapse plastic mechanism theory was used to elaborate a specialized computer program DUCTROT-M. Using the results obtained from this computer program, the geometrical parameters of wide-flange steel beams to avoid the out-of-plane buckling are determined.

1 INTRODUCTION

In the plastic analysis and seismic design of structures, the ductility, measured by the plastic rotation capacity, plays a predominant part. In the plastic design, the member should be capable of forming plastic hinges and these hinges must rotate until the global collapse mechanism is reached without losing moment capacity. Thus the required redistribution of bending moment is reached without losing moment capacity. In the earthquake-resistant design, this rotation capacity is essential to assure that a determined portion of the input seismic energy shall be dissipated by plastic behavior.

In the design practice it is generally accepted that steel is an excellent material for plastic structural analyses, due to its performance in terms of material strength and ductility, as it is capable of withstanding substantial plastic deformations. But in the last decades, specialists have recognized that so-called good ductility of steel structures under exceptional conditions may be a dogma, which is denied by the reality. A good material ductility does not certainly assure a good ductility at the level of overall structures, due to some factors among them the most important being the local plastic buckling.

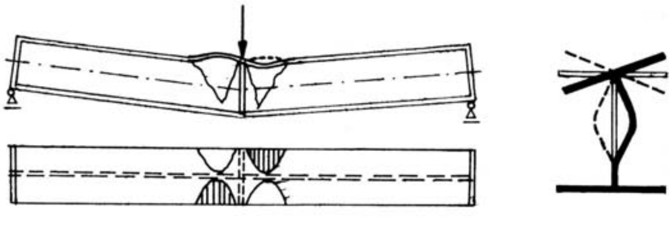
In this paper the local buckling will be considered only for the wide-flange beams. Local plastic buckling of compression flange and web reduces the rotation capacity, but in the same time this buckling operates in a filter against large strains in the tension flange reducing the danger of cracking (Gioncu & Petcu, 1997; Gioncu & Mazzolani, 2002). Two main buckling types are observed during the experimental tests, in-plane and out-of-plane buckling modes and interactions of them are observed (Lukey & Adams, 1969). Due to the fact that the out-of-plane buckling mode shows a drastically reducing of rotation capacity, both in static and seismic loads, the paper deals with the possibility to avoid this instability mode by adequate choosing of beams geometrical parameters.

2 PLASTIC BUCKLING, PLASTIC MECHANISMS AND COUPLED INSTABILITIES

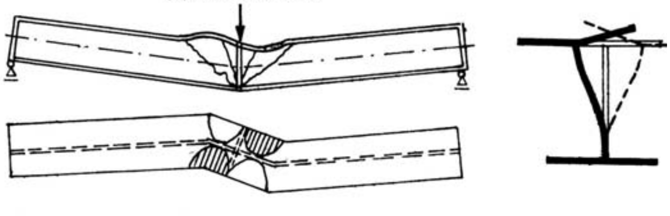
During the experimental tests on the profiles framed in Classes 1 or 2 (elastic buckling being avoided) one can observe that the plastic deformations are produced only in a limited zone, the rest part of the member remaining in elastic field. In this plastic zone large rotations are concentrated, working as plastic hinges. The plastic rotations are amplified if in these zones a buckling of flanges occurs. Examining the experimental and numerical simulation presented in literature, some very important conclusions results.

(i) During the plastic deformations, crumpling of flanges and webs can be observed, which form a local plastic mechanism, composed of yield lines and plastic zones. Therefore, the study of plastic buckling can be performed using the analysis of the corresponding local plastic mechanism.

(ii) There are many forms of local plastic buckling, depending on the geometrical proportions of



(a) In-plane buckling



(b) Out-of-plane buckling

Figure 1 Plastic buckling modes

beams, but the most important are the in-plane buckling (asymmetrical with the cross-section, Fig. 1a) and out-of-plane buckling (asymmetrical related to the beam middle, Fig. 1b).

(iii) For positive moments, due to the floor effect, only in-plane buckling mode occurs. In exchange, for negative moments, the both buckling modes can be active (Fig. 2).

(iv) A coupling between these two instability modes is observed during the experimental tests. In the majority of cases, the plastic buckling starts with in-plane buckling, but, due to the weakening in lateral rigidity caused by the plastic buckling, the lateral buckling occurs. In this case the lowering post-buckling curve is dominated by the interaction of the two buckling modes.

(v) The interaction between these two buckling modes frames in the category of weak one (Gioncu et al, 1996).

(vi) Due to this plastic buckling, in the moment-rotation curve a maximum value for bending is reached and a drop in a moment capacity is produced (Fig.3). The rotation capacity being conventionally determined in a lowering post-buckling curve at the intersection with the theoretical full plastic moment, the slop of this curve plays a leader role in the calculation of beam ductility.

(vii) Due to the fact that the slope of lowering curve is more pronounced for the out-of-plane mode in comparison with the in-plane mode, it is very important to determine if the interaction between these two buckling mode occurs over or under the line defining the rotation capacity. In Figure 4a, the interaction occurs under the line and has not any influence on determining the rotation capacity. Contrary, Figure 4b shows the case when the interaction takes place over this line, when the rotation capacity defined by the out-of-plane mechanism, for which a reduced value is obtained.

(viii) Considering these aspects, the best solution to obtain a larger value for rotation capacity is to determine the proportion of cross-section in the way to obtain an in-plane plastic buckling mode, avoiding out-of-plane buckling mode.

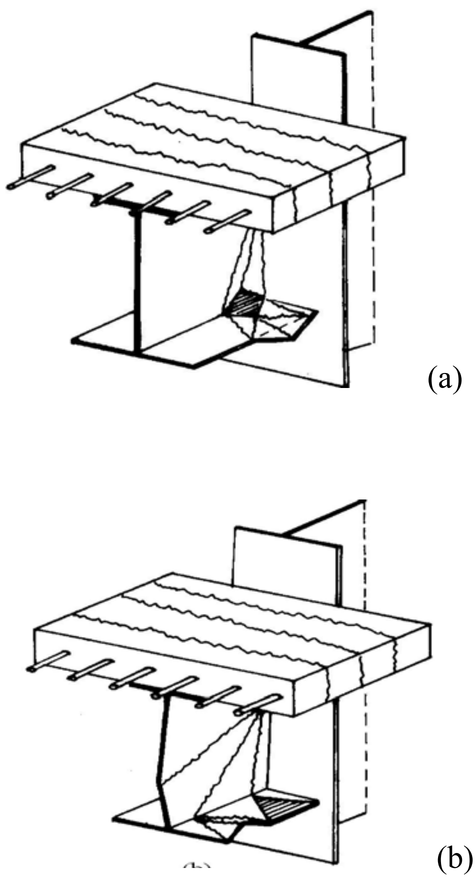


Figure 2 Plastic mechanisms for negative moment: (a) In-plane mechanism; (b) Out-of-plane mechanism.

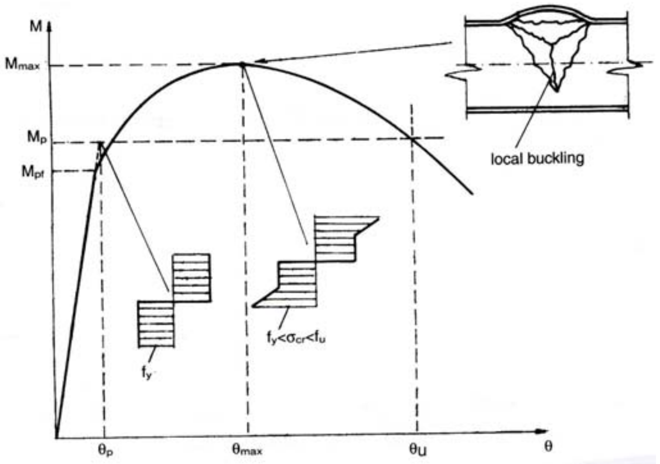
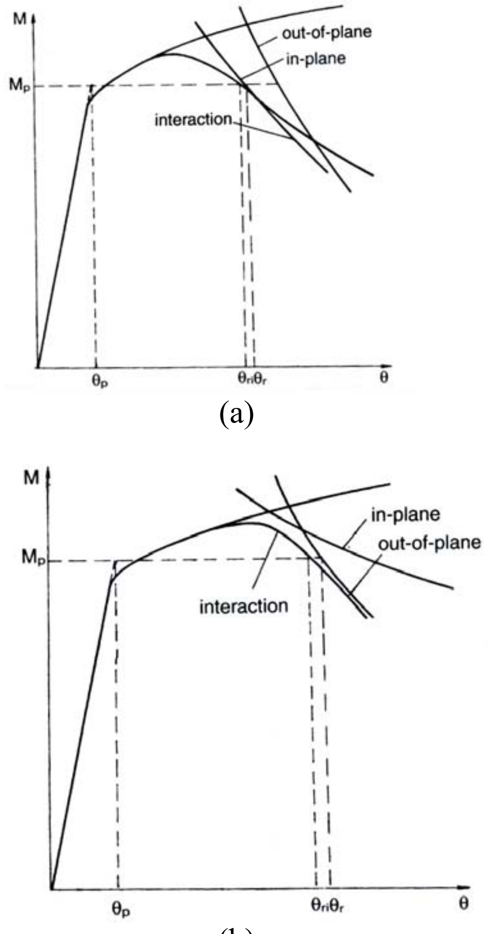


Figure 3 Moment rotation curve

3 DUCTROT-M COMPUTER PROGRAM

The specialized computer program DUCTOT-M (DUCTility of ROTation of Members) is developed



(a)

(b)

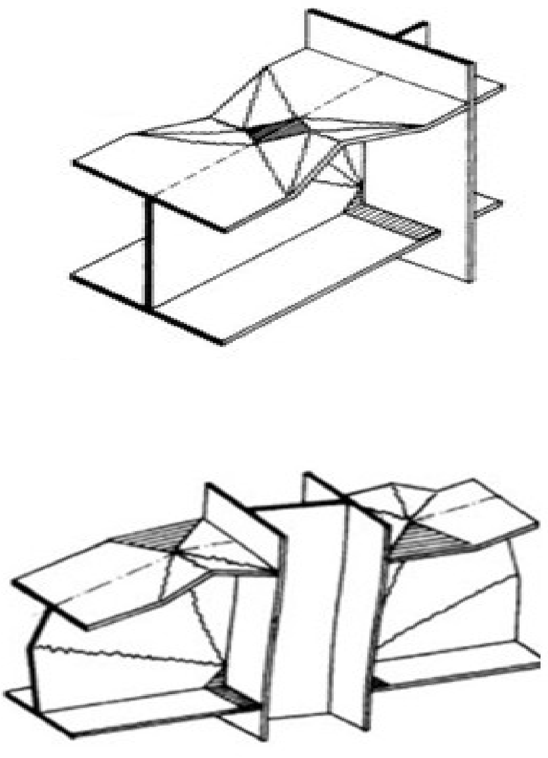
Figure 4 Interaction between in-plane and out-of-plane plastic buckling

at Timisoara University with the aim of determining the ultimate plastic rotation based on the method of collapse plastic mechanisms (Petcu&Gioncu, 2002). Two plastic mechanisms are considered: in-plane (Fig. 5a) and out-of plane (Fig. 5b) mechanisms. Using the principle of the minimum of the total potential energy for the plastic mechanisms, it results the post-buckling curves (Gioncu & Mazzolani, 2002):

$$\frac{M}{M_p} = a_1 + a_2 \frac{1}{\theta^{1/2}}; \tag{1}$$

$$\frac{M}{M_p} = b_1 + b_2 \frac{1}{\theta^{1/2}} + b_3 \frac{1}{\theta^{3/2}}; \tag{2}$$

The first equation refers to the in-plane mechanism and the second to the out-of-plane mechanism. The coefficients a…b contain the geometrical characteristics of beams and plastic mechanism, given in Gioncu & Mazzolani (2002). One can see that, in comparison with the equation (1) for in-plane mechanism, in equation (2) for out-of-plane mechanism, a supplementary term appears, which produces a more important degradation in the post-buckling range. A validation of the results obtained using DUCTROT-M program shows a very good correspondence with numerical results, using FEM, and experimental results, presented in literature, giving confidence in the developed local plastic mechanism methodology (Petcu & Gioncu, 2002).



(a)

(b)

Figure 5 Collapse mechanisms: (a) In-plane; (b)Out-of-plane

4 STATIC NUMERICAL RESULTS

In order to assure the required ductility in plastic or seismic analyses the paper presents the case of plastic instability of wide flange beams, where the rotation capacity is a very important characteristic. For wide-flange profiles there are two local buckling forms, in-plane and out-of-plane modes. To study these plastic instabilities, the using of local mechanisms has proven to be a very useful methodology. Based on the theory of plastic local mechanism, a computer program DUCTROT-M was developed at "Politehnica" University of Timisoara. Using this computer program the both local plastic mechanism can be studied. In the same time the interaction between them can be considered. For some values of cross-section characteristics, plastic coupled instabilities can occur, but this interaction can be framed in weak one. The most important aspect refers to the fact that out-of-plane buckling reduces the ultimate rotation capacity of beams due to the fact that the slop of lowering curve is more pronounced for the out-of-plane mode in comparison with the in-plane mode. The DUCTROT-M computer program allows choosing the geometrical dimension of beams in order to avoid the out-of-plane buckling. An application for some welded wide-flange beams shows the importance of flange and web thickness ratio in order to obtain the maximum values for rotation capacity.

5 NUMERICAL RESULTS

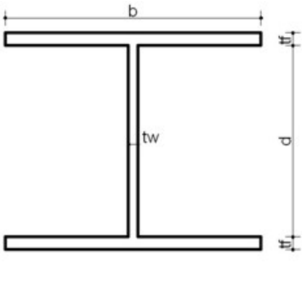
Using the possibilities offered by the computer program, a study of coupled plastic buckling was performed for welded wide-flange beams. The geometrical dimensions of considered cross-sections are presented in Table 1. The span for all the beams is 5000 mm and the steel qualities correspond to S235.

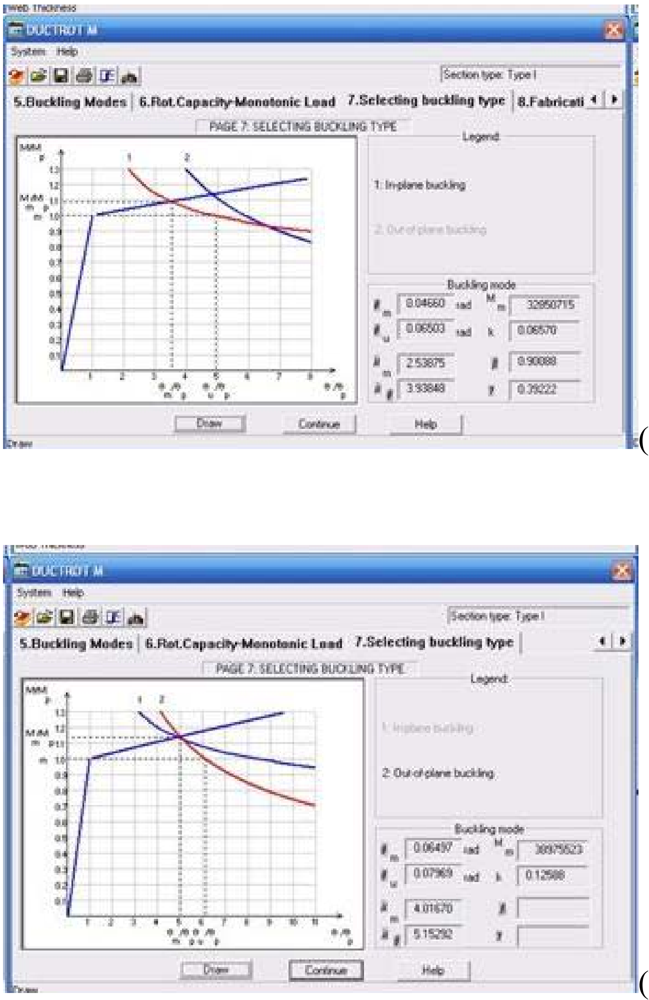
Figure 6 presents some snapshots specific for DUCROT- M's interface, for different cases (beams A2 from Table 1 with t_f =12 mm and t_f =14 mm). These figures illustrate the experimental observation (see section 2-IV) that during the plastic buckling an interaction between in-plane and out-of-plane modes occurs. In the first case the ultimate rotation is determined by the in-plane mechanism, having a reduced degradation of beam rigidity after a plastic buckling. In the second case, the ultimate rotation results from the out-of-plane mechanism, with a higher degradation after the plastic buckling.

The first Set A of beams (Table 1 and Figure 7) shows the influence on the rotation capacity of the flange thickness for a given web thickness. One can see that the in-plane plastic bucking is strongly influenced by the flange thickness increasing, while the out-of-plane plastic buckling is less influenced by thickness increasing. Therefore a limit value of web and flange thickness ratio can be defined in order to avoid the out-of-plane plastic bucking. For the Set A beams, this ratio ranges in interval 0.7 to 0.8, the lower and upper limits being available for reduced and larger profile height, respectively.

Table 1. Geometrical parametric of beams

Beam	b	d	tf	tw
	mm	mm	mm	mm
A1	160	240	8÷14	8
A2	200	300	10÷16	10
A3	300	400	12÷18	12
A4	400	500	14÷20	14
B1	160	240	12	6÷12
B2	200	300	14	8÷14
B3	300	400	16	10÷16
B4	400	500	18	12÷18





(a)

(b)

Figure 6 DUCTROT-M's interfaces

The second Set B of beams (Table 1 and Figure 8) presents the case of web thickness increasing, for a given flange thickness. One can see that, in the case of out-of-plane plastic buckling, web thickness increasing has less influence on increasing the rotation capacity. In exchange, the increasing has a contrary effect on the in-plane plastic buckling, the rotation capacity decreases drastically with the increasing of web thickness. The maximum rotation capacity is obtained at the intersection of two curves. Therefore, in order to have a good rotation capacity, the web to flange thickness ratio must be included in the interval 0.8 to 0.7. The first limit is valuable for reduced profile height and the second one for large profile height.

Considering these results, one can conclude that in order to obtain a valuable rotation capacity, the ratio between web and flange thickness must be chosen in the interval of 0.7 to 0.8.Similar parametrical studies, in order to eliminate out-of-plane mechanism, can be performed for another section dimensions.

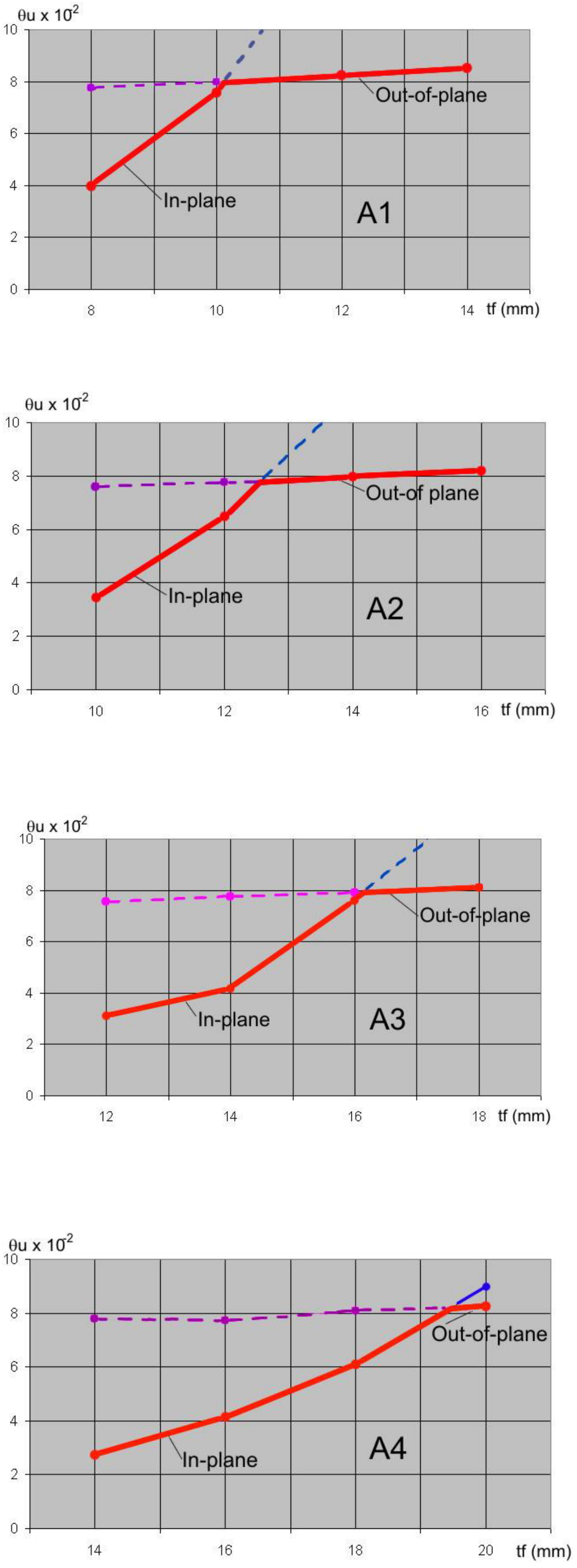


Figure 7 Plastic coupled instabilities vs. flange thicknesses

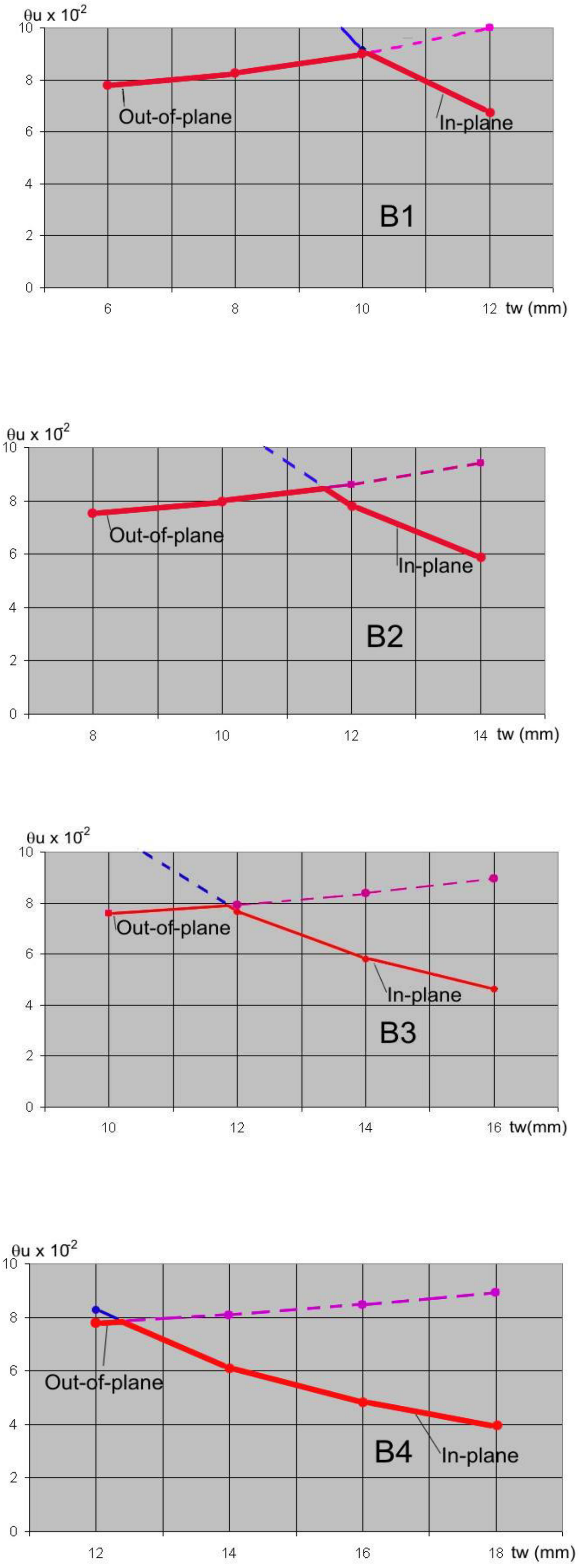


Figure 8 Plastic coupled instabilities vs. web thicknesses

6 WAY THE ELIMINATION OF OUT-OF-PLANE BUCKLING IS RECOMMENDED IN SEISMIC DESIGN?

In the companion paper (Gioncu & Mazzolani, 2009) for steel frames the verification of the available ductility is divided in two steps. In the first one, a static and monotonic value is determined and in the second one, the influence of seismic dynamic effects is considered. These effects can reduce more or less the static determined value, in function of earthquake type, but also depend of local plastic mechanism type, formed after the plastic buckling.

Theoretical and experimental tests (Mateescu & Gioncu, 2000) have shown that the most drastically reduction of carrying capacity and ductility, in case of pulse or cyclic loads, is obtained when the plastic buckling is governed by out-of-plane mechanisms.

In addition, it is very well known the dog-bone solution to protect the welded connections against brittle fracture. Experimental tests (Chi and Uang, 2002) have shown that the failure of connection during cyclic loads is due to out-of-plane plastic buckling of zone of reduced beam section and the degradation of connections is accelerated by this mechanism type.

Therefore, for seismic loading, it is recommended the elimination of out-of plane plastic mechanism, by choosing the section dimensions in such a way that the plastic buckling be governed by in-plane mechanisms.

7 CONCLSIONS

The paper presents arguments to choosing the member dimensions in such a way to eliminate the out-of plane plastic mechanism. These ones are required in order to improve the behaviour of steel structures: increasing the capacity of bending moments redistribution (for plastic structural analysis) and reduce the degradation after plastic buckling (for seismic analysis). The use of facilities offered by DUCTROT-M computer program allows performing this objective.

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