Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 45 (2020) 376–383

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 2nd International Congress on Transport Infrastructure and Systems in a changing world (TIS ROMA 2019), 23rd-24th September 2019, Rome, Italy

Evaluation of Load transfer in rigid pavements by Rolling wheel deflectometer and Falling weight deflectometer

Pawan Deep[a,*], Mathias B. Andersen[b] , Søren Rasmussen[b] , Nick Thom[a] , Alessandro Marradi[c], Davide Lo Presti[a]

[a]*University of Nottingham, Nottingham, NG7 2RD, U.K.*
[b]*Dynatest International A/S, Gladsaxevej 342, 2860 Søborg, Denmark*
[c]*Dynatest Italy Srl, Viale Palmiro Togliatti 108, 50059, Vinci (FI), Italy*

Abstract

Rigid pavements have widespread use, e.g, in motorways and airports, due to their excellent properties such as high bearing capacity and long lifetime. However, when rigid pavements fail it is often due to bad load transfer efficiency (LTE) at its joints. Traditional methods of measuring LTE can be time consuming. Here, we study the possibility of measuring LTE using a moving load with the aim of achieving higher productivity. An experiment simulating Rolling Weight Deflectometer (RWD) measurements on a joint was carried out to gain understanding and confidence that can guide the analysis of real RWD data. Continuous data from measurements across a joint allows for determination of not only the LTE but also additional parameters characterizing the pavement and the joint. A semi-analytical model was implemented for simulating the pavement response next to a joint and used for interpretation and verification of the experimental data. The results show promise for the use of moving loads for rapid evaluation of joints.

Peer-review under responsibility of the scientific committee of the Transport Infrastructure and Systems (TIS ROMA 2019).

Keywords: Rolling Wheel Deflectometer(RWD); Rigid Pavements; Load transfer

* Corresponding author. Tel.: +45-3189-7694.
E-mail address: pawan.deep@notingham.ac.uk & pdeep@dynatest.com

Peer-review under responsibility of the scientific committee of the Transport Infrastructure and Systems (TIS ROMA 2019).
10.1016/j.trpro.2020.03.029

1. Introduction

Assessment of rigid pavements is a routine maintenance activity for airports and rigid pavement infrastructure owners. An efficient maintenance procedure allows more time for the infrastructure to operate but requires faster structural assessment. The Rolling Wheel Deflectometer (RWD) is a non-destructive testing device operating at traffic speed while measuring the surface deflection of the pavement close to a heavy load on the rear axle. Use of the novel non-destructive RWD technology can potentially improve the efficiency of evaluation of rigid pavements.

Load transfer in jointed rigid pavements is one of the major indications of the structural condition. Faulting, spalling, corner breaking, transverse and longitudinal cracking are deteriorating factors linked to a joint's load transfer capabilities. The ability of slabs to transfer load indicates the capacity of rigid pavement to support designed loads while operating in unison. The response of rigid pavements depends on the subgrade, slab geometry, material properties, temperature, joint construction design, and type and position of loading. The evaluation of the ability to transfer load while aircraft wheels are moving over the pavement is important as it indicates the state of performance of the infrastructure. An efficient measurement and evaluation system will help infrastructure owners assess the condition of joints.

Rigid pavements are challenging to assess among other things due to their small response and non-uniformity, as well as the spatially localized reaction of the joint. These challenges have traditionally been tackled using devices such as the Falling Weight Deflectometer (FWD) for measuring load transfer. The FWD measures pavement deflections with a high accuracy in the micrometer range. However, the FWD has to be stationary while measuring with a typical measurement consisting of several load cycles. Furthermore, precise positioning of the geophones next to the joint is required. As a result, it can be time consuming to perform exhaustive joint measurements using a FWD. Moreover, traffic management and/or infrastructure closure are required adding to the cost of the measurements. To address the challenges using a FWD, continuous deflection measurement systems have been developed. A Rolling Dynamic Deflectometer (RDD) was used to assess the rigid pavement in ref. (Bay, Stokoe, Kenneth, & others, 1998). A relative position of the load and sensors with respect to the joint's position allowed for the measurement of the deflection on each side of the slab. The measurement of the response of a rigid pavement by the RDD resulted in the identification of weak joints that were to be rehabilitated (Chen, 2008). Despite its success in evaluating rigid pavements, the RDD travels at a speed of around a few km/h making it less attractive due to its low productivity and the need for traffic management.

In this paper, a 3D semi-analytical forward model is presented for computationally efficient simulations of rigid pavement responses close to joints. Furthermore, an experiment was performed in which the response of a rigid pavement around a joint was measured continuously and non-destructively. A comparison of the measured and modelled response shows good agreement and is used to gain understanding and confidence about continuous measurements of joints. The results show promise for using continuous deflection measurement systems for efficient assessment of rigid pavements and joints.

2. Methods

The response of rigid pavements is usually predicted only at specific locations as the traditional assessment by the FWD is performed only near the edge and at the centre of the slab. Mechanistic-empirical formulae have been used to backcalculate on these FWD measurements. For our application, the deflection due to a moving load is evaluated at many points moving continuously across the loaded slab, the joint and the unloaded slab.

2.1. Modelling

To predict the response of a jointed concrete pavement, a static 3D semi-analytical solution is developed. This forward model aims to be a sufficiently good approximation to real rigid pavements while being fast to calculate, e.g., in comparison with more numerically intensive approaches like finite element modelling. An efficient forward model is the foundation for the development of efficient backcalculation methods. Fig. 1 presents a schematic of the model. The origin of the coordinate system is at the position of the load and x is the driving direction, y is the transverse direction and z is the vertical direction. The formulation is based on two semi-infinite jointed concrete slabs resting on a Pasternak foundation with subgrade reaction k and shear modulus G. The load transfer efficiency δ in (I) is the ratio of the vertical deflection on the unloaded (w_{UL}) and loaded (w_L) slab right next to the joint. This formulation

$$\delta = \frac{w_{UL}}{w_L} \tag{I}$$

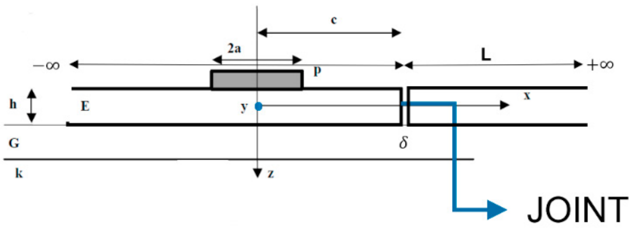

Fig. 1 Two semi-infinite jointed slabs on a Pasternak Foundation

has a vertical load of pressure p with a rectangular contact area $2a$ by $2b$ at a distance c from the joint. The slab is of thickness h with Young's Modulus E. The model is derived from the equilibrium equation of the system.. The boundary conditions imply zero vertical displacements at infinity in both x and y directions. The load pressure is assumed uniform and shear loads are not included in the model. The solution method is presented by Van Cauwelaert, (2004) but the numerically challenging implementation is done in this study.

2.1.1. Assumptions

The model follows linear elasticity and a small strain framework. A static loading is assumed and thermal effects are ignored. The load transfer in the y-direction is assumed constant here.

2.1.2. Formulation

The equilibrium equation in terms of the vertical deflection w is

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)-\frac{G}{D}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)+\frac{kw}{D}=\frac{p}{D} \tag{II}$$

where D is the flexural rigidity of the plate

$$D = \frac{Eh^3}{12(1-v^2)} \tag{III}$$

The relation between the radius of relative stiffness l and the flexural rigidity is

$$\frac{G}{D} = \frac{2g}{l^2} \tag{IV}$$

$$\frac{k}{D} = \frac{1}{l^4} \tag{V}$$

To solve equation **Errore. L'origine riferimento non è stata trovata.** both the load and deflection are expressed as double Fourier integrals. By virtue of the fourth order partial differential equation in **Errore. L'origine riferimento non è stata trovata.** four conditions are required to couple the solution across the discontinuity at the joint.

The conditions at the joint are:

- The ratio between the deflection on both sides of the joint, where $w_L = w + A(s)w_a + B(s)w_b$ and $w_{UL} = w + C(s)w_c + D(s)w_d$. Following from (I) the condition is

$$\delta(w + A(s)w_a + B(s)w_b) = w + C(s)w_c + D(s)w_d \qquad \text{(VI)}$$

- Cancellation of the moment at the edge of the loaded slab

$$\left(\frac{\partial^2}{\partial x^2} + \nu\frac{\partial^2}{\partial y^2}\right)(w + A(s)w_a + B(s)w_b) = 0 \qquad \text{(VII)}$$

- Cancellation of the moment at the edge of the unloaded slab

$$\left(\frac{\partial^2}{\partial x^2} + \nu\frac{\partial^2}{\partial y^2}\right)(w + C(s)w_c + D(s)w_d) = 0 \qquad \text{(VIII)}$$

- Equality of shear forces

$$\left(\frac{\partial^3}{\partial x^3} + (2-\nu)\frac{\partial^3}{\partial x\,\partial y^2} - \frac{2g}{l^2}\right)(w + A(s)w_a + B(s)w_b) = \left(\frac{\partial^3}{\partial x^3} + (2-\nu)\frac{\partial^3}{\partial x\,\partial y^2} - \frac{2g}{l^2}\right)(w + C(s)w_c + D(s)w_d) \qquad \text{(IX)}$$

Conditions (VI) to (IX) (VI) (VI) (VI) form a linear system of equations for the unknown "constants" $A(s)$, $B(s)$, $C(s)$ and $D(s)$ which is solved for each wave number s. The variables w_a, w_b, w_c and w_d are defined in the following way

$$w_a = \frac{p}{\pi k}\frac{1}{\sqrt{1-g^2}}\int_0^\infty [A(s)\cos(\beta x/l)]e^{\alpha x/l}\frac{\cos(sy/l)\sin(sb/l)}{s}ds \qquad \text{(X)}$$

$$w_b = \frac{p}{\pi k}\frac{1}{\sqrt{1-g^2}}\int_0^\infty [B(s)\sin(\beta x/l)]e^{\alpha x/l}\frac{\cos(sy/l)\sin(sb/l)}{s}ds \qquad \text{(XI)}$$

$$w_c = \frac{p}{\pi k}\frac{1}{\sqrt{1-g^2}}\int_0^\infty [C(s)\cos(\beta x/l)]e^{-\alpha x/l}\frac{\cos(sy/l)\sin(sb/l)}{s}ds \qquad \text{(XII)}$$

$$w_d = \frac{p}{\pi k}\frac{1}{\sqrt{1-g^2}}\int_0^\infty [D(s)\sin(\beta x/l)]e^{-\alpha x/l}\frac{\cos(sy/l)\sin(sb/l)}{s}ds \qquad \text{(XIII)}$$

where two new auxiliary parameters have been introduced:

$$\alpha^2 = \frac{1}{2}\left[\sqrt{(s^2+g)^2 + 1 - g^2} + (s^2+g)\right] \qquad \text{(XIV)}$$

$$\beta^2 = \frac{1}{2}\left[\sqrt{(s^2+g)^2 + 1 - g^2} - (s^2+g)\right] \qquad \text{(XV)}$$

2.1.3. Validation

The response from the semi-analytical model is compared to the result of a FEM solution from EverFE. EverFE is a free FEM tool that models the response of jointed slab systems due to various load configurations (Davids, Turkiyyah, & Mahoney, 1998). EverFE considers load transfer (Davids & Mahoney, 1999) and effects such as aggregate interlock and dowel properties (Davids, Wang, Turkiyyah, Mahoney, & Bush, 2003). Fig.2 shows a comparison of the modelled responses from the semi-analytical model and EverFE for two different slab moduli. Note how the semi-analytical model is very close to the FEM solution except immediately under the load (which is due to discretization error in the FEM solution). The deflection in Fig.2 is in the plane passing through the center of the load. The comparison in Fig. 2 validates the 3D semi-analytical model.

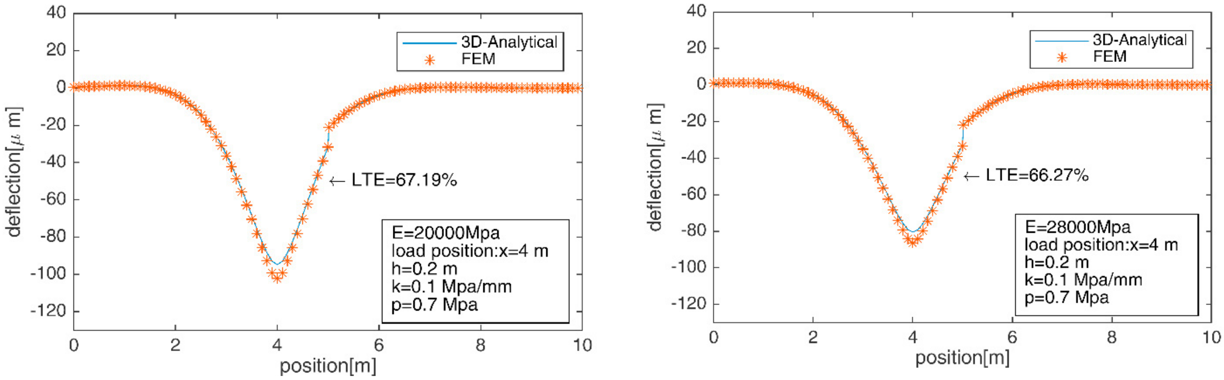

Fig. 2 Comparison of 3D semi-analytical solution and FEM solution (a) E=20000 Mpa (b) E=28000 Mpa

2.2. Experiment simulating RWD measurements across a joint

The test experiment is designed to measure with high accuracy and confidence the deflection bowl around a joint as a moving load pass across the joint. The experimental system consists of a long stiff beam onto which several displacement lasers are mounted. The moving load was rolled parallel to the beam across the joint so that the lasers measured the deflection of the loaded and unloaded slabs simultaneously at equidistant positions. An analysis of the measurements will enhance our understanding of how to incorporate RWD technology in rigid pavement assessment.

2.2.1. Equipment

The test setup uses the following components:

- Electrical components: 7 Line Lasers, Electrical cables (power and signal), Ethernet switch, Master for powering the lasers, Laptop for data collection, Encoder and encoder cable
- Mechanical: Ball and socket type support, Brackets for the support, Beam with slots for mounting laser brackets, 7 Brackets as a laser housing to be mounted on the beam and a Moving wheel load of 10 tons
- Software: A custom Recording software provided by Dynatest and a Software to configure the lasers provided by the laser manufacturer

2.2.2. Setup and schematic

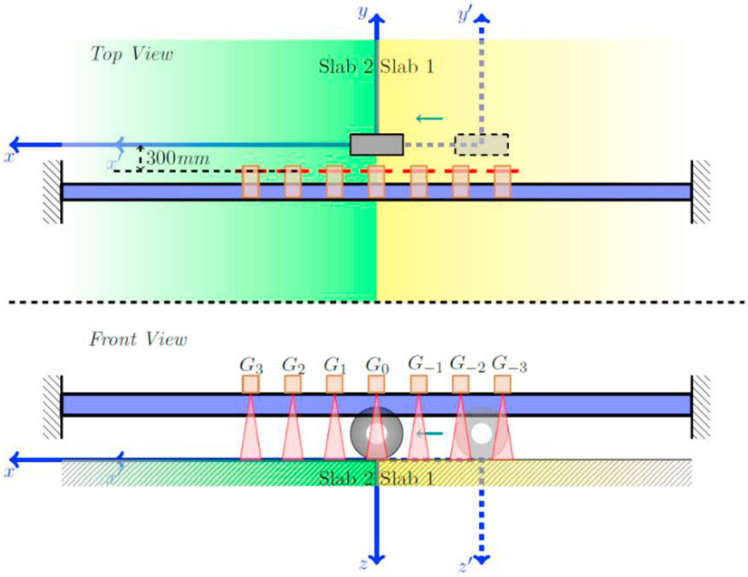

Fig. 3 Schematic of the experiment setup across the jointed slabs

Fig. 3 shows a schematic of the experimental setup and how the beam, lasers, joint and load wheel are positioned relative to each other. The distance from the center of the load wheel to the laser measurements is 300 mm. The moving wheel rolls parallel to the beam and Fig. 3 shows two of its positions. The load came from a prototype RWD at Dynatest. The deflection response was measured continuously with the lasers sitting on the beam as the load rolled next to the measurement setup. An initial measurement was taken without presence of the load wheel to obtain a baseline for subsequent calibration for effects such as beam bending and surface texture. The vertical deflection after calibration and averaging is plotted in Fig. 4(a).

3. Results and Discussion

3.1. Experiment

Fig. 4(a) shows the deflection measured by the lasers throughout the length of the experiment. The deflection shows a characteristic behaviour when as the load approaches and leaves the joint (situated at *x*=6 m). The deflection profiles

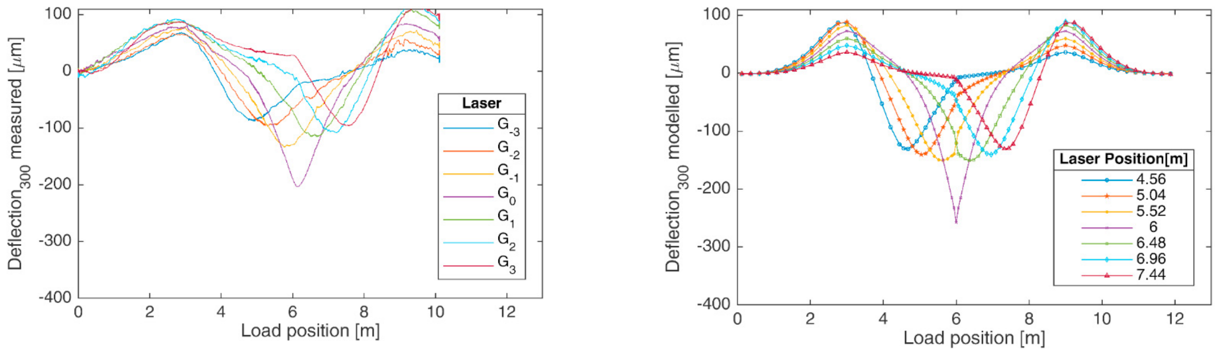

Fig. 4 Joint is at *x*=6 m (a) Measured deflection from the experiment (b) Modeled deflection from 3D semi-analytical model

from the seven lasers are different and depend on the distance from the laser to the joint and the load position. The negative peak in each deflection profile occurs when the load is exactly in front of the laser. As indicated by the order of the negative peaks, the load was moving from left to right. In Fig. 4(a), the deflection is zero for *x*=0 m, but does not end at zero at *x*=10 m because the recording was stopped before the load moved sufficiently far away from the measurement system. The first positive peak at around *x*=3 m represents the deflection that was picked up by all lasers when the load was passing in front of the left beam support. A similar positive peak was picked up as the load passed the right beam support at around *x*=9 m. The shape of the deflection profiles relates to stiffness of the slabs and the load transfer efficiency of the joint. Here, the response is not symmetric, which could be due to different pavement properties on either side of the joint.

3.2. Modelling

3.2.1. Modelled experiment by 3D semi-analytical model

The experiment was simulated using the 3D semi-analytical model. The geometrical parameters were measured directly and the material parameters were estimated from FWD measurements. Fig. 4(b) shows the modelled deflection profiles. As in the experiment, the seven deflection profiles come from seven positions corresponding to those of the lasers G_{-3} to G_3. The joint is again positioned at *x*=6 m. The modelled deflection profiles are symmetric around the joint as the material parameters were assumed to be the same on both sides of the joint. The effect of the supports was included in the model as witnessed in Fig. 4(b) by the two positive peaks.

3.2.2. Load transfer efficiency

We now study how the deflection profiles depend on the load transfer efficiency using the semi-analytical model. Fig. 5 shows the deflection profiles for load transfers of 0%, 50% and 100%. Note how especially the response close to

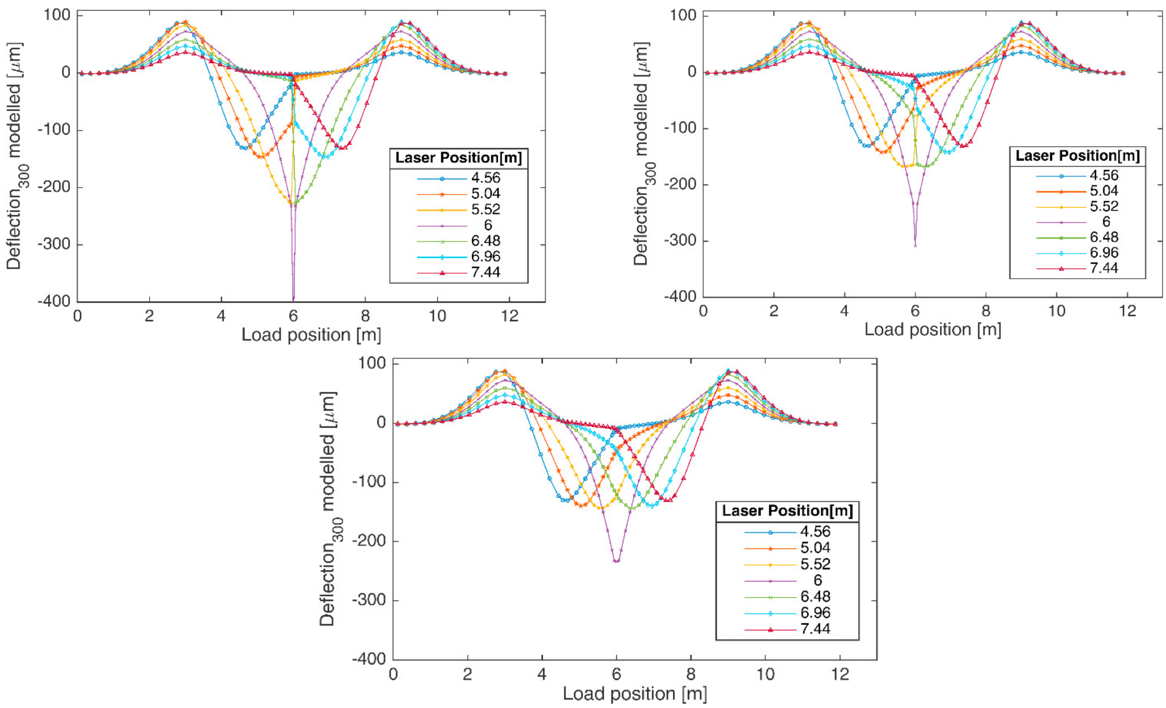

Fig. 5 Modelled deflections with Load Transfer Efficiency (clock-wise) (a) 0% (b) 50% (c) 100%

the joint is influenced when the load transfer efficiency is varied. In particular, the lasers at positions 5.52 m, 6 m and 6.48 m are affected by the state of the joint when the load passes in front of them.

The results from the measurements and the modelling indicate the possibility of backcalculation of rigid pavement parameters close to a joint. Future work is planned to analyze data from a real RWD, e.g., the Dynatest Raptor, using the current work as a guide for data collection and analysis. The current experiment was designed to have the same geometrical features as the Dynatest RAPTOR with the exception that the Raptor measurement setup moves along with the rolling load. Based on the results presented here, there is promise that real RWD data is viable for rigid pavement and joint assessment.

4. Conclusion

This study simulating the assessment of jointed rigid pavements with a moving load. At present, rigid pavement evaluation is based on the FWD, which is relatively slow, albeit very accurate. This study provides insights into a continuous structural assessment using lasers and a moving load to evaluate load transfer. A fast 3D semi-analytical model has been developed to predict the response across a joint on both the loaded and unloaded slabs. A detailed experimental study on an airport pavement with the current setup and different load transfer conditions is already underway. Moreover, a backcalculation algorithm based on continuous data is also planned. The backcalculation could lead to a more detailed assessment of slabs and the condition of their joints. Future work will involve measurements from the Dynatest RAPTOR. Evaluation of rigid pavements using continuous measurement technology is promising and should be studied further.

Acknowledgements

This work is carried out in collaboration with Dynatest International A/s and NTEC at the University of Nottingham. The research presented in this report/paper/deliverable was carried out as part of the H2020-MSCA-ETN-2016. This project has received funding from the European Union's H2020 Programme for research, technological development and demonstration under grant agreement number 721493.

References

Bay, J. A., Stokoe, I., Kenneth, H., & others. (1998). Development of a rolling dynamic deflectometer for continuous deflection testing of pavements. University of Texas at Austin. Center for Transportation Research.

Chen, D.-H. (2008). Field experiences with RDD and overlay tester for concrete pavement rehabilitation. Journal of Transportation Engineering, 134(1), 24–33.

Davids, W., & Mahoney, J. (1999). Experimental Verification of Rigid Pavement Joint Load Transfer Modeling with EverFE. Transportation Research Record: Journal of the Transportation Research Board, 1684, 81–89. https://doi.org/10.3141/1684-10

Davids, W., Turkiyyah, G., & Mahoney, J. (1998). EverFE: Rigid Pavement Three-Dimensional Finite Element Analysis Tool. Transportation Research Record: Journal of the Transportation Research Board, 1629, 41–49. https://doi.org/10.3141/1629-06

Davids, W., Wang, Z., Turkiyyah, G., Mahoney, J., & Bush, D. (2003). Three-Dimensional Finite Element Analysis of Jointed Plain Concrete Pavement with EverFE2.2. Transportation Research Record: Journal of the Transportation Research Board, 1853, 92–99. https://doi.org/10.3141/1853-11

Van Cauwelaert, F. (2004). PAVEMENT DESIGN AND EVALUATION : THE REQUIRED MATHEMATICS AND APPLICATIONS. Retrieved from https://trid.trb.org/view/698133.