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# ANALYSIS OF THE SHIELDING EFFECTIVENESS OF REINFORCED CONCRETE IN CASE OF A DIRECT LIGHTNING STRIKE

S. Naranjo-Villamil<sup>1</sup>, C. Guiffaut<sup>2</sup>, J. Gazave<sup>1</sup>, A. Reineix<sup>2</sup>

<sup>1</sup>Laboratoire des Matériels Électriques – EDF R&D, Moret-sur-Loing – France, susana.naranjo-villamil@edf.fr

<sup>2</sup>Institut XLIM – UMR 7252 CNRS, Limoges – France, christophe.guiffaut@xlim.fr

**Abstract.** It has been demonstrated that reinforced concrete, typically used in modern constructions, reduces the impact of the lightning electromagnetic pulse (LEMP). This paper aims to quantify the influence of the characteristics of the reinforcement on the shielding effectiveness of a full-scale building directly struck by lightning. A parametric study is conducted by implementing two different methods, and the results are analyzed in the frequency domain.

## I. INTRODUCTION

Reinforced concrete is a composite material in which steel grids are embedded in plain concrete to improve its tensile strength. Since the grids are made of conducting reinforcing bars (rebars) that work as natural down conductors, reinforced concrete is often included as a part of the Lightning Protection System (LPS). Even though most of the reinforcing grids used in modern constructions come prefabricated and thus their main characteristics are already defined, there is still a large variety of options. Better techno-economical choices could be made if, in addition to the mechanical properties of the reinforcement, its shielding effectiveness were also considered.

Numerous studies have been conducted to understand the transmission and reflection properties of reinforced concrete [1]-[6]; yet, only a few have been devoted to its electromagnetic behavior when the source is connected directly to the rebars. It has been shown that reinforcing grids reduce the effects of the lightning electromagnetic pulse. Additionally, the shielding can be improved by increasing the number of layers, separating the layers, or reducing the mesh size [7]-[10]. Aiming to quantify the impact of any modification made on the reinforcement on the electromagnetic shielding of a building, this paper presents a parametric study. In the study, the effect of each parameter is analyzed independently. The simulations are conducted using TEMSI-FD, a solver based on the finite-difference time-domain method (FDTD) [11], using a non-uniform grid with cell sizes varying from 5 m to 1 m. To verify the accuracy of the results, the computations are also carried out in FEKO [12].

## II. NUMERICAL MODEL

A 5 m × 5 m × 5 m reinforced concrete building with a 1-meter-deep foundation is considered. Its external walls, its roof, and its foundation are made up of a reinforcing grid with a squared mesh size. The internal walls, the columns,

and the beams are not taken into account. The conductivity of the rebars forming the grid is set to  $8.33 \times 10^6$  S/m. The concrete is modeled as a lossy dielectric material with variable conductivity and permittivity, in accordance with its moisture content. The soil is considered homogeneous with a relative permittivity of 10 and a resistivity of 100  $\Omega$ -m.

The building is directly struck by lightning in the corner of the roof. The lightning channel is represented by a 100-meter vertical lossy wire, excited at its base by a lumped current source and connected at the top end to a perfectly matched layer (PML) [13]. In TEMSI-FD, all the conductors, including the lightning channel, are modeled as thin wires [14]. In FEKO, the channel is open at the top and considered to be 2-kilometers-long. In both cases, the current waveform is a Gaussian function of 100 A, covering a frequency range from 0 Hz to 1 MHz.

When designing the reinforcement of a building, the options are not limited to the combinations of the radii of the rebars and the standardized mesh sizes. Reinforcing grids can have multiple interconnected layers and be made

Table 1. Reference values of the parameters considered.

Parameter	Reference value
Mesh size	30 cm
Radius	6 mm
Number of layers	1
Distance between the hoops	No hoops
Relative permeability of steel	1
Moisture content of concrete	No concrete

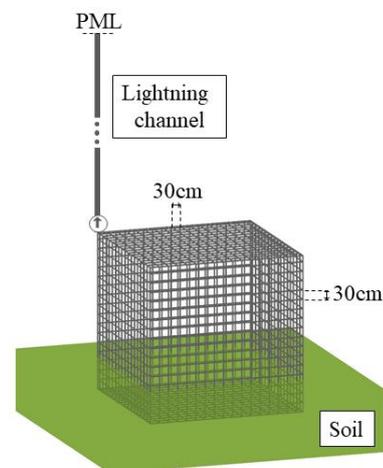


Fig. 1. Computation model of the building in TEMSI-FD when the parameters are set to the reference values.

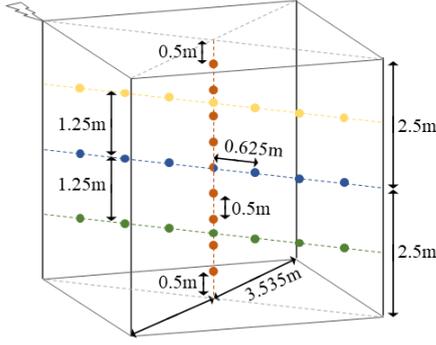


Fig. 2. Position of the computed electromagnetic fields inside the building.

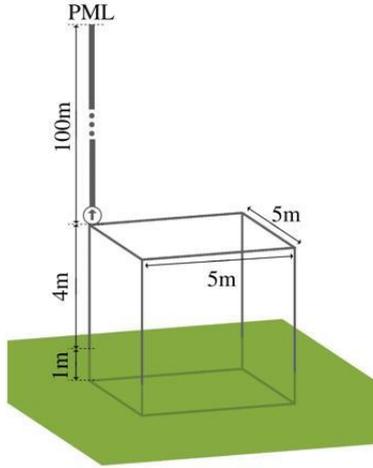


Fig. 3. Computation model of the building in TEMSI-FD when its LPS consists of four down-conductors.

out of different types of steel. Based on real configurations, six parameters are chosen to be analyzed independently starting from the reference values in Table 1. The computation model when all the parameters are set to the reference values is shown in Fig. 1.

The electric and the magnetic fields are computed at 9 points vertically distributed in the center of the building and at 21 horizontally distributed points. As shown in Fig. 2, the horizontally distributed points are positioned in the diagonal from the attachment corner to the opposite corner, at three different heights.

The shielding effectiveness is defined as follows:

$$SE = 20 \log(E_0/E) [dB], \quad (1)$$

$$SH = 20 \log(H_0/H) [dB], \quad (2)$$

where  $SE$  and  $SH$  designate, respectively, the shielding against the electric field and the shielding against the magnetic field.  $E$  and  $H$  are the magnitudes of the total electric and magnetic fields computed inside the reinforced concrete building.  $E_0$  and  $H_0$  are the magnitudes of the total electric and magnetic fields computed when the LPS system of the building consists of four down-conductors. The conductors, one in each corner, are connected at the top and the bottom, as shown in Fig. 3. The radius of the down-conductors is set to 6 mm as the reference value of the radius of the rebars.

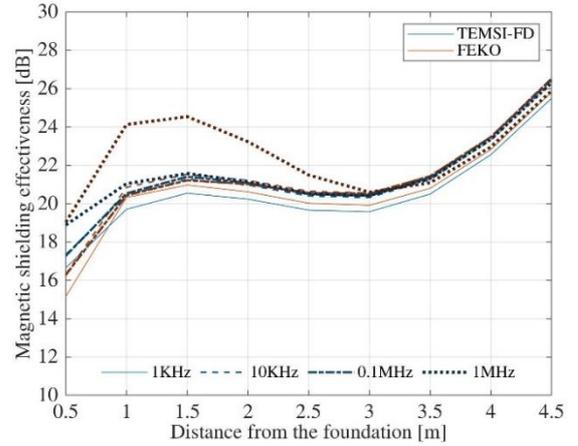
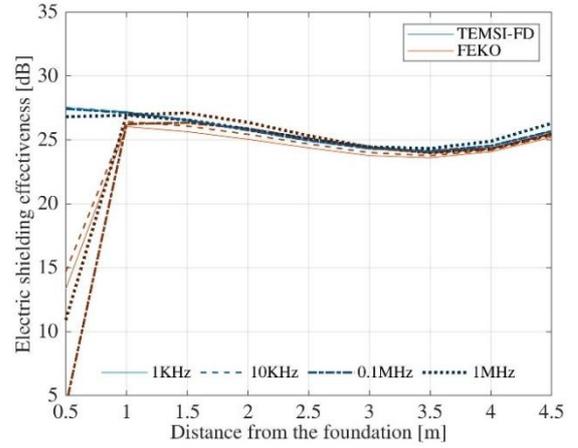


Fig. 4. Electric and magnetic shielding effectiveness at vertically distributed points.

The results when all the parameters are set to the reference values are presented in Fig. 4 and Fig. 5. Since the computed values exhibit a minor dependency to the frequency, we decided to plot them against the relative position of the points from the foundation and the striking point. Fig. 4 shows that whereas the electric shielding is almost constant as we move along the vertical axis in the center of the building, the magnetic shielding decreases as we get closer to the foundation and increases as we approach the roof. The decrease could be explained by the electromagnetic field induced by the currents flowing through the foundation as they dissipate in the soil. The interpretation of the increase is less straightforward. One could think that it is due to the shielding against the electromagnetic field radiated by the lightning channel, provided by the reinforcing grid in the roof, that is non-existent when the LPS consists of four down-conductors. Fig. 5 shows that the electric shielding increases as we move away from the down conductors. In contrast, the reinforcement provides a better magnetic shielding close to the striking point. It is interesting to observe the inverse symmetry of the curves, suggesting a dependency on the distance between the rebars of adjacent walls. The magnetic shielding starts decreasing with the distance from the striking point, then fluctuates slightly around the same values, and finally, the curve is inverted. This

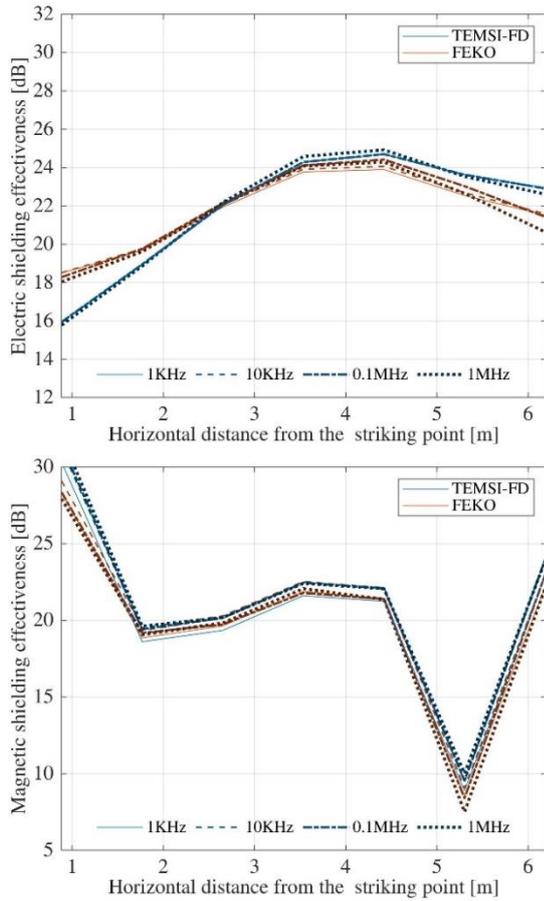


Fig. 5. Electric and magnetic shielding effectiveness at horizontally 3.75 m away from the foundation.

Table 2. Range within the parameters are varied.

Parameter	Range
Mesh size	10 cm – 50 cm
Radius	2 mm – 10 mm
Number of layers	1 – 3
Distance between the hoops	30 cm – 150 cm
Relative permeability of steel	1 – 1000
Moisture content of concrete	0.2 % – 12 %

Table 3. Effect on the average shielding effectiveness.

Case	SE [dB]	SH [dB]
Duplicating the mesh size	-13.700	-9.012
Duplicating the radius of the rebars	2.869	2.723
Adding one layer at a distance equals to the mesh size	16.555	12.497
Duplicating the distance between the layers	4.272	2.758

tendency is also observed in the results at different heights. The difference between the computations carried out in TEMSI-FD and FEKO is probably resulting from implementing two different full-wave methods to solve the equations. Nevertheless, it may also be a consequence of the discrepancies in the models of the lightning channel.

### III. PARAMETRIC STUDY

The characteristics of the reinforcement of the building are varied within the ranges defined in Table 2. When one of the parameters is changed, the others are set to the reference values. Table 3 summarizes the effect of the mesh size, the radius of the rebars, and the number of layers. The effect of the number of layers depends on the distance between them. Since a linear relation was not observed when varying the other parameters, their effect is not included in the table.

#### III.1. Effect of the mesh size and the radius

Even though the meshes are considered squared, the distance between the horizontal and the vertical rebars is different in some specific cases, when the building dimensions are not a multiple of the mesh size. The effect of both the mesh size and the radius on the shielding effectiveness is consistent with the behavior of reinforced concrete to an incident electromagnetic pulse. The electromagnetic shielding improves as the percentage of steel in the structure increases; thus, as the mesh size decreases or the radius of the rebars increases.

Also, we observed a linear tendency of the effect (see e.g. Fig. 6). On average, diving the mesh size by two enhances the electric shielding by 13.7 dB and the magnetic shielding by 9 dB. One would expect the radius to be as influential as the mesh size; yet, duplicating the radius only strengthens the electric shielding around 2.9 dB and the magnetic shielding around 2.7 dB. The latter explains why an optimization algorithm to reduce multi-layered grids into an equivalent grid [15] usually reaches the lower limit of the mesh size before it starts changing the radius.

#### III.2. Effect of the number of layers

Fig. 7 shows that adding an extra layer to the reinforcing grid improves the electric shielding effectiveness by 16.5 dB and the magnetic shielding effectiveness by 12.5 dB, approximately. These improvements, however, depend on the mesh size and the distance between the layers. Therefore, they are only valid if the extra layer is positioned at a distance equal to the mesh size. If the distance between the layers is divided or multiplied by two, the electric shielding would be  $16.5 \text{ dB} \pm 4.3 \text{ dB}$ , and the magnetic shielding would be  $12.5 \text{ dB} \pm 2.7 \text{ dB}$ . To illustrate, consider the shielding effectiveness when all the parameters are set to the reference values and the corresponding results in Fig. 4. The electric shielding effectiveness with a single-layered grid is around 25 dB. Adding a second layer 60 cm away from the first will lead to a shielding effectiveness of 45.8 dB. If the second layer is added 30 cm away from the first, the shielding effectiveness would be around 41.5 dB, and if a third layer is added at the same distance from the second layer, it would be 58 dB on average. Modifying the distance between those three layers from 30 cm to 15 cm would decrease the electric shielding effectiveness by 8.6 dB, making it 49.4 dB. Hence, if there are no restrictions on the wall's width, it would be preferable to add an extra

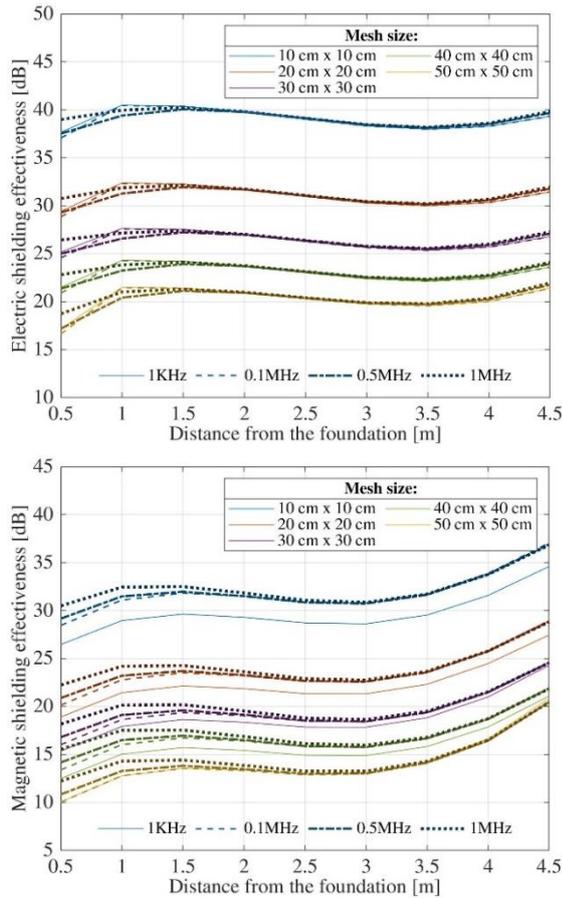


Fig. 6. Effect of the mesh size on the electric and magnetic shielding effectiveness.

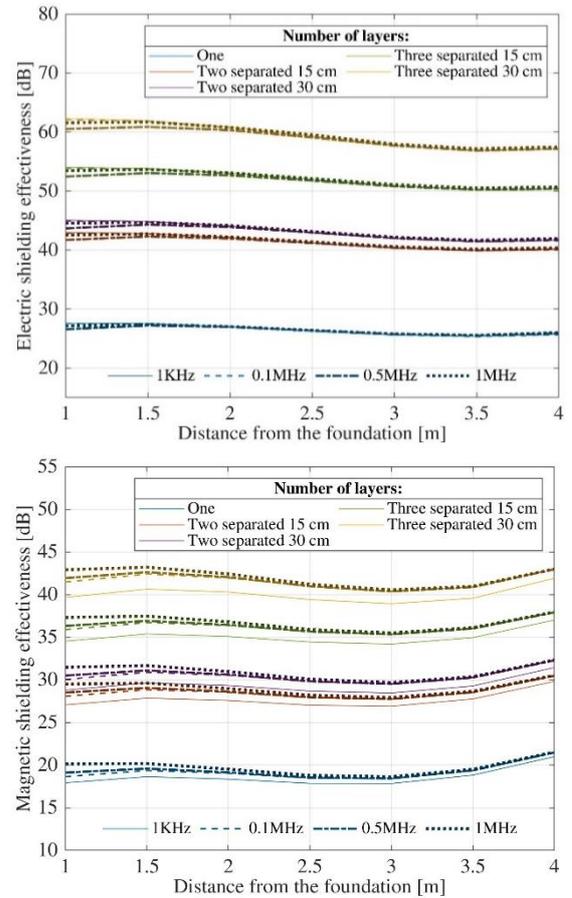


Fig. 7. Effect of the number of layers on the electric and magnetic shielding effectiveness.

layer than to reduce the mesh size, and the further it is placed from the outer layer, the better the shielding will be.

### III.3. Effect of the periodicity of the hoops

Generally, the hoops are vertical and horizontal rebars that interconnect the layers of the reinforcing grid. In this study, we considered their radius equal to the radius of the rebars forming the reinforcement and the meshes of the layers to be aligned. Under these considerations, the hoops are positioned at the intersection of the rebars.

As observed in [9], interconnecting the layers more often has an insignificant impact on the electromagnetic fields inside the building. Moreover, the effect of increasing the periodicity of the hoops on the shielding effectiveness is negligible. Only placing a hoop in every intersection could improve the shielding, but it would not be more than 2 dB. The currents flowing through the inner layers are mainly induced from those flowing through the outer layer. Fig. 8 shows that there is almost no derivation of the lightning current to the hoops. The lightning current is diverted to the down-conductors of the first layer.

### III.4. Effect of the permeability of steel

To the knowledge of the authors, all different types of steel are highly conductive, which makes the conductivity a

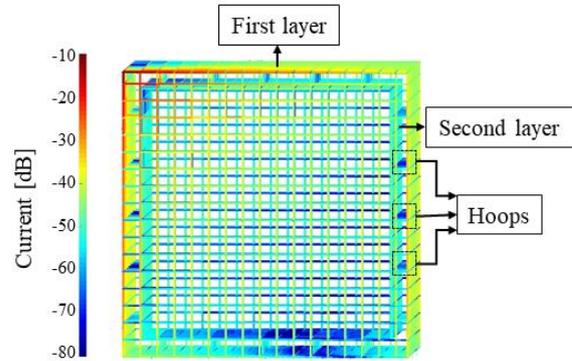


Fig. 8. Distribution of the normalized current in a double-layered reinforcing grid at 1MHz.

non-influential parameter in this study. On the other hand, depending on the chemical composition, the degree of magnetization of steel could significantly increase. The relative permittivity of carbon steel is on the order of 100, while it is in the range 750-1800 for annealed stainless steel and can be approximated to 1 for austenitic stainless steel [16]. The standard IEC 62305-4 [17] considers a relative permeability  $\mu_r = 200$  for the steel used in reinforced concrete buildings.

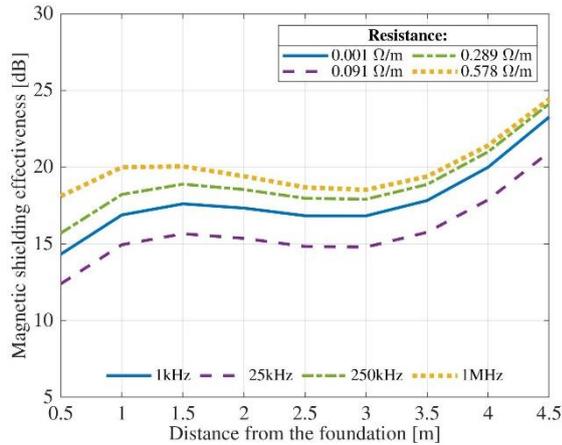
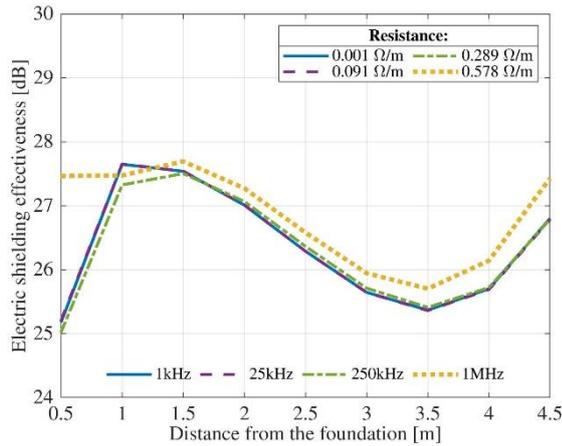


Fig. 9. Effect of the permeability of the steel on the electric and the magnetic shielding effectiveness.

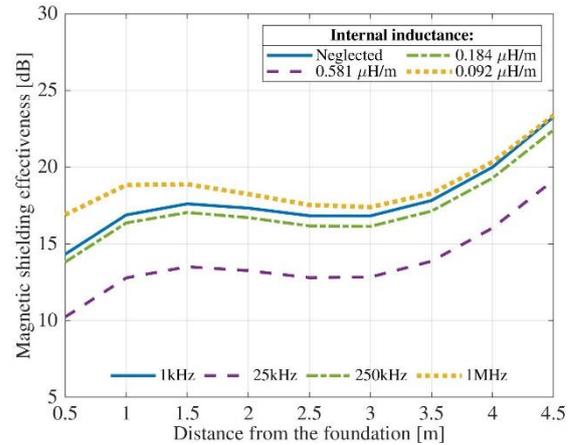
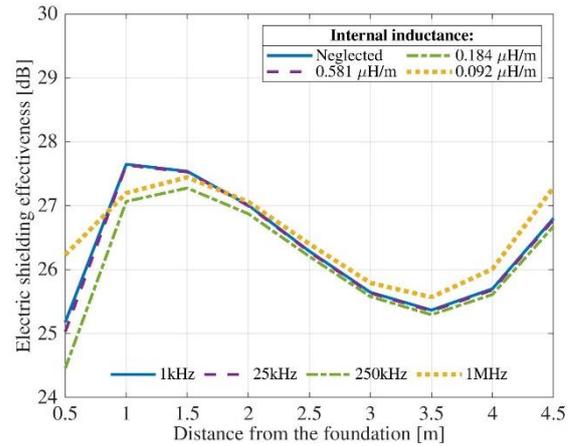


Fig. 10. Effect of the permeability of the steel on the electric and the magnetic shielding effectiveness.

The permeability is known to improve the shielding against an incident field; yet, when the excitation is connected to the reinforcement, the effects are contradictory. Increasing the permeability reduces the skin depth ( $\delta_i$ ) and, consequently, as the frequency increases, the increase in resistivity and the decrease in internal inductance are more pronounced. Nevertheless, the internal inductance of a conductor depends directly on the degree of magnetization of the material, and therefore it is also expected to increase with the permeability. Neglecting the skin effect and the internal inductance, the internal impedance can be approximated as  $Z_{int} = R_{DC} = 0.001 \Omega/m$ . At the frequencies characterizing the different return strokes in [17] and considering a worst-case scenario with  $\mu_r = 1000$ , the resistivity, approximated as  $R_{AC} = \frac{\rho}{2\pi a \delta}$ , is equal to  $0.0913 \Omega/m$ ,  $0.289 \Omega/m$ , and  $0.578 \Omega/m$  for 25 kHz, 250 kHz, and 1 MHz, respectively. The internal inductance, approximated as  $L_i = \frac{\mu \delta}{4\pi a}$ , is equal to  $0.581 \mu H/m$ ,  $0.184 \mu H/m$ , and  $0.092 \mu H/m$ .

Since the internal reactance of cylindrical conductors is often neglected, we carried out the simulations varying the resistance and the inductance independently at each frequency. Fig. 9 and Fig. 10 show that whereas the effect of taking into account the permeability is minor on the electric shielding, it could result in a considerable decrease

of the magnetic shielding effectiveness. However, one may not need to take it into account if the relative permeability of the steel used in the reinforcement is only a few hundred.

### III.5. Effect of the concrete

It has already been demonstrated that concrete does not contribute significantly to the magnetic shielding [8], [10]; yet, its effect on the electric shielding is critical. While the variations obtained in the magnetic shielding effectiveness, when including the concrete in the model, are less than 0.5 dB, Fig. 11 shows that the electric shielding effectiveness could duplicate. The improvement strengthens at lower frequencies and depends on the moisture content. The electric shielding enhances as the moisture content increases; thus, one could infer that it is correlated to the conductivity of the concrete.

## IV. CONCLUSION

The electromagnetic behavior of reinforced concrete changes when the reinforcement is characterized in transmission or conduction. Reinforced concrete does reduce the impact of the LEMP; however, the shielding effectiveness depends on the degree of magnetization of the steel used in the structure. The concrete itself

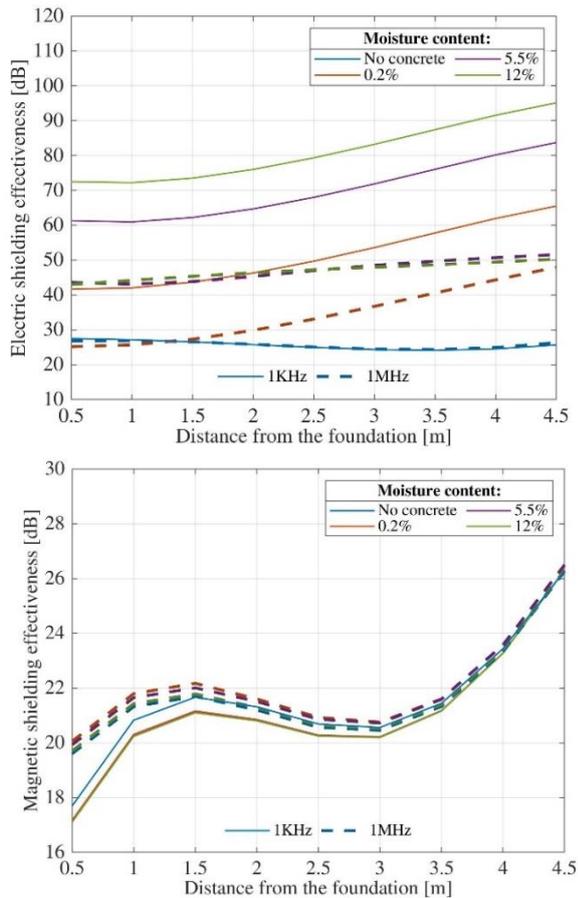


Fig. 11. Effect of the concrete on the electric and the magnetic shielding effectiveness.

strengthens the electric shielding, but its effect on the magnetic shielding is negligible. The most effective way to improve the electromagnetic shielding is by adding multiple layers. Nevertheless, a significant enhancement can also be obtained by reducing the mesh size. The effect of the radius of the rebars and the periodicity of the hoops is insignificant compared to the influence of these two parameters.

## REFERENCES

- [1] K. F. Casey, "Electromagnetic shielding behavior of wire-mesh screens," *IEEE Trans. Electromagn. Compat.*, vol. 30, no. 3, pp. 298–306, Aug. 1988.
- [2] L. Sandrolini, U. Reggiani, and A. Ogunsola, "Modelling the electrical properties of concrete for shielding effectiveness prediction," *J. Phys. D: Appl. Phys.*, vol. 40, no. 17, pp. 5366–5372, Sep. 2007.
- [3] R. A. Dalke, C. L. Holloway, P. McKenna, M. Johansson, and A. S. Ali, "Effects of reinforced concrete structures on RF communications," *IEEE Trans. Electromagn. Compat.*, vol. 42, no. 4, pp. 486–496, Nov. 2000.
- [4] E. Richalot, M. Bonilla, Man-Fai Wong, V. Fouad-Hanna, H. Baudrand, and J. Wiart, "Electromagnetic propagation into reinforced-concrete walls," *IEEE Trans. Microwave Theory Techn.*, vol. 48, no. 3, pp. 357–366, Mar. 2000.
- [5] D. Pena, R. Feick, H. D. Hristov, and W. Grote, "Measurement and modeling of propagation losses in brick and concrete walls for the 900-MHz band," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 1, pp. 31–39, Jan. 2003.
- [6] S.-Y. Hyun *et al.*, "Analysis of Shielding Effectiveness of Reinforced Concrete Against High-Altitude Electromagnetic Pulse," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 6, pp. 1488–1496, Dec. 2014.
- [7] T. Maksimowicz and K. Anisierowicz, "Investigation of Models of Grid-Like Shields Subjected to Lightning Electromagnetic Field: Experiments in the Frequency Domain," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 4, pp. 826–836, Aug. 2012.
- [8] A. Tatematsu, F. Rachidi, and M. Rubinstein, "Analysis of Electromagnetic Fields Inside a Reinforced Concrete Building with Layered Reinforcing Bar due to Direct and Indirect Lightning Strikes Using the FDTD Method," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 3, pp. 405–417, Jun. 2015.
- [9] I. A. Metwally and F. H. Heidler, "Reduction of Lightning-Induced Magnetic Fields and Voltages Inside Struck Double-Layer Grid-Like Shields," *IEEE Trans. Electromagn. Compat.*, vol. 50, no. 4, pp. 905–912, Nov. 2008.
- [10] I. A. Metwally, W. J. Zischank, and F. H. Heidler, "Measurement of Magnetic Fields Inside Single and Double-Layer Reinforced Concrete Buildings During Simulated Lightning Currents," *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 2, pp. 208–221, May 2004.
- [11] Institut XLIM, *TEMSEI-FD: Time Electromagnetic Simulator - Finite Difference Time Domain*. Limoges, France.
- [12] Altair, *FEKO: "FELDberechnung für Körper mit beliebiger Oberfläche"*.
- [13] J.-P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves," *Journal of Computational Physics*, vol. 114, no. 2, pp. 185–200, Oct. 1994.
- [14] C. Guiffaut, A. Reineix, and B. Pecqueux, "New Oblique Thin Wire Formalism in the FDTD Method With Multiwire Junctions," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 3, pp. 1458–1466, Mar. 2012, doi: 10.1109/TAP.2011.2180304.
- [15] S. Naranjo-Villamil, C. Guiffaut, A. Reineix, J. Gazave, "Simplified 3-D Modeling of Reinforced Concrete for the Calculation of Transient Electromagnetic Fields inside a Building Struck by Lightning," presented at XV International Symposium on Lightning Protection, 2019, São Paulo, Brazil.
- [16] S. W. Ellingson, "Constitutive Parameters of Some Common Materials," in *Electromagnetics*, vol. 1, Blacksburg, Virginia: VT Publishing, 2018.
- [17] I.E.C International Electrotechnical Commission, "IEC 62305-4: Electrical and electronic systems within structures," 2010.