Durability design of metal structures based on lifetime safety factor method

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ABSTRACT: Durability design of new and existing structures is a key issue for the sustainable development of built-up environment. While the design procedure for reinforced concrete constructions was deeply investigated, the durability evaluation of metal structures has still to be fully analyzed and codified. The aim of this paper is to provide a first proposal for a general approach to the durability design of metal structures based on lifetime safety factor method. All the phases relevant to the design procedure have been discussed and defined in detail, according to a performance based approach. In particular, among the environmental deteriorating mechanisms which affect the durability of metal constructions, the atmospheric corrosion was considered. On the basis of the selected probabilistic corrosion models, which take into account different metal materials, corrosiveness of environment and effectiveness of coatings, the procedure for evaluating the design life corresponding to different environmental loads and limit states has been defined.

1 INTRODUCTION

Sustainable Development (*SD*) was defined for the first time in the last 80s in the Brundtland Report (WCED 1987) as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In the beginnings the strategic objectives just focused on environmental protection, while nowadays the field of interest has greatly enlarged, including also economic and social concerns.

Among different human activities, which interact with the three *SD* dimensions, the construction sector plays an important role in delivering sustainable development requirements. Review of literature shows that the definition of a sustainable construction implies several statements, such as the efficient use of raw materials, the minimum use of energy and emissions during service life, the life duration and robustness, and a prolonged service life as target (CIB 1999).

Metal constructions can easily satisfy the above mentioned requirements thanks to different features. They are recyclable and have high structural efficiency, design and manufacturing flexibility and speed of building. Such advantages provide lower raw material consumption, facilitate changing requirements avoiding obsolescence, and reduce the construction activities impact on the local environment by reducing emissions and noises.

Despite all the previous advantages, metal structures present some drawbacks, which are mainly related to durability, whose evaluation is necessary for a suitable maintenance and rehabilitation planning during life span.

Among several factors that affect the life duration of metal structures, the atmospheric corrosion is recognized to be one of the major risk which decreases the performance of constructions, resulting in huge economic and societal losses.

In terms of structural effects, the atmospheric corrosion causes the thickness loss of the cross section that leads to a smaller resistant area. The loading capacity of the element itself is reduced and the safety margin rapidly decreases.

Besides the effects on coatings, which could modify the exterior appearance of constructions reducing their aesthetic and economic value, corrosion represents an additional critical load which is able to lead the structures to collapse, specially when it is associated with high stress rates and cyclic loads, such as in the cases of stress and fatigue corrosion (Figure 1).

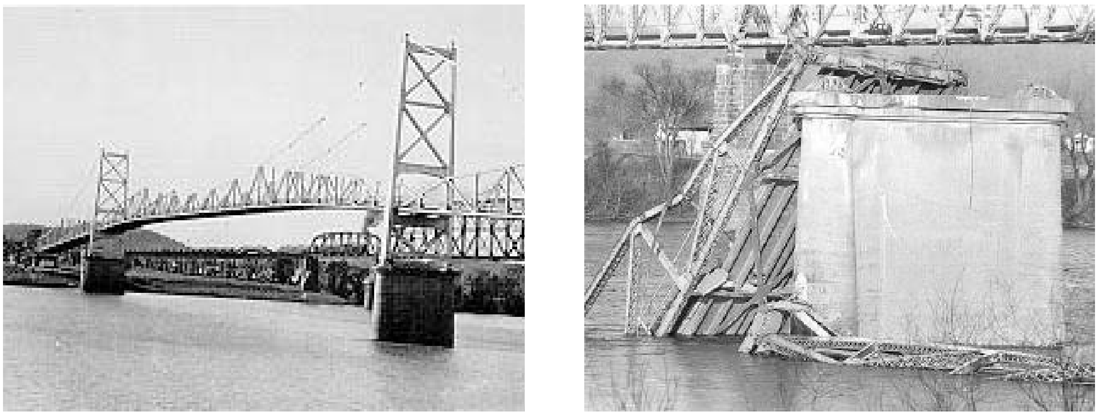


Figure 1. Collapse of the *Silver Bridge* on the Ohio River due to stress and fatigue corrosion (USA, 1967).

With regard to life duration, even if international standards and codes provide general recommendations for preventing early ageing of constructions, the durability design of metal structures has still to be fully defined and codified. In particular, a procedure for the evaluation of original and residual service life should be developed for each material under assigned environmental loads on the basis of available degradation models.

This paper represents a first attempt to propose and develop a durability design procedure for both new and existing metal structures with the aim of evaluating the residual service life of constructions with respect to corrosion degradation.

2 DURABILITY CRITERIA IN STANDARDS AND CODES

The main European standards and codes on constructions give only few qualitative and common provisions for durability of metal structures, that are mainly concerned with coating corrosion or with general recommendations on structural material redundancy. No specific design procedure is provided for the evaluation of design life time of constructions under the identified environmental loads.

A specific definition of durability with respect to the corrosion of metal structures is provided in ISO 8044 (1999), stating that durability is the capability of corrosion system, that is the metal itself or the coating, to fulfill the serviceability requirements for a specific period of time, when adequate maintenance actions are performed.

In EN 1993-1-1 (2004) only few common principles are stated for durability of metal structures and in particular for preventing steel buildings from possible causes of corrosion damage. The code refers to EN 1990 (2001) for durability in general and gives some recommendations such as the opportunity of providing corrosion protection measures by means of surface protection systems, improving the use of weathering or stainless steel and resorting to structural redundancy. However, in such a case no references are made to models able to estimate the corrosion depth as a function of time and of the different factors influencing the degradation rate.

Even if durability is analyzed in general terms, it should be noted also that in some codes for metal structures (DM 2005), an important innovation is being introduced concerning corrosion, which is expressly included among the different loads acting on constructions. In these standards corrosion is classified as a type of entropic load, which comprises deteriorating actions, caused by natural degradation mechanism of materials, and environmental loads, which affects the structural integrity.

Some specific references to durability are reported in the international standards with respect to life duration of the different coating protective systems.

EN ISO 12944-1 (1998) sets three durability classes with regard to protective paint system. In particular, durability means how long the protective coating is effective before a maintenance provisions have to be performed. The standard defines three durability classes: Low (from 2 years up to 5), Medium (from 5 years up to 15) and High (more than 15 years).

In EN ISO 14713 (1999), the life duration of zinc and aluminium coatings is related both to thickness loss and corrosiveness of environment. In particular, specific recommendations are given for each corrosivity class with respect to different coating typologies. However, it should be noted that in this case the design life of coating thickness is evaluated on the basis of linear extrapolation of corrosion rates per year.

Many other references (EN ISO 9226 1992) can be found in international standards, but a design procedure has still to be codified for predicting and preventing the potential damage that a specific environment could lead to both coatings and structural materials, during the entire service life. Taking into account the lack of codified durability design procedures, the application of the life time safety factor method to metal structures is discussed in the following.

3 DURABILITY ANALYSIS BASED ON LIFETIME SAFETY FACTOR METHOD

The lifetime safety factor method in durability design was first time presented in the RILEM Report on concrete structures (Sarja & Vesikari 1996) and then developed within the framework of the EU Project LIFECON (Sarja 2004).

The method is used for the calculation of design life of constructions and it is based on probabilistic degradation models, which consider the decrease of structural resistance caused by different classes of environmental loads. It is so called because of the safety factor applied to the average or the characteristic value of design life. The latter is calculated by degradation models, taking into account both the statistical values of resistance and loads and it is calibrated on the maximum allowable failure probability related to the considered limit states.

Such design approach belongs to semi-probabilistic methods. In this case, both the resistance R and the action effects E are considered as independent random variables. The failure probability P_f is conventionally defined by the reliability index β, which is related to P_f by the equation $P_f = \Phi(\beta)$, where Φ is the cumulative distribution function of the standardized normal distribution. According to semi-probabilistic methods, the design values of the basic variables X_d and F_d influencing both R and E are introduced with their characteristic values divided or multiplied by partial factors. Such partial safety factors are calibrated in order to satisfy the equation $P_f \leq P^*{}_f$ when $E_d \leq R_d$, where $P^*{}_f$ is the maximum allowable failure probability relevant to the considered limit state.

The durability design based on lifetime safety factor method is analogous with the static limit state design. In particular, it is related to control the failure probability by considering the effects on R of the environmental loads acting during the entire life time cycle, while static limit state design is devoted to control the structural reliability of constructions under external mechanical loading. In durability limit state design the resistance R is considered as a time dependant variable, contrary to static limit state design, where the effects of time are usually neglected for R (Figure 2).

In particular, a deterioration function D can be formulated on the basis of the time dependant resistance R according to formula:

$$D(t)= R(0)-R(t) \tag{1}$$

where: $D(t)$ is the deterioration at time t; $R(0)$, $R(t)$ are respectively the resistance at t=0 and at the generic time t of the life cycle.

Because of the different sources of uncertainties that are involved in the definition of the variation of capacity with time, the values in the previous equation are usually taken as mean or characteristic values. The load S is usually adopted to be constant with time, and its design value is also taken as a mean or characteristic value, multiplied by the relevant safety factors.

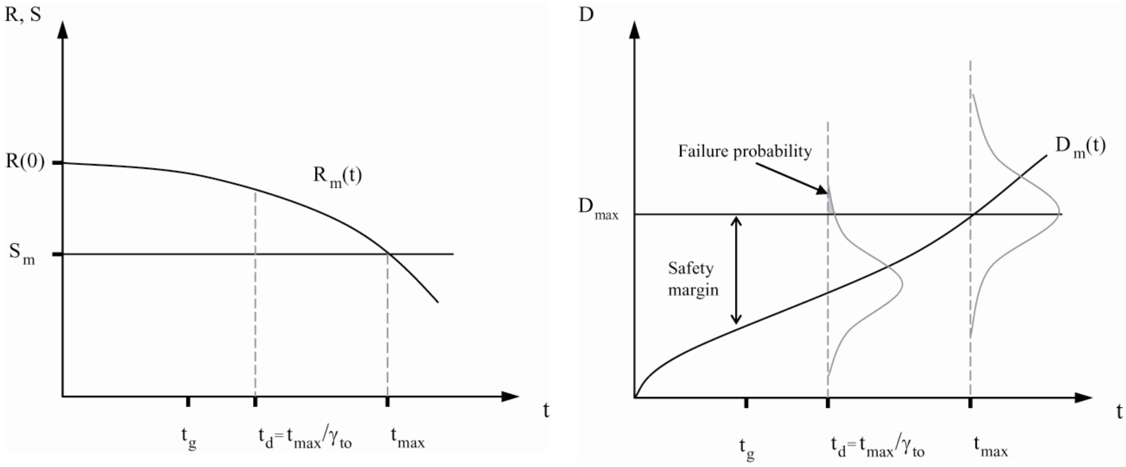


Figure 2. Representation of the life time safety factor design approach by *R, S, t* and *D, t* variables.

The failure event corresponds to time t_{max} when the capacity *R* is equal to load *S*. The difference $R(t)-S$ represents the reduction with time of the safety margin:

$$R(t_{max})=S \tag{2}$$

On the basis of previous considerations, a durability design procedure organized into different steps can be formulated, as specified in the following.

First, the target service life t_g has to be defined for the considered constructions. The target service life must be specified as a basis for assessing statistically variable actions and to evaluate the reliability with respect to durability. Target service life is assumed to be the time period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary (EN 1990 2001). The numerical reference values are selected according to common standards, regulations and codes. The standard EN 1990, with respect to target service life, defines different indicative values on the basis of the construction characteristics, typology and use (e.g. 50 years for building structures and other common structures, 100 years for monumental building structures, bridges, and others). The reference value of the target service life has to be selected according to mechanical design procedure.

Once the reference period has been stated, it is possible to identify the environmental loads S that will likely act onto structure. Each environmental load is analysed and quantified, where relevant, in a statistic way. The analysis of the environmental condition has to be performed in order to define the project background. With regard to atmospheric corrosion of metal structures the identification of both the climatic conditions (such as temperature, rain, condensation of moisture, freezing, solar radiation and air pollution), and the geological conditions (such as the location of ground water, possible contact with sea water, contamination of the soil by aggressive agents like sulphates and chlorides) has to be provided.

On the basis of the identification of environmental loads, the degradation factors and mechanisms should be evaluated.

Once deterioration mechanisms that could act onto structures during the life cycle have been identified, corresponding damage curves should be considered as a function of time in the form:

$$D_m(t) = \alpha \cdot t^n \tag{3}$$

where: $D_m(t)$ is the mean value of degradation; α is a constant coefficient; t time; n degradation mode coefficient.

Substituting t_{max} in eq. (3), we have:

$$D_m(t_{max})=D_{max} \tag{4}$$

where $D_{max}=R(0)-R(t_{max})=R(0)-S$ represents the maximum allowable value of degradation (e.g. the maximum allowable mass loss and/or corrosion depth in the cross section of a beam).

Durability requirements are fulfilled if the failure event (4) occurs after the design service life had expired, with a proper safety margin. That could be expressed according to formula:

$$t_d = t_{max}/\gamma_{t0} >= t_g \tag{5}$$

where: t_d is the design service life; t_{max} is the calculated mean value of the service life corresponding to $D(t_{max})=D_{max}$; γ_{t0} is the central lifetime safety factor; t_g is the target service life.

Assuming that degradation is normally distributed and the standard deviation of D is proportional to the mean degradation, the coefficient of variation V_D being constant, it can be shown that the central lifetime safety factor of the design life depends only on safety reliability index, the coefficient of variation of D and the exponent n, according to the formula:

$$\gamma_{t0} = (\beta \cdot V_D + 1)^{1/n} \tag{6}$$

On the basis of such assumptions, the safety reliability index β depends on both the maximum allowable failure probability for the selected limit state and the degradation function. In particular, it is a function of the mean values and standard deviations of R and S, as follows:

$$\beta = (\mu_R - \mu_S)/(\sqrt{\sigma_R^2 + \sigma_S^2}) \tag{7}$$

In the following sections, all the phases of the durability design procedure for metal structures are discussed in detail with respect to degradation due to atmospheric corrosion.

4 ENVIRONMENTAL LOADS: THE ATMOSPHERIC CORROSION

Corrosion is defined as a deterioration of metal materials that results from a reaction with its environment (NACE 2002), causing the degradation of both.

The deterioration is caused by a chemical and/or electrochemical attack of the metal surface. Corrosion processes are influenced by several factors, that could be divided in two broad classes: the endogenous and the exogenous factors. The first ones are related to the metal itself, e.g. the composition of the metal, the chemical and physical homogeneity of the surface. The exogenous factors are associated to the atmospheric composition, such as temperature, relative humidity and concentration of pollutants (Landolfo & Di Lorenzo & Guerrieri 2005).

Depending on the physical and chemical features of the environment, the corrosion phenomena could develop in different forms, and may be uniform or localised.

The atmospheric corrosion is mainly an electrochemical process that occurs when a thin electrolytic layer is formed on the metal surface; the rate at which the corrosion attack proceeds is strictly related to the corrosiveness of the environment. Relative humidity rate, the pollutants (sulphur dioxide, sodium chloride, ammonium sulphate, etc..) the airborne particles, dust, the weather condition, the wind and the temperature average are the main features that characterize the outdoor atmosphere.

5 CLASSIFICATION OF ENVIRONMENTAL LOADS

Within a durability design method, the classification of environmental loads is necessary for evaluating all the factors which affect the degradation rate during life time of constructions.

Several classification systems are provided by standards to assess the corrosiveness of environment. The codes usually provide the corrosivity of the environment on the basis of the mass loss after one-year exposure. It should be noted that these values represent the result of the corrosion attack after one-year and they cannot be extrapolated to estimate the extent of damage in a time t of the service life.

EN ISO 9223 (1992) defines five corrosivity classes C1-C5 on the basis of three key factors: the TOW (time of wetness), the deposition rate of chlorides and sulphures dioxide. EN 12500 (2000) defines the corrosiveness of the environment, according to ISO 9223, by assessing the mass loss of standard samples, after 1 year exposure and it establish five corrosivity categories from C1, very low corrosivity environment, up to C5, very severe corrosiveness atmosphere.

EN 12500 recommends to evaluate the corrosiveness of the environment quantitatively on the basis of the sample exposure but whether impossible, it could be used to assess qualitatively the atmospheric category. The standard points out that the qualitative classification of the environment could mislead designers in selecting protective measures, field test exposure are strongly recommended. According to EN 12550 the designer should run field test on standard carbon steel, zinc, copper and aluminium samples measuring, after 1 year exposure, the mass loss of the samples. The corrosiveness class of the local environment is thus established comparing the measured values with the guiding values reported in the following Table:

Table 1. Mass loss (g/m^2) for one year field test exposure. EN 12550.

MASS LOSS g/m^2				Corrosiveness category	
Carbon Steel	Zinc	Copper	Aluminium		
≤ 10	≤ 0,7	≤ 0,9	Negligible	Very low	C1
10-200	0,7-5	0,9-5	≤ 0,6	Low	C2
200-400	5-15	5-12	0,6-2	Medium	C3
400-650	15-30	12-25	2-5	High	C4
650-1500	30-60	25-50	5-10	Very high	C5

As an alternative to the previous procedure, the corrosiveness of the local environment could be assessed qualitatively on the basis on climatic and/or environmental parameters and/or construction location (EN 12500 2000). The qualitative classification of the atmospheres ranges from Rural to Marine industrial types and it is based on a general description of corrosive agents and degradation rates.

6 DEGRADATION MODELS

Several degradation models can be found in literature which have been defined for metallic materials. These models provide the corrosion depth or the mass loss with time for different corrosive environments. In general, they are formulated according to a probabilistic approach because of the uncertainties which affect degradation rates.

In order to use such models in the durability design of metal structures, it is necessary to relate the classification of the environmental loads to the corresponding corrosion rate. The thickness loss during structural life time can be predicted by means of the considered degradation law and on the basis of assigned environmental conditions.

At this stage of the study, it should be noted that no clear relationship between corrosion models and atmosphere classes are provided by the codes.

In the following, an application of degradation models provided in literature to corrosiveness classes defined in standards is reported. In particular, the corrosion models developed by Klinesmith (2007) are used. Such models were formulated for different materials taking into account the effects of four environmental variables, which are time-of-wetness, sulfur dioxide, salinity, and temperature.

The form of the degradation model is the following:

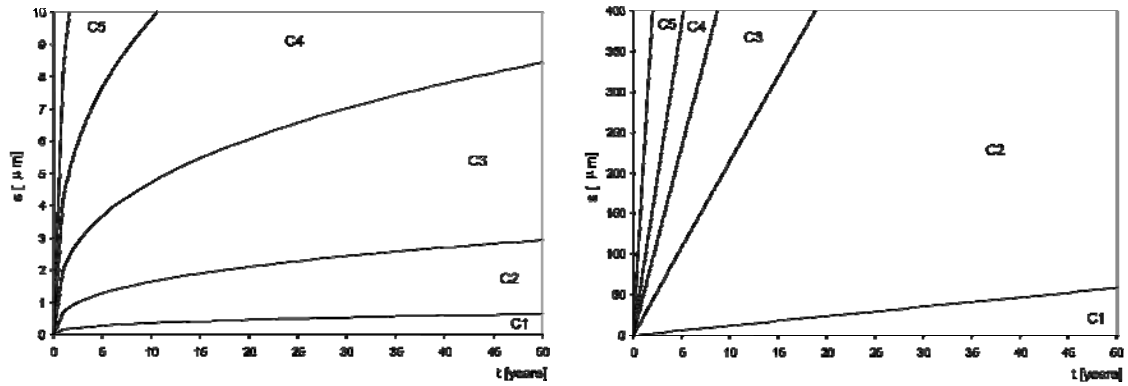
$$y = A \cdot t^B \left(\frac{TOW}{C}\right)^D \cdot \left(1+\frac{SO_2}{E}\right)^F \left(1+\frac{Cl}{G}\right)^H e^{J(T+T_0)} \tag{8}$$

where y=corrosion loss (μm); t=exposure time (years); TOW=time-of-wetness (h/year); SO_2=sulfur dioxide concentration ($\mu g/m^3$); Cl is chloride deposition rate (mg/m^2 /day); T=air temperature (°C); and A, B, C, D, E, F, G, H, J, and T_0 =empirical coefficients.

Table 2. Coefficients of Eq. (8) calibrated with ISO CORRAG data (Dean & Reiser 2002) for carbon steel and zinc materials.

Material	Equation coefficients									
	A	B	C	D	E	F	G	H	J	T_0
Carbon steel	13.4	0.98	3800	0.46	25	0.62	50	0.34	0.016	20
Zinc	0.16	0.36	3800	0.24	25	0.82	50	0.44	0.05	20

The degradation curves for zinc and carbon steel corresponding to the selected model (Table 2) are shown in Figure 3. The environmental variables have been considered with values corresponding to the different corrosiveness classes as defined in EN 12500 (2000).



a) *b)*

Figure 3. Thickness loss as a function of time for zinc (a) and carbon steel (b) for different corrosiveness classes, according to selected degradation models.

7 DURABILITY LIMIT STATES

In order to complete the development of a durability design procedure based on the partial safety factor method, both serviceability and ultimate limit states related to basic requirements need to be defined, such as functionality in use and structural safety. In particular, the definition of the maximum allowable degradation value for each material and limit state and of the relevant reliability index β is necessary for the calculation of design life t_d and of relevant safety factor γ_{t0}.

Durability limit states could be the same of the ones used for mechanical design, but some specific limit states should be defined for durability (Sarja 2004).

Serviceability and ultimate limit states in durability design can be referred to the thickness loss of coating and structural material respectively. In particular, serviceability limit states are related to changes in functionality or aesthetics and they are based on maintainability, economy and environmental impacts. As a consequence, such limit states can be ascribed to the attainment of partial or total loss of coating thickness. On the contrary, ultimate limit states are related to the thickness loss of structural material which compromises the mechanical safety of constructions.

With regard to serviceability limit states (SLS) relevant to zinc coating corrosion, it is suggested to use the definition provided by British Steel Construction Institute research (Popo-Ola & Biddle & Lawson 2000) on durability of galvanized cold formed steel section used in housing. In this case, different limit states have been defined depending on the possibility of a building component to be inspected. In particular, if the use conditions do not allow regular inspections, such as in case of wall frames and wall ties, the limit state is reached when 50% of the weight of zinc has been lost, otherwise for roof trusses and internal floors the limit state is defined as the 80% of the weight of zinc loss.

As far as ultimate limit states (ULS) are concerned, it is proposed to carry out a durability design which is separated from the mechanical one. In particular, the safety of constructions at the end of their life-time should be evaluated by considering the possible thickness loss of structural material which starts after the complete corrosion of coating. Such thickness should be added to the one obtained from mechanical calculation in design phase of new constructions, increasing the structural redundancy, or should be used for evaluating the actual safety factor and the residual service life in existing ones.

In order to evaluate the design service life t_d for different limit states, the central safety factors have to be calculated on the basis of both Eq. (6) and corresponding reliability indexes.

With respect to reliability index β, different values are given by standards and codes for serviceability and ultimate limit states. The reliability indexes to be used in the durability design should be defined close to the mechanical ones but, in order to balance the costs with the benefits, lower reliability level should be tolerated (Sarja 2004). In particular, the suggested values for ultimate and serviceability limit states are equal to 4.3 and 1.5 respectively, in case of reliability class RC2 as defined in EN1990.

By applying the proposed procedure in case of carbon steel and assuming V_d=0.3, the central safety factors calculated by Eq. (6) range from 1.5 to 2.5 for SLS and ULS, respectively. As far as zinc corrosion is concerned, the relevant central safety factor for SLS is equal to 2.8.

8 CONCLUSIONS

This paper focuses on a proposal for durability design of metal structures against corrosion. The different phases of the design procedure have been investigated considering the environmental corrosivity classes defined in current standards and by using degradation models which are available in literature for the calculation of the corresponding thickness loss.

Different limit states corresponding life time safety factors have been proposed, also on the basis of statistical values of considered degradation models.

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