Chapter 1
Multi-Scale Methods in Simulation—A Path to a Better Understanding of the Behaviour of Structures

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1.1 State of the Art—What We Can Do Today

The success of using simulation methods is highly connected to the efficiency one can use them. Efficiency depends on many factors like process factors (Fig. 1.1):

- Easiness of setting up the simulation,
- Seamless process integration: applying the correct data at the correct places,
- Effectiveness of interpreting the results of the simulation,
- Integration into optimisation runs.

For these processes and user interaction oriented tasks, the software companies tailor and provide their software platforms for the needs of their applications and users, see e.g. [1].

But there are also strong influences of the methodology on accuracy and efficiency of simulation tools:

- Get the correct material data,
- Adaptive calculation,
- Parallel computing.

To be able to improve the latter, a close collaboration between industry and research is necessary. For the industry it helps to get access the most efficient methods available, and for research it ensures that the newest developments find their way into real applications.

Here applied mathematics plays a crucial role to provide deep insights into the algorithms and applicability. So it is no surprise that the subsidiary of Siemens PLM for durability in Kaiserslautern was originally a spin-off of the Mathematics Department at the TU Kaiserslautern.

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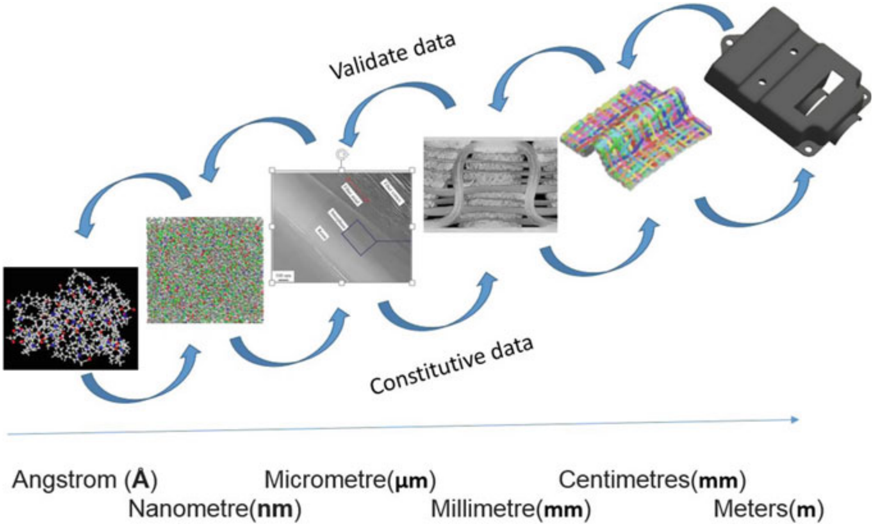

Fig. 1.1 In multi-scale approaches the smaller scales provide the information that the next level needs to run its analysis. Anything not coming from the scale below needs to be achieved by tests on the upper scale (Figures from [2–6])

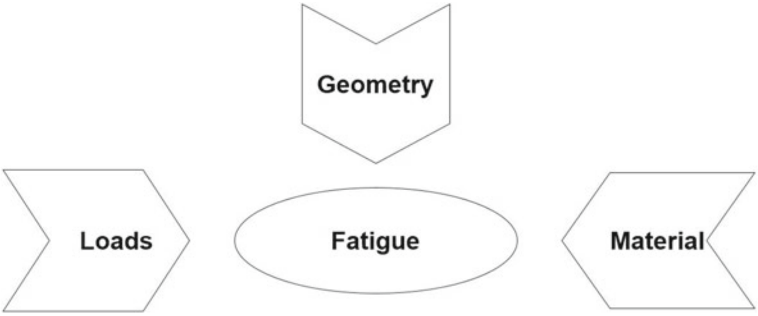

Fig. 1.2 Traditional view on the influences on fatigue life

Over the last decades new and highly efficient methodologies could find their way into software. More than twenty years ago fatigue simulation with realistic loads and complex structures could take weeks to run—no real time gain against testing. As usage in the daily design process was not possible, the loads typically were simplified, and very special load conditions were analysed. Another approach was to restrict the analysis to user defined points. As these approaches could not estimate the error introduced by the simplifications, the user had still to live with large safety factors and over-designs. In a joint project new filter tools had been developed in a Ph.D.-thesis [7] that provided good error estimates and efficient implementation. Using this approach, real live problems could be solved within hours, see [8] (Fig. 1.2).

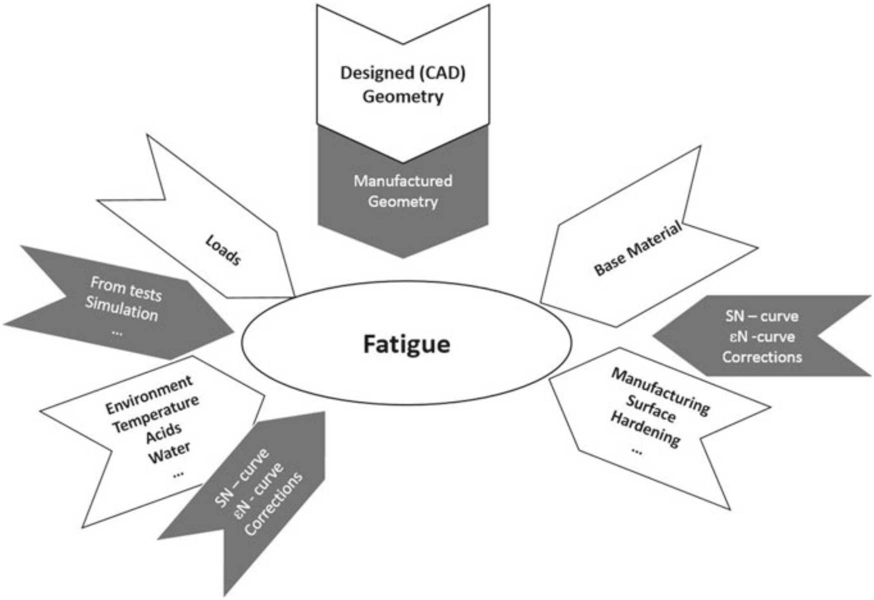

Fig. 1.3 In reality much more factors especially from the manufacturing process are acting. Traditionally they are captured by correction factors

1.2 Requirements from the Applications—New Materials Need New Methodologies

In metals the fatigue problems typically initiate on imperfections in the metal or on grain boundaries. These micro-structures are influenced by the manufacturing process but the local distribution is normally unknown. On the other hand, two centuries of fatigue testing on metal structures have given enough background to replace a real modelling of the micro-structure by test based material data. This was, and still is, possible as the material behaviour is quite homogeneous, and local behaviour can be handled by empirical correction factors, see Fig. 1.3. Once we face composite structures, we get a much more complex situation. While in metals the damage mechanism is more or less unique namely the initiation of micro-cracks, in composites there are multiple mechanisms as multiple materials are involved. Also in metals the behaviour is typically isotropic and the local anisotropic behaviour can again be handled by multi-axial criteria [8]. In composite structures the damage mechanisms are more complex and may influence each other.

So trying to follow the empirical based approach, like for metals to get material data, would at least lead to a tremendous set of test setups and also need so many simplifications due to the missing reliability in material data large safety factors would be needed.

In the next sub-sections, we depict the challenges for short fibre reinforced plastic materials analysed in the studies of this book project.

1.2.1 Orientation of Fibres

For composite structures, it is necessary to take the local microscopic structure into account, as it defines the basic structural behaviour. For injection moulded short fibre reinforced plastics the local distribution of the fibre orientation directly influences the (anisotropic) local stiffness of the structure and also defines the damage behaviour, see Fig. 1.1.

In order to study the behaviour of injection moulded short fibre reinforced plastic components the evaluation of the local mechanical behaviour is necessary. In a first step the simulation of the manufacturing process itself has to be conducted. An outcome of such a simulation is the local distribution of the fibres (to be more precise the probability distribution of the fibre orientations).

Nowadays the usage of injection moulding simulation software is a standard in the development process. Such simulation software provides the local fibre orientation distribution as an output. The fibre orientation subsequently has to be transferred from the model for the injection moulding simulation into the model for the structural simulation.

1.2.2 One Approach—The Master SN Curve Approach

The local distribution of fibres lead to different fatigue behaviour at each point of the structure. The behaviour also changes with the direction the load is applied. Therefore it is necessary that for a given material the fatigue behaviour is known for any fibre distribution and any direction with respect to applied loads.

One idea to estimate the local material data is to combine test based approaches with simulation approaches on the micro-scale. In a joint research project, the KU Leuven and Siemens developed a hybrid master SN-curve approach [6, 9, 10]. The basic idea is to separate the influences of the orientation from the basic fatigue behaviour of the material (incl. considering temperature, wetness, etc.).

It was found that taking into account the effect of fibre matrix debonding and fibre cracking on micro-level enables to split the effect of the fibre orientation from the effects of the base materials and the environment, see [9, 10].

The basic idea behind the approach is to calculate the damage on microscopic level. The first cycle of loading is modelled. The onset of debonding, progression of fibre matrix debonding, and the subsequent loss of stiffness is based on the concept of *equivalent bonded inclusions*. A thorough mathematical treatment of this concept has been presented in [11].

In order to calculate a point on a SN-curve for an arbitrary but given orientation, one starts from the point of same (macroscopic) damage on a given master SN-curve

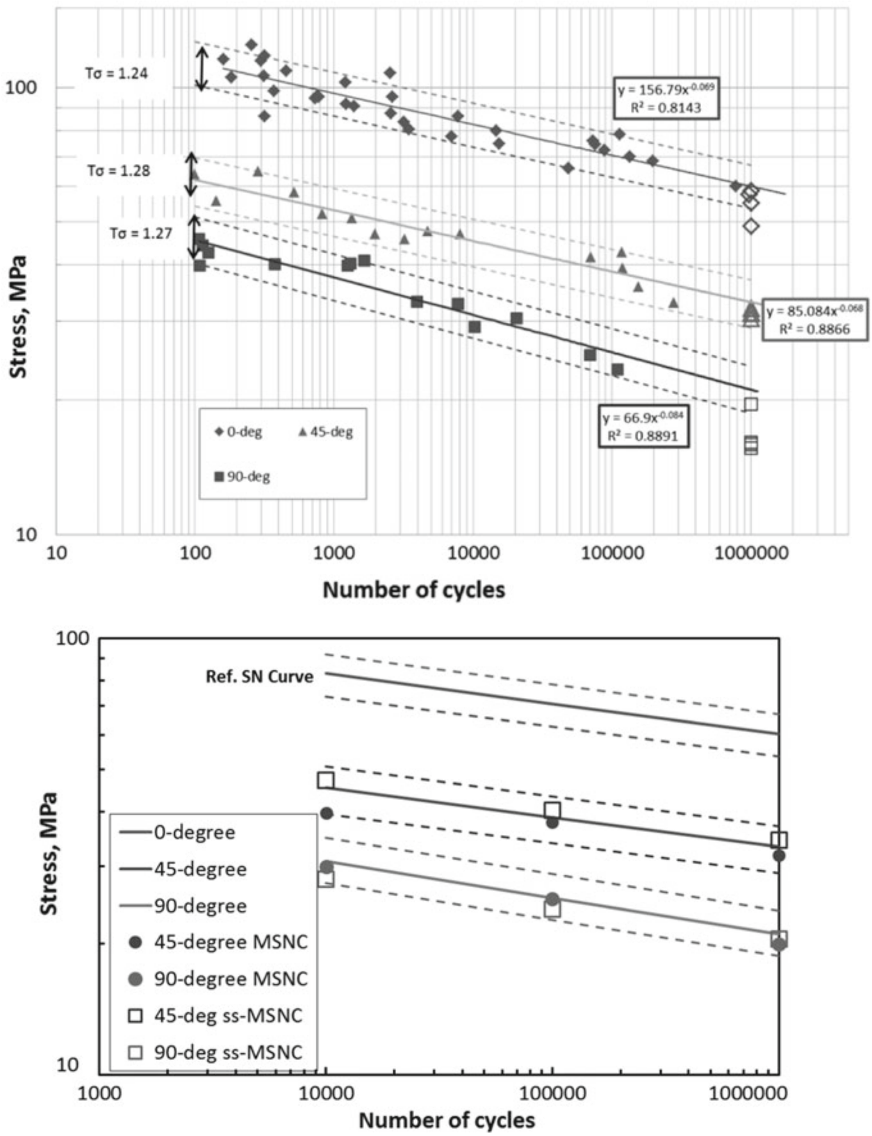

Fig. 1.4 Results of the master SN-curve approach (lower picture) compared to test results (upper picture): The predicted points lie within the scatter band of the tests [6]

and calculates the progressive damage on the microscopic scale for the orientation of the SN-curve. In order to get the point on the new SN-curve, the load that is needed to reach the same microscopic damage for the new orientation is evaluated by an iterative process. In Fig. 1.4 the results for a 50% Glass fibre reinforced PBT are shown.

1.2.3 Local and Global Stiffness Reduction

As opposed to metal structures, in composite structures a change in the local and global stiffness before failure of the complete structure is observed. It can be seen in the matrix material as well as in the composite structure. Detailed analysis on different specimen had shown that this stiffness reduction over the lifetime is (at least statistically) independent of the local fibre orientation [9].

These local stiffness changes lead to a redistribution of stresses. The influence of these re-distributions lead to large differences between the component behaviour and specimen behaviour. The slopes of specimen SN-curves are typically much smaller than those of the component SN-curves. Without taking stiffness reduction into account a correct simulation of the component behaviour was not possible, see [6, 9].

For short fibre reinforced composites an exponential decay down to 90–85% during the lifetime gives a good estimate, see Fig. 1.5.

To be able to apply a stiffness reduction algorithm with complex load scenarios, it is necessary to use mathematical modelling to understand the background fatigue simulation tools for metals and correctly enhance them for the needs of composite fatigue modelling.

In the case of variable amplitude, traditional fatigue approaches for metallic material use SN-curves, linear Miner-Palmgren [12] damage accumulation and cycle count (rainflow counted cycles [13]) based damage evaluations.

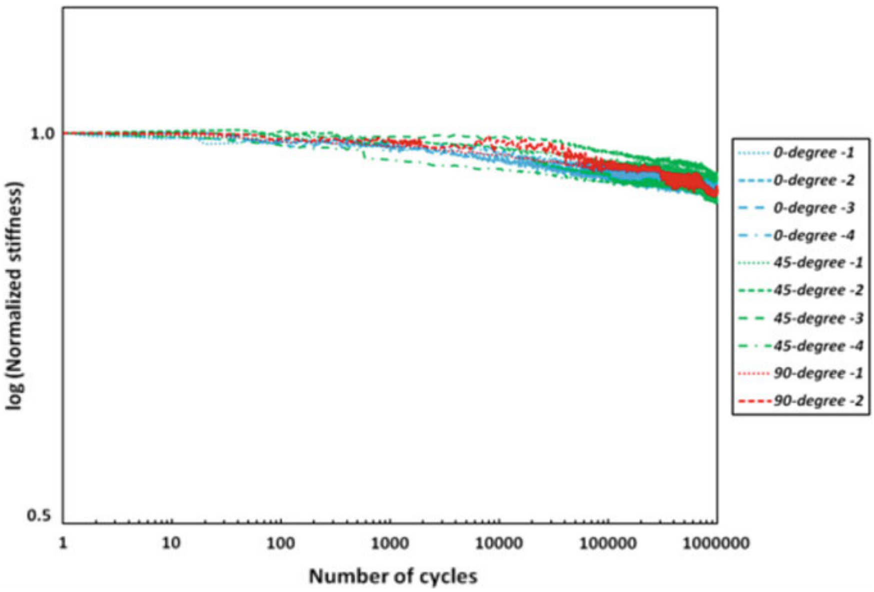

Fig. 1.5 Decay of stiffness for short fibre reinforced specimen under cyclic loading [6]

In 1945, Miner developed a linear damage accumulation method, based on the work of Palmgren and added the contribution of various stress amplitude loading to the damage. However, as for SN-curves, the loading history of the material is not accounted for. In rainflow counting methods the damage level depend on full closing hysteresis loop of load cycles. In the case of composite materials, the fatigue behaviour is changing over time due to changes in the matrix damage state. When applying variable amplitude loading, the largest load cycles that contribute to the larger amount of damage commonly take a very long time to complete, due to the many nested cycles. In this case, the approach to only consider cycles when they are completed can no longer be justified.

In the 1990 Brokate and Krejci [14] applied the mathematical tools of hysteresis operators to fatigue theory [15] analysing the linear damage accumulation and analogies between damage accumulation and energy dissipation.

Based on this work, it is possible to extend the rainflow based methodology to non-linear damage accumulation in a both mathematical and methodological sense: the damage hysteresis operator approach [7, 16].

The idea is based on the hysteresis operators for kinematic hardening (i.e. to calculate elastic-plastic stress-strain behaviour from pseudo elastic stress histories) and how dissipated energy is calculated in these models. The new idea is to replace the constitutive laws of elasto-plastic stress-strain behaviour with constitutive laws for a stress-damage potential behaviour [14, 15].

The hysteresis operator approach is able to calculate damage at any time increment instead of closed cycle increment. The extensions explained in [7, 16] allow the damage status and the damage behaviour to be updated depending on internal (i.e. pre-damage) and any external factors (i.e. temperature, humidity). Therefore this approach is also suited to follow the progressive damage curves and also including the damage history of the material.

Combining these methodology it is possible to simulate the fatigue life for injection moulded structures with limited effort in testing [6, 17].

1.3 Open Tools—Necessary for Including New Methodologies

We already learned in the sections before that for efficient and accurate simulation the methodology and process needs to be adapted to the

- material as is,
- manufacturing processes—i.e. material as manufactured,
- environmental factors and loads,
- pre-damages and actual local damages due to the load,
- and many more.

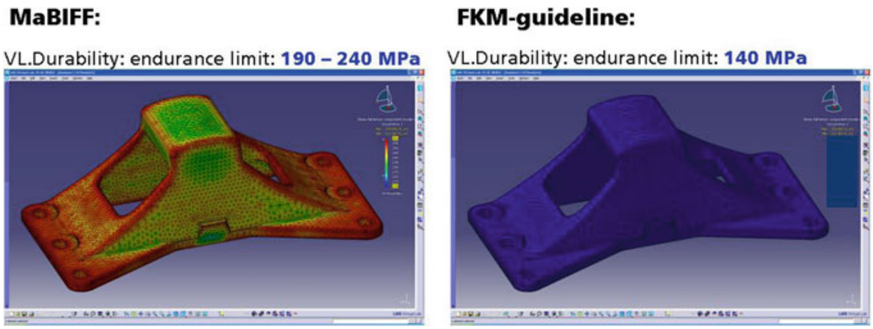

Fig. 1.6 Comparison of the allowable stress values (shift in SN-curves): In the left picture individual allowable stresses including the manufacturing simulation [19], on the right traditional approach using standards [18]

1.3.1 Manufacturing Influences

In Sect. 1.2 we have seen that classically, fatigue data have been taken from material tests for the material as available for the testing. In reality, the material as manufactured often has different properties. Indeed in many cases special treatment is added to manufacturing process to improve the properties of the material in places where the structure has to endure higher loads. The traditional approach to incorporate this influences in a fatigue simulation is to apply correction factors to modify the fatigue data (typically the SN-curve) [18].

From an application point of view this can get to a tedious process, as the influencing factors have to be extracted from the results of special manufacturing simulation tools. From those the correction factors have to be calculated (often done with spreadsheet calculation software) and applied to the fatigue simulation tools. The latter often uses different representations (FE-Meshes) of the structure and so even the simple application of the correction factors at the correct places (nodes/elements) is an error-prone process.

To establish more applicable processes to include manufacturing processes the BMBF-funded project MaBIFF [19] included this task for the manufacturing process of casting. In this project, first an investigation of the different properties of the casted material on a micro-scale (22 properties on the distribution, structure, and size of graphite, perlite, and ferrite) were analysed both from tests (micro-graphs) and simulation. In a second step, the micro-scale properties were correlated with fatigue data on the macro-scale.

For a real structure, first a simulation of the micro-scale material data was performed. A mapping used the correlated fatigue data directly in the fatigue solver. The fatigue solver for this was enhanced (opened) to be able to directly take the fatigue data directly from the process. The project showed for the analysed component that at the most loaded areas the manufacturing process lead to much better fatigue properties than for the rest of the structure and even better compared to standard fatigue data from literature, see Fig. 1.6.

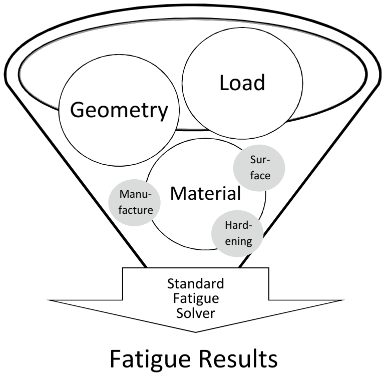

Fig. 1.7 Traditional approaches to incorporate influences into fatigue methodology: To be able to include it the influences where just added as correction factors to the material data, Hence the solver was a kind of bottle neck

1.3.2 New Methodologies

While for metallic structures, the methodology for fatigue is established and also the influence from manufacturing has widely been included in these methods by adapting the parameters, composite materials show more complex damaging behaviour. Often different damage mechanisms act at the same time: in material damage (matrix cracks, fibre cracking) but also interface damage (debonding) and interaction to other materials or plies (delamination). They may not only occur at the same time but also interact. The different mechanisms and the importance of them depend on many factors:

- Selection of combined materials,
- Volume fraction of the different materials,
- Geometry of the materials (Fibre length, aspect ratio, …),
- Topology of the materials,
- External factors like temperatures and humidity.

This means that a lot of different methodologies for different materials but maybe also for different levels of detail exist (Fig. 1.7).

Instead of implementing loads of different tools for each application and material the better way is to allow one solver tool to integrate different methodologies into one solver and only exchange parts of the implementation:

- how to filter the important areas in the structure and the important parts of the loads for efficiency,
- how to get from local finite element results to local input for damage and fatigue (forces, energies, stresses, strains),
- how to increase different damage modes,
- what is the influence on local stiffness,
- when local failure occurs (Fig. 1.8).

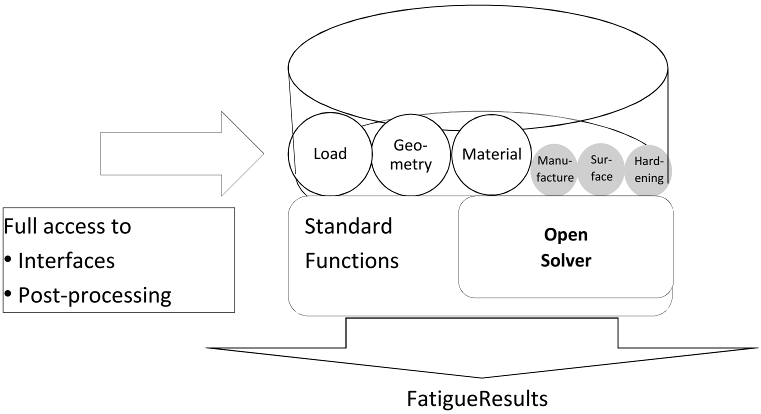

Fig. 1.8 In the open solver approach [1] the new influence factors are on the same level as traditional influence factors. They may also lead to changes in the solver, so we can go for any and the locally best methodology

This approach has already been successfully implemented for applications like

- Intra-laminar damage in continuous fibre structures, [20–22],
- Short-fibre reinforces plastics [6, 17],
- Adhesives.

1.4 On the Path with MuSiKo

In the project MuSiKo, as presented in this book, many of the efficiency aspects and the process aspects have been analysed in detail and with mathematical rigorousness for the application of damage in short fibre reinforced plastics. An important point in the project was also that it did not just focus on mathematical methods, but also, on the testing side, on how to get parameters to fill in the methods.

In all this means the study perfectly fits in the projects and developments mentioned in the sections above. Whereas in the examples, the influence on micro-scale is in most parts accounted for by a homogenisation to macro level on a testing based or at least hybrid approach, here a full scale of methods from empirical to full FE^2 is analysed.

Even though the main application case is static damage and not fatigue damage, results are important for the whole process.

Especially the filter methodology is of interest for many cases of fatigue and damage analysis, as they are not restricted to the application case of short fibre reinforced composites.

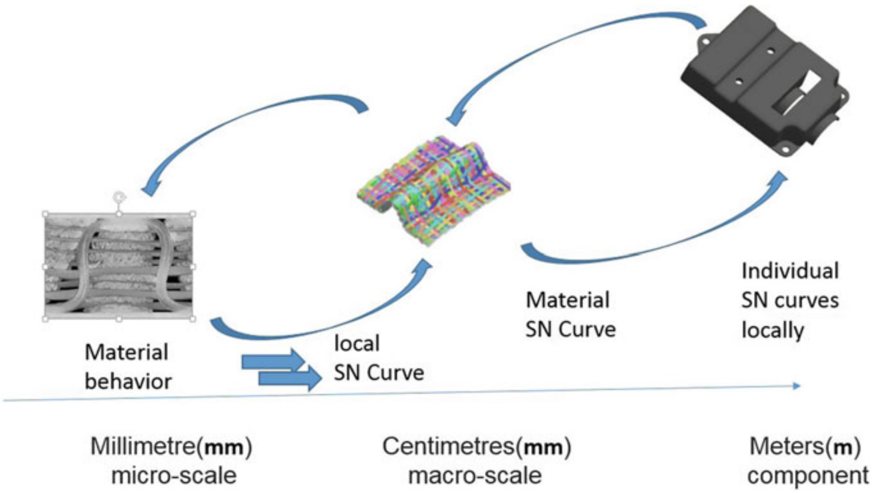

Fig. 1.9 In the past the step from marco-level to component level was established by the strain-life methods and the introduction of FE-methods. For composites we need the same step from micro-level to macro-level

1.5 Outlook—Virtual Testing and Material Design

We have seen that the applicability of simulation methods depends on the availability of the data that are needed to run them. Looking historically, there are several milestones in the fatigue of metals. Starting in the 19th century with component tests [23] that allowed to simulate the accumulation, the damage induced by realistic loads for a given structure, typically rail axles. An important step was to get from the component level to the local analysis. Nominal stress based and local strain-life approaches were developed. Here, material based fatigue data was needed. With the material based data and the correction mechanisms, it is possible to analyse arbitrary structures with these approaches with a limited set of test data. The scale here is what we call macro-scale today. When we look at the composite structures a similar step is needed. The material data needed at macro-level can hardly be tested. Again the goal is to start from basic data, the best that can be determined on the basic constituents of the material the matrix and the fibres. The goal is to be able to only use data on the material and the manufacturing process for estimating the behaviour of the material on macro level (Fig. 1.9).

We have seen there are different approaches to get the needed data. In Sect. 1.2, we describe a hybrid approach where data on micro level are combined with results of manufacturing simulation and test data on macro level. In [24], methods had been developed to bypass the tests on macro level and estimate those from data on the material level only.

The MuSiKo project, as described in this book, analyses several mathematical and numerical building blocks of methods that can be applied on micro-level directly, as well as how to derive the needed data from tests. Even though some of the methods may today still seem hard to use from an point of view of computation time, it is quite clear that several of the ideas will also progress the multi-scale methodology for damages in the future.

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