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MULTI-SCALE ANALYSIS OF ASPHALT MIXTURE IN LAYERED ROAD STRUCTURE

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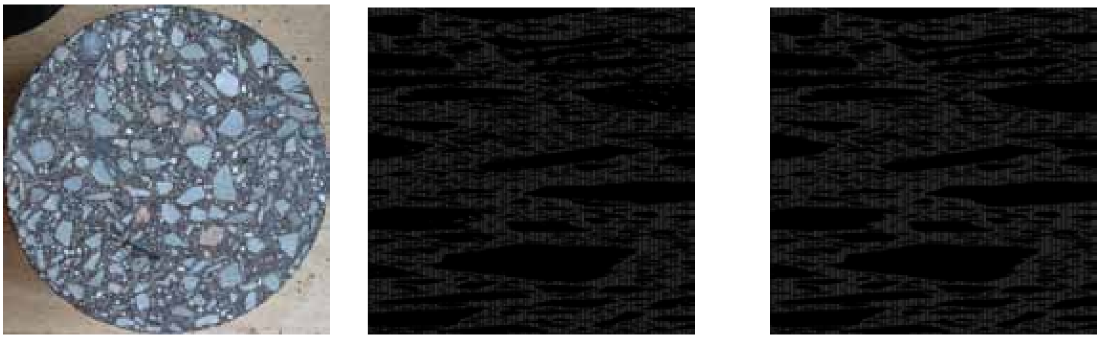
Abstract. The Mori-Tanaka averaging scheme is introduced in the place of demanding finite element analysis to assess the time-dependent macroscopic response of asphalt mixture as a part of the multi-layered road construction. In this computational framework the Mori-Tanaka method [1] is chosen to substitute the macroscopic constitutive model, which is not available in general. Instead we expect that the local constitutive laws of individual phases are known which allows for the derivation of macroscopic stresses and an instantaneous homogenized stiffness matrix of an asphalt layer through homogenization. The choice of the Mori-Tanaka method is supported by micromechanical analysis of a real microstructure of Mastic Asphalt mixture showing reasonable agreement with finite element simulations employing certain statistically equivalent periodic unit cell. This makes the application of the Mori-Tanaka method particularly attractive owing to computationally demanding nonlinear analysis of the layered system with subsoil deformation being governed by one of the available constitutive models for soils. Comparison with application of the macroscopic constitutive model for asphalt mixture, provided by detailed multi-scale homogenization, is also presented.

1 INTRODUCTION

As seen in Fig. 1(a), asphalt mixtures represent in general highly heterogeneous material with complex microstructure consisting at minimum of mastic binder, aggregates and voids. When limiting our attention to Mastic Asphalt mixtures, used typically in traffic



(a) (b) (c)

Figure 1: (a) A real microstructure of an asphalt mixture, (b) Original binary image, (c) Improved binary image

arteries of substantial importance, the fraction of voids becomes negligible. A binary image of such a two-phase material system plotted in Fig. 1(b) is then readily available.

Our contribution integrates various aspects of micromechanical modeling into a relatively simple, yet reliable and efficient computational scheme. The solution strategy relies on uncoupled multiscale homogenization approach and combines advanced simulation based homogenization techniques enabling detailed analysis of a certain representative volume element (RVE), here presented in the form of so called statistically equivalent periodic unit cell (SEPUC), and classical micromechanics based averaging techniques such as the Mori-Tanaka (MT) method in search for a reliable macroscopic constitutive law enabling a computationally efficient analysis of full scale structures.

Rendering the desired macroscopic constitutive model that describes the homogenized response of Mastic Asphalt mixture (MAm) to general loading actions thus endeavors to the formulation of a suitable micromechanical model on individual scales and to associated experimental work being jointly the building blocks of the upscaling procedure. Three particular scales shown in Fig. 2 are considered in the present study. It will be assumed that at each computational level the homogenized response can be described by the nonlinear viscoelastic generalized Leonov (GL) model, see [5, 6] for details . While mastic properties are derived from an extensive experimental program [7], the macroscopic properties of MAm are fitted to virtual numerical experiments performed on the basis of first order homogenization scheme. To enhance feasibility of the solution of the underlying nonlinear problem a two-step homogenization procedure is proposed. The introduced concept of *Virtual Testing Tool* (VTT) make possible to avoid expensive and often intricate large scale laboratory measurements and takes into account details of the microstructure of the analyzed heterogeneous material. The VTT is currently in the forefront of engineering interest [6].

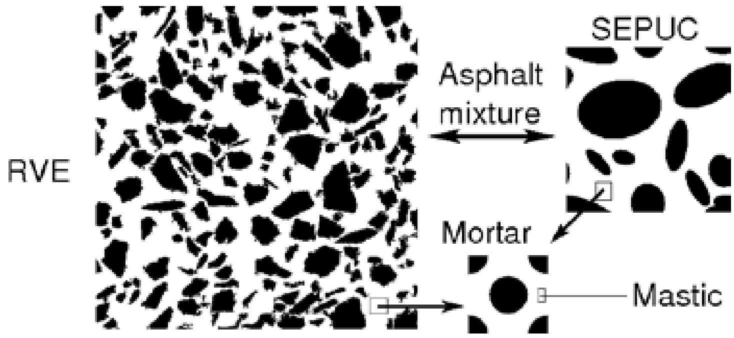


Figure 2: Three distinct scales of Mastic Asphalt mixture

2 VIRTUAL TESTING TOOL

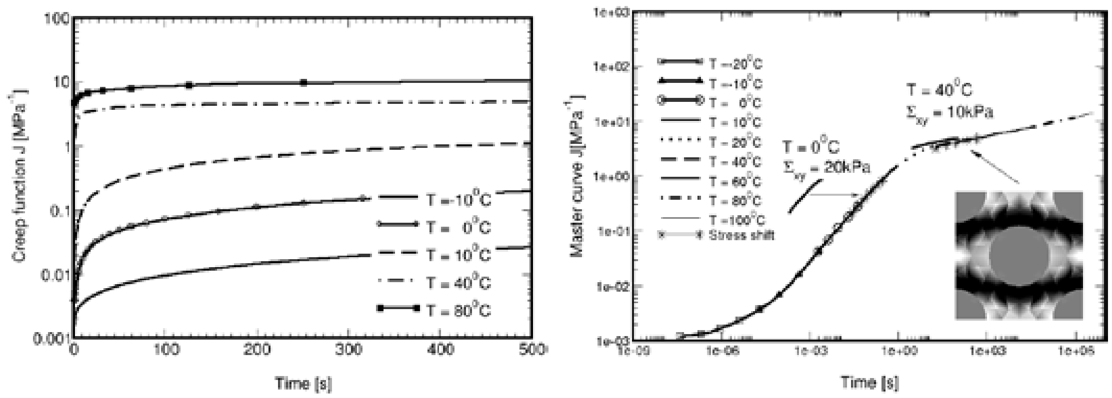
The concept of VTT introduced in [6] assumes the experimental program to be carried out only on the level of the individual constituents - stones and mastic. Although the mastic-phase itself is a composite consisting of a filler and a bituminous binder, it is assumed in the present study to be well represented by a temperature and rate dependent homogeneous isotropic material. Since limiting our attention to moderate and elevated temperatures exceeding 0°C the GL model is exploited to provide for experimentally observed nonlinear viscoelastic behavior of bituminous matrices. The required experimental program to calibrate the model parameters on the one hand and on the other hand to address the homogenized macroscopic response is outlined in [7, 6].

2.1 Response of mortar from virtual experiments

In the framework of VTT approach we introduce a virtual set of experiments to arrive at a homogenized master curve and associated temperature and stress dependent shift factors on the scale of mortar. The concept of first order homogenization of periodic fields outlined in [7] is given the preference to deliver the homogenized creep response of the mortar phase at different temperature and stress levels. The mortar-phase naturally arises through the process of removing aggregates from original microstructure, Fig. 1(b), passing 2.26 mm sieve. Simplified periodic hexagonal array model plotted in Fig. 2 allows us to derive the model parameters on the mortar-scale by running a set of virtual numerical experiments. The selection of this geometrical representation of the mortar composite is purely an assumption building upon the conclusion that at least for the mastic-phase and low-temperature creep the response is independent of the filler shape and mineralogy [4].

First, a uniformly distributed range of temperatures from 0°C to 100°C was considered to provide for a temperature dependent viscoelastic behavior of mortar loaded in shear by the remote stress $\Sigma_{yx} = 1$kPa. Individual curves plotted in Fig. 3(a) were then horizontally shifted to give the homogenized creep compliance master curve seen in Fig. 3(b).

The stiffening, observed for high temperatures, is attributed to a volumetric locking



(a) (b)

Figure 3: (a) Creep data at different temperatures for reference stress $\Sigma_{xy} = 1$kPa, (b) Master curve for reference temperature $T = 40$°C

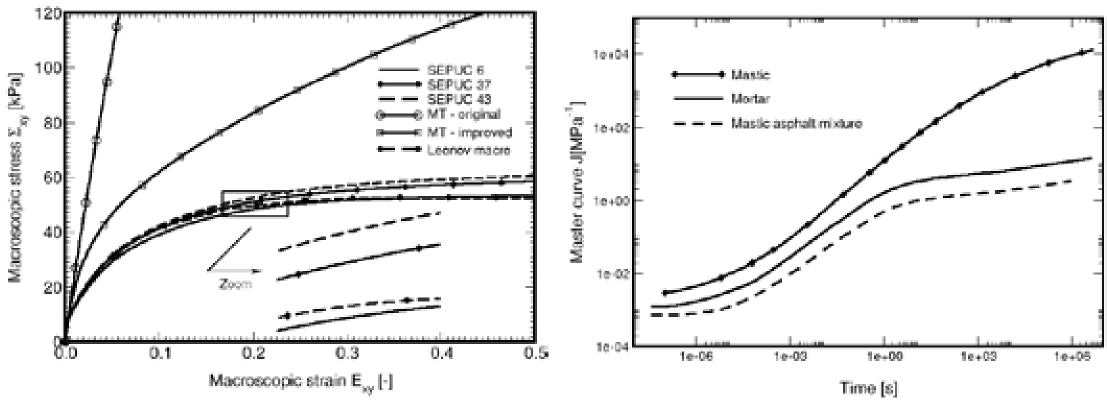
owing to a very low shear modulus approaching to zero. This in turn yields the Poisson ratio close to 0.5 in a finite zone of the binder phase that is progressed over the entire unit cell as seen in Fig. 3(b).

The second set of creep experiments was conducted at two different temperatures and two different levels of the remote stress Σ_{xy}. The two representative results, [40°C, 10kPa] and [0°C, 20kPa], are plotted as solid lines in Fig. 3(b). The indicated horizontal shifts identified with the corresponding star-lines then supplement the necessary data for the derivation of stress dependent shift factor a_σ. Note that prior to shifting the curves the result derived for 0°C was thermally adjusted to be consistent with the 40°C master curve.

2.2 Response of MAm from virtual experiments

Derivation of the macroscopic creep compliance master curve for a Mastic Asphalt mixture follows the general scheme sketched in the previous section. A SEPUC also seen in Fig. 2, is selected to predict the macroscopic response of MAm, where large aggregates are bonded to a mortar-phase being homogeneous and isotropic. The elliptical shape of aggregates has already been successfully used in detailed micromechanical simulations presented in [2]. The issue of constructing SEPUC by comparing the material statistics, e.g. the two point probability function, of the most appropriate representative of the real microstructure and the periodic unit cell is suggested in [9, 7, 6]. The underlying optimization problem was solved with the help of the evolutionary algorithm GRADE [3].

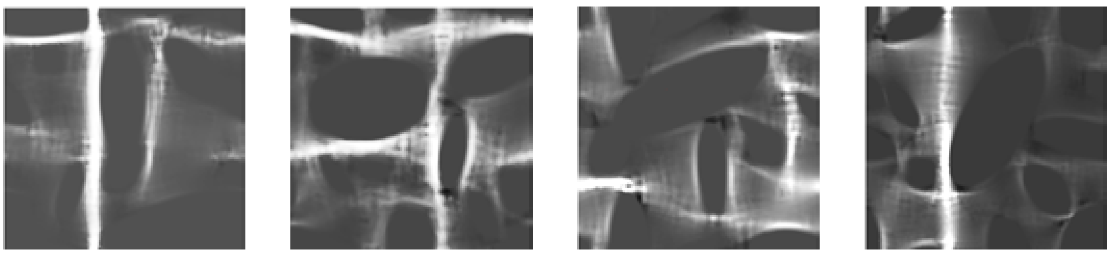
To address this issue, four SEPUCs all having the same statistics but different geometrical details, were subjected to a remote shear strain rate $\dot{E}_{xy} = 10^{-4}$. The resulting homogenized stress-strain curves for temperature $T = 20$°C are shown in Fig. 4(a). Although no "perfect match" is observed, the difference in estimated load bearing capacities is not exceeding 10%. On the contrary, the distribution of local fields varies considerably



(a) (b)

Figure 4: (a) Macroscopic response for various SEPUCs $T = 20°\mathrm{C}$, $\dot{E}_{xy} = 10^{-4}$, (b) Master curves on individual scales for reference temperature $T = 40°\mathrm{C}$

as seen in Fig. 5. While a highly localized distribution of shear strain γ_{xy}^{m} in the mortar phase, identified with the lowest bearing capacity in Fig. 4(a), is evident in Fig. 5(a), the variation of this quantity in Fig. 5(c) shows a rather distributed character consequently resulting in a slightly stiffer response on the macroscale.



(a) (b) (c) (d)

Figure 5: Distribution of local shear strain: (a) SEPUC 6, (b) SEPUC 37, (c) SEPUC 43, (d) SEPUC 48

Although certainly more accurate, the detailed finite element simulations are in general computationally very expensive and often call for less demanding alternatives such as the Mori-Tanaka method outlined in [7]. Unfortunately, the corresponding results also plotted in Fig. 4(a) clearly expose essential limitations of the two-point averaging schemes, unable to capture localization phenomena observed in composites with a highly nonlinear response of the binder phase [8]. The presented results in Fig. 4(a) correspond to a classical formulation with the localization and transformation tensors calculated only once being functions of elastic properties of individual constituents (MT-original), and to the formulation where these tensors are updated after each time step taking into account increasing compliance of the mortar phase with time (MT-improved). Note that even the latter case produces much stiffer response, although at a fraction of time, when compared to the FE results. A certain improvement has been achieved when putting on the same footing the localized character of matrix deformation, recall Fig. 5, and debonding of stone aggregates, both reducing the stress transfer from the matrix phase into the stones. This issue is addressed in Section 2.3.

Regarding the "similarity" of macroscopic response from various SEPUCs, the SEPUC No. 43 was selected to provide data needed in the calibration of the macroscopic GL model. Virtual numerical tests identical to those in the previous section were again performed to give first the homogenized master curve displayed in Fig. 4(b). The response of the homogenized asphalt mixture to the applied remote shear strain labeled as "Leonov macro" appears in Fig. 4(a) suggesting a reasonable agreement at least for this type of loading. Further applications are available in [6].

2.3 Augmented Mori-Tanaka method

Fig. 4(a) revealed essential limitations of the two-point averaging schemes hidden in their inability to properly capture the correct stress transfer between phases when highly localized deformation in the matrix is encountered. Here, we attempt to minimize this impact of the MT method on macroscopic predictions by introducing a damage like parameter ω into the local constitutive equation of stones thus controlling the amount of stress taken by stones. The stress increment in the stone phase is calculated as

$$\Delta\boldsymbol{\sigma}_s = \omega \mathbf{L}_s : \Delta\boldsymbol{\varepsilon}_s, \tag{1}$$

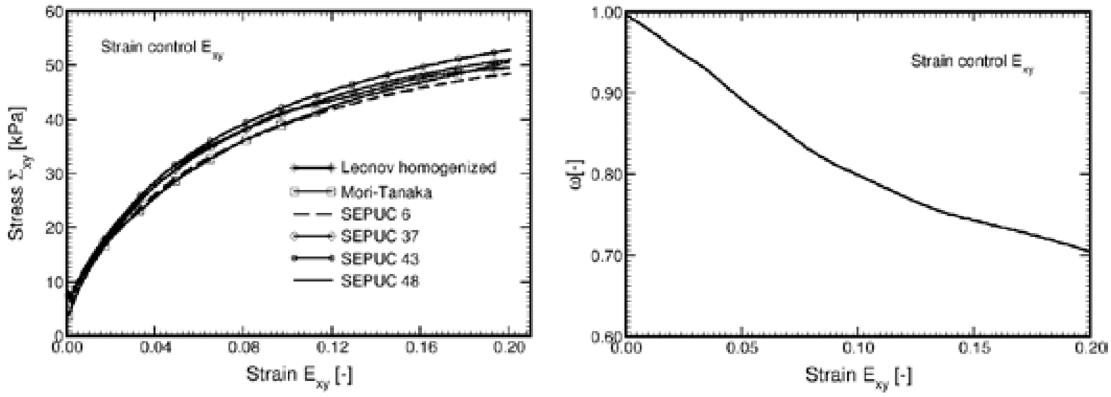
where the damage parameter ω being equal to one for intact material and zero for fully damaged material assumes the form

$$\omega = \left[\frac{\tau_{eq}^t}{N\tau_0} \Big/ \sinh\left(\frac{\tau_{eq}^t}{N\tau_0}\right) \right]^M, \tag{2}$$

where τ_{eq} is the current equivalent deviatoric stress and M, N are model parameters. In the present study, these were found by comparing the MT predictions with the results provided by the homogenized macroscopic Leonov (MGL) model under strain control condition for the prescribed macroscopic shear strain rate $\dot{E}_{xy}$.

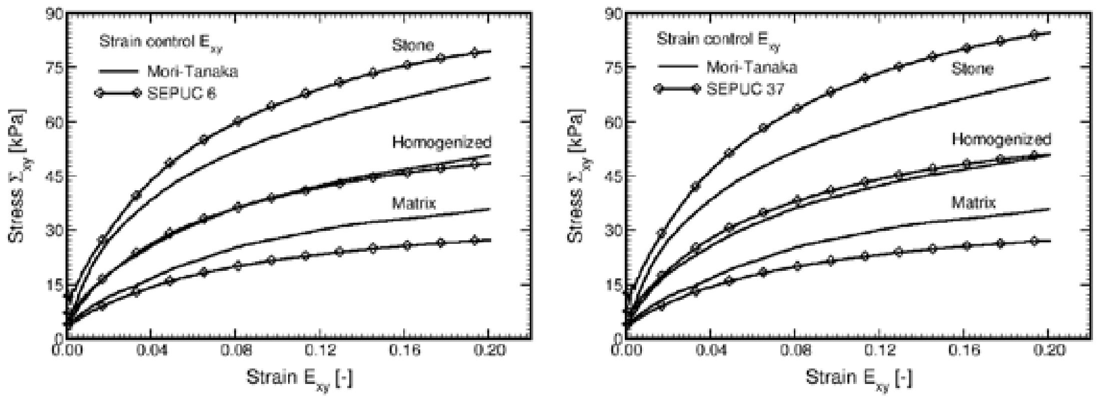
Comparison of the resulting macroscopic predictions including the results from various SEPUCs are available in Fig. 6(a) whereas evolution of damage parameter ω is plotted for illustration in Fig. 6(b). Considerable improvement of the behavior of MT method is evident particularly when compared to the original predictions presented in Fig. 4(a).

Another strong motivation for mastering the MT method, apart from avoiding the mesoscopic virtual tests, is the possibility to estimate at least the local phase averages. These estimates are compared separately with predictions from individual SEPUCs in Fig. 7. Realizing that parameters of the damage model were fitted against the homogenized response the agreement of local fields is quite satisfactory. A closer match might be

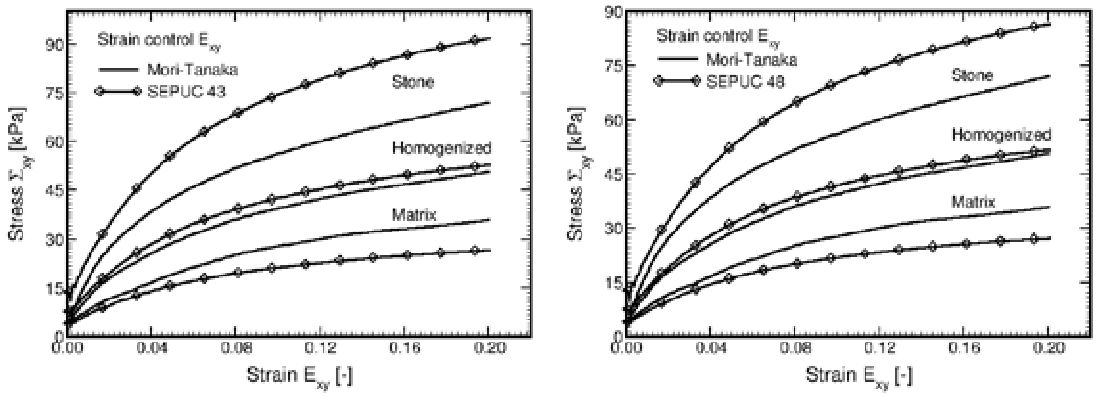


(a) (b)

Figure 6: (a) Macroscopic response for various SEPUCs, MGL model and MT method, (b) variation of damage parameter ω: $T = 20$C, $\dot{E}_{xy} = 10^{-4}$ s^{-1}



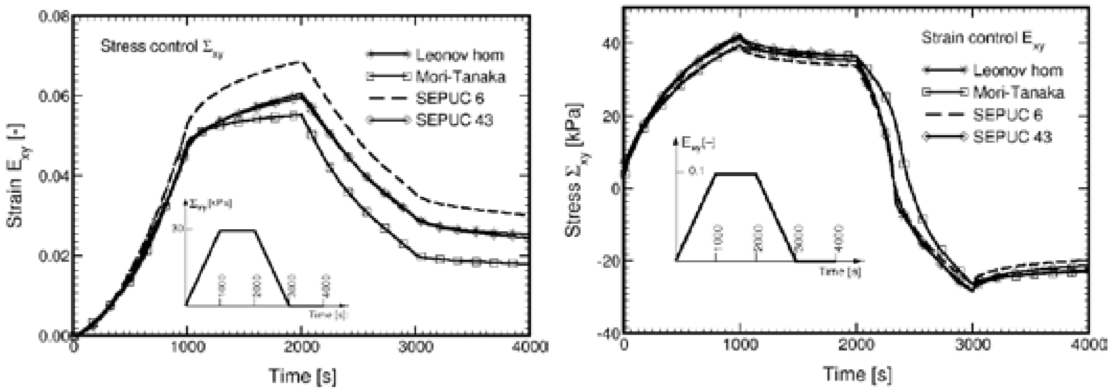
(a) (b)



(c) (d)

Figure 7: Phase averages of local fields from various SEPUCs and MT method, $T = 20$C, $\dot{E}_{xy} = 10^{-4}$ s^{-1}: (a) SEPUC 6, (b) SEPUC 37, (c) SEPUC 43, (d) SEPUC 48

expected if deriving the damage model parameters directly from the local matrix stress averages provided one of the periodic unit cell.



(a) (b)

Figure 8: Macroscopic response for reference temperature T = 40C (a) Stress control: loading–creep–unloading–recovery, (b) Strain control: loading–relaxation–unloading–recovery

At last we inspected the predictive capability of the MT method for loading conditions dominating the creep or relaxation response. The creep response is examined in Fig. 8(a). As expected, there is almost a perfect match between the results found from the MGL model and the finite element analysis of SEPUC No. 43. Considerable deviation of the results provided by SEPUC No. 6 agrees well with already observed deviations evident in stress control conditions. What is, however, more disturbing are the predictions pertinent to the Mori-Tanaka method associated especially with the interval of constant load (creep response). Its inability to predict a correct creep behavior is quite pronounced. The loading, as well as, unloading branches controlled by the damage parameter ω are on the other hand captured relatively well. Somewhat better agreement is provided by strain control loading visible in Fig. 8(b).

3 SUMMARY

Although research interests on flexible pavements have been quite intense in the past two decades, the field is still very much in development and will certainly witness considerable activity in the coming decade particularly in connection to hierarchical modeling and micromechanics. Within this framework, the present work provides theoretical tools for the formulation of macroscopic constitutive law reflecting the confluence of threads coming from experimental work, image analysis, statistical mechanics and traditional disciplines of micromechanics and the first order computational homogenization. Here, the totally uncoupled multiscale modeling approach is favored to enable an inexpensive analysis of real world large scale structures, which is the principle objective of our work.

The results from the proposed two-step homogenization scheme, promoted the SEPUC as a suitable computational model and in combination with the finite element formulation of the first order homogenization method to set a plausible route for the nonlinear viscoelastic homogenization. It is often desirable to identify local stress and strain fields in individual phases of the composite developed for various macroscopic loading conditions. However, fully coupled analysis employing detailed microsctructures, e.g SEPUC, is still often computationally prohibitive. Therefore, a simple Mori-Tanaka averaging scheme was examined to either support or decline its use in the framework of efficient coupled multiscale analysis. The presented results are in favor of this approach but at the same time suggest caution in applications where strong creep behavior is expected.

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