NUMERICAL ANALYSIS OF INTERACTION OF STEEL-FIBRE CONCRETE SLAB WITH SUBSOIL AND COMPARISON WITH VALUES MEASURED DURING EXPERIMENTAL LOADING TEST

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Abstract

Numerical interaction model of steel-fibre reinforced concrete slab and subsoil was created by two different software tools. Both software tools are based on finite element method (FEM). Input data for numerical analysis were observed experimental loading test of steel-fibre reinforced concrete slab. The loading was performed using unique experimental equipment constructed in the area Faculty of Civil Engineering, VŠB-TU Ostrava. The analysis of the interaction of steel-fibre reinforced concrete slab with subsoil was solved with application of inhomogeneous half-space. Application of inhomogeneous half-space allows better capture the subsoil behaviour and its increasing modulus of deformability with increasing depth of subsoil model. Homogeneous half-space this takes no account and calculated settlement is strongly dependent on the size of the subsoil model, as parametric study demonstrated. It has been proven by parametric study, that the settlement obtained by the analysis of inhomogeneous half-space is not so much dependent on the size of the subsoil model. The resulting values for analysis of homogeneous and inhomogeneous half-space were compared. Values calculated by both types of interaction models were compared with values measured during the loading test of steel-fibre concrete slab.

Keywords: Fibre concrete, steel-fibre concrete, subsoil-structure interaction, foundation structures, half-space, FEM analyses.

1. Introduction

Fibre reinforced concrete is a composite material. In principle it is based on concrete supplemented by randomly dispersed fibers. Fibre concrete, a composite with cement matrix reinforced by dispersed fibres, is a topic that is under great interest of the technical and scientific community [1, 3, 4, 10]. The number of contributions to the topic state of stress of fibre reinforced composite material in interaction with surrounding soil has

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increased in last years. Dependable quantitative and qualitative description of the subsoil-structure interaction represents the current issue. It includes a diverse range of determining factors (composition of fibre reinforced concrete, character of subsoil and loads, etc.). Furthermore, this interaction system has a strongly spatial and nonlinear character, which is very difficult to objectively describe by the simplified plane theories. The complexity, variability and inhomogeneity of the subsoil contribute to the complexity of description of behavior of the whole system. This is reflected in the necessity for research into the constitutive modeling of the behavior soil environment. A comprehensive system of methods for taking into account the subsoil-structure interaction and to establish appropriate distribution of contact stresses and strains or stresses and strains in deeper soil layers under the structure is not yet available.

2. State of the art

The subsoil-structure interaction could have a very complicated character which requires, among other things, the utilization of advanced constitutive models of the behavior of individual parts of cooperating system. Input characteristics of applied material models often have lower levels of reliability (especially in the case of the subsoil). This can lead to a lower level of reliability of results of modeling. For this purpose, research and experimental measurements focused on the settlement of loaded foundation soil, deformations of the slabs in interaction with subsoil and dependence of stress in the slabs on the characteristics of the subsoil are still performed. The work published by *Barros and Figuieiras (1998)* in article [2] developed aims to contribute to the research effort to clarify the behavior of fiber reinforced concrete slabs on soil foundation. For this purpose, experimental and numerical investigations were carried out. Also, the *Miltenberger, Attiogbe and Bissonnette (2007)* in article [17] present their experimental findings. Article [17] provides results from a controlled steel-fiber slab-on-grade experiment relating drying shrinkage, curling and joint opening. An extensive experimental investigation with the aim of studying the structural behavior of slabs on ground made of steel fiber-reinforced concrete (SFRC) is presented in paper [18] published by *Sorelli, Meda and Plizzari (2006).* Several full-scale slabs reinforced with different volume fractions of steel fibers having different geometries were tested under a point load in the slab center. A hybrid combination of short and long fibers was also considered to optimize structural behavior. Experimental results show that steel fibers significantly enhance the bearing capacity and the ductility of slabs on the ground. In paper [16] published by *Meda and Plizzari (2004),* the fracture behavior of steel fiber-reinforced concrete (SFRC) is studied by using nonlinear fracture mechanics (NLFM) finite element (FE) analyses. The fracture mechanics method has been validated by results from experiments performed by the authors. The comparison shows that NLFM analyses closely predict crack development, ultimate load, and the collapse mechanism of the slab-on-ground. *Falkner, Hunag and Teutsch (1995)* published in article [11] a comparative study of the strength and deformation behavior of plain concrete and SFRC ground slabs. The results of the theoretical analysis are compared with the experimental results. An extensive experimental investigation with the aim of studying the structural behavior of slabs on ground made of steel fiber-reinforced concrete (SFRC) are also described in [1, 3, 4, 5, 6].

3. Experimental loading test of steel-fibre reinforced concrete slab

The Faculty of Civil Engineering in VŠB-TU Ostrava has been monitoring, within its R&D activities, the strain-stress relationships during interaction of the foundation structures and subsoil. In 2010, testing equipment – a stand – was erected in the Faculty of Civil Engineering, VŠB – Technical University of Ostrava [8]. The test equipment can be used for experimental measurements of strain and state of stress and for monitoring of the stress-strain relationships in interaction of the foundation structures and subsoil.

The load is applied by a hydraulic press. The hydraulic press pushes the test sample into soil. The maximum loading force of the hydraulic press is 1 MN. For more details about the structure of the test equipment see [8]. The test equipment in the Faculty of Civil Engineering, VŠB – TU Ostrava, was used for testing different types of foundation slabs - they are different, for instance, from the point of view of concrete mixture, reinforcement, dimensions or size of the load surface. In 2014, steel-fibre concrete slab was loaded there.

The size of the fibre concrete slab was 2000 x 2000 x 170 mm. The C25/30 concrete was cast there - it was reinforced with scattered reinforcement. The reinforcement consisted of steel fibres, 3D DRAMIX 65/60B6–25 kg.m^{-3}. The slab casting process is shown in Fig. 1.

Fig. 1: Casting of the fibre concrete slab

From the geologic point of view, foundation soil is not complex. The upper layer of subsoil consists of loess loam with the F4 consistency. The layer is about 5 meter thick. The soil was described as follows: the specific weight γ = 18.5 kN.m^{-3}, Poisson coefficient μ= 0.35, and modulus of deformability E_{def} = 2.65 MPa.

During the test, the fibre concrete slab was loaded in the middle by the pressure applied by the hydraulic press. Dimensions of the area under load were 200 x 200 mm.

Fig. 2: Load test of the fibre concrete slab

The loading was carried out in steps: 20 kN / 60 minutes. The maximum estimated load was calculated 83 kN. In spite of assumptions, the slab did not fail even after nine loading cycles when the load was 180 kN, Then, the test was interrupted. For the repeated loading test of the fibre concrete slab a new cycle was chosen: 50 kN / 30 minutes. The slab failed during the 6th cycle when the loading force was 250 kN. The slab failed by being pushed through. The slab was raised then in such a way so that development of the crack could be investigated – the crack had developed at the lower part of the slab which was in contact with the soil. Fig. 3 shows the cracks at the lower surface of the failed fibre concrete slab. The failure of the slabs by punching shear is also described in [13, 14].

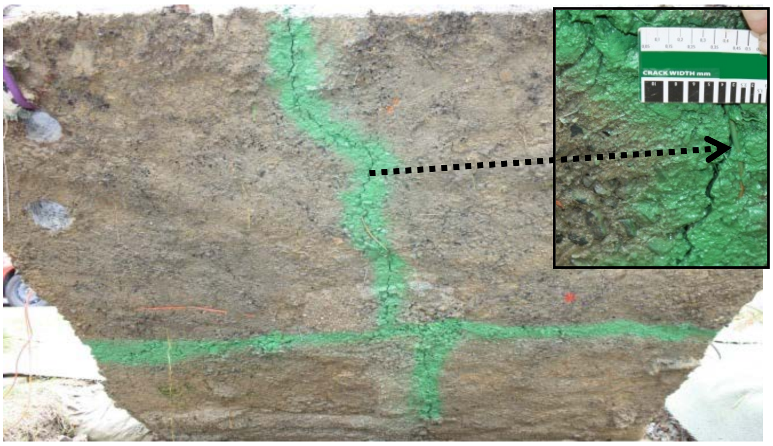


Fig. 3: Cracks at the lower surface of the failed slab

4. FEM analysis of subsoil and steel-fibre reinforced concrete slab

Two FEM software applications were used to analyse the interaction between the steel fibre reinforced concrete slab and subsoil: ANSYS 15.0 and MKPINTER [7]. The results obtained were compared with each other and were also confronted with the values measured during the experiment.

4.1 FEM analysis in software ANSYS

A 2D element, SHELL 181, was chosen for the foundation slab which was modelled as a surface with the specified slab thickness. The subsoil was modelled using a 3D element, SOLID 45. The material properties were modelled using the modulus of elasticity E (or the modulus of deformability E_{def} in case of soil) and Poisson coefficient μ.

The slab and subsoil were modelled using the regular finite-element mesh. The sizes of mesh elements were different for the subsoil and for the slab surface where the mesh was more dense. The force was specified for each node in the finite-element mesh of the slab. The location and value corresponded to the load applied onto the slab during the experiment. In order to transfer effects of the load, which was applied on the foundation slab, into the subsoil it was essential to create a mutual contact and define a contact surface. The FEM model was solved using the contact elements. Because it is a one-sided bond, structural non-linearity had to be introduced into calculations - it required an iteration and the analysis became automatically non-linear. Contact elements which represented two surfaces in mutual contact were used to solve the task. Contact elements mediate the kinematic process of deformation. The contact was created using the contact pair: TARGE170 – CONTA173. Friction between the slab and subsoil was neglected there.

In connection with the creation of a spatial model using 3D elements is particularly problematic correctly to determine the size of the modeled area representing the subsoil, to choose boundary conditions and finite size mesh.

A dependence deformation on these parameters was proved by parametric study [9, 15] published by *Cajka and Labudkova* (2014). Based on the parametric study, it was decided to choose 6.0 x 6.0 x 6.0m for the subsoil model. Such boundary conditions were specified which eliminated horizontal dislocations of nodes in external walls of the subsoil model and vertical dislocations of nodes in the lower base of the subsoil model. No boundary conditions prevented the nodes from dislocating in the upper level of the subsoil model which represented the level of terrain.

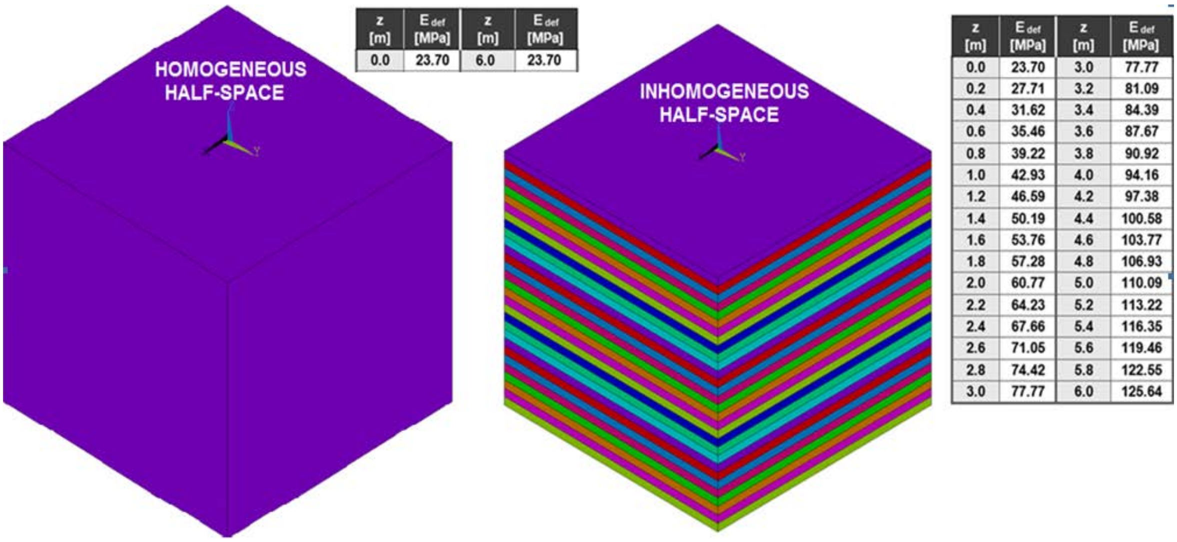
Since the soil is inhomogeneous, its properties are different from idealised properties of an elastic isotropic and homogeneous substance. In the homogeneous half-space, the modulus of deformability is constant and does not depend on depth (Fig. 4). In the inhomogeneous half-space, the concentration of vertical stress in the foundation axis is different from that in the homogeneous half-space. The modulus of deformability changes continuously, depending on the depth. This means that it is the model of the inhomogeneous half-space which describes the deformation behaviour of the soil better that the homogeneous model. Frölich [12] developed a relationship which was based on the minimum deformation work. In that relationship the modulus of elasticity increases with the increasing depth [12]:

$$E_{def} = E_0 z^m \quad (Fig.\ 4) \tag{1}$$

$$m = \frac{1}{\mu} - 2 \tag{2}$$

where

E_0 – is the modulus of elasticity on the model surface (E_0 = E pro z = 1),
z – is the z-coordinate (the depth),
m – is the coefficient which depends on the Poisson coefficient, μ.



z [m]	E_{def} [MPa]	z [m]	E_{def} [MPa]
0.0	23.70	6.0	23.70

z [m]	E_{def} [MPa]	z [m]	E_{def} [MPa]
0.0	23.70	3.0	77.77
0.2	27.71	3.2	81.09
0.4	31.62	3.4	84.39
0.6	35.46	3.6	87.67
0.8	39.22	3.8	90.92
1.0	42.93	4.0	94.16
1.2	46.59	4.2	97.38
1.4	50.19	4.4	100.58
1.6	53.76	4.6	103.77
1.8	57.28	4.8	106.93
2.0	60.77	5.0	110.09
2.2	64.23	5.2	113.22
2.4	67.66	5.4	116.35
2.6	71.05	5.6	119.46
2.8	74.42	5.8	122.55
3.0	77.77	6.0	125.64

Fig. 4: The modulus of deformability in the homogeneous (left) and inhomogeneous (right) half-space

4.2 FEM analysis in software MKPINTER

The values for interaction between the slab and foundation soil which were obtained in ANSYS (for both the homogeneous and inhomogeneous half-spaces) were compared with the results obtained in MKPINTER [7]. The deformation and internal forces in the slab were calculated using the Finite Element Method and isoparametric slab elements with shear influence.

The contact stress influenced deformation of both the slab and subsoil. An iteration method was used so that the contact stress could result in the same deformation of the slab and subsoil in the nonlinear interaction method. The stress, subsidence and contact stress were calculated using a general-purpose method and a transformation Jacobian. MKPINTER calculates the interaction by numerical integration of the calculated state of stress and subsidence of a modified elastic half-space using the structural strength. Accuracy of results is influenced by the number of integration points. More details and other results obtained in MKPINTER are described in [7].

The steel-fibre concrete slab was loaded in the middle at 200 x 200 m. The loading division is shown in Fig. 5. A cross-section through the centre is identified as A – A´. It contains the following nodes: 37, 38, 39, 40, 41, 42, 43, 44, 45.

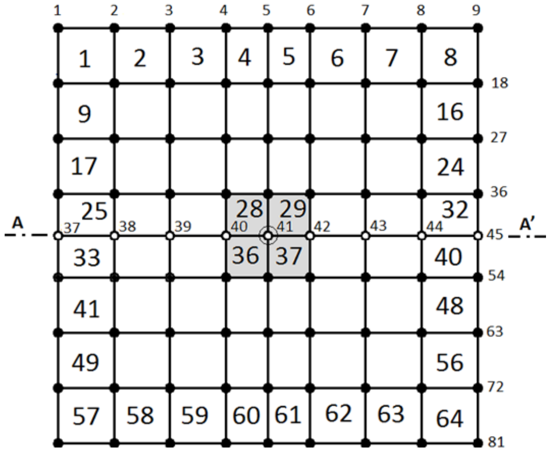


Fig. 5: Layout and division of a the slab into finite elements

The analysis results, this means the slab deformation, contact stress and specific bending moment, were drawn in the nodes 37 through 45 in the A – A´ cross-section. The final results are obtained after the 9th iteration for 12 integration points. The results are shown in Fig. 6, Fig. 7 and Fig. 8.

5. Comparison of results of FEM analyses

Fig. 6 compares the deformation of the steel-fibre concrete slab measured during the experiment (the orange curve) with the deformation calculated in the numerical models in ANSYS and MKPINTER. The comparison is made for the transversal section through the middle of the slab model. The maximum deformation was measured in the middle of the slab: 2.83 mm, while the minimum deformation, 1.91 mm, was reached at the slab edge. The real deformation is depicted best by the results of the numerical analysis in MKPINTER (the blue curve) and ANSYS with the inhomogeneous half-space (the green curve). The red curve shows the deformation in the homogeneous half-space where the modulus of deformability does not increase with the increasing depth. This causes bigger vertical deformation. It is the model of the inhomogeneous half-space which describes the deformation behaviour of the soil better than the other model. The difference between the calculated and measured deformations ranged from 4 per cent (at the edge of the slab) to 10 per cent (in the middle of the slab), see Fig. 6. In MKPINTER, the difference between the calculated and measured deformations ranged from 4 per cent (in the middle of the slab) to 30 per cent (at the edge of the slab), see Fig. 6.

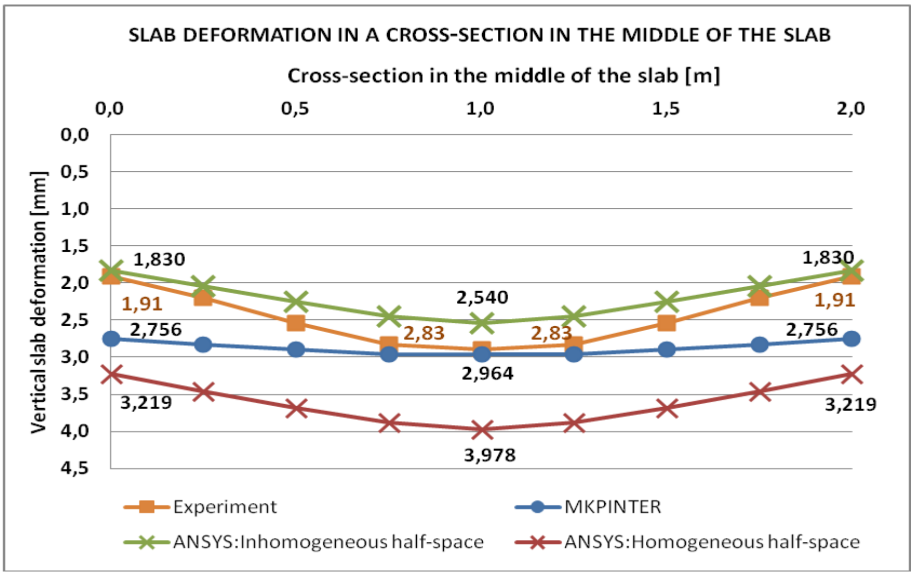


Fig. 6: Comparison of the calculated and measured values for vertical deformation.

The bending moments of steel-fibre reinforced concrete can be calculated using equation (3). Given that the parameters α_t, $m_{f,min}$ have values within a certain range, calculations are made for its minimum and maximum value. Calculated moment for the stress in a slab with cracks is in the range 19.63 to 21.89 kNm/m (Tab. 1).

$$f_{fctk} = f_{ctk}\left[1+\alpha_t\left(m_{f1}-m_{f1,\min}\right)\frac{L}{d}\left(\frac{20}{f_{ck}}\right)^{0,25}\right] \rightarrow \quad m_{Rk,\exp} = \frac{7}{24}.b.h^2.f_{fctk} \qquad (3)$$

Where:

f_{ck} tensile strength of the concrete similar composition,
f_{ctk} guaranteed cube strength of the concrete of similar composition,
α_t coefficient of tensile strength, which value is in the range of 0.4×10^{-4} to 6.0×10^{-4}
Note: The coefficient depends on the type and shape of the wires.
L/d slenderness ratio of steel fibers, i.e. the ratio of length and diameter of wires,
m_f mass concentration wires
$m_{f,min}$ minimum mass concentration wires

Tab.1: Calculated bending moments in steel-fiber reinforced concrete slab

	f_{ctk} [MPa]	α_t [-]	m_{f1} [kg/m^3]	$m_{f,min}$ [kg/m^3]	L/d [-]	f_{ck} [MPa]	f_{fctk} [MPa]	m_{Rk} [kNm/m]
Minimum values	2,56	0,00004	25	20	65	25	**2,60**	**21,89**
Maximum values	2,56	0,00006	25	50	65	25	**2,33**	**19,63**

Fig. 7 compares the bending moments calculated in the numerical models in ANSYS and MKPINTER. The maximum bending moment obtained in the MKPINTER analysis (the blue curve) is 17.927 kNm/m. The maximum bending moment obtained for the inhomogeneous half-space in the ANSYS analysis (the green curve) is 17.303 kNm/m. The maximum bending moment obtained for the homogeneous half-space in the ANSYS analysis (the red curve) is 20.26 kNm/m. The difference between the values for the maximum moment obtained in different models is 13 per cent only. The values correlate very well with the interval of values for the bending moment of the steel-fibre slab calculated in (3). See Tab. 1.

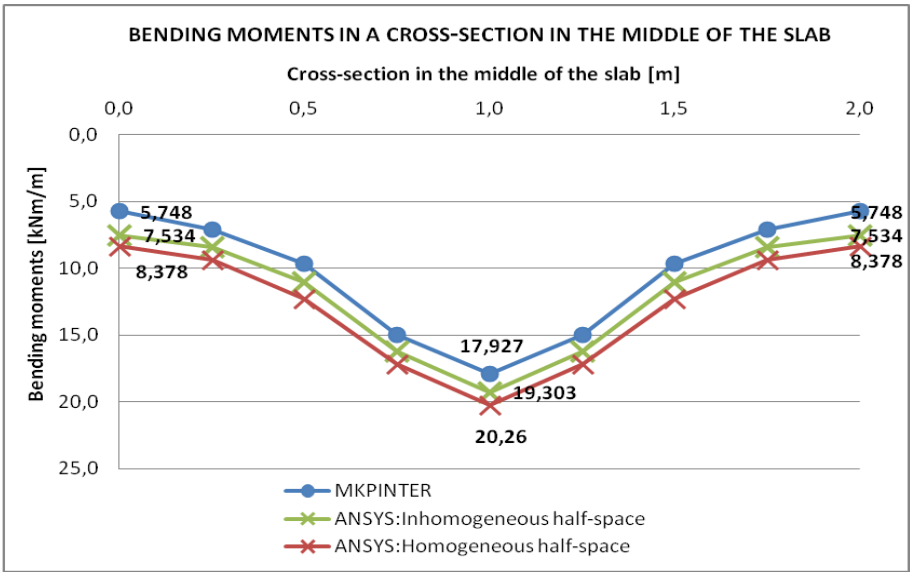


Fig. 7: Comparing the specific bending moments

Fig. 8 compares the contact stress calculated in the numerical models in ANSYS and MKPINTER. In each model, the stress increases towards the edge of the slab. The increase depends, among others, on the size of the finite-element mesh. Stress peaks can be limited in both software applications.

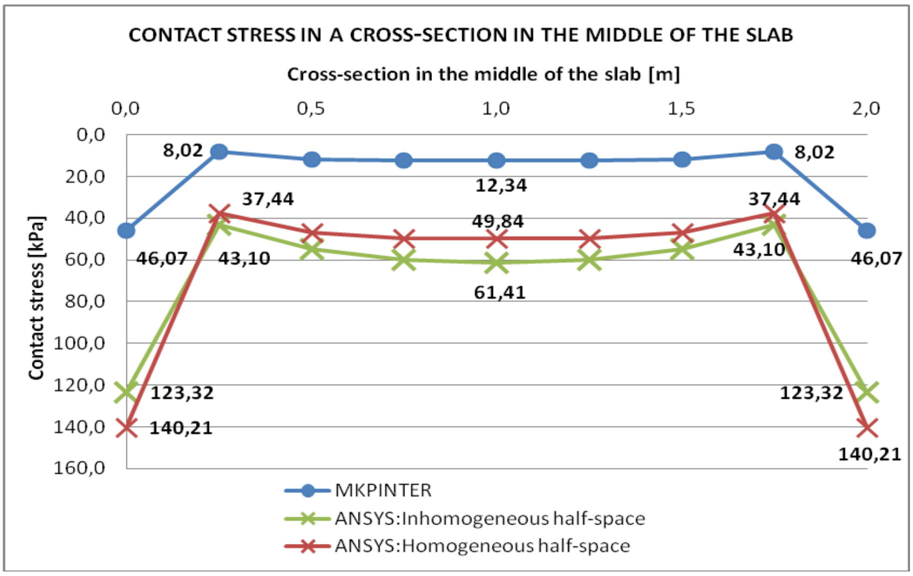


Fig. 8: Comparing the calculated contact stress

6. Conclusions

Steel-fibre reinforced concrete foundation slab model was loaded during experimental measurements. Steel-fibre concrete slab broke when the load reached the value 250kN. Using two FEM software tools were made numerical analyses of this contact task. Both software tools operate on the different principle. In software MKPINTER, interaction model is based on nonlinear iteration calculation, Gaussian numerical integration and transformation Jacobian used for calculation of stress and subsidence of modified elastic half-space [7]. Results obtained using this model correlate well with the measured slab deformation. The calculated slab deformations differ from the measured slab deformations only in the range from 4 per cent (in the centre of the slab) to 30 per cent (at the edge of the slab). In software ANSYS, interaction subsoil-structure model was made using 3D finite elements. Subsoil model was made as homogeneous half-space and as inhomogeneous half-space, which describes the deformation behaviour of the soil better. The calculated slab deformations differ from the measured slab deformations only in the range from 4 per cent (at the edge of the slab) to 10 per cent (in the centre of the slab). Calculated values of the maximum bending moment obtained by said numerical models differing from each other by only 13 per cent. Bigger differences are between calculated contact stresses. Even if course of contact stresses have a similar shape, the values are different. This is influenced, among others, also by the size and shape of the finite-element mesh. Scientific-research activities concerning interactions of steel-fibre foundation structures and subsoil and its numerical modelling will still continue at the Faculty of Civil Engineering, VŠB-TUO. Loading tests of other models steel-fibre concrete slabs are planned.

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