RESEARCH ON APPLICATION OF FINITE ELEMENT METHOD TO ANALYZE LOAD TRANSFER EFFICIENCY ACCORDING TO DEFLECTION OF AIRPORT RIGID PAVEMENT

Tien Dung Vo[1,*], Van Hieu Nguyen[2], Van Thuy Do[2], Huu Lam Nguyen[2]

[1]*Moscow Automobile and Road Construction State Technical University, Moscow, Russia*

[2]*Institute of Techniques for Special Engineering, Le Quy Don Technical University, Hanoi, Vietnam*

Abstract

The load transfer between adjacent cement concrete slabs at expansion joint locations is affected by many different factors. The load-bearing capacity of the pavement will be limited and even lead to destruction if the load transmission ability of the dowel bars does not meet the requirements. Especially, for airports that have just been put into operation or have been in operation for a long time.

In this article, the authors have researched and evaluated the effectiveness of load transfer according to deflection through the application of the 3D finite element method. The model utilizes material parameters and actual airport hard pavement structures and calculates for many types of aircraft commonly operating in Vietnam. Thereby calculating and evaluating the load transfer efficiency (LTE) according to deflection for each specific type of aircraft. The model also visually shows the deformation of the transmission dowel bars and concrete slabs at the expansion joint location. The authors tested the model's reliability through experiments conducted at Tan Son Nhat International Airport which is the largest-scale and oldest airport in Vietnam. The results of calculating LTE from the simulation and experimental models have a small error (3.39%) which shows that the model is highly reliable and can be used for similar research directions without being easily done through traditional methods.

Keywords: *Airport rigid pavement; deflection; dowel bar; finite element method; load transfer efficiency; LTE.*

1. Introduction

Nowadays, cement concrete pavement is always of great interest to researchers and managers. The standard system is increasingly perfected and construction technology is increasingly developed. Due to the advantages of longevity, large load capacity, and increasingly advanced construction technology, concrete pavement is being widely used in many countries, especially for airport pavement design. Therefore, the overall proportion of concrete pavement compared to other types of pavement is increasing over time and with the air traffic development strategies of countries, including Vietnam.

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[*] Email: vtdung.mta@lqdtu.edu.vn

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Also from the advantages of concrete, Vietnam's airports basically use concrete pavements such as Tan Son Nhat International Airport, Noi Bai International Airport, Da Nang International Airport,... Due to practical requirements as well as to promote the development of air traffic, we need to build a high-quality, large-scale airport system that can receive modern aircraft of the world with traffic volumes and take-off and landing frequencies many times greater.

Besides, thermal stress is a limitation of this type of pavement. To ensure limited damage due to temperature loads, the concrete pavement is slotted to form a system of panels connected to each other through expansion joints. These expansion joints create discontinuities in the road surface. The use of round steel bars is the most common method for transferring loads at expansion joints on cement concrete pavements.

Before accepting into service or putting into service a new type of aircraft, an assessment of the bearing capacity of the pavement structure is mandatory. At the same time, during operation, due to the influence of factors such as aircraft load, climatic conditions, and hydrothermal regime, the quality of the road surface has certain changes, so it needs to be checked, periodic assessment according to International Civil Aviation Organization (ICAO) regulations [1].

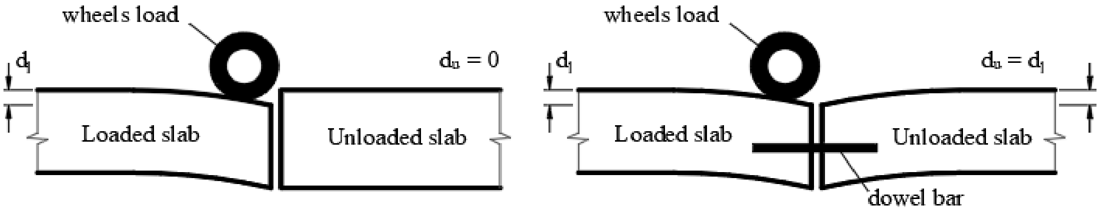
Currently, with advantages such as quick testing time, no damage to the road surface structure, high reliability, etc., non-destructive load testing methods are increasingly used. From the measured deflection results, through specialized software, it is possible to determine the ability to transmit load through deflection [2].

In Vietnam and around the world, many authors have applied finite element methods to study rigid pavements, as presented in [3-5]. These studies focus on analyzing pavement conditions to provide recommendations for optimizing pavement design and enhancing operational efficiency.

This article focuses on analyzing the load transfer efficiency according to deflection of jointed rigid pavement at the airport. Abaqus 2022 is the software used in this study. This software provides numerous interactions, constraints and different loading conditions which make it suitable to carry out a complicated analysis.

2. Theoretical basis for calculating load transfer efficiency based on deflection

Load transfer efficiency is a quantitative measurement of the ability of a joint or crack to transfer load from one side to the next. LTE is a parameter that can be calculated from a deflection test to characterize the ability of two concrete slabs to transfer loads through joints and cracks in a rigid pavement (Fig. 1). It may be defined in terms of either deflection load transfer or stress load transfer. Deflection LTE is more commonly used because it can be easily measured on existing pavements using falling weight deflectometers (FWD), and heavyweight Deflectometers (HWD) [6, 7].



a) 0% load transfer b) 100% load transfer

Fig. 1. Illustration of deflection load transfer concept [6, 7].

The most common mathematical formulation for expressing deflection LTE is:

$$LTE = \frac{d_u}{d_l} \cdot 100 \tag{1}$$

where LTE is the load transfer efficiency, %; d_u is the deflection stress on the unloaded side of the joint, mm; d_l is the deflection stress on the loaded side of the joint, mm.

In addition, LTE is also calculated based on stress according to the following formula:

$$LTE_\sigma = \frac{\sigma_u}{\sigma_l} \cdot 100 \tag{2}$$

where LTE is the stress LTE, %; σ_u is the corresponding stress at the joint of the unloaded slab, MPa; σ_l is the maximum stress at the joint of the loaded slab, MPa.

The following guidelines can be used to define different levels of deflection LTE [6]:

- Excellent: 90% to 100%;
- Good: 75% to 89%;
- Fair: 50% to 74%;
- Poor: 25% to 49%;
- Very Poor: 0% to 24%.

To avoid cases where concrete panels have too large deflections (damaged panels, loss of load-bearing capacity, etc.) but still give a high LTE index, the differential deflection parameter Δd (mm) is used. This is the relative displacement between the loaded and unloaded concrete panels on both sides of the joint, calculated:

$$\Delta d = d_l - d_u \tag{3}$$

It is suggested that Δd be limited to 0.13 mm or less and that peak corner deflections be limited to 0.63 mm or less [7].

3. Apply the finite element method to study the load transfer efficiency in terms of cement concrete slab's deflection

3.1. Material modelling and aircraft loading

In the article, the authors use the Abaqus 2022 software (Copyright by Le Quy Don Technical University) to simulate the airport cement concrete pavement system subjected to loads. This software has also been used by many authors around the world to simulate road surfaces for their research [3, 8, 9]. This is software that can simulate many types of problems related to mechanics and thermodynamics.

To improve the reliability of the model, the author used airport pavement structures and applied loads according to the actual conditions of the experiment [10]. The properties constants used are listed in Table 1.

Table 1. Concrete, base, and steel properties used for the finite element model [10]

Layer	**Cases**	**Thickness (cm)**	**Modulus of elasticity (MPa)**	**Poisson's ratio**
1	Concrete M350	40	31000	0.15
2	Concrete M150	38	16000	0.20
3	Graded Aggregate Base	18	450	0.35
4	Sand	50	180	0.35
5	Subgrade	250	130	0.40

The model uses 14 steel bars of d32 diameter, 50 cm long and the distance between 2 dowel bars is 35 cm. The elastic modulus and Poisson's ratio of steel are E = 210000 MPa and $\mu = 0.3$.

The load is circular in shape acting on the concrete pavement system with a diameter of 30 cm and the pressure is according to the load of the super heavy weight deflectometer (SHWD). In addition, the author also used a single-wheel load of aircraft in Vietnam for simulation. Traditionally, the contact stresses at the wheel-pavement interface is assumed to be equal to the tire pressure and is distributed regularly in a rectangular contact area. The contact area used in this research was designed using the Portland Cement Association method [11]. This technique assumes that the wheel-pavement contact area A_c (mm^2), calculated by dividing the load on each tire by the tire pressure, is a rectangular figure with 0.8712·L length and 0.6·L width. The following equation calculates the length of the contact area L (mm):

$$L = \sqrt{\frac{A_c}{0.5227}} \tag{4}$$

Table 2 shows the main characteristics of airplanes considered in this study.

Table 2. Characteristics of the airplanes (FARFIELD)

Aircraft	Tire pressure (MPa)	Footprint area (mm^2)	Tire contact length (mm)	Tire contact width (mm)
F15	2.344	61290	353	221
B777-200ER	1.413	163939	578	361
B737-500	1.338	105836	464	290
A330-200STD	1.420	189364	621	388

The foundation depth is 2.5 m to better simulate the foundation response as an approximation to an infinite foundation.

3.2. Contact surface model

Contact between surfaces is modeled by contact behavior in the tangential and normal directions to the contact surface. In particular, contact behavior uses the Coulomb friction model for the tangential direction characterized by the friction coefficient between surfaces and the "hard contact" model for the normal direction. According to the 1993 AASHTO guidelines [12], the coefficient of friction between the plate and the substrate is usually between 0.9 and 2.2. In the article, it was assumed to be 1.5. At the contact surface, there is a layer of oil paper, friction is significantly reduced, so the friction coefficient is chosen to be 0.5. The concrete surface and foundation are allowed to separate after contact. Loss of contact between slab and base modeled using normal hard contact that allows the surfaces to separate after coming in contact.

In fact, 2/3 of the length of the dowel bar is bitumenized, so the contact between the force transmitting steel and the modeled concrete slab ensures that half of the steel bar can slide freely in the direction of the dowel bar axis.

3.3. Model meshing and simulation elements

The concrete slab and foundation layers use eight-node linear continuum three-dimensional brick element, reduced integration (C3D8R) available in Abaqus 2022. At the position where the force-transmitting steel comes into contact with the plate as well as at the position where the load is applied, the mesh is fine-tuned to ensure accurate results. The components of the simulation are shown in Fig. 2.

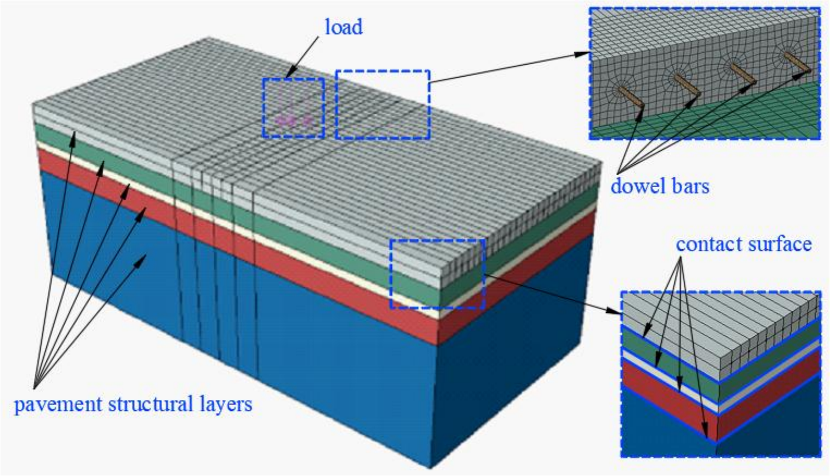


Fig. 2. Components of the finite element model.

The materials are simulated with elastic, linear, and isotropic material behavior. After creating the mesh, the model is divided into 110000 elements. Contact between material layers is modeled by contact behavior in the tangential and normal directions to the contact surface [13, 14].

3.4. Model results

In this study, the author focuses on the displacement of load-bearing and non-load-bearing concrete slabs as well as the deformation of dowel bars. After the analysis process, the results of deformation and displacement are shown in Fig. 3 and Fig. 4.

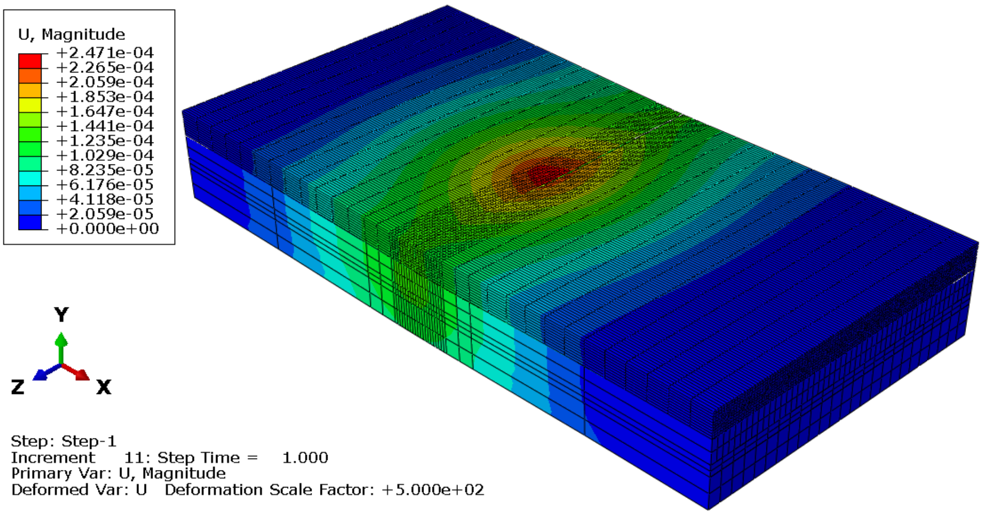


Fig. 3. Overall displacement of the concrete slabs.

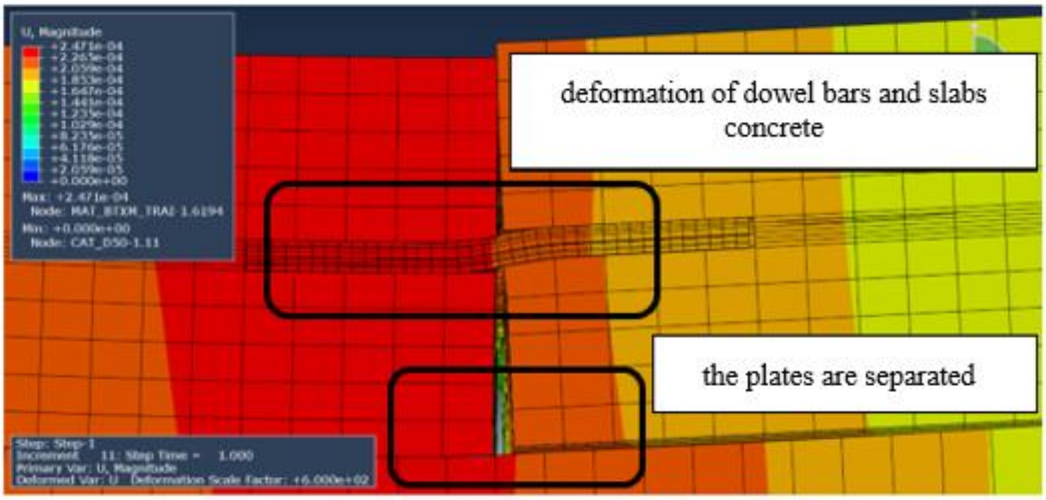


Fig. 4. Displacement and deformation at the location of the dowel bar.

According to the simulation method, one has the load transfer efficiency according to deflection due to the experimental load and the load of some types of aircraft as shown in Table 3.

Table 3. Load transfer efficiency according to deflection according to the simulation

Load	Tire pressure (MPa)	Deflection (10^{-3} mm)		$\Delta d = d_l - d_u$ (10^{-3} mm)	$LTE = \frac{d_u}{d_l}.100,\%$
		d_u	d_l		
Experimental load	-	171.4	188.5	17.1	90.93
F15	2.344	189.1	206.2	17.1	91.71
A330-200STD	1.420	317.1	346.0	28.9	91.65
B777-200ER	1.413	277.6	302.8	25.2	91.68
B737-500	1.338	177.1	193.2	16.1	91.67
Medium	-	226.5	247.3	20.9	91.53

Thus, according to finite element simulation, the load transfer efficiency according to the deflection of the structural system reaches 91.53%. At the same time, the average deflection difference $\Delta d = 0.0209\,\text{mm}$, satisfies the differential deflection parameter condition according to formula (3).

4. Calculate and determine the ability to transfer force according to deflection using SHWD equipment in the field

4.1. Introduction to SHWD device

To test the reliability of the finite element model, the authors conducted experiments at Tan Son Nhat International Airport. The experimental equipment is Model Pave SHWD 350 kN. Currently, in Vietnam, some airports have been using SHWD equipment, which was manufactured by Pavetesting in the UK in 2018 (Fig. 5). The main parts of the SHWD device:

- Impulse generator, including load block and shock absorber;
- Circular press plate with diameter is 30 cm, made of alloy, the bottom has a thin rubber layer, and the center of the plate has a hole to place the sensors;
- The deflection probes: Nine probes are installed in a straight line on support along the measuring vehicle direction. There is one probe placed at the center of the press plate, and the other probes are at a distance from the center, as shown in Table 4. In actual conditions, it is possible to change the position and upgrade the number of deflection probes.

Table 4. Distance between measuring heads relative to the center of the press plate [10]

D01 (center of the press plate)	D02 (mm)	D03 (mm)	D04 (mm)	D05 (mm)	D06 (mm)	D07 (mm)	D08 (mm)	D09 (mm)
0	300	600	800	1100	1400	1700	1900	2100

Fig. 5. Experimental measurement of road surface deflection.

4.2. Experiment sequence and process the results

- Collect deflection data: Install the SHWD device into the trailer, and re-align the distance of the measuring heads. Using a tow truck to reach the location to be assessed, the load is applied to obtain the deflection values.
- From the deflection value, we can calculate the load transfer efficiency according to the deflection at the locations that need to be evaluated.

The experimental and computational results are presented in Table 5.

Table 5. LTE calculation results according to field experiments [10]

Measuring point	Deflection, 10^{-3} mm		$\Delta d = d_l - d_u$ (10^{-3} mm)	$LTE = \frac{d_u}{d_l}.100,\%$
	d_u	d_l		
1	173.71	190.6	16.89	91.14
2	175.65	187.95	12.30	93.46
3	180.89	186.93	6.04	96.77
4	179.05	184.23	5.18	97.19
5	176.65	187.94	11.29	93.99
6	183.21	187.45	4.24	97.74
7	175.59	188.62	13.03	93.09
8	175.42	184.75	9.33	94.95
9	174.61	188.86	14.25	92.45
10	180.32	186.39	6.07	96.74
Medium	177.51	187.37	9.86	94.74

A comparison of deflection and load transfer efficiency according to deflection of experimental equipment measured in the field as well as by simulation method is presented in Table 6 and Fig. 6. The error of the two methods is acceptable (3.39%). This shows that the method of simulating the cement concrete-dowel bars system is to ensure reliability.

Table 6. LTE calculation results by 2 methods

Methods	Load transfer efficiency (LTE), %
Finite element method	91.53
Field experiments	94.74
Error (%)	3.39

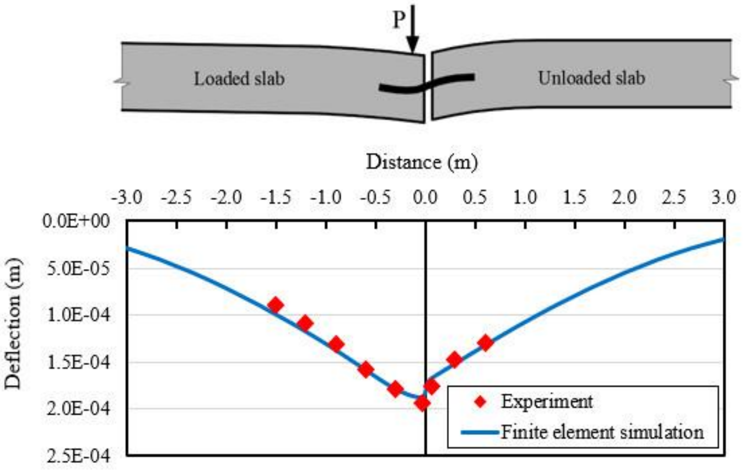


Fig. 6. Depletion comparison between experimental measurements and simulations.

5. Discussion

Simulation is the process of using a mathematical or computer model to simulate the behavior of a specific system or process. In the field of building construction, simulation methods play an important role in research, design, and optimization of structures. The most effective procedure to check the accuracy of the developed model is to match its results with field test measurements for the same arrangement under the same loading conditions. The author's simulation model has been tested in practice to evaluate its reliability.

From the results of calculating the load transfer efficiency according to deflection using the author's model, compared with the field experiment of the concrete pavement of taxiway S at Tan Son Nhat International Airport using SHWD equipment with small errors, there is acceptable as shown in Table 6. The cause of these errors comes from choosing input data for the model (such as friction coefficient between material layers, mechanical characteristics of the structure, number of dowel bars...). The deflection values of the two methods are shown in Fig. 6. This result also shows that, although Tan Son Nhat International Airport has been in operation for a long time, the load transfer efficiency in terms of deflection of the taxiway system is still good.

A great advantage of the simulation model is that it helps researchers to visually observe the overall deformation of the road surface and power transmission steel (Fig. 3 and Fig. 4) which in reality there are no observation conditions. From there, dangerous stress concentration areas in the structure can be identified.

6. Conclusion

Using a finite element simulation approach, the authors researched and calculated the load transfer efficiency in terms of LTE deflection, combined with experiments at Tan Son Nhat International Airport, the research results showed:

When subjected to different loads, the concrete slab will exhibit varying deflections. However, the load transfer efficiency in terms of deflection does not change significantly. This indicates that load transfer efficiency is not heavily dependent on the applied load but mainly depends on the nature and working conditions of the pavement structure.

Calculating the bearing capacity in terms of deflection according to the simulation method and according to experimental data has similar results (the error between the model and experiment is acceptable, only 3.39%). This shows that the finite element model built is to ensure reliability and can be used for similar studies for airport concrete pavements.

The stress and deformation of the dowel bars in the model are shown visually. At the same time, it is possible to accurately determine the unfavorable position during the working process of the dowel bars as well as the concrete slab.

Tan Son Nhat International Airport taxiway system still ensures good force transmission between concrete slabs in terms of deflection, ensuring safety for aircraft operations (according to the experiment, the load transfer efficiency in terms of deflection average equals 94.74%).

References

[1] *Part 3 Pavements*, ICAO Doc 9157-AN901, 2017.

[2] *Use of nondestructive testing in the evaluation of airport pavements*, AC 150/5370-11A, 2004.

[3] A. Szydlo and P. Mackiewicz, "Thermal Stress Analysis in Concrete Pavements", *Journal of Transportation Engineering, Part B: Pavements*, © ASCE, ISSN 2573-5438, 06020002-1-11, 2020.

[4] P. Mackiewicz, "Finite-Element Analysis of Stress Concentration around Dowel Bars in Jointed Plain Concrete Pavement", *Journal of Transportattion Engineering*, © ASCE, ISSN 0733-947X, 06015001-1-8, 2015.

[5] Hoàng Khắc Tuấn và Phạm Ngọc Thạch, "Mặt đường bê tông xi măng trên nền đàn hồi: Ứng xử do chênh lệch nhiệt độ và tải trọng xe đồng thời", *Kỷ yếu Hội thảo khoa học cấp trường 2022*, 2022, tr. 139-149.

[6] Using Falling Weight Deflectometer Data with Mechanistic-Empirical Design and Analysis, Volume III: Guidelines for Deflection Testing, Analysis, and Interpretation, 2017.

[7] *Concrete Pavement Preservation Guide*, 2nd Ed., 2014.

[8] Y. Zhou, B. Liu, L. Gu, and X. Huang, "Finite Element Simulation and Multi-Factor Stress Prediction Model for Cement Concrete Pavement Considering Void under Slab", *Materials*, 2020.

[9] Trịnh Trung Tiến và Nguyễn Quốc Văn, "Nghiên cứu ứng suất nhiệt trong tấm bê tông xi măng", *Tạp chí Cầu đường Việt Nam*, Số 5, tr. 48-51, 2022.

[10] Công ty Cổ phần Tư vấn kiểm định Sài Gòn Á Châu, *Báo cáo đo đánh giá sức chịu tải đường lăn S mặt đường sân bay Cảng hàng không quốc tế Tân Sơn Nhất*, 2022.

[11] Y. H. Huang, *Pavement Analysis and Design*, 2nd Ed., 2004.

[12] AASHTO, *Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, 1993.

[13] Dassault Systèmes, *Abaqus 6.11 Theory Manual*, 2016.

[14] W. Liu, T. Belytschko, B. Moran, and K. Elkhodary, *Nonlinear Finite Elements for Continua and Structures*, 2nd Ed., New Jersey, USA: John Wiley & Sons, Inc., 2014.

NGHIÊN CỨU ÁP DỤNG PHƯƠNG PHÁP PHẦN TỬ HỮU HẠN ĐỂ PHÂN TÍCH HIỆU QUẢ TRUYỀN TẢI TRỌNG THEO ĐỘ VÕNG CỦA MẶT ĐƯỜNG CỨNG SÂN BAY

Võ Tiến Dũng[1], Nguyễn Văn Hiếu[2], Đỗ Văn Thùy[2], Nguyễn Hữu Lâm[2]
[1]*Đại học Tổng hợp Kỹ thuật giao thông đường bộ Mátxcơva (MADI), Matxcơva, Nga*
[2]*Viện Kỹ thuật công trình đặc biệt, Trường Đại học Kỹ thuật Lê Quý Đôn, Hà Nội, Việt Nam*

Tóm tắt: Sự truyền tải giữa các tấm bê tông liền kề tại các vị trí khe co dãn bị ảnh hưởng bởi nhiều yếu tố khác nhau. Khả năng chịu tải trọng của mặt đường sẽ bị hạn chế thậm chí dẫn đến phá hoại nếu sự truyền tải của thanh thép truyền lực không đạt yêu cầu. Đặc biệt đối với các sân bay mới đưa vào khai thác hoặc đã khai thác thời gian dài.

Trong bài báo, các tác giả đã nghiên cứu đánh giá hiệu quả về mặt truyền tải trọng theo độ võng (LTE) thông qua ứng dụng của phương pháp phần tử hữu hạn 3D bằng phần mềm Abaqus 2022. Mô hình sử dụng các thông số vật liệu, kết cấu mặt đường cứng sân bay thực tế và tính cho nhiều loại máy bay đang khai thác phổ biến ở Việt Nam. Qua đó tính toán và đánh giá hiệu quả truyền tải trọng LTE cho từng loại máy bay cụ thể. Mô hình cũng cho thấy sự biến dạng của thép truyền lực và các tấm bê tông tại vị trí khe co dãn một cách trực quan. Nhóm tác giả đã kiểm định độ tin cậy của mô hình bằng thực nghiệm được tiến hành tại sân bay quốc tế Tân Sơn Nhất - sân bay có quy mô lớn và thời gian khai thác lâu đời nhất của Việt Nam. Kết quả tính toán hiệu quả truyền tải trọng LTE từ mô hình mô phỏng và thực nghiệm có sai số nhỏ (3,39%), cho thấy mô hình có độ tin cậy cao, có thể sử dụng cho các hướng nghiên cứu tương tự mà không dễ thực hiện được qua các phương pháp truyền thống.

Từ khóa: *Mặt đường cứng sân bay; độ võng; thanh truyền lực; phương pháp phần tử hữu hạn; hiệu suất truyền tải trọng; LTE.*

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