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New aspects concerning the ductility of steel members

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ABSTRACT: The paper place emphasis on the investigation of some important issues regarding the determination of the available ductility of steel I beams by using the methodology of local plastic collapse mechanism. The code prescribed cross-section classification against the member behavioural classes as well as the static-monotonic ductility against seismic one is more in-depth examined. By using the facilitations of DUCTROT-M software a numerical analysis was performed revealing the effectiveness of the member ductility criterion. Furthermore the main influencing parameters of different seismic loading conditions are examined demonstrating the dramatic reduction of the monotonic ductility when the strain-rate and the cycling loading conditions are taken into account.

1 INTRODUCTION

Earthquake resistant structures should dispose sufficient ductility capacity in order to undergo large inelastic deformations imposed by seismic actions. Accordingly, structural design codes prescribe rules in a way to ensure a suitable deformational capacity, when a structure is loaded under the seismic actions. Furthermore, the ductility is the appropriate mechanical property that develops the condition to avoid structural collapse, through the redistribution of internal forces and energy dissipation, when a structure is loaded more than the predetermined design actions. Earthquake events from the last twenty five years unveiled the lack of local inelastic capacity of steel structures that were consideredas very ductile.

Until now structural design codes, e.g. EN 1998: 2004, Part 1-1, ANSI/AISC 341-2005, do not recommend provisions for a straightforward prediction of ductility. The recent ANSI/AISC 360-10 addresses the design by inelastic analysis setting the base for a further discussion, but mentioning that the provisions given should not be applied to seismic design. Studying the above mentioned design codes it is evident that the ductility is ensured by strength design criteria as well as the provided rotation capacity limits are not clear and compatible with the wholedesign process.

Two main issues regarding the evaluation of the local ductility are evidenced (Gioncu & Mazzolani, 2002), namely, the inefficiency to capture the element's deformational capacity through cross section ductility classes as well as the influence of the loading conditions on the inelastic capacity of steel members. For the first one there are studies approaching the subject in different ways (Mazzolani & Piluso, 1993; Gioncu et al., 2000; Formisano et al., 2006). For the second one there are studies approaching the phenomena by low cycle fatigue (Vayas, 1997; Lee & Stojadinovic, 2004) or by taking into account the main seismic influencing parameters such as strain rate and plastic accumulation on local collapse mechanisms (Gioncu & Mazzolani, 2002).

The paper using the methodology of the plastic collapse mechanism and exploiting the capabilities of the DUCTROT-M software investigates the concept of ductility behavioural classes as well as the influence of different seismic actions on the local available ductility of steel I beams.

2 METHOD FOR THE DUCTILITY EVALUATION

The main goal with respect to prediction of the available ductility is to calculate the ultimate rotation, θ_u, or alternatively the rotation capacity, R, as a nondimensional measure of the local member inelastic capacity.

In order to determine the rotation capacity of the steel I beams the methodology of the plastic collapse mechanism was used (Gioncu & Petcu, 1997; Gioncu et al, 2000). With respect to this theory the ultimate rotation capacity is defined using the local plastic mechanism, which considers yielding lines and plastic zones, obtained from experiments and validated from the results of these experiments. From the intersection of two load displacements curves, the post buckling curve and the actual behavior curve, finally the ultimate rotation could be obtained (Fig. 1a, b, c). In order to facilitate the calculation of the rotation capacity the DUCTROT-M software was used. The computer program was elaborated at the Politehnica University of Timisoara by Petcu & Gioncu (2002).

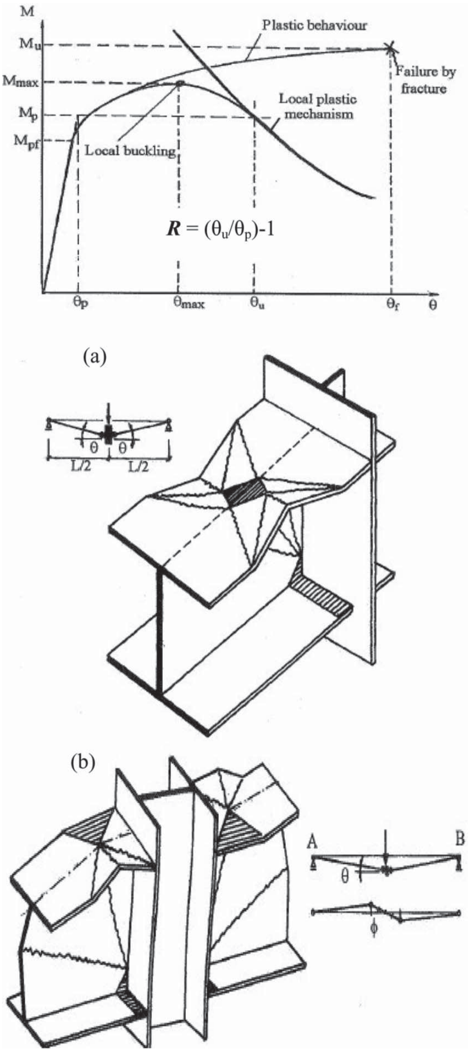


Figure 1. (a) Moment rotation curve. (b) Local plastic mechanisms (in plane, out-of plane).

3 CROSS SECTION VS. MEMBER DUCTILITY

The majority of structural codes in order to take into account the possibility of a steel element to develop plastic hinge provide a classification based only on cross-section slenderness without taken into consideration the interaction between flange and web as well as the span of the member. Focusing on European codes, EN 1998:2004 & EN 1993:2005, three important aspects could be remarked:

i. Width to thickness ratios for flange and web are prescribed independently without taking into account the assembling condition (fabrication detail e.g. the junction between the flange and web in case of hot-rolled sections, the type of weldment in case of built-up sections).
ii. The influence of the member span is introduced by the member verification against flexural-torsional buckling. In any case due to the presence of the slab that avoids such phenomena, it is possible to be formed a plastic hinge even when the element does not exhibit flexural-torsional buckling. This was demonstrated from the behavior of structures under real loading conditions. Therefore, only a model that directly introduces the influence of the span in the inelastic range could describe the aforementioned influence on the available ductility.
iii. Both EN 1998 and EN 1993 specify the same width to thickness ratio in order to provide sufficient local ductility. In this case it is no recognized that the first one contains provisions for the design of steel elements against seismic conditions, while the second one for static conditions. Therefore, the cross-section classification concept does not ensure the development of stable inelastic conditions due to the fact that the provided slenderness limits are determined from simple plate buckling calculations without taking into consideration the effect of loading type.

The first two issues will be discussed in this paragraph, while the third one in the following paragraph.

A proposal defining the member ductility has been made by Mazzolani & Piluso (1993) and Gioncu & Mazzolani (2002) as follows, (Fig. 2):

HD—High Ductility, corresponding to members designed, dimensioned and detailed such that they ensure large plastic rotations.

MD—Medium Ductility, corresponding to members designed, dimensioned and detailed such that they ensure moderate plastic rotations.

LD—Low Ductility, corresponding to members designed, dimensioned and detailed such that they ensure low plastic rotations.

For the member ductility classification the following limits is provided:

HD—R > 7.50
MD—4.50 < R < 7.50
LD—1.50 < R < 4.50

Members with a rotation capacity smaller than 1.50 are considered non-ductile.

In this study the above mentioned classification was taken into consideration for the numerical analysis performed in order to demonstrate the inefficiency of the cross-section classification as prescribed in Eurocodes (EN 1998:2004 & EN 1993:2003).

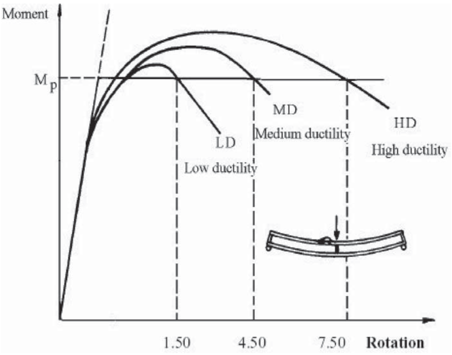


Figure 2. Member ductility classification.

However, the FEMA 356, a prestandard for seismic rehabilitation of structures, specifies according to different performance levels the following values:

Immediate occupancy, IO: R = 0
Life Safaty, LS:R = 5.0; NearCollapse, NC:R = 7.0

The FEMA's limits for the rotation capacity could be considered as provided for seismic loading conditions. The latest version of AISC code (ANSI/AISC 360-10) in the comments of the appendix 1 specifies that sections designed as compact should have a minimum rotation capacity of approximately R = 3.0. This limit could be considered as a value provided under static loading conditions.

Using DUCTROT-M computer program a numerical analysis was performed investigating the available ductility of steel I beams fabricated by hot-rolling or welding. In the study all the main influencing parameters were considered such as material properties, geometrical characteristics (section slenderness, element span) and fabrication details (rigid junction, type of weldment) (Anastasiadis & Gioncu, 1999). It is important to be mentioned that the rotation capacity is predicted under monotonic conditions.

From Table 1 it is evident that according to cross-section classification, as specified to EN 1993, the entire range of IPE sections are of class 1

Table 1. Cross section vs. member classification for hot rolled European sections.

		IPE 360		IPE 400	
Code/proposal		S235	S355	S235	S355
Classification according to EN 1993:2005		1		1	
Classification according to PLM criterion	L = 4000	HD	MD	HD	MD
	L = 5000	MD	LD	MD	MD
		IPE 450		IPE 500	
Code/proposal		S235	S355	S235	S355
Classification according to EN 1993:2005		1		1	
Classification according to PLM criterion	L = 4000	HD	MD	HD	MD
	L = 5000	MD	MD	MD	MD
		IPE 550		IPE 600	
Code/proposal		S235	S355	S235	S355
Classification according to EN 1993:2005		1		1	
Classification according to PLM criterion	L = 4000	HD	HD	HD	HD
	L = 5000	HD	MD	HD	MD

Where L is the standard beam span which is equal to two times the inflexion point of the real beam (0.25–0.30 L_{beam}) and PML is the plastic collapse mechanism.

Table 2. Cross section vs. member classification for built-up welded sections.

		$c/t_f = 5$ $d/t_w = 35$		$c/t_f = 5$ $d/t_w = 55$	
Code/proposal		S235	S355	S235	S355
Classification according to EN 1993:2005		1		1	
Classification according to PLM criterion	L = 4000	HD	MD	HD	MD
	L = 5000	HD	MD	MD	LD
		$c/t_f = 7$ $d/t_w = 35$		$c/t_f = 7$ $d/t_w = 55$	
Code/proposal		S235	S355	S235	S355
Classification according to EN 1993:2005		1		1	
Classification according to PLM criterion	L = 4000	HD	HD	HD	HD
	L = 5000	HD	MD	MD	LD

Where c, t_f, d, t_w, defined in Figure 3.

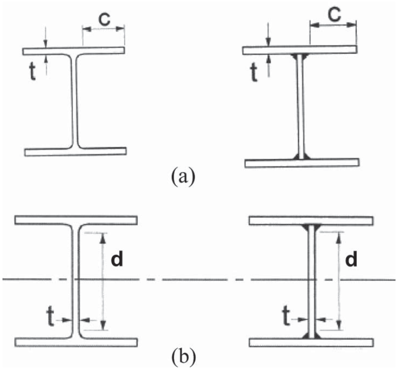


Figure 3. Definition of geometrical dimensions, (a) for hot rolled sections, (b) built-up sections.

which means that are able to redistribute the internal forces and to develop plastic hinge. However, when the influence of element's span is introduced, the available ductility is reduced with the increasing of the span as well as with the increasing of steel quality. Consequently, a section considered compact under cross section ductility criterion does not ensure sufficient ductility capacity under different design conditions.

The same thing could be remarked also for built-up steel I beams. Setting in our numerical analysis the limits specified by the EN 1993:2005, Part 1-1, as Class 1 (compact sections), for both the steel qualities (S235 and S355), it is observed that the ductility capacity is completely different as compared with the member ductility classification, Table 2. For that reason the member ductility criterion seems to be more realistic for design purposes.

3 STATIC VS. SEISMIC DUCTILITY

The ductility under static-monotonic conditions is defined as the ability of an element or a structure to deform significantly beyond the elastic limit while maintaining an ultimate resistance at a predetermined level of strength degradation. Mainly it depends on mechanical and geometrical parameters.

The ductility under seismic conditions has the same basic definition, however in this situation the factors affecting the inelastic capacity are strictly connected not only with the aforementioned influencing factors but with the way that seismic forces act on the structure. Consequently, seismic ductility depends on loading type and with the influence of this one the initial mechanical and geometrical structural conditions are deteriorated. Hence, the loading type dictates the further inelastic capacity of a member or a structure.

Generally, we distinguish two types of actions (Gioncu & Mazzolani, 2002) (Fig. 4):

i. Pulsive ground motions characterizing the near field earthquakes. Such seismic loading conditions induce high strain-rate. In this way the yield stress is increased and as a consequence the available ductility is reduced. As it was observed from earthquake events (Northridge, 1994, Kobe, 1995, Chi-Chi, 1999) in such cases the first or the second cycle could produce brittle fracture. The influencing parameter that should be studied is the strain-rate effect. Moreover, in order to evaluate the reduction of the plastic rotation capacity, firstly the strain-rate effect should be quantified and after that the monotonic rotation capacity should be reduced correspondingly. It is important to prevent a premature fracture that will change

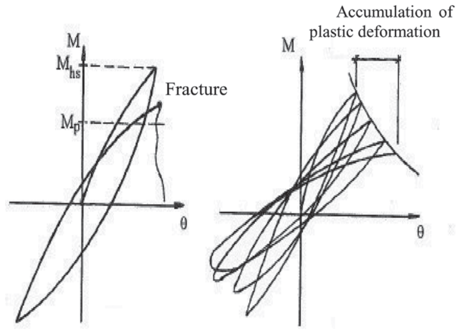


Figure 4. Inelastic behavior under pulsive and cyclic ground motions.

the plastic hinge mechanism from the ductile to the one of brittle manner. Therefore, local flange bucklingis beneficial avoiding fracture.

ii. Cyclic ground motions characterizing the far field earthquakes. Such seismic loading conditions induce to the structural elements an accumulation of plastic deformation due to its repetitive action. The inability of steel plate components to sustain the cumulative reversals leads, after a certain number of cycles, to a gradual deterioration of the plastic rotation capacity and finally to fracture. Therefore, the influencing parameter that should be studied is the number of cycles producing plastic accumulation. Another important factor regarding the cyclic behavior of the plastic hinge, as defined by the local plastic mechanism, is the time that takes place the development of the local flange buckling. When the flange buckling is produced at the maximum seismic action, the plastic hinge works with quasi-constant amplitude, or alternatively when the flange buckling occurs before reaching the maximum seismic actions, the plastic hinge works under increasing amplitude for each cycle (Fig. 5). In case when local buckling does not occur, a plastic accumulation leads to a brittle fracture of the tension flange. The presence of the slab generates to some extent conditions not permitting the development of the upper flange local buckling. For both cases (pulsive and cyclic motions) the local buckling is beneficial, hence special measures should be taken minimizing the composite action in the potential zone of the plastic hinge formation.

A numerical analysis exploiting the facilitations provided by the DUCTROT-M computer program, which implements several models evaluating the seismic ductility, was carried out.

Investigating the effect of the strain-rate on the available ductility of steel beams one can remark a dramatic reduction of plastic rotation capacity.

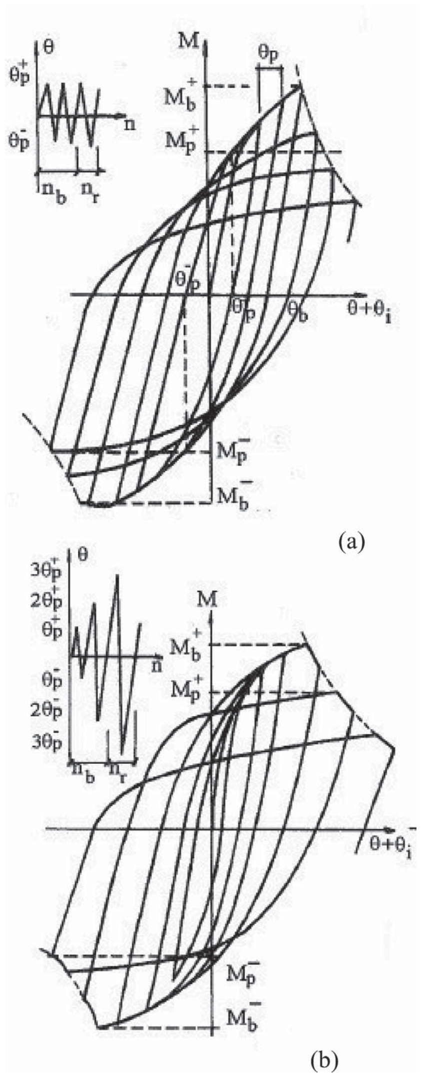
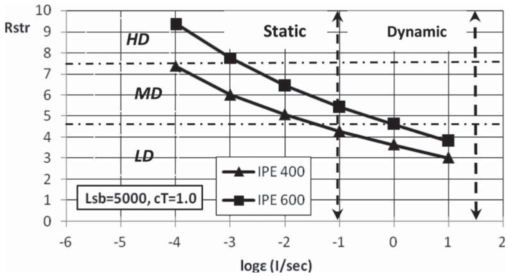


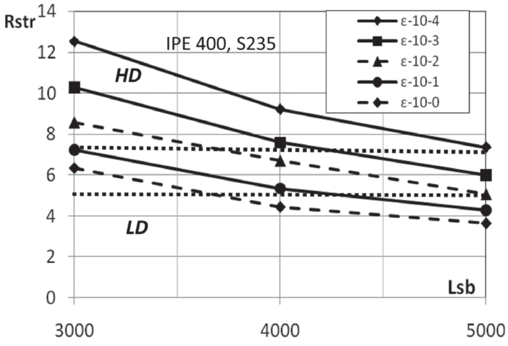
Figure 5. (a) Constant rotation amplitude, (b) Increasing rotation amplitude.

Referring to the Figures 6 and 7, it is observed that a steel section classified as highly ductile under static loading conditions it is transformed to a low ductile under dynamic conditions. Therefore, near field earthquakes with strain-rate levels of 10^{-1}/sec–10^{1}/sec are very dangerous not only for the aforementioned plastic rotation reduction but also for fracturing that provided under the effect of high velocity pulses. Moreover, in case of far field earthquakes the rotation capacity is also reduced but with a more smooth mode, diminishing with one level the ductility class, from high to medium ductility. Figure 8 shows the variation of the



where Lsb is the standrd beam span, cT is a coefficient with respect to the temperature effect. For near filed earthquakes the strain-rate varies between 10^{-1} /sec–10^{1}/sec, while for far field earthquakes between 0.5×10^{-2}/sec–10^{-1} /sec.

Figure 6. Influence of strain-rate effect on the rotation capacity.



Lsb-standard beam span. c_T =1.0 (room temperature)

Figure 7. Influence of the member span in different strain-rate conditions.

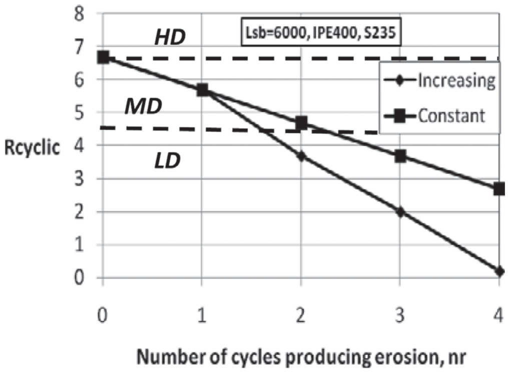


Figure 8. Influence of cyclic loading conditions on the available rotation capacity.

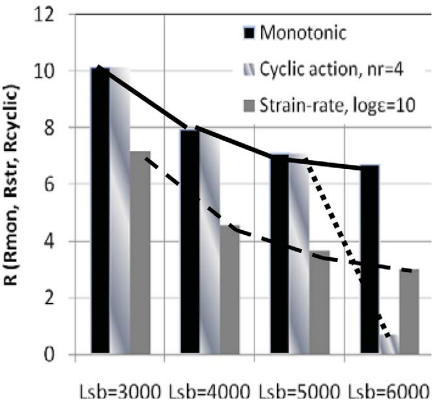


Figure 9. Static and seismic available ductility.

rotation capacity in function of member span for different levels of strain-rate. Beyond the reduction of the rotation capacity, it is evident that only the member ductility criterion could represent the variation of inelastic capacity considering different loading conditions.

The effect of cyclic loading conditions, with constant or increased amplitude, on the rotation capacity is presented in Figure 8. Taking into account the number of cycles, for increasing amplitude that produce a gradual deterioration, it is pointed out that after several cycles the rotation capacity was exhausted as compared with the monotonic one. Also for constant amplitude one can observe a dramatic erosion of the available rotation capacity that approach more than 50% of the monotonic one.

Trying to compare the different ductility types, it is obvious that the static-monotonic ductility should be considered only as a reference value (Fig. 9). For design purposes, the reference value could be properly reduced introducing the main influencing parameters as previously discussed. Therefore, using as the basis the monotonic rotation capacity, R_{mon}, the available rotation capacity under strain-rate, R_{str}, and cyclic conditions, R_{cyclic}, is possible to be obtained.

4 CONCLUSIONS

This study examined the effectiveness of the current code specified cross-section classification concept and investigated the main influencing parameters that affect the ductility under seismic loading conditions. The conclusions drawn from the presented study are summarized as follows:

i. The cross-section classification should be substituted with a member ductility classification combined with a suitable calculation methodology that predicts the available rotation capacity.

ii. The static ductility could be used only as a reference value. This one should be diminished taking into consideration the different seismic loading conditions.

iii. For near field action the strain-rate is the decisive parameter reducing the available rotation capacity. For far field earthquakes the number of cycles producing erosion of the basic monotonic ductility is the main influencing factor. Generally plastic collapse modes than fracture one should be promoted.

iv. Under exceptional seismic actions steel I sections are very difficult to achieve a high ductility level. Therefore, the plastic hinge should be moved away from the joint high stressed region by using weakening (reduced beam section) or strengthening solutions (ribs, haunch, cover plates, etc).

v. Despite the difficulties to select the most suitable loading type and the complexness of the seismic phenomena a step forward in practical design should be the direct implementation of a comprehensive ductility methodology. Only in this way the results of inelastic analysis, like pushover and time-history, could be considered stable and reliable, because there is an interrelation between the available rotation capacity and the target displacement. Each member of a structure should dispose sufficient local ductility otherwise the structure's target displacement is not achieved. Therefore, the prediction of the available ductility is of crucial importance.

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