ANALISI SEMPLIFICATA DEL COMPORTAMENTO CICLICO DI STRUTTURE IN ACCIAIO IN AMBIENTI AGGRESSIVI

SIMPLIFIED CYCLIC ASSESSMENT OF STEEL STRUCTURES IN AGGRESSIVE ENVIRONMENTS

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ABSTRACT

Steel structures such as offshore constructions or steel bridges are often placed in aggressive environments owing to their destination of use. Hence, the combined action of material degradation and cyclic loadings can induce premature corrosion fatigue failure if structures are not properly protected. In this paper, a simplified method for the cyclic assessment of steel constructions in aggressive environments is presented. The proposed technique is based on the concept of “critical corrosion degree” η^*_{Rd}, i.e. the minimum rate of corrosion which leads to fatigue failure for a selected target service life t^*. Corrosion fatigue checks are thus expressed in a “demand vs. capacity” form more in line with principles of performance-based engineering. An application of the presented procedure is reported with reference to an existing bridge located in Italy which already endured a significant service life. Finally, parametrical analyses are performed to highlight the sensitivity of cyclic performance to physical and mechanical variables governing corrosion fatigue phenomena.

SOMMARIO

Strutture in acciaio quali costruzioni offshore e ponti metallici sono spesso situate in ambienti aggressivi in ragione della loro destinazione d’uso. Pertanto, l’azione combinata del degrado dei materiali e dei carichi ciclici può indurre un collasso prematuro per fatica e corrosione se tali strutture non sono adeguatamente protette. Nel presente articolo si pro-pone un metodo semplificato per l’analisi ciclica di costruzioni in acciaio poste in ambienti aggressivi. La tecnica mostrata è basata sul concetto di “grado di corrosione critica” η^*_{Rd}, ovvero il minimo livello di corrosione che induce un collasso a fatica per un’assegnata vita di servizio t^*. Le verifiche a fatica e corrosione possono essere pertanto espresse in una esplicita forma “domanda vs. capacità” più in linea con i principi dell’ingegneria performance-based. Un’applicazione della procedura presentata è riportata per un

ponte esistente situato in Italia, il quale ha già sperimentato una consistente vita di servizio. Infine, vengono condotte delle analisi parametriche per mostrare la sensitività della performance ciclica rispetto ai parametri fisici e meccanici che governano la fatica in presenza di corrosione.

1 INTRODUCTION

After the second half of XXth century, fatigue performance of both new and existing steel structures has become a relevant topic for civil engineering due to some major fatigue-related failures [1]. When dealing with existing steel structures, fatigue damage can be coupled with another relevant source of damage, i.e. material degradation, mainly in the form of metallic corrosion [2]. Corrosion involves a progressive material loss due to electrochemical processes which are extremely sensitive to local environmental conditions (i.e., humidity, salinity, temperature). Hence, both time- and space-depending evolution of corrosion can sensibly vary during service life, leading to phenomena such as pitting (i.e. localized) corrosion or sudden changes in rate of corrosion in time. When corrosive processes occur in conjunction with cyclic loads, corrosion damage is not merely summed to fatigue damage; namely, the two processes influence each other due to multiple factors [2]:

1. On one hand, fatigue cracking creates preferable spots for corrosion development, as the cracks can penetrate through protective layers (i.e. zinc coatings, ducts…), if present;
2. On the other hand, corrosion induces a reduction of the resisting cross-section, resulting in stress amplifications which accelerate fatigue cracking.

In light of the above, it is clear that phenomenology of corrosion fatigue in steel structures is a complex topic to be addressed and it is still an open field of research at the present time [3].

The present work attempts at providing a unified and simplified methodological approach for the fatigue assessment of steel structures in aggressive environments. This purpose is addressed by introducing a "critical corrosion degree" η^*_{Rd} associated to an assigned fatigue life t^*, which allows carrying out fatigue checks in an explicit "demand vs. capacity" form. This paper is mainly divided in three parts. In the first part, each step of the procedure is presented. In the second section, an application of the presented methodology is reported for a corroded riveted bridge located in Italy. Finally, parametrical analyses are performed in the third part with regard to most critical members.

2 OUTLINE OF THE PRESENTED PROCEDURE

The proposed methodology for the simplified corrosion fatigue assessment of steel structures in aggressive environments is based on the well-known Miner's rule for damage cumulation, which is already codified in EN1993:1–9 [4] within the framework of the Damage Tolerant (DT) approach. Nevertheless, in this work, fatigue checks will be presented in a more direct "capacity vs. demand" approach in line with performance-based engineering. This aspect is addressed by introducing the concept of "critical corrosion degree" η^*_{Rd} for an assumed target fatigue life t^*.

2.1. Step 1

As highlighted previously, corrosive phenomena are highly sensitive to local boundary conditions. In general, in years immediately after the construction time, corrosion is limited due to the presence of preventive measures. Once the protection layer is worn, the corrosion process sharply accelerates. Finally, after significant superficial corrosion products have already formed, the corrosive process usually slows down, approaching a stabilized rate (See Fig. 1, dashed curve). Compliantly, and according to ISO 9224 [5], in the presented approach the corrosion development is approximated by a polyline with two branches (see Fig. 1, solid polyline). The slopes ratio among the two branches is equal to C : 1, with C = 1 ÷ 5 depending on the corrosivity category as defined in [5].

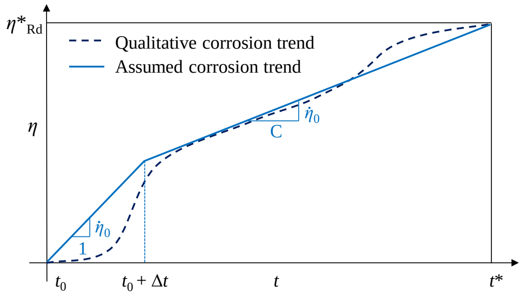


Fig. 1. Qualitative (black dashed curve) and assumed (red solid polyline) trends for corrosion development for the proposed methodological approach.

The knee point of the bi-linear curve is assumed to occur $\Delta t = 10$ years after construction time. The corrosion degree η is assumed null for $t = t_0$. Conversely, for $t = t^*$ (target fatigue life) a "critical corrosion degree" η^*_{Rd} is introduced, i.e., the minimum corrosion degree which induces corrosion fatigue collapse for $t = t^*$. The selection of a proper value for t^* has to be intended as a designer's choice, which depends on the expected influence of fatigue and material degradation on structural performance. The corrosion degree at a given time $\eta(t)$ is hence expressed by Eq. 1a-b:

$$\eta(t) = \begin{cases} \dot{\eta}_0 (t - t_0) & t \le t_0 + \Delta t \\ \dfrac{\dot{\eta}_0}{C}(t - t_0) + \Delta t\, \dot{\eta}_0 \left(1 - \dfrac{1}{C}\right) & t_0 + \Delta t < t \le t^* \end{cases} \tag{1a}$$

$$\dot{\eta}_0 = \frac{\eta^*_{Rd}}{\Delta t \left(1 - \dfrac{1}{C}\right) + \dfrac{t^*}{C}} \tag{1b}$$

in which $\dot{\eta}_0$ represents the corrosion rate assumed for the first branch of the polyline. Equation (1a-b) holds true for an arbitrary value of η^*_{Rd}, the actual value of which will be derived in Step 4.

2.2. Step 2

According to [5], the expected amount of material loss due to corrosion do not exceed few mg/(year·m^2) even in the case of extremely aggressive environments. Hence, global stiffness reduction due to corrosion can be initially neglected, performing structural analysis on the "unaltered" structure. In this way, extreme values of the stress characteristics ($S_{0,min}$; $S_{0,max}$) can be determined only once. Influence of corrosion will be later accounted in terms of local stresses amplifications.

2.3. Step 3

After estimating "unaltered" stress characteristics $S_{0,min}/\Delta S_0$, "unaltered" local stresses $\sigma_{0,min}/\Delta\sigma_0$ can be determined using expressions from the theory of elasticity. Hence, introducing appropriate stress magnification factors (SMFs), "real" corrosion-depending stresses $\sigma_{\eta,min}/\Delta\sigma_\eta$ can be can be evaluated. At least two sources of amplification have to be accounted for, i.e., local erosion of the resisting cross-section and the presence of mean tensile stresses $\sigma_{0,m} > 0$ [6]. Corrosion-induced amplification can be modelled by means of an SMF (SMF_η), which is a function of (i) cross-section properties in pristine conditions X_0; (ii) cross-section properties reduction ΔX_η; and (iii) the type of corrosive process (CP). In the simplest case (uniform corrosion), SMF_η can be expressed as follows:

$$SMF_{\eta,uniform} = \left(1 - \frac{\Delta X_\eta}{X_0}\right)^{-1} \approx (1 - \eta)^{-1} \tag{2}$$

Non uniform corrosion can be modelled by scaling $SMF_{\eta,uniform}$ by means of a function f(t, CP) defined case-by-case. “Real” corrosion-depending stresses $\sigma_{\eta,\min}/\Delta\sigma_\eta$ are hence derived as follows:

$$\sigma_{\eta,min} = SMF_\eta\, \sigma_{0,min} \tag{3a}$$

$$\Delta\sigma_\eta = SMF_\eta\, \Delta\sigma_0 \tag{3b}$$

In case of complex stress histories, “real” stress histories are expressed by means of “real” oscillograms, in which each point $\sigma_\eta(t)$ is derived by magnifying SMF_η times the related “unaltered” stress $\sigma_0(t)$. Hence, cycle counting is performed considering only the fluctuating part of amplified stresses (e.g. with Rainflow method [4]). Cycle counting yields an approximated “real” load spectrum ($\Delta\sigma_{\eta,i}$; n_i). The equivalent fatigue demand accounting for mean stress effect $\Delta\sigma_{eq,i}$ is hence estimated:

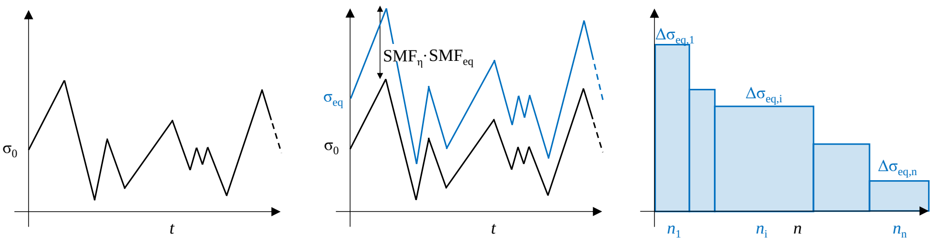
$$\Delta\sigma_{eq,i}(t) = \Delta\sigma_{\eta,i}(t) \cdot SMF_{Eq}(t) \tag{4}$$

where SMF_{Eq} is an equivalent magnification factor accounting for the mean stress effect. According to consolidated practice, Goodman’s model [6] is selected to deal with pulsating stress histories. It should be remarked that SMF_{Eq} implicitly depends on $\Delta\sigma_{\eta,i}$, as Eq. 5a-b holds:

$$SMF_{Eq}(t) = \frac{1}{1 - \dfrac{\sigma_{\eta,m,i}(t)}{f_u}} \geq 1 \tag{5a}$$

$$\sigma_{m,\eta,i}(t) = \sigma_{\eta,min,i}(t) + \frac{\Delta\sigma_{\eta,i}(t)}{2} \tag{5b}$$

with f_u being the ultimate tensile strength (UTS) of structural steel. The evaluation of $\Delta\sigma_{eq,i}$ is performed for each stage of the structural service life, thus obtaining (t^*–t_0) “equivalent” load spectrums, which represent the overall fatigue demand on the analyzed structure (Fig. 2).



(**a**) “unaltered” oscillograms (**b**) “equivalent” oscillograms (**c**) “equivalent” load spectrums

Fig. 2. Estimation of “real” load spectrum from aperiodic stress histories.

2.4. Step 4

Using Miner’s rule for damage accumulation, the actual value of the critical corrosion degree η^*_{Rd} can be estimated by imposing that total damage D_{TOT} reaches unity for $t = t^*$:

$$f(\eta^*_{Rd}, t^*) = 1 - D_{TOT}(\eta^*_{Rd}, t^*) = 1 - \sum_{t\,=\,t_0}^{t^*} \frac{n_i}{N_i\left(\Delta\sigma_{eq,i}(\eta^*_{Rd})\right)} - 1 = 0 \tag{6}$$

Evaluation of the number of stress cycles up to failure N_i has to be performed using a S-N-η fatigue strength domain to account for fatigue strength reduction due to material degradation [7]:

$$\log\frac{5\times10^6}{N_i} = m_{1,\eta}\log\left(\frac{\Delta\sigma_{D,\eta}}{\Delta\sigma_{Eq,i}}\right) \tag{7a}$$

$$\log\frac{N_i}{5\times10^6} = m_{2,\eta}\log\left(\frac{\Delta\sigma_{Eq,i}}{\Delta\sigma_{D,\eta}}\right) \tag{7b}$$

with $\Delta\sigma_{D,\eta}$ being the modified constant amplitude fatigue limit (CAFL, N = 5 × 10^6) for the selected element, accounting for the effect of corrosion, and $m_{1,\eta}/m_{2,\eta}$ being the corrosion-depending inverse slopes of LCF/HCF branch of the S-N curve, respectively. According to [7], modified CAFL can be derived assuming that the stress range $\Delta\sigma_{10000}$ inducing collapse for N = 10^4 does not depend on η. Thus, $\Delta\sigma_{D,\eta}$ can be calculated starting from the "pristine" detail class ($\Delta\sigma_C$, N = 2 × 10^6):

$$\Delta\sigma_{D,\eta} = \frac{\Delta\sigma_{10000}}{(5\times 10^2)^{\frac{1}{m_{1,\eta}}}} \tag{8a}$$

$$\sigma_{D,10000} = (2\times 10^2)^{\frac{1}{m_{1,0}}} \cdot \Delta\sigma_C \tag{8b}$$

with $m_{1,0}$ being the inverse slope of the LCF branch according to [4] in pristine conditions. Consistently with [7], the inverse slopes are assumed to linearly reduce as η increases:

$$m_{1,\eta} = m_{1,0} - \frac{\eta}{\eta_{ref}}\Delta m_{1,\eta} \tag{9a}$$

$$m_{2,\eta} = m_{2,0} - \frac{\eta}{\eta_{ref}}\Delta m_{2,\eta} \tag{9b}$$

in which $m_{1,0}/m_{2,0}$ are the inverse slopes of the S-N curve in pristine conditions, respectively; $m_{1,\eta}/m_{2,\eta}$ are the corrosion-affected inverse slopes and $\eta_{ref}/\Delta m_{1,\eta}/\Delta m_{2,\eta}$ are experimental parameters expressing the influence of corrosion on fatigue behavior. In this work, $\eta_{ref} = 0.2$, $\Delta m_{1,\eta} = 0.375\ m_{1,0}$, and $\Delta m_{2,\eta} = 0.375\ m_{2,0}$ are assumed compliantly with [7]. Conservatively no endurance limit is assumed. The resulting shape of S-N-η domains is **depicted in Fig. 3 for** increasing η.

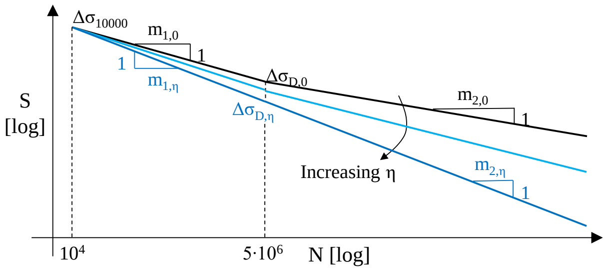


Fig. 3. Assumed shape of S-M-η domains for corrosion fatigue analyses.

2.5. Step 5

As η^*_{Rd} is known, corrosion fatigue checks are performed by controlling that "corrosion demand" at a given time $\eta_{Ed}(\bar{t})$ does not exceed the "corrosion capacity" $\eta_{Rd}(\bar{t})$ for the same $\bar{t}$:

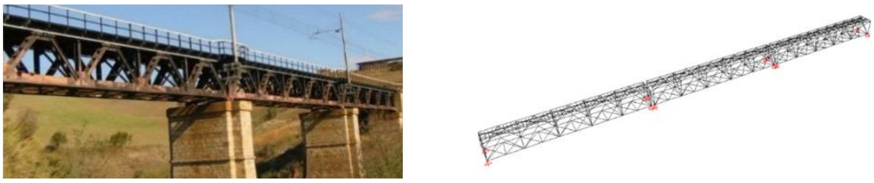
$$\eta_{Ed}(\bar{t}) \le \eta_{Rd}(\bar{t}) = \eta^*_{Rd} - \frac{\eta^*_{Rd}}{\Delta t(C-1)+t^*}(t^* - \bar{t}) \tag{10}$$

Based on **Eq. 10**, three different structural damage stages can be identified, namely:

1. For $0 < \eta_{Ed}(\bar{t}) < \eta_{Rd}(\bar{t})$, the structure can is safe with regard to corrosion fatigue failure;
2. For $\eta_{Rd}(\bar{t}) < \eta_{Ed}(\bar{t}) < \eta^*_{Rd}$, the necessity of maintenance measures emerges as values of $\eta > \eta^*_{Rd}$ are expected to be attained for $t < t^*$;
3. For $\eta_{Ed}(\bar{t}) > \eta^*$, the structure quickly requires safety measures against corrosion fatigue collapse, which is indeed predicted to occur.

3 CASE STUDY

The presented procedure is hence applied with reference to an existing riveted railway bridge located in Italy. The structure was erected during 1960s to replace a former masonry bridge damaged by 1962 Irpinia earthquake. Four existing masonry piles were preserved, while the deck was rebuilt by means of three identical 29 m long 3D truss steel bays (see Fig. 4a).



(**a**) (**b**)

Fig. 4. **(a)** View and **(b)** modelling of the selected case study (railway bridge over Gesso torrent).

Steel members were realized by coupling hot-rolled and/or welded profiles by means of riveted battens. 22 mm hot-driven rivets were also implemented for connecting members via gusset plates. Namely, chords have an inverted Π section made of battened angles and plates. H-shaped welded profiles were used for vertical struts. Diagonals were made by battening two C profiles. Due to Italian Railway Network Management provisions (RFI, [8]), no zinc coating was applied.
"Unaltered" global analysis accounting for "real" train loads as defined in [8] was performed using SAP2000 v.23 [9] (see Fig. 4b). All members were modelled by means of equivalent 1D elements. According to the original design report [10], an Fe 50.2 steel grade (f_u = 500 N/mm^2) was assumed for all elements. The number of passages per year was assumed based on data provided by RFI.
In order to reproduce the actual phenomenology of corrosion, a progressive thickness reduction for elements on the bottom was assumed. Indeed, due to stagnation of meteoric waters, degradation phenomena are highly promoted in the inferior portion of the 3D truss. Moreover, owing to the structural scheme, lower steel members are more prone to fatigue damage due to significant mean tensile stresses. For the sake of brevity, only corrosion fatigue analyses for most critical elements are reported, i.e. *i*) the mid-span segment of lower chords, *ii*) tension diagonals closest to supports and *iii*) vertical struts located at mid-span. Fig. 5a shows geometrical features and "unaltered" load spectrums for the considered members. Critical corrosion degree was estimated considering a C3 exposition class (C = 2.5) for all the elements (Fig. 5b-c). According to Italian provisions for bridges [11], t^* = 100 years was set, while $\Delta\sigma_C$ = 71 N/mm^2 was selected compliantly with [4].
It can be noticed that estimated values of η^*_{Rd} are rather variable for investigated members (η^*_{Rd} = 50.7%, 80.1% and 27.5% for the lower chord, the diagonal and the vertical strut, respectively). Indeed, while a significantly high critical corrosion is derived for both lower chords and diagonals, in case of vertical struts the effect of corrosion is more pronounced. This outcome depends on the small cross-section of struts, which lead to high stress ranges even for low η. Appreciable damage arise also in lower chords for $\eta \geq 30\%$. Conversely, diagonals show a high range of safety.

3.1. Parametrical Analyses

In order to investigate the influence of physical/mechanical variables on the corrosion fatigue performance, parametrical analyses were conducted varying the following parameters, namely: *i*) corrosivity class *CX*, *ii*) tensile strength f_u, *iii*) target service life t^* and *iv*) stress ratio *R* (see Table 1). Results of parametrical analyses are reported in Fig. 6. One can notice that, as expected, the diagonal is less sensitive (± 4%) to boundary conditions variations due to the negligible impact of corrosion fatigue on its service life. Conversely, lower chord displays a more significant sensitivity with respect to varied parameters. Namely, increasing t^* or R a significant increment of damage is predicted, with a variation $\Delta\eta^*_{Rd} \approx -10\%$ with respect to the reference value in both cases (see Fig. 6c-d, dark blue plots).

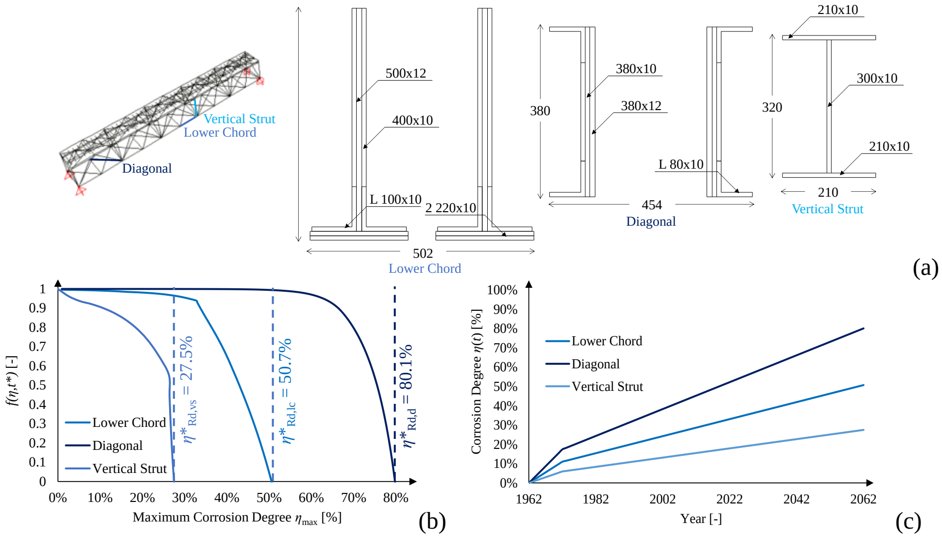


Fig. 5. **(a)** Geometrical features, **(b)** damage functions and **(c)** critical trends for critical elements.

Table 1. Assumed values of parameters for parametrical analyses.

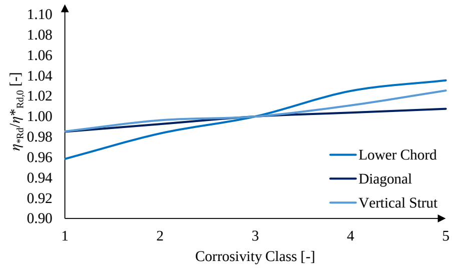
Parameter	Reference Value	Range of Variation
CX [-]	C3	C1 ÷ C5
f_u [N/mm^2]	500	340 ÷ 600
t^* [years]	100	50 ÷ 150
R [-]	0.3 (Lower Chord), 0.4 (Diagonal), 0.0 (Vertical Strut)	0.0 ÷ 0.5

Finally, vertical strut is highly sensitive to t^* ($\Delta\eta^*_{Rd} = -15\%$ for $t^* = 60$ years), while other parameters do not appreciably affect the value of η^*_{Rd}. It should be noted that, as compressive mean stress arises in such element due to permanent loads, f_u has no effect on η^*_{Rd}.

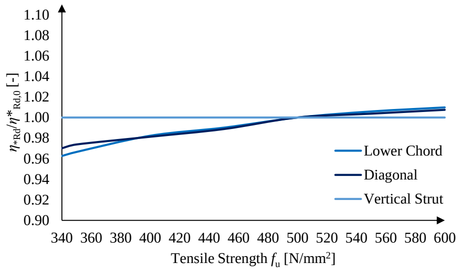
CONCLUSIONS

A simplified methodology for the corrosion fatigue assessment of steel structures in aggressive environments was presented. The proposed method was hence applied with reference to an existing riveted bridge located in Italy. In light of the results, the following conclusions can be drawn:

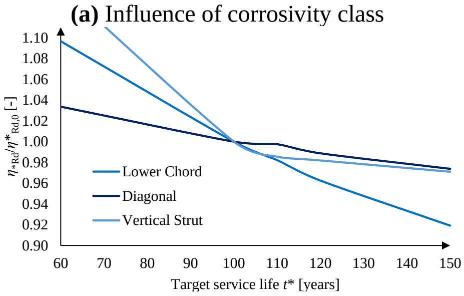
- The proposed method for the corrosion fatigue analysis of steel structures is based on the concept of “critical” corrosion degree η^*_{Rd}, which is derived for a selected target fatigue life t^*;
- The selected case study has a good performance against corrosion fatigue failure (i.e., η^*_{Rd} = 50.7%, 80.1% and 27.5% for the lower chord, the diagonal and the vertical strut, respectively). Vertical struts are the most exposed elements due to their reduced pristine cross-section;
- Parametrical analyses showed how target fatigue life t^* and stress ratio R are the most influent parameters for the corrosion fatigue performance of the selected case study;
- Further studies on different full-scale steel structures located in aggressive environments will be conducted to prove the reliability of the presented simplified procedure.



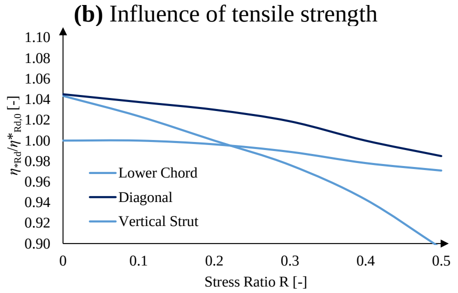
(a) Influence of corrosivity class



(b) Influence of tensile strength



(c) Influence of target service life



(d) Influence of stress ratio

Fig. 6. Results of parametrical analyses on investigated elements.

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KEYWORDS

Steel structures; Corrosion; Fatigue assessment; Material degradation.