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Effect of corrosion degree on different steel ductility parameters, based on "Equivalent Steel" criterion

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Abstract

Purpose – One of the meaningful effects of concrete reinforcement steel corrosion on concrete structures is the decrease of mechanical properties, specifically the ductility of steel. The term ductility of steel refers to a group of properties which determine the reinforced concrete structures (RCS) and it is necessary to take this property into account for the recalculation of structures that have been already corroded until the point to condition in many occasions the analysis methodology. The paper aims to discuss these issues.
Design/methodology/approach – This research studies the variation on ductility of concrete embedded steels bars after going through an accelerated corrosion process. Tensile strength of high ductility reinforcements with different corrosion levels has been tested. Ductility was studied in terms of ultimate tensile strength, yield strength, ultimate strain, energy density of deformation and "equivalent steel" criterion. It also makes some considerations about what is the best methodology of structural analysis according to the obtained results.
Findings – Based on the obtained results, conclusions are established that determine whether the corroded steel satisfy the requirements of different codes in order to identify them as "steels with special characteristics of ductility" assessing in each case the possibility of reallocating solicitations in structures which might need to be repaired.
Originality/value – The analysis of existing RC structures should address moment redistribution to be able to compare ultimate strength values, rather than to a single value obtained with elastic linear models to a range of values centered 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. In ductile structures the effect of actions can be distributed. The ascertainment of corroded reinforcement ductility variation is of key importance in structural re-engineering and recalculation of structures. The research developed in this paper is motivated by the need to contribute to knowledge of the behavior of RCS with reinforcement damaged.
Keywords Concrete structures, Ductility, Equivalent steel, Reinforcement corrosion
Paper type Research paper

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Introduction

Reinforcement corrosion is the main deteriorating factor of reinforced concrete structures (RCS) when there is moisture enough and the passive layer has already been destroyed (CEB Thomas Telford Ltd, 1992; González and Miranda, 2007; Feng *et al.*, 2011).

The consequence is the notable reduction of the useful life of RCS leading to values extremely under those initially stated in the project (Broomfield, 1991). Corrosion products occupy more space than the base materials. Tensile stresses produced on the concrete covering due to the pressure generated by the oxides, produce concrete cracks and spallings (Andrade *et al.*, 1993).

The reinforcement corrosion affects the bonding performance due to the interphase variation between steel and concrete, becoming concrete corrosion products (Fu and Chung, 1998; Calavera *et al.*, 1980) because of the loss of bars height and of concrete cracking. All this produces a strong reduction of the steel bars anchoring (Du *et al.*, 2005).

Consequences of corrosion on the reinforcement can be seen in the loss of bearing capacity of the bars, mainly due to the reduction and variation of the stress-strain. One of the most significant effects of reinforcing steel corrosion is the decline in the ductility related properties of steel.

Tests performed on the corroded bars show the changes experimented in the steel stress-strain diagram: a systematic decrease of the deformation when subject to maximum load can be observed as corrosion degree progresses; this leads up to values clearly lower than the minimum ones required by the standards (Apostolopoulos *et al.*, 2006; Apostolopoulos and Papadakis, 2008). In these cases, the use of an equivalent steel concept as a ductility criteria, can be highly beneficial, based on the joint consideration of the deformation under maximum load and the ratio between maximum stress and yield strength (Moreno *et al.*, 2007; Moreno, 2008).

When using high ductility steels (SD), performing calculations with redistribution of moments in beams or slabs subject to bending is possible. The redistribution of moments is considered by the EHE-8 (Instrucción para el Hormigón estructural, 1998) and Eurocode (Eurocode 2 (EC-2) (prEN-1992-1-1) (2004)). It refers to the transmission of negative to positive moments and vice versa.

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. The analysis of existing RCS should address moment redistribution so that ultimate strength values can be compared, rather than using a single value obtained with elastic linear models to a range of values. This greatly enhances the possibility of "saving" a standing structure. 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 (Broomfield, 1991; Cánovas, 1984).

Ductility, in addition to allowing to perform steel in rolls, has also other structural benefits. For example, for seismic or dynamic loads, it is very interesting to have a ductile behavior, since they are loads that often exceed the elastic area, and that require a large plastic zone, which provides a large reserve of energy. Therefore, knowing the variation of ductility in corroded reinforcement is of key importance in operations of structures recalculation.

High ductility reinforcements produced in Spain are manufactured following the Temcore procedure (Nikolau, 2004). This technique consists on a severe tempering by applying high pressure water on the bar surface just after coming out of the lamination train. The product is quickly and energetically cooled thanks to a cooling chamber. Hence, external temperature is reduced approximately from 800 to 400°C. A further tempering of this layer takes place caused by the residual internal heat which is kept in the core helping to reduce residual stresses produced during tempering. As a consequence of this manufacturing process, three layers of different metallographic composition are formed.

The external crown is formed by martensite structure, characterized by a very high tensile strength and hardness, and an internal core composed by a combination of ferrite and pearlite structure characterized by its very high ductility (Bairan *et al.*, 2011). By regulating the vapor pressure the thickness of the martensite crown can be varied, thus controlling the strength and ductility of the complete bar. This process allows producing bars that can reach high strength and high deformations from mild steel without inclusion of expensive additions of vanadium and niobum. This process provides high strength and ductility to the bars. This particular characteristic of SD bars (high ductility) is mandatory by the Spanish Concrete Code (EHE) in high seismic zones. As has been pointed out previously, the use of steel reinforcing bars with special ductility characteristics provides benefits in the design of concrete structures, allowing rotation plastic hinges and the redistribution of internal-forces.

Equivalent steel: the concept.

The CEB-FIP Model Code (CM-90) (Model Code CEB-FIP 1990, 1993) and Eurocode 2 (EC-2) (Cosenza *et al.*, 1993) classify steel into several classes of ductility depending on two parameters: the fs/fy ratio (tensile strength-yield strength ratio) and elongation at maximum loading (uniform strain on the steel specimen during the tensile test when subjected to the maximum load). The fs/fy ratio represents a steel's reserve strength over and above its yield strength, i.e., beyond its elastic limit. The higher this ratio, the higher the margin of safety against fracture is, for a higher ratio implies better plastic hinge performance and therefore greater ductility. Elongation at maximum loading 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 will be.

The above-mentioned codes set minimum requirements for both parameters to establish mechanical behavior of steel. These codes associate ductility classification with the admissible redistribution degree in the reinforcement structures.

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 specifications 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 if any of the values is surpassed, ductility can be compensates fulfilled by the other value. This allows the steel being considered to have greater ductility than the one that complies strictly with the two requirements for belonging to a certain class. In light of such considerations, the concept of equivalent steel, defined as steel having the same properties as those laid down in the EC-2 or CM-90 classes, although not necessarily meeting both minimum requirements, arose in Europe in the 1990s.

Corrosion effects on reinforcement become evident in the variation of mechanical properties related to ductility. Corrosion drastically decreases the maximum and ultimate strain of reinforcement. A systematic decrease of the deformation when subject to maximum load can be observed as steel corrosion progresses; this leads up to values clearly lower than the minimum ones required by the en force standards (Du *et al.*, 2005; Apostolopoulos and Papadakis, 2008). In these cases, the use of an equivalent steel concept as a ductility criteria, can be highly advantageous, based on the joint consideration of the deformation under maximum load and the ratio between maximum stress and elastic limit (Moreno *et al.*, 2007; Moreno, 2008). Therefore, the concept of "equivalent steel" defines ductility steel by means of a single parameter which joins both resistance and elongation values. Criteria applied to obtain equivalent steel have followed two conceptually different ways. For some researchers as Cosenza *et al.* (Cosenza *et al.*, 1998; Creazza and Russo, 1998), the criteria of equivalent steel is based on the rotation capacity of plastic hinges of a reinforced concrete beam. Cosenza *et al.* obtained that rotation capability of a section was proportional to a parameter "p" that can be used to define the criterion of equivalence between different reinforcements. They suggested that steel characterized by pairs of values generating the same value of "p" should be defined to be equivalent.

Other authors have used as steel equivalent criteria based on steel's capacity for plastic deformation. In this research, according to Creazza (Cobo *et al.*, 2011), two steels are equivalent when the areas enclosed by the curve of the stress-strain diagram, the horizontal line drawn by the elastic limit and the vertical one drawn by the point of maximum tension are equal. A* index (area) is defined as energy deformation of the material during the hardening phase and incorporates the ductility concept suggesting a single parameter (A*) that includes ε_{max} and fs/fy joined. Neverheless, this last parameter, depends on the value of elastic limit (Ortega, 1998). Steels with the same fs/fy and ε_{max} values but with elastic limit higher have mayor area A*. To eliminate the influence of the elastic limit in the parameter indicating the equivalent steel, Ortega (Moreno *et al.*, 2014) proposed "ID" as a ductility indicator: the "toughness index", as the quotient between toughness and elastic energy in such a way that two different steels are equivalent if they present the same ductility index value. It has the advantage of being dimensionless. Finally, the use of the "deformation energy density" concept as a ductility criterion – obtained as the area of the stress/strain curve until reaching the maximum load deformation – can be very beneficial also (UNE-EN 10002-1 Metallic Materials, 2002).

The research developed in this work is motivated by the need to contribute to knowledge of the RCS with damaged reinforcement. This paper presents an experimental study on the incidence in the mechanical properties of corroded reinforcing bars mainly in terms of ductility. To carry out this research study, an experimental work has been done with the objective of assessing the effect of corrosion on the mechanical characteristics of the rebars. Accelerated corrosion tests on the steel rebars embedded in concrete have been performed. Tensile tests have been carried out to determine their mechanical properties by applying the conventional criteria that quantify the ductility and by using the concept of "equivalent steel index".

Based on the obtained results, conclusions are established that determine whether the corroded steel satisfies the requirements of different codes in order to identify them as "steels with special characteristics of ductility" assessing in each case the possibility of reallocating loads in structures which might need to be repaired.

Experimental procedure

Concrete slabs with chloride ion, as calcium chloride were prepared. The variables considered were: positioning of the reinforcement in the concrete (defined in terms of cover and spacing between bar) concrete quality (three types of concrete were prepared, all used commercially for different purposes). In these slabs, bars of B500SD steel and diameter 16 mm have been embedded (Plate 1). Table I shows the minimum mechanical characteristics required as stated in the EHE-08 code. After placing the concrete and removing the formwork the elements have been cured in a moisture chamber al 25°C temperature and 99 percent humidity for 28 days.

Since corrosion attacks mainly the area of the concrete-air interphase, to avoid it, the part of the reinforcement located in that heterogeneous area was covered with

Plate 1.
Slabs manufacture

insulating tape, so that the tape would surround the reinforcement at an approximate length of 2 cm inside and outside the concrete.

To study corrosion variation in steel ductility properties, the bars were short circuited externally by passing a constant anode current between the steel and a lead plate set on top of the concrete slabs. Steel bars were then externally short-circuited and corrosion forced by applying a constant anodic current between the reinforcement and a lead plank placed on the surface of the slabs. Homogeneous distribution of the current has been achieved inserting between the slab surface and the lead sheet a wet cloth, which was moisturized as it dried (Plate 2).

During the process, the current passing through each of the bars has been checked using a digital multimeter and registering the data at two or three day's interval. In this way, any voltage dip could be corrected by the electric potential variation of the power supply. The average corrosion density on each of the bars has been approximately of 10 μA/cm^2. Bars were disconnected from the power supply at different moments to achieve different levels of reinforcement corrosion attacks. The bars were withdrawn from the slab after the concrete cracked and chemically cleaned to remove the rust and determine the degree of corrosion (Plate 3 and Figure 1). Tensile tests were then conducted and the findings used to assess steel ductility in accordance with the various criteria.

Tensile strength tests have been performed following UNE-EN 10002-1 (UNE-EN 10002-1 Metallic Materials, 2002) standards in a hydraulic, servo controlled press machine, MIB-40-MOD-AM, with adjustable pressure hydraulic clamps and a load capacity of 610 kN. This equipment has been upgraded with a WINTEST32 software computer program to register data. Tests have been carried out placing load control on the elastic area and strain control once the yield limit has been surprised. The strain measurements have been obtained with a JB-MFA-2 strain gauge of base 50 mm.

Results and discussion

Mechanical properties of the corroded reinforcement bars

Results of tensile strength tests on 16 mm diameter rebars are shown in Table II, where the data corresponding to the mechanical properties of the tested bars are supplied: yield strength (fy) and ultimate strength (fs). The level of corrosion reached in each one of the bars is expressed through variable *C*, representing the mass loss percentage (or section) of the bar regarding initial values, due to the corrosion process. Its values have been calculated gravimetrically, weighing bars after removing corrosion products, and assuming that the steel loss occurs evenly over the length of the corroded reinforcing bar. Mechanical characteristics have been obtained in relation to the equivalent section, calculated as the middle section of the bars after the corrosion process. This value has been gravimetrically calculated, weighing the bars after having eliminated the corrosion products and supposing the steel loss is produced in a uniform way over the length of the corroded bar. Table II shows the ultimate strength values (fs) for the bars with diameter 16, and the yield strength (fy)

fy (N/mm^2)	fs (N/mm^2)	ε_{max}(%)	fs/fy
500	575	7.5	1.15-1.35

Notes: Where fy, yield strength; fs, ultimate strength; εmax, strain corresponding to maximum stress

Table I. Mechanical requirements for B500 SD steel

Plate 2.
Slabs assembly during an accelerated corrosion test

Plate 3.
Slab and rebar after
corrosion process

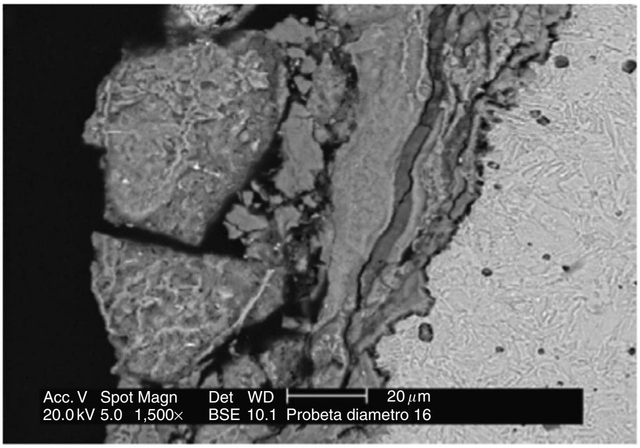


Figure 1. Micrograph of reinforced with the very adhered oxides

values, which span from 574.25 to 672.61 N/mm^2 and 458.25 to 562.10 N/mm^2, respectively. The fs/fy ratio moves between 1.11 and 1.34 and the value of the ultimate stress strain (ε_{max}) varies from 4.1 to 10.7 percent.

Bars in which the values of any of the parameters of ductility have been below the limits stated by the EHE for steels with special characteristics of ductility have been pointed with an asterisk (*) in the table. Therefore, due to corrosion, marked with asterisk bars show a mechanical behavior under the requirements of the codes for high ductility steel. As a result, the moment redistribution capacity will be reduced. In addition, values, which do not comply with the other codes, have also been marked in the same way. The ratio between ultimate and yield strength, one of the parameters generally used to measure steel ductility, was not significantly affected by corrosion (Plate 3). Indeed, in many cases it increased with the degree of corrosion. While this may initially appear to be beneficial, it should be considered with caution in seismic areas. In such zones, the ratio is limited to an upper value of 1.35 to prevent moment redistribution from raising 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 (5 and 6). The values of elongation under maximum loading declined substantially, in some cases to less than half of the elongation recorded for the control (Figure 2).

As shown in the figure above, fs decreases as the corrosion process progresses.

Figure 3 shows the values obtained for the tested bars. It can be observed that as the section loss increases due to corrosion process fs/fy ratio increases. This can be explained by the change produced in the steel types mixed in the composition of the bar section when the corrosion process takes place (Cobo *et al.*, 2011). With the corrosion process the material loss comes mainly from the external part of the section composed of martensite. This is the reason for the decrease of the stress values within the corrosion process, as the section loss belongs only to martensite (of higher strength than the ferrite core). However, the fs/fy ratio increases in the core, where this value is greater than at the periphery. In the plot it is also possible to appreciate that in almost all the cases, the values are over the minimal values fixed by the different codes (Figure 4).

Elongation in bars 21 and 36 was lower than the 5 percent required by Eurocode 2 and the model code to be classified as high ductility steel and accommodate up to

Bar	% C	fs	fy	fs/fy	ε_{max}
R-d16	0.00	649.10	540.92	1.20	10.70
B-1	4.01	632.38	517.48	1.22	8.50
B-2	4.97	636.94	533.83	1.19	10.30
B-3	5.12	652.92	531.03	1.23	9.90
B-4	5.88	631.30	522.49	1.21	9.04
B-5	6.55	672.61	562.10	1.20	8.80
B-6	6.78	616.56	458.25	1.35	10.10
B-7	7.07	640.84	528.21	1.21	8.50
B-8	7.14	644.30	522.74	1.23	8.90
B-9	7.43	645.23	525.66	1.23	9.60
B-10*	7.55	634.05	505.82	1.25	7.90
B-11*	7.92	633.08	530.27	1.19	7.50
B-12	7.93	665.58	552.80	1.20	9.10
B-13*	8.01	642.55	543.22	1.18	7.40
B-14	8.05	616.13	498.06	1.24	8.40
B-15*	8.10	610.62	469.30	1.30	7.80
B-16	8.52	653.04	550.14	1.19	8.90
B-17*	8.84	602.29	470.87	1.28	7.60
B-18	9.04	635.85	518.06	1.23	8.20
B-19	9.09	647.80	528.90	1.22	10.28
B-20*	9.16	658.14	554.11	1.19	6.40
B-21*	9.72	619.20	537.09	1.15	5.00
B-22	10.09	626.51	523.57	1.20	9.10
B-23	10.36	582.36	474.75	1.23	8.90
B-24*	11.36	637.48	518.06	1.23	7.16
B-25*	11.42	578.87	458.97	1.26	7.00
B-26	11.76	616.48	469.32	1.31	8.40
B-27*	11.91	591.00	495.85	1.19	6.20
B-28*	12.31	617.62	517.40	1.19	6.80
B-29*	12.35	593.73	491.95	1.21	7.80
B-30*	12.42	609.23	512.10	1.19	6.80
B-31*	13.00	594.38	504.37	1.18	5.60
B-32*	13.34	621.47	506.72	1.23	7.90
B-33*	13.64	633.20	527.68	1.20	7.60
B-34*	13.67	620.42	514.14	1.21	6.90
B-35*	14.01	622.22	506.90	1.23	7.00
B-36*	15.12	574.25	519.30	1.11	4.10
B-37*	15.21	622.61	521.18	1.19	7.90
B-38*	15.30	643.55	525.73	1.22	7.40

Table II. Mechanical properties of corroded reinforcements 16 mm in diameter

30 percent redistribution. Nonetheless, both bars exceeded the value required by these standards for the other parameter, the ratio between ultimate and yield strength. It is in such cases that the equivalent steel concept, i.e., the ability to consider both parameters to determine steel ductility, is particularly relevant. Results obtained, shown in Table II suggest that average penetration values of up to 7.4 percent do not imply reductions in the steel mechanical properties and therefore comply with the EHE code. From the latter values and up to 11.4 percent losses approximately half of the bars do not fulfill the ductility specifications of EHE code. When the average corrosion penetration exceeds the indicated values, practically none of the bars reaches the specifications established in the code. Results indicate that, average corrosion penetrations of approximately 7.4 percent with RCS corroded

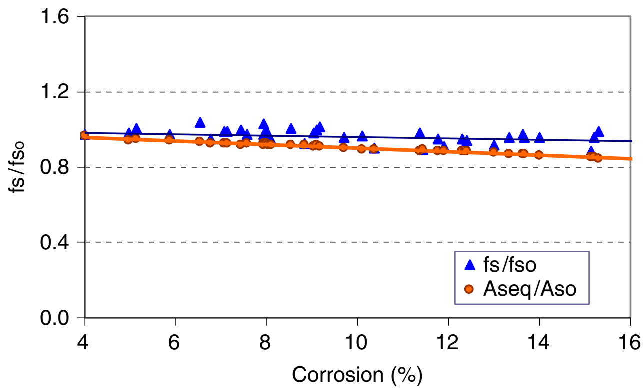


Figure 2.
Effect of corrosion on maximum strength

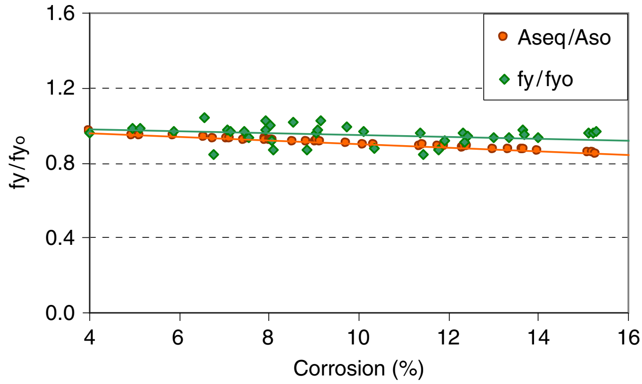


Figure 3.
Effect of corrosion on yield strength

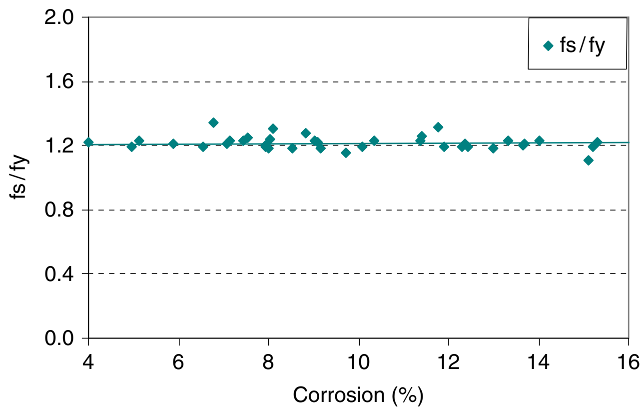


Figure 4.
Effect of corrosion on fs/fy ratio

reinforcement could be assessed using as steel mechanical capacity the value obtained considering only the section loss. If in these cases, the corrosion affected area is not located in the anchoring of the bars, the limit service states will be affected with slight increases of deflection as well as fissure openings in the reinforced concrete beams might be expected. However, the ultimate statelimits should not be affected. When corrosion penetrates more than in the previously stated values, the bar mechanical characteristics do not comply with EHE code specifications, mainly because of the elongation decrease. Moreover, the structure analysis needs additional checking when it is located in a seismic area, even when the corroded area does not affect the bar anchoring (Figure 5).

The reduction of strain values is caused by the necking phenomenon, produced in turn by the corrosion pitting which decrease the bar lengthening considerably(Cairns *et al.*, 2005). The most important structural consequence of the necking is the decrease of the experimented lengthening in steel during the tensile strength test. The reason can be found in the symmetric triaxial stress system produced at the closet zone to the necking area. This then makes the appearance of tangencial stresses difficult in this area, needed for the development of the yielding strain of this area. Table III shows the results for different ductility parameters: “p” Consenza, A* Creazza, “Id” Ortega and “E” deformation energy density. Figures 6-8 display the values of ductility parameters of corroded rebars by comparing them with the established by the codes.

Figure 9 shows that as the corrosion level increases and the deformation energy values decrease significantly.

Conclusions

Corrosion levels which mean an average section loss of 7.4 percent do not imply variations in the mechanical properties of the B500SD reinforcements, which can still be considered as high ductility ones. In the literature, there are researches according to which much lower mass losses are related to the mechanical properties degradation (Apostolopoulos *et al.*, 2013). Nevertheless, hot rolled steels which are manufactured in Spain as reinforcement have extraordinary properties of ductility in origin. As a result, high corrosion levels are required for decreases in ductility up to a point where steel does not comply with the requirements established by the codes.

When the corrosion levels in the reinforcement show as a result average section losses of 11.4 percent the lengthening decreases hinder the consideration as high ductility bars. As the corrosion levels rise, an increase in the fs/fy ratio is produced. This increases due to the fact that corrosion mainly affects martensite, which is located at the external ring and has a smaller fs/fy value than that of ferrite, located in the core

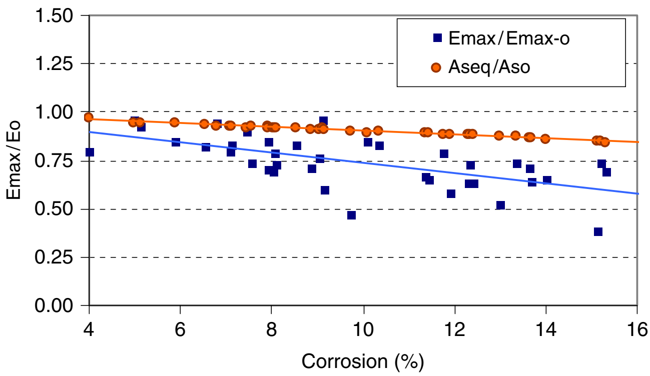


Figure 5.
Effect of corrosion on ultimate strain

Bar	% C	P	A	Id	E
R-d16	0.00	1.39	7.52	85.84	66.61
B-1	4.01	1.28	6.31	71.21	58.54
B-2	4.97	1.31	6.91	92.60	54.65
B-3	5.12	1.48	7.83	84.16	58.53
B-4	5.88	1.27	6.37	75.21	56.21
B-5	6.55	1.18	6.29	72.10	54.10
B-6	6.78	2.18	10.42	102.04	59.21
B-7	7.07	1.24	6.18	70.02	54.23
B-8	7.14	1.39	7.01	74.79	53.22
B-9	7.43	1.44	7.44	78.50	56.43
B-10*	7.55	1.37	6.52	64.22	45.74
B-11*	7.92	1.04	4.96	61.48	42.95
B-12	7.93	1.25	6.64	72.55	52.39
B-13*	8.01	0.97	4.72	57.88	43.57
B-14	8.05	1.35	6.42	74.22	51.11
B-15*	8.10	1.58	7.13	75.19	46.50
B-16	8.52	1.14	5.91	66.18	43.89
B-17*	8.84	1.45	6.45	72.29	41.12
B-18	9.04	1.28	6.24	69.28	43.61
B-19	9.09	1.51	7.93	82.86	62.68
B-20*	9.16	0.89	4.25	49.62	39.82
B-21*	9.72	0.62	2.59	38.93	31.23
B-22	10.09	1.21	6.06	73.07	53.00
B-23	10.36	1.35	6.21	80.18	47.70
B-24*	11.36	1.17	5.49	60.42	44.21
B-25*	11.42	1.29	5.41	66.87	33.66
B-26	11.76	1.74	8.01	79.54	47.22
B-27*	11.91	0.89	3.78	53.83	33.64
B-28*	12.31	0.96	4.37	56.41	38.04
B-29*	12.35	1.13	4.95	64.31	43.87
B-30*	12.42	0.94	4.23	54.87	37.90
B-31*	13.00	0.77	3.21	46.63	29.98
B-32*	13.34	1.26	5.68	64.88	45.11
B-33*	13.64	1.08	5.15	60.16	43.40
B-34*	13.67	1.03	4.72	56.24	38.50
B-35*	14.01	1.14	5.19	60.29	46.21
B-36*	15.12	0.38	1.41	33.80	30.41
B-37*	15.21	1.08	5.16	62.23	45.72
B-38*	15.30	1.17	5.61	61.39	42.64

Table III.
Ductility parameters

and which is kept unaltered. In higher corrosion levels (17 percent) the percentage decrease of the deformation energy density is much greater than the strength decrease. This is due to the pit effect, since in high damage levels, the strain values decrease more than the strength ones, as has been confirmed by other researches (Apostolopoulos and Kappatos, 2013) and as a result, the energy density decreases more in percentage. Therefore, in situations of corrosion of the reinforcement, together with the decrease of strength values, the decrease in the values of deformation energy density should be taken into account when this parameter is critical, as in the case of seismic risk. The lack of homogeneity in the section composition, and the lack of uniformity in the development of the corrosion along the bar produce greater decreases in the bar strength to those predicted for a uniform corrosion as has been previously verified by

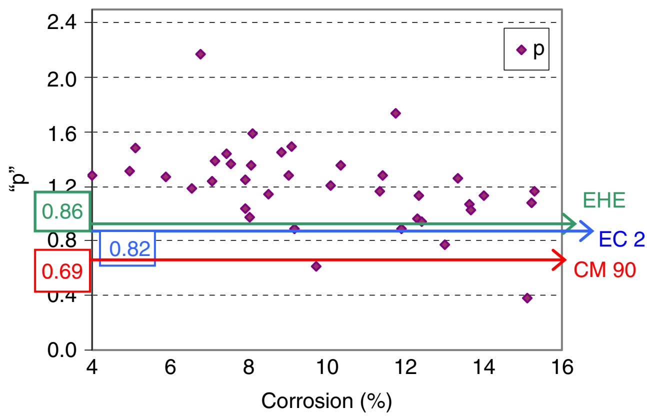


Figure 6.
Effect of corrosion on the value of "p"

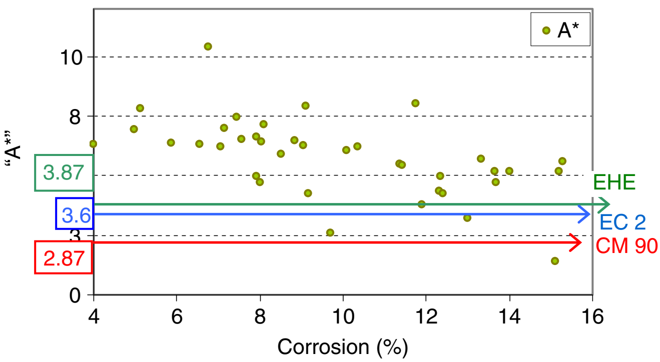


Figure 7.
Effect of corrosion on the ductile Area "A*"

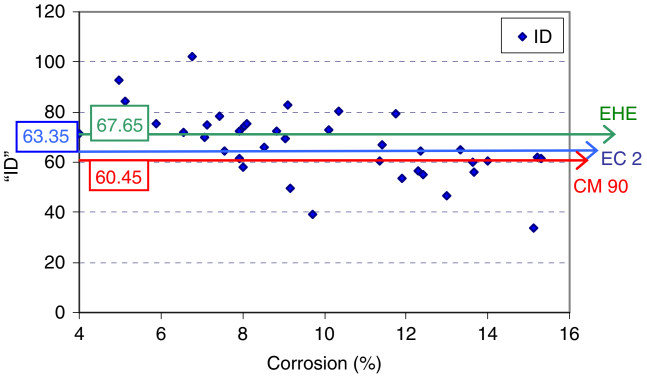
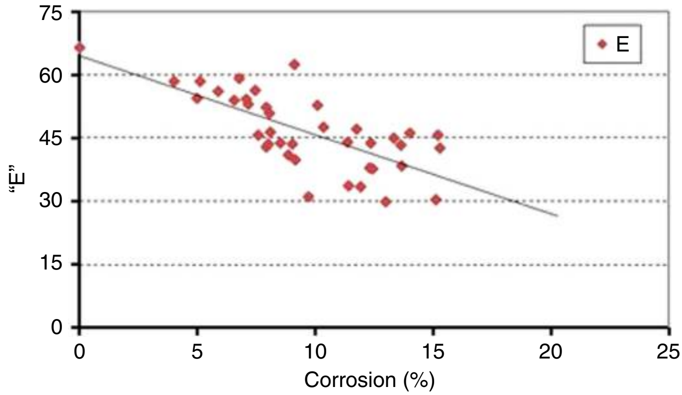


Figure 8.
Effect of corrosion on ductility index in bars

other authors (Torres-Acosta *et al.*, 2007). Elongation under maximum loading was observed to be highly sensitive to corrosion, declining drastically in corroded reinforcement. In some cases it was under the 7.5 percent minimum requirement for high ductility laid down in some standards. In such cases, using "equivalent steel index" as a single parameter to define ductility, these bars would be regarded as



Note: Energy of deformation values range between 30.41 and 66.1 N/mm^2

Figure 9. Effect of corrosion on the energy density of deformation

showing high ductility. Taking into account the equivalent steel criterion even the bars that do not reach some value determined by standards, could be regarded to be highly ductile and the structure in question could be re-engineered assuming high level of moment redistribution.

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