Modelling of the fatigue damage of a geogrid-reinforced asphalt concrete

Ioana Maria Arsenie, Cyrille Chazallon, Jean-Louis Duchez & Saida Mouhoubi

To cite this article: Ioana Maria Arsenie, Cyrille Chazallon, Jean-Louis Duchez & Saida Mouhoubi (2016): Modelling of the fatigue damage of a geogrid-reinforced asphalt concrete, Road Materials and Pavement Design, DOI: [10.1080/14680629.2016.1159973](https://doi.org/10.1080/14680629.2016.1159973)

To link to this article: <http://dx.doi.org/10.1080/14680629.2016.1159973>

Published online: 04 Apr 2016.

Submit your article to this journal [↗](#)

View related articles [↗](#)

View Crossmark data [↗](#)

Modelling of the fatigue damage of a geogrid-reinforced asphalt concrete

Ioana Maria Arsenie^{a,b}, Cyrille Chazallon^{a*}, Jean-Louis Duchez^c and Saida Mouhoubi^a

^aLaboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie, ICUBE, UMR 7357, CNRS, INSA de Strasbourg, 24 Boulevard de la Victoire, 67000 Strasbourg, France; ^bEiffage Infrastructures, 12 rue de Molsheim, 67120 Wolxheim, France; ^cEpsilon Ingénierie, Parc de Ruissel – Avenue de Lossburg, 69480 Anse, France

(Received 26 May 2014; accepted 23 February 2016)

This paper presents a modelling approach to predict the fatigue damage of glass fibre grid-reinforced asphalt concrete in the fully reverse four-point bending (4PB) test configuration. The objective of the present study is to predict the fatigue damage of a composite material made of asphalt concrete and geogrid, using a damage model proven for asphalt mixes. The non-local damage model of Bodin, implemented in a finite element code, is used. Parameter identification is performed with 4PB test results of non-reinforced asphalt (NRA) and reinforced asphalt concrete beams. A unique model is developed and two analyses are performed for both NRA and geogrid-reinforced asphalt (GRA) in the 4PB fully reverse fatigue test configuration: monolayer beams and five-layer beams. A comparison between the predicted and the experimental fatigue damage curves indicates that the finite element model is able to predict the fatigue behaviour of GRA mixtures.

Keywords: asphalt concrete; glass fibre grid; fatigue damage; four-point bending test; continuum damage model; finite elements modelling

1. Introduction

For more than 40 years, geocomposite materials such as glass fibre grids or 'geogrids' have been extensively used as a rehabilitation solution for fractured pavements, to delay fatigue crack propagation. More recently, geogrids have been used in the design of new pavements, to improve performance, extend service life and therefore reduce the maintenance costs (Nguyen, Blanc, Kerzrého, & Hornych, 2013).

At the present time, there is no standard pavement design method which takes into consideration the presence of the geogrid. In the French pavement design method (NF P98-086, 2011), the admissible tensile strain at the bottom of the asphalt layer is calculated as a function of the fatigue characteristics of the materials: the strain level ε_6 leading to failure after 1 million cycles and the fatigue curve. These characteristics result from standardised laboratory fatigue tests. Moreover, the strain level ε_6 is not a material property; it depends on the type of fatigue test and specimen geometry (Di Benedetto, De la Roche, Baaj, Pronk, & Lundstrom, 2004). A complete laboratory study of the fatigue behaviour is made using 18 fatigue tests (EN 12697-24, 2012).

Modelling of the fatigue damage of geogrid-reinforced asphalt (GRA) concrete would reduce significantly the number of fatigue tests necessary for determining the fatigue characteristics of the materials. Characterisation of the fatigue behaviour of GRA concrete is required for the

*Corresponding author. Email: cyrille.chazallon@insa-strasbourg.fr

understanding of pavement behaviour, in order to find a way to take into consideration the presence and the efficiency of the geogrid in the pavement design.

Different modelling approaches have been used to predict asphalt damage: viscoelasticity coupled to damage (Lefeuve, de La Roche, & Piau, 2000) and viscoelasticity uncoupled to damage using the Schapery correspondence principle (Lee & Kim, 1998). In the case of sinusoidal loading (Alimami, 1987; Ullidtz, Kieler, & Kargo, 1997), damage was interpreted as a variation in the material stiffness represented by the decrease of complex modulus. The accumulative damage concept was used in the models by Lee, Daniel, and Kim (2000), Bodin (2002) and Castro and Sanchez (2008).

The Bodin damage model (Bodin, Pijaudier-Cabot, De la Roche, Piau, & Chabot, 2004; Chkir, Bodin, Pijaudier-Cabot, & Gallet, 2009) is an elastic isotropic continuum damage model, based on the variation in elasticity parameters with loading. The model was used for the prediction of fatigue damage of asphalt mixes in the configurations of the tensile compression (T/C) test and the two-point bending (2PB) test. The kinetic of the damage law is based on a self-adaptive jump-in-cycle procedure for high-cycle fatigue computations. The constitutive relations are simpler than the ones proposed by Lee et al. (2000) since they rely on a scalar, isotropic, damage model which is widely used for asphalt mixes (Bodin et al., 2004). This model is used in this study to predict the fatigue damage of an asphalt concrete and of the composite material made of asphalt concrete and glass fibre grid.

The study is organised in five sections. Section 2 presents the materials and the experimental background. Section 3 presents the Bodin damage model. Section 4 presents the modelling used for the non-reinforced asphalt (NRA) and GRA concrete. Section 5 presents the modelling results and analysis. The accuracy of the models is discussed. Section 6 presents the conclusions and perspectives.

2. Materials and experimental background

This study is based on laboratory investigation of fully reverse four-point bending (4PB) fatigue tests, performed on NRA and GRA beams (Arsenie, 2013; Arsenie et al., 2016). The beams were made in three layers of 25, 50 and 25 mm. For the NRA specimens, a quantity of 400 g/m² of bitumen emulsion (containing 65% of residual bitumen) was used between the asphalt concrete layers. In the GRA specimens, a geogrid was bonded with a quantity of 600 g/m² of bitumen emulsion (containing also 65% of residual bitumen) between the asphalt concrete layers. The materials and the experimental programme are briefly presented in this section.

2.1. Asphalt concrete

The studied asphalt mixture is a semi-coarse asphalt concrete (SCAC) according to the European classification (EN 13108-1, 2007), made with 5.39% binder content by weight of the asphalt mixture. The formula is (40.68% of 0/4 mm, 9.46% of 4/6 mm, 42.58% of 6/10 mm, 1.89% of filler). The aggregates' provenance is Courzieu quarry in France. The binder is a bitumen class 35/50, according to the European classification (EN 12591, 2009) and 5.39% of binder has been used. It is widely used in France for wearing courses. The SCAC void content is 7.5%. The stiffness modulus E is 9 GPa and it has been determined in 4PB tests, performed at $T = 5^{\circ}\text{C}$ with $f = 10$ Hz (Arsenie, 2013).

2.2. Glass fibre grid

The studied geogrid is a coated glass fibre grid whose stiffness is 100 kN/m. The product is an elastic composite made of warp yarns, filling yarns and nonwoven parts of polyester fibre, with

Table 1. Properties and geometry of the geogrid.

Grid: 100 kN/m

Grid: fibre glass + resin (type styrene butadiene (SB))

Fibre of polyester: 17 g/m²

Strength at failure: 100 kN/m

Bitumen emulsion for embedding: 600 g/m²

a mesh of 40 mm × 40 mm (Table 1). The warp and filling yarns are made of continuous *E* fibreglass roving and styrene butadiene styrene resin.

The Young's modulus of the geogrid is 44 GPa (Themeli, 2011). The endurance limit of both types of yarns in cyclic tensile fatigue displacement controlled tests is larger than 2‰ (Sagnol, 2013).

2.3. Experimental background

2.3.1. Experimental programme

A total of 36 fully reverse 4PB fatigue tests (EN 12697-24, 2012) were performed, creating a symmetrical bending around the original position (null loading), with displacement control (constant strain), at $T = 10^\circ\text{C}$ with $f = 25$ Hz. Among the 36 specimens, there were 18 NRA specimens and 18 GRA specimens. The NRA specimens were loaded at three strain levels (150 $\mu\text{m/m}$, 135 $\mu\text{m/m}$ and the range (111, 116) $\mu\text{m/m}$) with six replicates per strain level. The GRA specimens were tested at three strain levels (150 $\mu\text{m/m}$, 135 $\mu\text{m/m}$ and the range (126, 129) $\mu\text{m/m}$), with six replicates per strain level.

The fatigue curves of the NRA and GRA specimens were

$$\log_{10} N_f = -14.853 - 5.293 \log_{10} \varepsilon, \quad (1)$$

$$\log_{10} N_f = -17.000 - 5.904 \log_{10} \varepsilon, \quad (2)$$

where N_f is the classical fatigue life (number of cycles for 50% decrease of the initial sample stiffness) and ε is the strain level.

The initial dynamic modulus (at 100 loading cycles) of the NRA and GRA beams, determined in fully reverse 4PB fatigue tests, was similar; therefore, the average value equal to 13.5 GPa was considered in the modelling in Section 4. The Poisson ratio ν was considered 0.35, which is the conventional value for asphalt mixtures.

The experimental fatigue damage curves ($E/E_i - N$), which represent the evolution of the dynamic modulus ratio E/E_i with the number of cycles N , are presented in Section 5 with the modelling results.

3. Bodin model

The Bodin model is a fatigue damage model, which expresses the decrease in dynamic modulus with cyclic loading. The damage evolution is achieved by Bodin's three regimes law (Bodin,

2002), which simulates the three phases of the damage evolution of asphalt mixtures. The evolution of damage depends on the amount of tensile stress that the material experiences during mechanical loading. It is expected that repeated tensile stress is the main source of local decohesion in asphalt concrete. The damage model that we have used is a volumetric damage model for asphalt concrete materials and to study the sliding between the grid and the AC layer, a specific surface damage model should be used taking into account the grid and AC materials. Moreover, we think that before vertical macro cracks appear, there is no shear stress in the central third of the beam, so a perfect cohesion is considered.

In Equation (3), the damage variable is introduced as a scalar D in the range $[0, 1]$. The damage $D = 0$ for virgin material and $D = 1$ for material failure.

$$\sigma_{ij} = C_{ijkl} \cdot \varepsilon_{kl} = (1 - D) \cdot C_{ijkl}^0 \cdot \varepsilon_{kl}, \quad (3)$$

where σ_{ij} and ε_{kl} are the components of the stress tensor and strain tensor. C_{ijkl} and C_{ijkl}^0 are the damaged and initial (elastic) secant stiffness of the material. C_{ijkl}^0 is a function of the Young's modulus E and of the Poisson ratio ν . In the above equation, which corresponds to a time independent formulation, the Young's modulus E is the complex modulus at a given temperature and frequency of the cyclic load. In the present study, the Poisson ratio is assumed to be independent from damage. The Poisson ratio of bituminous material was experimentally evaluated in the range between 0.2 and 0.5 (Sayegh, 1967). Here, we use $\nu = 0.35$.

The damage growth criterion is based on a modified Rankine criterion (Patzak & Jirasek, 2001) with zero threshold damage growth in which $\bar{\varepsilon}$ is the average of equivalent strain $\tilde{\varepsilon}$ defined as

$$\bar{\varepsilon}(x) = \frac{1}{V_r(x)} \cdot \int_{\Omega} \psi(x-s) \cdot \tilde{\varepsilon}(s) \cdot ds, \quad (4)$$

where $V_r(x)$ is the representative volume at a point of coordinate x calculated in Equation (5) and $\tilde{\varepsilon}$ is the equivalent strain, calculated with Equation (6)

$$V_r(x) = \int_{\Omega} \psi(x-s) \cdot ds, \quad (5)$$

$$\tilde{\varepsilon} = \sqrt{\sum_{i=1}^3 \left(\frac{\langle \sigma_i \rangle}{E \cdot (1-D)} \right)^2}, \quad (6)$$

where Ω is the studied volume, $\psi(x-s)$ is the weight function, s is a relative coordinate, $\langle \sigma_i \rangle$ are the principal tension stresses and E is the dynamic modulus (10°C, 25 Hz). The Macauley brackets are used to account only the positives values.

$\psi(x-s)$ is the weight function

$$\psi(x-s) = \exp \left(-\frac{4\|x-s\|^2}{l_c^2} \right) \quad (7)$$

and l_c is the internal length of the non-local continuum.

The model takes into account the three phases of damage evolution (Paas, Scheurs, & Brekelmans, 1993)

$$\dot{D} = f(D) \cdot \bar{\varepsilon}^\beta \cdot \langle \dot{\tilde{\varepsilon}} \rangle, \quad (8)$$

where $f(D)$ is a function of three material parameters ($\alpha_1, \alpha_2, \alpha_3$) defined in Equation (9), $\bar{\varepsilon}$ and $\dot{\tilde{\varepsilon}}$ are the average of the equivalent strain defined in Equation (8) and its strain rate. The parameter

β is calculated directly from the slope p of the fatigue curve in log–log coordinates, as follows:
 $\beta = p - 1$.

$$f(D) = \frac{\alpha_2}{\alpha_1 \cdot \alpha_3} \cdot \left(\frac{D}{\alpha_2}\right)^{1-\alpha_3} \cdot \exp\left(\frac{D}{\alpha_2}\right)^{\alpha_3}. \quad (9)$$

The damage law is implemented in the finite element code cast3M (cast3M, 2010). This model was used for the modelling of fatigue damage of asphalt concrete material subjected to a fully alternate 2PB test and one-dimension tension–compression fatigue test (Chkir et al., 2009). It has never been used until now for the calibration and prediction of 4PB tests.

4. Modelling approach

4.1. Models

Two different two-dimensional models were made for the NRA and GRA specimens using the software cast3M: monolayer models and five-layer models. The fatigue damage of 4PB fully reverse loading is modelled with the Bodin model.

The monolayer models were called 1NRA and 1GRA and the five-layer models 5NRA and 5GRA. The model 1NRA is made of one asphalt concrete layer of 100 mm. The model 1GRA is made of one layer of 100 mm of composite material. The composite material is made of geogrid and asphalt concrete, which are homogenised so that one material is considered. The five-layer models have the following structure: the first layer of 24 mm, the second layer of 1 mm, the third layer of 50 mm, the fourth layer of 1 mm and the fifth layer of 24 mm. The model 5NRA is made of five asphalt concrete layers. The model 5GRA is made of three asphalt concrete layers (the first, the third and the fifth layer) and two geogrid layers (the second and the fourth layer).

$E_i = 13.5$ GPa is the initial dynamic modulus for SCAC and it has been obtained at 10°C and 25 Hz. It has been used for all the SCAC layers in 5GRA and 5NRA models, and for the homogenised models (1GRA and 1NRA models).

The geogrid layers are characterised by $E_i = 44$ GPa and $\nu = 0.35$ and they have been used for the geogrid layer characteristics in 5GRA model. This modulus is determined by the law of mixtures if we take into account the glass fibre, the resin and its porosity. It has been confirmed by uniaxial tensile tests at 20°C. Moreover, as the resin modulus is rather low, its influence on the geogrid modulus is low.

Figure 1. Geometry and boundary conditions of monolayer models (1NRA and 1GRA).

Figure 2. Geometry and boundary conditions of five-layer models (5NRA and 5GRA).

The hypothesis of plane stresses is used to model half of the NRA and GRA beams ($315 \times 100 \times 100 \text{ mm}^3$). The geometry and the limit conditions of the models are presented in Figures 1 and 2. The loading is a constant strain range (or a constant displacement range).

The elements are triangular, three nodes per element, and the internal length (l_c Equation (7)) is set at 30 mm. The internal length, which controls the size of the damage zone, was chosen equal to three times the maximum aggregate size, as recommended by Bodin (2002).

The loading is discretised with a total of 1000 loading cycles for a calculation step, which gives satisfactory results (Bodin et al., 2004).

4.2. Parameter identification

The fatigue damage parameters ($\alpha_1, \alpha_2, \alpha_3$) of the Bodin model were calibrated with the experimental 4PB test results of NRA and GRA specimens, respectively, on the average fatigue damage curve ($E/E_t - N$) at the strain level $\varepsilon = 135 \mu\text{m/m}$. The choice of strain level for parameter identification was the intermediate strain level, tested for both NRA and GRA specimens. The parameter β was determined from the fatigue curve equations NRA (Equation (1)) and GRA (Equation (2)). For the five-layer models, the same β (from Equation (1)) was considered for both 5NRA and 5GRA models.

One can observe (Table 2) that the damage parameters β are different between the 1NRA and 1GRA models.

On the other hand, only one damage parameter (α_1) is different between the five-layer models 5NRA and 5GRA. The parameter α_1^* is slightly higher than α_1 , which can be explained by the influence of geogrid, which changes the fatigue slope of the NRA concrete. The 5GRA model considers the same β as the 5NRA model, so the influence of the geogrid is taken into consideration with the parameter α_1^* . The work of Sagnol (2013) showed that when subjected to fatigue strain levels lower than $2.0 \times 10^{-3} \text{ m/m}$, the geogrid yarns are not damaged. This is taken into consideration in the 5GRA model with the parameter α_{1g} , which controls the fatigue life of the geogrid. The parameter α_{1g} was fixed 10^6 times higher than α_1^* to characterise the geogrid fatigue life. The same damage parameters α_2 and α_3 , identified for the asphalt layers, are considered for the geogrid layers. These two parameters do not have any influence on the fatigue damage evolution, for the fatigue strain levels studied here.

The advantage of the five-layer models is the reduction in the number of fatigue tests required to perform the parameter identification from 18 tests (6 tests $\times$ 3 strain levels) to 6 (6 tests $\times$ 1 strain level), using the finite element modelling.

Table 2. Parameter identification of monolayer and five-layer models performed at $\varepsilon = 135 \mu\text{m/m}$.

Damage parameters Material	Monolayer models		Five-layer models	
	SCAC	Composite	SCAC	Composite
Model name	1NRA	1GRA	5NRA	5GRA
Bodin model damage parameters	$\alpha_1 = 1.6 \times 10^{-16}$ $\alpha_2 = 0.95$ $\alpha_3 = 1.6$ $\beta = 4.3$	$\alpha_1 = 1 \times 10^{-18}$ $\alpha_2 = 0.9$ $\alpha_3 = 1.7$ $\beta = 4.9$	$\alpha_1 = 2.1 \times 10^{-16}$ $\alpha_2 = 0.95$ $\alpha_3 = 1.6$ $\beta = 4.3$	<div style="border: 1px dashed black; padding: 5px; display: inline-block;"> $\alpha_1^* = 3.2 \times 10^{-16}$ $\alpha_2 = 0.95$ $\alpha_3 = 1.6$ $\beta = 4.3$ $\alpha_{1g} = 3.2 \times 10^{-10}$ </div> <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> SCAC layers 1, 3, 5 Geogrid layers 2, 4 </div>

5. Modelling results and analysis

The predicted fatigue damage curves ($E/E_i - N$) are compared with the experimental fatigue damage curves, at all the tested strain levels, in Figures 3–6. Three experimental fatigue damage curves are illustrated at each strain level: the fatigue damage curves with the minimum (respectively maximum) fatigue life and the average fatigue damage curve. Because most of the fatigue tests were stopped at a dynamic modulus ratio $E/E_i = 0.35$, the damage fatigue curves are plotted from $E/E_i = 1$ till $E/E_i = 0.35$.

Models 1NRA and 5NRA were used to predict the fatigue damage evolution of the asphalt concrete at $\varepsilon = 150 \mu\text{m/m}$ and $\varepsilon = 115 \mu\text{m/m}$, since the calibration is carried out at $\varepsilon = 135 \mu\text{m/m}$. At $\varepsilon = 150 \mu\text{m/m}$, one can observe that the predicted fatigue damage curves (Figures 3 and 4) are satisfying compared to the experimental average fatigue damage curves. At $\varepsilon = 115 \mu\text{m/m}$, the prediction is between the minimum and maximum experimental curves, as follows: for the model 1NRA when the ratio E/E_i is in the range (0.73, 0.35) and for the model 5NRA when E/E_i is in the range (0.77, 0.35). Models 1NRA and 5NRA give similar predictions of the fatigue damage of the asphalt concrete.

Models 1GRA and 5GRA were used to predict the fatigue damage of the GRA concrete at $\varepsilon = 150 \mu\text{m/m}$ and $\varepsilon = 127 \mu\text{m/m}$, since the calibration is carried out at $\varepsilon = 135 \mu\text{m/m}$. The predicted fatigue damage curves (Figures 5 and 6) at the tested strain levels (150, 135, 127 $\mu\text{m/m}$) are situated between the minimum and maximum experimental fatigue damage curves and they overlap the average fatigue damage curves. Models 1GRA and 5GRA give similar predictions of the fatigue damage of the geogrid asphalt concrete. Whereas the 1GRA model requires four new parameters compared to 1NRA model, the 5GRA model reuses three parameters of the 5NRA model and only one parameter (α_1^*) has been recalibrated from 2.1×10^{-16} to 3.2×10^{-16} to improve the predictions.

The fatigue life N_f predicted by the four models is compared with the experimental fatigue life and the fatigue life calculated from the fatigue curves (Equations (1) and (2)) in Table 3. The predictions are close to the experimental results and fatigue curve estimations, which confirms that the Bodin model is adequate for the damage prediction of the tested materials.

Figures 7 and 8 show the propagation of the top-down and bottom-up damaged volumes under fully reverse loading in the monolayer and five-layer beams.

Figure 3. Fatigue curves of the model 1NRA versus experimental fatigue damage curves (minimum, average and maximum) at $\varepsilon = 150 \mu\text{m/m}$ (prediction), $\varepsilon = 135 \mu\text{m/m}$ (calibration) and $\varepsilon = 115 \mu\text{m/m}$ (prediction).

Figure 4. Fatigue curves of the model 5NRA versus experimental fatigue damage curves (minimum, average and maximum) at $\varepsilon = 150 \mu\text{m/m}$ (prediction), $\varepsilon = 135 \mu\text{m/m}$ (calibration) and $\varepsilon = 115 \mu\text{m/m}$ (prediction).

Figure 5. Fatigue curves of the model 1GRA versus experimental fatigue damage curves (minimum, average and maximum) at $\varepsilon = 150 \mu\text{m/m}$ (prediction), $\varepsilon = 135 \mu\text{m/m}$ (calibration) and $\varepsilon = 127 \mu\text{m/m}$ (prediction).

Figure 6. Fatigue curves of the model 5GRA versus experimental fatigue damage curves (minimum, average and maximum) at $\varepsilon = 150 \mu\text{m/m}$ (prediction), $\varepsilon = 135 \mu\text{m/m}$ (calibration) and $\varepsilon = 127 \mu\text{m/m}$ (prediction).

Table 3. Experimental fatigue life and fatigue life calculated from the fatigue line versus predicted fatigue life, for NRA and GRA specimens.

Strain ($\mu\text{m}/\text{m}$)	Average fatigue life N_f (cycles) of NRA specimens			
	Experimental	Fatigue line	Model 1NRA	Model 5NRA
$\varepsilon = 150$	257,873	242,917	239,000	237,000
$\varepsilon = 135$	414,752	423,965	419,000	416,000
$\varepsilon = 115$	1,097,290	1,070,349	989,000	1,029,000

Strain ($\mu\text{m}/\text{m}$)	Average fatigue life N_f [cycles] of GRA specimens			
	Experimental	Fatigue line	Model 1GRA	Model 5GRA
$\varepsilon = 150$	354,240	374,532	368,000	394,000
$\varepsilon = 135$	724,416	695,089	694,000	690,000
$\varepsilon = 127$	1,095,474	983,059	1,008,000	959,000

Figure 7. Prediction of the propagation of top-down and bottom-up damaged volumes in the asphalt beam model 1NRA at $\varepsilon = 150 \mu\text{m}/\text{m}$, damage maps at $E/E_i = 0.5$ (239×10^3 cycles) and $E/E_i = 0.35$ (260×10^3 cycles).

The damage propagation in the monolayer beam model 1NRA simulates correctly the damage propagation in an asphalt concrete beam. The top-down and bottom-up damaged volumes initiated in the central third of the beam are supposed to propagate vertically to the centre of the beam (Figure 7). The damage propagation in the five-layer beam model 5GRA simulates correctly the damage evolution of the composite material. In a composite material made of asphalt concrete and geogrid, top-down and bottom-up fatigue damaged volumes are supposed to propagate vertically until reaching the geogrid. Then, the damage propagation is delayed at the interface by the geogrid, followed by the propagation in the middle asphalt layer (Figure 8).

Figure 8. Prediction of propagation of top-down and bottom-up damaged volumes in the composite beam model 5GRA at $\varepsilon = 150 \mu\text{m/m}$, damage maps at $E/E_i = 0.5$ (394×10^3 cycles) and $E/E_i = 0.35$ (414×10^3 cycles).

6. Conclusions

In this study, our objectives were to model the fatigue behaviour of a composite material made of asphalt concrete and fibreglass grid subjected to fully reverse 4PB fatigue tests. We have used the Bodin model which has been developed for the modelling of fatigue damage of asphalt concrete material subjected to fully reverse 2PB tests and one-dimension tension–compression fatigue tests. The challenge was to use this model to predict the fatigue damage of asphalt concrete and of the composite material made of asphalt concrete and fibreglass grid. The test which has been used is the fully reverse 4PB test for fixed temperature and frequency.

Two types of models were made: monolayer and five-layer beams. Four models were tested, two for the NRA concrete (1NRA and 5NRA) and two for the GRA concrete (1GRA and 5GRA).

The parameter identification was performed with fully reverse 4PB fatigue test results obtained in a previous study (Arsenie et al., 2016) on NRA and GRA beams.

The fatigue life predictions made by the four models are satisfying compared to experimental fatigue life obtained in the 4PB fatigue tests. The predicted fatigue damage curves of the asphalt concrete (1NRA and 5NRA) give accurate results, which confirm the accuracy of the Bodin model. The predicted fatigue damage curves of the GRA concrete (1GRA and 5GRA) are situated between the minimum and the maximum fatigue damage curves, which show that the model is able to predict damage of reinforced asphalt mixtures.

The analysis of the damage propagation in the damage map pointed up the models that simulated correctly the damage propagation of the tested materials: the monolayer model 1NRA for the asphalt concrete and the five-layer model 5GRA for the reinforced asphalt concrete. The 5GRA model is based on three parameters determined with 5NRA model and only one parameter (α_1^*) is recalibrated to improve the predictions, whereas the 1GRA model requires four new parameters (compared to 1NRA).

These results, showing the increase in the fatigue life of fibreglass grid-reinforced asphalt concrete, have been obtained for one set of test conditions (temperature 10°C , frequency 25 Hz, fixed position of the grids, placed at 25 mm from the neutral axis of the beam). The model will

help to generalise these results; it appears necessary, in particular, to take into account the effects of two important parameters:

- the temperature (which will modify the stiffness of the asphalt layers, and thus the relative ratio between the stiffness of the asphalt layers and of the grid) and
- the vertical position of the grid.

It is quite a challenge to predict the fatigue damage of a composite material like GRA concrete, made of different materials with different properties and fatigue behaviours.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

- Alimami, M. (1987). *Contribution à l'étude de l'endommagement par fatigue des enrobés bitumineux* (PhD thesis). University de Paris 6, Paris.
- Arsenie, I. M. (2013). *Study and modelling of the pavement reinforcement with glass fibre grids under fatigue loading* (PhD thesis). INSA de Strasbourg, Strasbourg.
- Arsenie, I. M., Chazallon, C., Duchez, J. L., & Hornych, P. (2016). Laboratory characterisation of the fatigue behaviour of a glass fiber grid reinforced asphalt concrete using 4PB tests. *Road Materials and Pavement Design*. doi:10.1080/14680629.2016.1163280
- Bodin, N. D. (2002). *Modèle d'endommagement cyclique: Application à la fatigue des enrobés bitumineux* (Thèse de doctorat). Ecole Centrale de Nantes, Nantes.
- Bodin, D., Pijaudier-Cabot, G., De la Roche, C., Piau, J. M., & Chabot, A. (2004). Continuum damage approach to asphalt concrete fatigue modeling. *Journal of Engineering Mechanics (ASCE)*, 130(6), 700–708.
- Cast3M. (2010). *cast3M is a research FEM environment; its development is sponsored by the French Atomic Energy Commission*. Retrieved from <http://www-cast3m.cea.fr>
- Castro, M., & Sanchez, J. (2008). Estimation of asphalt concrete fatigue curves – A damage theory approach. *Construction and Building Materials*, 22(6), 1232–1238.
- Chkir, R., Bodin, D., Pijaudier-Cabot, G., & Gallet, T. (2009). An inverse analysis approach to determine fatigue performance of bituminous mixtures. *Mechanics of Time-Dependent Materials*, 3, 357–373. doi:10.1007/s11043-009-9096-7
- Di Benedetto, H., De la Roche, C., Baaj, H., Pronk, A., & Lundstrom, R. (2004). Fatigue of bituminous mixtures, Rilem TC182-PEB performance testing and evaluation of bituminous materials. *Materials and Structures*, 37, 202–216.
- EN 12591. (2009, December). *European standard. Spécifications des bitumes routiers. Bitumes et liants bitumineux*.
- EN 12697-24. (2012, August). *European standard. Méthodes d'essai pour mélange hydrocarboné à chaud, Partie 24: Résistance à la fatigue*.
- EN 13108-1. (2007, February). *European standard. Spécifications des matériaux, Partie 1: Enrobés bitumineux*.
- Lee, H. J., Daniel, J. S., & Kim, Y. R. (2000). Continuum damage mechanics-based fatigue model of asphalt concrete. *Journal of Materials in Civil Engineering*, 12(2), 105–112.
- Lee, H. J., & Kim, Y. R. (1998). Viscoelastic constitutive model for asphalt concrete under cyclic loading. *Journal of Engineering Mechanics*, 124(1), 32–40.
- Lefevre, Y., de La Roche, C., & Piau, J. M. (2000). Asphalt material fatigue test under cyclic loading: An interpretation based on a viscoelastic model including unilateral damage. *Proceedings of the 2nd Euraspphalt and Eurobitume Congress*, Barcelona.
- NF P98-086. (2011, October). *French standard. Dimensionnement structurel des chaussées routières - Application aux chaussées neuves*.
- Nguyen, M.-L., Blanc, J., Kerzrêho, J.-P., & Hornych, P. (2013). Review of glass fibre grid use for pavement reinforcement and APT experiments at IFSTTAR. *Road Materials and Pavement Design*, 14(Supplement 1), 287–308.

- Paas, R. H. J. W., Scheurs, P. J. G., & Brekelmans, W. A. M. (1993). A continuum approach to brittle and fatigue damage: Theory and numerical procedures. *International Journal of Solids and Structures*, 30(4), 579–599.
- Patzak, B., & Jirasek, M. (2001). Consistent tangent stiffness for non local material models. *European conference on computational mechanics, ECCM-2001*, Cracow, Poland, June 26–29, 2001.
- Sagnol, L. (2013). *Etude de la grille en fibre de verre pour le renforcement de l'infrastructure* (Master thesis). INSA de Strasbourg, Strasbourg and University of Karlsruhe, Karlsruhe.
- Sayegh, G. (1967, August 7–11). Viscoelastic properties of bituminous mixes. *Proceedings of the 2nd international conference on the structural design of asphalt pavements proceedings* (pp. 743–755). University of Michigan, Ann Arbor, MI, USA.
- Themeli, A. (2011). *Etude de la fatigue de bétons bitumineux renforcés par des grilles en fibre de verre* (Master thesis). The Institute National Polytechnique of Lorraine, Lorraine and INSA de Strasbourg, Strasbourg.
- Ullidtz, P., Kieler, T. L., & Kargo, A. (1997). Finite element simulation of asphalt fatigue tests, mechanical tests for bituminous materials. Recent improvement and future prospects. *Proceedings of the 5th RILEM symposium* (pp. 233–239), Rotterdam.