A TOOL FOR STRUCTURAL ANALYSIS OF BLOCK PAVEMENTS BASED ON 3DFEM

Nishizawa, T.

Associate professor, Ishikawa National College of Technology, Tsubata Ishikawa, Japan 929-0392.
Tel: (81) 76 288 8167. Fax: (81) 76 288 8171. E-mail: nishi@ishikawa-nct.ac.jp

ABSTRACT

It is difficult to model block pavements by finite elements, because their surface layer consists of a large number of very small blocks with complicated laying patterns. In this study, a program package for the structural analysis (BLPAVE3D) has been developed based on 3 dimensional finite element method (3DEFM). The package consists of a mesh generator, a solver and a post processor. Using the mesh generator with a user-friendly interface, users can avoid time consuming data handling task in mesh generation of 3DFEM. They have to input information only on loading and pavement structural conditions including block size, laying pattern, mechanical characteristics of cushion layer, bases and subgrade. The solver computes displacements, stresses and strains not only in the blocks but also those in the bases and subgrade using a 3DFE model, where the blocks, bases and subgrade are divided into solid elements and the cushion layer and joints are modeled by a general interface element. The post processor displays deformations and stress contours of the entire or partial region of the pavement structure. The effects of block thickness, stiffness of joint and cushion layer on pavement responses were investigated using the tool.

1. INTRODUCTION

It is difficult to model block pavements by finite elements for structural analysis, because their surface layer consists a large number of very small blocks with complicated laying patterns (Huben, et. al., 1984 and Nishizawa, et al, 1984). In this study, a program package of the structural analysis for block pavements, BLPAVE3D, has been developed based on a 3 dimensional finite element model for pavement structure, PAVE3D (Nishizawa, et. al., 2001). The BLPAVE3D consists of a mesh generator, a solver and a post processor. The mesh generator with a user-friendly interface allows users to create a mesh data for a particular pavement without time consuming data handling. They have to input information only on loading and pavement structural conditions including block size, laying pattern, mechanical characteristics of cushion layer, bases and subgrade. The solver computes displacements, stresses and strains in the blocks, bases and subgrade. In the model, the blocks, bases and subgrade are divided into solid elements and the cushion layer and joints are modeled by a general interface element. The post processor graphically displays deformations and stress contours of the entire or partial region of the pavement structure.

The effects of block thickness, stiffness of joint and cushion layer and laying pattern on deflection, stress and strain in concrete block pavements are investigated using this tool.

2. 3DFE MODEL

In this study, in order to simulate mechanical behavior of block pavements, a structural model based on a 3DFEM was developed. In this section, outline of 3DFEM model for pavement structures and its application to block pavements are presented.

2.1 3DFE Model for Pavement

Figure 1 shows a pavement structure considered in PAVE3D. This pavement consists of elastic layers that represent concrete slabs, bases, and subgrade, all of which are divided into solid elements. The interface between the concrete slabs and a base is modeled using a general interface element. The dowel bar element can be included in the joint interface element.

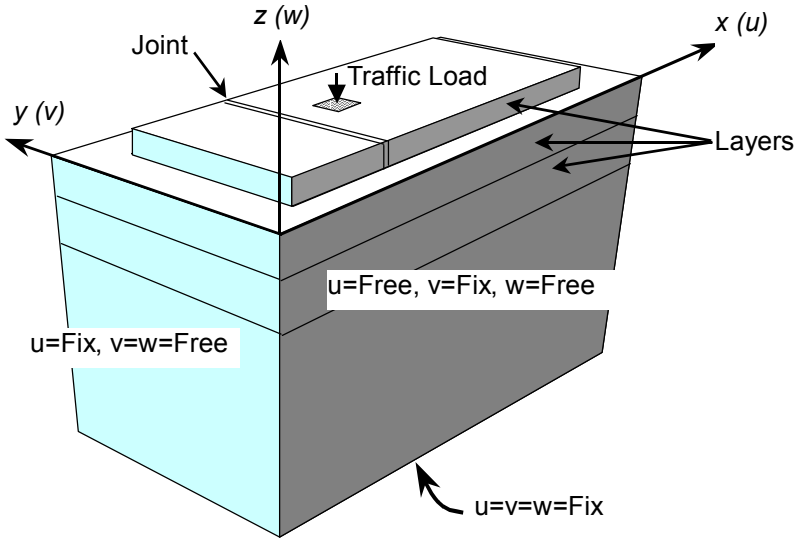


Figure 1. Structural model of pavement.

Each layer has a finite horizontal extent and displacement in the normal direction is fixed on all side faces of the layer; other displacements are free. This boundary condition is not applied to the top layer. All displacements are fixed at nodes on the bottommost surface of the structure. Loads are applied on the surface both vertically and horizontally as uniformly distributed rectangular loads.

2.2 3DFEM for Block Pavement Structures

A block pavement consists of small blocks, joints between the blocks, a cushion layer, a base, a subbase and a subgrade. The pavement structure is modeled as a combination of solid elements and interface joint elements as shown in Figure 2. The blocks, base, subbase and subgrade are divided into the solid elements and the joints and the cushion layer are represented by the interface elements. In the joints, the shear springs (k_s, k_t) model the shear load transfer due to interlocking of the sand between the blocks. In the cushion layer, the normal spring (k_n) represents the support function of the layer and has a value depending on the vertical stiffness of the layer, while its shear spring constants (k_s, k_t) are assumed small values because of weak shear interaction in the layer.

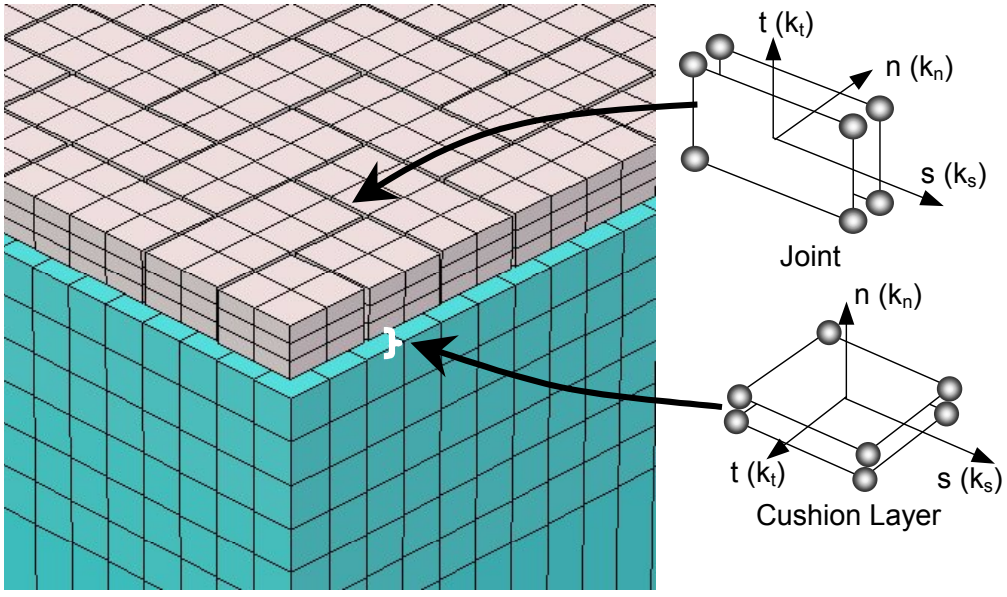


Figure 2. 3DFEM model for a block pavement.

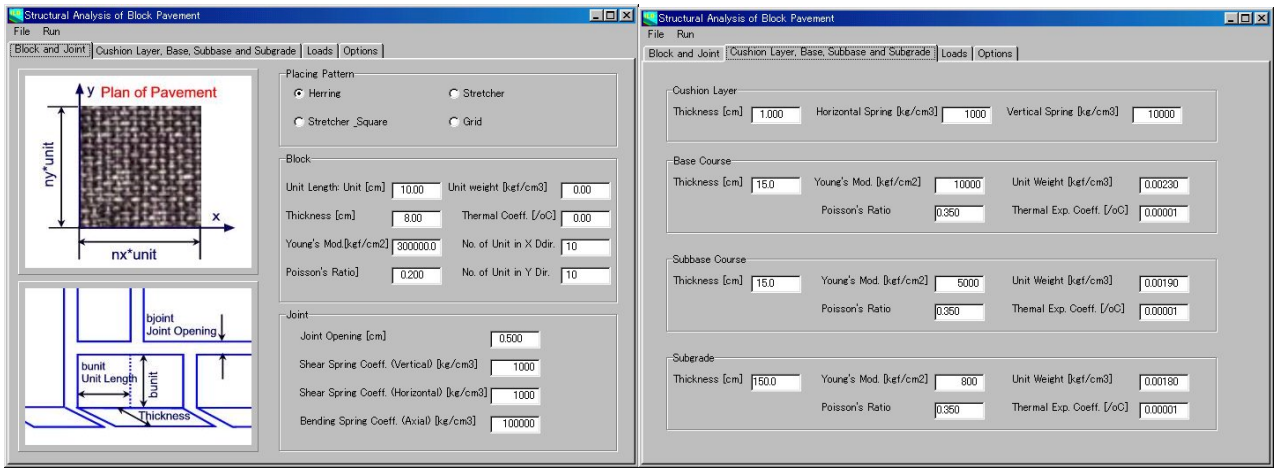
3. PROGRAM PACKAGE

3.1 Outline

The program package (BLPAVE3D) developed in this study for structural analysis of block pavements consists of a pre-processor, a solver and a post-processor. The pre-processor has a user-friendly interface, through which users input data regarding the configuration and laying pattern, material properties of block, thickness and mechanical properties of cushion layer, base, subbase and subgrade as well as loading condition. It generates a 3DFEM mesh data and creates an input data file. The solver runs the FEM program using the input data file and stores the results in an output data file. The post processor graphically displays the computed results and provides response data of specified nodes.

3.2 Pre-processor

Figure 3 shows the user interface of BLPAVE3D, which contains four tab panels on a window. After inputting all data required, the user clicks [Run]-[Computation] from the menu bar. Then a mesh generator, PRE3D, creates an input data file and the solver starts to run.



(a) Panel for Block and Joint **(b) Panel for Cushion, Bases and Subgrade**

(c) Panel for Loads **(d) Panel for Other Options**

Figure 3. User interface of pre-processor of the package.

3.3 Solver

The solver, FEM_3D, computes displacements, stresses and strains using the input data file created by PRE3D. The FEM_3D opens a MS-DOS window showing an iterative solution process for a nonlinear equation.

The computation will take several minutes up to several hours depending on the problem size and the platform. The computed results are stored in a text file with an extension of "out".

3.4 Post-processor

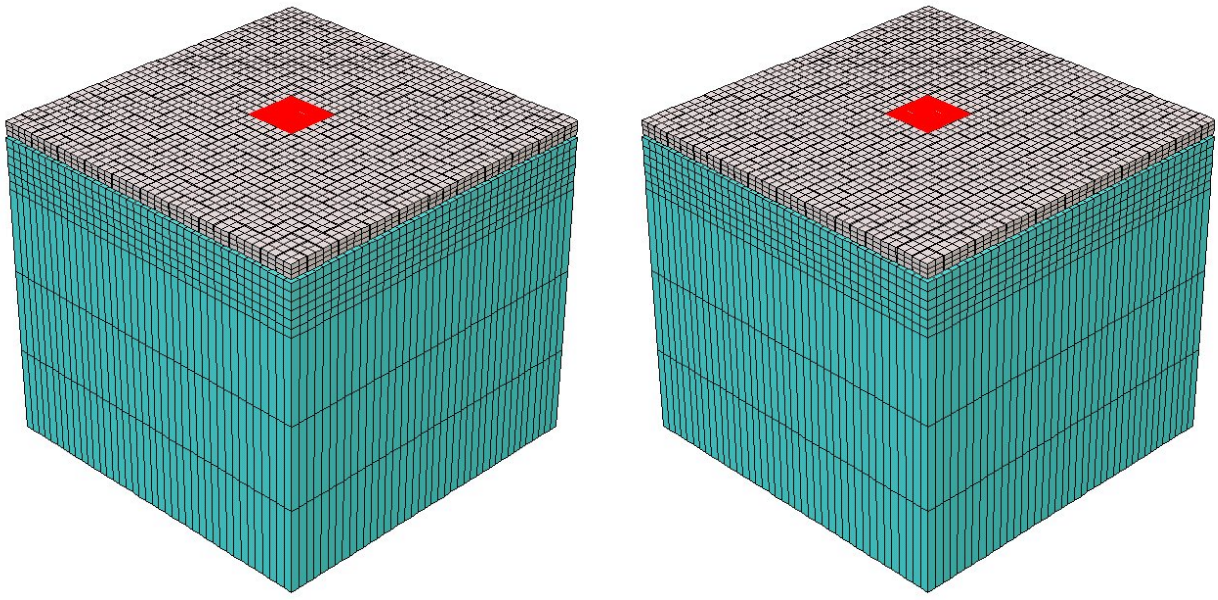
Clicking [Run]-[Graphics] from the BLPAVE3D starts the post-processor, P3D, with an interface window. On the window, the user is able to load the output file and view displacement, stress or strain contours on the client area. The user is also able to know those values of displacements, strains and stresses at specific nodes by opening another window.

4. SIMULATIONS

This section examines the effects of block thickness, stiffness of joint and cushion layer on deflection, stresses in block, base and subbase, and strain at the top of subgrade based on the simulation results.

4.1 Input data

Pavement structures used in the simulation have a block layer with 100 mm by 200 mm blocks, a 20 mm thick cushion layer, a 150 mm thick cement stabilized base, a 150 mm thick crusher run subbase and a 1500 mm thick subgrade with a CBR of 8%. This structure is a typical one for a medium traffic condition in Japan (Japan Interlocking Block Pavement Engineering Association, 1996). Two types of laying pattern of blocks, the herringbone and stretcher bonds, were employed. 3DFEM models used in the simulation are shown in Figure 4. The area of the pavement was 2m by 2m. A 0.3 m by 0.3 m rectangular load of 49 kN was applied at the center of the area.



(a) Herringbone Pattern **(b) Stretcher Bone Pattern**

Figure 4. 3DFEM models used in the simulation (29830 nodes).

The block thickness and the stiffness of the joint and cushion layer varied as presented in Table 1. The values of the joint stiffness were 10^2 MN/m^3 and 10^5 MN/m^3 to model high and low load transfer joint, respectively. As for the cushion layer, the value of k_n was set to be 10^4 MN/m^3 and 10^6 MN/m^3 for soft and stiff supports, respectively. Four combinations of the stiffness of the joint and cushion layer were assumed and named as Cases A to D.

5. RESULTS

5.1 Deflection

Figure 5 shows effects of the block thickness on the deflection (downward deflection is defined as negative) at the center of the pavement. If the joint stiffness is high (Cases B and D), the deflection decreases as the thickness increases. On the other hand, if the joint stiffness is low (Cases A and C), the thickness hardly affects the deflection. If the stiffness of the cushion layer is low (Cases A and B), the deflection is large.

Table 1. Input Data for 3DFEM Simulation.

Parameter [Unit]	Case A	Case B	Case C	Case D
Elastic Modulus of Block [MPa]	29400			
Poisson's Ratio of Block	0.2			
Block Thickness [mm]	60, 80, 100			
k_s, k_t and k_n for Joint [MN/m^3]	10^2	10^5	10^2	10^5
k_s, k_t for Cushion Layer [MN/m^3]	10^2			
k_n for Cushion Layer [MN/m^3]	10^4	10^4	10^6	10^6
Elastic Modulus of Base [MPa]	980			
Poisson's Ration of Base	0.35			
Thickness of Base [mm]	150			
Elastic Modulus of Subbase [MPa]	490			
Poisson's Ration of Subbase	0.35			
Thickness of Subbase [mm]	150			
Elastic Modulus of Subgrade [MPa]	79			
Poisson's Ration of Subgrade	0.35			
Thickness of Subgrade [mm]	1500			

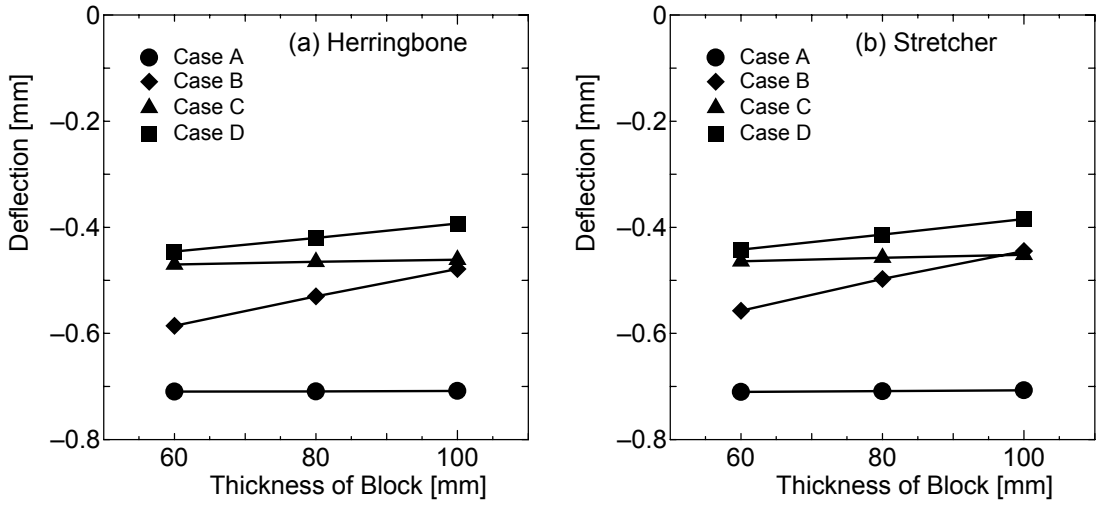
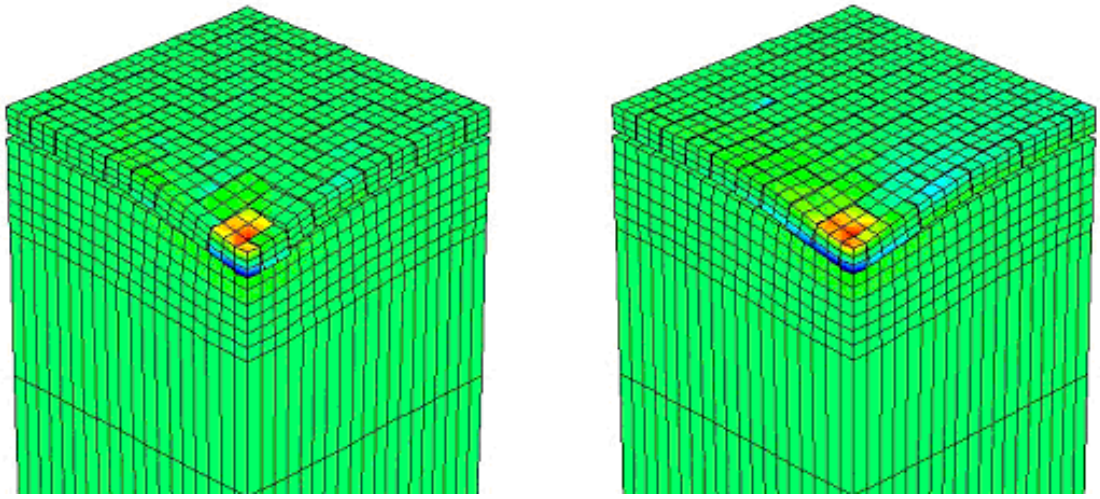


Figure 5. Deflections of concrete block pavements under the load.

5.2 Block Stress

Figure 6 shows horizontal stress distributions for quarter regions of the entire pavements. It can be seen that large compressive and tensile stresses occur at the top and bottom of a concrete block, respectively, under the load.



(a) Herringbone **(b)Stretcher**

Figure 6. Horizontal stress distributions.

Figure 7 shows the effect of the block thickness on the maximum bending stress of the block. In the case of low stiffness of both joint and cushion layer (Case A), the stress is small, while, in other cases, the stress is relatively large and decreases as the thickness increases. High joint stiffness tends to produce large stresses (Cases B and D). In Cases B, C and D, there is very little difference between two laying patterns of blocks.

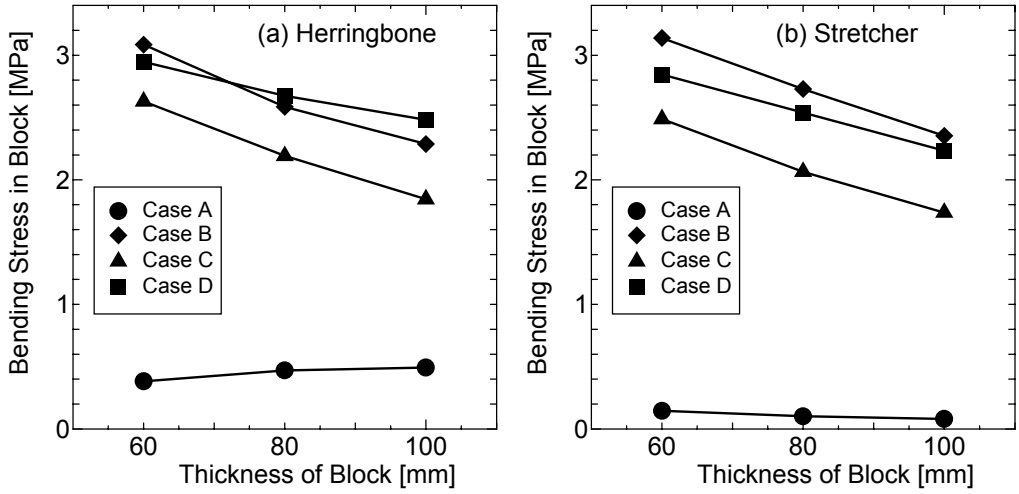


Figure 7. Maximum bending stress in concrete block.

5.3 Stresses in Base

One of the advantages of 3DFEM is the ability to evaluate responses of not only blocks but also base, subbase and subgrade at the same time. Figure 8 shows the maximum bending stress at the bottom of the base under the load, which was caused by the bending action of the base. In the herringbone pattern, the stress is hardly affected by the block thickness and the stiffness of joint and cushion layer, while, in the stretcher pattern, large block thickness and high stiffness of joint and cushion layer produce small stress. The stress in the herringbone pattern is much smaller than that in the stretcher pattern.

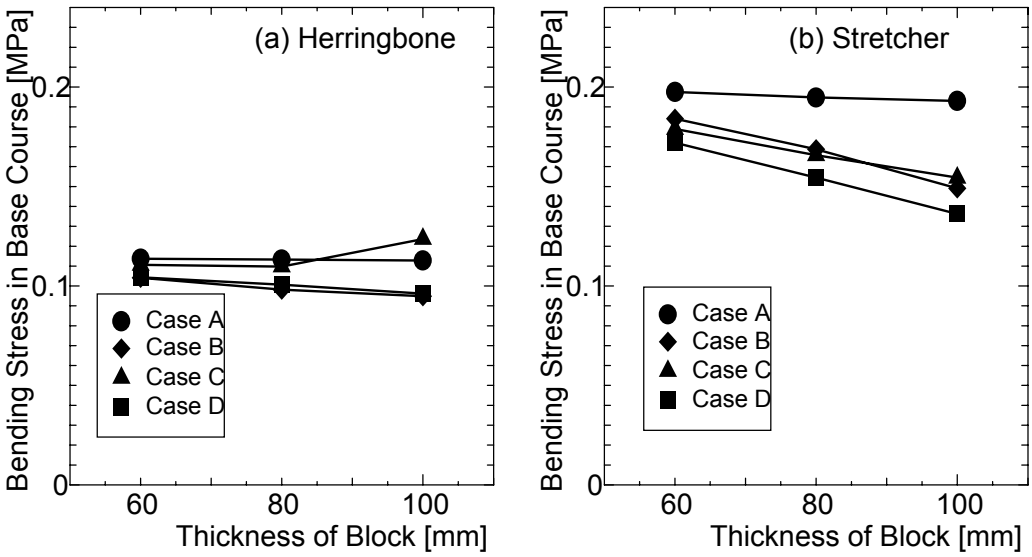


Figure 8. Maximum bending stresses in base.

5.4 Stresses in Subbase

Figure 9 shows the maximum tensile stress in the granular subbase. The stress is very small and almost the same between two laying patterns.

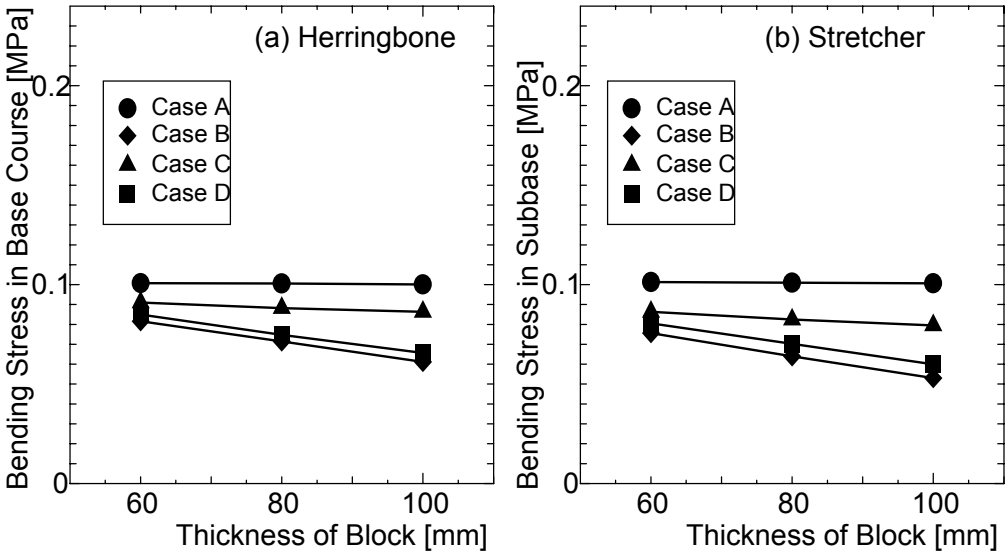
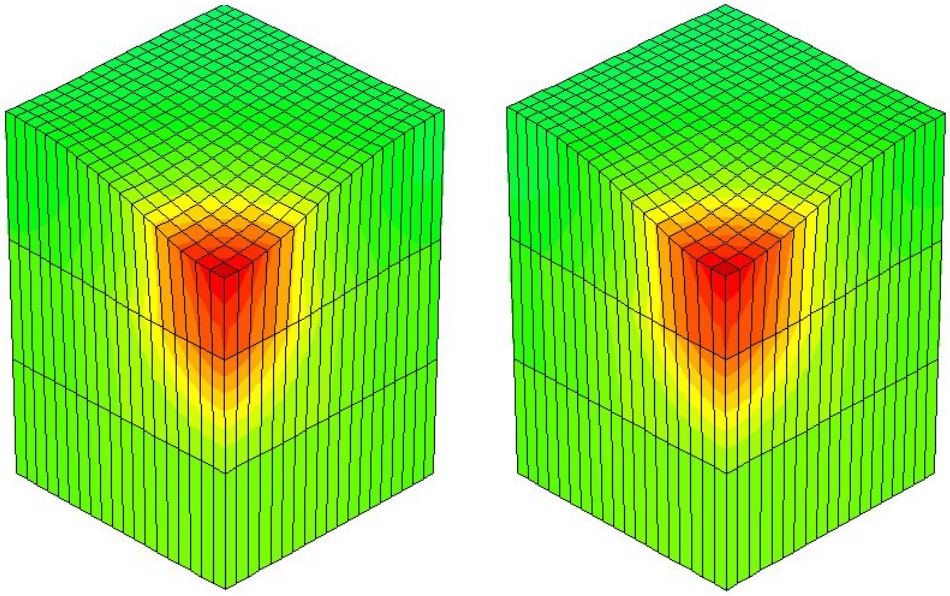


Figure 9. The maximum tensile stresses in subbase.

5.5 Stresses in Subgrade

Figure 10 shows vertical strain distributions in the quarter regions of the entire pavements. Large compressive strain is generated at the top of subgrade under the load. In the structural design of pavements, the vertical compressive strain at the top of a subgrade is important in terms of plastic deformation in the subgrade (Knapton, 1985, Shackel, 1985, and Silwerbrand, et. al., 2000).



(a) Herringbone **(b) Stretcher**

Figure 10. Distributions of vertical strain.

Figure 11 shows the maximum vertical compressive strain (compressive is negative) at the top of the subgrade. If the joint stiffness is low (Case A and C), the effect of the block thickness is small. On the other hand, if it is high (Case B and D), the strain decreases by about 20 % as the block thickness increases from 60 mm to 100 mm. As for the strain in the subgrade, the effect of lay1ing pattern is very small.

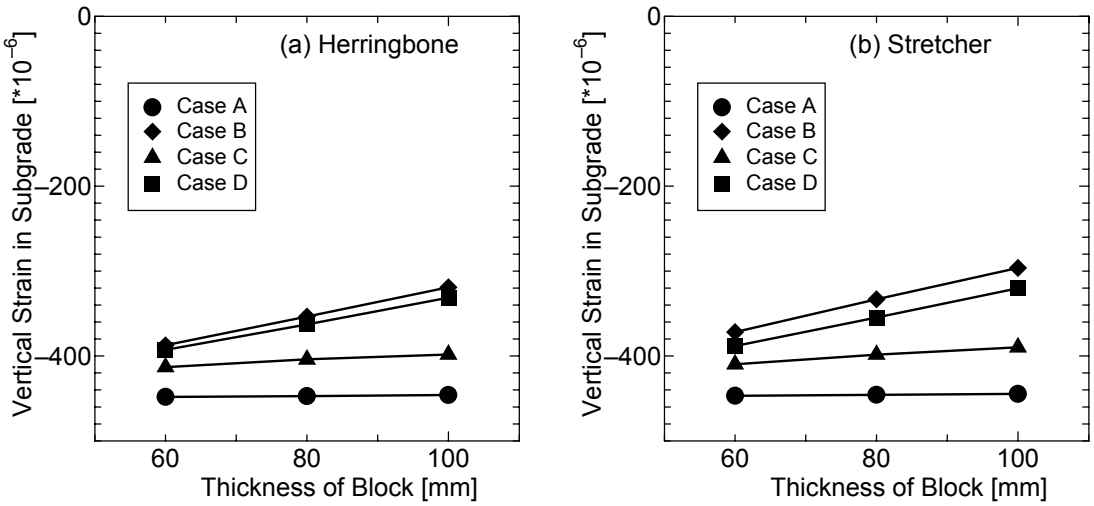


Figure 11. The maximum vertical strain at the top of subgrade.

6. CONCLUSIONS

In this study, a 3DFEM model was applied to concrete block pavements to investigate mechanical behaviors of the pavements. In order to create complicated meshes in the block layer with various laying patterns, a pre-processor with a user interface was developed, which allows users to specify various features of a block pavement and generates a mesh for the pavement without time consuming data handling relating to meshing of 3DFEM. A 3DFEM solver computes deflections, stresses and strains in base, subbase and subgrade as well as blocks. The results are displayed graphically on a window of a post-processor.

Using the tool, the effect of the block thickness, laying pattern, stiffness of joint and cushion layer on deflection, stress and strain in pavements were investigated. As a result, the following conclusions are drawn:

- The bending stresses in the block and base are larger in case of high joint stiffness than those of low joint stiffness. In that case, the block thickness largely affects the stresses.
- The tensile stress in the base due to bending action is larger in the stretcher pattern than in the herringbone pattern.
- There is very little difference in the tensile stress of the subbase and the compressive strain of the subgrade between the herringbone and stretcher patterns.

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Associate professor, Ishikawa National College of Technology, Tsubata Ishikawa, Japan 929-0392.
Tel: (81) 76 288 8167. Fax: (81) 76 288 8171. E-mail: nishi@ishikawa-nct.ac.jp

Tatsuo Nishizawa is an associate professor in the Department of Civil Engineering at Ishikawa National College of Technology, Japan.

He obtained Ms. Eng from Kanazawa University, Japan in 1981.

He obtained Dr. Eng. from Tohoku University, Japan in 1989.

He specializes in structural analysis and evaluation of pavement structures.

He is a member of JSCE and chairs the subcommittee of pavement design in JSCE(Japan Society of Civil Engineers).

He is also a member of the committee of rigid pavement design in TRB, USA.