IOP Conf. Series: Journal of Physics: Conf. Series **830** (2017) 012046 doi:10.1088/1742-6596/830/1/012046

Simulation of pre-breakdown phase of electrical discharge in reinforced concrete

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Abstract. The application of an electrical discharge technology for destructive recycling of the reinforced concrete is considered. Its main advantages, in comparison with the mechanical methods, are that the electrical discharge channel acting as a rock-breaking tool has an unlimited service life, and a lifetime of the electrode systems is much higher. The physical and mathematical model of the discharge development is described. The simulation results have shown that the discharge channel propagation velocity and the trajectory depend on the reinforcement locality and the voltage amplitude. The voltage affects the average speed of the discharge structure development which can reach the value of up to $\upsilon=5\cdot10^3$ m/s. It is also shown that the reinforcing elements located between the electrodes attract the growing discharge structure. The lower the distance between the vertical axis of the high voltage electrode and the metal reinforcement position, the more probability of the discharge channel orientation towards this element.

1. Introduction

A big amount of apartments and industrial buildings were built using a precast reinforced concrete in the 50-s and 70-s of the last century in Russia. Taking into account that a service life of such buildings is approximately 50–100 years, they need a massive demolition and recycling in the near future. Under low demolition, the fairly conditioned structural elements could be used in low-rise and private buildings or transported to the landfills, or finally, employed in new construction projects. An increased the volume of the construction and demolition work over the next decades does not allow us to employ such schemes for economic and environmental reasons. It raises the question of recycling of the building refuse and overage concrete elements.

Undoubtedly, the easiest method in terms of the utilization is a mechanical one, nevertheless it has some disadvantages. The limiting factors are: firstly, the large weight and an overall size of the equipment; secondly, the above-mentioned characteristics and operating costs rise nonlinearly with an increase of the destroyed products strength, and impose a limit on the maximum strength of products that could be destroyed. These problems are absent in the technologies of electro-impulse and electro-hydraulic fracture of concrete products [1, 2]. Moreover, with the increasing material strength and therefore, it brittleness, an efficiency of the method increases.

The method is based on the following processes: the shock waves generated by the penetrated discharge channel expansion, as well as the tensile and compression waves generated at further stages of the discharge lead to the progressive crack growing that results to the splitting-off of the concrete fragments with a subsequent release of the concrete reinforcement elements. The advantage of such technology, in comparison with the mechanical ones, is that the electrical discharge channel acting as a rock-breaking tool has an unlimited service life, and the life of electrode systems is much higher.

Nevertheless, the proposed technology has some disadvantages. As noted in [3], the destruction process is working more or less successfully only with the relatively deep bedding of the reinforcement cage and widely spaced reinforcement elements. Otherwise, there is a possibility of direct contact of the high voltage electrode with the reinforcement cage, leading to the almost complete cessation of the concrete item fracture process due to the lack of breakdown in the bulk of the item when a high voltage pulse is applied.

The use of mathematical modeling has a great potential for the quantitative description of the discharge development and prediction of the discharge trajectory.

In this paper, the results of computer simulation of the discharge channel formation under various conditions of the reinforcement position in a concrete and the voltage wave parameters are presented. The simulation is focused on a pre-breakdown phase of the electrical discharge in the reinforced concrete which starts from the channel initiation at the high-voltage electrode tip to the gap bridging by the discharge structure. The computer simulation is carried out with the use of numerical modeling on the base of a software developed in Moscow Engineering and Physical Institute.

2. Model of the discharge development

The discharge development is simulated with the help of a numerical discrete model created on the basis of the stochastic-deterministic approach [4–7]. The discrete algorithm involves a stochastic description of the discharge channel growth and a deterministic calculation of the electric field by means of Poisson equation, a charge dynamics on the basis of Ohm law and a charge conservation law, and the channel conduction variation in the form of a modified Rompe-Wiezel equation.

The equivalent scheme describing the operation of the pulse-voltage generator and the discharge structure growth is shown in figure 1. This scheme is determined by the type of generators which are used in the high voltage laboratories and pulse electrical discharge technology.

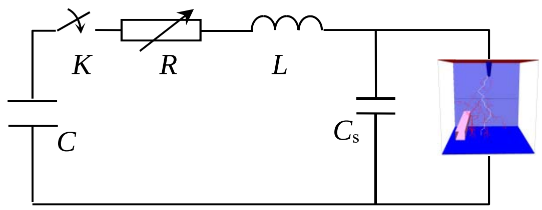

Figure 1. The equivalent scheme of reinforced concrete breakdown: C is the generator capacitance, K is the commutator, L is the circuit inductance, R is the variable resistance of the circuit, C_s is the stray capacitance.

The main equations of this model are presented in [7–9]. The circuit resistance R exponentially decreases:

$$R = R_1 + (R_0 - R_1)e^{-t/\theta_R}, \quad (1)$$

where R_0 is the initial resistance at the time $t=0$, R_1 is the minimal value of the resistance, which is equal to (1–3) Ohm for the 6-10 stepped Marks multiplying circuit; θ_R is the resistance decrease characteristic time. The stray capacitance C_s is the sum of the stray capacitances of the circuit elements.

The dynamics of the current and voltage in the discharge generator circuit is calculated on the basis of the finite-difference approximation of Kirchhoff equations [9].

The probability density ω_n of the discharge channel growth in a direction $\vec{n}$ is assumed to be proportional to the square of the local field projection E_n along this direction, if the projection value exceeds the critical strength:

$$w_n = \alpha\theta(E_n - E_c)E_n^2, \quad (2)$$

where α is the growth rate coefficient, E_c is the critical field for the discharge channel growth, $\theta(x)$ is the step function ($\theta(x)$=1, for $x > 0$ and $\theta(x)$=0 for $x \leq 0$).

The channel conduction during the discharge development is estimated on the basis of the modified Rompe-Wiezel equation [5]:

$$\frac{\partial\gamma}{\partial t} = \chi\gamma E_l^2 - \xi\gamma, \quad (3)$$

where χ and ξ are parameters of the rate of increase and decrease of the conduction, respectively. The first term in the right part of equation (3) is related to the conduction increasing due to Joule energy release within the discharge channels. The second term describes the conduction decrease due to energy dissipation into the surrounding material.

The presented model describes the discharge channels propagation, charges motion in the channels, dynamics of the electric field potential and the change of channels conductivity. Discharge development is considered in the homogenous dielectric for the needle-plane electrode geometry (figure 2).

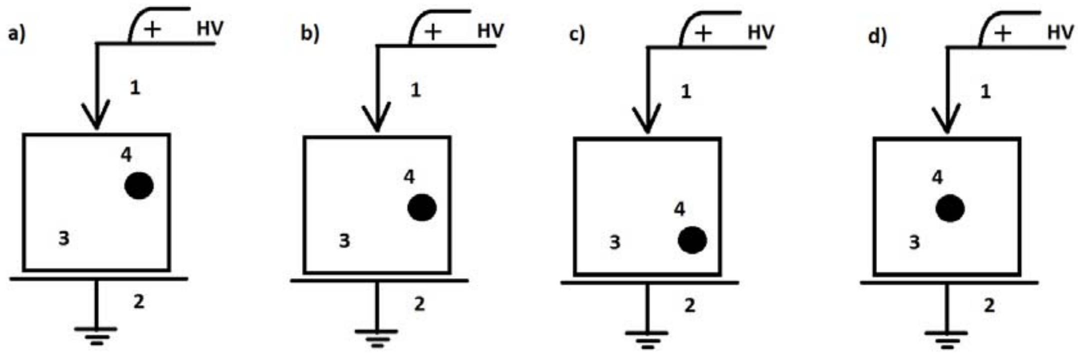

Figure 2. The schemes of the simulation region: 1 – HV electrode; 2 – ground electrode; 3 – concrete; 4 – reinforcement element.

3. Simulation results of the discharge development in the reinforced concrete

Simulation of the discharge development has been carried out in the needle-plain electrode geometry for the concrete. The computer experiments were made for the following parameters of the discharge circuit: U_0=450 kV, C=14,8 μF, L=10 μH, Cs=0,2 nF, R_0= 10 MOhm, R_l=2 Ohm, θ_R=10 ns. The results of computer investigations of the electrical discharge in concrete by means of the presented model under the different reinforcement positions are presented in figure 3.

The electrical discharge initiates with the formation of one or several channels at the initiating needle, when the electric field strength exceeds the critical value (t = 216 ns). The rate of channel growth increases with the voltage build-up and discharge structure eventually approaches the ground electrode. The average speed of the discharge development equals to $\upsilon=3{,}97\cdot10^3$ m/s. As a result of the discharge structure propagation, the electrode gap bridging by the main discharge channel occurs (the main discharge channel is shown in figure 3 by the thick line). As the most part of the current flows through the main discharge channel, the conduction of the remaining channels quickly decreases and they attenuate. As a result, only the main discharge monochannel remains.

The discharge structure orientation in the concrete strongly depends on the reinforcement location. The reinforcing elements located between the electrodes attract the discharge structure. The less the distance between the vertical axis of the high voltage electrode and the metal reinforcement position, the more the probability of the discharge channel orientation towards this element.

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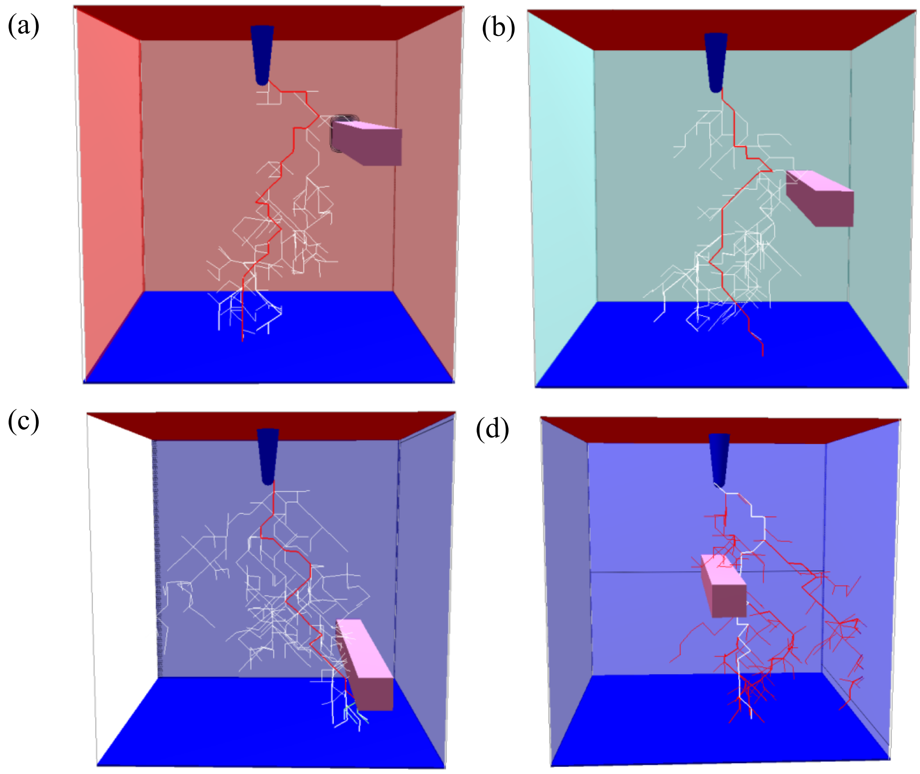

Figure 3. Discharge channels structure at the various positions of the concrete reinforcement

After the bridging of the electrodes gap by the main discharge channel, the abrupt increase in the discharge current and the decrease in the discharge voltage occur, whereas the inductive voltage rise. After the concrete breakdown, the damped oscillations begin in the generator circuit (figure 4). During this process, the main discharge channel operates as the variable nonlinear resistance.

The period of the oscillations is determined by the generator capacitance and inductance. At the given simulation parameters, the oscillations stop occurs in a twenty microseconds. The oscillation of the discharge voltage has a trapezoidal form. It is caused by the variation of the mono-channel conduction during the electrical discharge.

The dynamics of the discharge channel energy release is caused by the current and voltage oscillations (figure 5).

The energy stored in the pulse generator capacitor is equal to 14,98 kJ. The whole energy which released within the main discharge mono-channel amounts to 20 % of the generator energy. Almost half of the plasma channel energy is released during the first period of the current oscillation. Other part of the energy is released within the active resistance R of the generator.

Oscillation of the plasma channel conduction occurs due to the power oscillation (figure 6). The minimal values of the channel conduction correspond to the time moments when the discharge current takes on a zero value.

The voltage increase leads to the growth of the discharge structure branching, a speed of the channel propagation and the discharge current (figure 7). The voltage build-up affects the average speed of the discharge structure development which can reach the value of up to $\upsilon=5\cdot103$ m/s. The channel trajectory is placed mainly close to the reinforcement cage (the main mono-channel is shown in figure 7 by the thick line).

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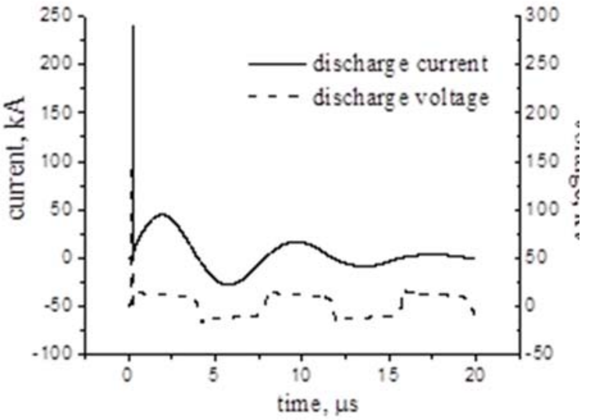

Figure 4. Time dependencies of the discharge voltage and current.

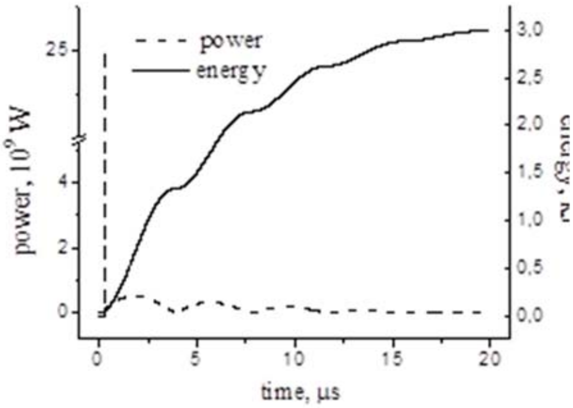

Figure 5. Time dependencies of the total energy and Joule power release within the discharge channel.

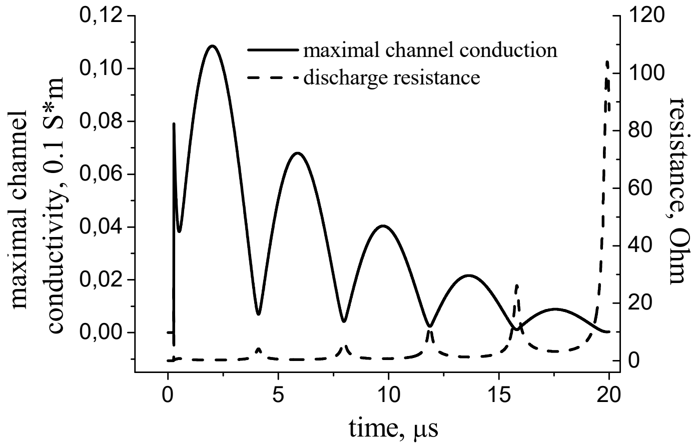

Figure 6. Time dependencies of the maximal conduction of the discharge channels and electrode gap resistance

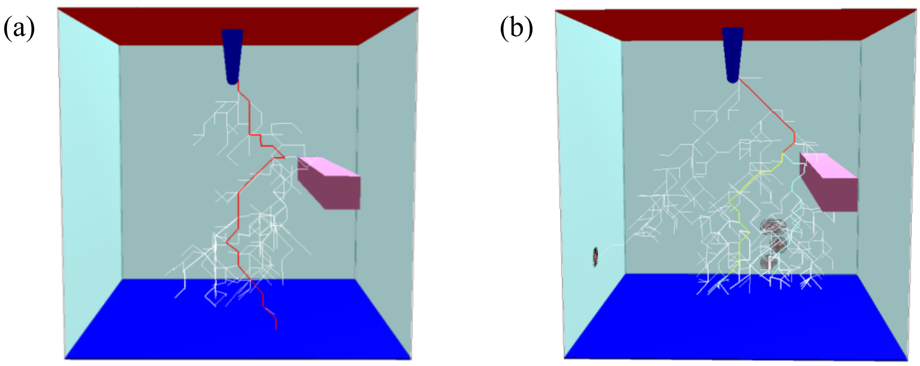

Figure 7. Simulated discharge structure (a) U_0=450 kV, D=2.25, t=260 ns; (b) U_0=600 kV, D=2.67, t=252 ns.

The heterogeneity of spatial distribution of the concrete conductivity and presence of the reinforcing steel in the concrete affect the discharge development. The discharge channel locality is controlled by an existence of the concrete reinforcement with a high conductivity. The reinforcing steel of the high conductivity located between the electrodes attracts the growing structure. The shorter the distance between the high voltage electrode vertical axis and the metal reinforcement position, the higher efficiency of the concrete distraction nearby it.

4. Conclusion

The presented mathematical model takes into account the main physical processes determining the reinforced concrete breakdown, consistently with the high-voltage generator operation. The obtained simulation results are helpful in understanding of a breakage behavior of the reinforced concrete in the electro-discharge technology of solid destruction.

5. Acknowledgements

This work was supported by grants of RFBR № 14-08-01088 and RFBR № 16-48-700278.

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