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Probabilistic Analysis of Corrosion Rates and Degradation of Weathering Steel Bridges

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Abstract

Corrosion of weathering steels in outdoor conditions has been observed since their pioneering applications in construction in the 1960s. Changing environmental conditions such as decreasing SO_2 concentration and changes in temperature and relative air humidity affect the formation and development of a protective layer of corrosion products on the surface of these steels. The study compares the long-term corrosion rates of weathering steels according to EN ISO 9224 with the measured rates for various environments in the Czech Republic and abroad, with a focus on sites with increased concentrations of chlorides from road salt. It is shown that the considered corrosion rate models provide estimates in a wide range, and in-situ measurements can significantly improve corrosion loss predictions. The reliability of bridges made of weathering steels is insignificantly affected by corrosion with a well-developed protective layer. However, low reliability levels may be experienced in critical details where for example leakage may damage the protective layer of patina.

Keywords

atmospheric corrosivity, chloride exposure, corrosion, reliability analysis, weathering steel bridges

1 Introduction

Road, railway and several pedestrian bridges made of weathering steel are in operation in the Czech Republic, and several others are in the design phase. These structures are intended to be used without protective coating and low maintenance costs are the main advantage of weathering steels.

Monitoring and evaluating the condition of an adherent protective oxide layer ("patina") is key for predicting the service life and ensuring reliability of the bridge structure. The submitted contribution aims to analyze reliability of selected cross-sections of load-bearing bridge members affected by uniform corrosion. The probabilistic corrosion model considers new measurements obtained by the authors in the framework of Grant TA CR CK03000125 along with measurements available in literature. Corrosion loss predictions are critically compared with the predictions based on the models in ISO standards.

2 Probabilistic model for corrosion rate of weathering steels

Weathering steels have specific weather-resistant properties due to the small content of alloying elements (Cr, Cu, Ni, P and Mo), which normally do not exceed 2%. Some newly developed weathering steels have a higher content of alloying elements. The first weathering steel was patented in 1953 in the USA under the trademark CORTEN. In the 1970s, low-alloy steel with similar properties was developed in the former Czechoslovakia, named Atmofix.

The model for corrosion rates of weathering steels can be based on the model for carbon steel according to ISO 9223 and 9224. However, the specific properties of alloys of weathering steels, their different chemical composition, and their improved surface resistance need to be taken into account. The ISO model makes it possible to consider atmospheric corrosivity of the environment and the effects of environmental changes during the service life of bridge structures.

ISO 9224 provides the corrosion rates of metals and alloys subjected to atmospheric exposure as a function of time for different categories of atmospheric corrosivity. Corrosion rates normally decrease with time of exposure, t_{exp}, due to the accumulation of corrosion products on the surface which decelerates the progress of corrosion. Focusing on uniform corrosion, the total corrosion loss D can be predicted as follows:

$$D = \theta \times r_{\text{corr}} \times t_{\text{exp}}{}^{b} \quad (1)$$

where θ denotes the model uncertainty, t_{exp} is time of exposure in years, r_{corr} denotes the corrosion rate in the first year of exposure and b is the exponent specific to the metal-environment combination.

2.1 Model uncertainty

According to the JCSS Probabilistic Model Code [1], model uncertainty can be considered as a random variable. Considering relationship (1), model uncertainty may cover the effects of:

- simplified classification of categories of atmospheric corrosivity,
- ignoring factors affecting the development of corrosion, such as temperature, humidity or solar radiation,
- simplification of the mathematical model for the development of corrosion (two or more parametric models or types of regression relationship), etc.

It is usually considered that the model uncertainty can be estimated from the multiplicative relationship $D_{actual} \approx \theta\ D_{model}$, where D_{actual} denotes the actual (measured) total corrosion loss and D_{model} is the total corrosion loss determined by the model, i.e. $D_{model} = r_{corr} \times t_{exp}{}^{b}$.

The statistical characteristics of model uncertainty θ can be estimated by comparing measurements with corrosion model predictions. From ISO 9223 and related background material [2] it follows that the r_{corr}-values provided in the standard for a particular carbon steel composition correspond well to the measurements; for the smaple of 128 measurements a coefficient of determination R^2 = 0.85 was obtained. Assuming unbiased predictions and a linear relationship between measurements and model predictions, it can be shown that this variance can be approximated by model uncertainty θ with a unity mean, μ_θ = 1, and coefficient of variation V_θ = 8.5%. In the absence of statistical data, a lognormal distribution can be assumed for the model uncertainty [1], [3]. Considering the variability of the exponent b for carbon steels according to ISO 9224, coefficient of variation $V_\theta \approx$ 12-13% was derived for long-term exposures, t_{exp} = 20-50 years [4].

In a similar way, coefficients of variation V_θ are estimated from the coefficients of determination in the database of of experimental results provided in previous studies. Measurements from 22 previous studies were included in the database, covering 75 sites in total:

- Measurements were obtained in Europe (Belgium, Czech Republic, Estonia, Finland, Germany, Italy, Norway, Netherlands, Russia, Spain, Sweden, UK) and in America (mainly USA, some in Canada and Panama).
- They include rural, urban and industrial environments (atmospheric corrosivity categories C2 through C5); measurements from coastal environments are not relevant for the conditions of the Czech Republic and are therefore not analysed further as the main focus of this study is reliability analysis of bridges in mild – Central European climate.

Measurements were mostly taken for CORTEN A (70 sites), less frequently for CORTEN B (5 sites); see ASTM G101-04:2015 for Atmospheric Corrosion of Weathering Steels (hereafter "ASTM") for specification of CORTEN A and B. these weathering steels. The database contains data on r_{corr}, time of stabilization of the corrosion process, steady-state corrosion rate, SO_2 concentration, exponent b and coefficient of determination describing the fit between relationship (6-1) and obtained measurements. Many details on experiamntal results in the database can be found in a seminal paper by Morcillo et al. [5].

For 66 different sites, it appears that coefficient of variation V_θ is mostly around 10% and thus slightly lower than for carbon steel; exceptionally it can reach up to 20%. This is why V_θ = 10 % is considered as a representative value for weathering steels; further investigation may update this assumption. See Tab. 1 for statistical characteristics of model uncertainty for weathering and carbon steels considered in this study.

Tab. 1 Indicative statistical characteristics of basic variables for determining corrosion loss D for different categories of atmospheric corrosivity and types of weathering steels (reference values for carbon steel in *italics*)

Corrosivity category	Model uncertainty θ		Corrosion rate r_{corr}		Exponent b	
	μ	V	μ (μm/year)	V	μ	V
C2	1	10 % (*12.5 %*)	20	27.5 %	CORTEN A 0.32	25 %
C3			35	15 %	Atmofix 52A 0.39	35 %
C4			65		CORTEN B 0.45	50 %
C5			100		*Carbon steel 0.56*	

μ – mean, V - coefficient of variation

2.2 Corrosion rate in the first year of exposure

The initial corrosion rate r_{corr} can be estimated according to ISO 9223 for various metals and atmospheric corrosivity. Fig. 1 displays available information about r_{corr}:

- ranges for carbon steels according to ISO 9223,
- measurements given in ASTM,
- measurements in the project for weathering steel in C2 and on the bridge in Ostrava, CZ for Atmofix 52A (weathering steel with properties close to CORTEN A).

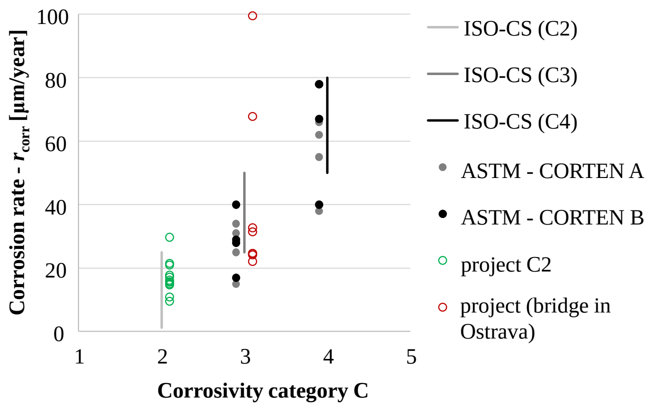


Fig. 1 Corrosion rate r_{corr} in the first year in [µm/year] - ranges for carbon steels according to ISO 9223 measurements given in ASTM and measurements in project for atmospheric corrosivity category C2 and on bridge in Ostrava

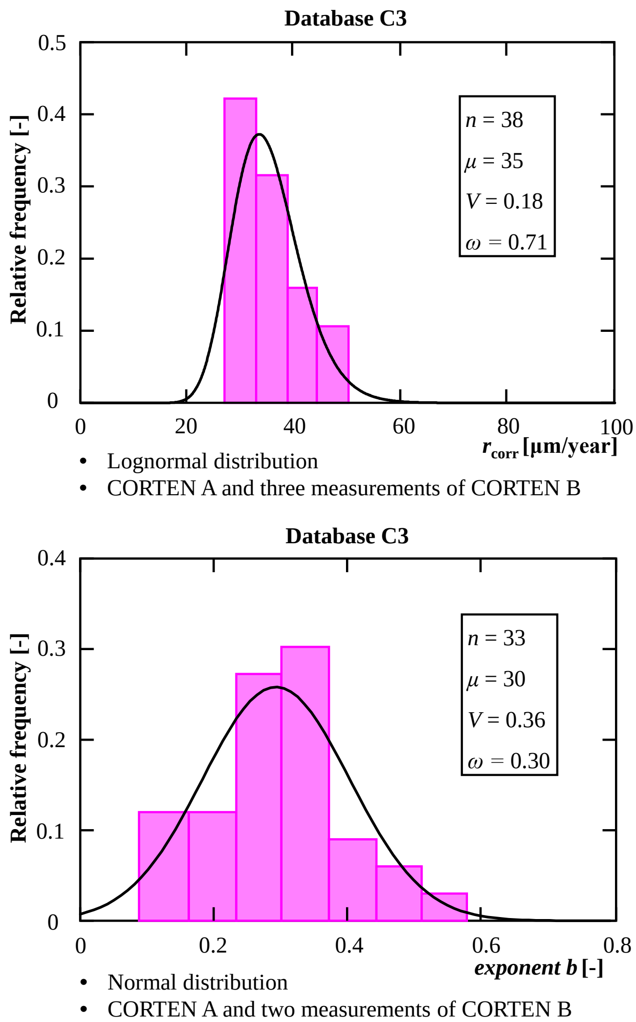


Fig. 2 Histogram and statistical characteristics of r_{corr} and exponent b for C3 from database of previous studies (n – sample size, μ – mean, V – coefficient of variation, ω – skewness)

Fig. 1 shows that the r_{corr}-values given in ISO 9223 for carbon steels correspond well to the corrosion rates of weathering steels. The classes of atmospheric exposure considered in ASTM and in many international studies [5] and the corrosivity categories according to ISO 9223 correspond well – the rural environment in ASTM corresponds to C3 in ISO 9223 and the urban environment to C4. The exposure of the bridge in Ostrava appears to correspond to C3 category. Further, no significant differences in r_{corr}-values are observed between CORTEN A and B and Atmofix 52A in Fig. 1.

Detailed analysis reveals the statistical characteristics of r_{corr} provided in Tab. 1; see also Fig. 2. While mean μ_{rcorr} increases with increasing corrosivity category, coefficient of variation V_{rcorr} is independent of exposure constant except for C2 category. Increased variability of corrosion rates for this class might be attributed to misclassification of some environments in the database. Due to insignificant influence of corrosion losses in C2 on reliability of bridges, this issues is not further analysed.

A detailed analysis of the measurements further indicates that corrosion rates are nearly independent of a type of weathering steel but they do depend on the orientation of the exposed surface. Preliminary measurements for I-profiles indicate approximately doubled corrosion losses mainly for the upper surface of the lower flange and the lower surface of the upper flange in comparison to other parts of cross-section.

2.3 Time development of corrosion

Exponent b in Eq. (1) takes into account the development of corrosion with time of exposure. Its value can be estimated from the chemical composition of the material according to ISO 9224 or can be evaluated from long-term exposures. Fig. 2 displays the histogram and statistical characteristics of the exponent b, based on the database of previous studies for C3 category. The following preliminary conclusions can be drawn:

- The mean value of μ_b is almost independent of a corrosivity category; the values determined from the database with most measurements for CORTEN A well correspond to the values according to ISO 9224 for this steel.
- Coefficient of variation V_b is high (25-50%) and increases with corrosivity category. The estimate of the exponent for a particular bridge in exposures C3 through C5 can be significantly refined by in-situ measurements.

Indicative statistical characteristics of the exponent b for various categories of atmospheric corrosivity are given in Tab. 1. These estimates should only be used for preliminary assessments. In detailed analyses, it may be necessary to update the value of the exponent for the specific conditions of the bridge under investigation. Comparison with measurements in the database of previous studies suggests that the ISO 9224 procedure (considering the content of C, S and alloying elements – Cr, Cu, Ni, P and Mo) provides a good estimate of μ_b.

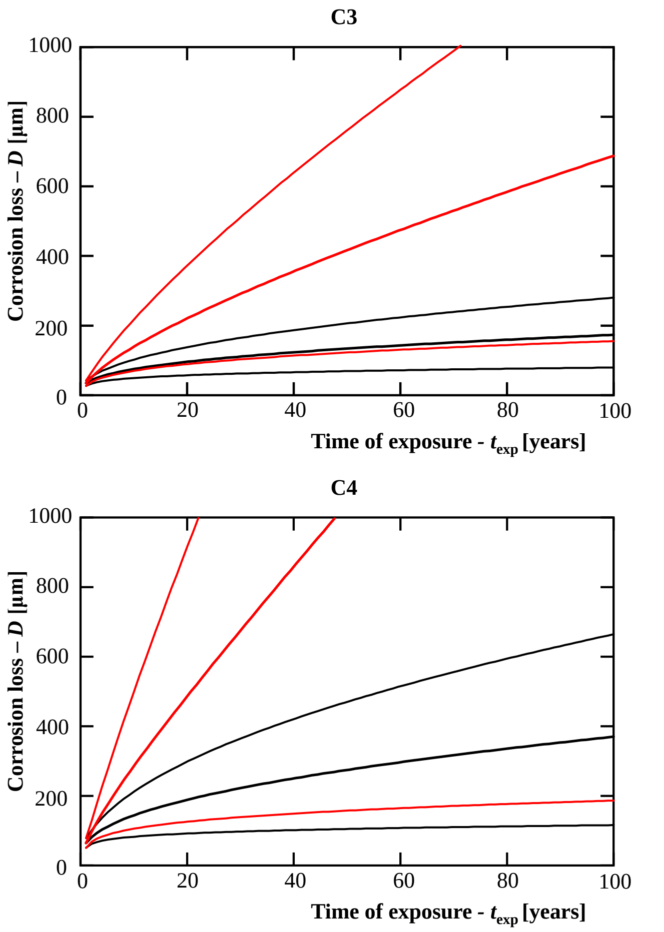


Fig. 3: Uniform corrosion loss D in µm as a function of time of exposure for C3 and C4 atmospheric corrosivity categories (average – bold lines, 75% confidence interval – thin lines; CORTEN A in black, carbon steel in red)

2.4 Probabilistic modelling of corrosion losses

The basic variables in Eq. (1) are considered to be statistically independent. Tab. 1 provides indicative statistical characteristics of the basic variables for determining the total corrosion loss D for different categories of atmospheric corrosivity and different types of weathering steels. A two-parameter lognormal distribution is considered for θ and r_{corr}, and a normal distribution for the exponent b. Fig. 3 portrays the uncertainties in uniform corrosion loss D, the mean and bounds of the 75% confidence interval are shown as a function of time of exposure t_{exp} for atmospheric corrosivity classes C3 to C4, CORTEN A and carbon steel. It follows from the figure that uncertainties in the estimation of corrosion losses increase with increasing corrosivity category and with decreasing resistance of steels to atmospheric corrosion. The probabilistic analysis also reveals that:

1. Carbon steel exhibits higher corrosion losses than all analysed weathering steels; the lowest corrosion losses are then predicted for CORTEN A.
2. The highest corrosion losses of the weathering steels are estimated for CORTEN B, for which the corrosion losses in C4 environment approximately correspond to the losses of carbon steel in C3.
3. No significant difference is observed between the mean corrosion losses for CORTEN A in C2 and C3 (with a steady-state corrosion rate ≤ 2 µm/year), in C4 the corrosion rate increases to ≈ 4 µm/year and in C5 to about 6 µm/year.
4. For carbon steel, coefficient of variation of corrosion loss, V_D, exceeds those for weathering steels. The lowest V_D-value is estimated for CORTEN A.
5. For all types of steels, V_D increases with corrosivity category.
6. For long-term exposures, say $t_{exp} \geq 20$ years, V_D is high. For instance, for CORTEN A it eceeds 40%. It is expected that in-situ measurements will significantly reduce these uncertainties for a particular bridge.

Further, probabilistic sensitivity analysis indicates for longer exposures (t_{exp} > 20 years) that:

- In C3 thgrough C5 exposures, uncertainties in the exponent b are dominating while importance of uncertainties in r_{corr} is medium and uncertainties in θ are rather insignificant.
- Importance of uncertainties b and in r_{corr} is comparable only in C2 exposure.
- the influence of uncertainties in the exponent b continues to increase with decreasing corrosion resistance of the material.

Preliminary results further suggest that corrosion development is often affected by:

- the orientation of the exposed surface (with unfavourable values for east and north orientation),
- local conditions within the cross-section as lower flanges and lower parts of the webs tend to experience higher corrosion rates than upper parts of the webs and upper flanges,
- the use of de-icing agents and the associated increased concentrations of chlorides.

For example, the operational guidance of the Czech Ministry of Transportation TP 197 [6] notes a steady-state corrosion rate (after approximately seven years) of 75-100 µm/year (in the most severe cases then up to 125-150 µm/year) in urban environments and the most exposed locations on bridges. These indicative values significantly exceed the maximum values in the database (with a maximum of 30 µm/year) and indicate a significant influence of local conditions (leakage or chlorides). These effects are the subject of further research.

~~3 Preliminary reliability analysis of corroding cross-sections from weathering steel~~

~~Due to significant uncertainties, the effect of corrosion on the reliability of the structure should be analysed using probabilistic analysis [1], [4], [7], taking into account the randomness of load and resistance effects. As part of the first studies, a simplified reliability analysis based on a semi-probabilistic approach was carried out, see for example EN 1990 and ISO 2394. The design value of resistance R_d takes into account the variability of material strength, geometric variables and the uncertainty of the resistance model [4]:~~

~~$R_d = \mu_R \exp(-\alpha_R \beta V_R)]$ (2)~~

~~where μ_R and V_R denote the mean and coefficient of vari-~~

ation of the resistance; α_R = 0.8 is the sensitivity coefficient for resistance and β = 3.8 is the reference value of the reliability index according to EN 1990 and ISO 13822 for a reference period of 50 years, limit states of bearing capacity and medium consequences of failure. According to ČSN 73 0038 for the assessment of existing structures, the value of V_R for steel structures not affected by corrosion ranges from 3.3-8.7%, 5% is considered as a representative value in this preliminary study.

It is further assumed that the design resistance of the uncorroded section is equal to the design effect of the load, E_d, which does not change with time. Therefore, for members affected by corrosion, Eq. (2) can be expanded as:

$R_d = \mu_R \exp(-\alpha_R \beta V_R)] = E_d = R_d'(t_{exp}) = \mu_R \delta(t_{exp}) \exp(-\alpha_R \beta' V_R')]$ (3)

where $\delta(t_{exp})$ is the degradation function and the symbol " ' " indicates the updated value for the corroded structure.

As an example, an I-section beam stressed in tension, bending or shear is considered. The degradation function needs to be specified separately for each considered failure mode. The following relationships give examples of uniform corrosion acting on all surfaces (without considering the mutual interactions of these failure modes):

tension: $\delta(t_{exp}) = \frac{A_{deg}(t_{exp})}{A}$

bend: $\delta(t_{exp}) = \frac{W_{deg}(t_{exp})}{W}$ (4)

shear: $\delta(t_{exp}) = \frac{A_{vz,deg}(t_{exp})}{A_{vz}}$

where $A_{deg}(t_{exp})$ denotes the area of the cross-section reduced by corrosion for time of exposure t_{exp}, A is the area of the uncorroded cross-section, $W_{deg}(t_{exp})$ is the sectional modulus reduced by corrosion, W the original sectional modulus, $A_{vz,deg}(t_{exp})$ denotes the effective area that transmits shear in the direction of the z-axis reduced due to corrosion and A_{vz} is the original area.

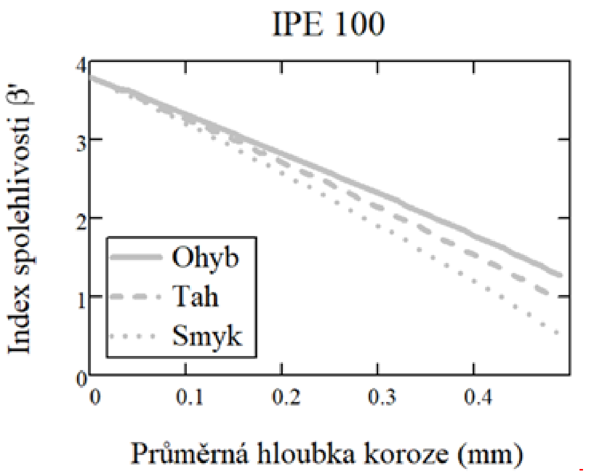
The effect of pitting corrosion is ignored in the preliminary analysis. For a known degradation function δ, the reliability index for a structure affected by β' corrosion can be obtained from Eq. (3) as:

$\beta' = [\ln \delta(t_{exp}) + \alpha_R \beta V_R] / (\alpha_R V_R')$ (5)

Coefficient of variation of the resistance V_R of a corroded structure should also consider the uncertainty of the corrosion loss.

Considering the results of corrosion loss measurement, it is expected that the uncertainties of corrosion loss D may be insignificant for large cross-sections members (for example, main bridge girders with large web thickness and flanges) and, on the contrary, significant for small cross-sections members (side load-bearing members, truss members bridges). In the following example, I-type of cross-sections with a height of h = 100 to 870 mm are analysed (IPE 100, IPE 500 and a welded I-profile with a height of 870 mm – railway bridge stringer, hereinafter "I-870"). V_R' ≈ 10% considers uncertainties in the total corrosion loss D.

Fig. 4 displays the reliability index β' depending on the average uniform corrosion loss D - comparison for a small cross-section (IPE 100 - secondary load-bearing members, members in lattice structures) and a high cross-section (I-870 - main load-bearing members). D in the interval 0-0.5 mm is considered. It can be seen from Fig. 4 that the reliability of a small cross-section is much more significantly affected by corrosion, for all observed failure modes- the reliability index can drop to very low values, β' ≈ 1. Even with a high cross-section, however, the reduction of reliability can be significant. The effect of corrosion is mainly dependent on the thickness of the flanges for bending ($t_{f,IPE}$ 100 = 5.7 mm and $t_{f,I}$ 870 = 25 mm) and the web thickness for shear ($t_{w,IPE}$ 100 = 4.1 mm and $t_{w,I}$ 870 = 12 mm). The most unfavourable decrease occurs in shear resistance.



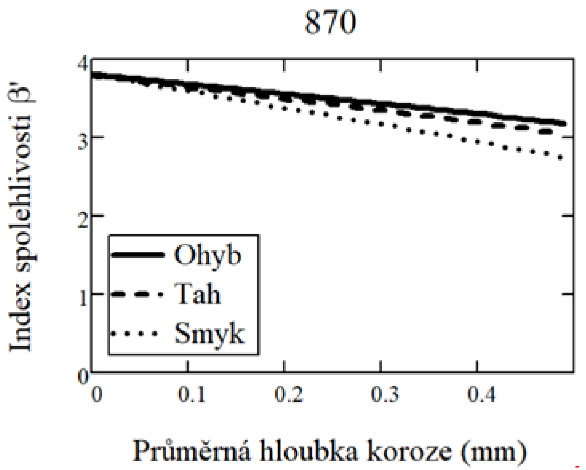
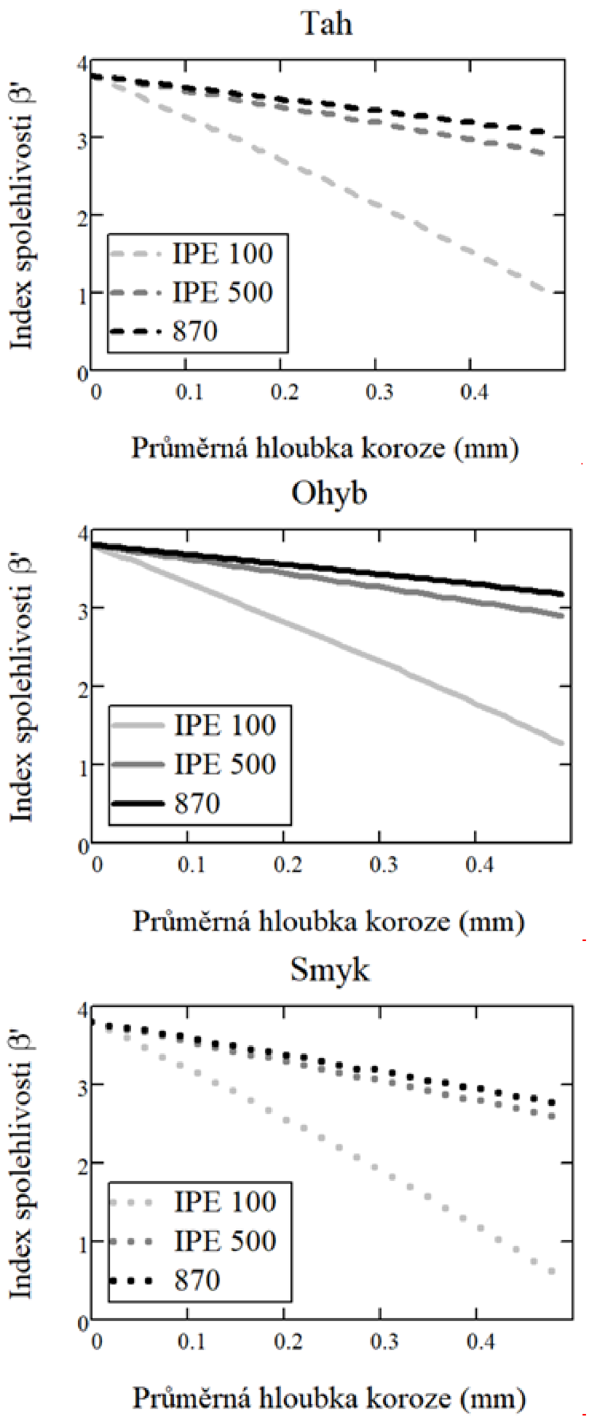


Fig. 4: Reliability index β' depending on the average uniform corrosion loss D (mm) for tensile, bending and shear resistance of the cross-section.

Fig. 5 shows the reliability index β' depending on the average uniform corrosion loss D - a comparison for tensile, bending and shear resistance for three selected cross-sections. The observations from Fig. 4 are confirmed – a very adverse effect on IPE 100 is evident, and the difference between IPE 500 and I-870 is small.



~~**Fig. 5** Reliability index β' depending on the average uniform corrosion loss D (mm) for the analysed failure mode – comparison for IPE 100, IPE 500 and a welded I-section with a height of 870 mm~~

4 Conclusions

The study demonstrates that generic corrosion rate models provide a wide range of values, and in-situ measurements are expected to significantly improve predictions of corrosion losses in weathering steels in most cases. Probabilistic analysis of cross-sections subjected to bending (mid-span), shear (near supports) or tension (in truss bridges) reveals that reliability of weathering steel bridges is insignificantly affected by corrosion when the protective layer is well-developed.

However, in critical details, reliability can be significantly reduced. Probabilistic analyses reveal that small cross-sections are sensitivive to corrosion losses and their reliability may drop to low levels. However, even for large profiles of main bridge girders, the drop in reliability level can be significant.

The effect of corrosion is primarily dependent on thickness of flanges (for bending) and web thickness (shear). The most unfavourable decrease of reliability seems to be experienced for shear resistance, then for tension and least for bending.

As preliminary results indicate significant variability of corrosion losses in various locations of sections, the effect of non-uniform corrosion attack on reliability will be analysed within further research. Other topics of subsequent investigations include analysis of:

– uncertainty in estimates of short- and long-term corrosion losses by comparison with in-situ measurements,
– the combined effect of pitting corrosion and fatigue on reliability of bridges (welds, joints, etc.),
– the effect of traffic intensity (actual loading and influence on chloride deposition),
– the effect of deceleration of corrosion process due to e.g. changes in environmental exposure.

References check format

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