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MAGNETIC FIELDS AND INDUCED VOLTAGES INSIDE LPZ 1 IN CASE OF A DIRECT STRIKE – RESULTS OBTAINED FROM MEASUREMENTS AT A 1:6 SCALED BUILDING AND COMPARISON WITH CALCULATIONS BASED ON IEC 62305-4

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Abstract - For the application of the concept of "Lightning Protection Zones (LPZ)", the knowledge of the magnetic fields and induced voltages inside a structure is necessary. The new lightning protection standard IEC 62305-4 gives formulae to assess these magnetic fields and induced voltages for structures with grid-like spatial shields in case of direct strikes. However, these formulae are based on theoretical investigations with necessary neglects. To validate the IEC-formulae experiments at a down-scaled model of a building (scale factor 1:6) in the lightning current laboratory of the University of the Federal Armed Forces Munich were conducted.

1 INTRODUCTION

Due to the ever increasing use and sensitivity of micro-electronic circuits and due to the interconnection of equipment by extended information technology networks during the last few decades, the control of the electromagnetic interferences has become the dominant task of lightning protection. As the basic philosophy to control lightning generated electromagnetic interferences, the principle of "Lightning Protection Zones (LPZ)" has been developed by the committee IEC TC 81 and has been laid down in the international standard series IEC 62305 [1, 2]. The principle of LPZs requires to form nested zones of successively reduced electromagnetic environment. This objective is achieved by a) shielding to reduce the electromagnetic fields and b) equipotential bonding of all lines at the LPZ-boundaries to limit the line conducted overvoltages and currents.

A cost effective method to form electromagnetic shields is to use existing metallic structural components, like the reinforcement of concrete. In IEC 62305-4 [2] formulae for the assessment of the magnetic fields and induced voltages inside grid-like spatial shields caused by a direct strike to the structure are given as a function of mesh width and location inside the structure. These formulae do not exactly represent the field inside for a given configuration. Moreover, they are worst case curves derived from the computation [3, 4] of numerous configurations of buildings or structures consisting of a single-layer metallic grid-like shield. These numerical simulations, however, were limited to a minimum mesh width of about 40 cm and had to be extrapolated for smaller mesh widths (typical 15 cm for practical reinforcement of concrete). Furthermore frequency dependent effects as well as transient phenomena were disregarded for the IEC-formulae.

Experimental investigations at a down-scaled model of a building (scale factor 1:6) with double-layer reinforcement in the lightning current laboratory of the University of the Federal Armed Forces Munich should help to validate the assessment formulae given in IEC 62305-4. The model dimensions were 3 m x 2 m x 2 m, representing a small industrial building with a base of 18 m x 12 m and a height of 12 m. Compared were the magnetic field, the magnetic field derivative and the induced voltage on three typical cable trays inside the model. The additional shielding effectiveness of the second layer of reinforcement grid has been analysed in previous experiments [5].

2 SCALE FACTORS

Measurements at scaled models necessitate that not only the geometry, but all relevant physical quantities have to be scaled according to the laws of the similarity theory. A detail description of the derivation of scale laws is given in [6]. Under the prerequisite that the permeability μ and the dielectric constant ε of the model and the real structure be the same, the scale factors relevant to the experiments conducted can be derived (Table 1). The relationship between a physical quantity of the model Q_m and the same quantity of a real structure Q_r is given by

$Q_m = Q_r / f$, with f being the scale factor.

The scale factor f for 'length' was chosen to M = 6, mainly because of material considerations: The ratio of the conductivity of steel (real reinforcement) to that of copper (model structure) is about 1:6.

Table 1: Scale factors

Physical Quantity	Length	Time	Conduc-tivity	Current
Unit	m	s	S/m	A
Scale Factor f	M	M	1/M	M

Physical Quantity	Magnetic field	Magnetic field derivative	Voltage
Unit	A/m	A/(m s)	V
Scale Factor f	1	1/M	M

3 TEST CURRENTS AND GENERATORS

Two impulse current waveforms were simulated:

- a positive stroke current of 200 kA, 10/350 µs according to IEC 62305-1 [1];
- a negative first stroke current of 100 kA, 1/200 µs according to the German standard KTA 2206 [7] for the lightning protection of nuclear power plants.

Table 2 gives the main parameters (current peak value i_{max}, front time T_1 and decay to half value T_2) of the test currents as defined in the standards, the down-scaled parameters for M = 6 and the parameters actually obtained in the model experiments. It was not possible to simulate the waveform 0,25/100 µs [1] of negative subsequent strokes: The down scaled front time of 0,25 µs/6 ≈ 40 ns could not be implemented in the laboratory at the models with physical dimension of several meters.

Table 2: Test current parameters

		i_{max} (kA)	T_1 (µs)	T_2 (µs)
Positive stroke	IEC 62305-1	200	10	350
	Scaled M=6	33,3	1,67	58,3
	Experiment	18	1,8	57
Negative first stroke	KTA 2206	-100	1	200
	Scaled M=6	-16,7	0,167	33,3
	Experiment	-5,5	0,25	12
Negative subsequent stroke	IEC 62305-1	-50	0,25	100
	Scaled M=6	-8,3	0,04	17
	Experiment	not possible		

Primary objective for the design of the impulse current generators was to achieve the required front time as close as possible. The positive stroke currents were generated by an over-critically damped 100 kJ capacitor bank with an additional peaking capacitor. The negative first stroke currents were obtained from a 250 kV three-stage Marx generator with an erected capacitance of 400 nF equipped with a low impedance peaking capacitor and a peaking spark gap.

4 TEST SETUP

The model represented a building with an ideally interconnected grid-like shield of two layers of reinforced concrete. It is well known that the concrete itself does not significantly contribute to the electromagnetic shielding. Therefore, the scale modeled structure simulated only the double-layer steel reinforcement of the concrete. The reinforcement of the roof and the side walls was simulated by copper grids (wire diameter 1,5 mm) having a mesh width of 20 mm. The distance between the two grid layers was 25 mm. At the edges of the grids all individual wires were soldered. Also all wires of the grids were soldered to the 2 mm copper ground plate. The inner and outer reinforcement layers were connected by 1,5 mm copper wires in a 200 mm spacing.

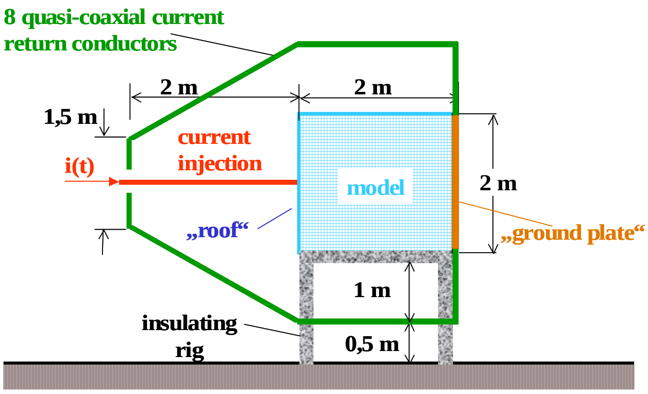

Figure 1: Schematic representation of the test setup

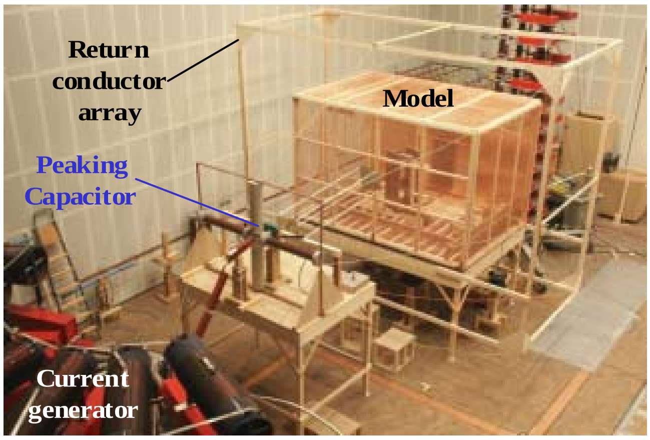

Figure 2: Test setup in the laboratory

The models were placed on a wooden support rig, 1,5 m above laboratory floor. In order to facilitate a symmetric arrangement of the model with respect to the test current generator, the model had to be rotated by 90° (see Figures 1 and 2, the roof is pointing to the left and the floor to the right). The current return paths from the ground plate was formed by an array of eight copper return conductors (10 mm^2 each) that were quasi-coaxially arranged around the model in a distance of 1 m to the side walls.

5 MAGNETIC FIELD MEASUREMENT

The currents were injected at 4 locations of the roof: to the center, to the edge of one long side and to two opposite corners as indicated in Figure 3. The magnetic field H and its derivative dH/dt were determined at four locations inside the model. The first location was in the center of the model. The other three locations were at half-height of the model (i.e. 1 m above the ground plate) in a distance of 0,75 m to the smaller (right) side wall. The distances to the long side wall were 5,5 cm, 0,5 m und 1 m, respectively.

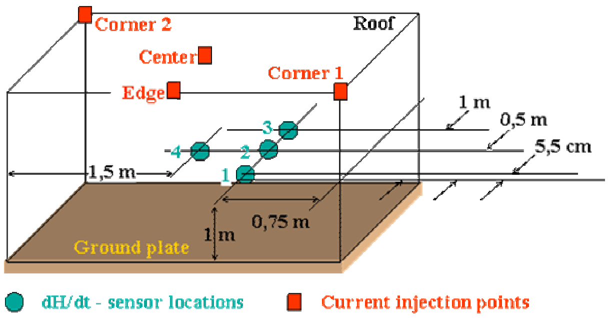

Figure 3: Sensors location and current injection points

The x, y and z components (definition of coordinates see Figure 4) of the magnetic field derivatives (dH/dt) were measured using shielded loop sensors of 6 cm, 15 cm and 20 cm diameter. The corresponding bandwidth of the sensors were 70 MHz, 22 MHz and 16 MHz, respectively. The signals were transferred to the digital scopes (HP 54510A, 200 MHz single shot bandwidth) via 300 MHz fiber optic link systems NanoFast OP 300-2A. The magnetic fields were derived from the (dH/dt)-waveforms by numeric integration. Background noise originating from the current generator spark gaps (start gaps, crowbar gap, peaking circuit gaps) was eliminated during the integration process. The shielded loop sensors reduce the electric field components by > 40 dB.

6 CABLE TRAYS

The model was equipped with the simulation of three typical cable trays as they are widely used in industrial plants and buildings. The down-scaled cable trays were made of 1 mm sheet copper. At both ends, the cable trays were connected by 1 mm copper wires to the inner reinforcement layer or the ground plate the shortest possible way. Figure 4 shows the arrangement of the cable trays inside the model.

To measure the induced voltage along the cable tray a 2 mm isolated sensor wire was located in the middle of each cable tray. At the roof side the wire was connected to the cable tray's metal structure. At the bottom side the sensor wire terminated into a fiber optical transmission system (50 Ω input).

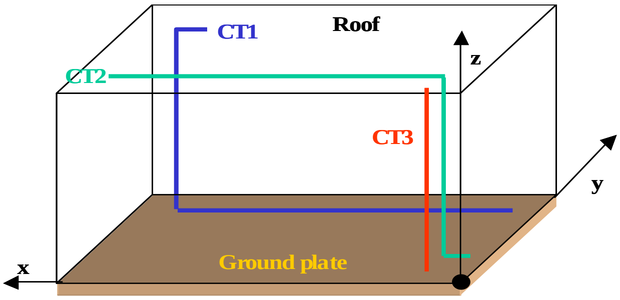

Figure 4: Routing of cable trays

7 RESULTING WAVESHAPES

Figure 5 shows a typical waveshape of the magnetic field for a positive stroke injected to the center of the roof (x-component of the sensor located 50 cm from the side wall of the model). As it can be seen, the magnetic field rise is much slower compared to the injected current rise. This effect has also been described in [5].

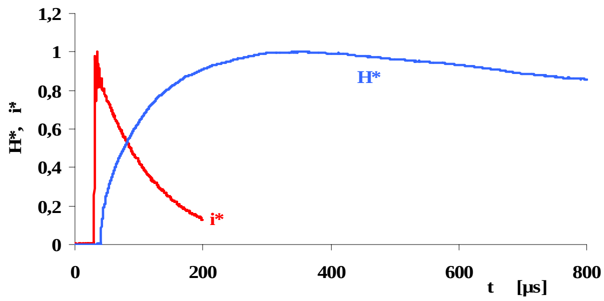

Figure 5: Normalized magnetic field H* and injected current i*

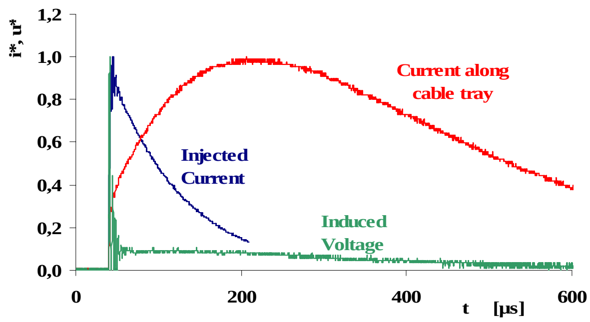

Figure 6: Normalized injected current, current along the cable tray and induced voltage

An example of the voltage induced to the sensor wire on the cable tray is given in Figure 6 for CT 1 and injection of a positive stroke to the roof center (normalized quantities). The current along the cable tray has, similar to the magnetic field H in Figure 5, a substantial slower rise compared to the injected current.

The induced voltage starts with a sharp peak which is about proportional to the steepness di/dt of the injected current. The sharp peak is followed by a slow decay, which is mainly due to the resistive voltage drop along the cable tray. At the instant of the peak of the current along the cable tray, where di/dt is zero, the voltage corresponds well to the d.c. resistance of the cable tray multiplied by the current.

8 MEASUREMENT RESULTS FROM THE MODEL EXPERIMENTS

Table 3: Peak values of H_{max} (in A/m) measured in the model and extrapolated to the real size building and to the standardized test currents

Current	Sensor location	Model data (1:6)	Extrapolated values (1:1)
First impulse current [1]	1	8,27	15,3
	2	12,5	23,1
	3	13,5	25,0
	4	12,6	23,3
First negative impulse current [7]	1	0,657	1,99
	2	0,508	1,53
	3	0,687	2,08
	4	0,622	1,88

Table 4: Peak values of $(dH/dt)_{max}$ (in A/m/µs) measured in the model and extrapolated to the real size building and to the standardized test currents

Current	Sensor location	Model data (1:6)	Extrapolated values (1:1)
First impulse current [1]	1	0,763	0,254
	2	1,03	0,343
	3	1,10	0,367
	4	1,09	0,363
First negative impulse current [7]	1	3,19	2,42
	2	2,66	2,02
	3	4,27	3,24
	4	2,46	1,87

Tables 3 and 4 show the peak values of the magnetic field H_{max} and the magnetic field derivative $(dH/dt)_{max}$ at the four sensor locations (see Figure 3). Table 5 shows the peak values of the induced voltages u_{max} at the three cable trays (see Figure 4). The representation in the tables is reduced to the maximum measured values, because the calculation according to IEC 62305-4 also gives only the highest values. Consequently for each sensor location and each cable tray only the value for the current injection point leading to the highest value is given. Further results of the measurement investigation are discussed more deeply in [8].

The results obtained at the model (1:6) are extrapolated firstly to the real size of the building (1:1) by using the scale factors of Table 1. Secondly the extrapolation includes the adaption of the measurement results which are based on the real test currents in the laboratory to the exact current parameters defined in the relevant standards (Table 2).

Table 5: Peak values of the voltage u_{max} (in V) measured in the model and extrapolated to the real size building and to the standardized test currents

Current	Cable routing	Model data (1:6)	Extrapolated values (1:1)
First impulse current [1]	CT 1	0,302	3,62
	CT 2	0,308	3,70
	CT 3	0,457	5,48
First neg. impulse current [7]	CT 1	0,814	22,2
	CT 2	0,741	20,2
	CT 3	1,050	28,7

9 CALCULATIONS ACCORDING TO IEC 62305-4

The fundamentals for the calculation of magnetic fields, magnetic field derivatives, and induced voltages in case of a direct strike to a building with a grid-like electromagnetic shield are given in Annex A of IEC 62305-4 [2]. The grid-like spatial shield forms a Lightning Protection Zone 1 (LPZ 1). The equations further used in this paper are valid for a single-layer shield, and they assume, that the distance from the point considered or from the cable routing to the wall or the roof is at least one mesh width of the electromagnetic shield.

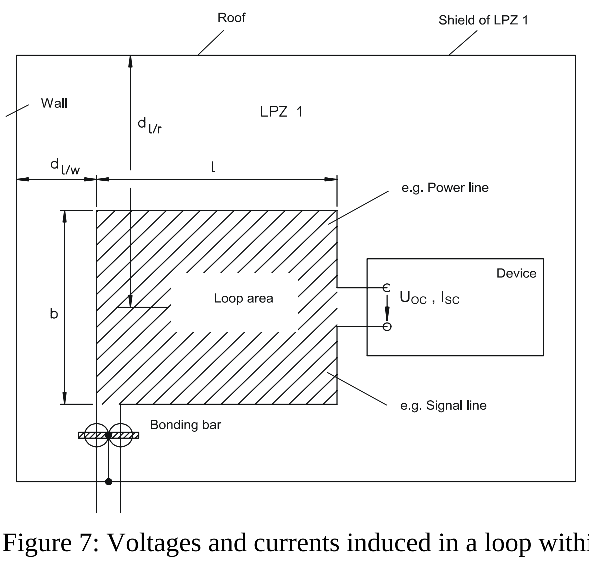

Figure 7: Voltages and currents induced in a loop within a building directly struck by lightning [2]

The peak values of the magnetic field H_{max} and the magnetic field derivative $(dH/dt)_{max}$ within LPZ 1 (Figure 7) can be estimated as:

$$H_{\max} = k_h \cdot i_{\max} \cdot \frac{w}{d_w \cdot \sqrt{d_r}} \quad (1)$$

where: k_h configuration factor (k_h = 0,01 $m^{-1/2}$);
i_{max} peak value of the lightning impulse current;
w mesh width of the grid-like shield of LPZ 1;
d_w shortest distance between the point considered to the wall of shielded LPZ 1;
d_r shortest distance between the point considered and the roof of shielded LPZ 1.

$$\left(\frac{dH}{dt}\right)_{\max} = \frac{H_{\max}}{T_1} \quad (2)$$

where: T_1 front time of the lightning impulse current.

For open circuits in structures directly struck by lightning the peak value of the induced voltage is given by (Figure 7):

$$u_{d/\max} = \mu_0 \cdot b \cdot \ln\left(1 + \frac{l}{d_{l/w}}\right) \cdot k_h \cdot \frac{w}{\sqrt{d_{l/r}}} \cdot \frac{i_{\max}}{T_1} \quad (3)$$

where: μ_0 = $4\pi*10^{-7}$ Vs/Am;
b width of the loop;
l length of the loop;
$d_{l/w}$ distance of the loop from the wall of the shield (LPZ 1);
$d_{l/r}$ average distance of the loop from the roof of the shield (LPZ 1);
k_h configuration factor (k_h = 0,01 $m^{-1/2}$);
w mesh width of the grid-like shield of LPZ 1;
i_{max} peak value of the lightning impulse current;
T_1 front time of the lightning impulse current.

In case of real cable routings it is essential to separate the entire routing into different sections having constant "geometrical quantities". This is for example necessary for the horizontal and vertical sections of the cable routings CT 1 and CT 2. The partial voltages are calculated based on eq. (3) for each section and then the partial voltages are added. This is a strong worst-case assumption because dependent on the orientation of the induction loop the partial voltages may also compensate each other partly. However, the orientation is usually unknown, therefore a simple addition seems to be correct. Further details of the calculation are given in [9].

10 CONSIDERATION OF ASECOND LAYER OF REINFORCEMENT

The calculations according to IEC 62305-4 are valid for a single-layer grid-like shield. However, the model for the experiments should represent a real building made of reinforced concrete, which usually consists of two grid layers. The additional shielding of a second reinforcement layer has already been investigated in [5] for a 1:1 size model. It is considered by reduction factors R according to Table 6.

Table 6: Reduction factor R for H_{max}, $(dH/dt)_{max}$ and u_{max} for a double-layer reinforcement compared to a single-layer

	H_{max}	$(dH/dt)_{max}$ & u_{max}
First impulse current [1]	1,4	3,1
First negative impulse current [7]	1,7	3,5

11 COMPARISON OF MODEL AND CALCULATION RESULTS

Following, the results of the model experiments (chapter 8) and of the calculations according to IEC 62305-4 (chapter 9) are compared for the peak values of the magnetic field (Table 7), the magnetic field derivative (Table 8), and the induced voltage (Table 9). The model results correspond to the extrapolated values from Tables 3, 4 and 5. For the calculations the results for the single-layer as well as for the double-layer grid-like shield (i..e. without and with the consideration of the reduction factors R from Table 6) are given.

Table 7: Comparison of model and calculation result for H_{max} (in A/m)

Sensor location	First impulse current [1]			First negative impulse current [7]		
	Model results	Calculation		Model results	Calculation	
		1 layer	2 layer (with R)		1 layer	2 layer (with R)
1	15,3	27,2	19,4	1,99	13,6	8,0
2	23,1	40,8	29,1	1,53	20,4	12,0
3	25,0	371	265	2,08	186	109
4	23,3	20,4	14,6	1,88	10,2	6,0

Table 8: Comparison of model and calculation result for $(dH/dt)_{max}$ (in A/m/µs)

Sensor location	First impulse current [1]			First negative impulse current [7]		
	Model results	Calculation		Model results	Calculation	
		1 layer	2 layer (with R)		1 layer	2 layer (with R)
1	0,254	2,72	0,88	2,42	13,6	3,89
2	0,343	4,08	1,32	2,02	20,4	5,83
3	0,367	37,1	12,0	3,24	186	53,1
4	0,363	2,04	0,65	1,87	10,2	2,91

Comparing the peak values of the magnetic field H_{max} and the magnetic field derivatives $(dH/dt)_{max}$ it is found, that the calculations according to IEC mostly lead to higher

results, i.e. they give results on the safe-side. Consideration of the reduction factor R for the second layer of reinforcement is necessary; otherwise the calculations would lead to unrealistic high values.
For the sensor locations 1, 2 and 4 the differences between model experiment and calculation are moderate. Considering the simplifications implied in the IEC-formulae, differences by a factor of up to 5, or so, had to be expected.
For the sensor location 3, however, which is very close to the wall, the differences are significantly higher. It seems that the increase of the magnetic field close to a reinforced wall is less dramatic than the IEC-formula suggests. Also in [4] it is stated: *"The results .... show that it is indeed not possible to calculate the complicated field distribution near the shield by a simple formula ..."*

Table 9: Comparison of model and calculation result for u_{max} (in V)

Cable rout-ing	First impulse current [1]			First negative impulse current [7]		
	Model results	Calculation		Model results	Calculation	
		1 layer	2 layer (with R)		1 layer	2 layer (with R)
CT 1	3,62	15,0	4,84	22,2	75,2	21,5
CT 2	3,70	14,2	4,58	20,2	71,0	20,3
CT 3	5,48	11,9	3,84	28,7	59,6	17,0

The induced voltages u_{max} in the cable routings correspond remarkably well, if the second layer of reinforcement is considered. The differences between the calculation and the model results then are usually below 20%, the maximum deviation is about 40%.

12 CONCLUSIONS

Voltages and currents in cable routings within reinforced structures directly struck by lightning can be calculated according to IEC 62305-4 [2]. Basis for the formulae is a grid-like spatial shield with a single-layer.
For comparison laboratory experiments have been conducted at a down-scaled model of a building (scale factor 1:6) to determine the electromagnetic quantities in case of a direct strike. The model simulates a realistic concrete reinforcement with two layers. It is found that the shielding effect of the second layer is to be considered.
At locations not too close to the wall the peak values of the magnetic fields and the magnetic field derivatives in the experiment are within reasonable agreement with the calculation results. Only the H and dH/dt peak values very close to the wall, i.e. directly at the reinforcement, differ considerably. The calculated values, however, are on the safe-side in almost all cases studied.
For lightning and overvoltage protection of the electrical and electronic system within a reinforced building usually the voltages induced in the cabling are the most important quantity. These voltages are reduced by at least 40 dB for a structure directly struck by lightning having a double-layer reinforcement as a grid-like shield. Calculations of the voltages induced along cable routings can be performed as follows:

- The voltages are calculated based on IEC 62305-4, Annex A with the mesh width of the (outer) layer of the reinforcement. If necessary, the investigated cable routing is separated into different sections having constant "geometrical quantities".
- Then the calculated voltages are reduced by the reduction factor from Table 6, to consider the shielding effect of further (at least a second) layers of reinforcement usually existing in real structures.

13 REFERENCES

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