EXPERIMENTAL INVESTIGATION and ANALYTICAL MODELING of the CYCLIC BEHAVIOR of SMOOTH STEEL BARS

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ABSTRACT :

Most of existing Reinforced Concrete (RC) structures, built until the 1970s in areas declared seismic by the recent zoning of national territory, are internally reinforced by smooth steel bars. The study of cyclic behavior of such bars has an important role in the assessment of seismic vulnerability of existing RC structures. The detailed analysis of experimental outcomes obtained by an extensive experimental campaign on smooth steel bars with different L/D ratios (L is the stirrups spacing and D is the longitudinal bar diameter) represents the focus of this paper. The cyclic damage and buckling in compression depend on such ratio, and they strongly influence the hysteretic response of smooth steel bars in terms of stress-strain relationship. The analyzed ratios have ranged between 5 and 100 in order to take into account all the real configurations within the joint zones. In particular, the higher ratios (i.e. 75 or 100) represent the innovative aspect of this study: they are representative of geometrical conditions, in terms of stirrups spacing and longitudinal bars diameter, within RC elements of the years between the '60s and '70s which are typically characterized by high stirrups spacing.

KEYWORDS: stress-strain relationship, cyclic damage, smooth steel bars, beam-column joints

1. INTRODUCTION

This paper presents the results of an extensive experimental campaign on cyclic behavior of smooth steel bars used as internal reinforcement of existing Reinforced Concrete (RC) structures. The construction practice, in many old existing RC buildings now located in seismic regions, used smooth steel bars as internal reinforcement with inadequate stirrups spacing close to the dissipative zones, i.e. joints. After cracking, the influence of the steel on flexural response of an RC element is more important than concrete. Furthermore, the presence of a high axial load and high curvature values enhances the effect of the steel constitutive behavior on non-linear response of a RC element. These considerations find application in the existing RC buildings. The effects of inelastic buckling and cyclic damage of the steel reinforcing bars have to be considered when performing the assessment of existing structures by means of a non-linear static analysis (i.e., push-over analysis) according to modern codes [Eurocode 8 - Part 3, 2004; Italian Code D.M. 14 January, 2008]. The present paper focuses on a fundamental part of a wider study on the mechanical characterization and theoretical modeling of smooth reinforcing bars.
The cyclic response of a smooth steel bar is influenced geometrically by the L/D ratio, where L is the stirrups spacing and D is the longitudinal bars diameter, as well as by loading history. In this paper the cyclic stress-strain relationship is analyzed for different values of L/D ratio; the influence of the loading history on mechanical response of the bars is not here discussed.
The experiments have concerned bars with L/D ratios ranging between 5 and 100: the very high values of L/D ratio (i.e. 75 or 100) are analyzed to simulate cases where there is absence of stirrups close to the joints. Cyclic tests on ribbed steel bars, for which cyclic degrading models are available in literature, are carried out for only few L/D values, in order to define the different behavior of ribbed bars compared to smooth steel bars when these are subjected to a cyclic load history. After the analysis of test results, the theoretical predictions obtained by the most significant existing models available in literature about cyclic behavior of ribbed steel bars are discussed and compared to the experimental outcomes. These comparisons allow underlining the ranges of applicability as

well as the potential of these formulations for predicting the damage and buckling that occur for different L/D ratios of the smooth steel bars.

2. EXPERIMENTAL TESTS

2.1. Specimens and Test Setup

The diameters selected for tests are of 8 mm, 12 mm, 14 mm and 16 mm; the L/D ratio ranges in the field 5÷100. The test setup was inherited by a previous work on mechanical characterization of smooth steel bars in compression [Cosenza and Prota, 2006]. The tests were carried out in a displacement control mode, with a low strain rate (0.05 mm/s) through an universal machine (MTS 810) in the Department of Structural Engineering laboratory. The specimens was tightened within hydraulic grips; the clear length between the grips was equal to L. The stress was obtained by dividing the load by the bar initial cross-section area of the bar, and the strain by the readings of extensometer and a linear variable inductive transducer (LVDT).
Some tests were performed on ribbed steel bars in order to enrich the experimental knowledge of smooth bars. Two types of ribbed reinforcing bars differing in steel tensile properties (table 2.1) were selected: the former (Ribbed 1) fulfils the recommendations made under Italian [Italian Code D.M. 14 January, 2008] and European [Eurocode 2 - Part 1-1, 2004] provisions to limit the over-strength of steel (i.e., $1.15 \le f_t/f_y \le 1.35$), while the latter (Ribbed 2) is completely outside the above limits.

Table 2.1 Monotonic tensile properties of tested steel bars

	ε_y *[mm/mm]*	f_y *[MPa]*	ε_h *[mm/mm]*	ε_t *[mm/mm]*	f_t *[MPa]*	$b=E_\infty/E_0$ *a-dim.*	f_t/f_y *a-dim.*
Smooth	0.0021	350	0.032	0.231	440	0.020	1.26
Ribbed 1	0.0031	540	0.0245	0.115	640	0.015	1.18
Ribbed 2	0.0028	535	0.0061	0.095	850	0.076	1.59

2.2. Loading Histories

The experimental campaign has concerned cyclic tests with arbitrary loading histories, but only the most significant loading histories will be shown in this paper. They can be summarized in table 2.2.

Table 2.2 Loading histories

TEST	ε_1 *[%]*	ε_2 *[%]*	ε_3 *[%]*	ε_4 *[%]*	ε_5 *[%]*	ε_6 *[%]*
S	+1	-1	+2	-2	+3	-3
T[0.5ε_y]	+(0.5ε_y)	-20				
T[0.9ε_y]	+(0.9ε_y)	-20				
T1	+1	-20				
T2	+2	-20				
T3	+3	-20				

It is underlined that, in tests T[0.5ε_y] and T[0.9ε_y] the bar remains in the elastic portion before compression: it reaches different load values in tension (the 50% and 90% of the yielding value) without exceeding the yielding strain.

2.3. Experimental Results

Tests S represent the core of the experiments; their outcomes have underlined a good repetitiveness of the curves and the independence of stress-strain relationship by the bar diameter (D). In fact the overlapping of the curves with different diameter suggest that L/D ratio is the only geometric influencing parameter of cyclic damage. Figure 1 shows the effect of L/D ratio on cyclic response of smooth steel bars with different L/D.

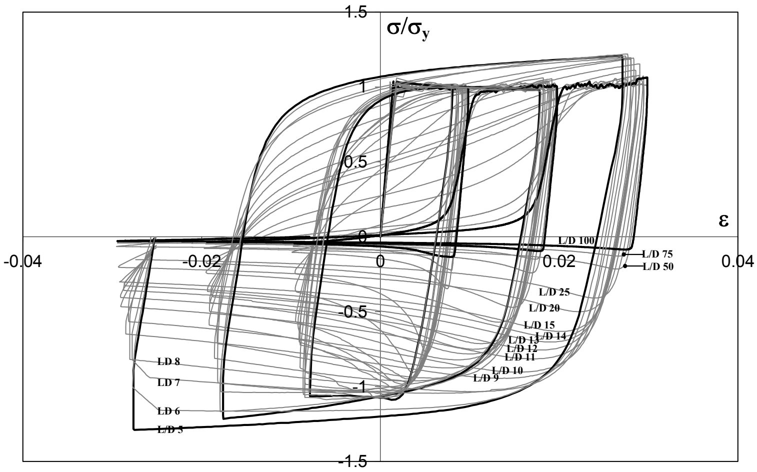


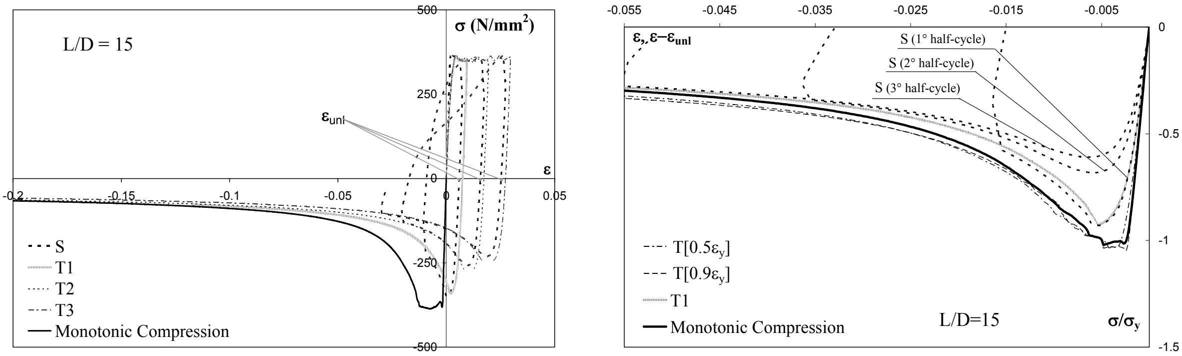
Figure 1 Evolution of cyclic response for smooth bars with L/D ranging between 5 and 100

The cyclic behavior is symmetric in tension and compression only when L/D≤5. In this case the classical physical phenomena reported in the literature for the ribbed steel bars [Monti and Nuti, 1992] were also observed for the smooth bars, namely *Bauschinger effect* and *isotropic hardening*. For L/D>5 the cyclic behavior stops to be symmetric, showing a gradual passage from a typical cyclic diagram of the steel material (for L/D=6, 7) to a typical diagram of a slender steel beam (for L/D=50, 75, 100).
The threshold L/D=8 divides two curves families:

- for the curves with L/D ratio ranging in the field 5≤L/D≤8, in the generic loading branch (portion of diagram between two consecutive strain reversal points), in tension and compression, the curvature sign does not change: the generic half-cycle starts with a linear elastic behavior, then it tends to a final asymptote through a non-linear behavior; the strength and stiffness damage is very minimum passing from 5 to 8,
- for the curves with L/D ratio ranging in the field L/D>8, the sign of the curvature of the generic loading branch changes and the half-cycle can not be modeled through an hyperbolic function as it will be better explained in the section on theoretical and experimental comparisons; furthermore, the comparison of the curves underlines a strong decreasing of reloading stiffness (initial stiffness of the half-cycles in compression) and strength in compression as the L/D ratio increases, while the unloading stiffness (initial stiffness of the half-cycles in tension) and tensile strength do not decrease as L/D ratio varies.

The comparisons of the results of tests S with the results obtained by the other loading histories (table 2.2) have allowed to contribute to the knowledge of the cyclic damage of smooth steel bars. Such damage can be named as *low-cycle fatigue functional* because due to fatigue under low number of cycles. Figure 2 a) shows the comparisons of diagrams obtained by tests S, T1, T2, T3 and monotonic compression. It clearly appears that cyclic damage is defined by maximum plastic excursion, in fact the curves of tests T1, T2 and T3 overlap the loading branches in compression of test S when the previous plastic excursion is 1%, 2% and 3%, respectively.
In fact, the strength-stiffness damage in a smooth steel bar subjected to a cyclic load history depends also on plastic energy dissipated n the previous cycles, which is in line with the findings of Cosenza and Manfredi [1994] and of Dodd and Restrepo-Posada [1995]. In figure 2 b), for a generic L/D ratio (i.e. 15), the loading branches in compression of the tests S, T1, T[$0.5\varepsilon_y$] and T[$0.9\varepsilon_y$], previously moved in the axis origin, are compared with compressive monotonic curve. Such figure shows that cyclic damage occurs only when the steel does not exceed the yielding strain. In other words, every loading branch overlaps the monotonic curve, in tension and compression, when the bar does not attain plastic deformations (plastic excursion equal to zero) computed

as $\xi_p^i = \varepsilon_r^i - \varepsilon_y^i$.



a) b)

Figure 2 Experimental comparisons for L/D=15

2.4. Cyclic Strength Damage

The strength values in compression of cyclic curve shown above can be used to analyze how the maximum stress of the first half-cycle in compression (normalized to the yielding stress) varies when the a-dimensional slenderness changes (see figure 3). The a-dimensional slenderness is the parameter that all modern codes like Eurocode 3 [1993] use to evaluate the buckling of compressive members; it can be expressed as:

$$\bar{\lambda} = \frac{\lambda}{\lambda_c} = \sqrt{\frac{N_{pl}}{N_{cr}}} = \sqrt{\frac{\sigma_{pl}}{\sigma_{cr}}} = \frac{4\beta}{\pi}\sqrt{\frac{\sigma_y}{E}}\frac{L}{D} = 0.025\sqrt{\frac{\sigma_y}{320}}\frac{L}{D} \tag{2.1}$$

In this section only the strength damage due to maximum plastic elongation (ξ_p) is discussed; the strength damage due to plastic energy dissipated during cycles is not here discussed.

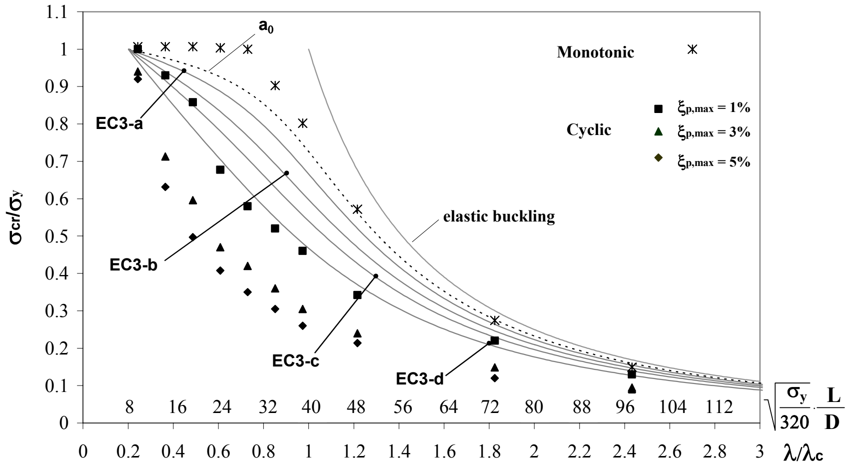


Figure 3 Buckling curves. Experimental comparisons

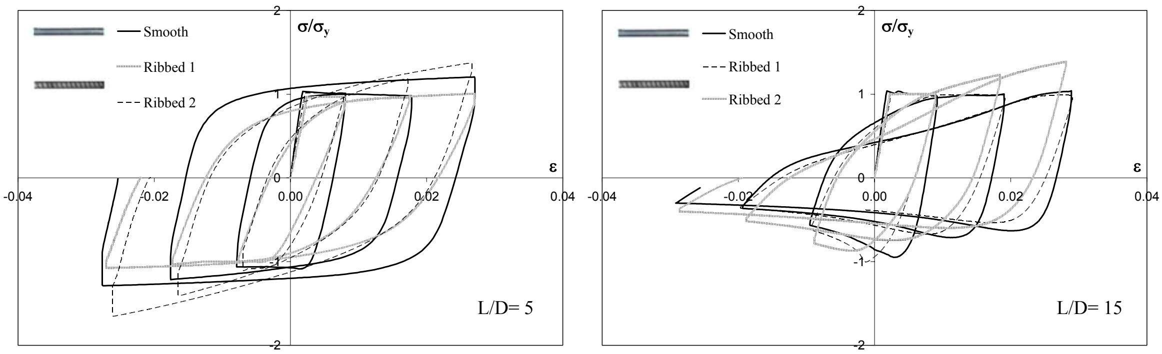
In figure 3 monotonic and cyclic strength values are reported; cyclic strength is referred to three different maximum plastic elongations (ξ_{max}). The monotonic points are contained between the Eulerian elastic buckling curve and that provided by Eurocode 3, in particular the curve a_0. The cyclic values of the strength are smaller than monotonic values because of cyclic damage.

The main features of this comparison can be summarized in only two points:

- the tendency of the strength cyclic damage is well represented by buckling curves provided by Eurocode 3: the rate of cyclic damage which is due to maximum plastic elongation is very small when L/D ratio is both low (close to 8) and high (close to 100),
- strength cyclic damage is not proportional to the increasing of maximum plastic elongation (ξ_{max}).

2.5. Smooth and Ribbed bars. Experimental Comparisons

In this section some comparisons of the experimental outcomes of test S between smooth and ribbed bars are presented in order to better define the cyclic behavior of smooth steel bars. The mechanical properties of tested bars are reported in Table 2.1. Figure 4 shows the comparisons for L/D=5 and L/D=15 which represent a low and high ratio, respectively.



a) b)
Figure 4 Smooth and Ribbed bars. Experimental comparisons

From comparisons, the following remarks can be made:

- for low L/D values (figure 4 a)), the classical cyclic characteristics (Bauschinger effect, isotropic hardening) are also found in the cyclic curves of Ribbed 1 and Ribbed 2. Every branch curve can be modeled by a non-linear function in which the curvature sign does not change. The slope value of the final asymptote in the generic branch is larger than that of a smooth bar; this is only partially due to different hardening ratios (table 2.1), in fact Ribbed 1 and smooth bar exhibit the same asymptote slope even though smooth bar has a higher hardening ratio than that of Ribbed 1. Ribbed bars exhibit a higher stiffness damage and curvature values than those of smooth bars.

The findings on the difference between smooth and ribbed bars with low L/D ratios will be detailed by the comparisons with theoretical models presented in section 3, in particular by table 3.1.

- for high L/D values (figure 4 b)), for ribbed bars, every loading branch in tension and compression is characterized by a double concavity like it happens for smooth bars with L/D>8: the three curves tend to be very close. The threshold, in terms of L/D ratio, which divides the two families of curves (it was evaluated equal to 8 for smooth bar) is higher for ribbed bars, and was evaluated equal to 11 for Ribbed 1 [Monti and Nuti, 1992] and to 13 for Ribbed 2.

3. THEORETICAL-EXPERIMENTAL COMPARISONS

In order to predict the behavior of smooth steel bars when cyclic damage occurs, the experimental curve are compared with the most significant hysteretic models available in the literature. As far as the authors know all models developed for steel reinforcing bar were referred to ribbed bars with low L/D ratios, typical details of modern RC structures. Figure 5 shows the theoretical-experimental comparisons for smooth, Ribbed 1 and Ribbed 2 for two different L/D values (5 and 15) considering the loading history of test S. The comparisons for L/D equal to 5 are used also in order to quantify the differences between smooth and ribbed bars when the L/D ratio is small (table 3.1).

Many existing formulations on steel reinforcing bars are developments of the original laws proposed by Menegotto and Pinto (M-P) [1973]: one of the most known was developed by Monti and Nuti [1992]. In this paper the theoretical curves will be obtained by the M-P model, because this section aims to underline the intrinsic abilities of this model to capture the physical evidences underlined in the experimental outcomes for smooth bars.
In M-P model the following expression is used to define any branch curve:

$$\sigma^* = b\varepsilon^* + \frac{(1-b)\varepsilon^*}{\left(1+|\varepsilon^*|^R\right)^{1/R}} \tag{3.1}$$

Obviously (ε^*, σ^*) are the adimensional strain and stress defined by:

$$\varepsilon^* = \frac{\varepsilon - \varepsilon_r^n}{\varepsilon_y^{n+1} - \varepsilon_r^n}, \quad \sigma^* = \frac{\sigma - \sigma_r^n}{\sigma_y^{n+1} - \sigma_r^n} \tag{3.2}$$

in this way the starting point for any branch is determined by the stress and strain at the last strain reversal.
The generic branch "n" is described by five parameters (E^n, b^n, $\sigma_y{}^n$, $\varepsilon_y{}^n$, R^n), which have a clear mechanical meaning and have to be updated and stored at every strain reversal. Parameter b is the hardening ratio, while R controls the curvature of the branch curve and is a function of parameters R_0, A_1, A_2, and previous maximum plastic strain ξ_{max} through the expression:

$$R = R_0 - \frac{A_1 \cdot \xi_{\max}}{A_2 + \xi_{\max}} \tag{3.3}$$

where R_0 is the value of parameter R during the initial loading, and A_1 and A_2 determine the rate of the degradation of the yield limit as a function of the previous maximum plastic strain.
The coordinates of the intersection point of the initial and final straight line (bilinear envelope) are $\varepsilon_y{}^n$ and $\sigma_y{}^n$.

The numerical values assumed by the parameter of M-P model in the case of L/D=5 can be summarized in table 3.1. Such values confirm all the considerations listed in the previous section.

Table 3.1 Parameters of M-P model for L/D=5

	E_0 *[MPa]*	$E_{UN} \equiv E_{REL}$ *[MPa]*	$R(\varepsilon_1)$ *a-dim*	$R(\varepsilon_2)$ *a-dim*	$R(\varepsilon_3)$ *a-dim*	$R(\varepsilon_4)$ *a-dim*	$R(\varepsilon_5)$ *a-dim*	$R(\varepsilon_6)$ *a-dim*	b_{UN} *a-dim*	b_{REL} *a-dim*
Smooth	165000	165000	18.00	4.00	2.10	2.00	1.98	1.98	0.010	0.010
Ribbed 1	175000	80000	25.0	2.70	2.54	2.26	2.17	2.13	0.010	0.010
Ribbed 2	191000	80000	25.0	2.70	2.56	2.27	2.19	2.14	0.050	0.050

The summary of these comparisons show that the formulations available in the literature for steel reinforcing bars are sufficiently able to predict the cyclic curves of smooth and ribbed steel bars when the L/D ratio is less than L/D<8 for smooth bars. This is basically due to the ability of M-P law to model the generic branch curve belonging to the first range which is characterized by only one concavity. For L/D>8 the change in the curvature sign lies outside the analytical predictions of M-P law as figure 5 clearly shows.
Finally, figure 5 focuses on bars with L/D equal to 15; the experimental curves of Ribbed 2 are closer to the predictions of M-P model, compared to smooth and Ribbed 1 bars. Such evidence is due to the fact that, for Ribbed 2 bar, the generic loading branch starts to exhibit a double concavity with an L/D ratio (L/D=13) which is closer to the ratio used in the comparisons (L/D=15).

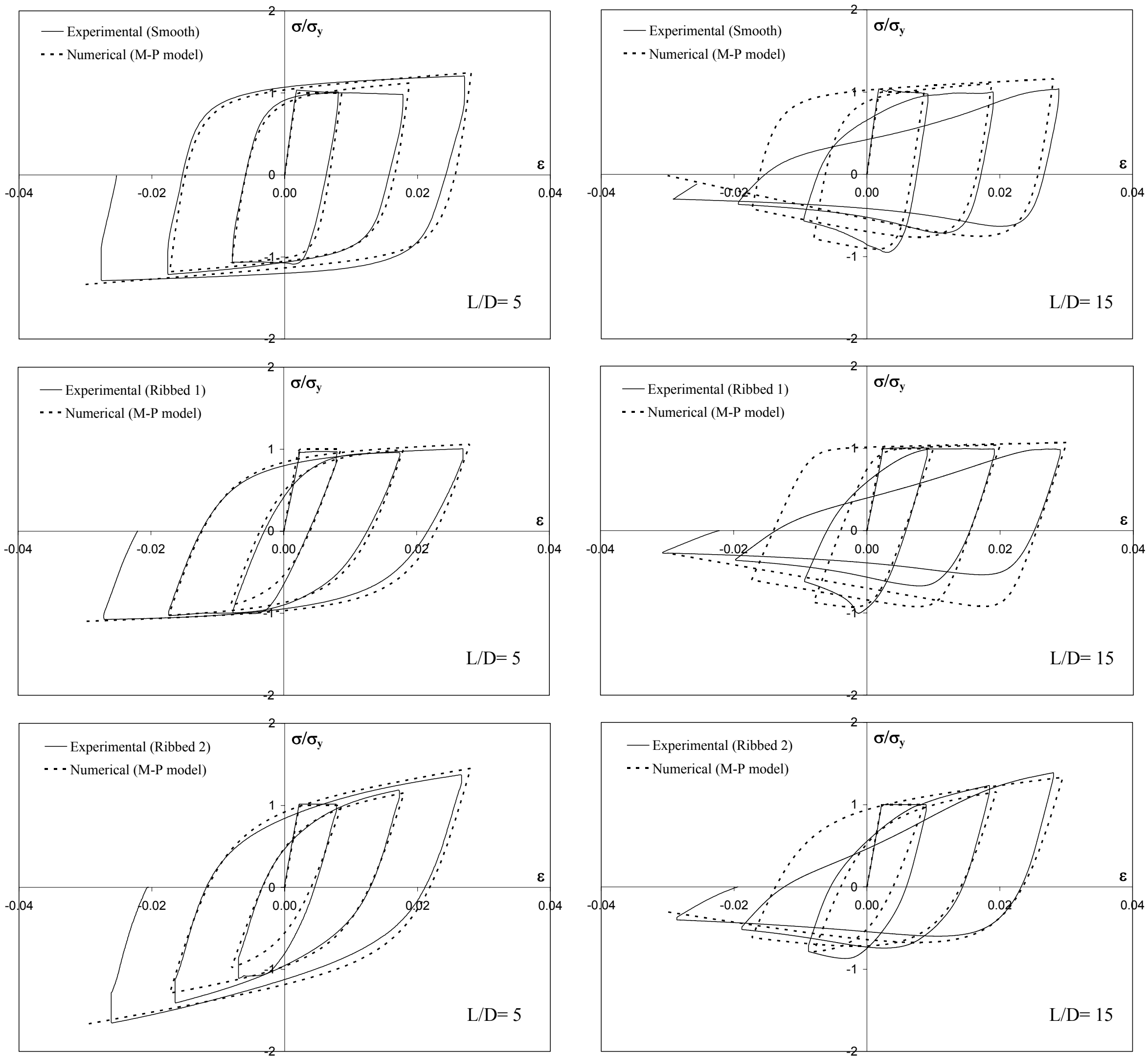


Figure 5 Experimental-Theoretical comparisons for L/D=5, 15

4. CONCLUSIVE REMARKS

The paper has discussed the principal aspects of a wider study on mechanical characterization of smooth steel bars subjected to cyclic loading histories with low and high L/D ratios. The study focused for the first time on the effects of high slenderness induced on hysteretic behavior of smooth steel bars. The main results drawn by the experimental investigation can be summarized as follows:

- repetitiveness of experimental curves with the changing of the bar diameter: geometrically, the only influencing parameter is the L/D ratio,
- the threshold L/D=8 separates two different curves shapes: when the L/D ratio is smaller than 8, the generic loading branch, in tension and compression, does not ever change the curvature sign; instead, with high L/D ratios (L/D>8), the stress-strain relationship is characterized by a change of the loading branch concavity,
- cyclic behavior of ribbed bars looks like that exhibited by smooth bars; with low L/D ratios, smooth bars differ from ribbed bars in the values of the modeling parameters (adopting the M-P formulation) and the threshold which divides the curves shapes: for ribbed bars it is equal to 11,
- strength and stiffness cyclic damage is influenced by the L/D ratio, and by previous loading history, and it

occurs only when the maximum plastic excursion is not equal to zero; in absence of damage, the loading branches overlap the monotonic curve; the trend of cyclic strength damage in compression with L/D ratio is very similar to the curves provided by European code for buckling of slender steel elements,

- The experimental-theoretical comparisons showed that, with the re-calibration of some parameters, the M-P model, which is used by many theoretical formulations found in the literature, might fit the branch curves in tension and compression, for L/D≤8. For larger L/D values, instead, these models do not capture the mechanical phenomena which occur during loading history.

The experimental and theoretical content of this work represents a starting point for the development of an analytical model for bars accounting for inelastic buckling and cyclic damage, which change as a function of L/D ratio. This information could be implemented in computer programs for the analysis of RC cross-sections.

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