A combined electromagnetic induction and radar-based test for quality control of steel fibre reinforced concrete

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Summary

The authors of the paper have made an attempt to detect the fibre content and fibre spacing in a steel fibre reinforced concrete (SFRC) industrial floor. Two non-destructive testing (NDT) methods: an electromagnetic induction technique and a radar-based technique were applied. The first method allowed to detect the spacing in subsequent layers located in the thickness of the slab. The result of the second method was a 3D visualization of the detected fibre in the volume of concrete slab. The conducted tests showed aptitude and limitations of the applied methods in estimating fibre volume and spacing. The two techniques also allowed to locate the areas with relatively low fibre concentration which are very likely to be characterized by low mechanical properties.

Keywords: *SFRC, non-destructive testing, quality control, electromagnetic induction, radar, fibre*

1. Introduction

Despite its brittleness and low capacity to bear tensile stress (Mehta and Monteiro, 2013; Silva et al., 2015) ordinary concrete is the most frequently used building material in the world. Concrete is almost always reinforced by some kind of steel elements (e.g. bars, stirrups, meshes) when used for construction to counteract its brittleness. For the last 50 years, steel fibre have become a more and more popular type reinforcement for concrete. Currently, Steel Fibre Reinforced Concrete (SFRC) is one of the main building materials (Kovács and Balázs, 2004; Katzer and Domski, 2012). SFRC is characterized by higher tensile, shear and flexural strength (Patil and Sangle, 2017; Soetens *et al.*, 2017; Jang and Yun, 2018; Li *et al.*, 2018) better performance when exposed to elevated temperatures (K.Srinivasa Rao, S.Rakesh kumar, A.Laxmi Narayana) and lower shrinkage (Yousefieh *et al.*, 2017) than ordinary concrete of similar composition. Usually, steel fibre is arranged randomly, but evenly in the SFRC volume but in some circumstances irregularity in the fibre distribution may occur. These irregularities in fibre spacing significantly affect its properties. Homogeneous spacing of randomly oriented fibre within a structural element is crucial for guaranteeing proper structural performance with

a satisfactory degree of repeatability (Ferrara and Meda, 2007). Many attempts are being made to study fibre spacing using different destructive and non-destructive methods. The most successful methods are X-ray tomography (Suuronen *et al.*, 2013; Ponikiewski *et al.*, 2015) and cross-section analysis (Dupont and Vandewalle, 2005). Both methods give very precise results but are not feasible in common *in-situ* test scenarios. Simplicity of a conducted test and affordability of used equipment are two main factors influencing the practicability and popularity a testing method. In many cases construction companies already have apparatuses dedicated for NDT location of steel bars in existing concrete structures. Harnessing such apparatuses for assessment of steel fibre volume and spacing would be the most practical and sustainable solution. In authors' opinion two existing NDT techniques: electromagnetic induction and radar-based techniques have the potential for testing SFRC. The inductive technique was proven as a robust and simple non-destructive method to assess the content and the distribution of steel fibre. Nevertheless, there is still a necessity to define its accuracy. The equations for the conversion of the inductance into fibre volume and spacing (Cavalaro *et al.*, 2015) are also needed. Multiple attempts have also been made to use radar-based technique for similar assesment of SFRC. Fundamental differences between electromagnetic induction and radar technologies are the detectability of objects of different materials and the dependency on the properties of the base material. Using the induction technology only ferrous materials can be detected. While radar techniques allow to detect objects of different materials including ferrous and non-ferrous metals, water-filled pipes, voids, etc. (Korl, Wuersch and Zanona, 2013). Moreover, the radar based technique can be applied not only to detect location of reinforcement but also moisture assessment in reinforced concrete (Agred, Klysz and Balayssac, 2018).

Authors decided to conduct a research programme focused on using both techniques simultaniously to assess fibre spacing in hardened SFRC. Combining two separate NDT methods proved to be very efficient in assessment of mechanical properties of concretes with no fibre reinforcement (Katzer and Kobaka, 2009). Results achieved this way were much closer to real strength characteristics than the results based on only one method. In authors' opinion it is feasible to harness devices which are commercially available (and commonly used to detect rebars) to instantly detect fibre and assess their volume and spacing. The main aim of the conducted research programme was to prove the concept and enable further research in this area.

2. Materials and equipment

The tests were carried out on the industrial floor located inside a depot building in Koszalin, Poland (see **Fig. 1**). The tested floor (493m^2) was composed of two layers: a 100mm thick

concrete undercoat and a 150mm thick main SFRC layer. Hooked steel fibre (dimensions of the fibre 50x1.0mm, tensile strength 1115 MPa according to EN 14889-1 standard) in the volume of $V_f = 0.3\%$ constituted the reinforcement. The declared strength class of concrete was C20/25. The tests were carried out after 6 years since the moment of casting the concrete.

Fig. 1. The tested industrial floor

Both NDT devices used in the research programme were developed for assessment of rebar location in hardened concrete (Mohshin, 2017). The measuring device using electromagnetic induction technique (*Operating instruction PS 200*, 2016) was designed to scan a flat square area of 0.36m^2 (Dérobert, Aubagnac and Abraham, 2002). The principle of the device's operation is as follows: when alternating current runs through the probe coil of the device, electromagnetic field appears around the coil , and if there is a ferromagnetic material in the field, it brings about a change in the voltage of the coil, the voltage change appears according to the diameter around the cover thickness of the rebar (Kobayashi and Kawano, 1991). The method dedicated to the rebar detection was adopted in the tests to localize steel fibre in the area. Using the electromagnetic induction device 32 randomly chosen square areas of the floor were tested. The total tested area was equal to 11.5m^2 which represented 2.3% of the area of the whole floor. The measuring device allowed to conduct tests in depth up to 150mm. During the tests four measuring depths were scanned: 30mm, 60mm, 90mm and 120mm.

The applied radar apparatus emitted radar pulses spread over the frequency range from 1.0 to 4.3 GHz (*Operating instruction PS 1000*, 2017). The lower the frequency the deeper the subsurface is penetrated and the higher the frequency, the smaller objects can be spotted (Korl, Wuersch and Zanona, 2013).

When the radar device is moved over the surface a measurement is taken every 5mm. At one scanner position a high number of pulses are emitted and recorded to determine the full reflection pattern of the objects under the surface. Multiple acquisitions are used to reduce the noise in the data which leads to a clean image (Korl, Wuersch, & Zanona, 2012).

The signal acquired by the radar front-end is further conditioned by the following steps (Korl et al., 2012):

• Correction of antenna sizes and positions;

• Background removal with automatic foreground/background detection to mask uniform structures such as the surface and possible stratifications;

• Automatic gaining to compensate the damping of the radar waves in the base material;

• Time-zero estimation (automatic recognition of the surface position);

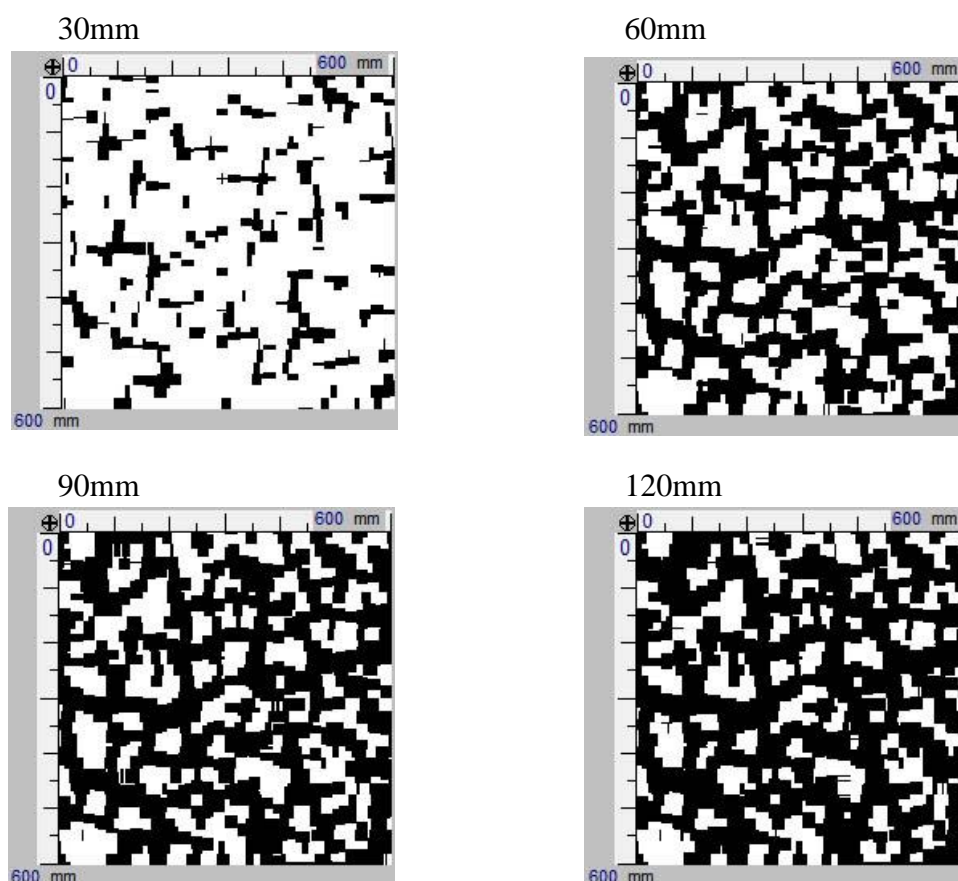• Temperature compensation to allow immediate and accurate measurements directly after start-up.

30mm

60mm

90mm

120mm

Fig. 2. Exemplary images of a scanned area (600mm · 600mm) at various depths using electromagnetic induction technique
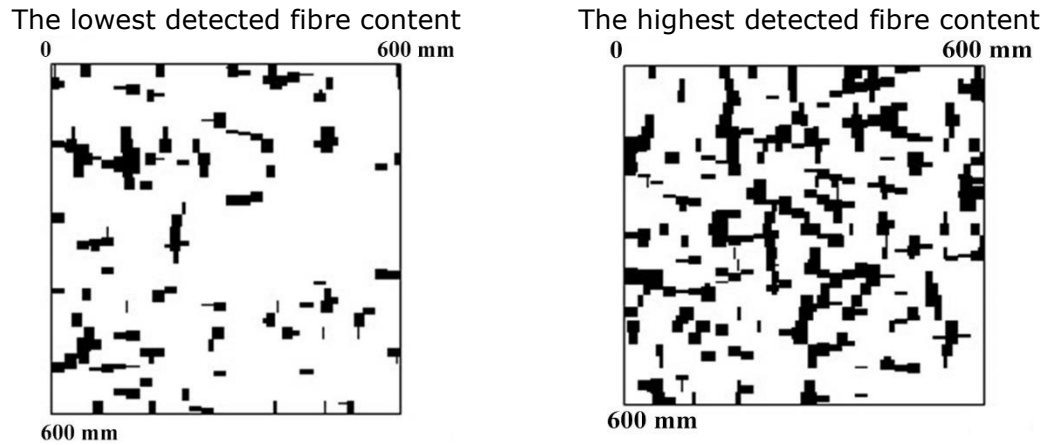
Fig. 3. Images of detected fibre (using the electromagnetic induction technique) in different tested areas at the same depth of 30mm

3.   Test results and analysis

The exemplary images of the tested industrial floor using an electromagnetic induction technique are shown in the **Fig. 2**. The obvious disadvantage of this scanning method is the "shadow" cast by the fibre present in the top layers. The created "shadow" increases blackening of the images in deeper layers. Therefore, in subsequent layers the shaded areas should not be taken into account to assess fibre presence.

The advantage of the electromagnetic induction method is a possibility of instant assessment of fibre volume and spacing in the scanned area. The examples of such possibility are images of tested areas located at the depth of 30mm, presented in **Fig. 3**.

Relative percentage of detected fibre in the layers located every 30mm is presented in **Fig. 4.** In subsequent layers the shaded areas were not taken into account to assess relative percentage of fibre content. The electromagnetic induction technique detected almost 50% of steel fibre in the second layer located at the depth of 30mm - 60mm. Other layers contained from 15.5% to 20.2% of steel fibre. Low fibre content in the top layer can be explained by the so-called "wall effect" thoroughly described in literature (Gettu *et al.*, 2005; Torrents *et al.*, 2012; Singh, 2017). Smaller amount of fibre detected at depth of 60mm to 120mm does not harmonize with genuine fibre content. The analysis of specimens obtained by coring confirmed high uniformity of fibre spacing across the thickness of the floor. The explanation for this phenomenon might be too low measuring sensitivity of the apparatus. The depth and "shadow" cast by the fibre present in the top layers play a key role in this phenomenon.
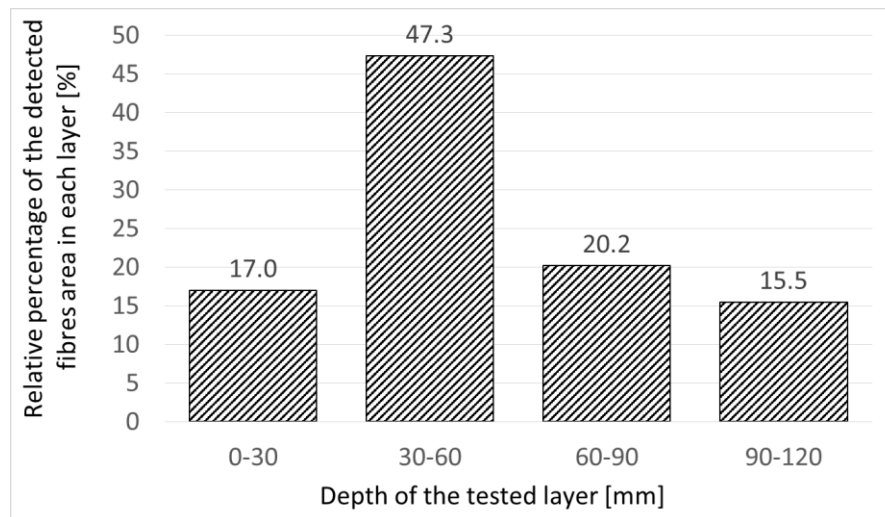
Fig. 4. Relative percentage of the detected fibre at each scanned depth

Percentage deviation of fibre volume for 32 tested areas is presented in **Fig. 5.** The results are grouped by depth. The top layer was characterized by the highest percentage deviation of fibre volume. The proximity of the surface influenced homogeneity of fibre distribution. The second layer placed at the depth of 30mm - 60mm was characterized by the lowest value of the percentage deviation of fibre volume. Along with the depth, the value increased. The second layer, due to the best reading parameters and lowest percentage deviation of fibre volume is the most suitable for assessing volume and spacing of steel fibre.
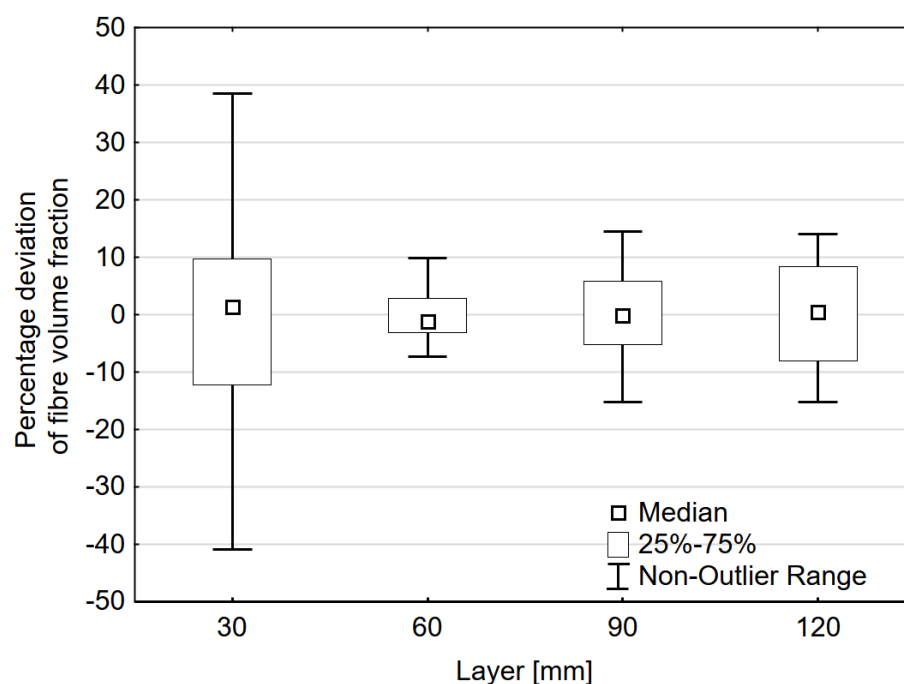

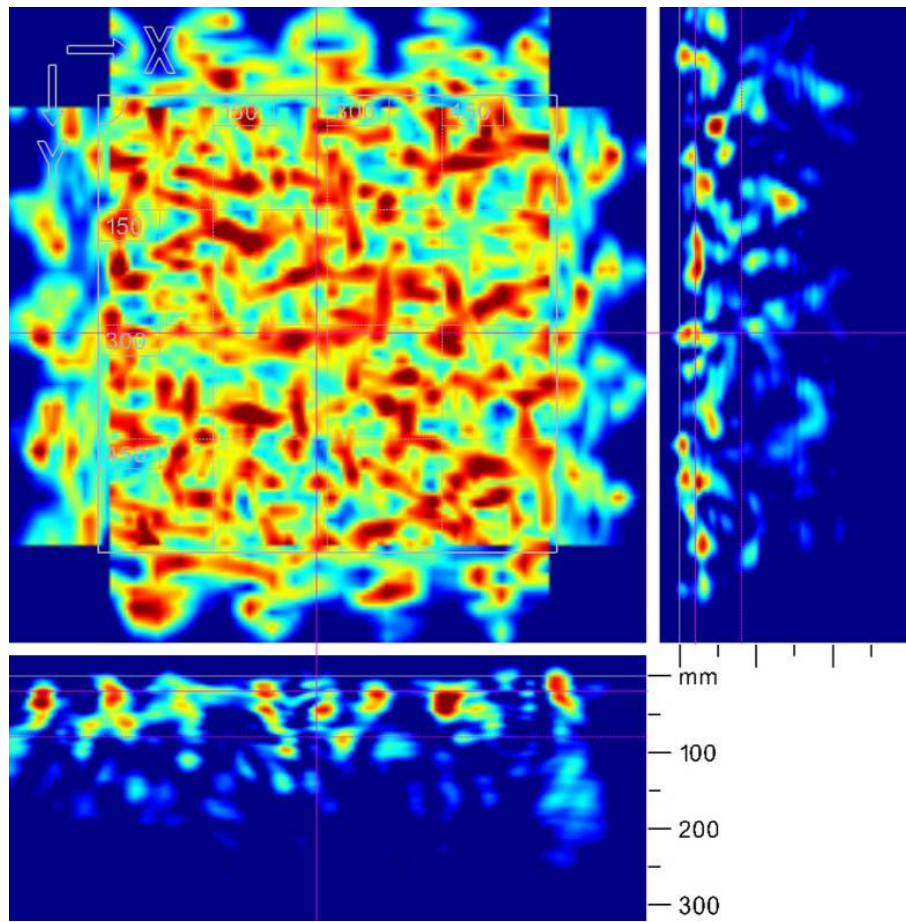**Fig. 5.** Percentage deviation of fibre volume

Fig. 6. 2D visualisation of data obtained by the radar-based technique

The results of fibre detection process of a square section (600mmx600mm) of the industrial floor, based on the radar technique, are presented in **Fig. 6.** The red colour indicates areas characterized by high concentration of fibre. The testing equipment was able to detect high concentration of fibre only in the top layer which can be observed in the bottom and right view of the image. The advantage of the method is the 3D image of the tested area which can be rotated at any angle in the program supplied with the device (**Fig. 7**).
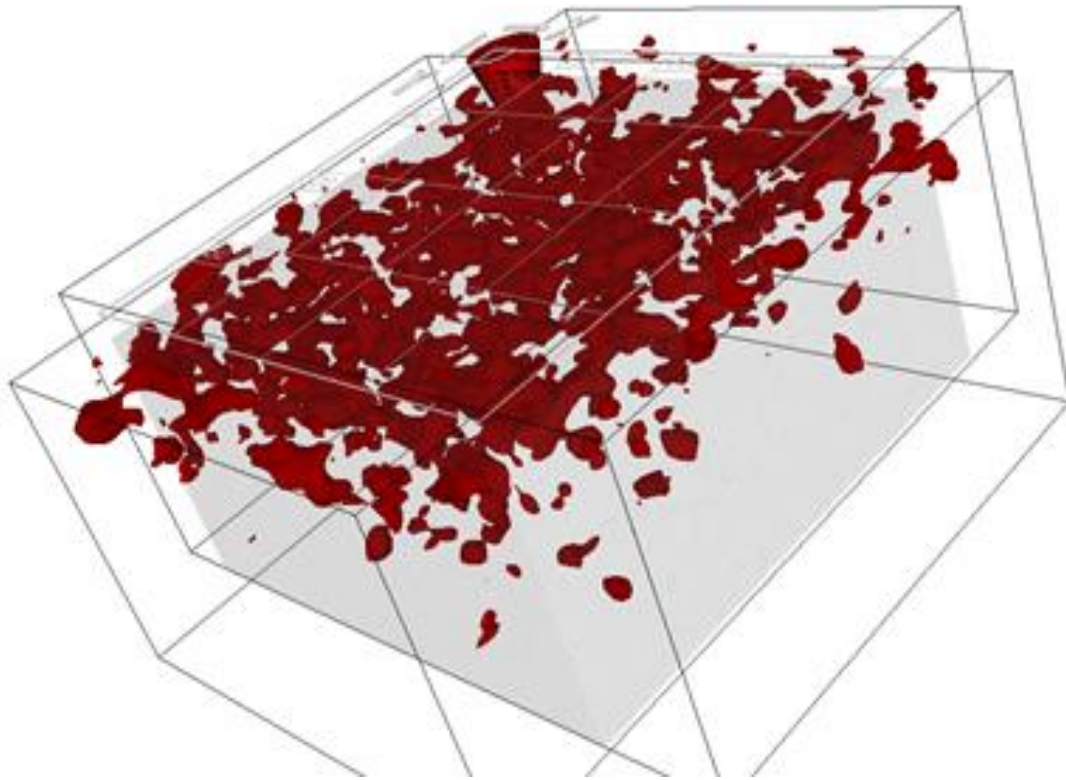
Fig. 7. 3D visualisation of data obtained by the radar-based technique

4. Fibre spacing determination and discussion

The *three-parameter generalised beta distribution* was chosen to define fibre spacing. This is the three-parameter distribution with the PDF (probability density function) described by the following formulae:

$$g(x; p, \gamma, \delta) = \frac{p}{B(\gamma,\delta)} x^{\gamma p - 1} (1 - x^p)^{\delta - 1}, \quad 0 < x < 1 \qquad (1)$$

in the formulae $B(\gamma, \delta)$ is *beta function* defined by the following equation:

$$B(\gamma, \delta) = \frac{\Gamma(\gamma)\Gamma(\delta)}{\Gamma(\gamma + \delta)} \qquad (2)$$

where Γ (gamma function):

- for positive integer numbers n: $\Gamma(n) = (n - 1)!$, $\qquad (3)$

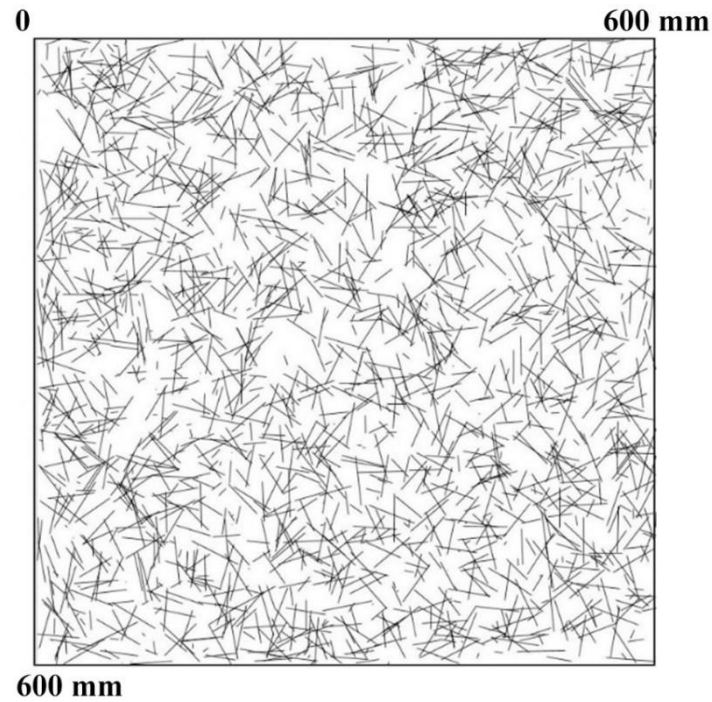- for other positive numbers z: $\Gamma(z) = \int_0^\infty x^{z-1} e^{-x} dx.$ (4)

Fig. 8. A computer simulation of fibre spacing based on the *three-parameter generalised beta distribution* at the depth of 30mm
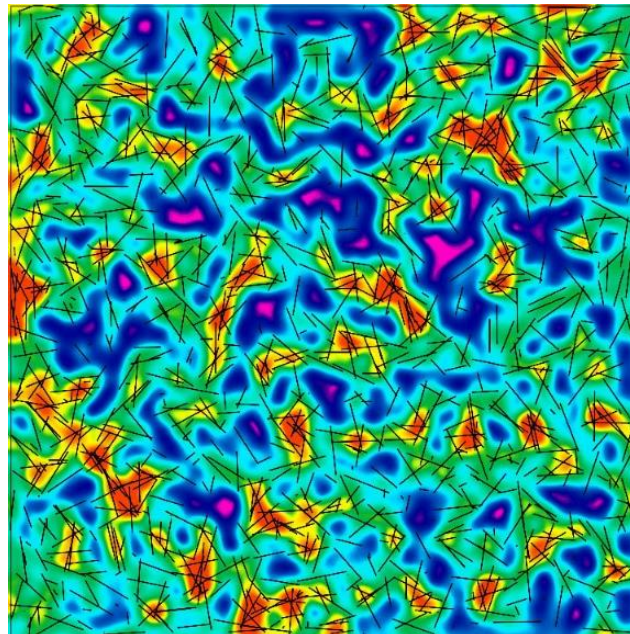

Fig. 9. A computer simulation of fibre spacing exposing fibre concentration fields (warm colours) and low intensity of fibre appearance (cold colours)

The main advantage of using the *three-parameter generalised beta distribution* is easy adjustment of the probability function shape. In **Fig. 8** the results of the computer simulation of fibre spacing based on *three-parameter generalised beta distribution* are presented. The graphical representation of fibre spacing shown in **Fig. 8** is difficult to analyse especially in terms of fibre concentration fields and lack of fibre fields. Due to the fact that uniformity of fibre spacing is essential to the safety of SFRC structure one should look for fibre concentration fields and lack of fibre fields. A special spot map was prepared (see **Fig. 9**) to clearly expose fibre concentration fields.

There is noticeable conformity of displaying steel fibre spacing obtained by the radar based technique (**Fig. 5**) and by the computer simulation (**Fig. 9**). In the red fields steel fibre is highly concentrated. The similarity of the two pictures leads to the conclusion that the testing equipment based on radar waves used for fibre detection is able to recognize fibre concentration fields but not a single fibre.

5. Conclusions

The results obtained during the research programme allow to form the following conclusions:

1. The method based on the electromagnetic induction technique can be applied to estimate the approximate volume of steel fibre in a hardened SFRC element and the uniformity of fibre spacing. However, the method requires calibration to obtain good quality of results in deeper layers due to the "shadow" cast by the fibre present in the top layers. The method can be applied to detect steel fibre up to the 120 mm thickness of the tested element.

2. The method based on the radar technique is suitable for instant detection of the areas with a clearly spaced fibre volume (too low or too high local fibre concentration). Theoretically the method can be applied to detect steel fibre presence up to the 200 mm thickness of the tested element, yet only fibre present in upper layers is correctly detected. The testing equipment based on the radar technique used for fibre detection is able to recognize fibre concentration fields but not a single fibre.

3. Both methods together can detect fibre concentration in SFRC volume but cannot detect a single fibre.

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