3D-FEM SIMULATION OF CONCRETE BLOCK PAVEMENTS

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SUMMARY

Numerical models permit a more realistic description of the load-bearing behaviour of pavement structures. Using numerical models, the effects of different external factors or structural parameters may be systematically assessed for practical engineering applications. In order to analyze the load-bearing behaviour of pavement structures, 3-D models should be chosen.

The aim of the research was to implement concrete block pavements into an analytical pavement design program. Full-scale dynamic laboratory tests on block pavements formed the basis of the investigation. Possibilities for modelling concrete block pavements using the 3D-Finite Element (FE/BE) Program REFEM are described in detail in the paper. By using this program it is possible to model different paving blocks and laying patterns under dynamic loading. The non-linear deformation behaviour of basecourse and subbase materials was taken into account in the modelling process. Using the results of 3D FE-calculations it should be possible to determine the

influences of joints and bedding materials on the deformation behaviour of concrete block pavements. Finally, FE back-calculation results of full-scale dynamic laboratory tests are presented in the paper.

INTRODUCTION

Block pavements have traditionally been designed using empirical design methods; i.e., the material types and layer thicknesses of the different structural layers have been selected in accordance with very inflexible predetermined design criteria. A typical feature of many empirical design methods is that they have been progressively calibrated over many years by means of either systematic road tests or observations made from actual pavement structures as well as back calculations. As a result, the design and construction of the pavements has traditionally been directed towards more or less standardized cross sections and road construction materials.

Hence, current empirical pavement design methods are in most cases insufficient for the analysis and design of pavements. Nonetheless, there are increasing worldwide efforts towards developing analytical approaches to solve this problem. The analytical or mechanistic design method aims to model the behaviour of each pavement layer based on the basic mechanical and physical properties of the structural materials. The key idea is to evaluate the stresses and strains under real traffic loads at critical points in the structure based on the analysis of the stress-strain conditions of the whole pavement, taking into consideration the climatic conditions. Based on the values of stresses and strains, the service life of the pavement can thus be estimated.

In the last few years, a significant effort has been made to understand the complex deformation behaviour of materials used in the pavement structure (e.g. basecourse materials, asphalt, concrete). There are now various material models and computation tools available those are able to predict the performance of these materials. In previous research, elastic (Gleitz 1996, Numrich 2004) and plastic (Werkmeister 2003) deformation behaviour model for Unbound Granular Materials (UGM) (DRESDEN-Model) was developed based on laboratory (repeated load triaxial) test results. The model was implemented into a 3D-Finite Element (FE) Program REFEM that is currently under development at the Dresden University of Technology, Germany, by Oeser (2004).

A pre-requisite for any successful analytical design methodology is the acquisition of reliable measurements from representative experimental investigations followed by appropriate mathematical characterization of the deformation behaviours of the materials in the pavement structure. In order to study the in-situ behaviour of block pavements, it is necessary to create testing conditions as close as possible to those occurring in the pavement. Hence, full-scale laboratory tests were conducted at Dresden University of Technology by Lerch (2005) to investigate the performance of various concrete block layers. In particular, the influence of the different block shapes, block sizes, laying patterns as well as bedding and jointing sands on the deformation behaviour of concrete block layers was investigated (Lerch 2006). The tests were analysed using the results of surface deformation measurements with displacement transducers. In addition, photogrammetry was used to investigate the horizontal deformation and the torsion behaviour of the blocks. From the full-scale laboratory tests the development of the vertical and horizontal deformation versus the number of load cycles for various block pavements could be determined. To limit the number of material parameter/models (for the bedding and joint filling material) that are required for the FE modelling process, the results of the laboratory tests were used.

2. THE PROGRAM REFEM

For a detailed investigation of pavement response, a 3-D computational model is required. The Chair of Statics and Dynamics of Structures at Dresden University of Technology, Germany has developed a 3D-FE Program REFEM (Oeser 2004) with a special tool for block pavements. REFEM is a FE/BE program that processes huge numerical capabilities and experience is needed to utilise its full capacity. It can simulate a very broad range of soil and pavement engineering materials (UGM, asphalt, concrete) with non-linear elasto-visco-plastic behaviour under a range of loads both dynamic and static (Oeser 2004).

Currently, the number of degrees of freedom in the FE Program REFEM is restricted to 299,997. Structural non-linearity as well as physical non-linearity will be taken into account in the calculation process. Structural non-linearity results from the adjustment of the interface element stiffnesses as a function of the horizontal deformation of the concrete block layer. The physical non-linearity results from the behaviour of the basecourse layer. To model the basecourse layer, the non-linear elastic DRESDEN-Model) (Gleitz 1996) was used.

GENERATION OF THE CONCRETE BLOCK PAVEMENT USING REFEM

Generation Process

The FE Program REFEM was used to carry out this investigation. Special isoparametric FEs (Bathe 1996) were used applying 60 degrees of freedom and tri-quadratic displacement shape functions (Figure 1). The number of FE for one block and the coordinates of the edge nodes were chosen according to the geometry of the concrete blocks. It is possible to generate more than one basecourse layer. However, the structure of the FE mesh of all layers must coincide among each other.

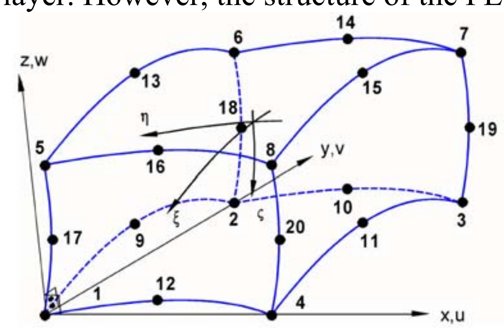

Figure 1. Isoparametric 20-Nodes-3D-Element [Möller 2003]

Figure 1 shows the FE type that was utilized for the approach. Each element possesses 20 nodes. The displacements in the interior of the FEs are approximated by three-cubic displacement shape functions. Neighbouring surfaces of FE mesh of different layers can be coupled rigidly or flexibly. If rigid coupling is applied, nodes with identical coordinates are substituted by one common node. If, however, flexible coupling is applied coinciding element surfaces of different layers are connected by interface elements. Each interface element has 16 nodes that are equal to the nodes of the connected element surfaces. Flexible coupling was used to model the interaction of the paving blocks and the basecourse.

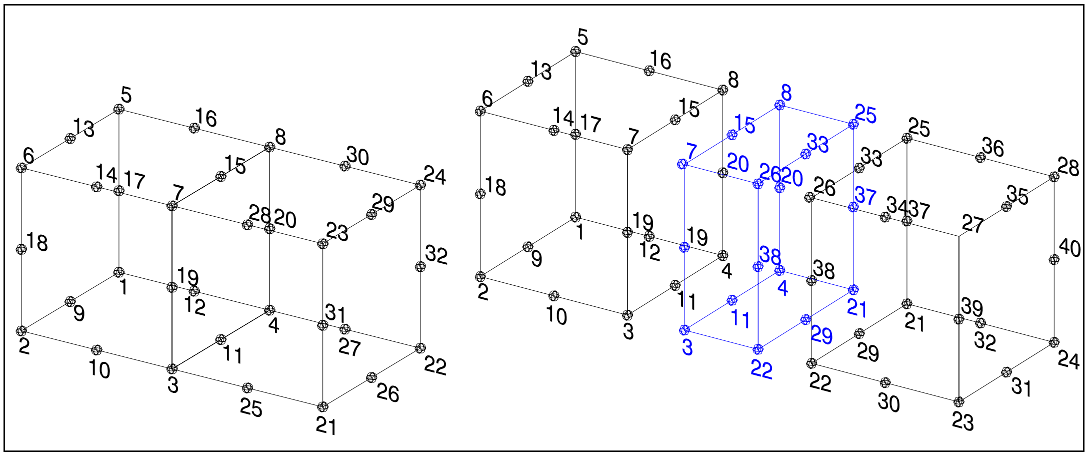

Figure 2. Coupled 20-node elements, left: rigid coupling, right: flexible coupling (Ascher 2003)

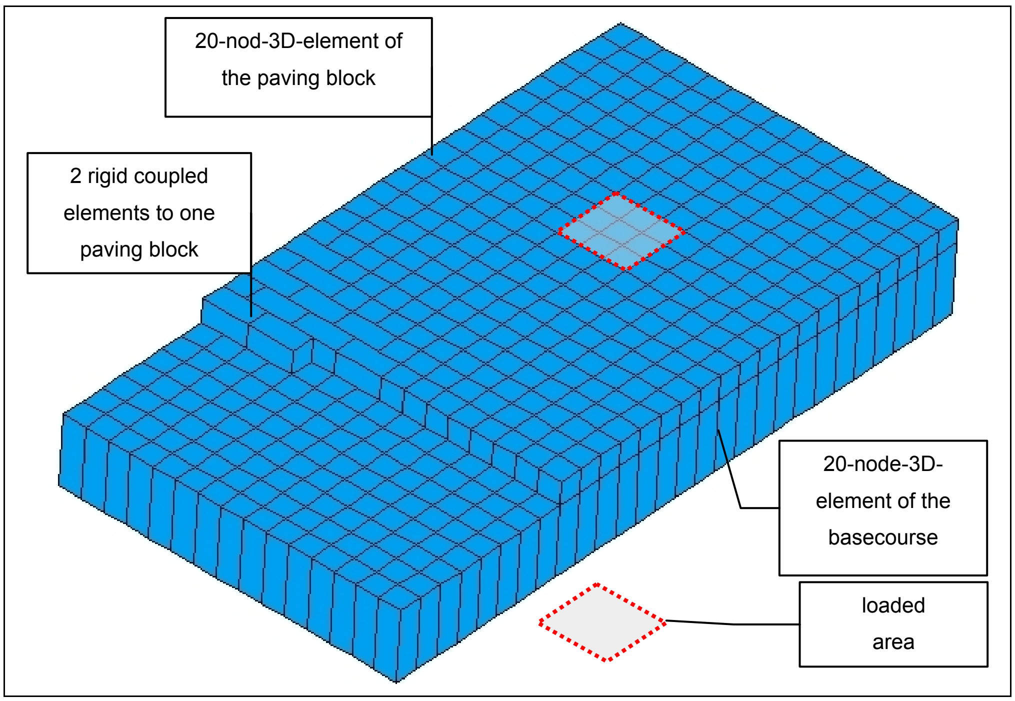

Figure 3. FE-mesh (Lerch 2005)

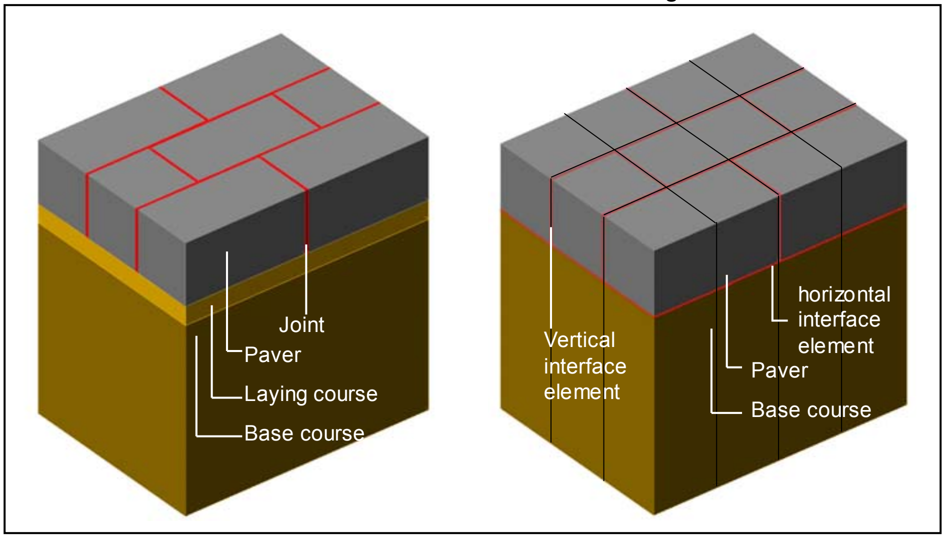

Figure 4. Block pavement model (Ascher 2003)

The properties of the interface elements are defined by the stiffness E_3 (perpendicular to the interface plane) and the two shear stiffnesses G_1 and G_2 (parallel to that plane). The initial thickness of the interface element is zero. Neighbouring FEs of different layers may overlap if (pressure-) loads are applied. This effect occurs since the initial value of the stiffness E_3 of the connecting interface elements is finite. As this can't appear in reality, a special iterative algorithm is used to restore the overlap to zero. This algorithm uses so-called "correction forces" that counteract the development of overlaps. Interface elements can also be used to model the interaction between paving blocks. In this case the thickness of the interface elements corresponds to the thickness of the joins. Huurman et al. (2003) modelled the interaction between the paving blocks using springs (aligned in horizontal and vertical direction). The springs are located between the element nodes of the neighbouring surfaces. To avoid overlaps Huurman et al. (2003) proposed to control the stiffness of the springs. However, a change in the spring-stiffness leads to a change in the stiffness of the total FE-system as well and requires the total stiffness-matrix to be solved frequently.

Unbound Granular Layer

The basecourse layer was model using the non-linear elastic DRESDEN-Model. Detailed information regarding the DRESDEN-Model can be found in Gleitz et al. (1996) and Werkmeister et al. (2005).

Concrete Blocks

The concrete blocks were modelled as a linearly elastic material with an E value of 39,000 N/mm^2 and a ν value of 0.2.

Joints

A contact law was introduced to take into account in the load transmission via the joints and the interaction of neighbouring paving blocks. This law permits the consideration of elastic and plastic components of the relative displacement between the paver's perpendicular to the contact (interface) plane (Oeser 2005, Equations 1, 2 and 3). The elastic deformation component ΔV_{EL} depends exclusively on the contact pressure between the paving blocks, while the plastic component ΔV_{PL} additionally depends on the number of load cycles applied. The parameter B_F can be interpreted as the joint width.

$$\Delta V_3^{EL} = E_3 \cdot \sigma_3 \cdot B_F \qquad \text{with} \quad E_3 = 0{,}0002 \text{ mm}^2/\text{N} \qquad \text{(Eq. 1)}$$

$$\Delta V_3^{PL} = P_3 \cdot \sigma_3 \cdot B_F \qquad \text{with} \quad P_3 = \left[0{,}03 - 0{,}01012 \cdot \left(\frac{1000}{LW}\right)^{0{,}15}\right] \text{mm}^2/\text{N} \qquad \text{(Eq. 2)}$$

$$\Delta V_3 \quad = \Delta V_3^{EL} + \Delta V_3^{PL} \qquad \text{(Eq. 3)}$$

ΔV_3 relative displacement between adjacent blocks [mm],
ΔV_3^{EL} relative displacement between adjacent blocks (elastic portion) [mm],
ΔV_3^{PL} relative displacement between adjacent blocks (elastic portion) [mm],
E_3, P_3 material parameter [mm²/N],
σ_3 joint contact pressure [N/mm²],
B_F joint width (5 mm),
LW number of load cycles.

Relative deformations of the surfaces parallel to the contact plane are considered as shown by Equation 4 and 5. In order to describe these deformations more realistically, an extension of the contact law is intended but not realized yet.

$$\Delta V_1 = G_1 \cdot \tau_1 \qquad \text{(Eq. 4)}$$

$$\Delta V_2 = G_2 \cdot \tau_2 \qquad \text{(Eq. 5)}$$

ΔV_1, ΔV_2 relative displacement between adjacent blocks [mm] (parallel to the contact plane)
G_1, G_2 material parameter [mm²/N],
τ_1, τ_2 joint shear stress [N/mm²],

Load transition via the joints in case of tension perpendicular to the contact plane does not happen in reality. To consider for this effect in the model the stiffness E_3, G_1 and G_2 might be set to zero. However, this causes numerical instabilities. To prevent the occurrence of numerical instabilities due to a total loss in stiffness a lower limit value for E_3, G_1 and G_2 was introduced, see (Wellner 1994, Gleitz 1996, Numrich 2003 and Wenzel 1988).

Bedding Layer

The bedding layer was also modelled by interface elements. As the values of G_1 and G_2 were assumed to be low (i.e. low friction between the paving blocks and the basecourse) an almost unrestricted sliding of the paving blocks under loading on the basecourse surface was possible. In other words, the horizontal movement of the loaded paving blocks was almost fully prevented by interlocking effects between them.

Pavement Loading

The test pavement was loaded by a steel loading plate (rigid load action) with a diameter of 300 mm. However, this area could not be modelled identically in the version of the FE Program that was used in this investigation. The loaded area was composed of 300 x 300 mm according to Figure 6.

FE CALCULATION RESULTS

The results of the FE-analysis are nodal displacements. The nodal displacements depend on the number of load cycles applied. Figure 5 shows the maximum displacements in horizontal direction (blue lines) for different numbers of load cycles. It can be seen from Figure 5 that the results of the FE analysis agree with the results of the dynamic load tests (black lines) quite well. Major differences between the laboratory test and the numerical simulation results appear in the proximity of the loaded paving blocks. These differences are supposed to be caused by a tilting of those blocks.

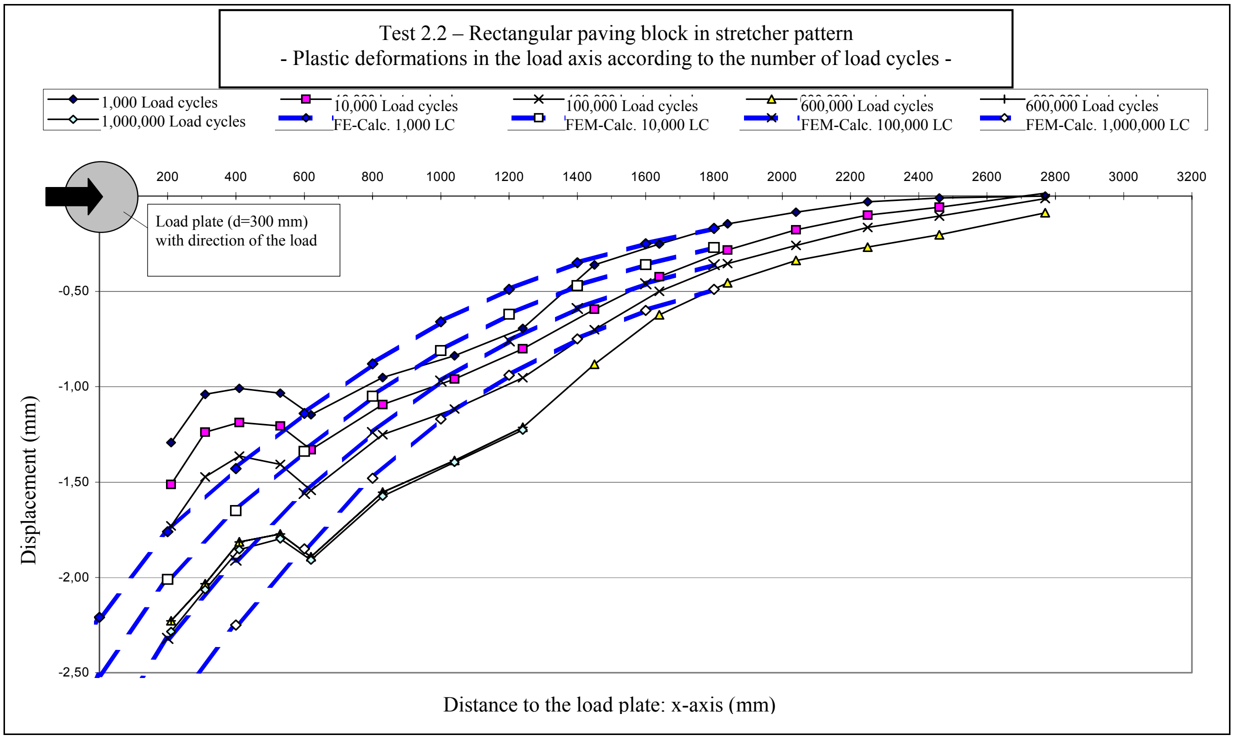

Figure 5. Laboratory test results (thin lines) versus results of numerical simulations (dashed line)

Figure 6 shows the horizontal displacement of the entire surface that has been investigated.

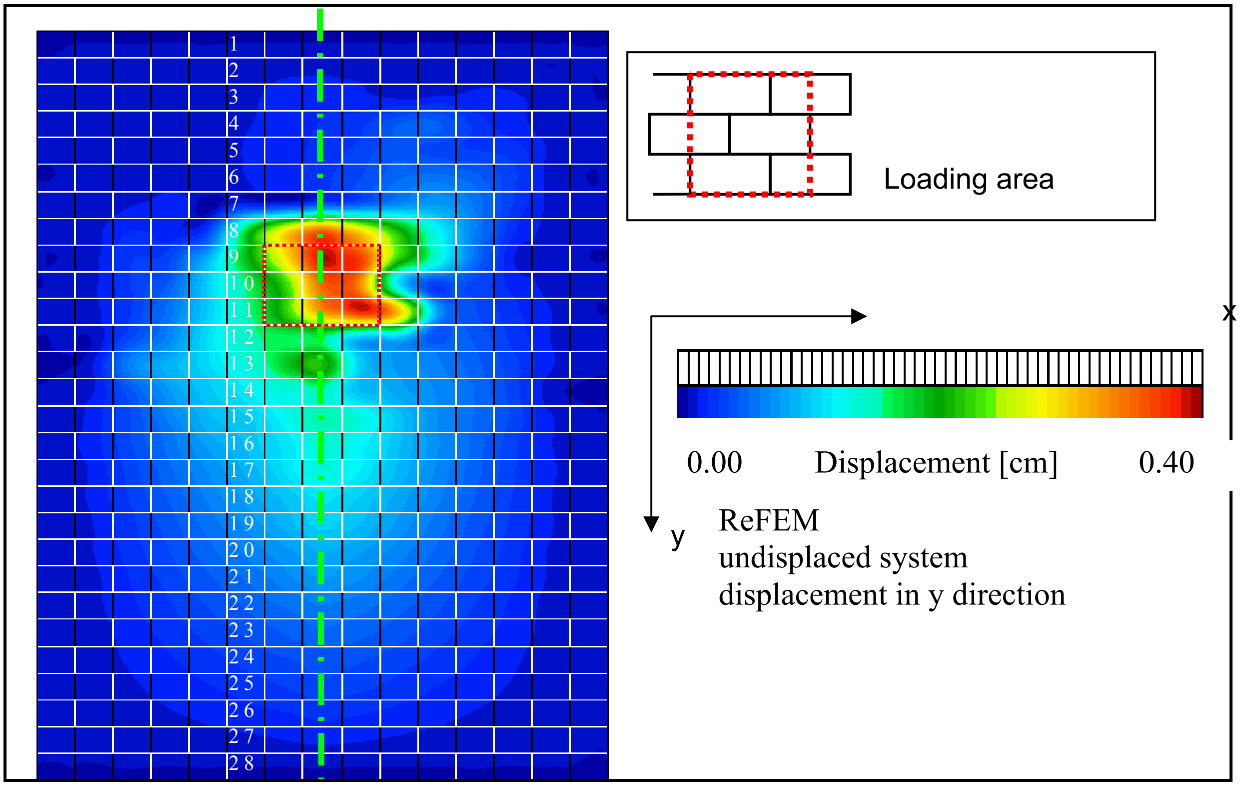

Figure 6. Results of the numerical simulation for the stretcher pattern

CONCLUSIONS

The aim of the research was to implement concrete block pavements into an analytical pavement design program. Full-scale dynamic laboratory tests on block pavements formed the basis of the investigation. Possibilities for modelling concrete block pavements using the 3D-FE Program REFEM were described in detail in the paper. By using this program it is possible to model different paving blocks and laying patterns under dynamic loading. The non-linear deformation behaviour of basecourse and subbase materials was taken into account in the modelling process.

The experimental results from the full-scale dynamic laboratory tests were compared with those from block pavement modelling performed with the REFEM FE Program, incorporating the non-linear elastic DRESDEN-Model for basecourse materials. A good agreement between the measured horizontal deformations in the laboratory tests and the calculated horizontal deformations using REFEM was observed. Using the results of 3D FE-calculations it will be possible in future to determine the influences of joints and bedding materials on the deformation behaviour of concrete block pavements. Furthermore, the most suitable geometric design (laying patterns) of the blocks and the optimal lock shape can be chosen using the FE calculation results.

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