MODELING MAGNETIC EFFECTS OF STEEL REBAR OF CONCRETE SURROUNDINGS FOR ELECTROPHYSICAL APPARATUS

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Abstract

The article describes an advanced approach to modelling magnetic properties of reinforced concrete structures taking into account the anisotropic effect due to rod layers orientations. The equivalent model has been validated in the computation of a test problem. For comparison, simulations have been carried out with a detailed 3D FE model that describes each of the steel rods. The equivalent model has required a few times less finite elements than the detailed model. A comparison of the fields obtained has demonstrated a very good match, even for the distances comparable with the rebar rod gaps.

INTRODUCTION

Buildings for large electrophysical apparatus, such as accelerators, experimental fusion devices, customs examination equipment, industrial and medical tomography systems etc, are typically constructed of reinforced concrete with steel rebar. Particularly, the ITER Tokamak Complex has steel rebar with a complex pattern [1, 2]. The rebar is arranged as a stack of criss-cross layers of steel bars filling from 1.5% to 12% of the structures [1]. Some of the reinforced structures are located as close as 5 – 10 m to the tokamak. The steel rebar in concrete are magnetized by the stray fields generated by the plasma and tokamak magnets (EMS ITER) up to saturation.

Previous studies have revealed a noticeable effect of the magnetized rebar on a field distribution in the plasma region [3] and outside the tokamak [4], thus making concern for performance, electromagnetic compatibility and safety. Strict design criteria are adopted for the acceptable level of field perturbations and efficiency of shielding the tokamak components, primarily injectors and analyzers.

Voluminous ferromagnetic structures may reduce the natural level of Earth's magnetic field (EMF) in the buildings. Russian safety standards for construction specify the acceptable EMF reduction as a half of the natural level [5]. For assessment of the interior EMF, mathematical modelling is applied with the use of simplified models for reinforced structures.

HOMOGENEOUS ISOTROPIC MODEL

Large electrophysical devices produce stray fields that are much higher than EMF, while massive ferromagnetic structures of the building affect the field distribution noticeably. This makes correct information about the stray field essential for the medical and safety engineering provisions as well as to ensure the normal operations of equipment sensitive to magnetic fields. The effect of the magnetized ferromagnetic structures can be evaluated with the use of solid steel models, models with effective volumetric steel fractions, or isotropic models for reinforced concrete. In particular, the authors have developed the Magnetic Model of the ITER Tokamak Complex, ver.1 (MMTC1) [6] that includes the bioshield with its lid, basemat, ceiling, walls, and seismic pit.

A challenging issue in modeling reinforced structures is to adequately describe the steel rebar arrangement. The layered pattern of the rebar produces a complicated field map inside the structures and near the tokamak building. However, at a distance comparable with a typical step of the rebar, contributions of separate steel bars are smoothed, and the reinforced concrete structure acts as a solid body with averaged magnetic properties. These properties are dictated by a magnetization curve of the steel and the layered pattern of the rebar.

In the MMTC1 each reinforced concrete structure was represented via a spatially homogeneous equivalent with isotropic magnetic properties [6]. The B-H characteristic of the equivalent was given as $B = 0.5 \cdot k \cdot f(H)$, where $B = f(H)$ is the magnetization curve of the steel rebar [7], k is the filling factor, 0.5 is the correction coefficient for the layered pattern. The correction coefficient is taken from the assumption that only 50% of bars which are co-directed with the magnetic field can effectively conduct the flux. $\eta = 0.5$ is applicable for any direction of the external field coplanar with the rebar layers. If the external field has a component normal to the rebar layers, the equivalent permeability and magnetization should be significantly lower as the bars are oriented normally to the field. The results obtained with the MMTC1 suggest that the normal field would have a weak effect on the rebar magnetization. However, more reliable modeling seems desirable.

ADVANCED LAYERED MODEL

Papers [1, 2] describe an advanced isotropic model for concrete structures with steel rebar that that takes into account anisotropic effects due to the rebar pattern. As compared to the homogeneous isotropic model, the proposed model provides more accurate assessment of the magnetic effect of the rebar with the same computational cost. For a detailed model describing every steel bar individually the computational cost is extremely high.

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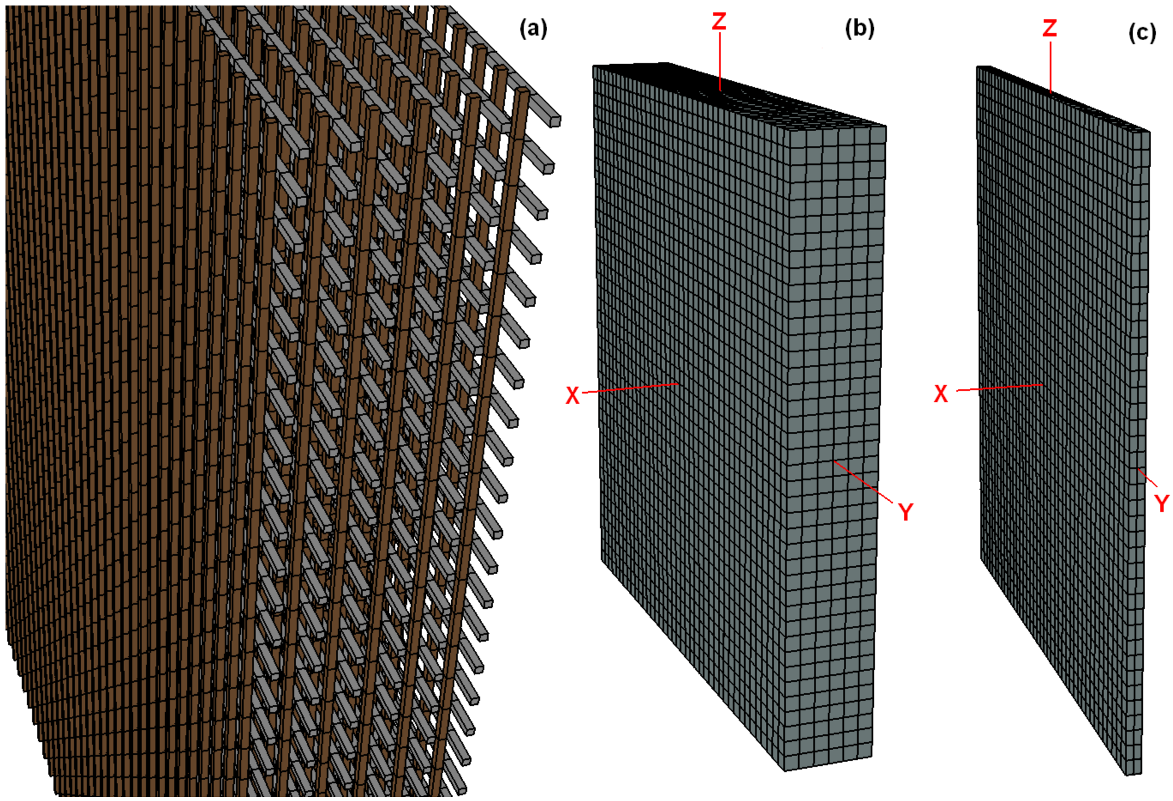

Figure 1: Computational models for test problem with a set of criss-cross rebar layer magnetized in parallel or perpendicular to layers external field: detailed (a), homogeneous isotropic (b) and single-layer (c) models, prepared for KLONDIKE code [8].

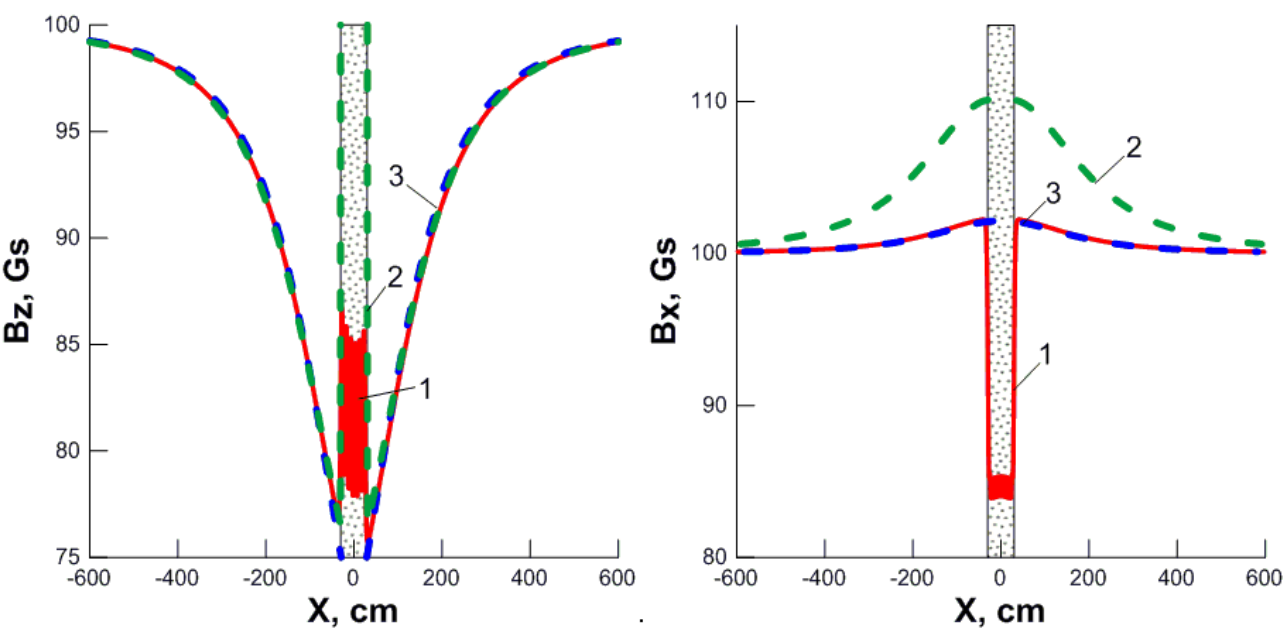

Figure 2: 100 Gs field disturbed by reinforced concrete structure. Field co-planar (B_z) or normal (B_x) to rebar. 1 – detailed models, 2 – homogeneous isotropic models, 3 – single-layer models.

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In the advanced model, reinforced concrete is modelled as a layered structure formed with alternating magnetic and non-magnetic isotropic layers in the plane coplanar with the rebar layers. In the extreme case, the model is limited to a single isotropic layer. Geometry and effective properties of every layer are pre-determined in field simulations over a periodicity cell of the modeled structure.

The model has been validated in comparative simulations [1, 2] of the test problem with the use of 3 models (Fig. 1):

1) detailed 3D FE model with realistic description of the geometry, configuration and permeability of every bar (Fig. 1a);

2) isotropic model with a single homogeneous isotropic material, as in MMTC1 [6] (Fig. 1b);

3) advanced model representing a layered structure formed with alternating magnetic and non-magnetic isotropic layers, as described in [1], Fig 1c).

The study [2] has demonstrated that the layered model enables sufficient generality and is applicable for reinforced structures with a complex rebar pattern, non-linear magnetic properties, and non-uniform external field. A high accuracy of field evaluation is achieved, with a calculation error below 1%. The *optimized double-layer model* provides the error as low as 0.1%. For the majority of practical computations, the *single-layer model* gives sufficiently accurate predictions. The *double-layer model* is recommended for field simulation in the regions near the edges of reinforced structures where field behaviour is most complicated.

VALIDATION

The test simulations have been performed with the use of the finite-element code KOMPOT [8, 9] that utilizes differential formulation of the magnetostatic problem and enables high discretization of a calculated domain.

In order to ensure a smooth solution, the authors have carried out a benchmark with the code KLONDIKE [8] based on the integral formulation. The integral formulation of the magnetostatic problem provides a smooth solution for distant areas and is preferable for a range of applications.

The test problem represented concrete cuboid 60cm×400cm×400 cm reinforced with 12 criss-cross layers of steel bars each 400 cm long (Fig. 1a). The bar cross section was taken as 2cm × 2cm. The volumetric fraction of steel in the structure was 8%. For *homogeneous isotropic models* (Fig. 1b) an average filling factor $k = 8\%$ and isotropic correction coefficient $\eta=0.5$ were applied. The *layered models* (Fig. 1c) used the width contraction of 0.17 and filling factor of 0.24 pre-determined in field simulation in the periodicity cell.

A uniform external field distorted by this structure was simulated. Two options for the external field orientation were considered, (1) parallel and (2) normal to steel bars (Fig. 2). Numerical experiments have shown that *homogeneous isotropic models*, both finite-element and integral, overestimate magnetic effect of the rebar by several times if the external field is directed across steel bars. This leads to ~10% inaccuracy in the resulting field. On the other hand, the proposed *layered models* provide practically the same result, as the *detailed models*, for any field direction.

A discrepancy between results obtained with two codes is as low as 0.1%. This implies that the proposed approach of modeling reinforced structures can be utilized with any magnetostatic code and type of formulation.

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