Metal Loss for Metallic Reinforcements and Implications for LRFD Design of MSE Walls

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ABSTRACT

Previous calibrations of resistance factors for load and resistance factored design (LRFD) of mechanically stabilized earth (MSE) retaining walls with galvanized metallic reinforcements have not considered cross-sectional area as a variable in the reliability analysis. The remaining cross section at the end of a 75- or 100-year design life is considered, however the metal loss from corrosion is estimated using recommended rates of metal loss that render conservative estimates of remaining cross section. This paper describes reliability-based calibration of resistance factors for the rupture limit state considering the variability of observed corrosion rates. Results are compared with resistance factors cited in the current American Association of State Highway and Transportation Officials (AASHTO) design specifications. The comparison identifies conditions for which the current AASHTO resistance factors achieve the targeted probability of failure inherent to the LRFD strategy.

INTRODUCTION

Most MSE walls owned by state departments of transportation are designed using some form of the AASHTO LRFD Specifications (AASHTO, 2009) as a guide. The approach to metal loss has been to calculate the expected loss of both zinc and steel, then add sufficient sacrificial steel to the reinforcement cross-section to satisfy resistance requirements for the intended design-life. Table 1 summarizes the AASHTO-recommended metal loss model for design of MSE structures and the corresponding fill material requirements.

Table 1. AASHTO Metal Loss Model and Fill Material Requirements

Metal Loss Model		**Fill Requirements**	
Component Type (age)	Loss (μm/yr)	pH	5 to 10
		Resistivity	≥ 3000 Ω-cm
Zinc (< 2 yrs), r_{z1}	15	Chlorides	< 100 ppm
Zinc (> 2 yrs), r_{z2}	4	Sulfates	< 200 ppm
Steel (after zinc), r_s	12	Organic Content	< 1%

Based on the metal loss rates (zinc and steel) in Table 1 the steel loss per side (X) in μm/yr for a given service life, t_f, and initial thickness of zinc coating, z_i, is computed as:

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$$X(\mu m) = 12\frac{\mu m}{yr} \times \left(t_f - 2yr - \frac{(z_i - 30\mu m)}{4\frac{\mu m}{yr}} \right) yr \qquad (1)$$

LRFD is a reliability based design method whereby loads and resistances are factored as:

$$\sum \gamma_i Q_i \leq \phi R \qquad (2)$$

where, Q_i are loads from sources that may include earth loads, surcharge loads, impact loads or live loads, γ_i is the load factor for the ith load source and is greater than 1, R is the resistance, and ϕ is the resistance factor and is usually less than 1.

Load and resistance factors are selected such that the probability of the load exceeding the resistance is relatively low. The AASHTO LRFD Specifications (2009) include resistance factors for the rupture limit state that were calibrated matching the safety factors that prevailed in the former allowable stress based design (ASD). The ASD employed safety factors of 1.8 (i.e., 1/0.55) or 2.1 (i.e. 1/0.48) relative to rupture of strip type reinforcements or grid type reinforcements respectively. The higher safety factor for grid reinforcing members connected to a rigid facing element (e.g., a concrete panel or block) accounts for the greater potential for local overstress due to nonuniform connection loads in grids (three or more longitudinal rods or wires) as compared to steel strips or bars (single element).

D'Appolonia (2007) described a reliability-based calibration to assess resistance factors for the rupture limit state, but did not considered metal loss from corrosion as a variable. This paper extends that study to consider variability of metal loss. Calibration of the resistance factors use load factors from the AASHTO LRFD Specifications (AASHTO, 2009) and the calibration methodology recommended by Allen et al. (2005). The resistance factor is calibrated with respect to a target reliability index (i.e. probability of failure) (β_T) that accounts for the redundancy of the system and load redistribution inherent to the rupture limit state. The bias of tensile strength and the corresponding statistics and distributions are used to calibrate resistance factors for LRFD. Monte Carlo simulations are performed considering each variable used to compute load and resistance.

PERFORMANCE DATABASE AND DATA ANALYSIS

The calibration relies on an extensive database of corrosion rate measurements from in service reinforcements. Performance data have been collected and archived from sites located in the Northeast, mid-Atlantic, Southeast, Southwest and Western United States, and includes data from 170 sites located throughout the United States and Europe. Corrosion rate measurements include direct physical observations of metal loss (e.g., weight loss measurements) and electrochemical measurements that render observations of corrosion rate at an instant in time (e.g., linear polarization resistance (LPR) measurements). The ages of reinforcements considered in the database range from less than two-years old to approximately 40-years old.

Data are grouped to consider the effects on observed corrosion rates of time (age since burial), fill character, climate and reinforcement type. Figure 1 depicts observations of corrosion and metal loss with respect to age of the reinforcements for fill conditions meeting the AASHTO criteria (Table 1). Observations included in Figure 1 are via electrochemical techniques (e.g., LPR) wherein corrosion rate is measured at an instant in time. For the purpose of MSE reinforcement design, the remaining metal loss at the end of the service life must be considered to estimate the metal resistance at that time. Since metal loss measurements at the end of service are not available (i.e., none of the monitored MSE walls depicted in Figure 1 have reached the end of their service life), there is a need to extrapolate existing observations of performance to the end of service condition. Measured corrosion rates are adjusted for the effects of time and metal loss considered as the product of corrosion rate over the applicable time interval.

Approximately 404 data points are included in Figure 1; 114 points from galvanized coupons and 290 points from galvanized reinforcements. The effect of time on corrosion rates is apparent in the data. In general, higher corrosion rates are observed during the first two years of service. On average, lower corrosion rates are realized from samples with ages between two and 16 years compared to those that are younger than two years, or older than 16. This is due to the attenuation of corrosion rate with respect to time as reported by Romanoff (1957), and the possibility that higher corrosion rates prevail after zinc is consumed from galvanized samples. The AASHTO line is a good upper limit for metal loss throughout the experience period and most of the data points lie well below the envelope described by the AASHTO model. Many of these data represent metal loss that is less than half of what is computed with the AASHTO model. This is consistent with the analysis of metal loss and corrosion rate measurements reported by Gladstone et al. (2006).

Observed corrosion rates are most affected by the quality of the reinforced fill. On average, observations from sites with fill resistivities less than 3,000 Ω-cm are approximately an order of magnitude higher than observations from sites with fill resistivity greater than 3000 Ω-cm. Observations from sites with fill resistivities between 3,000 and 10,000 Ω-cm have average corrosion rates slightly higher than those associated with resistivity greater than 10,000 Ω-cm.

There does not appear to be a significant effect of climate on measured corrosion rates. Therefore measurements from different regions are combined to evaluate the effects of fill character, time, and reinforcement type on corrosion rates and observations of metal loss.

RELIABILITY ANALYSIS

The reliability-based calibration of resistance factors for LRFD follows the procedure described by Allen et al. (2005). Figure 2 illustrates how the steel incorporated into the design of a reinforcement cross section can be construed to include three components including (1) nominal structural steel needed to resist the applied load without yielding, (2) steel consumed by corrosion, and (3) residual steel that was intended to serve as sacrificial steel, but not actually consumed by corrosion. Residual steel contributes to the reinforcement resistance, and consequently the bias inherent in the design. Differences between the metal

loss model used in design and the prevailing corrosion rates determine the amount of residual steel at the end of the service life. Prevailing corrosion rates depend on the electrochemical properties of the fill, making fill quality an important factor to include in the calibration.

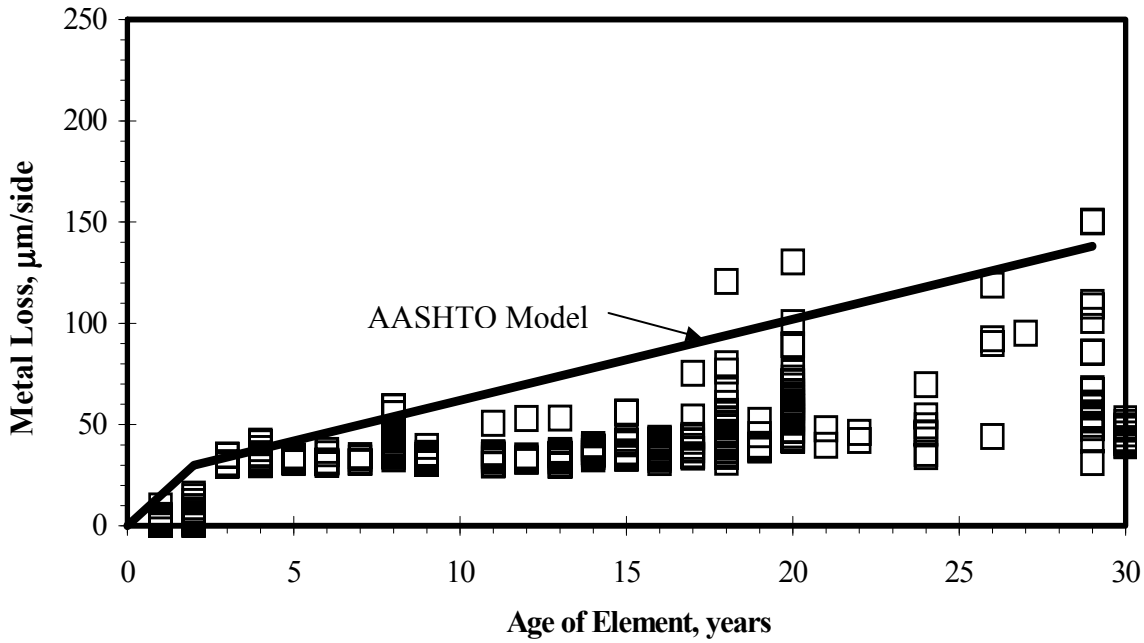

Figure 1. Metal Loss vs. Time for Galvanized Elements and Reinforced Fill Satisfying AASHTO Criteria Described in Table 1.

Reinforcement size is also important because the significance of residual steel becomes less as the cross sectional area of the reinforcement increases. In consideration of these factors the reliability-based calibration is performed in terms of the following design parameters:

- Service lives of 75 and 100 years.
- Different reinforcement thickness for strips of 3 mm, 4 mm, 5 mm and 6 mm, or wire diameters for grids W7, W9, W11, W14.
- Different reinforced fill conditions (all meet AASHTO criterion).

Resistance Bias

Corrosion rate measurements are extrapolated to compute remaining cross section at the end of a given design life considering the statistics and distribution of the corrosion rate measurements. The variation of remaining cross section and yield stress are then used to assess the statistics and distribution of remaining tensile strength. These results are compared to the nominal remaining tensile strength computed using Eq. (1).

The rupture resistance of the reinforcements is computed as:

$$R = \frac{R_c F_y A_c}{b} \tag{3}$$

where, R is resistance per unit width of wall, R_c is the coverage ratio, b is the width of the reinforcements, F_y is the yield strength of the steel, and A_c is the cross sectional area of the reinforcement at the end of the service life.

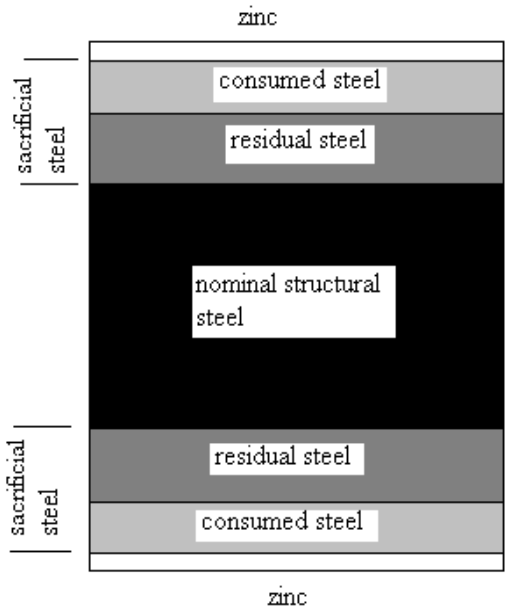

Figure 2. Idealized Reinforcement Cross Section

For strip type reinforcements:

$$A_c = bE_c \tag{4}$$

and for grid type reinforcements:

$$A_c = n \times \pi \times \frac{D^{*2}}{4} \tag{5}$$

where, E_c is the strip thickness corrected for corrosion loss; $E_c = b \times (S - \Delta S)$ for $\Delta S < S$ and 0 for $\Delta S \geq S$, S is the initial thickness, ΔS is the corrosion loss, n is the number of longitudinal rods/wires, D* is the diameter of the rod or wire corrected for corrosion loss and is equal to D_i-ΔS for $\Delta S < D_i$ and 0 for $\Delta S \geq D_i$, where D_i is the initial diameter.

For galvanized reinforcements:

$$\Delta S = 2 \times r_s \times (t_f - t_i) \qquad \text{For } t_i < t_f$$

$$\Delta S = 0 \qquad \text{For } t_i \geq t_f \tag{6a}$$

$$t_i = 2yrs + \frac{(z_i - 2 \times r_{z1})}{r_{z2}} \tag{6b}$$

where, r_s is the corrosion rate of steel after zinc has been consumed, t_f is the intended service life, t_i is the time to initiation of steel loss, z_i is the zinc initial thickness per side, r_{z1} is the initial corrosion rate for zinc, and r_{z2} is the corrosion rate for zinc after the first two years.

Variables for the resistance calculation include F_y, A_c, r_s, r_{z1}, r_{z2}, and z_i. The width of the reinforcements and the coverage ratio are taken as constants. Using the statistics and

observed distribution for measurements of corrosion rate, the bias of the remaining strength is computed and used as input for the reliability-based calibration of resistance factor. The bias is computed as:

$$\lambda_R = \frac{F_y^* A_c^*}{F_y A_c} \tag{7}$$

The denominator includes nominal values used in design; A_c is based on the metal loss model recommended by AASHTO for design of metallic MSE reinforcements, and F_y is the nominal yield strength. The statistics of the observed corrosion rates from the database are used to describe the variable A_c^* and the statistics for F_y^* are taken from Bounopane et al. (2003). Bounopane et al. consider yield strengths to be normally distributed with a mean 1.05 times the nominal and COV = 0.1.

Calibration of Resistance Factor for LRFD

Monte Carlo simulations are employed to compute the relationship between β and ϕ. The Monte Carlo simulation method is used because the approach is more adaptable and rigorous compared to other techniques, and it has become the preferred approach for calibrating load and resistance factors for the LRFD specifications (Allen et al, 2005; D'Appolonia, 2007). The simulations are performed in terms of a given load factor, γ, load bias, λ_Q, and resistance bias, λ_R. The Monte Carlo technique utilizes a random number generator to extrapolate the limit state function, g = R-Q, for calibration of rupture resistance. Random values of g are generated using the mean, standard deviation, and the distribution (normal, lognormal, or Weibull) of the load and the resistance. The extrapolation of g = 0 makes estimating β possible for a given combination of γ and ϕ. A value of $\gamma = 1.35$ is adopted compatible with the static earth load calculations (AASHTO, 2007). A range of ϕ values is assumed and estimated values of β (by iteration) are checked against a target reliability index, β_T, of 2.3 as used in previous LRFD calibrations for MSE wall reinforcements (Allen et al., 2005; D'Appolonia, 2007).

The load bias depends on use of the simplified or coherent gravity method to compute maximum reinforcement tension and may depend on reinforcement type (strip or grid) as described by Allen et al. (2001), Allen et al. (2005), and D'Appolonia (2007). Results from these studies demonstrate that the load bias has a lognormal distribution with mean, μ_{λ_Q}, and standard deviation, σ_{λ_Q}, as shown in Table 2.

Since the oldest MSE walls are approximately 40 years old, direct measurements of remaining strength after a service life of 75 or 100-years are not available. Therefore, corrosion rate measurements must be extrapolated to estimate "measurements" of remaining strength used in the numerator of Eq. (7). The extrapolation also employs equations similar to Eqs. (3)-(7), but with corrosion rates r_{z1}, r_{z2}, and r_s from the observed performance of reinforcements during service. The corrosion rates used to extrapolate metal loss are considered constants over prescribed time intervals, and higher than those expected to prevail at the end of service. This approximation is considered conservative due to the likely attenuation of corrosion rate with respect to time.

Table 2. Mean (μ_{λ_Q}) and Standard Deviation (σ_{λ_Q}) of Lognormal Load Bias

Parameter	Strip		Grid	
	Simplified Method	Coherent Gravity Method	Simplified Method[1]	Coherent Gravity Method[2]
μ_{λ_Q}	0.973	1.294	0.973	1.084
σ_{λ_Q}	0.449	0.499	0.449	0.737

Good quality fill meets the AASHTO requirements for electrochemical and mechanical properties, and has ρ_{min} in the range between 3000 Ω-cm and 10,000 Ω-cm. Measured corrosion rates for zinc do not vary significantly with respect to the age of reinforcements, and the statistics for reinforcements that are between 2- and 16-years old are representative. Therefore, the measurements of corrosion rate for zinc are assumed to be constant with respect to time with a mean rate of 1.7 μm/yr (r_{z1} and r_{z2}) and standard deviation 1.09 μm/yr.

Given such a low rate of zinc loss, and since measurements were made on reinforcements that are less than 30-years old, very few measurements are available to describe the corrosion of steel after zinc has been consumed from a galvanized reinforcement. Two different assumptions are applied as described by Elias (1990) that either (1) consider that the base steel will corrode at the same rate as plain black steel (i.e., not galvanized) corresponding to the age of the reinforcement after the zinc coating is consumed, or (2) assume that the base steel will corrode at a rate similar to that prevailing as zinc is finally consumed (i.e. corrosion rate does not change abruptly after zinc is consumed). In addition, "measured" corrosion rates for steel were multiplied by two to render the loss of tensile strength from LPR measurements similar to that described by Elias (1990).

A conservative model for steel consumption assumes that the base steel corrodes at the same rate as plain steel (i.e. not galvanized) after the sacrificial zinc layer is consumed. Most of the data used for corrosion rates of steel embedded in fill materials meeting current AASHTO guidelines are from steel coupons installed at MSE sites located in California, New York, and Florida. The statistics of this data set render a mean corrosion rate and standard deviation of 27 μm/yr and 18 μm/yr, respectively; and the distribution can be approximated as lognormal.

A resistance bias is computed for different sizes of strip-type reinforcements (4 mm, 5 mm and 6 mm) and both 75 and 100-year service lives. The bias tends to decrease with respect to increase in reinforcement size, and is higher considering longer service life. The mean resistance bias, λ_R, ranges between 1.2 and 1.5 with a coefficient of variation approximately 40% and a distribution that is approximated as a Weibull distribution.

The zinc residual model for steel consumption considers that the corrosion rate of the base steel is affected by the presence of zinc residuals. Zinc residuals include a zinc oxide film layer adhered to the metal surface and zinc oxides within the pore spaces of the surrounding fill. The presence of the zinc oxides tends to promote passivation of the steel. There are very few measurements describing corrosion rates of base steel after zinc has been consumed. A few observation may be applicable from the data set collected in Europe (Darbin, et al.,

1988) considering that some of the reinforcements only include a minimum zinc thickness of 30 μm and were placed within fills with less desirable electrochemical properties compared to AASHTO requirements such that zinc is consumed relatively rapidly (i.e., within a few years). A review of these data renders corrosion rates for steel that are close to 12 μm/yr. Since this is close to the metal loss model recommended by AASHTO it is adopted as a basis for comparison from calibrations performed by extrapolating measured corrosion rates with the conservative steel model. Similar to other data sets, a coefficient of variation of 60% and a lognormal distribution is used to describe the variation. The calibration was performed for both strip and grid type reinforcements. The mean of the resistance bias is approximately 1.4 with COV approximately 20%, and a distribution that is approximately normal.

High quality (select) reinforced fills have ρ_{min} > 10,000 Ω-cm and corrosion rates corresponding to these conditions were observed from sites in Florida (Sagues, et al., 1998; Berke and Sagues, 2009) and North Carolina. These data render mean and standard deviation of corrosion rates for the zinc coating of 0.8 μm/yr and 0.5 μm/yr, respectively. Corrosion rates observed from plain steel coupons older than 16 years correspond to mean and standard deviation values of 11.5 μm/yr and 9.4 μm/yr, and these parameters are assumed to represent the loss of base steel subsequent to depletion of the zinc coating for this case. The mean of the corresponding resistance bias is computed as ranging from 1.4 to 2.0 with COV approximately 10%. The bias distribution is approximately normal considering a 75-year service life, but is better represented by a Weibull distribution considering a 100-year service life.

DISUSSION OF RESULTS

Figure 3 presents results from Monte Carlo simulations considering strip type reinforcements and considering the load bias corresponding to the simplified method and the computed resistance bias for each of the cases described above. The AASHTO resistance factor corresponding to this case (ϕ = 0.75) is also shown for comparison.

In general, the computed resistance factors decrease with respect to initial reinforcement thickness (S). Resistance factors computed for select fill conditions correspond most closely to current AASHTO specifications, and for this case higher resistance factors are rendered considering a service life of 100-years compared to a 75-year service life. The 75-year service life corresponds to higher resistance factors considering good quality fill. The conservative steel model renders very low resistance factors that are between 0.25 and 0.50. The zinc residual model renders resistance factors that appear to be closer to the current AASHTO specifications.

Table 3 is a summary of typical resistance factors that were computed for different reinforcement types and considering either the simplified or coherent gravity methods for estimating reinforcement tension. In general, calibrations for grid type reinforcements rendered resistance factors that are 0.05 to 0.10 less than those computed for strip type reinforcements. Also the load bias corresponding to the coherent gravity method renders resistance factors that are approximately 0.10 less than those obtained considering the simplified method.

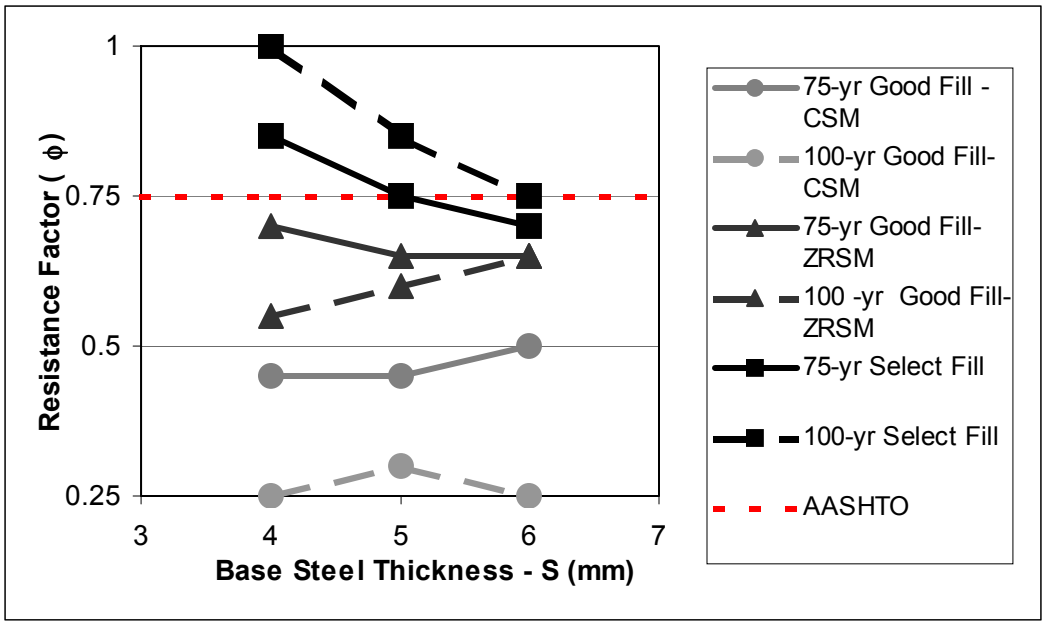

Figure 3. Resistance Factors Considering Strip Type Reinforcements and the Simplified Method of Analysis (CSM- conservative steel model; ZRSM – residual zinc steel model).

Table 3. Summary of Computed LRFD Resistance Factors

Fill Quality	Current AASHTO Resistance Factors (φ) Strip/grid	Computed Resistance Factors (φ)	
		Strip Simplified/Coherent	Grid Simplified/Coherent
Good	0.75/0.65	0.60/0.50	0.55/0.45
Select	0.75/0.65	0.75/0.65	0.65/0.55

CONCLUSIONS

Reliability-based calibration of resistance factors for MSE reinforcements is described considering the remaining cross section at the end of the design life as a variable. The computed resistance factors depend on fill conditions, reinforcement geometry, method used to compute reinforcement tension and service life. Current AASHTO specifications appear to employ resistance factors for the rupture limit state corresponding to select fill conditions. Lower resistance factors are obtained for fill conditions that are considered good, meaning they satisfy AASHTO requirements, but not by a very wide margin. More data are needed to identify the proper statistics describing the corrosion rates of steel after zinc is consumed from galvanized reinforcements.

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