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Durability of galvanized steel reinforcements as a function of their shape

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ABSTRACT : It is known that the tensile strength of galvanized steel member decreases faster than its average weight, or thickness, as a result of pitting and stress concentrations. The ratio between loss of strength and loss of thickness is not independent from the shape and cross section of the bar : a local pit has a more detrimental effect on a narrow strip, or on a round bar of small perimeter than on large sections. The residual long term rupture strengths of reinforcements of various shapes and sizes are assessed together with the values of the sacrificial thickness which should logically be adopted for bars of such various shapes and sizes.

1. STATEMENT OF THE PROBLEM

The corrosion of galvanized steel rods buried in soils is not quite homogeneous, even if galvanized steel behaves much better from this point of view than black steel. Although it is adequate to characterize its corrosion by an average uniform loss of weight or thickness, the surface of a corroded piece of galvanized steel looks more or less like a lunar landscape, with shallow craters here and there (fig.1). Its surface is affected by pitting.

It is also known that the tensile strength of a steel bar decreases faster than its average weight or thickness, as corrosion progresses : this is a consequence of the notch effects and stress concentrations resulting from that pitting, in the most critical sections. Terre Armée Internationale found experimentally that the ratio between the relative loss of strength and average loss of thickness is of the order of 1.7 to 2.0 for thin galvanized steel reinforcing strips a few centimetres wide (Darbin, Jailloux, Montuelle, 1988).

It can be easily understood that this ratio is not independent from the shape and cross section of the reinforcing member. The image of figure 2 shows two strips of different widths, A and B, affected by the same corrosion pattern. It is clear that the deep pit found in cross section II is more detrimental to the resistance of the narrower strip, at that particular section, even though the average losses of superficial thickness along the samples are identical.

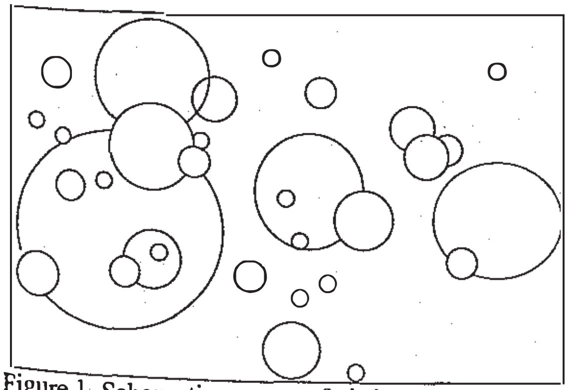

Figure 1. Schematic pattern of pitting

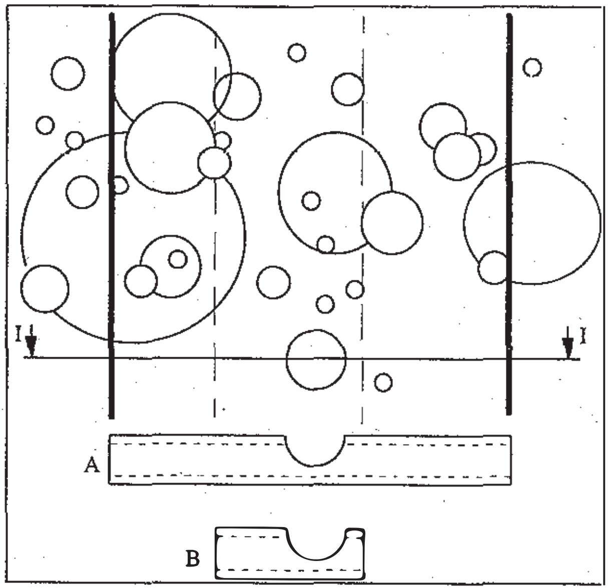

Figure 2. Corrosion of one wide, one narrow strips

It is also clear that the same findings apply to different shapes, when imagining that band A could be the developed surface of a flat strip, say size 40x5 with a perimeter of 90mm, while band B could be the developed surface of a round bar Ø10mm (B') with a perimeter of about 30mm, i.e. 3 times smaller (fig.3).

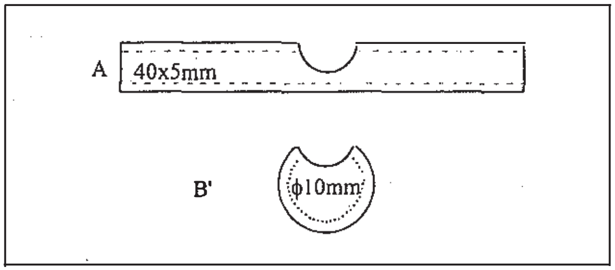

Figure 3. Corrosion of one flat strip, one round bar

A gross way of assessing the influence of various shapes and sizes on the long-term tensile capacities of soil reinforcements is outlined in this paper.

It must be remembered that the computation of the tensile capacity is usually based on a design sacrificial thickness, which is meant to be equivalent to the anticipated loss of strength. The above remarks mean that these sacrificed thicknesses should depend on the size and shape of the reinforcements. However, up to now, all official Codes and Specifications presume that the sacrificed thicknesses which were initially and specifically determined for flat thin galvanized steel strips, also apply to all other types of galvanized steel reinforcements, whatever their size and shape. This might be far from true, as will be shown herebelow.

2. NOTATIONS AND CORRELATIONS

Before entering the discussion and working out a few equations, we need to define some notations and establish a few basic correlations. In general the notations are consistent with the ones used by Anderson *et al.* (1996).

2.1 *Geometry*

The notations below are illustrated on figure 4 for flat strips, on figure 5 for round bars. For the purpose of this first basic study, things are intentionally somewhat idealized, we assume that :

i - there is only one deep local pit in the critical cross section

ii - outside the pit, corrosion is uniform and equal to the average loss of thickness

iii - the pit is of hemispherical shape (or semicircular in cross section).

S_0 : original cross section of reinforcement
ΔS : average loss of cross section along the sample
S : remaining (long-term) average cross section $S = S_0 - \Delta S$
Δa : average loss of steel thickness along the sample
d_p : depth of deepest pit
S_p : cross section of deepest pit

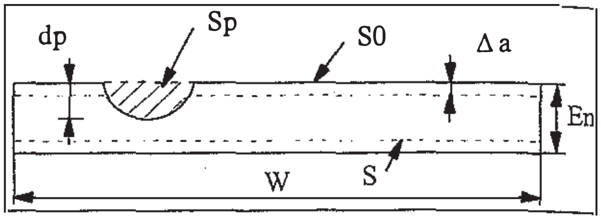

Figure 4. Notations for a flat strip

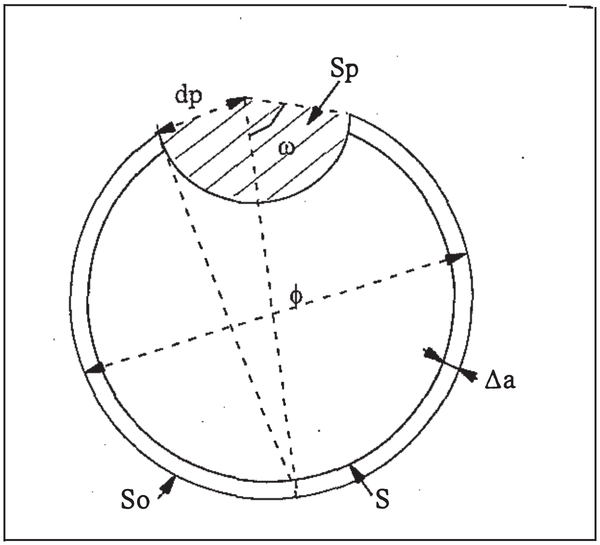

Figure 5. Notations for a round bar

2.2 *ΔS and S_p for strips and round bars*

For a strip :

$$\Delta S = 2w\Delta a \qquad S_p = \pi \frac{d_p^2}{2}$$

For a round bar :

$$\Delta S = \pi(\Phi - \Delta a)\Delta a \qquad S_p \approx \omega d_p^2$$

with :

$$\omega = \mathrm{Cos}^{-1} \frac{d_p}{\Phi}$$

2.3 *Stresses and tensile strength*

σ_u : initial (short term) ultimate tensile rupture stress
σ_a : apparent ultimate tensile rupture stress of corroded sample

$$\Delta\sigma = \sigma_u - \sigma_a$$

T_u : initial (short term) rupture strength of reinforcement $T_u = \sigma_u * S_0$
ΔT : loss of strength
T_{ul} : anticipated remaining (long-term) rupture strength $T_{ul} = T_u - \Delta T = \sigma_a S$
K : factor (> 1.0) expressing corrosion heterogeneity and effects of stress concentration

2.4 *Correlation between ΔS, Δσ and K*

As stated above, the relative loss of strength is proportional to the relative loss of weight, or cross section, along the sample :

$$\frac{\Delta T}{T_u} = K\frac{\Delta S}{S_0} \qquad ①$$

Initially : $T_u = \sigma_u S_0$

After corrosion : $T_{ul} = T_u - \Delta T = \sigma_a S$

From ① and $\frac{T_{ul}}{T_u} = \frac{\sigma_a}{\sigma_u}\frac{S}{S_0}$

we get : $$1 - K\frac{\Delta S}{S_0} = \left(1 - \frac{\Delta\sigma}{\sigma_u}\right)\left(1 \quad \frac{\Delta S}{S_0}\right) \qquad ②$$

2.5 *Correlation between ΔS, S$_p$ and K*

As a general rule, the monitoring of notch effects denotes that the relative decrease in ultimate stress is proportional to the ratio between the section of the notch in the critical section and the residual cross section :

$$\frac{\Delta\sigma}{\sigma_u} = \lambda\frac{S_p}{S} \qquad ③$$

From ② and ③ : $\lambda S_p = (K - 1)\Delta S$ ④

or : $$\boxed{K = 1 + \frac{\lambda S_p}{\Delta S}} \qquad ⑤$$

4. EXPERIMENTAL RESULTS

We refer on one hand to results of experimentations carried out by Romanoff (Romanoff, 1957), which allow to estimate d_p, hence S_p, on the other hand to the monitoring of the K coefficient by Terre Armée Internationale for flat strips. This allows to get a correlation between λ and Δa, which in turn allows to calculate K for other shapes.

4.1 *Romanoff : depth of deepest pits*

As a part of his extensive study of underground corrosion conducted for the US National Bureau of Standards from 1910 to 1957, Romanoff investigated the corrosion of various black or galvanized steel pieces, including bars and pipes of small diameter. For galvanized steel one finding was that the depth of the deepest pits is about 7 times the average loss of thickness, for the range of loss which is considered here :

$$d_p \approx 7\Delta a \qquad ⑥$$

4.2 *Terre Armée Internationale : K ratio*

From their systematic and periodical monitoring of coupons of galvanized steel strips retrieved from aggressive backfills, Terre Armée Internationale found that the K factor is around 1.7 for 60x3 strips, again for the range of average loss of thickness which is considered here.

4.3 *Correlation between coefficient λ and Δa*

Using equation ④, with $\Delta S = 2w\Delta a = 2*60*\Delta a$ and S_p as shown in §2.2, it comes :

$$\lambda = 2\frac{(1.7 - 1)*2*60\Delta a}{\pi(7\Delta a)^2}$$

or $$\boxed{\lambda = \frac{1.1}{\Delta a}} \qquad ⑦$$

5. VALUES OF K FOR VARIOUS SHAPES

Using equations ⑤ and ⑦ with the appropriate ΔS and S_p defined in §2.2, specific K factors can now be calculated for different shapes of reinforcements. These values correspond to the range of average loss of steel thickness Δa considered here (for a 70 years service life, in environments complying with standard specifications) i.e. about 0.2 to 0.4mm.

After a first rough calculation based on the above formulae, we will adjust the K values by taking into account a more precise estimate of the depth of the deepest pits.

5.1 *First estimate*

With $d_p = 7\Delta a$ (see ⑤) we get the following tables :

Δa (mm)	40x5 strip	50x4 strip	60x3 strip
0.2 to 0.4	2.06	1.85	1.70

Table 1. Rough estimate of K for flat strips

Δa (mm)	Ø6mm bar	Ø8mm bar	Ø10mm bar
0.2	4.95	4.07	3.50
0.3	4.65	3.91	3.40
0.4	4.33	3.74	3.30

Table 2. Rough estimate of K for round bars

5.2 *Adjustment*

In fact, Romanoff's results also show that the depth of the deepest pits decreases a little when the area, or perimeter L, exposed to corrosion is smaller. The following relationship can be drawn from Romanoff's data :

$$d_p = (345L)^{0.183}\Delta a$$

with L in millimetres (the equation gives $d_p = 7\Delta a$ when $L = 120$mm).

This leads to less unfavourable values for the round bars, as shown in the tables below :

Δa (mm)	40x5 strip	50x4 strip	60x3 strip
0.2 to 0.4	1.91	1.78	1.70

Table 3. Adjusted estimate of K for flat strips

Δa (mm)	Ø6mm bar	Ø8mm bar	Ø10mm bar
0.2	3.11	2.78	2.56
0.3	3.01	2.72	2.52
0.4	2.92	2.66	2.48

Table 4. Adjusted estimate of K for round bars

The tables show that the K factor which links the relative loss of strength to the relative loss of weight is about 1.5 larger for bars Ø8mm than for strips 50x4.

6 - ASSESSMENT OF ALLOWABLE STRENGTH

6.1 *Reminder*

Following Romanoff's and TAI approaches, the anticipated average loss of peripherical thickness is equal to :

$$\Delta e = At^n$$

and the loss of steel thickness to :

$$\Delta a = At^n - Z$$

where Z is the thickness of the zinc coating.

With a decrease in section ΔS calculated from Δa (see §2.2), the anticipated long-term rupture strength T_{u1} is equal to :

$$T_{u1} = T_u\left(1 - K\frac{\Delta S}{S_0}\right)$$

6.2 *Material factor of safety*

Although this relies on thorough and conservative studies, it remains advisable to apply a "material factor of safety" FSe, covering specifically the uncertainties in the knowledge and experience about long-term corrosion or the adequacy of extrapolations, as explained by Anderson et al. (1996).

The "extrapolation factor of safety" is best applied to the loss of thickness itself (where the uncertainties actually lie), and this leads to the following conservative average loss of steel thickness Δa_d, used for design :

$$\Delta a_d = FS_e At^n - Z$$

then to a design loss of cross section ΔS_d, based on the equations of § 2.2.

As a result, the *allowable* long-term tensile *strength* T_{u2} of the reinforcement is expressed by the equation :

$$T_{u2} = T_u\left(1 - K\frac{\Delta S_d}{S_0}\right) \qquad ⑧$$

6.3 *Application*

Let us compare the T_{u2}/T_u ratios resulting from the above analysis for various types of reinforcements, all over the required service life. We consider the case of dry-land structures built with backfills having a resistivity higher than 1000Ωcm, as usually specified in Europe. The reinforcements are galvanized with a 70μm zinc coating.

In this case a conservative envelope of all experimental results is defined by the following parameters :

$$A = 25\mu m \qquad n = 0.65$$

Using the K values of §5.2 above and adopting for FSe the reasonable enough value FSe = 1.5 we get the evolutions of T_{u2}/T_u depicted on figure 6.

The graph shows that the allowable long-term tensile *strength* of bars Ø10mm and especially Ø8mm decreases more quickly than that one of 40x5 strips.

The diagram comprises a horizontal line at T_{u2}/T_u = 30% below which equation ⑧ should not be considered as reliable. This criteria means that, in environments with electro-chemical characteristics close to the limits of standard specifications, Ø8mm bars should not be utilised for a 70 years service life.

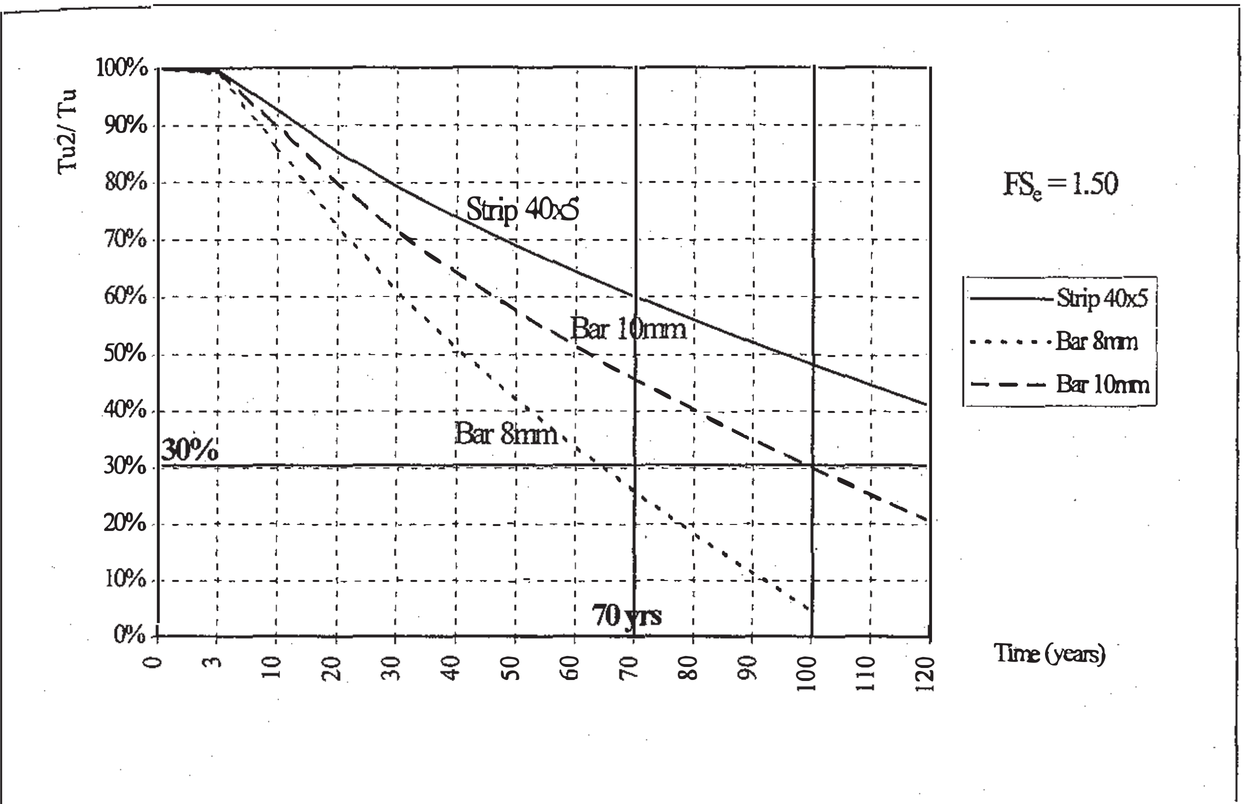

Figure 6. Evolution of Tal/Tu through time

Their behaviour might indeed become unpredictable before the end of the service life. Similarly, bars Ø10mm are adequate for a 70 years service life, but they should not be used for 100 years, as long as a "material extrapolation factor of safety" FSe of at least 1.50 is deemed advisable. It should be noted that today, as shown by Anderson *et al.* (1996), all major existing Codes still implicitely include (and hence require) an extrapolation factor as high as about 1.8 for galvanized steel reinforcements.

The above comments pertain to projects where backfill materials with minimum resistivities of 1000Ωcm are considered. In countries where the specified minimum resitivity is for example 3000Ωcm, the potential loss of strength of Ø8mm and Ø10mm bars is less critical (although still faster than that one of 4 or 5mm thick flat strips). The same kind of analysis can be worked out for such a case with A = 20μm and n = 0.65.

7 SACRIFICIAL THICKNESSES

The above analysis allows to determine what should be the allowable tensile load (Tallow) of a given reinforcement. It also gives a way of estimating which pseudo sacrificial thickness should be taken into account in a calculation carried out according to one of the major national Codes.

7.1 *Derivation of the pseudo sacrificial thickness*

This sacrificial thickness for design can be drawn from the comparison of the two equations of Tallow, the one derived from Tu2 in §6.2 above and the one found in the considered Code, for example the French AFNOR NF P 94-220 (similar correlations could be established in the context of the British BS 8006 Code of practice or the US AASHTO 1994 Interim Specifications).

From § 6.2, with the notations used by Anderson *et al.*

$$T_{allow} = \frac{T_{u2}}{FS_o} = \frac{T_u}{FS_o}\left(1 - K\frac{\Delta S_d}{S_0}\right)$$

$$T_{allow} = \frac{\sigma_u}{FS_o}\left(S_0 - K\Delta S_d\right)$$

From AFNOR :

$$T_{allow} = \frac{S_{(Ec)} * \sigma_u}{1.5FS_2}$$

As a result :

$1.5(S_0 - K\Delta S_d) = S_{(Ec)}$ ⑨

In this equation ΔSd is calculated on the basis of Δad, according to §2.2. In the current example of a backfill with a minimum resistivity of 1000Ωcm, for a 70 years service life, assuming SFe = 1.5 :

$$\Delta a_d = 1.5 * 25 * 70^{0.65} - 70 = 523\mu = 0.52mm$$

7.2 *Example of 40x5 strips*

For the 40x5mm strips we have :

$$S_0 = wE_n$$
$$\Delta S_d = 2w\Delta a_d$$
$$S_{(Ec)} = wE_c = w(E_n - E_s)$$
$$K = 1.91$$

The equation ⑨ becomes :

$$1.5(40*5 - 1.91*2*0.52*40) = 40(5 - E_s)$$

hence Es = 0.48mm

A design (or pseudo) sacrificial thickness of 0.5mm would be therefore adequate in the context of the AFNOR NF P 94 220 design method, instead of the 1.0mm which is presently specified.

7.3 *Example of bars Ø10mm*

For a round bar, Ø10mm, we have :

$$S_0 = \frac{\pi}{4}\Phi^2$$
$$\Delta S_d = \pi(\Phi - \Delta a_d)\Delta a_d$$
$$S_{(Ec)} = \frac{\pi}{4}(\Phi - E_s)^2$$
$$K = 3.2$$

The equation ⑨ becomes :

$$1.5\left[\frac{\pi}{4}10^2 - 3.2\pi(10 - 0.52)0.52\right] = \frac{\pi}{4}(10 - E_s)^2$$

hence Es = 2.56mm

A design sacrificial thickness of 2.5mm should be therefore taken into account in the context of AFNOR NF P 94 220, instead of the 1.0mm which is at first considered, as for flat strips.

8 CONCLUSIONS

In the paper it has been shown that the superficial pitting of galvanized steel is more detrimental to the long term strength of soil reinforcements made of round bars of small diameter than it is for flat thin strips. A method has been outlined which allows to determine this long term strength, depending on the size and shape of the galvanized steel members. It is clear that, for round bars, this numerical approach will have to be refined and adjusted after more experimental data.

The paper also demonstrated that the standard sacrificial thicknesses specified by the existing Codes and Specifications are presumably too conservative for flat strips but less safe, if not unsafe, for reinforcements composed of round bars of small diameter.

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