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Ductility Aspects of Steel Beams

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Abstract

Using the DUCTROT-M computer program, a comparison between cross-section ductility classes, recommended in codes, and member ductility classes, proposed in technical literature, is performed, showing very important differences. Because the out-of-plane plastic mechanism produces very high ductility degradation during a cycling earthquake, the study determines the measures to eliminate this mechanism mode. The parametrical study considers as parameter the dog-bone procedure, fabrication (welding or hot-rolling), material properties, geometrical beam dimensions and effects of constructional details..

Rezumat

Folosind programul de calcul DUCTROT-M se face o comparative intre clasele de ductilitate de sectiune, cerute in norme,si clasele de ductilitate de element, propuse in literature tehnica, rezultand diferente foarte mari. Deoarece mecanismul plastic in afara planului produce o importanta degradare in timpul cutremurelor, studiul stabileste masurile pentru eliminarea acestui tip de mecanism. Studiul parametric considera ca parametri solutia dog-bone, tipul de fabricatie (sudura sau laminare), proprietatile materialului, dimensiunile principale ale grinzilor, precum si efectele masurilor constructive.

Keywords: Ductility, rotation capacity, local plastic mechanism, in-plane mechanism, out-of-plane mechanism, parametrical studies

1. Introduction

In the book [1] a methodology based on local plastic mechanism and the development of a computer program DUCTROT-M (annex in [1]) for determining the rotation capacity of wide-flange beams are presented. Based on the experimental evidences, two main plastic mechanisms are developed, in-plane and out-of-plane.. A validation of this methodology using the experimental data from the technical literature shows that the results obtained the DUCTROT-M can be used in practical design [2]. In this paper, the applications of the computer program are considered, by analyzing the practical aspects of structural design.

The first analyzed problem refers to the dispute cross-section ductility versus member ductility, the first methodology being used by codes, being contested by many research works [3]. Having the possibility to compare the results of the two approaches, it is on right side to lighten this dispute.

Examining the theoretical and experimental results obtained on standard beams presented in the [1] and relating these ones to the practical aspects, two main critics can be mentioned:

- The neglect of the presence of steel or concrete floors on rotation capacity, the formation of plastic local mechanism being impeded by the presence of floor. Therefore, in many cases, the quasi-constant moment case must not be considered in design practice.

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- All of these theoretical and experimental research work neglect the fact that the beams are connected to columns and the rotation in out-of-plane of nodes is not free (as in case of standard beams) due to the presence of transversal beams connected in joint. In these conditions, the main local plastic mechanism is the in-plane one.

The last part of paper examines the main characteristics influencing the member ductility for rolled and welded beams.

2 Cross-section ductility versus member ductility

There are two ductility type widely used in literature to characterize a beam into a structure [3] (Fig. 1):

(i) Cross-section ductility, or curvature ductility, which refers to the plastic deformations of cross-section, considering the independence behaviour of the parts composing the cross-section itself.

(ii) Member ductility, or rotation ductility, when the properties of members (interaction between cross-section parts, influence of beam span and loading system) are considered.

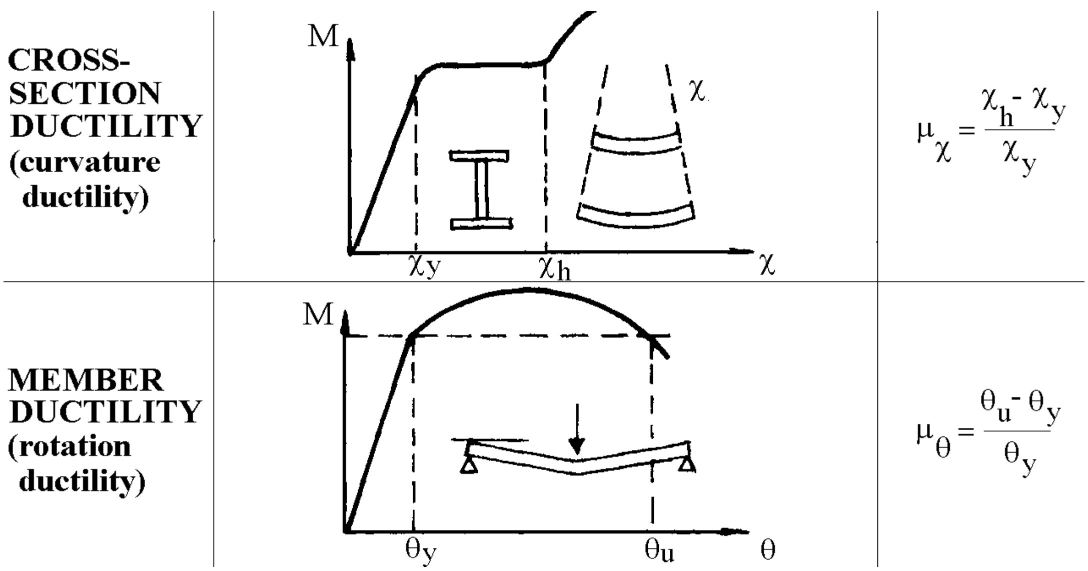

Figure 1.Ductility types: Cross-section and member ductilities

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The characterization of structural ductility by one of these two types gives rise to many discussions in the frame of specialists [3].

The first definition is mainly used in code provisions, based on cross-section behaviour classes (Fig. 2) [4]:

- C1, class 1, plastic sections; sections are characterized by the capacity to develop a plastic hinge with high rotation capacity;
- C2, class 2, compact sections; sections are able to provide their maximum plastic flexural strength, but they have a limited rotation capacity due to some local effects.

- C3, class 3, semi-compact sections; the bending moment capacity for the first yielding can be attained, without reaching the plastic moment.
- C4, class 4, slender sections; sections are not able to develop their total flexural resistance due to the premature occurrence of local buckling in their compression parts.

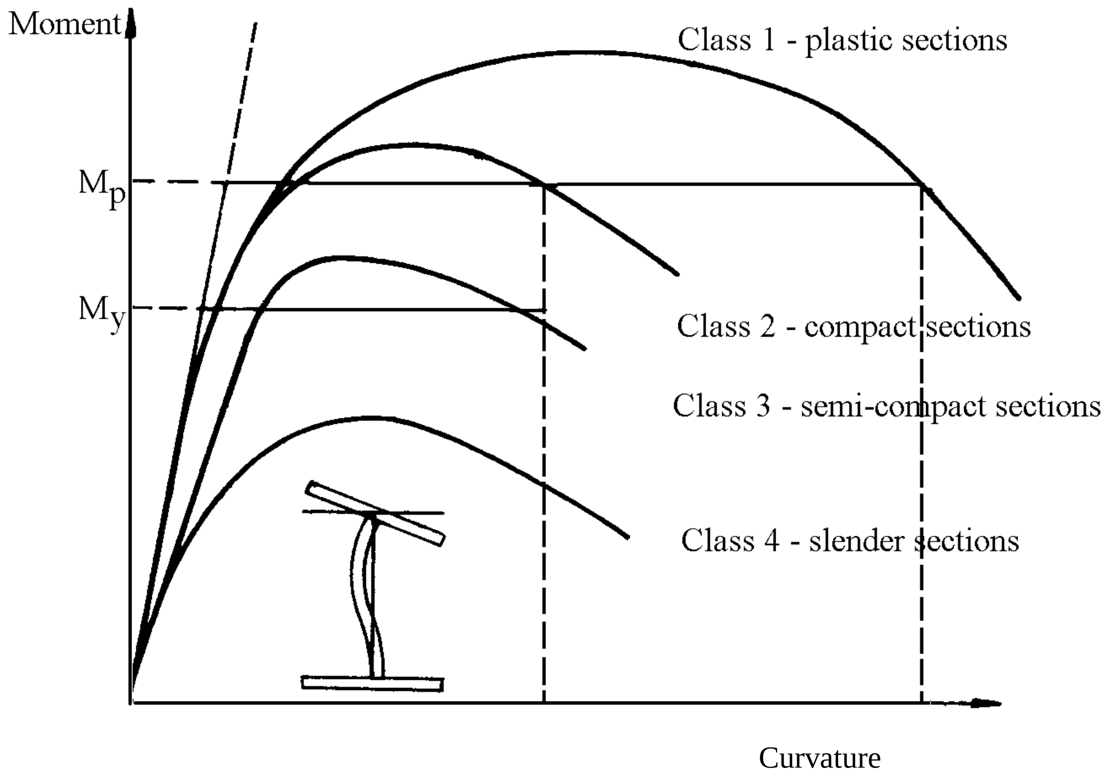


Figure2. Cross-section classes

This classification limited at the cross-section level only has many deficiencies [3]:

(i) Independent limitations between flanges and web ratios are unreasonable because, obviously, the flange is restrained by web and the web by the flange.

(ii) The local ductility depends not only on cross-section dimensions, but also on the ratio between width of flange and web, member length, and loading type.

(iii) The subdivision in different classes does not correspond to the actual behaviour of beams which it is continuous and the given discrete values of slenderness to define different classes seem to be very arbitrary.

In spite of these of these recognized deficiencies, this classification is used in codes, due to its simplicity in design practice.

Another more effective classification at the level of member ductility for design has been proposed in [1], [5] (Fig. 3):

- HD, high ductility, corresponding to members designed, dimensioned and detailed such that they ensure the development of large plastic rotations.
- MD, medium ductility, corresponding to members designed, dimensioned and detailed such that they ensure the development of moderate plastic rotations.
- LD, low ductility, corresponding to members designed, dimensioned and detailed such that they ensure the development of low plastic rotation only.

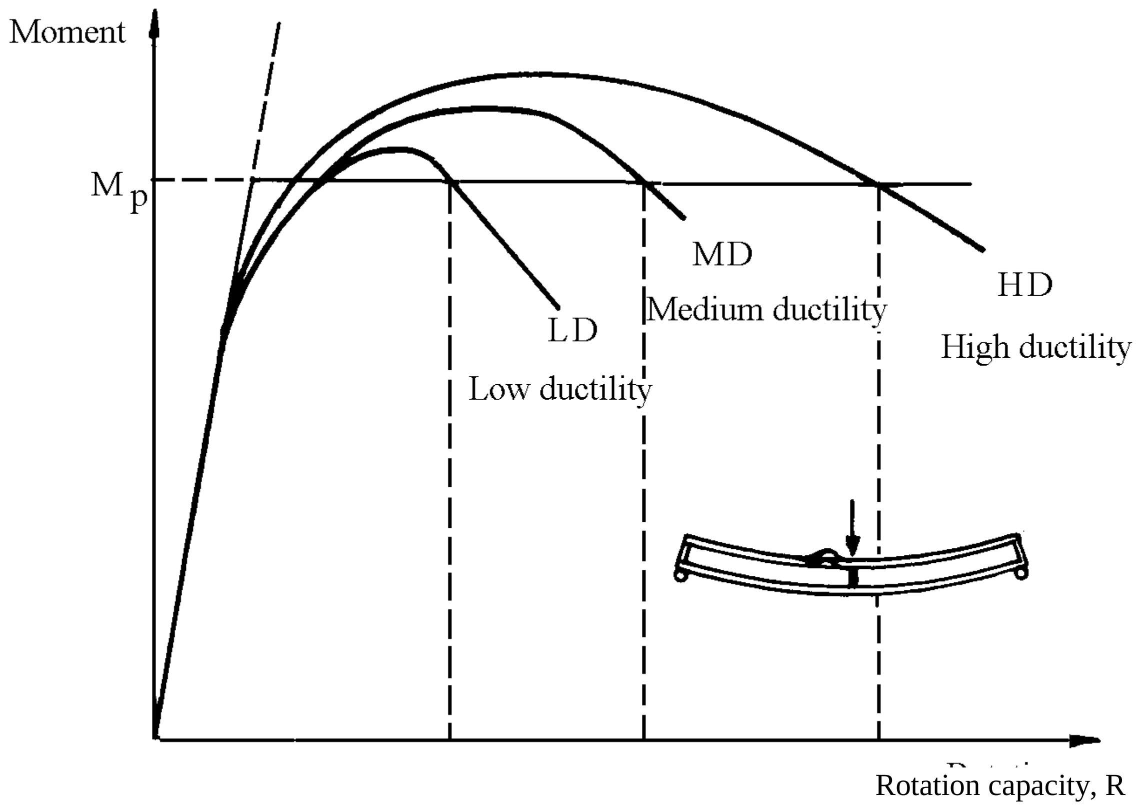


Figure3. Member ductility classes

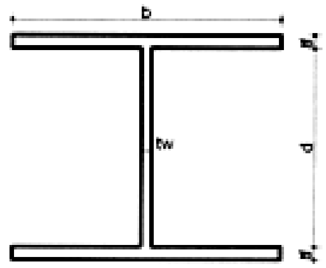
Considering the definition of ultimate rotation capacity given by relationship (3) from [1], the classification criteria are:

- HD, R.> 7.5
- MD, 4.5 < R < 7.5
- LD, 1.5 < R < 4.5

Members having R <1.5 are considered non-ductile.

The comparison between the results obtained using DUCTROT- M computer program for member ductility and the code provisions for cross-section ductility is presented in Figures 4 and 5 for welded beams. Only in-plane plastic mechanisms are considered (see Section 3). In these Figures the hachured areas show the cases when the two classifications are coincidental. One can see that the coincidence is very poor.

In Figure 4 a section with web slenderness belonging to C1 class. For t_f = 8, 10, 12 mm on can see that, while in member ductility the profile belongs to LD, MD, HD classes, respectively, independent of flange width, in cross-section the belonging to cross-section classes changes in function of flange width. For instance, the profiles with t_f = 12 mm can be framed in HD class for entire field of flange width b = 120 – 280 mm, while for b > 216 mm the profile framed in C2 class, and for b > 240 mm in C3 class. So, the framing in different classes in function of flange slenderness is contestable.



Beam	b mm	d mm	tf mm	tw mm
	120-280	300	8-12	8

L = 5000 mm

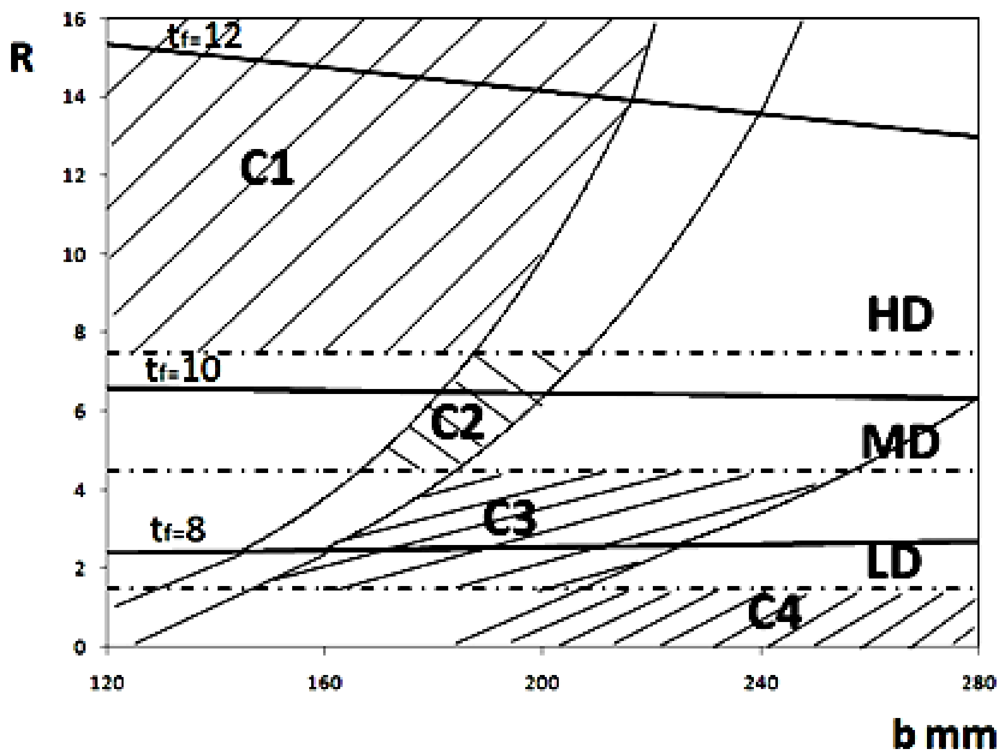
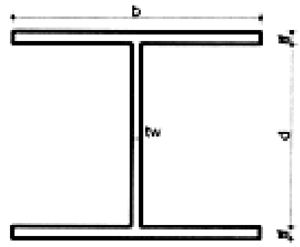


Figure4. Cross-section versus member classes for a profile with C1 class for web

Figure 5 considers a profile with web slenderness belonging to C2 class due the high slenderness of web. In spite of this classification, having t_f = 12 mm, the profile can be classified having HD class. So, even the framing in different classes in function of web slenderness is contestable.



Beam	b mm	d mm	tf mm	tw mm
	120-360	450	8-12	6

L = 6000 mm

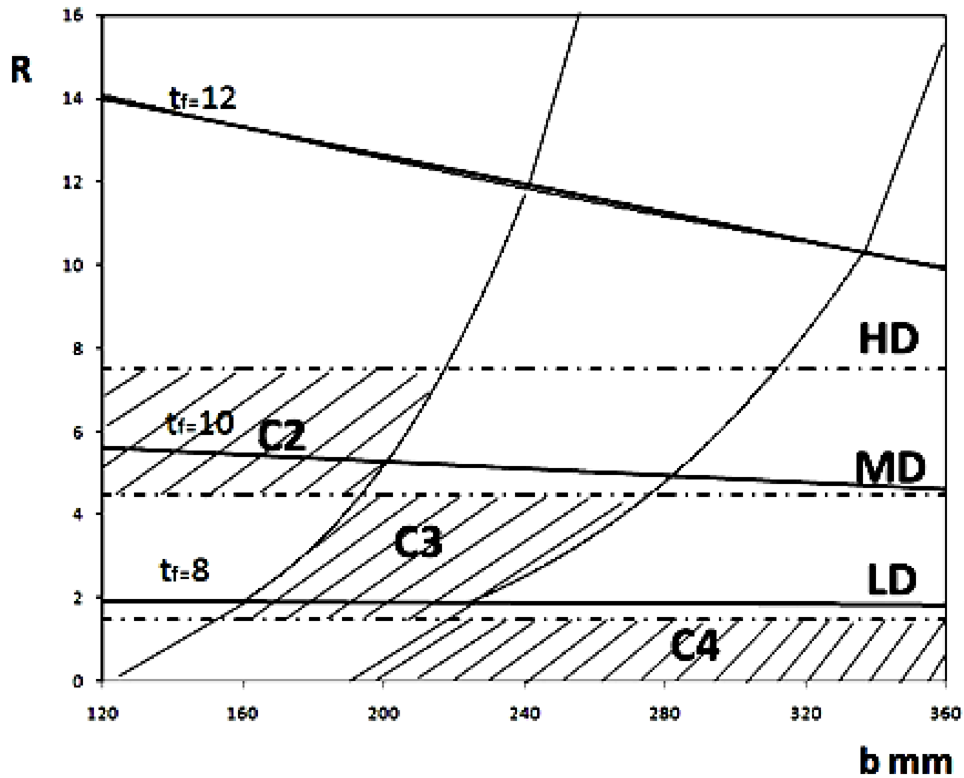


Figure5. Cross-section versus member classes for a profile with C2 class for web

Therefore, examining these Figures, one can observe great differences between the two classifications and that the framing in cross-section ductility and member ductility gives very different results. If the results obtained with DUCTROR-M computer program is considered available (the confrontation with experimental results is positive), results that the cross-section ductility cannot be used in design practice and must be replaced by member ductility.

3 In-plane versus out-of-plane plastic mechanisms

The plastic buckling for SB 1 standard beam occurs for hogging moment in compressed part by in-plane or out-of-plane plastic mechanism (Fig. 6).

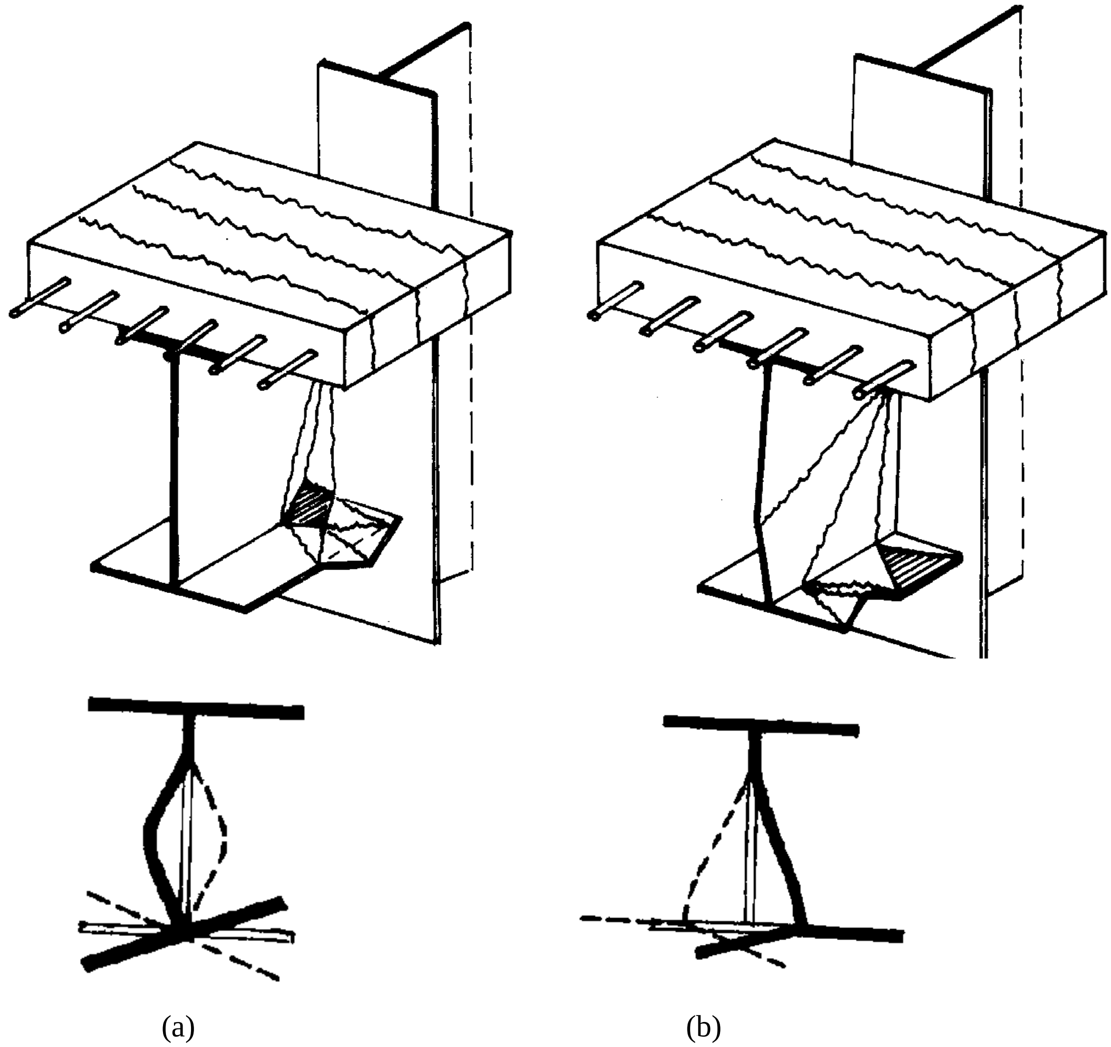


Figure6. Local plastic mechanisms for hogging moments: (a) In-plane mechanism;
(b) Out-of-plane mechanism

The experimental tests used the validation of DUCTROT-M computer program used only a simple reinforcement under the force which cannot impedes the lateral rotation of beam during plastic buckling. The verifications of theoretical and experimental results have provided that the great majority of tested beams (especially for rolled sections) lose their carrying capacity by out-of-plane plastic mechanism shape. But, in practical situations, the beam ends belong to a complex node, composed by a column reinforced with horizontal reinforcements and transversal beams which impede the free lateral rotation (Fig. 7). Therefore, the results obtained during the experimental tests on the standard beams must be used only with a careful examination about the plastic mechanism type.

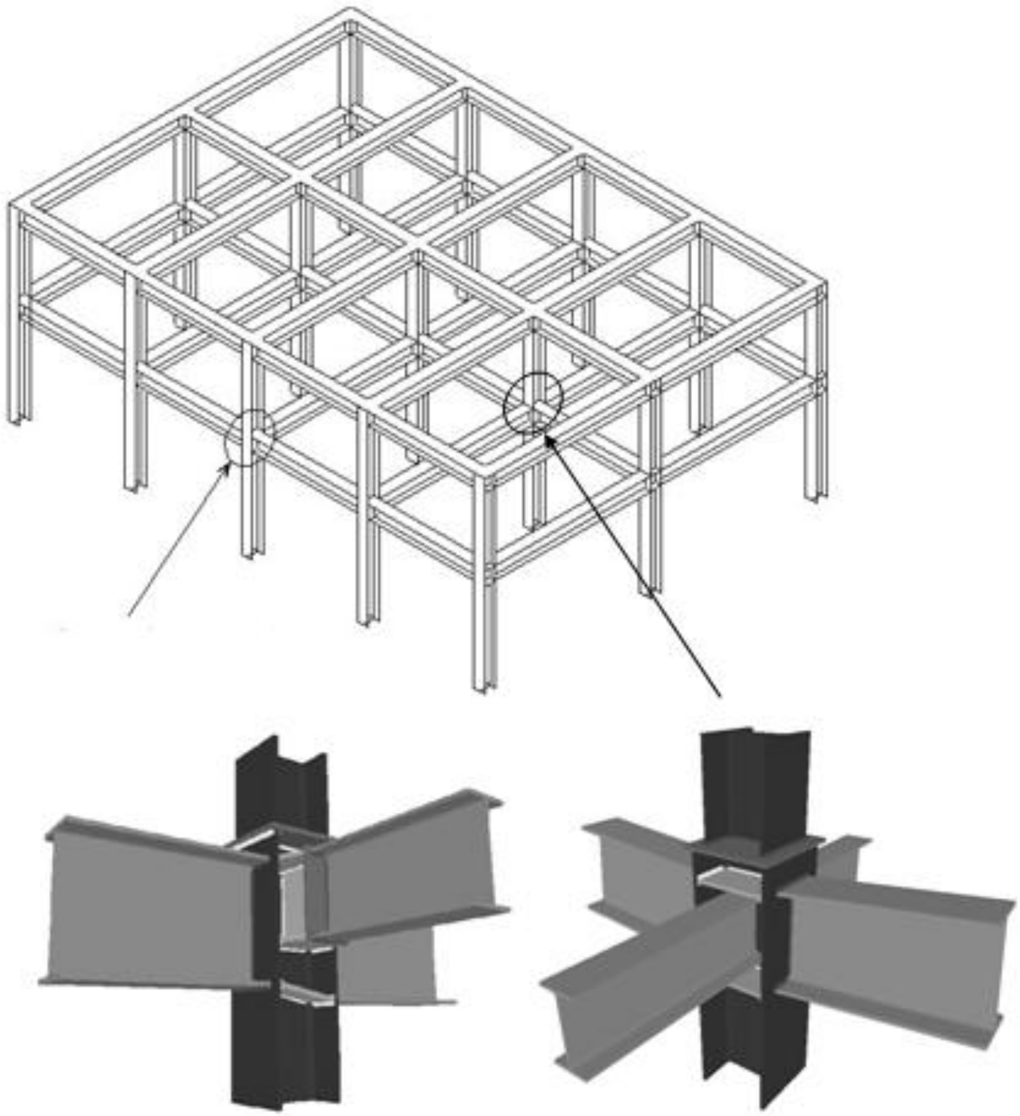


Figure7. Beams in complex structures

In addition, it is essential to mention that during the experimental test provided during SAC [6] and RECOS experimental programs [7], where the beam ends were connected in columns, not one of collapse mode is produced by out-of- plane.

Only in the case of reduced beam section, RBS, (dog-bone) experimental tests [8], used after the Northridge earthquake in order to protect the column-beam connections, the out-of-plane plastic mechanisms are observed associated with an accelerated degradation of connection rigidity. This degradation is due to the lateral-torsional buckling, producing out-of-plane force components. This is an additional reason to eliminate in practice design the out-of-plane buckling mechanisms.

With this observation, it is necessary to mention that the DUCTROT-M computer program is the single one which can find out the cases when the ultimate carrying capacity of beam is produced by out-of-plane plastic buckling.

For rolled sections, the numerical tests, using DUCTROT-M computer program, performed on the European sections IPE and HEA have shown that for these profiles the dominant local plastic mechanism is the out-of-plane one (in accordance with the experimental tests presented in first part of this paper), with an important reduction of rotation capacity in comparison with the in-plane mechanism.

ROTATION CAPACITY FOR EUROPEAN SECTIONS

Rolled sections	IPE300	IPE400	IPE500	HEA400	HEA500	HEA600
		L = 5000			L = 6000	
In-plane	9.03	13.41	15.00	21.13	36.12	40.59
Out-of-plane	6.27	8.12	8.83	9.75	10.29	10.51

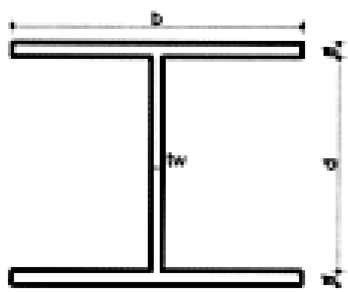
Therefore, for European sections, in order to obtain an increased local ductility, it is very important to solve the details end beams in nodes to impede the out-of-plane plastic buckling, by increasing the node twisting rigidity so this one to be greater than the lateral rigidity of beam.

For welded sections, there are two way to eliminate the out-of-plane plastic mechanism:

(i) To solve the node torsional rigidity so that be greater than the lateral beam rigidity.

(ii) To chose the section dimensions so the out-of-plane be eliminate.

For the first case the constructional measures are the same as for rolled profiles. When the dimensions of cross-sections can be choice in order to obtain the elimination the out-of-plane mechanism, the solutions are presented in [9] (Fig. 8). One can observe that for an increasing of flange thickness, an increasing of ultimate rotation is obtained for in-plane plastic mechanism. But from a given value, the in-plane mechanism is transformed in out-of-plane plastic mechanism, and the ultimate rotation remains practically invariably with the flange thickness increasing. In order to eliminate the out-of plane plastic mechanism, the ratio between web and flange thickness must be chosen in interval of 0.7 to 0.8. Because the European profiles do not respect this condition, results the observation that these profiles have the tendency to lose the carrying capacity by out-of-plane plastic mechanisms.



Beam	b mm	d mm	tf mm	tw 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

Figure 8 (continues)

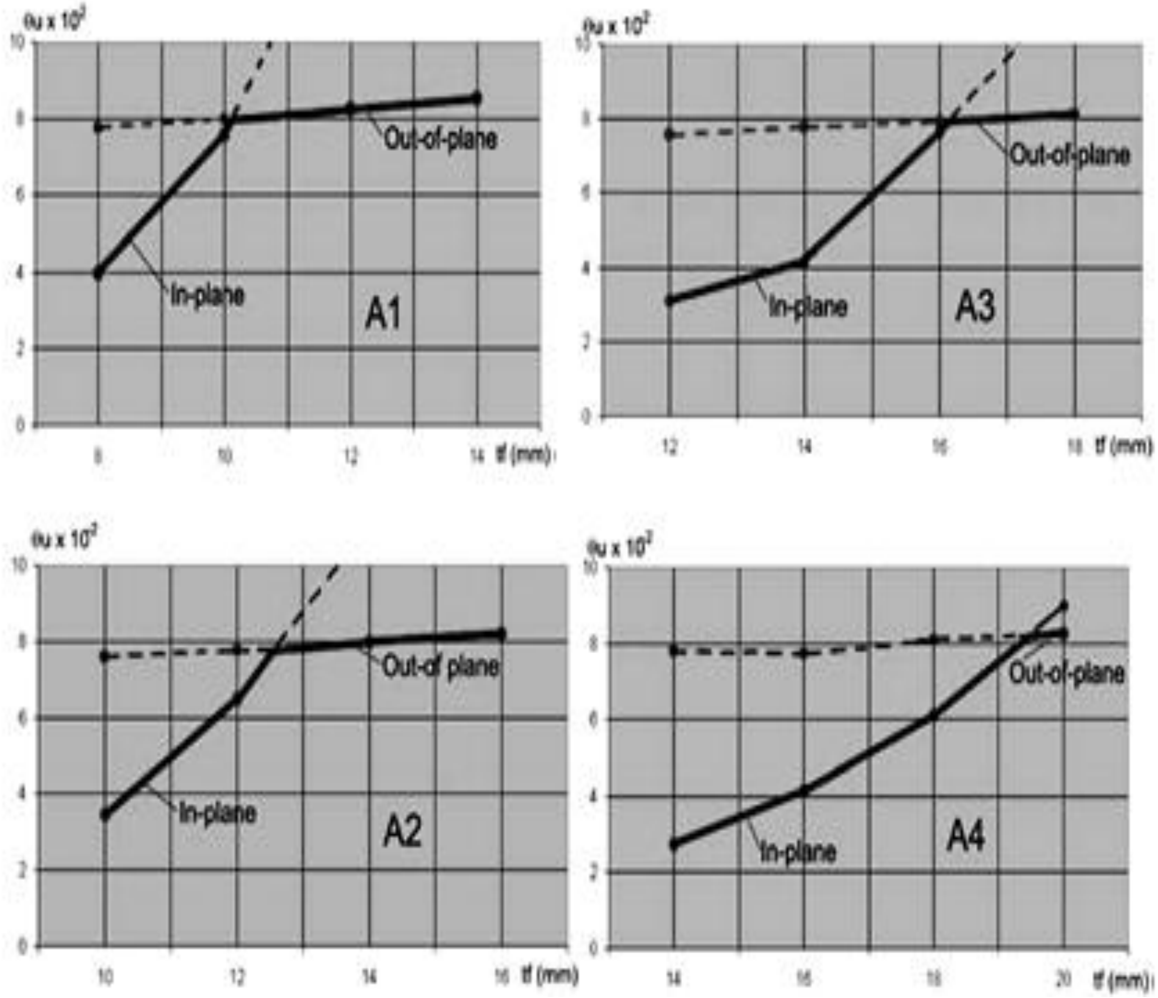


Figure 8. Influence on ultimate rotation of in-plane and out-of-plane mechanisms

4. Ductility of reduced beam section (RBS)

Among the solutions for safeguard of brittle joints, the idea of the weakening of flanges at the beam ends has been proved to be very effective. By cutting the beam flange near the joint in a specific zone (dog-bone), the formation of plastic hinges away from the column-to-beam flange welds, allowing stable yielding of beam, is assured by the reduced moment capacity (Fig. 9). Geometrical characteristics of reduced beam section are presented in [10].

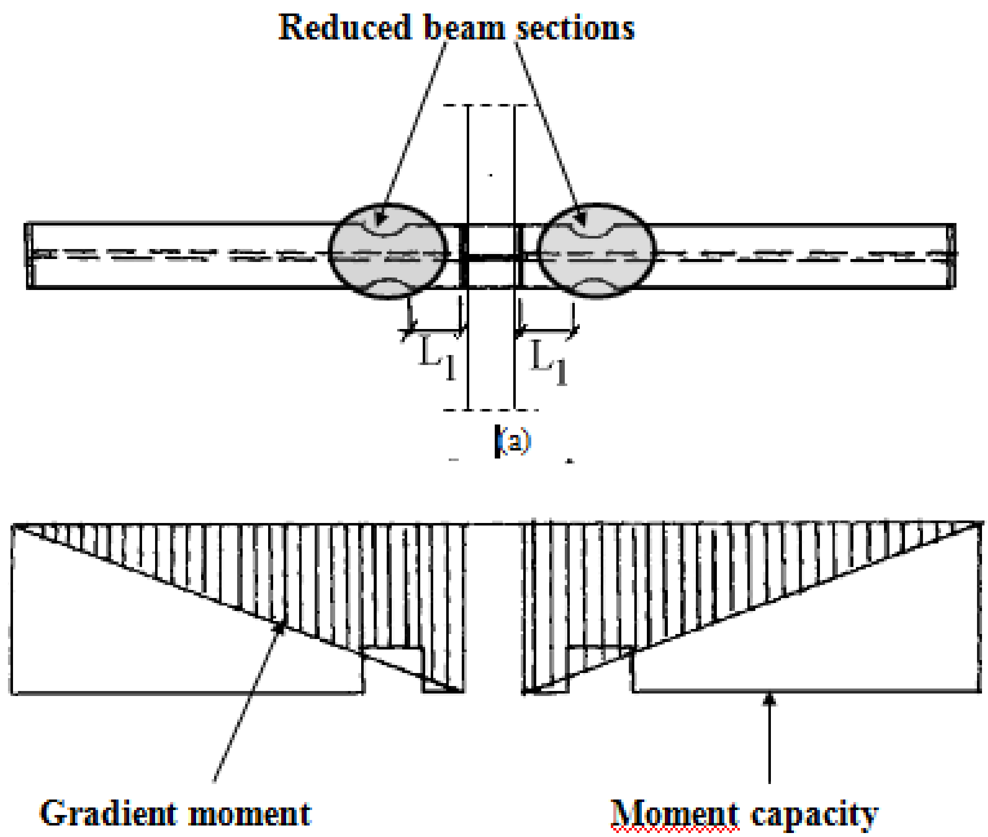
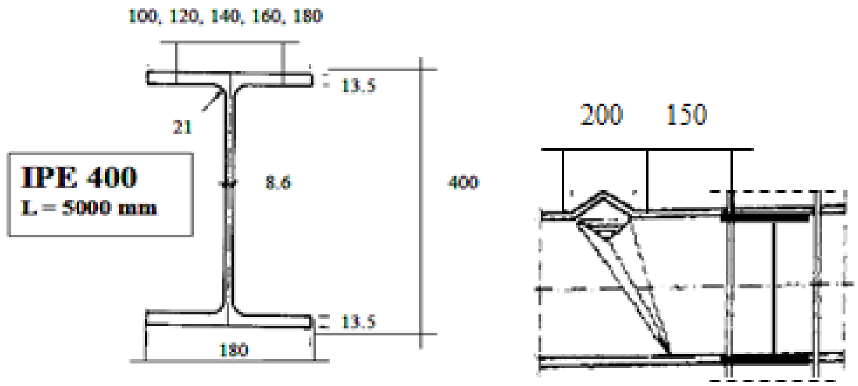
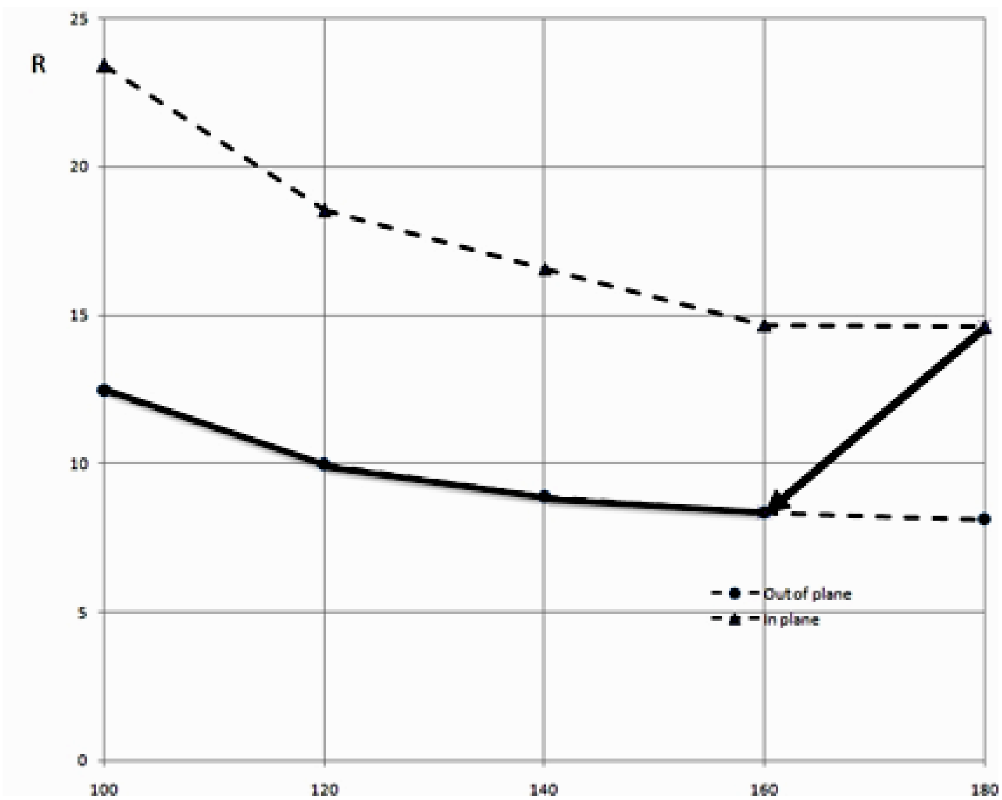


Figure 9. Reduced beam section (RBS): (a) Beam scheme; (b) Positions of RBS

Figure 10 presents the example of IPE profile, for which the rotation capacity is determined in function of the flange reduction for in-plane and out-of-plane plastic mechanisms. One can see that an important increasing of in-plane rotation capacity is obtained, if the measure to impede the node twisting is assured. During the experimental tests performed on standard beams it is observed that always the plastic buckling starts in-plane mechanism, followed by out-of-plane mechanism due to the weakened of buckled flange. Experimental tests performed in [10] have shown that, due to flange reduction, this phenomenon is accelerated due to flange reduction, and, consequently, the reduction of lateral rigidity. Because the plastic buckling occurs in the reduced beam section, away from the node, the measures to increasing the node rigidity have no effects. So, practically the collapse mechanism occurs by the out-of-plane plastic mechanism and, consequently, a reduction of rotation capacity must be considered. In addition, due to the presence of out-of-plane forces (Fig. 11) the degradation of lateral rigidity during cyclic loading is accelerated. Therefore, in [10], the providing extra lateral bracing near the RBS region, to impede the out-of-plane buckling, is recommended.



(a)



(b)

Figure 10. Rotation capacity for RBS

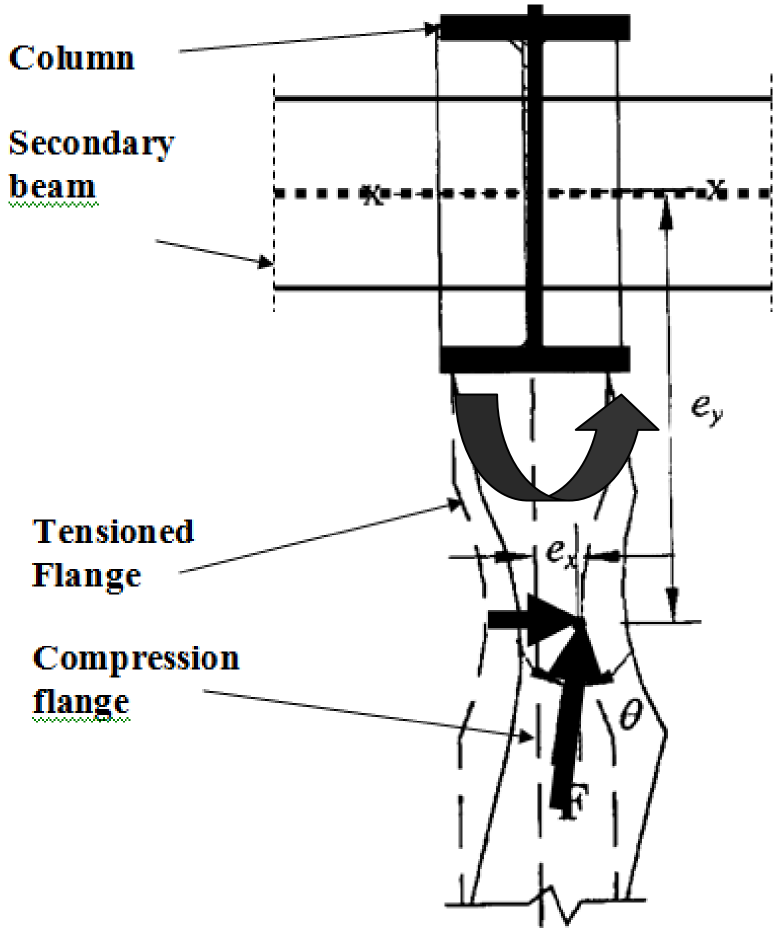


Figure11. Out-of-plane mechanism for RBS, producing lateral forces

5 Influence of welding type and material properties

One problem for practical design of welded beams for ductility is the definition of flange width as a function of welding type. Using the same method as for rolled sections, in the first step the rotation capacity is determined without joint and a correction of obtained value is obtained using relations (1) and (2a) for the effective widths, where:

-for filled welds (Fig. 12a):

$$c_r = c - 0.5\, t_w - 1.1a \quad (3a)$$

-for penetrated welds (Fig. 12b):

$$c_r = c - 0.5\, (t_w + a) \quad (3b)$$

where a is the weld thickness. For the welded profile from Figure 12 (with L = 5000 mm), the influence of welding type, using DUCTROT-M computer program, is:

Rotation capacity

Welding type	a, mm 4	5	6	7
Without welding		3.14		
Filled welds	3.71	3.78	3.86	3.91
Penetrated welds	3.55	3.58	3. 62	3.65

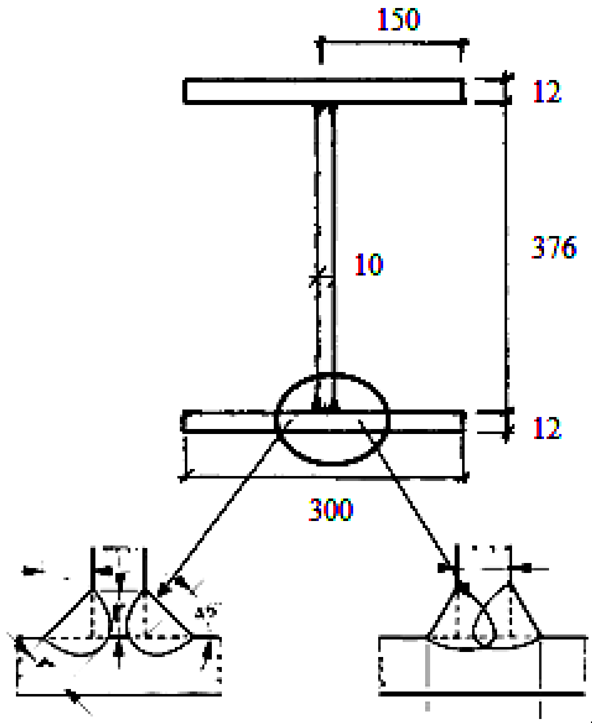


Figure12. Welded profile types: (a) Filled welds; (b) Penetrated welds

One can see that, the influence of welding thickness and the welding type are not very important.

Figure 13 presents the influence of steel grade on rotation capacity. One can see that the ductility decreases with the increase of yield stress. The decreasing is more important that the method proposed in [4], in which the results must be multiplied with the factor $(235/f_y)^{1/2}$

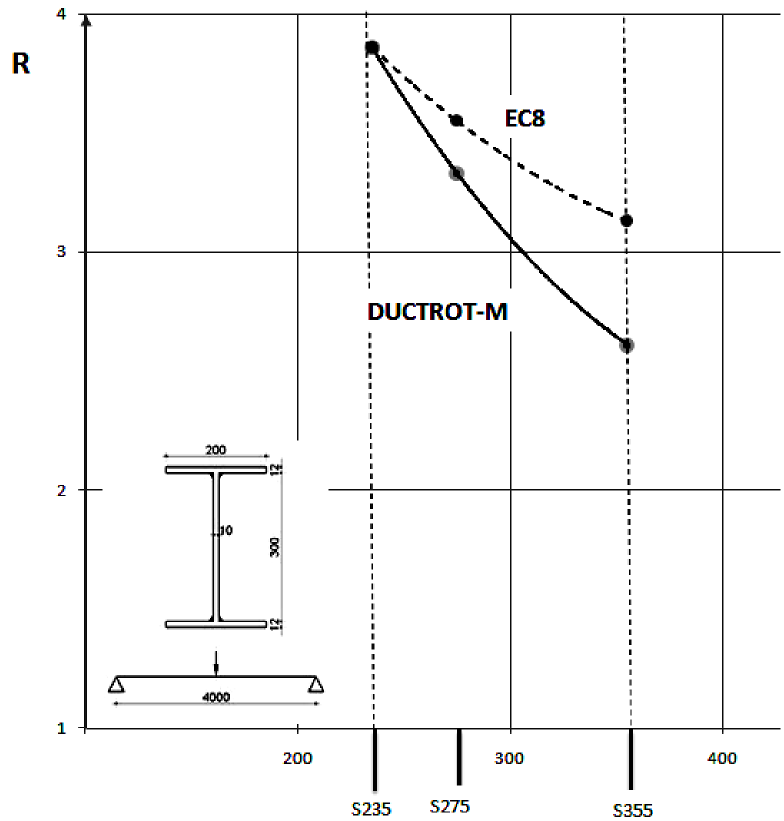


Figure13. Influence of yield stress and steel grade on rotation capacity

Due to this fact, contrary to the strength verifications when the minimum of yield stress must be used, the ductility verifications must be performed for the maximum yield stress. Considering the random variability of yield stresses [1], an approximate relation between f_{ymax} and f_{ymin} can be used: $f_{ymax} = f_{ymin} + 50\ldots70$.

Figure 14 shows the decreasing of rotation capacity taking account of random variability, which can be very important. Due to this fact the determination of rotation capacity in the DUCTROT-M computer program is performed considering the random variability of yield stresses.

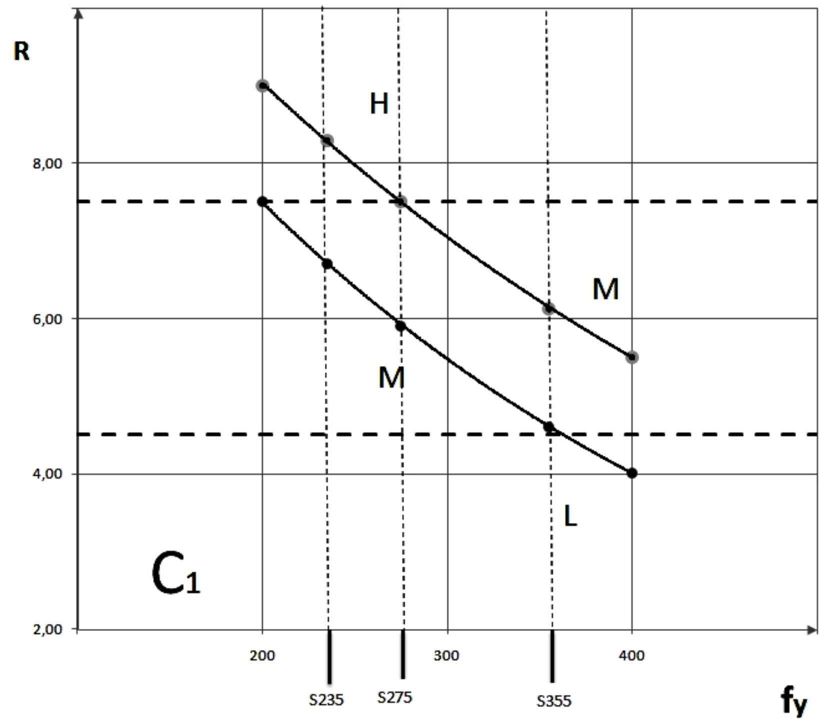


Figure14. Influence of random variability on rotation capacity

6 Parametric studies on member rotation capacity

The influence of important geometrical cross-section dimensions is examined in order to establish the best solution having the maximum member ductility.

Influence of flange thickness. Figure 15 shows the influence of flange thickness on the member ductility, the increasing of rotation capacity being very high with the increasing of flange thickness. A comparison between cross-section classes and member classes is presented in Figure. One can see that the observation from Section 2, critics about the discrete subdivision in classes are confirmed, member class M superposing over the cross-section class C3. The out-of-plane mechanism limits the increasing of ductility resulted from in-plane mechanism.

Influence of flange width. The profile can be classified in C1 class reported to cross-section classification, but the member classification introduces the profile in class M, the variation of flange width having no significant results (Fig. 16).

Influence of web thickness. Contrary to influence of flange thickness, the decreasing of rotation capacity with the increasing of web thickness is very important (Fig. 17). The profile is framed in class C1, but can have M (medium) or L (low) ductility as member classification. The out-of-plane mechanism limits the increasing rotation capacity with the decreasing of web thickness

Influence of web height. Like the flange width, neither the web height has no a very important effect in increasing of rotation capacity (Fig 18). One can see that the profile framed in class C1 has M (medium) rotation capacity.

Influence of beam span. Another demonstration about the incapacity of cross-section classification to give proper information about the ductility of profiles results from Figure 19, where rotation capacity of a profile framing in class C1, presents M (medium) and L (low) rotation capacity, in function of the beam span

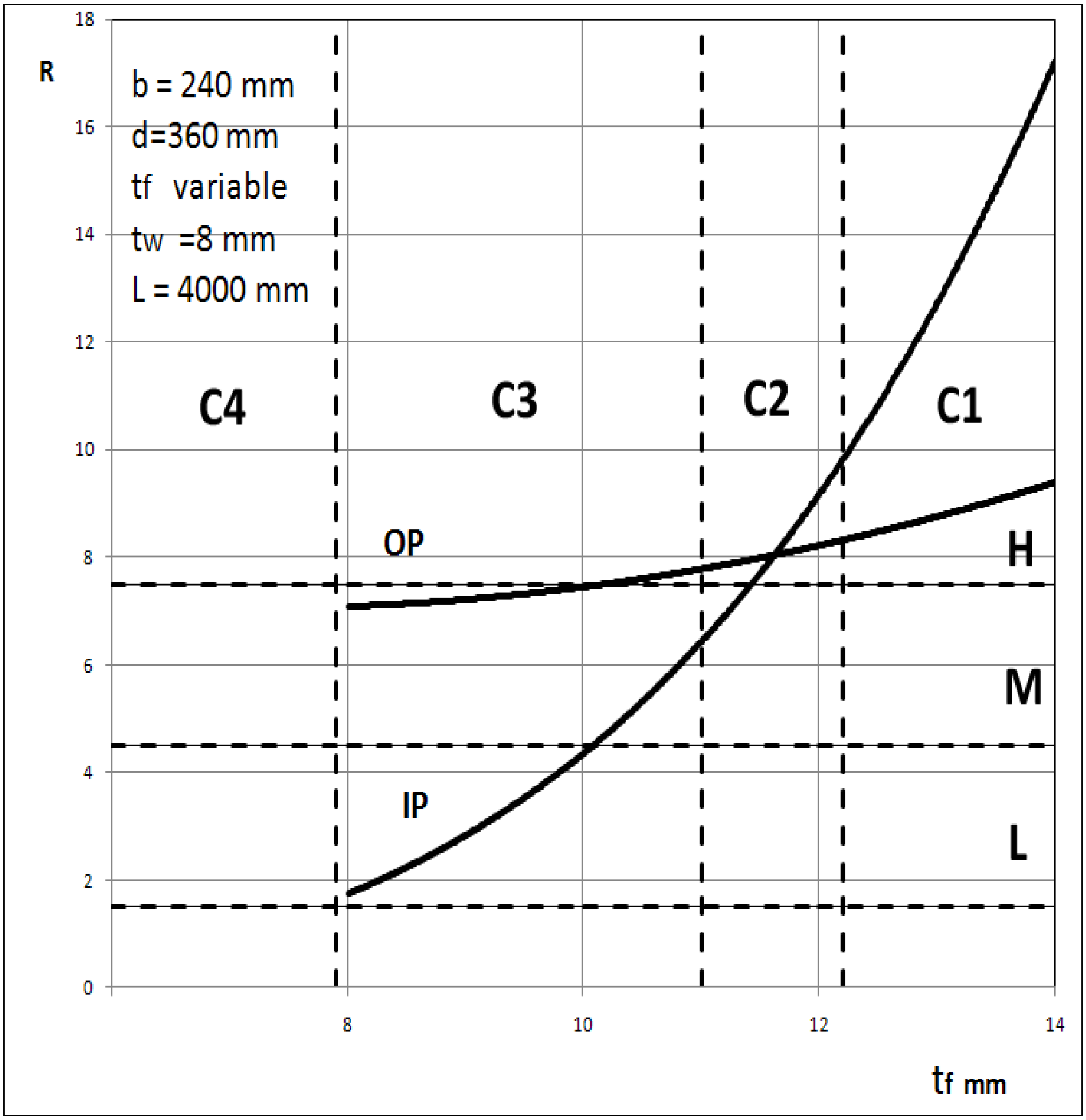


Figure15. Influence of flange thickness

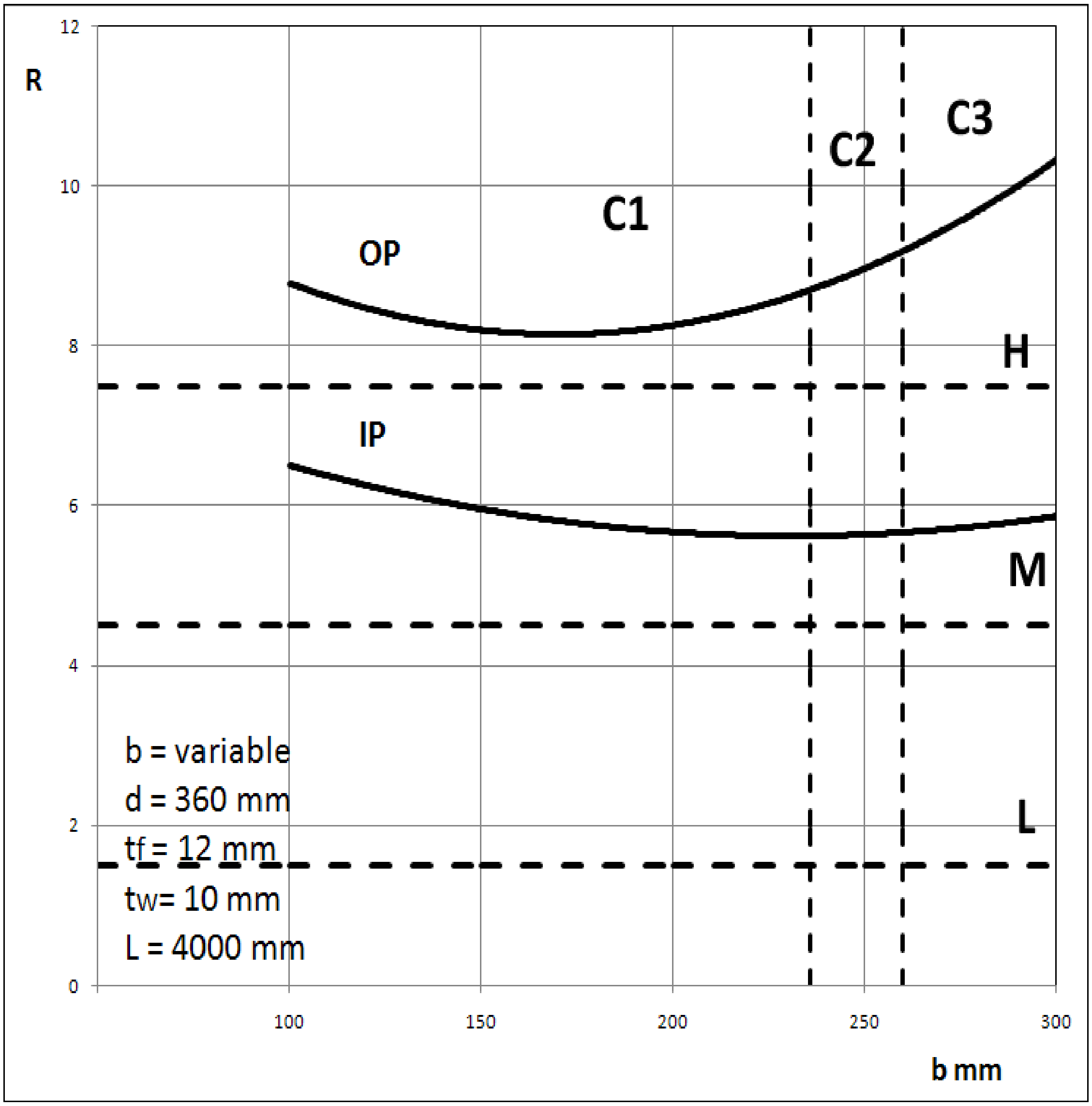


Figure16. Influence of flange width

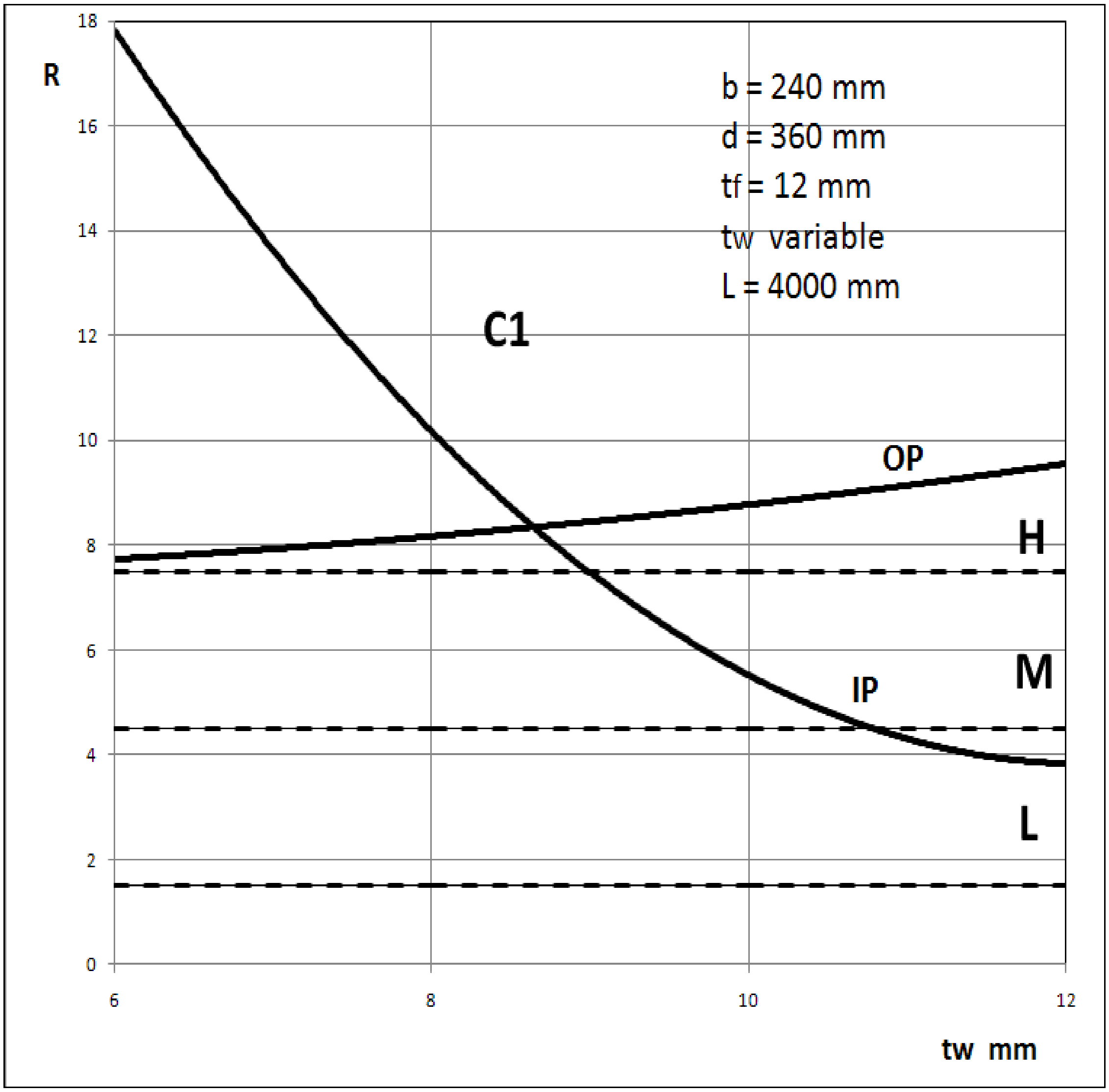


Figure17. Influence of web thickness

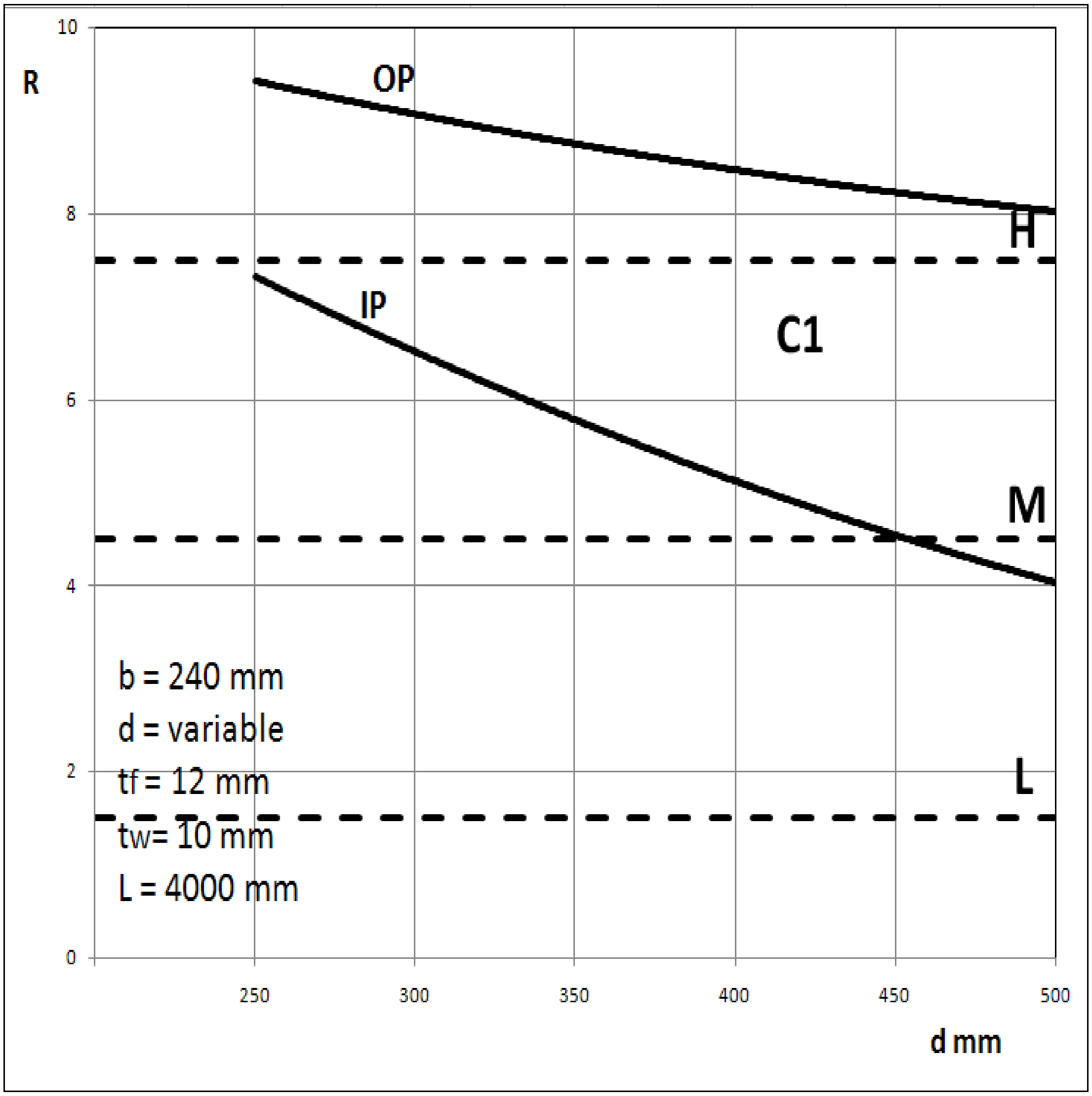


Figure18. Influence of web height

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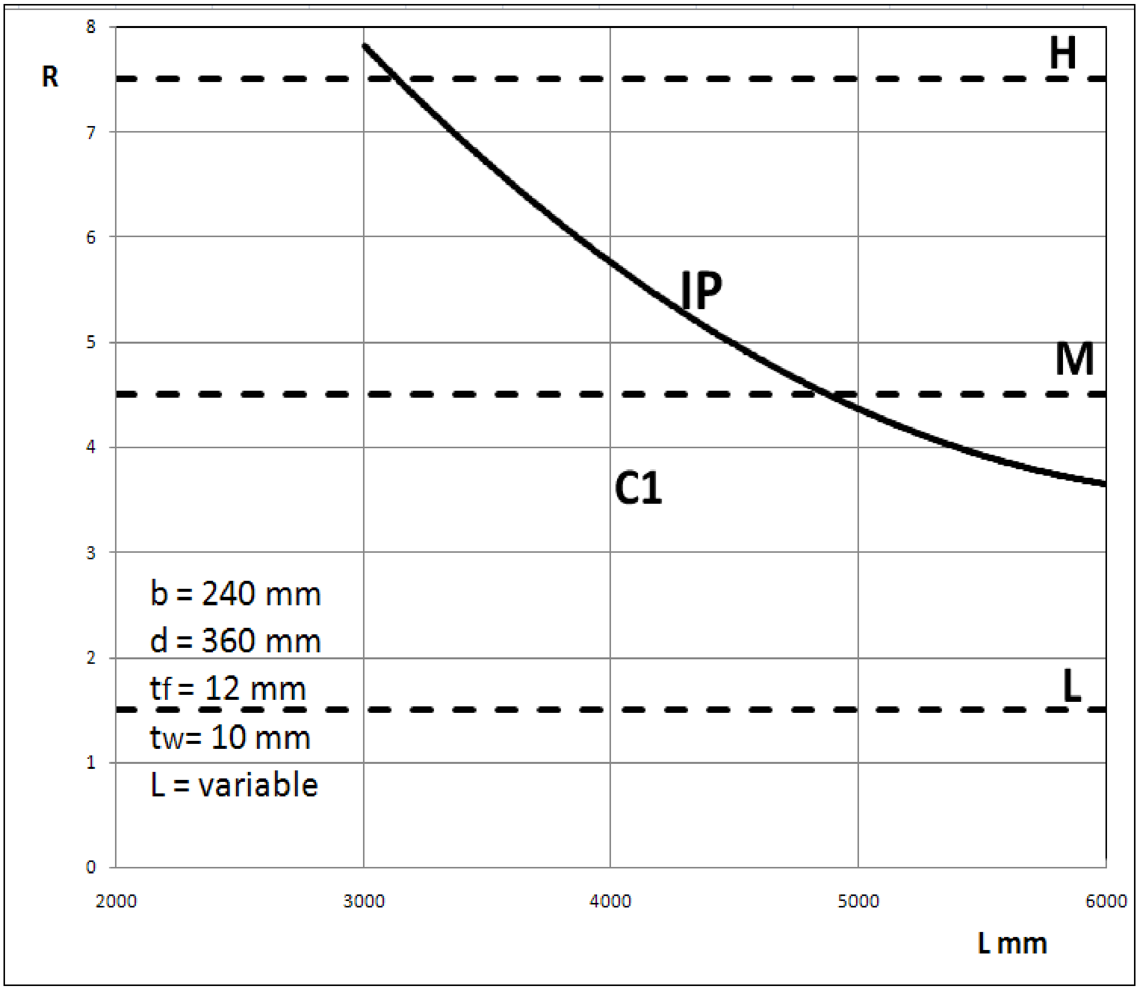

Figure 19. Influence of beam span

Conclusions for a proper selection of profile dimensions. Because the beam span is not a parameter which can be modified, in order to obtain a good rotation capacity remains only to select the optimum dimensions of cross-section, thicknesses and width of flanges and thickness and height of web. The parametrical studies have shown that the flange width and web height have no important effects on increasing the rotation capacity, and that the increasing of flanges and web thicknesses has contrary effects. The reasons of these conclusions are related to the wave-length of plastic mechanism. For in-plane mechanism the rotation capacity is function of this length, the capacity of dissipating energy being multiplied by increasing of yielding line lengths. The length of plastic mechanism is given in [11], based on theoretical researches and experimental data as:

$$L_m = 0.6\,(t_f/t_w)^{3/4}\,(d/b)^{1/4}\,b$$

One can see that the ration t_f/t_w has a great influence on the plastic mechanism length, while the ratio d/b has a reduced influence. These observations are confirmed by the numerical tests on rotation capacity, the main factor in rotation capacity increasing being the flanges thickness, and the factor producing the most important decreasing of rotation capacity being the web thickness.

As it is shown in Section 3, an important attention must be paid to eliminate the possibility to occur the out-of-plane mechanism, due to the effect of reducing the rotation capacity and the acceleration of degradation during cycle loads. Figures 20 presents influence of the flanges width and web height, kipping constant the web thickness t_w = 8 mm the One can see that for t_f = 10 mm (Fig. 20a) for all the section parameters, the dominant mechanism is the in-plane one. For t_f = 12 mm (Fig. 20b), the both plastic mechanisms are presents, in function of flanges width and web height. For t_f = 14 mm (Fig. 20c), only out-of-plane mechanism is present. Therefore, in order to eliminate the out-of-plane plastic mechanism, the thicknesses of flanges and web is recommended to not be very different as dimensions.

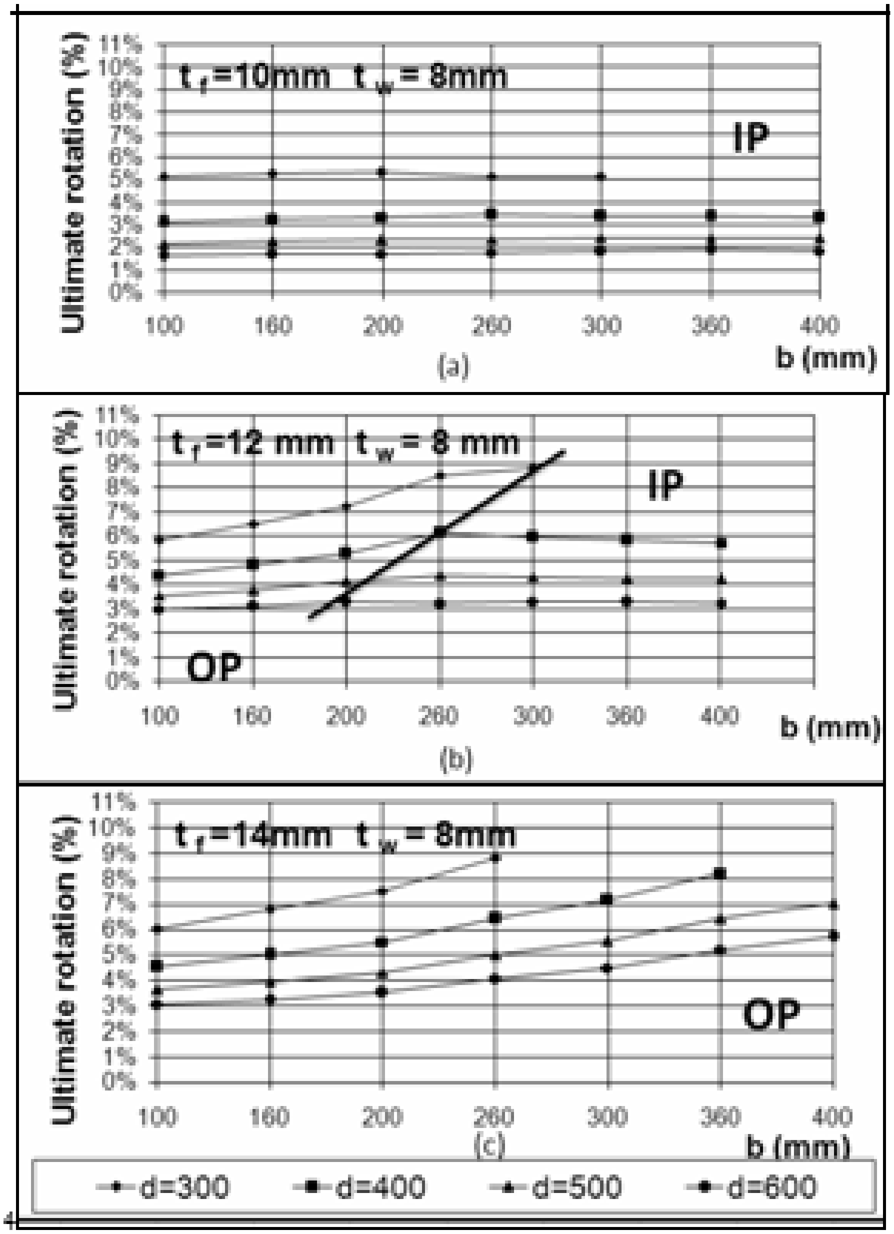

Figure 20. Optimum adjustments for profile dimensions:
IP- in-plane mechanism, OP-out-of-plane mechanism

7 Influence of beam-column details

The DUCTROT-M computer program gives the possibility to study the influence of some beam-column details on rotation capacity, by considering the position of plastic mechanism and rotation point. Three possible connection types are presented in Figure 21.

(i) Column without continuity plates (Fig. 21a), when flange plastic mechanism is situated near the column and the column flange is involved in the plastic mechanism. The rotation point is situated near to column flange. In this case the determined rotation capacity is R = 5.69

(ii) Column with continuity plates (Fig. 21b), when the position is remote from the column flange, an increasing of rotation capacity is obtained due to asymmetry of plastic mechanism shape: R = 7.13

(iii) Connections with cover plates (Fig. 21c), used in order to protect the welded connections and to force the development of plastic hinges away from the column face, case in which the plastic mechanism is free to develop an optimum shape by choosing a favorable rotation point. Due to this fact the increasing of rotation capacity is very important: R = 12.48

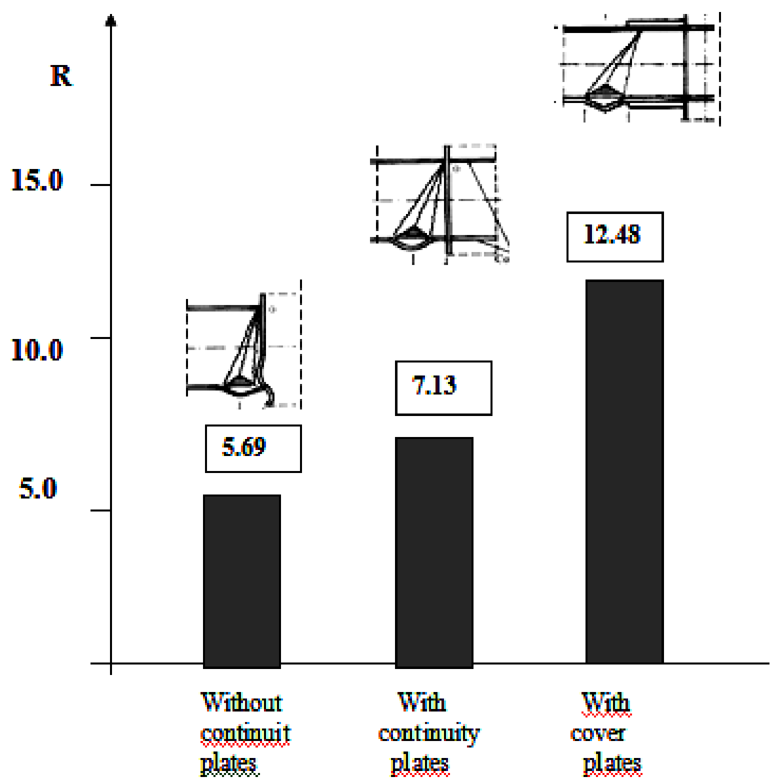

Figure 21. Influence of beam-column details

8 Conclusions

The applications of DUCTROT-M computer program prove the possibilities of this one to solve many important problems in determining the structural ductility. The comparison between cross-section and member ductility classification shows that the first cannot determine the proper structural ductility and the code provisions must be modified, by adopting the member classification. The computer program gives the possibility to decide if the plastic buckling mode is in-plane or out-of-plane. Another very important discussed problem is the importance to eliminate with constructional details the out-of-plane buckling mode. The studies on the ductility of Euro-profiles IPE and HEA show that the out-of-plane buckling is the main buckling mode for these profiles. Therefore, it is very important to solve the node details to impede this buckling mode. The reduced beam section, RBS, reduces the beam ductility and increases the ductility degradation, in case of cyclic loadings. For the welded profiles, the proportion between flanges and web plays a leading role in eliminate the out-of-plane buckling.

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