Comparison of existing long term deformations with models

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Summary
For the description of the long term behavior several different rheological models have been developed, considering normal creep as well as mechano-sorptive creep. However for the application the question arises which model should be used, since especially differences in a prediction of the creep strain after more than 20 years appear. Since tests can hardly be performed over such a long period, the deflection of beams in existing buildings is compared to the values given in the standards as well as to the rheological models.

1. Introduction
In composite structures or elements subjected to compression, the creep deformation influences directly the ultimate limit state as well as the serviceability limit state. In order to predict the time dependent deformations, creep values are given in the standards.

If the creep coefficients of different standards in Germany and studies (see [1], [2], [3] and [4]) are compared, a quite variability of possible values can be found (see Fig. 1).

These differences are not only quantitavly but also qualitatively. So in the German standard [2] the stress level influences the creep deformation, whereas in other standards (see [5] or [1]) the creep strain is only influenced by the service class.

Beside the creep coefficients in the standards different rheological models have been developed (see [6], [7], [8], [9] among other and Fig. 2), in order to determine the creep deformation in a much more exact way, since different parameters as variability of the moisture content or stress level can be considered.

Fig. 1 Creep coefficient for solid timber in dependence on the equilibrium moisture content \( u \) (SCL = service class)
The comparison of these models leads to the conclusion, that within the first 5 to 7 years the models hardly differ, since they are often calibrated with comparable tests (see Fig. 3(a)). However extrapolating these models leads to differences even for constant relative humidity (see Fig. 3(b)). The reasons for the differences are on the one hand different parameters and coefficients of the models and on the other hand the different build-up of the models. So some models consist of serial Kelvin-Voigt-bodies. Within these models often the normal creep and the mechano-sorptive creep are modeled by different Kelvin-Voigt-bodies. Other models consist of parallel Maxwell-bodies, which consider the mechano-sorptive creep as well as the normal creep.

These differences in the build-up lead to different responses of the models if they are extrapolated, since two different independent influences – time and moisture variation – are considered in these models. Therefore the duality of the differential equations of the parallel Maxwell- and the serial Kelvin-Voigt-models is not valid any more. In the serial Kelvin-Voigt-models the creep limit is reached independently of the influences, so the creep limit of the normal creep as well as the creep limit of the mechano-sorptive creep have to be reached in order to reach the creep limit of the total

**Fig. 2:** Studied models

**Fig. 3:** Comparison of the models
strain (see Fig. 4). In difference to this, the total strain is limited in the parallel Maxwell-elements, so

\[
\begin{align*}
\eta_0 &= \infty \\
\eta_1 &= \eta_2
\end{align*}
\]

(a) serial Kelvin-Voigt-bodies (see [7], [9], [8])

(b) parallel Maxwell-bodies (see [6], [11])

For the application of these models in systems, such as timber-concrete-composite systems, the question arises, which model should be used for the extrapolation of about 50 years, since the models are often calibrated at tests which lasted about 5 to 7 years. To answer this question, tests can hardly performed for the interesting period of time of about 50 years. In order to get an idea of the time dependent deformation, the deflection of existing structures shall be measured.

2. Measuring of the time dependent behavior

To estimate the creep coefficient after a duration of load for a period of more than 5 years, tests are hardly possible. One way to approximate the creep deformation of timber is to measure the time dependent deformation of existing structures. For this reason the deflection is measured by a measuring device (see Fig. 5). In order to determine the elastic deformation an integral stiffness of

Fig. 4: Influence on the results due to the different build-up of the models

Fig. 5: Measurement of the deflection
the beam is determined by loading the beam by a defined load. Using this integral stiffness of the system, the elastic deformation can be estimated, since the dead-load of the system can be determined.

If the deflection due to the dead-load is known, the difference between the measured and the evaluated elastic deflection leads to an effective creep coefficient, which should have been used by the engineer in order to determine the real time dependent deformation. This means that with this procedure not the real creep coefficient of the timber cross sections but an effective creep coefficient can be determined, since the determined time dependent deformation consists of the deflection due to creep, to imperfection, to different shrinkage/swelling etc.. In order to reduce the influences of these unknown parameters some criteria concerning the choice of the buildings as well as the procedure of the measurement have been introduced:

- Imperfection: Since the elements of the building aren’t measured before the erection, the imperfection of the single element is not known. In order to reduce this influence only elements in a building are considered if several identical elements can be measured in the building.

Since the variability of the imperfection of timber elements is given by (see [12] resp. [13])

\[ e = (1.150 \pm 10.538) \cdot 10^{-4} \cdot L \]  

where \( e \) Imperfection in mid span  
\( L \) length of the element

the average imperfection can be determined, if enough elements are measured.

Performing a Monte-Carlo-simulation in order to determine the influence of the imperfection on the creep coefficient, the required number of elements can be estimated. As visible in Fig. 6(a) the influence of the imperfection on the creep coefficient is less than 10%, if more than 10 elements are measured.

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**Fig. 6: Criteria in order to reduce the influence of the imperfection**

Beside that only elements are considered, which deformation is affine to the assumed elastic deformation. Applied on the measurements, only elements are considered, where the deformation in the quarter of the beam length is in the range of affine deformation ± 50% of the mid-span value (see Fig. 6(b)).

- Climate: On the one hand the climate strongly influences the time dependent deflection especially within the first years (see Fig. 3(a)), so it should be recorded as exact as possible, although such a documentation of the climate in the buildings does not exist.
On the other hand, the changing of the moisture content is a quite slow process. So the daily or weekly changing of the relative humidity only influences the moisture content in the very outer layers (see Fig. 7). Since the influence of the daily or weekly changing moisture content is small, it is reasonable, only to consider weekly or larger cycles. Therefore the climate of a weather station can be used for the re-evaluation, if the elements are protected but not heated. For this reason, only carports or agricultural machine shops are measured (see Fig. 8).

![Fig. 7 Influence of the duration of the cycle of the relative humidity on the moisture content of a cross section according to the model given in [7]](image)

- **Load history:** All measured elements are elements of the roof for two reasons. First the load history can be reconstructed by the data of different weather stations. Second, according to [5] snow load has to be only considered as permanent loading, if the location is over 1000m above sealevel. All the measured buildings are below 450m above sea level, so for the determination of effective creep coefficients no snow load has to be considered.

- **Initial moisture content:** The initial moisture content in the cross section is not known. However in the rheological models the mechano-sorptive creep is a function of the accumulation of the moisture content. So regarding the variation of the moisture content, the initial moisture content influences the time dependent stiffness of the beam only a little (see Fig. 9), since during the life time of the building a much larger accumulation of the changing of the moisture content due to the changing surrounding conditions appear.
3. Measured increase of the deformation

Up-to-now 8 buildings with an age between 19 and about 450 years have been measured resp. the results of measurements have been taken from literature (see [14]). Within these 8 buildings the deflections of in total 117 beams of roof structures have been determined. Basing on these measurements the “real” creep coefficient of every beam has been evaluated. Since the climate and the loading of the single elements in every building seem to be comparable, the average creep coefficient and the standard derivation of the elements within one building can be determined (see Fig. 10). For the determination of the standard derivation, a normal distribution of the creep coefficients is assumed.

As visible in Fig. 10 the measured average creep coefficient is in the range between 1.5 to 2.4. The average standard derivation is 1.0. So a quite large variability of the existing creep coefficient can be stated. However up-to-now no relevant material property or stress level can be identified to cause this variability, because the creep coefficients show neither a clear dependence on the common stress level within a building (see Fig. 11(a)) nor a clear dependence on the Modulus of Elasticity (see Fig. 11(b)). If the average creep coefficients of the single buildings are compared (see Fig. 10), it can be concluded from this – maybe too – small database of different buildings, that the differences of the creep coefficient between the building with an age of about 20 years and the older buildings with 350 resp. 450 years are relatively small, resp. no systematic difference in the average creep values of the single buildings can be determined.

Concerning the design, the creep coefficient according to [1] is in all buildings 0.8 except the indoor
(a) Creep coefficient of the chapel of the castle Nymphenburg in dependence on the stress level (see [15]).

(b) Creep coefficient in dependence on the MoE of the building Futter / Jungviehweide, Ofterdingen.

Fig. 11: Influence of the estimated stress level and the MoE elements according to [14]. In Fig. 10 this creep coefficient according to [1] is set into relation to the measured creep values. As visible this creep coefficient represents the lower values within the standard variation of the measured creep values.

For the comparison of these measurements the model according to [7] is used since this creep model leads to an effective creep in the range of 1.8, whereas the other models lead to lower creep coefficients (see Fig. 12). For the re-evaluation a cross section of 10×20 cm is chosen. Although the dimensions of the measured beams differ from this cross section, the creep coefficient according to the model of [7] is hardly influenced, since the creep limit of the model is reached within the first 50 years for cross section thicknesses smaller than 20 cm, if the variation of the relative humidity is about 15%.

Fig. 12 Creep coefficients after 50 years according to the models of [7], [6], [9] and [8] for an annual amplitude of the relative humidity of 15% in dependence of the thickness of the timber element.

4. Conclusions and outlook

Creep coefficients are given in the standards. If the measurements are compared to those creep coefficients, a larger discrepancy between the value given in the standards and the ”real” creep coefficient seems to appear. So the value given in [1] of 0.8 for outdoor, but sheltered climate is the lower values within the standard derivation of the creep coefficient.
If the models are compared to the up-to-now performed measurements, it seems, that the model B according to [7] leads to the best correspondence between measurement and evaluation for the period of 50 years, although all models fit quite well to test results and to each other within the period of 5 to 7 years.

However although 117 beams have been measured, the deflection of additional elements shall be determined in order to expand the data basis, since larger variabilities of the results appear. Beside that, beams of different globale climate, e.g. in quite foggy regions shall be measured in order to discuss the influence of the mechano-sorptive creep concerning the long term behavior.

References


