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불연속면 조건을 고려한 다층구조체에서의 비선형 하중전달해석

Nonlinear Simulation of the Load Transfer Mechanism in Multi-layered Systems Considering Various Interface Conditions

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국문요약

하중전달의 문제는 구조체가 하중을 지지할 때 하중을 받는 부재로부터 하중을 지지하지 않는 쪽의 구조로 얼마만큼의 하중이 전달되는가를 해석하는 것이라고 간단히 정의 할 수 있다. 효율적인 Load transfer mechanism 은 구조체의 설계와 해석의 중요한 인자와 직접적으로 관련이 되어 있기 때문에 구조체의 해석시에는 이러한 하중전달의 개념이 반드시 포함되어야 한다. 그러나 일반적인 구조체의 해석시에는 하중전달의 개념은 그 해석의 어려움과 이론적인 해석해의 부재 그리고 본질적으로 존재하는 복잡성 때문에 무시되어져 왔다. 또한 이러한 하중전달의 문제가 다른 역학적인 거동과 연관되어 해석되어 질때는 그 이론적인 해는 구할 수가 없게 된다. 따라서 본 연구에서는 다층구조체에 존재하는 하중전달의 문제를 구조체 내에 존재하는 불연속면의 영향을 고려하수 있는 수치해석적인 모델의 개발을 통하여 하중전달효율의 개념으로 분석하여 각각의 불연속면의 영향에 따른 구조체내에 존재하는 하중전달의 현상을 규명하고자 한다.

INTRODUCTION

The load transfer mechanism is the problem which regards how much load is transferred from the loaded side of the structure to the unloaded side of the structures. Because the load transfer mechanism is directly related to important design values such as critical stresses and deflections, it is one of the most important structural behaviors that must be explained by computational or analytical approaches. However, the load transfer mechanism has been treated as difficult problems to be analyzed numerically and to be explained analytically due to its inherent complexities. The problem associated with various interface conditions thus become much more complex although various mechanics have been introduced to clearly explain load transfer mechanisms resting on multi-layered system. Since different interface conditions certainly affect the behavior of the load transfer system as well as the behavior of the structure, interface condition effect should included in the analysis of multi-layered system. Therefore, the main objective of this research is to develop an analytical model that capture all the essential mechanics present in load transfer mechanism and to investigate the interaction between interface conditions and joint performance by analyzing jointed rigid airport pavement systems. The rigid pavement structures are good models for studying the load transfer mechanism resting on multi-layered structures because rigid pavement systems have all the structural components we need such as load transfer devices, various interface conditions and they are usually constructed on multi-layered sub-structures.

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CURRENT ANALYTICAL MODELS

A small gap is constructed in general rigid pavement systems between adjacent concrete slabs to allow for expansion and contraction of the concrete. Naturally, this gap does not allow transfer of the transverse load between slabs, and so round steel bars are often employed to bridge the gap, Figure 1 demonstrates the basic mechanisms involved. A continuous slab is able to distribute an applied load to the foundation across the full length of the slab. When a joint is placed in the continuous slab, load transfer to the foundation is possible only through the loaded slab. In addition, the local stresses in this loaded slab will be greater than in the continuous case.

Round steel bars have been used as load transfer devices in rigid pavements for most of this century, and have therefore received much attention from researchers and practitioners. Ioannides and Korovesis [1992] present a thorough overview of most of the relevant work in this area. Almost all of models are based on the theory of plates resting on an elastic foundation. The load transfer devices are usually modeled as beams, and are connected to the plates by elastic springs[Huang 1993]. Thus, two additional stiffnesses enter into the model: the foundation modulus, k, and the modulus of dowel support, K[Channakeshava, *et al.* 1993, Zaman 1995]. Therefore, chosing a reasonable values of these two parameter is critical because structural behaviors are greatly depend on these values.

Since the purpose of the doweled joint is to transfer load from a loaded slab to an unloaded slab, various measures of joint efficiency have been proposed and used. The two most widely used measures are the load transfer efficiencies based on deflection and stress. A common efficiency based on displacements is[Guo 1995, Ioannides 1992]

$$LTE_{\delta} = \frac{\Delta_u}{\Delta_l} \tag{1}$$

where Δ_l and Δ_u are the vertical displacements of the loaded and unloaded slabs, respectively, measured at the joint on the top of the slabs. Considering stresses, an efficiency is defined as[Tabatabaie and Bareanberg 1980]

$$LTE_{\sigma} = \frac{\sigma_u}{\sigma_l} \tag{2}$$

where σ_l and σ_u are the stresses at the bottom of the loaded and unloaded slabs, respectively, measured at the joint. An additional measure of efficiency is the transferred load efficiency [Ioannides and Korovesis 1992], defined as

$$TLE = \frac{P_{transferred}}{P_{applied}} \tag{3}$$

where $P_{transferred}$ and $P_{applied}$ are the transferred and applied loads, respectively. An alternative measure of joint efficiency is proposed in this paper, and defined as

$$\eta_{shear} = \frac{V_{slab}}{V_{dowel}} \tag{4}$$

where V_{dowel} the shear force transferred across the gap through the dowel bar and V_{slab} is the shear force that would be transferred through a continuous slab. This measure is motivated by the observation that the dowel bar can do no better than equal the performance of the continuous slab it is replacing.

CONTACT SOLUTION ALGORITHMS

Because one of the primary objective of this study is to examine the interaction between load transfer behavior and various interface conditions, simulating different interface conditions is a major concern in this research. Among various approaches in solving contact problems, imposing a contact constraints conditions based on nonlinear optimization theory was adopted in this study. In these approaches, contact problems are characterized by contact constraints which must be imposed on contact boundaries. Although the Lagrangian multiplier method and the penalty parameter method are well known and commonly used solution procedures, the Augmented Lagrangian method was introduced into finite element solution process in this research.

The Augmented Lagrangian method was proposed to overcome the problem of ill-conditioning in general Lagrangian multiplier method by combining the penalty parameter. The basic equation of the Lagrangian multiplier method is

$$\Pi(\boldsymbol{u}) = \int_{\mathrm{B}^a} W(\boldsymbol{u})dv - \int_{\mathrm{B}^a} \rho\ \boldsymbol{b}^a \cdot \boldsymbol{u}^a dv - \int_{\partial_f \mathrm{B}^a} f^a \cdot \boldsymbol{u}^a da + \int_{\gamma^c} \lambda \cdot (\boldsymbol{B}^T \boldsymbol{u} - g_o) \qquad (5)$$

where B is the body, ρ is the mass density, $\boldsymbol{b}^a$ is a body force of the structure and γ^c stand for the contact surface between two deformable bodies. The Lagrangian multiplier method has some numerical difficulties such as an indefiniteness of the system matrix due to zero diagonal terms. The Augmented Lagrangian algorithm can be represented as follow[Simo and Laursen 1992];

$$\Pi(\boldsymbol{u}) = \int_{\mathrm{B}^a} W(\boldsymbol{u})dv - \int_{\mathrm{B}^a} \rho\ \boldsymbol{b}^a \cdot \boldsymbol{u}^a dv - \int_{\partial_f \mathrm{B}^a} f^a \cdot \boldsymbol{u}^a da$$
$$+ \int_{\gamma^c} \left\{ \lambda \cdot (\boldsymbol{B}^T \boldsymbol{u} - g_o) + \frac{\varepsilon}{2} \boldsymbol{\lambda}^T \boldsymbol{\lambda} \right\} \qquad (6)$$

As shown in the above equation, the ill-condition problem can be cured by adding the term $(\varepsilon/2)\ \boldsymbol{\lambda}^T \boldsymbol{\lambda}$. As a discrete form of the equation is,

$$\Pi(\boldsymbol{u}, \boldsymbol{\lambda}) = \frac{1}{2} \boldsymbol{u}^T \boldsymbol{K} \boldsymbol{u} - \boldsymbol{u}^T f + \lambda^T (\boldsymbol{B} \boldsymbol{u} - g_0) + \frac{\varepsilon}{2} \lambda^T \lambda \qquad (7)$$

The main idea of this approach is very similar to that of general perturbed Lagrangian methods. The main difference between the Augmented Lagrangian method and the Perturbed Lagrangian methods lies in the solution procedures. The solution procedure of the Augmented Lagrangian method start from,

$$\textit{Minimize}\quad \Pi(\boldsymbol{u}) + \frac{\varepsilon}{2} \boldsymbol{u}^T \boldsymbol{B}\boldsymbol{B}^T \boldsymbol{u}$$
$$\textit{with the contact constraints}\quad \boldsymbol{B}^T \boldsymbol{u} = 0$$

The penalty term in the above relation does not change the optimal values of $\boldsymbol{u}$ or the Lagrangian multiplier $\boldsymbol{\lambda}$ during the solution process. For each solution step, the Lagrangian multiplier is constant while the penalty term is continuously updated [Landers and Tylor 1985, Simo, *et al.* 1985].

FINITE ELEMENT MODELS

This study is primarily concerned with the use of finite element models to examine the performance and failure of load transfer systems. This requires the development of nonlinear three dimensional models capable of representing features such as the different interface conditions between the structural components, spalling of the matrix, such as concrete, near the joint in rigid pavement systems, deterioration of the layers and the interface between load transfer equipments and the surrounding matrix materials. In this paper, however, a relatively simple two dimension model is considered, and is used to examine the influence of interface conditions and of deteriorations in each structural components on overall joint performance.

The geometry of the model problem considered is shown in Figure 2, and is based on published data for the Denver International Airport [Warren 1991]. A rounded steel bar of length 610 mm is placed along the centerline of the slabs as load transfer system to bridge the joint of width 6.35mm. The material properties used for the various components are given in Table 1 [Warren 1991], together with the thickness of each layer considered in the model. The length of each slab was chosen to be 2.54m after a careful study of the influence of the slab size on the deformation at the joint. The extents of the subgrade layers were chosen in a similar manner. A uniformly distributed load of magnitude 1,480kPa acting vertically downwards over a length of 508mm was placed on the right-hand slab to approximate a wheel load of an aircraft.

One of the primary objectives of this study was the examination of the interaction between joint performance and the interface conditions between each structural components. Four different interface conditions were considered between the three structural components: from perfect bond to frictionless sliding. Table 2 shows the nomenclature adopted to describe the various combinations of interface conditions possible between these components. The contact algorithm assume that interaction between the two contact surfaces is governed by a Coulomb friction law, and thus require the specification of a coefficient of friction. Introduction of sliding between components complicated the solution of the problem in two ways. First, it introduced geometric nonlinearities, thereby requiring an iterative solution to the governing equations. Second, it introduced the possibility of spurious rigid body motions.

The second item of interest is the effect of structural deteriorations on joint performance with interface conditions to determine whether η_{shear} can represent load transfer behavior better than a measure of load transfer efficiency based on displacement. Load transfer efficiencies were evaluated for each different combination of degree of fiber loosenesses and of sub-layer deteriorations as shown in Figure 3. The parameter ***a*** denote the degree of fiber looseness and the ***b*** stand for the size of sub-layer deterioration. The steel slip interface condition was assumed for this study.

RESULTS AND DISCUSSION

Two basic quantities were used to study the interaction between interface conditions and joint performances in the model problem. The traditional measure of load transfer efficiency, LTE_δ in equation (1), and the shear load transfer efficiency, η_{shear} in equation (4). Displacements at 0 and 15.0 cm were chosen to calculate LTE_δ. Table 3 reports these forces for the perfect fit case and for all of the interface and loading conditions considered. The table 3 demonstrates that releasing the bond between the slab and a selected component reduces the load transferred through that component. For example, introducing slip between the load transfer system and the slab results in an increased load carried by the foundation. Similarly, slip between the slab and the foundation produces an increase in the load in the transfer equipments. Interestingly, a consequence of this phenomenon is the observation that the load in the transfer device is maximized when slip is present only between the slab and the foundation. Tables 4 and 5 present the calculated load transfer efficiencies for all of the interface conditions examined in this study. The reported data do demonstrate some important features of the overall joint performances with respect to different interface conditions. Clearly, the traditional measure of joint efficiency, LTE_δ, does not differentiate between the various interface conditions and degrees of structural deterioration, since the value of LTE_δ never falls below 0.90 for the perfect fit case. However, the efficiency η_{shear} does reflect the ability of the joint system to transfer load to the unloaded slab in the different configurations considered here. The effects of releasing the various interfaces in the system described previously are reflected in the data in Table 4. This measure also captures the reduction in joint efficiency that accompanies an increase in the deteriorations in the system, something that LTE_δ is unable to do. The conventional load transfer efficiencies for the deteriorated structural system were shown in Table 5. They are still higher than we expect for each degree of deterioration, range from 81% to 92% for $LTE_\delta^{(0)}$ and 79% to 88% for $LTE_\delta^{(15)}$ for 10cm radius sub-layer deterioration. All load transfer efficiency values in Table 4 and 5 shows that conventional efficiency might not be suitable for representing load transfer behavior when we analyze a load transfer system resting on multi-layered system by numerically. Figure 4 shows that the local frictional behaviors of the load transfer system by changing friction coefficients.

CONCLUSIONS

The rationale for and results of relatively simple finite element analyses of the interaction between interface conditions and joint performances have been presented. In spite of simplifications in the analysis model, it required a large number of elements to ensure accurate results. The use of the Augmented Lagrangian contact solution algorithms facilitated a study of the effects on the joint performance of the interface conditions. However, numerical instabilities introduced by rigid body modes had to be carefully eliminated. In some cases, it was impossible to produce accurate results due to the presence of these spurious modes.

The results presented in this paper provide an explanation for the load transfer mechanism across a joint when different interface conditions are considered: releasing the bond between the slab and the load transfer system or the sub-layers will reduce the load transferred through the transfer device or the sub-layer. Joint efficiencies measured using the calculated displacements at the joint on the loaded and unloaded slabs were found to be above 0.90 for all cases considered here. The shear load transfer efficiency introduced here was found to be a more useful measure of joint performance with various interface conditions when we solve load transfer system resting on multi-layered structures. Therefore, this efficiency measure should be useful when performing parameter studies directed towards obtaining optimum designs.

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Table 1. Material properties and depth of the layers

	E(GPa)	ν	depth(m)
concrete slab	27.6	0.15	0.43
base course	13.8	0.20	0.20
subgrade	0.34	0.35	0.30
soil	0.06	0.45	0.51

Table 2. Nomenclature on interface conditions

	full bond	steel slip	base slip	full slip
dowel/slab	bond	slip	bond	slip
slab/sublayer	bond	bond	slip	slip

Table 3. Load transfer system and foundation reactions

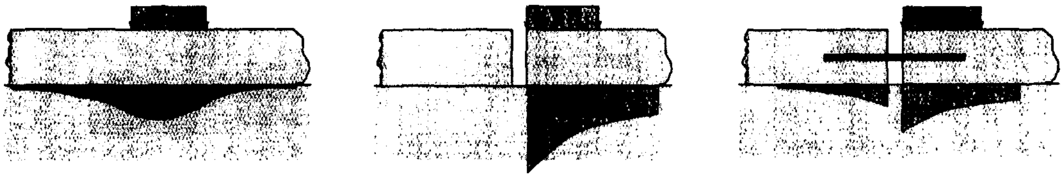
Interface	Edge Load		Center Load	
	V_{dowel}(kN)	R_f(kN)	V_{dowel}(kN)	R_f(kN)
full bond	4.94	14.60	2.74	17.17
steel slip	2.71	15.58	1.08	18.85
base slip	5.70	14.06	2.90	16.91
full slip	3.87	15.89	1.64	18.19

Table 4. Load transfer efficiencies for perfect fit case

Interface	full bond	steel slip	base slip	full slip
dowel/slab	bond	slip	bond	slip
slab/base	bond	bond	slip	slip
$LTE_\delta^{(0)}$	0.973	0.963	0.983	0.973
$LTE_\delta^{(15)}$	0.929	0.921	0.922	0.891
η_{shear}	0.72	0.39	0.78	0.53

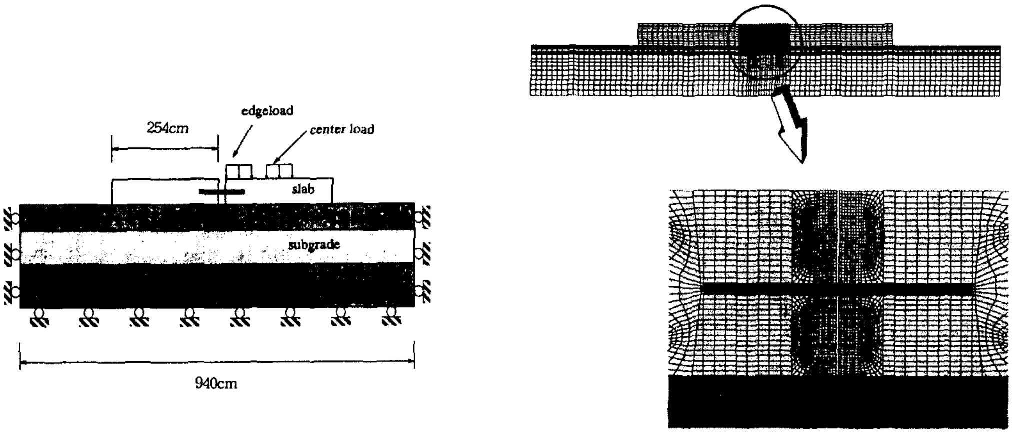
Table 5. Load transfer efficiencies for the deteriorated system

b(cm)	a(cm)	$LTE_\delta^{(0)}$	$LTE_\delta^{(15)}$	η_{shear}
0.0	0.0	0.96	0.92	0.39
	2.5	0.96	0.92	0.26
	5.0	0.95	0.91	0.14
	10.0	0.93	0.90	0.06
5.0	0.0	0.94	0.90	0.60
	2.5	0.93	0.89	0.45
	5.0	0.91	0.88	0.27
	10.0	0.89	0.87	0.11
10.0	0.0	0.92	0.88	0.77
	2.5	0.90	0.87	0.64
	5.0	0.86	0.84	0.44
	10.0	0.81	0.79	0.23



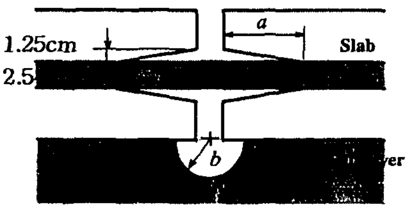
(a) Continuous system (b) Jointed system (c) Load transfer mechanism

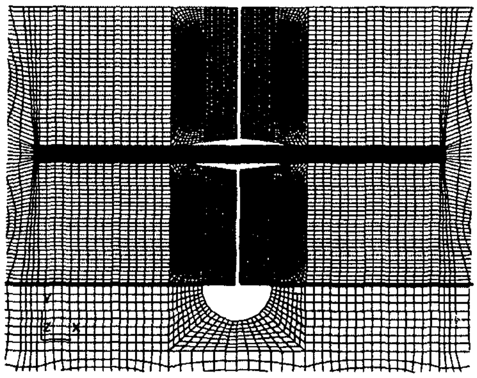
Fig 1. Concept of the load transfer mechanism



(a) Model geomerty (b) Mesh plot

Fig. 2 Geometry and mesh for the model problem





(a) Model geomerty
(b) Mesh plot

Fig. 3 Geometry and mesh for the deteriorated system

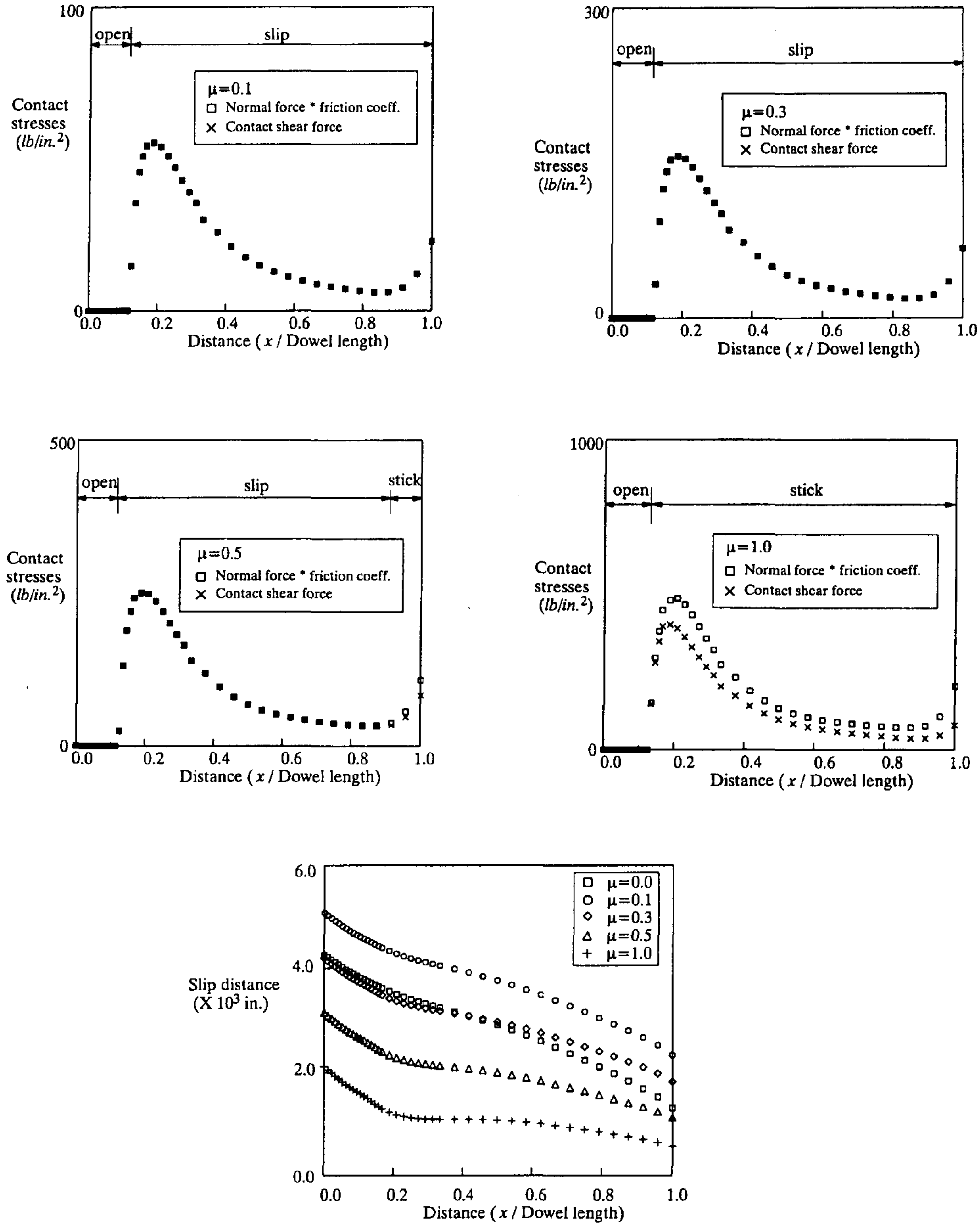


Fig.4 Frictional behaviors of the load transfer system