Seismic load resistance of reinforcing steels in the as delivered condition and after corrosion - relevant material characteristics for performance evaluation

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1. Introduction

Reinforced concrete (r.c.) buildings in seismic areas shall be designed to guarantee enough ductile resources as for example a sufficient rotational capacity to allow for load re-distribution. The rotational capacity is directly dependent on the ductility of the reinforcing steel which is generally expressed as elongation at maximum load (A_{gt}) and the hardening ratio (R_m/R_e). A direct testing of the seismic load resistance of reinforcing steels is not part of the construction product standards. Therefore it was decided by European Commission to introduce this performance requirement in the mandate for the revision of EN 10080:2005. In parallel to the standardization process a research project [1] was carried out to deliver the scientific background.

2. Research programme

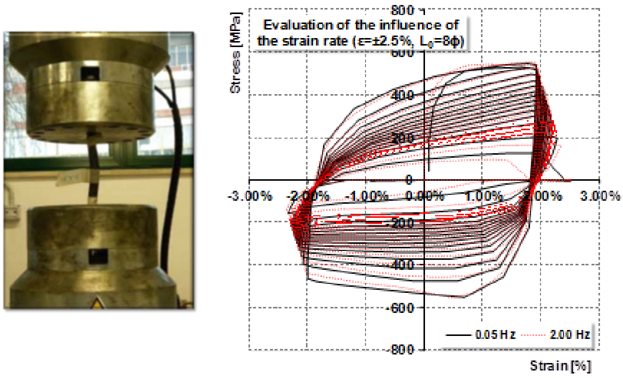
In the Rusteel research project a detailed investigation of the seismic behaviour of reinforcing steel bars in r.c. and composite steel/concrete structures was executed. In the first step the real seismic demand on the rebar was evaluated considering numerical and experimental analysis carried out on existing buildings under real earthquake events. The results delivered the testing parameters for the monotonic tensile- and low-cycle fatigue tests used for an extensive testing campaign on a representative set of reinforcing steel types widely used all over Europe (see table I).

In a subsequent campaign the same number of monotonic and low cycle fatigue tests was carried out on corroded reinforcing bars in order to compare the performance in the as delivered and the corroded condition. This part of the project is important for the determination of the residual seismic load resistance of the reinforcing steel and finally required for the safety evaluation of older buildings especially in coastal or industrial areas. A detailed description of the full programme and its details can be found in [1].

2.1. Mechanical testing

Tensile tests on the reinforcing bars were carried out according to ISO EN 15630. The ductile capacity was evaluated in terms of mechanical properties R_e, R_m, A_{gt}, R_m/R_e and cross section reduction Z.

For the execution of low cycle fatigue tests, a specific test protocol was elaborated. Two levels of imposed deformation, respectively, equal to ±2.5% and ±4.0%, were adopted for the execution of at least 20 symmetrical hysteretic cycles or until fracture. The strain rate was fixed to 2.0 Hz. Two different free test lengths were chosen to 6ϕ and 8ϕ respectively to study the influence of stirrup spacing. The seismic load resistance was evaluated in terms of dissipated energy dE (= $\int \sigma d\varepsilon$) and the number of cycles to failure N_{cycles}. In figure 1 the low cycle fatigue test set up and an example for a stress strain curve are presented.



a) b)

Fig. 1: a) Cycle fatigue test set up and b) example for a stress strain curve

2.2. Reinforcing bars

In Table I the tested reinforcing bar types are presented. This test set up covers the wide range of different reinforcing steel types applied in the European construction market. It allows evaluating the influence of production type, ductility grade and diameter on the seismic load resistance of reinforcing steels.

Table I: Tested reinforcing bar types

Nominal yield strength [MPa]	Ductility Class	Production type	Diameter [mm]
400	C	Tempcore	16
		Micro-alloyed	
			25
450	C	Tempcore	12
			16
			25
500	A	Cold drawn	12
	B	Hot rolled +	12
		Stretched	16
		Tempcore	16
			25

2.3. Accelerated corrosion tests

The salt spray chamber test was selected in relation to practical and efficiency requirements, such as easiness in the preparation of the samples, limited duration of the exposure period, possibility to evaluate and control the relevant parameters, and availability of codified procedures. A protocol based on ASTM B117-11 and ISO 9227 was modified in relation to the specific requirements of the research project. Two different exposure periods 45 days and 90 days respectively were considered. A more detailed description can be found in [1].

At the end of the corrosion test, the specimens were rubbed and cleaned and maintained at a temperature of about −5∘ to avoid the loss of the volatile part of hydrogen before the execution of mechanical tests. Cross-sectional analyses, SEM evaluations, measures of notch depth, crack depth and width, hydrogen content, cross section reduction, and, in particular, mass loss were executed.

3. Results and discussion

The complete set of results of monotonic tensile and low-cycle fatigue tests on uncorroded and corroded specimens is presented in Rusteel research project [1], since it is not possible for reasons of brevity to directly insert all the data in the present paper. Therefore this paper concentrates on the major effect of corrosion on the mechanical performance of reinforcing steels.

3.1. Accelerated corrosion tests

In figure 2 the differences in pitting depth obtained in salt spray testing and on samples embedded in salt containing mortar are presented.

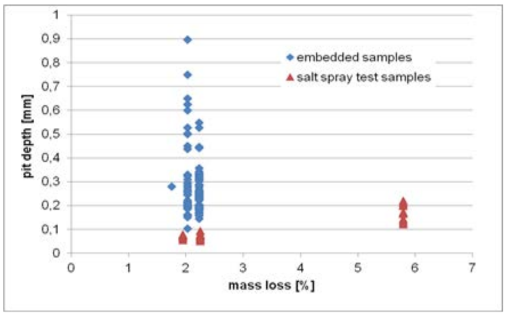


Fig. 2: Pit depth depending on mass loss for embedded samples and salt spray samples.

This result confirms results in /2, 3/. The local attack expressed by pitting factor especially in the case of uncracked concrete, where critical chloride content at the rebar surface is just reached, cannot be simulated well with salt spray testing. The pitting factor (ratio of maximum pit depth to average corrosion penetration depth) in salt spray tests with bare samples is significantly lower for same mass losses. This phenomenon represents more the uniform corrosion due to carbonation of concrete and perhaps an overlap of carbonation and chloride induced corrosion at high chloride contents. It seems that in salt spray testing the relation between anodic and cathodic surface area is much higher than for chloride induced corrosion in concrete especially for the case the critical chloride content is just reached.

3.2. Static performance after corrosion

All measured mechanical performance characteristics for static loading condition after corrosion (yield strength - $R_{e,corr}$, tensile strength - $R_{m,corr}$, hardening ratio - $(R_m/R_e)_{corr}$, strain at maximum load - $A_{gt,corr}$ and necking strain - Z_{corr}) were related to the one evaluated in the "reference – as delivered" conditions, for example in terms of residual percentage A_{gt}= $100A_{gt,corr}/A_{gt,0}$.

The most important performance indicator for static loads was, finally, strain at maximum load (A_{gt}): a strong reduction of A_{gt} was observed already in presence of reduced mass losses (see figure 3), while all the other performance characteristics did not exhibit a significant decrease with the increase of mass loss, according to what well evidenced in e. g. /2,4/.

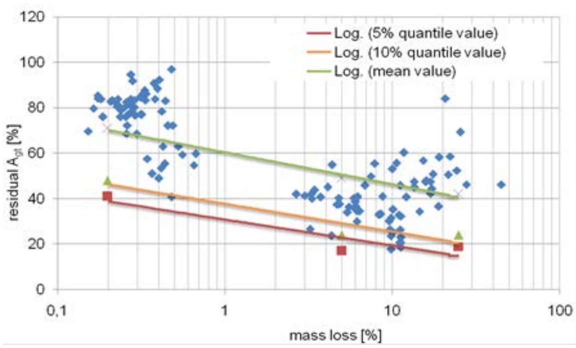


Fig. 3: Influence of mass loss on residual A_{gt} for nominal diameter 16 mm (5%-, 10%- and 50%-quantile)

3.3. Seismic performance after corrosion

The performance indicators for low cycle fatigue tests after corrosion in salt spray chamber were the residual dissipated Energy (res. dE=100*dE_{corr}/dE_0) for the cumulated number of load cycles till fracture of the sample (or till the stop of the test) and the residual number of cycles (res. N=N_{corr}/N_0) till fracture (or till the stop of the test).

It was obvious that both performance indicators (PI´s) res. *N* and res. *dE* were strongly influenced by corrosion (see figure 4). In order to estimate the PI´s as a function of mass loss, the following approximations were made:

- Normal distribution of mass loss in a range between 0 and 5% and between 5 and 10%.
- Normal distributions of res. *N* and res. *dE* in the above mentioned mass loss ranges.

With these approximations, the 5% and 10% quantile values for res. *N* and res. *dE* were calculated and implemented at the mean value for mass loss in the predefined mass loss range: for example, for a mass loss range from 5% to 10%, the mean value for mass loss is equal to 7,41 % and the 5% quantile value for res. *dE* is equal to 48,79%.

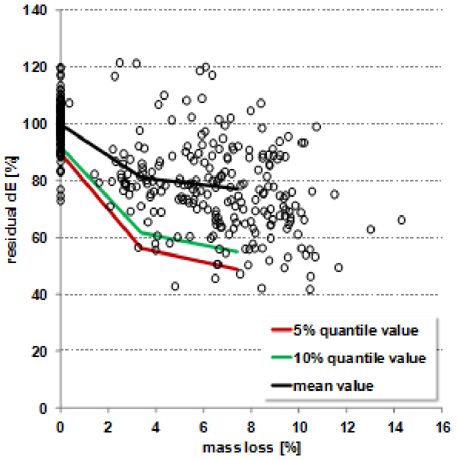


Fig. 4: Scatterplot for res. *dE* versus mass loss and quantile slopes for res. *dE*

4. Conclusions

In the present work the results of a statistical analysis executed on the experimental data of tensile and low-cycle fatigue tests on a wide range of corroded steel reinforcing bars are presented, evidencing the correlation between performance indicators (PI´s) and corrosion damage indicators (CDI´s). Results were presented with reference to the PI's A_{gt} and dissipated energy *dE* or number of cycles to failure *N* for, respectively, the monotonic and cyclic behaviour of reinforcements, and in relation to the CDI mass loss obtained in salt spray testing on bare samples. This type of accelerated corrosion test was used to study the high number of test samples in due time. The corrosion phenomena obtained in salt spray testing deviate significantly from corrosion phenomena (pitting factor) obtained in practical conditions. Salt spray testing represents practical conditions for the more uniform corrosion as a result of a severe carbonation of the concrete and/or for higher chloride contents at the surface of the rebar. At low corrosion current densities the effect of pit depth on residual mechanical performance might be underestimated. The most important effect of corrosion phenomena was evidenced in the case of monotonic behaviour (i.e., PI residual A_{gt}), while the ductility capacity related to the cyclic behaviour (i.e., PI dissipated energy and/or number of cycles) was generally less affected by the effects of corrosion in terms of mass loss.

As a consequence of what is presented concerning the relationship between Corrosion Damage Indicators (CDIs) and Performance Indexes (PIs), engineers and designers are enabled to estimate residual mechanical performance depending on the degree of corrosion expressed through mass loss, a value which can easily be determined with an acceptable accuracy.

In order to fully satisfy the seismic ductile requirements in exposure conditions with significant corrosion rates (i.e., XC2 to XC4, XD2 and XD3, XS1 to XS3) and to prevent damage due to aggressive environmental conditions with the following degradation of the mechanical properties, additional indications, completing and improving what is already presented in Eurocodes, were suggested, such as the adoption of higher strength concrete (at least one class) or, in a similar way, the design of concrete cover with the same concrete strength but concrete cover with higher thickness (increase by 5.0 mm or more).

Obviously, in the case of very aggressive environmental conditions, additional measures like, for example, the coating of the surface of concrete, cathodic protection could be proposed.

The statistical analysis executed using ANOVA technique also evidenced that the influence of corrosion, in terms of mass loss, on the decrease of the elongation to maximum load generally decreased with the increase of the diameter (i.e. for bigger diameters the effects of corrosion on the A_{gt} were lower). As a consequence, despite an accurate analysis of the effects of large diameter for what concerns the bond condition between steel and concrete, probably the adoption of higher diameters can be suggested (e.g., for a required reinforcement of 24 cm^2 the use of 8 bars ϕ 20mm instead of 12 bars ϕ 16 mm). Obviously, higher initial values of ductility (in terms of A_{gt}) were associated with higher residual values after corrosion attack: this was evidenced, for example, in the case of microalloyed steel, for both 16 and 25 mm diameters.

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