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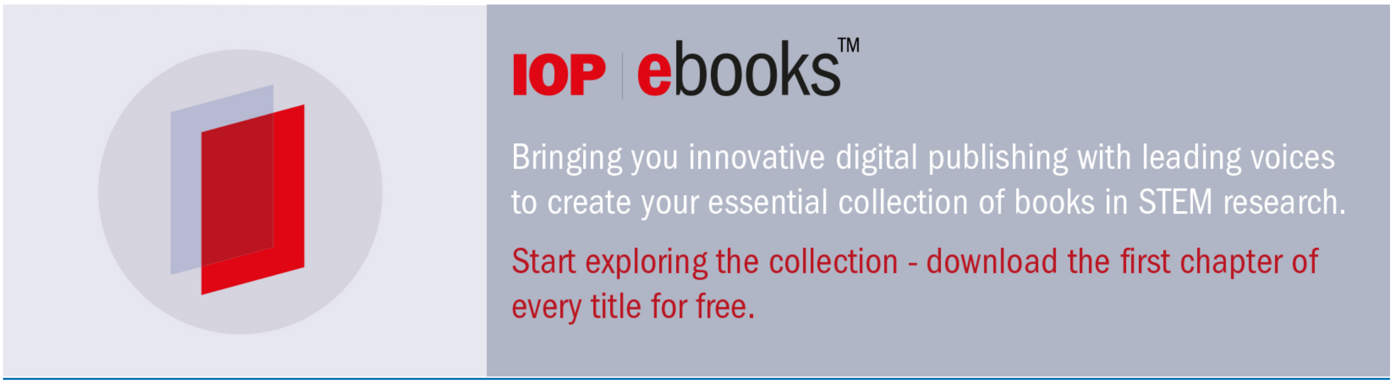

Demolition-and-Reconstruction or Renovation? Towards a Protocol for the Assessment of the Residual Life of Existing RC Buildings

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Abstract. When is demolition mandatory? To date there is a lack of specific tools and protocols enabling a rigorous scientific assessment of the deterioration level of existing structures, guiding the choice between the real possibility of renovation or the unavoidable need of demolition. In the present paper, an attempt is made to develop a protocol suitable to assess the actual capacity of existing structures and predict their future behaviour based on inspection and diagnosis of the building. The potential benefit of such a tool is to help detecting the best intervention strategy making the renovation process more sustainable and efficient. Toward this perspective, a critical analysis and comparison of literature models on the residual capacity of structural elements has already been carried out by the authors. The assessment of the preservation state is herein further extended to the overall structural level, by proposing a new approach relating the performance of deteriorated elements over time to the behaviour of the whole structural system.

1. Introduction

The poor state of preservation of existing RC buildings will require deep renovation actions in the near future to address both structural and environmental issues: while the former is related to deficient structural performances, seismic vulnerability and material deterioration, the latter concerns high energy consumption and high CO_2 emissions. In addition, 40% of the existing European RC building stock has exhausted its nominal structural service life.

Two main strategies can be pursued to face these issues: demolish-and-rebuild or deep renovation. The effects of an intense rebuilding involve CO_2 emissions and construction/demolition waste disposal; moreover, when rebuilding in place is not possible, the use of open green spaces could also be required, causing a further increase of land consumption rate (in Italy, doubled with respect to 60 years ago). To reduce the environmental and social impact of the existing building stock upgrading, a sustainable renovation process should thus be preferred, unless demolition is mandatory. Concerning demolition, several aspects, such as economic, social and environmental indicators, play a role in the decision process. As for structural performances, not only the knowledge of the actual capacity is necessary, but also whether the level of deterioration allows the existing structure to handle a renovation process has to be determined.

In order to identify the real potential of the building from a structural point of view there is a need of new assessing tools. Analytical models need to be defined to account for the structural decay in the evaluation of the building behaviour, allowing to identify the best retrofit intervention strategy. To date, the decay of the structural elements is seldom included in the capacity assessment of buildings. The definition of models providing the actual capacity of the building considering the decay would allow identifying those parameters which are really significant and necessary, hence to be measured during the building inspection. Focusing on Reinforced Concrete (RC) structures, steel rebar corrosion is acknowledged as the most common and dangerous cause of deterioration as it can lead to a reduction in strength, stiffness and ductility of the structural elements [1]. In the literature, some models are proposed to evaluate the residual strength of structural elements, both for beams and columns, depending on their level of corrosion. In this paper, a critical analysis and comparison of those models is implemented to assess their effectiveness.

2. Models for the evaluation of the residual strength of existing structural elements

Beams and columns represent the main components of existing RC structures. The first step towards building assessment consists in identifying some models able to evaluate the residual strength of deteriorated structural elements. Concerning beams, two models have been selected among those available in the literature, while a new model is defined for columns starting from literature results.

2.1. Residual strength of beams

Some significant results obtained by the authors [2] on the evaluation of the residual strength of beams are summarized herein. The comparison of the models proposed in the literature highlights the weaknesses of the **empirical models.** Above all, the difference between artificial and natural corrosion represents the main limitation: in the artificial simulated processes, very high values of corrosion current density (80–10^3 μA/cm^2) are impressed to the elements for a short time (hours to days) in order to simulate a natural corrosion process (0.1–10 μA/cm^2) which, instead, requires many years. Such alteration may produce an accelerated expansion of rust products and concrete cracking, thus resulting in a more severe deterioration of the element with respect to the real conditions. As a consequence, the empirical models, which are formulated through the regression of experimental data obtained from artificial processes, result not adequate to describe natural processes of corrosion, with some few exceptions [3]. Besides, the **analytical models** [4][5] have been identified as the most suitable for providing a reliable estimation of the residual strength of beams, entailing a good control of the decay mechanism to be considered into the model; in particular, the reduction of both cross-section and yield strength of steel rebars may be implemented.

Actually, there is no agreement among researchers about the occurrence of deterioration of steel mechanical properties as a consequence of corrosion; however, experimental works [6] show a significant effective strength reduction for bare rebars subjected to artificial corrosion processes and tensile tests. In the present work, the reduction of steel rebar area ($A_{s,corr}$) and yield strength ($f_{y,corr}$) as a function of time are considered as proposed by Du et al. [7]:

$$A_{s,corr} = (1-0.01Q_{corr})A_{s,0} \tag{1}$$

$$f_{y,corr} = (1-0.005Q_{corr})f_{y,0} \tag{2}$$

Such variables are obtained from correcting the initial values $A_{s,0}$ and $f_{y,0}$ according to the corrosion level Q_{corr}, which depends on the penetration of the corrosion attack. Comparative analyses have been implemented to evaluate the difference between empirical and analytical models by applying the models to a generic beam and assuming the attainment of a safety factor equals to 1 as its end of life. A clear discrepancy is observed in relation to the residual life evaluation (Figure 1) and the influence of some parameters as the rebar diameter (Figure 2). The effectiveness of the models has also been assessed by implementing the same input data of an experimental campaign [8] and comparing the calculated and experimental results; in such comparisons both the maximum (Figure 3) and the mean (Figure 4) value of the rebar cross-sectional loss were considered. The results show that all the selected models provide a good estimation of the experimental results, also the empirical one. However, it is worth to note that the empirical model was calibrated on very similar experimental data. In addition, the analyses highlight that the more accurate residual strength estimation is obtained from accounting for the maximum value of section loss, that is due to pitting corrosion. As a result, the two analytical models have been chosen to be implemented in the following at a global structural level to estimate the residual strength of beams.

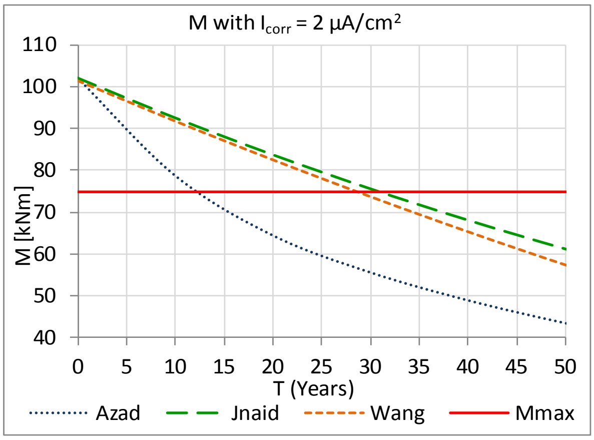

Figure 1. Residual life evaluation with empirical (Azad et al.[3]) and analytical (Wang et al. [4], Jnaid et al. [5]) models.

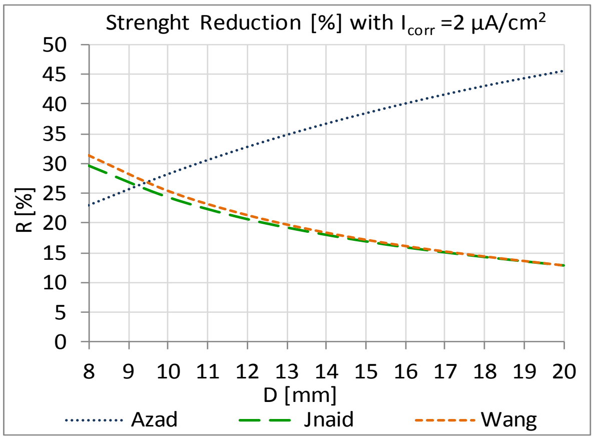

Figure 2. Variation in strength reduction in the models (T=20 years) by varying only the diameter, keeping the same reinforcement ratio.

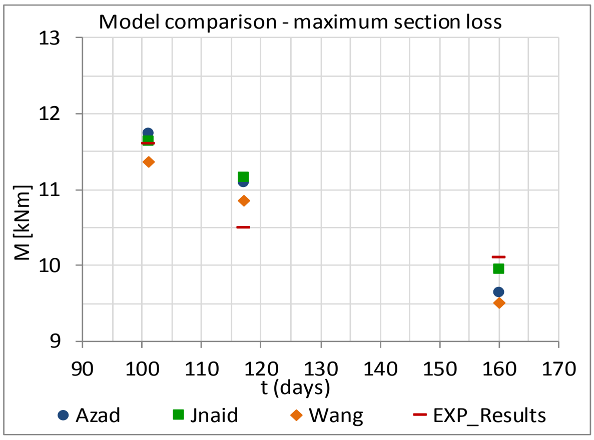

Figure 3. Models results compared with experimental campaign [8] by implementing maximum section loss.

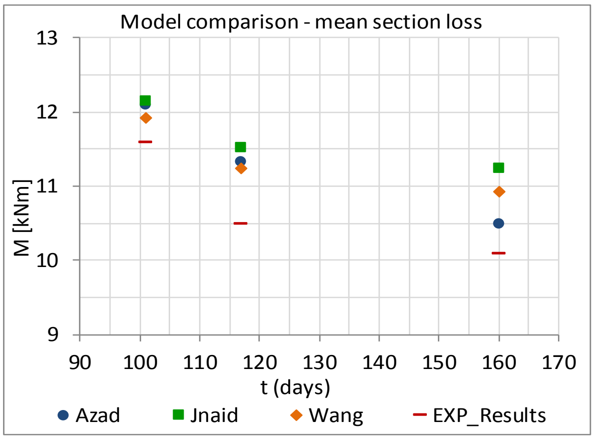

Figure 4. Models results compared with experimental campaign [8] by implementing mean section loss.

2.2. Residual strength of columns

Very few models are present in the literature on the residual strength of columns, so a new analytical model is herein proposed. Additional deterioration effects need to be accounted for when dealing with columns: concrete cover cracking and spalling, buckling of steel rebars due to stirrups opening, loss of bond between rebars and concrete and the absence of beneficial confinement effect should be considered in addition to the reduction of rebar cross-section and steel mechanical properties. In a first simplified model (referred to as '**base model**'), the effect of column deterioration is evaluated by defining a simplified moment-axial force domain including the effects of:

- steel rebar area and mechanical properties reduction (as in beam analytical models);
- actual dimension of cross section and loss of cover for a threshold level of corrosion;
- absence of beneficial confinement effect and constant compressive strength of concrete.

As for the estimation of concrete cover spalling, two different criteria are proposed in the literature: Xia et al. [9] consider the threshold limit of 6% of reduction of the longitudinal rebars area; while Tapan and Aboutaha [10] propose a linear proportion considering the limit of 2.25% for a cover to longitudinal rebar diameter ratio (C/D) equals to 1 and 5.25% for C/D = 2.5. Here, the latter criterion is adopted. Concerning concrete strength and confinement effect, Campione et al. [11] define a reduction coefficient ψ depending on the level of cracking both for confined and un-confined concrete. In the present model, the beneficial effect of the confinement is neglected to provide a safe prediction of residual strength; in fact, cover spalling is assumed to occur even for low levels of corrosion. It has also been assumed that cracking due to rust products expansion does not reduce the strength of the concrete internal core. Furthermore, the compressive strength of concrete may be detected through on site tests, so its actual value can be evaluated and considered in the model. The domain of the “base model” is obtained from defining four points:

- **A** - Pure flexure (N=0): compressive failure of concrete (ε_{cu}) and tensile yielding of rebars are assumed and the neutral axis position is obtained from an iterative equilibrium process;
- **B** - Balanced failure: contemporaneous compressive failure of concrete (ε_{cu}) and tensile yielding of steel rebars (ε_{yd}) is assumed to calculate the neutral axis position;
- **C** - Neutral axis assumed at the effective depth of the rebars and concrete assumed at failure;
- **D** - Pure compression (M=0): section is fully compressed.

A more complex model (‘BB model’) is then defined to consider some other aspects of column deterioration, mainly the reduction of bond strength between steel and concrete and the possible **buckling of longitudinal bars** as a consequence of the cover loss and the opening of stirrups. These aspects are accounted for by defining two reduction factors of the yielding stress of longitudinal rebars respectively in tension and compression. Such coefficients may be simply included in the model in case of clear loss of concrete cover and stirrups opening occurred in the examined structure. The risk of rebar buckling increases in the case of cover spalling. In this case, the maximum allowable stress in the rebars is taken as the minimum between the yielding stress and the critical buckling stress. So, the reduction factor of rebar in compression can be calculated as $\beta=\sigma_{cr}/f_{yd}$. Several methods are proposed in the literature to account for possible buckling of longitudinal bars:

- Rodriguez et al. [12] propose to multiply the yield stress for a *k* factor assumed equal to 0.5 if one link fails, 0.2 if two consecutive links fail and 0 if more links are missing; in fact, the possible buckling of rebars depends on their slenderness which is related to the effective distance of the links, therefore considering stirrups opening;
- Campione et al. [11] and Tapan and Aboutaha [10] propose two different formulations of σ_{cr}: in the former the critical load is obtained by considering an axially loaded elastic beam on an elastic medium, represented by the spread springs simulating the stirrups; while in the latter, the Euler’s buckling equation is applied considering the rebar and its unsupported length.

The coefficient β defined by Campione et al. is here adopted and considered only when the concrete cover has spalled. Another aspect to be considered is that **rust products due to corrosion** of rebars can also reduce the bond strength between rebars and concrete. In this case, as highlighted in [10], strain compatibility is not valid. In Tapan model [10] the strain in deteriorated reinforcement is compared with the average concrete strain in the unbonded region. Campione et al. [11] define a γ coefficient as the ratio between the bond strength of corroded and uncorroded bars; such factor accounts for cover depth, rebars and stirrups spacing and dimension, corrosion attack penetration and tensile strength of concrete. Parametric studies show that γ usually assumes values ranging from 1 to 0.8 when dealing with natural corrosion processes. It is also worth noting that not homogeneous cover spalling on the cross-section sides can cause a not negligible increase of the **load eccentricity**.

Figure 5 reports the difference between the moment-axial force domain provided by the model when accounting for only the basic factors (‘base’) or also for possible **buckling** and loss of **bond** of rebars ('BB’). A comparison with experimental campaign results has been carried out to check the effectiveness of the proposed model. In Figure 6 and Figure 7, the data from two experimental campaigns [13][9] have been used to obtain the failure condition of some corroded columns. The element characteristics and the corrosion levels have been implemented to build the moment-axial forces domain by using the proposed model. In the first example both the ‘base’ and ‘BB’ model are used for the comparison; in the second, for the sake of clarity, only ‘BB’ models are represented for their best correlation with experimental data.

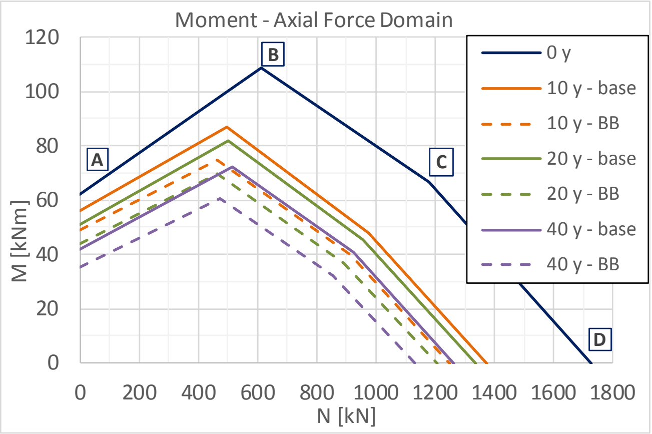

Figure 5. Example of the proposed moment-axial forces domain according to corrosion level (I_{corr}=2 μA/cm^2) in time considering only basic aspects (base) and possible buckling and loss of bond of steel longitudinal bars (BB)

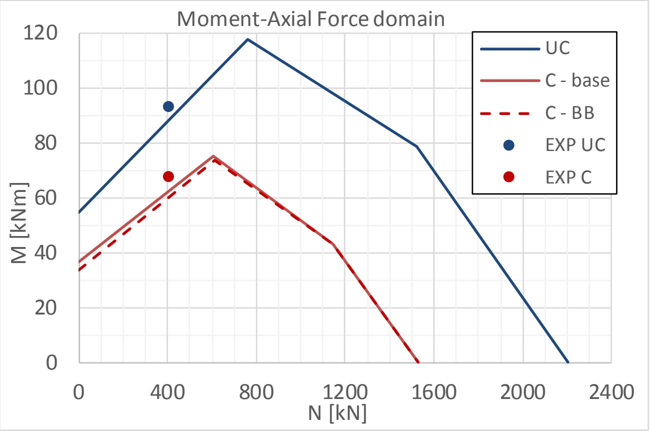

Figure 6. Comparison of the proposed model with experimental results from Meda et al. [13]: UC-Uncorroded element, C-corroded element.

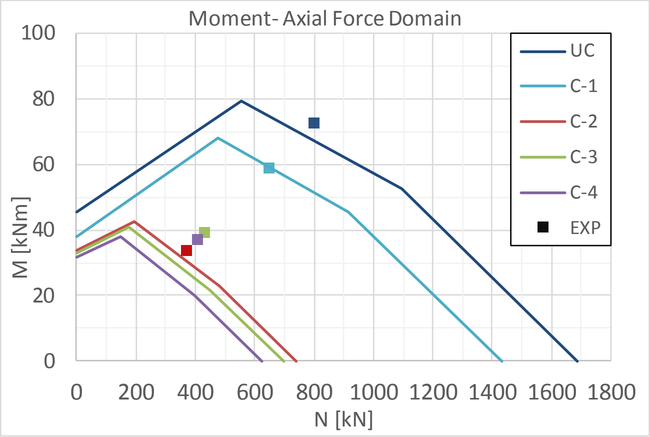

Figure 7. Comparison of the proposed model accounting for possible buckling and loss of bond of bars with experimental results from Xia et al. [9]: results are related to elements AL of the campaign at different corrosion levels (1 to 4).

The proposed model is under further investigation with the aim to make it more general and reliable. Currently, the selected models are considered reliable enough to start considering the whole structural system, whose assessment is the final aim of the research. However, given the flexibility of the proposed assessment framework, future research achievements or more accurate parameters may be easily implemented in the model when available.

3. From the elements to the structure: equivalent parameters method

The assessment of the residual capacity of single structural elements is not enough when the aim is the global evaluation of the residual life of a building: interactions among elements need to be considered, also accounting for different environmental conditions or quality of the materials. In this regard, a model that relates the deterioration of single elements with the global structural behaviour is not available to the authors' knowledge.

Coronelli [14] provided an important contribution by dividing the structure in similar components according to their exposition and structural function, and by calculating damage indexes for each class. A global deterioration class and a strength reduction factor for each element class are obtained from such indexes. Even though this method provides conservative results, it highlights the importance of considering the role of each element in the global behaviour of the structure and it defines an interesting procedure for the qualitative mapping of the building decay. A novel approach is herein proposed as a further step to obtain quantitative information on the global structural deterioration by starting from the analytical models selected for beams and columns.

3.1. A novel approach: equivalent parameters method

All the experimental campaigns carried out on structural elements show an evident reduction of elements stiffness as the corrosion level increases (Figure 8). This is probably due to the coexistence of some phenomena as the reduction of cross-sectional area, concrete cracking and spalling, decay of mechanical properties and possible reduction of concrete-steel bond strength. As known, the variation of elements stiffness can cause a redistribution of internal actions in the structure. Based upon these observations, a simple method able to describe the element stiffness variation according to its deterioration in time is proposed. For the beams, a simplified bilinear moment-curvature relationship is adopted. The ultimate moment is obtained from applying the previous analytical models as a function of the corrosion level. The reduction of stiffness as a function of time is obtained from the slope of the bilinear curve (Figure 9) [2] by varying only the moment and the yielding curvature of the beam as a function of time. Such slope is here defined as the secant equivalent stiffness EJ_{eq}. Following this approach, other parameters varying in time can be defined, like the residual area of the elements or the residual ductility.

As a proof of concept, the method is applied to a very simple structure such as a single-bay frame. The deterioration effects on the frame are evaluated both considering the reduction of secant equivalent stiffness in the beam and the loss of concrete cover in the columns. The second scenario is very common in existing structures; in fact, even low corrosion levels lead to an increase of rust products both in the stirrups and longitudinal bars which can produce cracking and consequent spalling of the concrete cover. In the first case, a corrosion current density of 8 $\mu A/cm^2$ for 50 years has been considered for the beam (Figure 10), while in the second case the complete loss of cover of both columns has been modelled (Figure 11). The beam deterioration leads to a 20% increase of the bending moment at the beam ends, while the columns deterioration leads to an increase of 30% of the bending moment in the beam span.

The results obtained outline the importance of evaluating not only the single structural element decay, but also its effect on the whole structural system. Indeed, it is clear that, while the capacity of the element decreases in time according to the deterioration level, an increase of internal actions in the element itself occurs; this leads to a further reduction of the residual life (Figure 12). Such a reduction could not have been detected without considering the interactions of the single elements inside the structural system. Despite the simple example used to introduce the concept, the proposed method presents a high application potential for several reasons: it represents a first step toward a global evaluation of the structural system, it is applicable even to very complex buildings, with the help of numerical simulations, by modifying the material mechanical parameters, and it describes well the different environmental conditions or deterioration mechanisms observed inside the same structure.

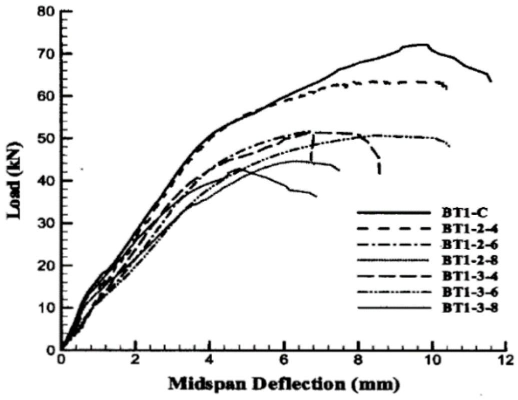

Figure 8. Example of experimental load-displacements curves for increasing levels of corrosion from Azad et al. (2007) [15].

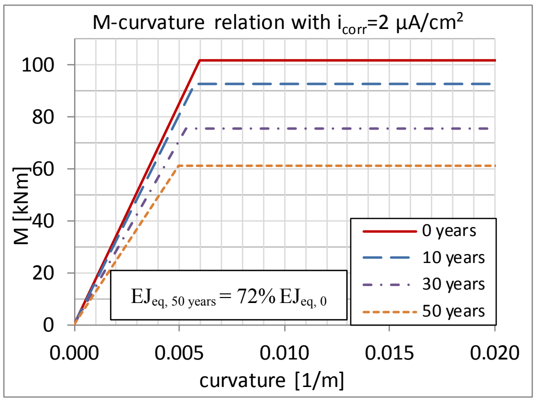

Figure 9. Example of secant equivalent stiffness definition for a beam (section 30x30 cm and 5ϕ14).

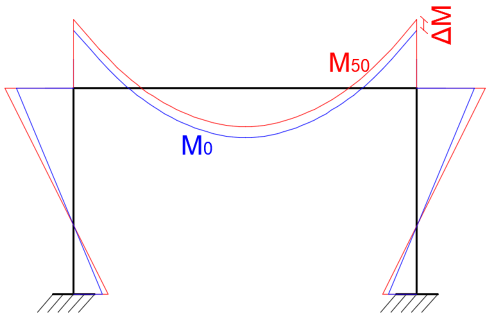

Figure 10. Effect of beam secant equivalent stiffness reduction on the frame.

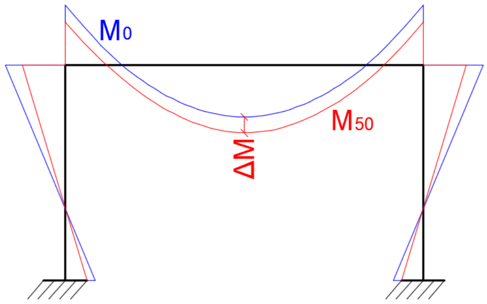

Figure 11. Effect of columns concrete cover loss on the frame.

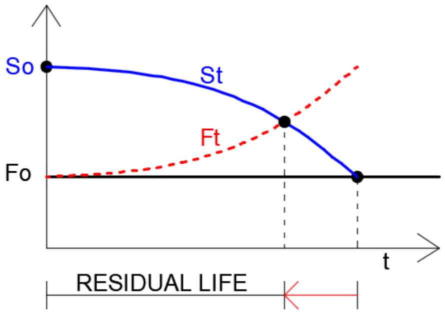

Figure 12. Example of contemporaneous element capacity reduction (St) and internal force increase (Ft) in time. Its residual life is shorter than taking into account constant internal forces (F0) over time.

4. Conclusions

Most of the European RC building heritage has exhausted its nominal service life and it requires deep renovation actions. Tools capable of providing the actual capacity of aging buildings in order to estimate their effective residual life, the possibility of their renovation and the best renovation strategy, are required. A global evaluation of the residual life of existing structures can be pursuit by analysing both the single elements and their interaction inside the structural system. Some aspects of the problem have been herein emphasized:

- While analytical models have been identified as the most suitable for providing a reliable estimation of the residual strength of beams and columns as a function of their corrosion level, empirical models, calibrated on specific experimental tests results, are often inadequate to describe the corrosion processes in existing structures.
- Two models for beams and columns have been respectively selected through a critical analysis and proposed for the evaluation of residual strength according to the observed corrosion level.
- A first step towards the assessment of the whole structural system has been made by proposing a new approach, based on the definition of some equivalent parameters. Such approach allows to relate the single element deterioration with the whole structural behaviour and it highlights how the elements interaction can lead to a further reduction of the structural residual life.

Ongoing research is focused on the extension of the proposed approach to more complex structural systems to provide the estimation of the actual capacity of buildings and so the prediction of their future performances.

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