Proposal of a new indicator to define ductility applied to corroded steel reinforcement on concrete structures

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Abstract

The carbonation of concrete or the chlorides ingress in such quantity to reach the level of bars is triggers of reinforcement corrosion.

One of the most significant effects of reinforcing steel corrosion on reinforced concrete structures is the decline in the ductility-related properties of the steel. Reinforcement ductility has a decisive effect on the overall ductility of reinforced concrete structures. Different Codes classify the type of steel depending on their ductility defined by the minimum values of several parameters.

Using indicators of ductility associating different properties can be advantageous on many occasions. It is considered necessary to define the ductility by means of a single parameter that considers strength values and deformation simultaneously.
There are a number of criteria for defining steel ductility by a single parameter.

The present experimental study addresses the variation in the ductility of concrete-embedded steel bars when exposed to accelerated corrosion. This paper analyzes the suitability of a new indicator of ductility used in corroded bars.

Keywords: concrete structures, reinforcement corrosion, ductility, equivalent steel.

1. Introduction

Progress in the understanding of the behaviour of reinforced concrete structures has depended upon appearance and acceptance of analytical methods that attempt to provide an increasingly achúrate explanation of the phenomena observed in actual structures. At the same time, new engineering procedures are making new demands on structures and their constituent materials. Specifically, the application of analytical methods based on moment redistribution calls for structures with sufficient rotation capacity in the portions under greatest stress. Reinforcement must, for this reason, meet a series of requirements that can be enveloped in the term ductility.

In ductile structures the effect of actions can be redistributed; when the maximum load carrying capacity is reached in one section, another can bear a higher load, but only if the former section and the structure as a whole can accommodate further deformation.

In new construction, various structural design methods may be used to analyze ductility and obtain the most convenient reinforcement layout for on-site works. Moreover, ductile structures have higher ultimate load values and in the event of special circumstances their risks are more predictable thanks to their greater deformability.

Ductily also provides for higher leves of energy absorption, a concern of cardinal importance in seismic area design.

The foregoing issues are well understood and have been the object of a host of articles in both national and international journals [1-4]. The present paper aims to look at the question from a new angle.

The analysis of existing RC structures should address moment redistribution to be able to comare ultimate strength values, rather than to a single value obtained with elastic linear models, to a range of values centred on the elastic and linear models, to a range of values centred on the elastic and linear values obtained and defining an interval equal to double the value of the maximum redistribution capacity. This greatly enhances the possibility of “saving” a standing structure.

Such an analysis should determine, first, whether moment redistribution is possible and second, the scope of the redistribution, which should be a extensive as possible.

In European and other codes commonly used in structural analysis, steel ductility is regarded to be one of the instrumental parameters for defining moment distribution capacity, but no consensus has yet been reached about the maximum redistribution that should be allowed or the minimum values required to be able to proceed to such redistribution. Consequently, the ascertainment of corroded reinforcement ductility is of key importance in structural re-engineering.

2. Ductility requirements

The CEB-FIB Model Code (CM-90) [5] and Eurocode 2 (EC-2) [6] classify steel into several grades of ductility depending on two parameters: the ratio between the ultimate and yield strength of steel and elongatin at maximum loading, ε_{max}. (uniform strain on the steel speciment during the tensile test when subjected to the maximum load). It is expressed as a percentage of the initial length between two previously defined points on the specimen.

The greater the elongation, the more ductile the steel (Table 1).

Table1. Moment redistribution allowed in concrete codes and specifications for special ductility steel.

CODE	MOMENT REDISTRIBUTION	DUCTILITY SPECIFICATIONS
EUROCODE EC-2	a)High ductility steel (C) $f_{ck} \le 50$: $\delta \ge 0,44 + 1,25\ x/d$ $f_{ck} > 50$: $\delta \ge 0,54 + 1,25\ x/d$ Non sway frame: Máx. 30% Sway frame: No redistribution b)Standard Ductility steel (B) Max. 15% c) Low ductility steel (A) Max. 20%	Class A: $(f_s/f_y)_k \ge 1,05$; $\varepsilon_{max,k} \ge 2,5\%$ Class B: $(f_s/f_y)_k \ge 1,08$; $\varepsilon_{max,k} \ge 5,0\%$ Class C: $1,15 \le (f_s/f_y)_k < 1,35$; $\varepsilon_{max,k} \ge 7,5\%$
CEB-FIP MODEL CODE 1990	a) High or Standard ductility steel (S and A, respectively) $f_{ck} \le 35$: $\delta \ge 0,44 + 1,25\ x/d$ $f_{ck} > 35$: $\delta \ge 0,56 + 1,25\ x/d$ Non sway frame: Max. 25% Sway frame: Max.10% b) Low ductility steel (B) $\delta \ge 0,75 + 1,25\ x/d$ Max. 10%	Class B: $(f_s/f_y)_k \ge 1,05$; $\varepsilon_{max}, \ge 2,5\%$ Class A: $(f_s/f_y)_k \ge 1,08$; $\varepsilon_{max,k} \ge 5,0\%$ Class S: $(f_s/f_y)_k \ge 1,05$; $\varepsilon_{max,k} > 6\%$

3. Equivalent steel. The concept.

Reinforcement ductility has a decisive effect on the overall ductility of reinforced concrete structures. Codes such as EC-2 and CM-90 classify steel by type depending on their ductility as defined by the minimum values of two parameters: the ultimate strength-yield strength ratio (fs/fy) and elongation under maximum loading ε_{max}. It is nonetheless possible for a given steel to fail to meet one of the two requirements for inclusion in a certain class, while amply exceeding the specificatios for the other.

According to the above codes, the steel in question would be relegated to the next lower class, whereas experimental observations suggest that amply exceeding one of the values may compensate for not meeting the other and afford the steel in question greater ductility than one that complies strictly with the two requirements to belong to a certain class.

In light of such considerations, the equivalent steel concept arose in Europe in the 1990s, that may be defined as a steel that gives the same benefits of ductility that the defined ones in the classes of EC-2 or CM-90, although not necessarily meetin both minimum requirements.

They exist, in addition other criteria to define the ductility as a single parameter. The present paper analyzes the ones put forward by Cosenza [7] and Creazza [8].

The definition of “equivalent steel” developed by Cosenza is based on two concepts:

It regards rotation capacity to be themost important structural parameter: two different steel are equivalent only if they generate the same rotational capacity.

The steel is defined only by only two parameters: elongation under maximun loading and the ultimate strength-yield strength ratio.

Pursuant to these ideas, the plastic rotation borne by a reinforced steel beam prior to failure is assumed to be the chief parameter to define structural behaviour and the rotational capacity is understood to depend solely on the steel properties.

An extensive parametric analysis was conducted to assess the efect of steel characteristics on plastic rotation and thus define equivalent steel.

In this analysis, the referece beam was defined to have a section of 30x60 cm^2, a length of 6m and to be reinforced with 2Φ12 bars; the depth of the neutral fibre was set at x/d=0,10.
Results were found for steel with and without a definite yield point.

Figure 1 shows the results for steel with no definite yield point, in which the Ramberg and Osgood formula was used to describe the stress-strain behaviour:

$$\varepsilon_{máx} = \frac{f_S}{\varepsilon_S} + \left(\frac{f_S}{B}\right)^n \qquad n = \frac{\ln\dfrac{\left(\varepsilon_{máx} - {f_S}/{\varepsilon_S}\right)}{0{,}002}}{\ln\left({fs}/{fy}\right)} \qquad B = \frac{f_y}{0{,}002^{\left(1/n\right)}}$$

where f_s is the ultimate strength and fy the yield strength. According to the results in Figure 1, all the curves tend to zero for low values of strain to fracture regardless of the ft/fy ratio and for low values of fs-fy-1 irrespective of ε_u. The following expression was obtained from numerical analysis: elongation, independently from the fs/fy ratio. The numerical analyses performed provided this formulation:

$$\theta_{pl} = 1{,}3 \cdot \varepsilon_{máx}^{0{,}73}\left(\frac{f_S}{f_y} - 1\right)^{0{,}92}$$

where, θ_{pl} is plastic rotation.

Hence plastic rotation is proportional to parameter p where:

$$p = \varepsilon_{máx}^{0{,}73}\left(\frac{f_s}{f_y} - 1\right)^{0{,}92} \cong \varepsilon_{máx}^{0{,}75}\left(\frac{f_s}{f_y} - 1\right)^{0{,}9}$$

which only depends on steel characteristics.

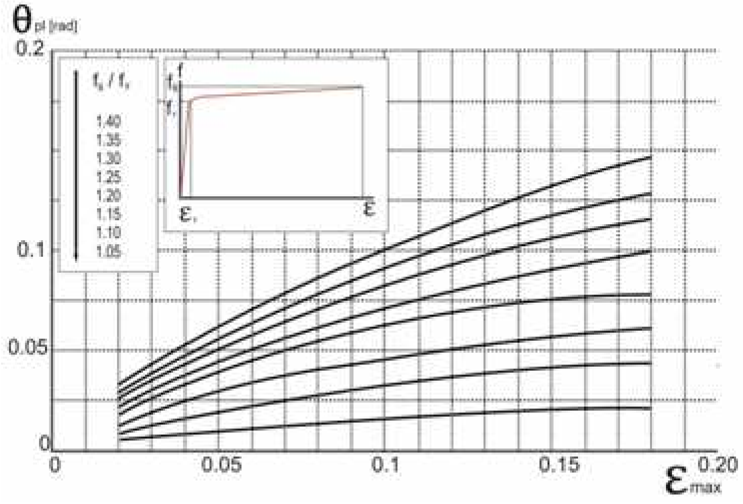

Figure 1. Results of parametric análisis for steel with no definite yield point. (5)

On the ground of this reasoning, Cosenza et al. suggested that steel characterized by pairs of (εu, ft/fy) values, generating the same value of p should be defined to be equivalent.

In the event, for instance, of a steel with no sharply defined yield point, the values of ft/fy and Eu that define each CM-90 and EC-2 class of steel are used instead to compute the limit value of parameter p that defines each class. The results of this operation are given in Table 2.

Consequently, the value of parameter p for a given steel suffices for classification in terms of ductility.

Creazza, in turn, also seeking a single parameter to define steel ductility, determined the value of the area bounded by the following for values: yield strength, ultimate tensile strength, elongation under maximum loading and elongation at the elastic limit (Figure2)

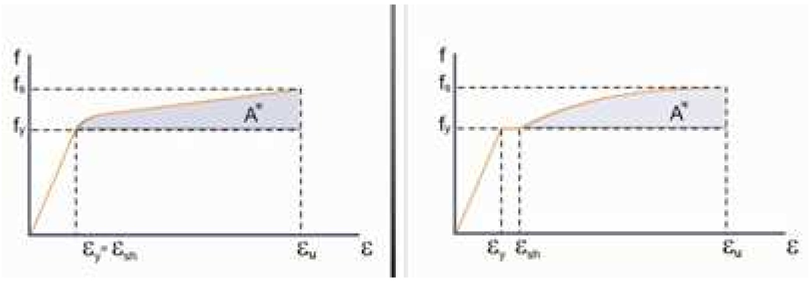

Figure 2. Stress-strain curves for a steel without and with definite yield point.

The shaded areas marked in the typical stress-strain diagrams for steel define the deformation taking place in the material during the plastic phase. In the opinion of these authors, such areas embody the conept of ductility, constituting a single parameter that takes simultaneous account of stress and strain values and can consequently be used as an indicator to establish whether a steel is sufficiently ductile.

If operations similar to tose described above were conducted, a table of values could be built for the new parameter defined by Creazza. Table 2 gives such results for one steel with a yield strength of 500 N/mm^2 and no definite yield point.

Despite the enormous scientific and technical interest of the two criteria equivalent steel discussed in the preceding paragraphs, they have two serious drawbacks [9].

Cosenza's criterion is only valid when the depth of the neutral axis is less than 0.259d a situation, which corresponds to very low rates, rarely occurring in real situations.
Creazza's criterion depends on the value of fy, where as the yield strength of the steel used increases, the area values increase too.

This paper proposes a new ductility indicator which is obtained as the ratio of the area considered by Creazza and the steel yield strength. Thereby, eliminating the disturbing effect caused by too high or too low elastic limit. Table 2 shows the corresponding values.

Tabla 2. Parameter p, area and new index values for steel ductility classes.

	Clase B	**Clase A**	**Clase S**
ε_u (%)	2,5	5	6
f_s/f_y	1,05	1,08	1,15
P	0,134	0,344	0,695
Area (N/mm^2)	0,41	1,33	3
Area/fy	$8{,}2.10^{-4}$	30.10^{-4}	60.10^{-4}

4. Reinforcement corrosion and steel ductility

Many studies have been published on corrosion in RC structures. There are many fewer papers on the structural effects of corrosion and only a small portion of these specifically address the impact of corrosion on the mechanical properties of steel.
M.D García [4] studied the effect of corrosion on steel stress-strain curves plotted after passing an anode current through steel reinforcing bars immersed in a solution.
M. Maslehuddin [10] evaluated the effect of air pollution on the mechanicals properties of steel. The media in which the above two experiments were

conducted do not accurately reproduce the environment surrounding reinforcing steel.

R. Palsson [11] tensile tested bars taken from demolition rubble from a corroded reinforced concrete bridge and analyzed the effect of different degrees of corrosion on the stress-strain curve.

A.A. Torres, [12] exploring the loss of flexural carrying capacity in reinforced concrete beams and the loss of steel due to localized corrosion, reported a 20% decline in bending strength for radius losses of 14%.

C.A. Apostolopoulos [13] subjected bars to saline spray to assess the decline in their mechanical strength.

A.A. Almusallam [14] studied the impact corrosion on the stress-strain diagram for 6 and 12 millimeter bars with a yield strength of 600 N/mm^2.

Nonetheless, the literature is wanting sufficiently extensive papers directly and explititly relating steel ductility to the degree of corrosion to establish the grounds for possible moment redistribution when re-engineering standing structures.

5. Objetives

This research work determines the stress and strain properties of reinforcing steel when subjected to corrosion. The criteria on ductility requirements are applied to establish the relationship between the degree of corrosion and the stress and strain values found and ascertain on that basis whether moments may be redistributed in structures in need of intervention.

6. Experimental procedure

Concrete slabs with 2% chloride ion content by weight of cement, were prepared. The variables considered were:

- Positioning of the reinforcement in the concrete: defined in terms of cover and spacing between bars.
- Concrete quality: three types of concrete were prepared, all used commercially for different construction purposes.

The slab was reinforced with six 16 mm B500SD quality steel bars spaced at 5 cm intervals and with a 5 cm cover (Table 4).

To study corrosion mediated variation in steel ductility properties, the bars were short-circuited externally by passing a constat anode current between the steel and a lead plate set on top of the concrete slabs.

Table 4. Minimum mechanical characteristics required for B500SD steel as stated in the EHE-08 code [15].

fy (N/mm^2)	fs (N/mm^2)	$\varepsilon_{u,5}$ (%)	ε_{max} (%)	fs/fy
500	575	16	7,5	1.15-1.35

6. Results

The bars were withdrawn from the slab after the concrete craked and chemically cleaned to remove the rust and determina the degree of corrosion. Tensile test were conducted and the finding used to assess steel ductility in accordance with the various criteria.

Results of the tensile stregth tests are shown on table 5 where data corresponding to the mechanical properties of the tested bars and the level of corrosion reached in each one of them can be seen.

Mechanical characteristics have been determined in relation to the equivalent section, which implies an average section of the reinforcement in the corroded area.

Table 5 shows the ultimate strength values (fs) for the bars with diameter 16, and the yield strength (fy) values, which span from 591 to 649,1 N/mm^2 and 495,85 to 543,22 N/mm^2 respectively. The fs/fy ratio moves between 1,18 and 1,23 and the ultimate stress strain ($\varepsilon_{\text{máx}}$) varies from 5,6 to 10.7 %. Values obtained for the lengthening on five diameters ($\varepsilon_{u,5}$), vary from 12,5% to 22,5%.

Table 5. Mechanical characteristics of diameter 16 bars after the process of corrosion.

Bar	Corr (%)	fs N/mm^2	fy N/mm^2	fs//fy	$\varepsilon_{\text{máx}}$ %	$\varepsilon_{u,5}$ %	p	Área	Área/fy (x10^{-4})
Rsc-16	0,00	649,10	540,92	1,20	10,70	21,20	1,39	7,52	139
B-74-16	4,00	632,38	517,48	1,22	8,50	17,50	1,27	6,31	122
B-6-16	5,90	631,30	522,49	1,21	9,00	22,50	1,28	6,34	121
B-7-16	7,10	644,30	522,74	1,23	8,90	18,70	1,20	7,00	134
B-70-16*	8,00	642,55	543,22	1,18	7,40*	16,20	1,37	4,72	87
B-8-16	9,00	635,85	518,06	1,23	8,20	20,00	0,96	6,24	120
B-38-16*	10,10	626,51	523,57	1,20	9,10	14,50*	1,29	6,07	116
B-52-16*	11,90	591,00	495,85	1,19	6,20*	12,50*	1,23	3,78	76
B-50-16*	13,00	594,38	504,37	1,18	5,60*	13,70*	0,88	3,21	64
B-9-16*	14,00	622,22	506,90	1,23	7,00*	15,20*	0,78	5,19	102
B-1-16*	15,30	643,55	525,73	1,22	7,40*	15,00*	1,15	5,61	107

In table the asterisk (*) refers to the bars in which the values of one of the mechanical ductility indicators resulted lower than the limits established by the the Spanish structural concrete code EHE-08 [15] for steels with special ductility characteristics. In addition, values, which do not comply with the code, have also been marked in the same way.

7. Analysis and discussion

As can be seen in table, average corrosion penetration values of up to 7,1 %, do not imply reductions in the steel mechanical properties and therefore comply with, EHE-08. From the latter value and up to 11,9 % losses, approximately half of the bars do not fulfill the ductility specifications of the EHE code. When the average corrosion penetration exceeds the indicated values, practically none of the bars reaches the specifications established in the code.

The stress-strain diagram for the reference bar exhibited a clearly defined yield point that was not found on the curves for the corroded bars.
The ratio between ultimate and yield strength, one of the parameters generally used to measure steel ductility, was not significantly affected by corrosion. Indeed, in many cases it increased with the degree of corrosion. While this may initially appear to be beneficial, ot should be viewed with caution in seismic areas. In such zones, the ratio is limited to an upper value of 1,35 to prevent moment redistribution from raisin normal or shear stress above the limits the structure is able to bear, a situation that would lead to fragile fracture.

As the data obtained show, corrosion is more sensitive to strain than to stress. The values of elongation under maximum loading declined substantially, in some cases to less than half of the elongation recorded for the control.

When used the criterion of ductility defined by Creazza or the new proposed indicator, all bars are capable of overcoming the specifications of Instruction EHE-08.

8. Conclusions

The shape of tensile test curve for corroded bars differed from the curve for the control bar in that, like diagrams for cold-formed steel, they lacked a well defined yield point.

Elongation under maximum loading was observed to be highly sensitive to corrosion, declining drastically in corrodes reinforcement. In two cases it was under the 5% minimum requirement for high ductility laid down in some standards.

In such cases, under Cosenza criterion, for instance, based on plastic rotation capacity in the section, these bars would be regarded to exhibit high ductility. The same result is reached if the Creazza criterion is applied, uin which ductility is defined in terms of part of the area under the stress-strain curve for the bar tested. Under such criteria, some bars could be regarded to be highly ductile and the structure in question could be re-engineered assuming high levels of moment redistribution.

For the bars tested, the proposed new criterion of ductility provides the same results as the criterion of Creazza, mainly because all the bars have very similar elastic limits.

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