Assessment of the impact of the electromagnetic field of the catenary system on crack formation in reinforced concrete supports

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Abstract. Destruction of reinforced concrete supports is a complex physical and chemical temporary process. The inevitability of destruction is due to the nature of the materials used and the activity of the environment. Centrifuged concrete is an extremely heterogeneous material over the thickness of the products made thereof: in centrifuged structures, several layers are formed over the wall thickness, which differ in their texture and structure. While in operation, the supports are subjected to a complex temperature impact, microorganisms and chemically active media have an impact on them. In addition to the main adverse factors, it is worth noting the effect of the electromagnetic field of the catenary suspension, the impact of which promotes the formation of transverse cracks mainly in the upper part of the support. Therefore, this phenomenon requires the study and development of reinforced concrete support diagnostics and monitoring facilities to provide continuous movement of railway transport and prevent support breakage and falling.

1. Introduction

When an electromagnetic field acts on the support reinforcement, electric current is induced therein, which, going through the reinforcement, heats it up. It is known that even a slight increase in the temperature of a conductor (reinforcement) over the ambient temperature (concrete supports) results in concrete drying, gradual spalling and cracking. Due to a larger cross-section of longitudinal reinforcement, the impact of the induced current on the surrounding concrete heating is minor [1].

The values of the currents and the subsequent reinforcement heating will depend on the value of the affecting voltage and the distance between the support and its source, on electrical reinforcement resistance, as well as on the current that goes through the catenary suspension, and, as it is known, it depends on the load [2].

We will use the following assumptions in calculations: let us submit the spiral reinforcement in the form of separate rings located at a certain interval (spiral pitch distance) [3] equal to 0.075 m; let us assume that the rings are interconnected in parallel, then the induced current in the ring will be the same in other reinforcement rings, that is, in the spiral.

For calculations, let us submit the following: the support type is S 136.6, the distance from the catenary system to the support axis is 3 m, the lower diameter of the support is 492 mm, the upper one is 290 mm, the spiral fitting diameter is 3 mm, the current in the catenary system is taken within the range from 100 A to 500 A in increments of 100 A [4].
2. Determination of currents in the reinforcement of reinforced concrete supports of the catenary system induced by a traction load

Let us define the electric current induced in the spiral reinforcement of the support \([5]\), mA

\[ I_{\text{m}} = \frac{E}{Z}, \]

where \(E\) is the electromotive force induced by the current of the catenary suspension in the reinforcement ring, V; \(Z\) is the overall resistance of the reinforcement ring, \(\Omega\).

Figure 1 presents a design diagram in which: \(H\) is the distance from the rail head to the contact wire (cw); \(h\) is the distance from the rail head to the transverse ring of support reinforcement; \(\epsilon\) is the distance from the path axis to the support (let us neglect the zigzag of the catenary suspension); \(a\) is the radius of the ring perpendicular to the radius \(\rho\)

![Diagram of concrete support spiral reinforcement current diagram.](image)

Using the equations of the ring in the \(x\)-\(y\) coordinate system, as well as the radius of the ring and \(\cos \alpha\), we obtain

\[ B_n = \frac{\mu_n \cdot I}{2\pi \cdot \rho} \cdot \cos \alpha = \frac{\mu_n \cdot I \cdot x}{2\pi \left[ x^2 + (H-h)^2 \right]}, \quad \Phi = \int \int \frac{\mu_n \cdot I \cdot x \cdot dxdy}{2\pi \left[ x^2 + (H-h)^2 \right]}, \]
where \( \mathbf{B} \) is the magnetic induction vector at an arbitrary point with an \( x \) coordinate perpendicular to the radius \( \rho \), \( B_n \) is the projection of this vector, \( \phi \) is a magnetic flux that penetrates the surface \( S \) bounded by a ring with a radius \( a \), Wb; \( I \) is the current in the contact wire, A; \( \mu_n \) is a magnetic invariable equal to \( 4\pi \cdot 10^{-7} \) H/m.

Within the ring area, \( x \) varies from \( \alpha - a \) to \( \alpha + a \), and \( y \) varies from \( y_2 \) to \( y_1 \), therefore

\[
\phi = \int_{\alpha-a}^{\alpha+a} \int_{\alpha^2-(x-a)^2}^{\alpha^2} \frac{\mu_n \cdot I \cdot x \cdot dy \cdot dx}{2\pi \left[ x^2 + (H-h)^2 \right]} = \frac{\mu_n \cdot I \cdot a^2 \cdot (x-a)^2}{2\pi (a^2 + (H-h)^2)} \cdot dx.
\]

we obtain

\[
M = \frac{\mu_n \cdot I \cdot a^2}{2\pi (a^2 + (H-h)^2)} \cdot dx.
\]

Since \( a << \alpha \), then for practical calculations it can be considered that \( x \approx \alpha \), then

\[
B_n = \frac{\mu_n \cdot I \cdot \alpha}{2\pi \left[ \alpha^2 + (H-h)^2 \right]} = \text{const}, \quad \phi = B_n \cdot ds = \int_{S} B_n ds = \frac{\mu_n \cdot I \cdot \alpha^2}{2 \left[ \alpha^2 + (H-h)^2 \right]}.
\]

\[
M = \frac{\mu_n \cdot \alpha^2}{2 \left[ \alpha^2 + (H-h)^2 \right]}.
\]

The electromotive force induced by the current of the catenary system in the support ring will be determined by the expression, V

\[
E = \omega \cdot M \cdot I.
\]

where \( \omega \) is the circular frequency.

Overall resistance of the ring, \( \Omega \)

\[
z = R + jx + jx',
\]

where \( R \) is the active resistance of the ring, \( \Omega \); \( x, x' \) is inductive resistance of the ring due respectively to the external and internal magnetic fluxes.

Active and internal inductive resistance of the ring per length unit [6], \( \Omega/m \)

\[
R = \sqrt{\frac{\omega \cdot \gamma \cdot \mu \cdot \epsilon_0}{2\pi \cdot r \cdot \gamma \cdot \epsilon_1}} \cdot \cos \left( \beta_0 - \beta_1 - 45^\circ \right), \quad x = \sqrt{\frac{\omega \cdot \gamma \cdot \mu \cdot \epsilon_0}{2\pi \cdot r \cdot \gamma \cdot \epsilon_1}} \cdot \sin \left( \beta_0 - \beta_1 - 45^\circ \right).
\]

where \( \gamma \) is the conductivity of steel, 0.8 \cdot 10^7 S/m; \( \mu \) is the magnetic permeability of steel 1.256 \cdot 10^{-6}; \( r \) is a conductor radius, m; the coefficient values are determined using the Bessel functions [7].

Let us define the external inductive resistance of the reinforcement ring per length unit by using the formula, \( \Omega/m \)

\[
x' = \omega \cdot L,
\]

where \( L \) is the inductance of the ring, circular section, H.

Since the radius of the ring is much larger than the radius of the wire, then we can use the formula to find the inductance, \( H \)
To determine the overall resistance of the reinforcement ring, it is necessary to determine the length of the ring, m

\[ C = 2\pi a = 2\pi \times 0.182 = 1.14. \]

We obtain the following final value

\[ Z = 1.14 \times 0.0144 = 0.01642 \, \Omega. \]

Having found the electromotive force induced by the current in a 100 A catenary system, we can determine the induced current value \( I_{in} = 13.26 \, mA. \)

3. Experimental study of the electromagnetic impact on the support reinforcement

In parallel with the calculations, an experimental determination of the induced current in the reinforcement of reinforced concrete supports in the field environment was carried out.

The experiment was aimed to determine the order of numbers in finding induced voltages and currents.

The induced voltage was measured in a ring made of reinforcing wire of a reinforced concrete support with a section of 3 mm.

The induced voltage was measured on the support using a developed device \([4]\) mounted on the support to monitor the current induced in the reinforcement (figure 2).

![Figure 2. A gauge to measure induced current in the AC catenary system concrete support reinforcement: 1 is the reinforced concrete support of the catenary system; 2 is a steel reinforcing ring; 3 is a belt (fastener); 4 is terminals; 5 is a current sensor; 6 is a power converter; 7 is a solar panel; 8 is a controller; 9 is a power controller; 10 is a battery; 11 is a wi-fi antenna.](image)

This permanent device reads, processes and transmits information as follows: the current (current circuit) passes the input current circuits of the sensor through the device terminals \([8,9]\). A sensor with input power circuits and an output measuring circuit converts the current signal into a voltage signal proportional to the effective current value. The output signal of the sensor (through the measuring output circuit) goes to the analog-to-digital converter of the controller, where the conversion operation takes place \([10]\). The controller transfers this data to the server via the wi-fi communication channel \([11]\).

The information measuring and receiving process takes place according to the functional diagram of the device (figure 3).
The experiment showed that the induced voltage in the ring (conventionally representing a spiral coil) located on a support at the height of 4 meters was 0.31 - 1.02 mV. The rated current induced in the ring is 0.018 - 0.062 A.

Thus, we can conclude that the above methods for determining the induced current value are reliable. The obtained range of induced EMF and current values has justified the premise.

The experimental data give somewhat higher values of the induced voltage with respect to the rated ones. This is because at the time of the experiment, we do not know the real value of the current both in the catenary suspension and in the wires located on the field side [12].

4. Coil reinforcement thermal heating processes in the body of the support

Having proved the impact of the electromagnetic field and having determined the value of the induction current, we describe the origination of possible thermal processes in the body of the support.

The excess of the temperature of the reinforcement above the ambient temperature, when the found induced currents pass therethrough, are determined using the differential equation [13], °C

\[ c \cdot m \cdot \Theta'(t) = I_m \cdot \frac{\rho_{20}}{S} \cdot \left[ 1 + \alpha \cdot (T_a + \Theta(t) - 20) \right] - \sigma \cdot P(\Theta(t)) \cdot h, \]  

where \( c \) is the specific heat of steel; \( m \) is the cross-sectional area of the reinforcement wire; \( \Theta(t) \) is the excess of the induced temperature over the ambient temperature, ° C; \( I_m \) is the rated value of the induced current, mA; \( \rho \) is the specific electric resistance of steel at a temperature of 20°C; \( S \) is the cross-sectional area of the reinforcement wire; \( \alpha \) is a resistance change temperature coefficient; \( T_a \) is an ambient temperature °C; \( \sigma \) is a coefficient that depends on the ambient temperature equal to \( \sigma = 6.72 \); \( h \) is the circular coefficient of the line equal to \( h = 1.25 \); \( P \) is a wire reinforcement perimeter.

The equation (1) is solved using a numerical Runge-Kutta method in a Mathcad software environment [14].

Figure 4 shows a plot of the temperature of spiral reinforcement overheating versus the ambient temperature at different currents in the catenary suspension.
The excess of coil reinforcement temperature over the concrete temperature can reach $4.3 \times 10^{-3} \, ^{\circ}C$. Over time, the concrete heats up, first of all, at the point of its adhesion to the spiral reinforcement, and then other layers of concrete closer to the surface will be included in the thermal process [15]. This will result in a gradual drying of the concrete and a change in its initial structure, thereby reducing its tensile strength [16].

5. Dielectric power losses in the concrete of supports

It is known that concrete used in the manufacture of catenary system supports is a dielectric [17]. The main process characteristic of any dielectric when it is exposed to an electric field is polarization which is accompanied by dielectric losses, i.e. the power dissipated in a dielectric by an electric field due to the passage of through currents $I_{es}$ and absorption currents $I_{abs}$ [18]. It is characteristic that this process mainly occurs in about 2/3 of the upper part of the support relative to the conditional foundation edge.

Let us determine the power losses from through currents, kW

$$P = \omega \cdot C \cdot U^2 \cdot \text{tg} \delta,$$

where $\text{tg} \delta$ is a dielectric loss tangent equal to

$$\text{tg} \delta = \frac{1}{R \cdot \omega \cdot C},$$

where $R$ is the active resistance of the concrete support, $\Omega$.

The voltage applied to the walls is, kV

$$U = E \cdot h,$$

where $E$ is a rated electric field strength, kV/m; $h$ is a support wall thickness, m.

The electric field strength can be found by solving the problem using the method of image charges.

As an example, let us consider a single-track line of the catenary system with a CCSC-95+CSC-100 [copper-clad steel conductor-95+copper shaped conductor-100] chain suspension (Point 1) and TWR wires (Point 2) made by using AS-70 wires [aluminum-steel conductors] located on the field side [19]. Let us find the electric field strength from the currents in the contact wire, the suspension wire and TWR wires near the reinforced concrete support (Point 3) [20]. The design diagram is presented in figure 1.
Where: $h_e$ is the suspension height of the equivalent wire (suspension wire + contact wire), m; $h_{twr}$ is the suspension height of the equivalent TWR wire, m; $d$ is the distance between the centers of two equivalent wires, m; $a, c$ are the distances from the points to the geometric centers of wires, m; $x$ is the distance from the equivalent wire of the catenary suspension to the support body, m; $y$ is the height of the equivalent wire, m; LCF - level of conditional cutoff of the foundation.

The potential at Point 3 induced by the electric field of equivalent wires will be equal to, V

$$
\phi_3 = \tau_1 q \ln \frac{\sqrt{(h_e + y)^2 + x^2}}{\sqrt{(h_e - y)^2 + x^2}} + \tau_2 q \ln \frac{\sqrt{h_{twr} + y^2 + (d - x)^2}}{\sqrt{h_{twr} - y^2 + (d - x)^2}}.
$$

Horizontal and vertical components of the electric field, kV / m

$$
E_x = \frac{d\phi_3}{dx} = \tau_1 q \left[ \frac{x}{(h_e + y)^2 + x^2} + \frac{x}{(h_e - y)^2 + x^2} \right] + \tau_2 q \left[ \frac{d - x}{(h_{twr} + y)^2 + (d - x)^2} + \frac{d - x}{(h_{twr} - y)^2 + (d - x)^2} \right].
$$

$$
E_y = \frac{d\phi_3}{dy} = \tau_1 q \left[ \frac{h_e + y}{(h_e + y)^2 + x^2} + \frac{h_e - y}{(h_e - y)^2 + x^2} \right] + \tau_2 q \left[ \frac{h_{twr} + y}{(h_{twr} + y)^2 + (d - x)^2} + \frac{h_{twr} - y}{(h_{twr} - y)^2 + (d - x)^2} \right].
$$

The potentials of points 1 and 2 are respectively determined by the expressions, B

$$
\phi_1 = \tau_1 q \ln \frac{2h_e}{r_s} + \tau_2 q \ln \frac{(h_{supp} + h_e)^2 + d^2}{(h_{supp} - h_e)^2 + d^2},
\phi_2 = \tau_1 q \ln \frac{(h_{supp} + h_e)^2 + d^2}{(h_{supp} - h_e)^2 + d^2} + \tau_2 q \ln \frac{2h_{supp}}{r_{supp}}.
$$

Substituting all the accepted initial conditions, let us solve the resulting equations. The values of electric field strength (horizontal, vertical and resulting) [21] for the accepted conditions of the
example at the suspension height of the contact wire \( y = 6.25 \) m will be respectively equal to \( E_y = 3.02 \) kV/m.

The results of calculations of the value of the resulting electric field strength at different voltage values are presented in table 1.

**Table 1.** Resulting electric field strength, kV / m.

| \( U, \) kV | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 27.5 | 28  |
|-------------|-----|-----|-----|-----|-----|-----|-----|------|-----|
| \( y = 6.25 \) | 2.54| 2.66| 2.78| 2.90| 3.02| 3.14| 3.26| 3.32 | 3.38|

Specific power losses from absorption currents in concrete [22], kW / m³

\[
p = E_y^2 \cdot f \cdot \frac{\varepsilon_t \cdot \tan \delta}{1.8 \cdot 10^6},
\]

where \( \varepsilon_t \) is the relative dielectric permittivity of concrete.

Figure 6 shows the dependence of the total power losses on the through currents and absorption currents per 1 m³ of the support for different voltage values in the catenary system.

![Figure 6. Dependence of total power losses on through currents and absorption currents.](image)

We have revealed earlier that the electromagnetic field of the catenary suspension additionally affects the crack formation processes in reinforced concrete supports and the flowing induction current heats it up. Then the power losses from the induced currents in the reinforcement of supports [22], W · 10⁻³

\[
P = I_{in}^2 \cdot R,
\]

where \( R \) is the active resistance of the spiral coil, \( R = 0.0114 \) Ω.

The calculation results for various currents of the catenary system and induced currents in the reinforcement of the support are presented in table 2.

Figure 7 shows the dependence of power losses on the induced current in the support reinforcement at a current in a 500 A catenary system.
It has been revealed that the power losses from the induced currents in the reinforcement, from through currents and absorption currents (polarization) in concrete, happen to be.

The currents induced in the spiral reinforcement under the influence of the electromagnetic field of the catenary suspension promote the heating of the transverse reinforcement, and, as a consequence, the heating of concrete. It has been determined that dielectric power losses are additionally dissipated in concrete, affecting the temperature conditions of concrete and causing local heating.

This heating is not constant in time, but it can ultimately result in the thermal weakening of bonds in concrete. This process will most likely begin from inside, where the concrete is adhered to the reinforcement [23].

It is obvious that the weakening and loss of bonds between the structural elements in the body of the support during external examination cannot be detected [24]. However, as soon as the “drying” of the concrete reaches the surface of the support, “efflorescences” will be noticeable [25]. This process will promote crack formation. It is worth reminding that the operating instructions signify that those cracks are recognized as the most dangerous the development of which corresponds to the location of reinforcement.

6. Conclusions
When exposed to an electromagnetic field, an electric current is induced in the reinforcement of the support, which heats it up. This is an additional factor (to stresses) that induces crack formation in the supports.

It has been determined that dielectric power losses are additionally dissipated in concrete, affect the temperature of the support body, promoting even more heating of the coil reinforcement.

### Table 2. Power losses from the induced currents in the support reinforcement.

| $I =$100 A | $I =$200 A | $I =$300 A | $I =$400 A | $I =$500 A |
|-----------|-----------|-----------|-----------|-----------|
| $I_{in}$, mA | $P,W$ | $I_{in}$, mA | $P,W$ | $I_{in}$, mA | $P,W$ | $I_{in}$, mA | $P,W$ |
| 13.704  | 2.141  | 13.704  | 2.141  | 13.704  | 2.141  | 13.704  | 2.141  |
| 13.618  | 2.114  | 13.618  | 2.114  | 13.618  | 2.114  | 13.618  | 2.114  |
| 13.515  | 2.082  | 13.515  | 2.082  | 13.515  | 2.082  | 13.515  | 2.082  |
| 13.322  | 2.023  | 13.322  | 2.023  | 13.322  | 2.023  | 13.322  | 2.023  |
| 13.259  | 2.004  | 13.259  | 2.004  | 13.259  | 2.004  | 13.259  | 2.004  |
| 13.107  | 1.958  | 13.107  | 1.958  | 13.107  | 1.958  | 13.107  | 1.958  |
| 12.940  | 1.909  | 12.940  | 1.909  | 12.940  | 1.909  | 12.940  | 1.909  |
| 12.758  | 1.856  | 12.758  | 1.856  | 12.758  | 1.856  | 12.758  | 1.856  |
| 12.563  | 1.799  | 12.563  | 1.799  | 12.563  | 1.799  | 12.563  | 1.799  |

### Figure 7. Dependence of power losses on the induced current in the support reinforcement.
The excess of the temperature of the conductor (reinforcement) over the ambient temperature (support concrete) promotes the thermal weakening of the bonds between the structural elements of concrete, reducing the total bearing capacity of the supports.

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