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LOCAL DUCTILITY OF ROLLED STEEL BEAMS
Using The Theory Of Plastic Collapse Mechanism

Anthimos Anastasiadis [a], Marius Mosoarca [b] and Victor Gioncu [b]

[a] ASAnastasiadis Structural Engineering & Consulting, Thessaloniki, Greece
[b] Politehcnica University of Timisoara, Dept. of Architecture, Romania

INTRODUCTION

Earthquake resistant structures should be designed in order to dissipate seismic energy through inelastic action. The ductility is the capacity of a component element (local ductility) or a structure (global ductility) to dissipate energy through plastic deformation. One of measures of ductility, universally recognized, is the rotation capacity, [1]. According to ultimate limit state design, for the development of a global plastic mechanism it is necessary that plastic hinges posses an available rotation capacity greater than the required rotation.

Generally, we distinguish five levels of ductility: material ductility, section ductility, member ductility, joint-connection ductility and structure ductility. The first four levels define the local ductility of a component element while the fifth one the global ductility. Regarding the local ductility, the final versions of European codes, EN 1993-1 [2], EN 1998-1 [3], consider that the element posses available ductility assured by a given cross section classification. Based on the aforementioned concept and defining a target value of plastic rotation of beam-to-column connection a designer, finally, tries to compare the target displacement, obtained from the code-prescribed target rotation, with a displacement obtained from inelastic analysis. This is an indirect process and it is not considered the real deformation capacity at the member level. Codes confuse the section ductility with the member ductility not considering the span of the steel element, compromising the element's capacity for the formation of plastic hinge, [1],[4]. It is recognized, both experimentally and analytically, that the deformation capacity of a member strongly depends from the span and the level of gravitational forces. Member ductility is especially necessary to be calculated when the joint is formed with cover plates, ribs, haunches while the plastic hinge is formed away from the column face with the joint region remaining intact. In that case the real joint is rigid in the connection region as well as in the weak axis due to transversal floor beams; hence the connection ductility does not measure the local deformation capacity.

In order to study the local member ductility of steel beams, made by hot rolled IPE and HEA sections, and to determine the rotation capacity, the theory of plastic collapse mechanism was used, [1],[5],[6],[7]. According to this theory the ultimate rotation capacity was defined using the local plastic mechanism, which considers yielding lines and plastic zones, obtained from experiments and validated from the results of these experiments. By the assistance of a specialized computer program, namely DUCTROT-M, [1], parametrical studies were made investigating the behaviour of IPE and HEA steel beams. The failure of beam can be due to the local plastic plate buckling of compression flange, local plate buckling of the web in flexural compression, produced in plane or out of plane. In the same time, the failure can occurs by the coupling of two or more of these local buckling mechanisms. The outcome was the comparison between the classifications given to current Eurocodes, which are based on the cross section ductility classes, with the one based on member ductility classes, achieving a different behaviour when the span of the member is taken into account.

1 LOCAL DUCTILITY IN DESIGN CODES

In Europe, there is an interaction between EN 1993-1, [2], and EN 1998-1, [3]. Regarding design rules prescribing the local ductility of elements in bending, as beams, the EN 1998-1:2004 defines two ductility levels interconnecting local (by means of cross sectional classes) and global (by means of q-factor) ductility as given in *Table 1, Fig 1a*. As mentioned in paragraph 6.5.3., [3], '*sufficient* *local ductility of members which dissipate energy in compression or bending shall be ensured by restricting the width-thickness ratio b/t according to EN 1993-1-1:2005'*. In any case the dissipation capacity should not depend only to independent b/t rations but also to the interaction between the ratios of flange and web, the span of the element as well as the loading conditions. The earthquake type (high number of cycles vs low number of cycles) strongly affects the dissipation capacity of an element, so it is evident that the limits given in Eurocodes, *Table 1* (class 1, 2), do not consider the seismic effect and seems to be taken from the independent calculation of plate buckling formula with some adjustments. One can consider that the values given in the codes should be considered only under monotonic loading conditions. Furthermore, EN 1998-1-1-:2004 is not providing any formula or other information for the evaluation of the member rotation capacity (joint-connection ductility is beyond the scope of this paper).

Table 1. Classification of ductility according to European Norms.

Ductility Class	Reference value of q-factor, EN 1998-1-1:2004	Required cross sectional class, EN 1993-1-1:2005 (I-sections)		
		Class	c/t_f	d/t_w
Ductility Class Medium, DCM	$1.5 < q < 2.0$	1/2/3	9/10/14ε	72/83/124ε
	$2 < q \leq 4.0$	1/2	9/10ε	72/83ε
Ductility Class High, DCH	$q > 4.0$	1	9ε	72ε

According to USA codes as AISC-2005 (ANSI-360-05, ANSI-341-05), [8], we distinguish a similar procedure defining width-to-thickness ratio limitations which are connected to the members that frame the seismic load resisting system. Only, American FEMA 356 document provides information regarding the acceptance criteria for plastic rotation capacity of beams/columns in flexure as a function of performance based design for rehabilitation projects, *Table 2*. The same concept, as of European and USA practice we can be finding to Japanese steel codes, with the exception that in cross section classification the interaction between flange and web is considered.

Table 2. Acceptance criteria according to FEMA 356, Seismic rehabilitation prestandard

Performance based design	Limit State Design	Acceptance criteria, plastic rotation	
		Primary element	Secondary element
Immediate Occupancy, *IO*	Serviceability Limit State, *SLS*	$\theta_{y\,...}$ (R=0)	$\theta_{y\,...}$(R=0)
Life Safety, *LS*	Ultimate Limit State, *ULS*	$6\theta_{y\,...}$(R=5)	$9\theta_{y\,...}$(R=8)
Collapse Prevention, *CP*	Collapse Prevention State, *CPS*	$8\theta_{y\,...}$(R=7)	$11\theta_{y\,...}$ (R=10)
θ_y – Yield rotation, where $\theta_y = M_pL_b / 6EI_b$ R-Rotation capacity, where R= $(\theta_u/\theta_y)-1$ and θ_u equal to the limit of the acceptance criterion			

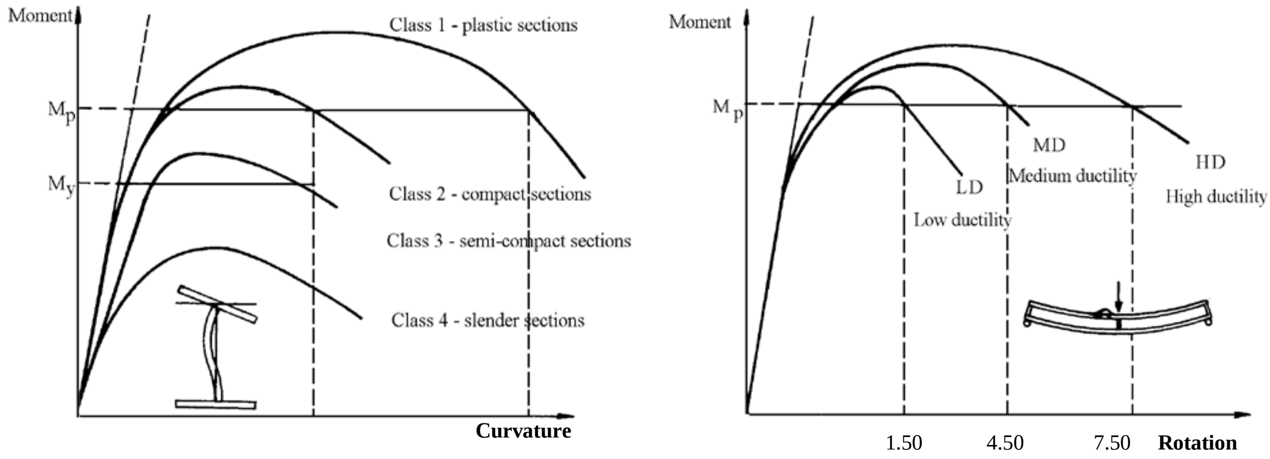
In spite of these of recognized deficiencies, this classification is used in codes, due to its simplicity in design practice. Another more effective classification at the level of member ductility for design has been proposed in [1], [4], *Fig. 1b*:

- 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.

In this paper for the calculation of the rotation capacity of steel beams made by hot-rolled IPE and HEA sections, the aforementioned definition is used. Considering the definition of ultimate rotation capacity, *Fig.1b* the classification criteria are:

- *HD*, R> 7.50
- *MD*, 4.50 < R < 7.50
- *LD*, 1.50 < R < 4.50

Members having R <1.50 are considered non-ductile.



a) Cross section classification

b) Member classification

Fig. 1. Cross section ductility vs Member ductility

Another direction in order to capture all the aforementioned deficiencies is presented in Italian new seismic code (OPCM 3431, 2005), which is numerically investigated in [9], considering as criterion for member ductility, the over-strength factor s.

2 AVAILABLE LOCAL DUCTILITY OF HOT ROLLED BEAMS

2.1 Specification of plastic collapse mechanism

From the analysis of the behaviour of I sections, [1], [6], we recognize that there is a difference between welded and hot rolled sections. The *influence of junction*, *r*, connecting the web with the flange creates different deformational conditions. This effect is introduced in code provisions [2] by changing the limits between ductility classes (hot-rolled vs. welded sections). The junction, r, creates a condition under which the flange buckles around the rigid zone, *Fig. 2a, b*, thus reducing the flange width and as a consequence increasing the rotation capacity of the element. In order to evaluate the available ductility under real constructional circumstances an improved plastic collapse mechanism was proposed [1], verified with experimental results collected from literature [5], [7] and implemented to the DUCTROT-M computer program.

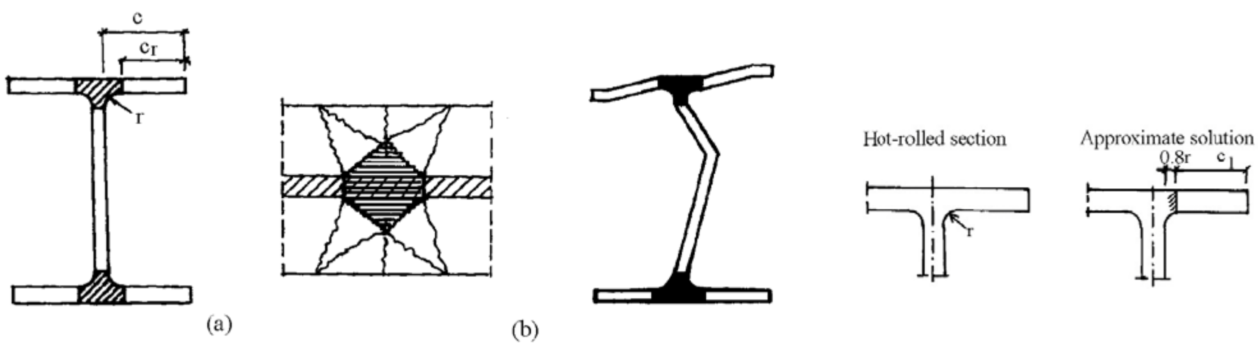
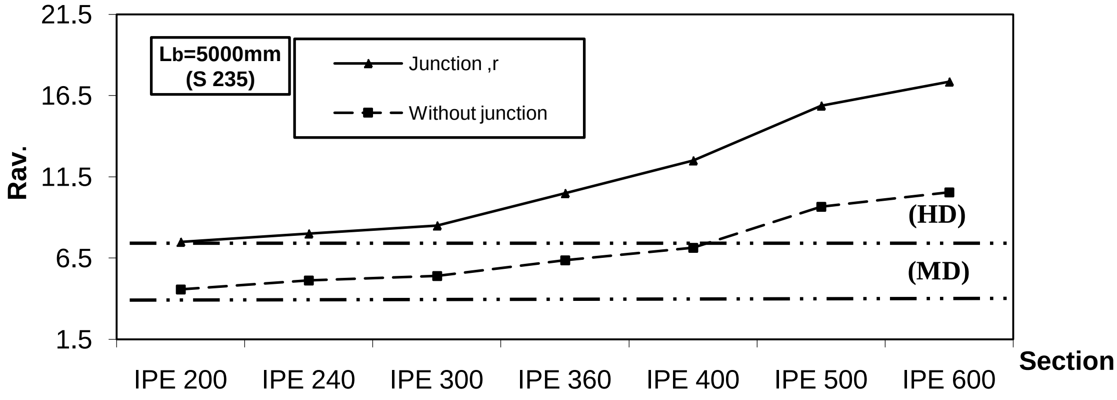
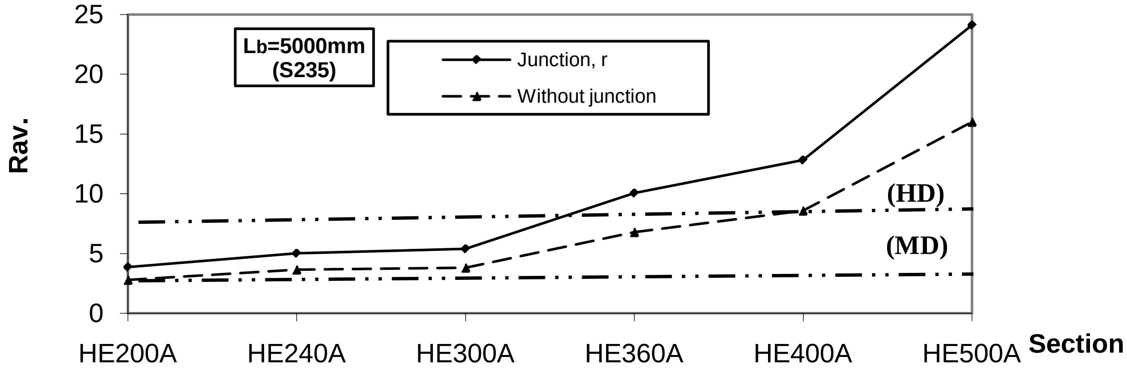


Fig. 2. Plastic mechanism of hot rolled profiles

By using the DUCTROT-M computer program, which implements the usual constructional details of I -wide flange sections, a parametrical analysis under monotonic loading took place. The main target is to demonstrate the contribution of the junction on the plastic rotation capacity. Concerning the contribution of the junction on the plastic rotation capacity, one can remark a very significant increasing of available ductility attaining approximately 50% and 85% for HEA and IPE sections respectively as compared with the same sections without junctions, *Fig.3*, improving the ductile behaviour especially of IPE beams.



a) Influence of junction on the available rotation capacity of IPE beams



b) Influence of junction on the available rotation capacity of HEA beams

Fig. 3. Influence of sectional fabrication detail on available rotation capacity

After an extensive parametrical study, using DUCTROT-M computer program, performed on the European IPE and HEA sections have shown that for these profiles the dominant local plastic mechanism is the out-of-plane mechanism [6], with an important reduction of rotation capacity in comparison with the in-plane mechanism, *Table 3*. A first remark is that all the European profiles reveal an out-of-plane mechanism due to the fact that the thickness ratio of web and flange, t_w/t_f, varies between 0.63-0.66 for IPE sections and 0.52-0.63 for HEA sections. This is a confirmation of the numerical results presented in [10] that, in order to avoid the out-of plane mechanism this ratio must be greater than 0.7-0.8.

Table 3. In plane and out of plane available rotation capacity of European steel sections

Type of mechanism	IPE300	IPE400	IPE500	HEA400	HEA500	HEA600
	L_b=5000mm			*L_b=6000mm*		
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

L_b- The real beam span

2.2 Member ductility of IPE and HEA beams

Based on the validated methodology of plastic collapse mechanism a new member ductility classification was proposed, *Table 4* and *Table 5*, presenting the monotonic available member ductility of IPE and HEA European I-sections. For the elaboration of the tables, using the DUCTROT-M computer program, all the crucial factors affecting the local ductility (section and member characteristics, steel quality, constructional details, type of loading) was taken into account.

Table 4. Member classification of IPE beams

Steel section	**Buckling mode**	**L = 2000mm**		**L = 3000mm**		**L = 4000mm**		**L = 5000mm**	
		S235	***S355***	***S235***	***S355***	***S235***	***S355***	***S235***	***S355***
IPE 300	*IP*	HD	HD	HD	MD	---	---	---	---
IPE 330	*IP*	HD	HD	HD	MD	HD	MD	---	---
IPE 360	*IP*	HD	HD	HD	HD	HD	MD	MD	LD
IPE 400	*IP*	HD	HD	HD	HD	HD	MD	MD	LD
IPE 450	*IP*	---	---	HD	HD	HD	MD	MD	MD
IPE 500	*IP*	---	---	HD	HD	HD	MD	MD	MD
IPE 550	*IP*	---	---	---	---	HD	HD	HD	MD
IPE 600	*IP*	---	---	---	---	---	---	HD	MD

Table 5. Member classification of HEA beams

Steel section	**Buckling mode**	**L=4000mm**		**L=5000mm**	
		S235	***S355***	***S235***	***S355***
HEA 320	*IP*	HD	MD	HD	MD
HEA 340	*IP*	HD	HD	HD	MD
HEA 360	*IP*	HD	HD	HD	HD
HEA 400	*IP*	HD	HD	HD	HD
HEA 450	*IP*	HD	HD	HD	HD
HEA 500	*IP*	HD	HD	HD	HD
HEA 550	*IP*	HD	HD	HD	HD
HEA 600	*IP*	HD	HD	HD	HD

IP **–** In plane post elastic buckling mechanism obtained with measures to increase the torsional rigidity of nodes
--- - Sizing of the member would be other than ductility limit state. For instance serviceability limit state would be the predominant criteria for member sizing.
L- The standard beam span [1], considers that the beam belongs to a frame with complex behaviour, loaded with gravitational and seismic forces, and that the inflexion point is situated at about (0.20…0.30)L_b, where L_b is the real beam span.

From the *Table 6* comparing the section classification according to [2], with the proposed classification it is evident that the available ductility changes as a function of member span. For IPE beams a lowering plastic capacity could be observed as the member span increases and the steel quality becomes higher. Generally, the same conclusions could be observed for the case of HEA beams.

Table 6. Comparison between cross sectional classification, [2], and proposed member ductility

Code / Proposal		IPE 300		IPE 330		IPE 360		IPE 400		IPE 450		IPE 500		IPE 550		IPE 600	
		S235	*S355*	*S235*	*S355*	*S235*	*S355*	*S235*	*S355*	*S235*	*S355*	*S235*	*S355*	*S235*	*S355*	*S235*	*S355*
Classification according to EN 1993 Part 1-1:2005		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Classification according to plastic collapse mechanism	L=2000	HD	HD	HD	HD	HD	HD	HD	HD	---	---	---	---	---	---	---	---
	L=3000	HD	MD	HD	MD	HD	HD	HD	HD	HD	HD	HD	HD	---	---	---	---
	L=4000	---	---	MD	MD	HD	MD	HD	MD	HD	MD	HD	MD	HD	HD	---	---
	L=5000	---	---	---	---	MD	LD	MD	MD	MD	MD	MD	MD	HD	MD	HD	MD

Legend:

Worst behaviour than predicted in EN 1993, Part 1-1:2005

--- - Sizing of the member would be other than ductility limit state. For instance, serviceability limit state would be the predominant criteria for member sizing

3 CONCLUSIONS

By the aid of DUCTROT-M computer program a number of parametrical studies were made investigating the available ductility of European IPE and HEA hot rolled profiles. The study shows that the out-of-plane buckling is the main buckling mode of these profiles. Therefore, it is very important to solve the node details to impede this buckling mode. 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.

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