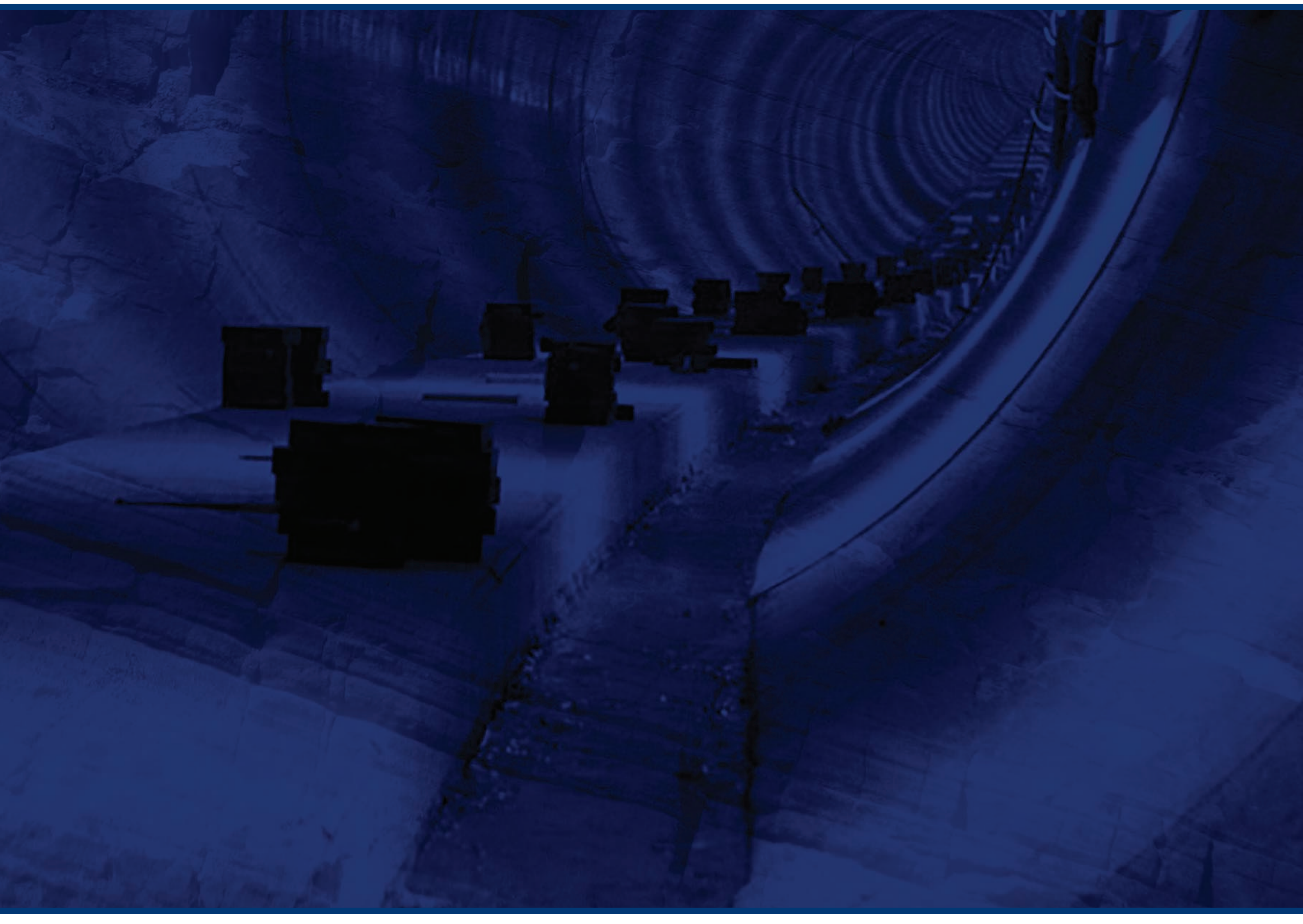
PROCEEDINGS

2018 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

Geotechnics and transport infrastructure

Wednesday, 24 October 2018, 8:00am – 6:00pm
Rydges Hotel, 186 Exhibition Street, Melbourne



AUSTRALIAN GEOMECHANICS SOCIETY
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PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2018 Australian Geomechanics Society Victorian Symposium on ‘Geotechnics and transport infrastructure’ held on 24 October 2018.

In recent years Victoria has seen significant investment in transport infrastructure as part of a plan to manage the demands of a growing population and expanding urban fringe. The construction of Melbourne Metro, a second crossing of the Yarra River, rail and freeway upgrades as well as numerous level crossing removal projects are just some of the major transport projects currently underway in Melbourne and regional Victoria. Many of these projects carry numerous complex geotechnical challenges.

The 2018 Australian Geomechanics Society Victorian Symposium covers a variety of geotechnical challenges associated with transport geotechnics and present overviews of current infrastructure challenges, state of the-art practices, innovation, new research results and case studies demonstrating applications of advanced techniques and cost effective solutions in the construction and design of local transport infrastructure. The Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of transport infrastructure and associated geotechnical challenges and applications.

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A micromechanics-based approach as an alternative to the experiment to characterise the fatigue behaviour of pavement materials

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ABSTRACT

Pavement materials feature a heterogeneous microstructure, consisting of differently-graded granules randomly distributed in the material domain and/or connected by a binder matrix. This microstructural feature significantly contributes to the complicated fatigue behaviour of the materials when subjected to traffic loadings. Existing experimental methods for pavements have faced difficulties in controlling the material microstructure and its effects on the macro-behaviour. This results in scattered experimental data often observed in the fatigue tests of pavement materials, making it hard to characterise the material behaviour and quantify parameters for practical design. This paper presents a micromechanics-based numerical approach for characterising the fatigue behaviour of pavement materials. This numerical approach can physically reproduce the heterogeneous microstructure of the materials with different gradations thanks to the application of Discrete Element Method (DEM). Moreover, the incorporation of a damage-plastic contact model enables DEM to capture the fatigue behaviour of pavement materials. Through several numerical examples, the numerical approach is shown to predict well the fatigue behaviour and real crack development in pavement materials. Given its better controllable and cost-saving features, this numerical approach can be an effective alternative (to experiments) to assist engineers in the design of road pavements.

Keywords: pavement materials, fatigue damage, micromechanics modelling, Discrete Element Method

1 INTRODUCTION

In current designs of pavements, fatigue damage due to repeated vehicle loads is considered as one of the main distress modes. The repetitive vehicle loads applied to pavement surface can induce tensile stress at base/subbase layer, causing fatigue crack to propagate upwards. Mechanically, fatigue cracking in pavement materials is described as the progressive process of micro-cracking with increasing the number of load cycles. The micro-cracks can develop even when maximum nominal cyclic stress is below the material yielding limit. This is due to the heterogeneous microstructure of the materials, which is composed of aggregates and/or cement bridges with pre-existing micro-cracks at the cement bridges or at the interfaces between cement bridges and aggregates. Under cyclic loadings, stress can concentrate near the tips of micro-cracks, causing the localised stress to be higher than nominal stress and expand micro-cracks. Alongside with the development of micro-cracks, the material will gradually degrade, represented by the reduction of material modulus with respect to cyclic loadings. The development of micro-cracks is hidden in the material body and only after the micro-cracks grow to macro-crack, they are observable from the pavement surface. However, the pavement already failed at this stage. Therefore, it is necessary to improve the understanding of micro- processes in fatigue damage of pavement materials and how it affects the performance of pavements, thereby mitigating the loss caused by fatigue damage.

So far, great effort has been dedicated to improving the prediction of fatigue damage in pavements. The most widely used method is the experimental method. In Australia, the four-point bending cyclic test has been employed to study the fatigue behaviour of pavement materials and develop the mechanistic-empirical design model to quantify the pavement fatigue life (Austroads, 2014). This design model, nevertheless, does not provide the link between the mechanical insights of the materials (e.g. micro-cracking, microstructural changes) and their macro-behaviour. Furthermore, it often requires an extensive number of tests to quantify material parameters and develop a trustful fatigue design model, given the highly-scattered results of fatigue tests for pavement materials. The scatter of fatigue test results can be attributed to the effects of microstructural features of pavement materials, which is hard to control in experiments. This is evidenced by the fact that tests of two different samples subjected to the same cyclic loading would result in different fatigue life.

Apart from the experimental method, the numerical method has also been applied to investigate the behaviour of pavement materials. Numerical methods can offer a cheap alternative to experiments to support the design and investigation of pavement materials. Among others, Discrete Element Method (DEM) (Cundall & Strack, 1979) has emerged as an effective numerical tool to model the microstructural behaviour of materials. In DEM, a material domain is discretised into an assemblage of particles, carrying their own physical properties and motions. These particles explicitly interact with each other through contacts and these interactions are governed by a contact model. This discrete nature enables DEM to naturally replicate the microstructure of pavement materials, by using particles to represent aggregates and contacts to represent the cement bridge matrix. This micromechanics-based feature indeed makes DEM standing out from other continuum methods (e.g. Finite Element Method). Moreover, DEM can handle the localised failure and cracking in the materials without any ad-hoc treatment on the models. Therefore, DEM can be a potential tool to model and the fatigue damage of pavement materials and provide more insights into how micro-cracks grow and microstructure changes during fatigue process. A fundamental issue of DEM modelling is to provide a contact model that can faithfully describe the fatigue response of materials at the grain scale. Once a correct contact model is supplied, the macro behaviour is a natural outcome. Existing contact models, however, are unable to describe the fatigue damage in cemented materials owing to the lack of intrinsic fatigue mechanisms at the grain scale. As a result, it is essential to have a contact model incorporating the grain-scale fatigue mechanisms to capture the fatigue responses of pavement materials.

The aim of this paper is to introduce a modelling approach based on DEM to characterise fatigue damage of pavement materials. In this approach, DEM plays the role in simulating the heterogeneous microstructure and localised failure in the materials. A fatigue contact model is also introduced to describe the grain-scale fatigue mechanisms of the materials. The capability of this modelling approach in capturing and predicting the fatigue behaviour of cemented materials is evaluated by comparing with the experimental data. Subsequently, findings drawn from this work are given.

2 THE MICROMECHANICS-BASED APPROACH

In this section, the technical aspect of the micromechanics-based approach is explained. Basically, this modelling approach employs DEM as a numerical platform to replicate the microstructural features of pavement materials. In particular, the aggregate of pavement materials is simulated in DEM by a set of poly-dispersed particles in the same particle size distribution. These particles interact with each other through a bonding contact representing the cement bridge between aggregates in pavement materials (see Figure 1). The fatigue mechanisms occurred at the cement bridge are described by a contact model, which is then incorporated into DEM to govern the mechanical behaviour of the bonding contact. More details of DEM and the contact model are presented in the following sub-sections.

2.1 Discrete Element Method (DEM)

In DEM, a material domain is discretised into a set of rigid particles. These particles can move and rotate in accordance with Newton's second law as follows:

$$\ddot{\boldsymbol{u}} = \frac{\boldsymbol{F} - \boldsymbol{F}_d}{m} + \boldsymbol{g} \tag{1}$$

$$\dot{\boldsymbol{\omega}} = \frac{\boldsymbol{M} - \boldsymbol{M}_d}{I} \tag{2}$$

where $\ddot{\boldsymbol{u}}$ is the translational acceleration; $\dot{\boldsymbol{\omega}}$ is the rotational acceleration; m is the mass and I is the moment of inertia of the particle. $\boldsymbol{F}$ and $\boldsymbol{M}$ are the total force and moment acting on the particles computed as the vectorial summation of all applied and contact forces as follows:

$$\boldsymbol{F} = \sum \boldsymbol{F}_c + \boldsymbol{F}_a \tag{3}$$

$$\boldsymbol{M} = \sum \boldsymbol{F}_c \times \boldsymbol{r} + \boldsymbol{M}_a \tag{4}$$

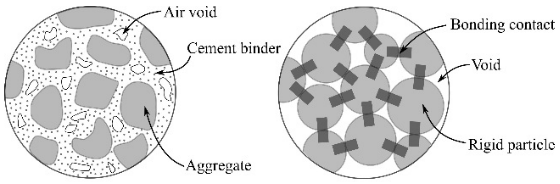

Figure 1. Microstructures *of pavement materials and DEM simulation*

where $\boldsymbol{F}_a$ is the applied force; $\boldsymbol{F}_c$ is the contact force, which is obtained based on the force-displacement relationship determined in contact models; $\boldsymbol{r}$ is the vector connecting the particle centre to the contact point; $\boldsymbol{M}_a$ is the applied moment; $\boldsymbol{F}_d$ and $\boldsymbol{M}_d$ are the damping force and moment.

Once the particle accelerations are known. The particle motions are updated using standard Leap-Frog algorithm as follows:

$$\dot{\boldsymbol{u}}^{t+\Delta t/2} = \dot{\boldsymbol{u}}^{t-\Delta t/2} + \ddot{\boldsymbol{u}}^{t}\Delta t \tag{5}$$

$$\boldsymbol{\omega}^{t+\Delta t/2} = \boldsymbol{\omega}^{t-\Delta t/2} + \dot{\boldsymbol{\omega}}^{t}\Delta t \tag{6}$$

$$\boldsymbol{u}^{t+\Delta t} = \boldsymbol{u}^{t} + \dot{\boldsymbol{u}}^{t+\Delta t/2}\Delta t \tag{7}$$

$$\boldsymbol{\theta}^{t+\Delta t} = \boldsymbol{\theta}^{t} + \dot{\boldsymbol{\omega}}^{t+\Delta t/2}\Delta t \tag{8}$$

2.2 Fatigue contact model

In general, a contact model for DEM provides a relationship between contact stress and the relative displacement of two intact particles (see Figure 2). The fatigue contact model given in this section also follows this principle. Fatigue mechanisms are incorporated into the model by introducing two fatigue variable, i.e. fatigue displacement and fatigue damage, and their evolution laws into the stress-displacement relationship. This model has been developed by the authors (Nguyen et al. 2018). Herein, key formulations of the model are presented.

The expression of total displacement at a contact is first decomposed into elastic, plastic and fatigue displacements as follows:

$$\boldsymbol{u} = \boldsymbol{u}^{e} + \boldsymbol{u}^{p} + \boldsymbol{u}^{f} \tag{9}$$

The fatigue displacement $(\boldsymbol{u}^{f})$ represents the irreversible displacement at cement bridges caused by fatigue cracking, which distinguishes itself from the plastic displacement $(\boldsymbol{u}^{p})$ developed when stress reaches the yielding limit. The separation of fatigue and plastic displacements is necessary to reflect fundamental differences between the underlying mechanisms of these two irreversible processes. As a result of the incorporation of fatigue displacements, the stress-displacement relationships now include the effect of fatigue displacement as:

$$\begin{aligned}\sigma_n = k_n^0(1-D)\left(u_n - u_n^p - u_n^f\right) \\ - Dk_n^0\langle -\left(u_n - u_n^p - u_n^f\right)\rangle\end{aligned} \tag{10}$$

$$\sigma_s = k_s^0(1-D)\left(u_s - u_s^p - u_s^f\right) \tag{11}$$

Where D is the damage variable, which is also decomposed into damage due to yielding and fatigue

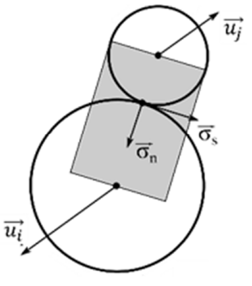

Figure 2. Contact *stress-displacement relationship*

effect as follows:

$$D = \sum_{i=1}^{N} \delta D = \sum_{i=1}^{N} \left[(1 - f_i)\delta D_p + f_i \delta D_f\right] \tag{12}$$

where D_p and D_f are damage due to yielding and fatigue; f_i is a shift factor in each load cycle, which equals 0 if the stress state in the contact reaches its yield surface and 1 if the stress state in the contact is below its yield surface within a load cycle. The evolution of fatigue damage is described by the Paris' law of contact (Paris & Erdogan 1963):

$$\frac{\delta D_f}{\delta N} = \frac{C(\Delta K)^m}{d} \tag{13}$$

where N is the number of load cycles; C and m are the material fatigue parameters; and ΔK is the stress intensity factor range in a load cycle.

To capture fatigue response of cemented materials in which damage can develop even when the applied cyclic stress is under the material yielding limit, the fatigue displacement and fatigue damage variables in this model are allowed to increase when the stress state in the contact is under the yield criterion. This can be achieved by incorporating a so-called fatigue criterion. The shape of the fatigue criterion is displayed in Figure 3 along with the yield criterion. The shaded area represents the range of maximum cyclic stress state in the bonding contact wherein fatigue damage can develop.

3 NUMERICAL APPLICATIONS

In this section, the modelling approach is applied to perform numerical experiments of a cemented pavement material. In particular, the four-point bending test of samples subjected to both monotonic and cyclic loads carried out at Monash University (Sounthararajah et al. 2018) are adopted for the simulation. Numerical results are then compared with the experimental data to evaluate the capability of the modelling approach (Nguyen et al. 2018).

3.1 Simulation setup and calibration

The numerical setups of the four-point bending tests are displayed in Figure 4. The sample dimension is 200×50 mm, placed on two supporting rollers at the span of 150 mm and loaded by two loading rollers placed on the top surface of the sample at the distance of 50 mm. This sample is simulated in DEM by generating an assemblage of particles with similar gradation as the aggregate size distribution (particles from 1 mm to 19 mm) of the physical material (see Figure 5). The numerical sample is then filled by particles of 1 mm diameter until reaching a pre-defined porosity. The enriched contact model is then assigned to all bonding contact between these particles. The contact model parameters are calibrated as follows: $E^0 = 1.55$ GPa, $k_n^0/k_s^0 = 2.4$, $\sigma_\tau^0 = C^0 = 74$ kPa, $u_n^c = u_s^c = 0.02$ mm, $\varphi = 20^0$ and $\psi = 10^0$. The fatigue parameters are as follows: $m = 1.2$, $C = 1.8{\times}10^{-11}$ and $\omega = 0.84$.

Subsequently, the numerical sample is loaded by applying a velocity to the loading walls. The monotonic loading pattern is replicated in the simulation by using a servo-control technique. During loading processes, the values of applied load (P) and mid-span deflection (δ) are continuously recorded. The flexural stress, flexural strain and flexural modulus are then calculated by the following equations:

$$\mathrm{FS} = \frac{PL}{WH^2} \tag{14}$$

$$\varepsilon_\mathrm{f} = \frac{108H\delta}{23L^2} \tag{15}$$

$$\mathrm{E_f} = \frac{23P_cL^3}{108\delta_c WH^3} \tag{16}$$

where FS is the flexural stress, L is the support span, W is the average beam width, H is the average beam height, ε_f is the flexural strain, P_c is the maximum magnitude of applied cyclic load and δ_c is the sample deflection corresponding to P_c.

3.2 Monotonic test result

Figure 6 compares the flexural stress-strain curves obtained in the experiments and simulation of the monotonic test. It shows that the numerical curve falls within the experimental range. During the loading process, the cemented sample undergoes three stages including a linear elasticity stage, a non-linear hardening stage prior to peak stress and a residual stage after the peak. All of these observed responses are captured well in the simulation. In addition, the cracking pattern in the numerical sample agrees with the experimental result as illustrated in Figure 7. In both the experiment and simulations, the pattern of major cracks can slightly vary depending on the arrangement of particles, but the major

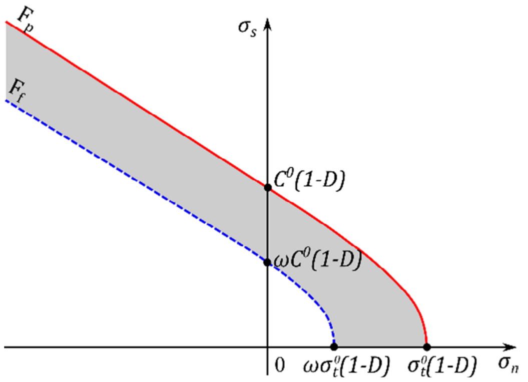

Figure 3. The shape and evolution of the fatigue criterion against the increment of damage variable

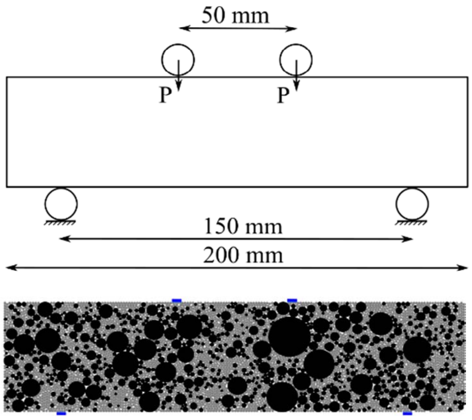

Figure 4. The experimental and numerical setups of the four-point bending test

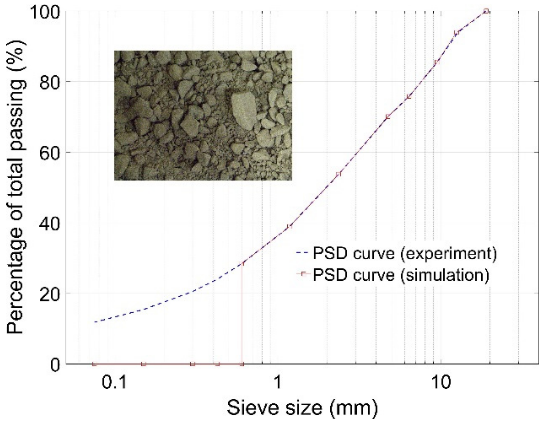

Figure 5. The particle size distribution of experimental and numerical samples

cracks always initiate at the bottom of the beam in the area between the two loading rollers and then propagates upwards along particle interfaces. The localised fracture and crack development are naturally captured in the simulation without any ad-hoc treatment on the contact model.

3.3 Fatigue test result

The numerical fatigue test is then performed on the same sample. A cyclic loading pattern with maximum cyclic stress equal to 77% of the flexural strength measured in the monotonic test is applied to the sample (see Figure 8). During the cyclic loading process, the flexural modulus of the sample is calculated using Equation 16 to reproduce the modulus degradation curve in the experiment.

Figure 9 presents the results of the flexural modulus degradation curves obtained in the experiment and simulations using the extended model and the original model. The reduction of flexural modulus in the experiment is observed to go through three stages including the initial, middle and final stages. The simulation using the proposed fatigue model can closely capture the gradual reduction of flexural modulus in the middle stage and the unstable reduction of flexural modulus at the final stage. However, there stands a deviation in the initial stage in which the flexural modulus in the simulation is observed to drop faster than the flexural modulus in the experiment. This can be attributed to the difference in microstructural configuration between the experimental and numerical samples. The simulation using the original damage-plasticity model (Nguyen et al. 2017), nonetheless, is unable to capture the reduction of the flexural modulus as well as the sample failure in the cyclic test. The flexural modulus in the simulation with the original cohesive model remains constant with increasing the number of load cycles.

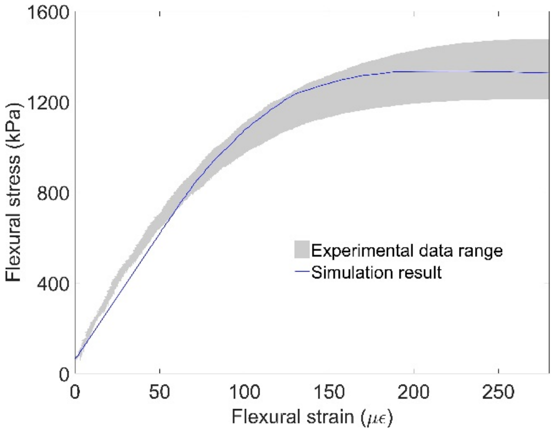

Figure 6. The flexural stress-strain curves in the experiment and simulation of the monotonic test

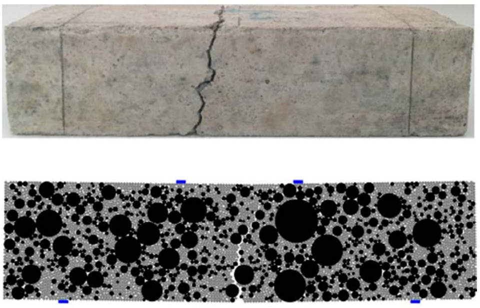

Figure 7. Sample crack patterns in the experiment and simulation of the monotonic test

The simulations of fatigue test at different maximum cyclic stress are further conducted to predict the S-N curve in the experiment. Figure 10 displays the S-N curves obtained in the experiments and simulations. It shows that, given a single set of model parameters and a microstructural configuration of the numerical sample, the proposed modelling approach can predict the decrease of sample fatigue life with increasing the maximum cyclic stress level. The small deviation is

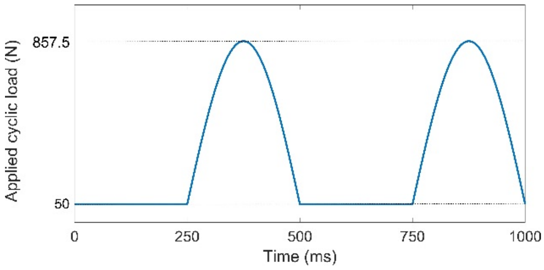

Figure 8. The applied cyclic loading pattern of the fatigue test

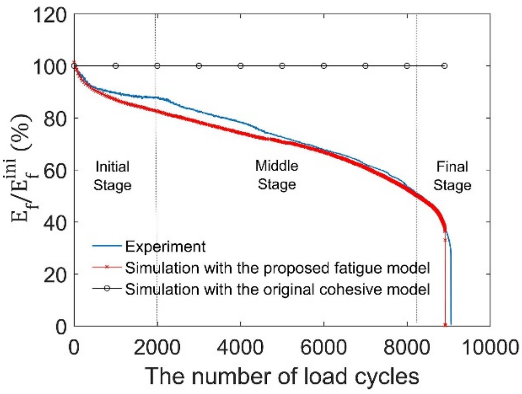

Figure 9. The modulus degradation curves obtained in the experiment and simulations of the fatigue test

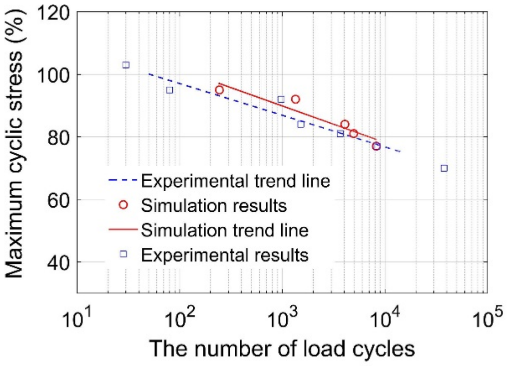

Figure 10. The S-N curve obtained in the experiment and simulation of the fatigue test

considered due to the differences in the microstructural configurations of the numerical and experimental samples. The results of the fatigue numerical tests clearly show the capability as well as the necessity of the proposed fatigue model for the DEM simulations of fatigue damage in cemented materials.

Furthermore, Figure 11 depicts the crack patterns of the experimental and numerical samples obtained in the fatigue tests of different samples. Micro-cracks are shown to gradually grow during the initial and middle stage of fatigue degradation. The macro-crack only appears when it comes to the final stage, leading to the failure of beam samples. In all experiments and simulations, cracks initiate in the area between the two loading rollers and develop from the bottom to the top surface of the samples. However, the location and shape of cracks are varied in each sample, and this can be attributed to the difference in the microstructural configuration of each sample due to the rearrangement of particles. The difference of sample microstructure induces the change of stress transmission and concentration in the sample, thus changing the crack location. Besides, as the crack propagates along particle interfaces, the direction of crack propagation highly depends on how particles arrange near the crack tip. The variation of crack patterns can be well captured by the proposed approach thanks to it physical reproduction of the material microstructural behaviour.

4 CONCLUSIONS

A micromechanics-based modelling approach that combines DEM and a fatigue contact model is presented in this paper. This modelling approach is shown to successfully reproduce the heterogeneous microstructure of pavement materials. The incorporation of the fatigue contact model is necessary to account for the microstructural details missing in DEM simulations and enables DEM to fully capture the degrading response of pavement materials subjected to cyclic loadings. Through the simulation of standard fatigue test of pavements, the capability of the modelling approach in capturing the fatigue behaviour of pavement materials has been demonstrated. Compared to existing continuum methods, this modelling approach is more advantage in the sense that both mechanical response and localised fracture in cemented materials can be captured, while the simplicity of contact model formulation is retained. More importantly, the ability of reproducing microstructural features of pavement materials allows this approach to model and investigate the effects of microstructural factors (e.g. micro-cracking, microstructural changes) on the overall fatigue performance of pavements, which were inaccessible by the experimental method. Given those advanced features, this modelling approach can be a potential tool to assist engineers in improving the understanding of the fatigue behaviour of pavement materials and providing better design solutions for pavements against fatigue damage.

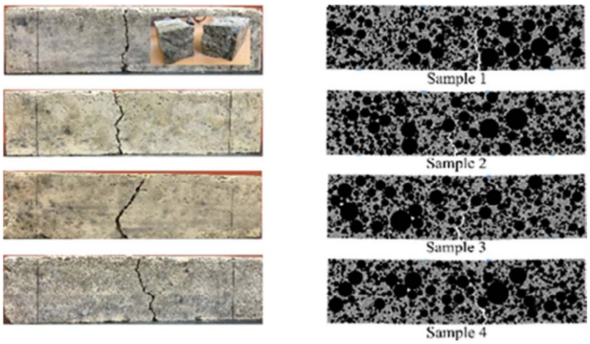

Figure 11. Crack patterns of experimental and numerical samples in the fatigue tests

5 ACKNOWLEDGEMENTS

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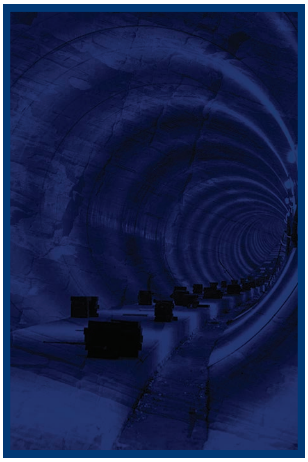

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