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FATIGUE DAMAGE VERSUS CREEP DEFORMATION – DIFFERENTIATION USING THE DEVELOPMENT OF STIFFNESS –

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Abstract: Concrete structures, especially bridges, can exhibit deformations due to creep, induced by cyclic loading at serviceability limit state. These deformations can exceed the deformation when static creep is considered. For loading levels corresponding to serviceability stress-levels, structural damage in terms of micro-cracking is not supposed to occur. In contrast, in fatigue testing viscous deformations (without structural damage) are not supposed to happen. Therefore, measured deformations are usually regarded as fully damage-induced. A collaborative research project, supported by the German Research Foundation (DFG), was set up to experimentally determine the influence of superposition of viscous creep deformations in static creep and cyclic loading. Special attention was paid to the transition from linear to non-linear creep due cyclic/fatigue loading. Linear creep is regarded as a purely viscous deformation, non-linear creep as a superposition of viscous deformation and damage-induced deformation. Finally, deformations in fatigue loading are regarded as predominantly induced by structural damage respectively micro cracking. The overall aim was to test the hypothesis that development of stiffness during cyclic loading can be used to differentiate viscous deformations from deformations induced by micro-cracking. As long as only viscous deformations occur, stiffness is supposed to stay constant. Damage in terms of micro-cracking is supposed to be characterized by a gradually decreasing stiffness – as usually measured in fatigue loading. The experimental program covers different load-levels, loading-amplitudes, loading-frequencies, as well as different moisture contents of normal strength concrete. Conventional static creep-tests as well as cyclic loading tests were performed for direct comparison. Different loading-frequencies in cyclic loading enable both, an evaluation of damage-induced and viscous deformations, in terms of duration of loading as well as number of cycles. It is shown that loading at serviceability stress-levels up to about 45 % of the compressive strength show a stabilization or even increase of stiffness. However, stress-levels in non-linear creep and fatigue with load-levels exceeding 45 % of the compressive strength show a continuous degradation of stiffness. Furthermore, the loading frequency affects the development of stiffness. Finally, it can be concluded, that the development of stiffness is suitable to differentiate viscous deformations from deformations induced by structural damage/micro-cracking.

1 INTRODUCTION

Concrete structures are subjected to multiple different types of loading throughout their lifetime. Live loads due to traffic, wind or waves are just a few examples for cyclic loading on concrete structures. Additionally, dead weight brings a constant stress-level.

In this paper, a comprehensive experimental study is described, which aims at analyzing firstly the influence of cyclic compressive loading in comparison to conventional creep loading of normal strength concrete. The study secondly offers the possibility to differentiate between viscous strains and strains induced by structural damage in the concrete matrix. The scope of the study covers stress-levels from linear creep, usually below 45 % of the static compressive strength to stress-levels in non-linear creep up to 65 % of the static compressive strength. This project was funded by the DFG (German Research Foundation) carried out in a cooperation between the Leibniz University Hannover and University of Wuppertal due to the large scope of time-consuming creep and cyclic creep tests. The term “cyclic creep” was chosen to describe a force-controlled cyclic loading generally comparable to fatigue loading with two differences: Firstly, stress-levels are lower compared to conventional fatigue loading, indicating that the long-term viscous and plastic deformations are in focus. Secondly, it is not intended to reach structural failure of concrete, even if failure is somewhat likely to occur at stress-levels of about 65 % of the static compressive strength.

2 STATE OF THE ART

2.1 Strains in creep and fatigue

Common design approaches for creep assume constant loading and an elastic material behavior [1]. For e.g. bridges or prestressed slabs creep as time-dependent and long-term strain component has to be taken into account, because creep strains may change stresses and stress distribution in the structure as described in [2,3]. In design, creep is defined as constant stress neglecting effects of cyclic stresses which can arise e.g. from traffic or wind loads. As mentioned, stresses resulting from these loads are often below the level of 45 % of the compressive strength, corresponding to the serviceability limit state. Creep is said to exhibit purely viscous strains without structural damage in terms of micro-cracking, which is supposed to occur at higher stress-levels. In the non-linear creep range at stress-levels above 45 % up to about 65 % additional micro-cracking is expected, inducing plastic strains. In Model Code 2010 [3] an estimation for these deformations is outlined. To include long-term strains due to cyclic loadings, an estimation of effects of cyclic loading on viscous strains is given. It is assumed that the relevant stress-level for cyclic creep is the mean stress. The amplitude and thus load-level has no effect. It is further known, that factors as the loading frequency and numbers of cycles have a big impact on the resulting deformations. [1]

With cyclic stress-levels exceeding about 60 %, the range of usual fatigue loading is reached. Here, strains occurring are usually attributed to ongoing degradation of the concrete due to micro-cracking. Viscous deformations are neglected in fatigue due to the rather short time of loading which is usually shorter than three days [4]. Fatigue tests are often evaluated either choosing development of strain or development of stiffness as damage-indicator [5–9].

In this paper, an approach is outlined to differentiate viscous strains from strains being induced by micro-cracking. It is shown that the development of stiffness is a suitable parameter to identify damage-induced parts of strain.

2.2 Estimation of creep strains

When referring to basic creep, typically lower stress-levels in the range of the serviceability are used. This is lower than approximately 45 % ($S_{max} \leq 0.45$) of the characteristic compressive strength of concrete. For modelling of this viscous strain, approaches basing on rheological models are often applied [2,3,10–12]. As can be seen from Eq. (1), the creep strain ε_{cc} is determined by multiplication of the linear-elastic deformation with the time- and stress dependent creep coefficient $\varphi(t, t_0)$.

$$\varepsilon_{cc}(t, t_0) = \frac{\sigma_c(t_0)}{E_{ci}} \cdot \varphi(t, t_0) \qquad (1)$$

In Eq.(1) ε_{cc} equals the viscous creep strain, $\sigma_c(t_0)$ the stress, E_{ci} the modulus of elasticity at the time of loading and $\varphi(t, t_0)$ the creep coefficient.

In this project, shrinkage is not considered due to the preparation and sealed testing of the specimen. Therefore, all mentioned creep strains can be interpreted as basic creep, because drying out is not possible.

In literature, higher load-levels lead to non-linear deformations which are considered to be induced by micro-cracking and structural damage [13,14]. In diagrams that display the strain development during creep, strains are displayed over time, whereas in fatigue strains are typically displayed depending on the number of load-cycles (LC).

If stresses are increased to a level between 45 % and 65 % of the compressive strength, micro-cracking is supposed to occur even in constant creep resulting in higher deformations. E.g. Model Code 2010 [3] provides a factor $\varphi_\sigma(t, t_0)$ (see Eq. (2)) which is applied in Eq. (1) instead of the creep coefficient $\varphi(t, t_0)$. Other approaches are e.g. published by Dummer [15].

$$\varphi_\sigma(t, t_0) = \varphi(t, t_0) \cdot \exp[1.5 \cdot (S_{max} - 0.4)]$$

$$For\ 0.4 < S_{max} \leq 0.6 \quad (2)$$

$$S_{max} = |\sigma_{c,max}| / f_{cm}(t_0) \quad (3)$$

Equation (2) is the modified term from the Model Code 2010 that takes the effect of high stresses in account. It uses the stress-level S_{max} as in [3] defined by Eq. (3) as the stress to strength ratio of the upper stress-level in case of fatigue or the constant stress in case of creep referred to the compressive strength at the time loading. In [3] the stress-strength ratio used with constant creep is originally named k_σ.

In conclusion it can be said, that for modelling of linear and non-linear creep deformations, viscous models are prevailing. Structural damage due to micro-cracking, which is primarily depending on the number of load-cycles is not considered.

2.3 Fatigue

Testing and description of fatigue performance and the development of degradation of the concrete is usually tested on stress-levels, leading to failure of the specimen depending on the number load cycles. This is in contrast to creep, where time-dependent curves are preferred.

Formerly, S/N-curves [16,17] which display the number of cycles to failure depending on the stress-level were the typical results of fatigue tests. Since the 1990s, interest not only in the number of cycles to failure, but also the development of damage started to grow e.g. [4,5,8,9,18]. For instance, Cornelissen and Reinhardt [19] found that the secondary creep rate (meaning the linear growth of strain between about 20 % to 80 % of the number of cycles to failure) is related to the number of cycles to failure. Hordijk [18] further was among the first to include effects such as moisture and submerged conditions.

Meanwhile, development of strain, stiffness (measured as a modulus of elasticity between maximum and minimum stress in one loading cycle), acoustic emission or ultra-sonic runtime are acknowledged means to describe damage evolution in concrete loaded in fatigue [20].

From the above mentioned it gets obvious, that for creep strains the focus are viscous strains. Usually they are used without structural damage, due to lower stress-levels. For fatigue, on the other hand, stress-levels are higher and the focus of degradation development shifts to meso-scale, which are induced by micro-cracking. Thus, viscous deformations are usually neglected in fatigue analysis.

However, in Model Code 2010 an estimation for deformations of concrete subjected to cyclic loading is proposed (Eq. (4)). A rheological model similar to creep estimation $\varphi(t, t_0)$ is chosen. It is further assumed that the relevant stress-level is the mean stress-level S_{mean}. It is shown in [21] that Eq. (4) underestimates basic creep. Creep induced by cyclic loads nearly reaches the strains of creep on the upper stress-level (S_{max}).

$$\varepsilon_{cf}(n) = \frac{\sigma_{c,max}}{E_{ci}(t_0)} + \frac{\sigma_{mean}}{E_{ci}} \cdot \varphi(t, t_0) \quad (4)$$

(fib Model Code 2010 [3], 5.1-114 (modified))

For purely viscous creep functions Eq. (4) should only be used for stresses corresponding to serviceability. Therefore, in this paper an approach is outlined to detect and describe strains induced by structural damage using the development of stiffness.

3 MATERIALS AND METHODS

3.1 Geometry and material properties

The compression tests were carried out on cylindrical specimens with about 60 mm in diameter and 180 mm in height. The concrete, classified as C25/30, is composed of 290 kg/m³ CEM I 42.5 R with a relatively high w/c-ratio of 0.7 to ensure the desired low strength. In addition, a pronounced capillary pore system is required for another part of the project investigating effects of hygric cycles on creep [22]. The aggregates consist of 55 % coarse quarzitic aggregate with a maximum grain size of 8 mm and 45 % quartz sand. Quartz powder, superplasticizer and stabilizer are used in small quantities. Within the first 180 days after casting the compressive strength (28 d, 180 d, 360 d) and Young's modulus are determined experimentally.

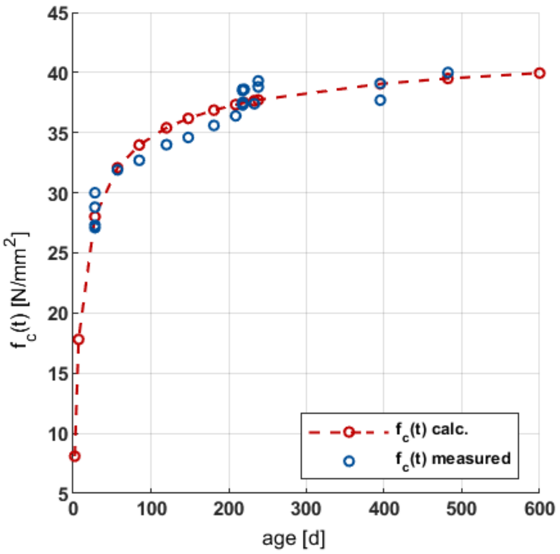

Figure 1: development of the compressive strength exemplarily given for batch 5 on cylindrical specimens

Additionally, further compressive strength and Young's modulus tests were carried out parallel to the test program allowing to estimate the actual compressive strength on the day of loading (see Figure 1). Afterwards, full stress up to S_{max} is applied within the first load-cycle. In this paper, tests at stress-levels between 0.35 and 0.65 are presented and discussed. In the research program further tests on e.g. different stress or moisture levels were made and are described in [21]. Strains are measured using three LVDTs oriented longitudinally, spaced evenly at 120° and attached outside the specimen on an aluminum ring. The data acquisition rate is at least 100 times the loading rate.

3.3 Calculation of strains and development of stiffness

The gathered data are carefully filtered and processed to keep the relevant information. The measured total deformations used to calculate the strains are the mean values of all three LVDTs. To calculate viscous strains from the measured total strains, the elastic strain components are subtracted. In case of creep tests, the elastic strain when first reaching the creep-stress in chosen. In case of cyclic creep, the elastic strain when first reaching the upper stress-level in taken.

The stiffness needs to be calculated from the total strain (including elastic and viscous components). Following approaches as reported in literature [5,6] the unloading branch of a load-cycle is used. That means, stresses and strains from a maximum and the following minimum are applied. $E_{cycl}(t)$ respectively $E_{cycl}(n)$ are the current stiffnesses calculated as the ratio between the differences of stress and strain in one loading cycle. Therefore, using the stiffness reduces the impact of temperature changes on the curves. The initial stiffnesses $E_{cycl}(t_0)$ and $E_{cycl}(n_0)$ are the first values taken from smoothed datasets. Smoothing is needed, because the first cycles can produce stiffness values with high scatter and inaccuracies.

4 RESULTS AND DISCUSSION

4.1 Development of strain

In the following Figure 2, development of strains is plotted against the loading duration typically for stress-levels of 0.55 and 0.35. It can be seen, that strains induced by constant creep loading are higher than strains measured in cyclic loading, regardless the loading frequency. This result is in accordance with the findings for lower stress-levels as described by [21]. As described in section 2.2 and Eq. (4) Model Code 2010 assumes that cyclic creep strains are induced by the mean stress-level S_{mean}. Figure 2 displays that the cyclic strains are only little lower than strains induced by a stress-level of S_{max}. Therefore, strains induced by cyclic loading should be calculated by applying the upper stress-level instead of the mean stress-level as mentioned in Model Code 2010.

In Figure 2 for the upper load-level of S_{max} = 0.55 it can be seen, that the loading frequency affects the strain development. Measured strains are higher for higher loading frequency of 1 Hz (stars). This result was also reported for other loading-levels and frequencies [1,21].

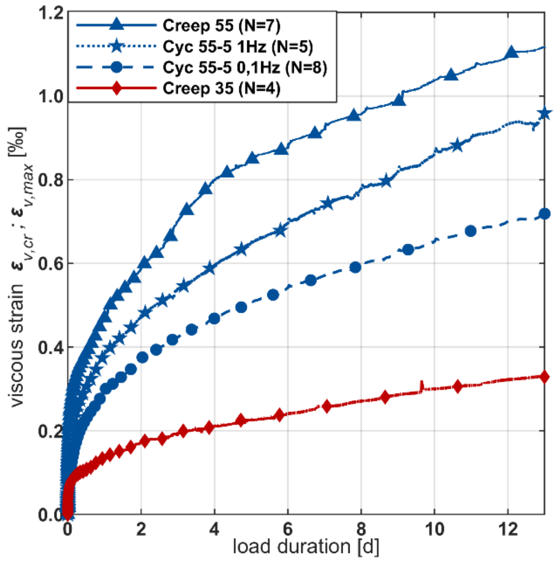

Figure 2: viscous strains due to constant creep and cyclic loading

As previously mentioned, measured strains comprise of different parts: viscous strains (in this case including visco-elastic strains) and strains induced by structural damage and micro-cracking. Micro-cracking itself can be macroscopically detected in a degradation of stiffness. As described in section 2 an evaluation in terms of creep must plot the stiffness over time (see the following section 4.2). In contrast, evaluation in terms of fatigue must plot it against number of load-cycles (see section 4.3).

4.2 Development of stiffness over load duration

In

Figure **3** development of stiffness is shown for cyclic tests in the load range of S_{max} = 0.35 - S_{max} = 0.65 with the associated lower stress-level of 0.05 referred to the compressive strength at the time of loading. Each line is the mean value of several specimens.

Figure **3** represents the stiffness plotted against loading duration and thus the conventional view from creep. As expected, at the beginning of loading a kind of compaction of the concrete is visible, resulting in a decrease in stiffness of about 5 % to 10 %. This effect is well known in fatigue as well as creep testing not only in terms of stiffness but also in terms of strain. Afterwards, in the secondary creep phase different behavior occurs. For loading-levels of less than 0.45, stiffness seems to partly recover. For the upper stress-level of 0.45 stiffness consolidates. To the authors opinion these effects prove that no micro-cracking occurs in the matrix. Therefore, these stress-levels are in range of linear creep respectively linear-cyclic creep. Similar results are published by [21] for upper stress-levels between 0.25 and 0.45. It should further be noticed, that the consolidation of stiffness does not mean that no further strain occurs. The stiffness only represents the elastic and to a very little extent visco-elastic strain. Viscous creep strains develop simultaneously, but they do not affect the stiffness.

For stress-levels of 0.55 and 0.65 represented in blue and green lines in

Figure **3**, an ongoing degradation of stiffness is found. This effect is assumed to be related to micro-cracking in the matrix, regardless the loading frequency. As a further point, the effect of loading frequency can be compared. In

Figure **3** the higher loading frequency of 1 Hz shows little lower stiffnesses compared to the loading frequency of 0.1 Hz. This reduction ranges between 2 % and about 5 % This effect was also shown by [21] for lower stress-levels.

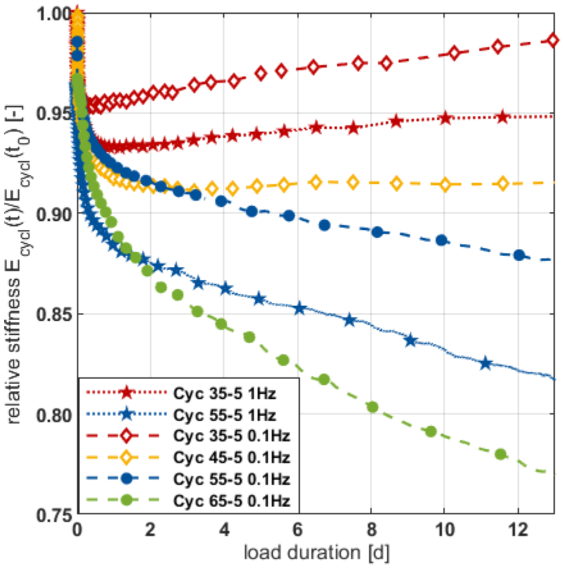

Figure 3: mean relative stiffness plotted against the duration of loading. Upper stress-levels range from 0.35 to 0.65, lower stress is 0.05. Loading-frequencies are 0.1 Hz and 1 Hz

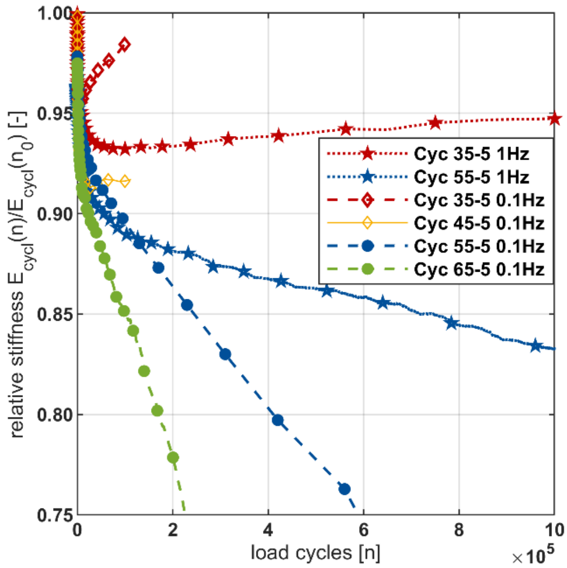

Figure 4: mean relative stiffness plotted against load-cycles. Upper stress-levels range from 0.35 to 0.65, lower stress is 0.05. Loading-frequencies are 0.1 Hz and 1 Hz

To sum up, the measured stiffnesses seem to confirm, that specimens loaded up to stress-levels of about 0.45 do not exhibit micro-cracking. Thus, the usual assumption, that linear creep strain is purely viscous, can be confirmed. For higher stress-levels, stiffness development enables us to quantify strains attributed to structural damage. In a second step, these strains can be quantitatively added to viscous strains.

4.3 Development of stiffness over cycles

In Figure 4 the same stiffnesses as displayed in section 4.2 are plotted, but now against the number of load-cycles. Thus, the lines for a loading frequency 0.1 Hz are significantly shorter compared to loading at 1 Hz. This graph is the usual way of displaying results from fatigue tests. The degradation of stiffness plotted against the number of cycles to failure provides a different view for the stress-level S_{max} = 0.55. While the initial slope of the load frequency at 1 Hz (blue stars) is steeper, the slope decreases compared to the lower frequency of 0.1 Hz (blue dots). Thus, a higher loading frequency shows a visibly lower degradation rate.

In Figure 3 where stiffness is plotted against time, the specimens loaded at 0.1 Hz seem to degrade little slower. This effect can also be seen in [1] where a higher load frequency results in a longer fatigue life and less damage. At the lower stress-level S_{max} = 0.35 this effect turns to the opposite as the lower loading frequency leads to an increasing gradient over load cycles.

For lower stress-levels of 0.35 and 0.45, again the consolidation of stiffness occurs. In contrast to

Figure 3 the lines are significantly shorter due to the low loading frequency.

This leads to the approach, that fatigue degradation can be estimated with knowledge of the stiffness development. If the relative stiffness stays constant in stage two, no further damage occurs.

It seems to be a useful approach to differentiate on the one hand consolidation of stiffness (representing no micro-cracking) and on the other hand continuous degradation using stiffness plotted over time. In order to further calculate strains attributed to cycling and micro-cracking the load-cycle based approaches seem to be more useful.

4.4 Comparison of results with non-linear creep functions

The results of the previous sections confirme that in linear creep respectively linear cyclic-creep only viscous strains occur. Generally, these strains can be estimated using Equation (1). As mentioned in section 4.1 the upper stress-levels needs to be inserted in case of cyclic loading. In this case the calculated results for cyclic-creep would overestimate the measured values. This is most probably due to less visco-elastic strains being accumulated throughout a test in cyclic creep compared to constant creep.

For non-linear stress-levels exceeding about 45 % of the compressive strength Equation (2) was proposed. The non-linear creep coefficient $\varphi_\sigma(t,t_0)$ not only depends on age of first loading and loading duration but also the creep stress-level. In the following Figure 5 two exemplarily chosen cyclic creep tests were approximated using Equation 2. It has to be mentioned, that larger differences occurred in the first days of loading between measured and calculated values. Therefore, the aim was to correctly estimate the gradient of total strain after about three days. The calculated strains were fixed to the measured total strain at three days of loading. The solid lines in Figure 5 are measured strains. The dotted lines are the estimated strain developments inserting the upper stress-level S_{max} in Equation (2). For both curves, the factor $\varphi_\sigma(t,t_0)$ is not high enough to reach the gradient of the measured curves. Therefore, a theoretical value S^*_{max} was calculated that fits the measured values best. For the measured curve with upper stress-level of 0.65 and lower stress-level 0.05 an S^*_{max} of 2.65 would be needed. For the curve with upper stress-level of 0.65 and lower stress-level 0.15 an S^*_{max} of 1.75 would be needed. Without considering the exact values, it gets clear, that Equation (2) cannot predict strains due to cyclic-creep in the non-linear stress region.

It should be mentioned, that Equation (2) is used here outside its application range, since the effect of high stresses is only described for static creep. Using equation for cyclic creep, it shall only be seen as a comparison to the

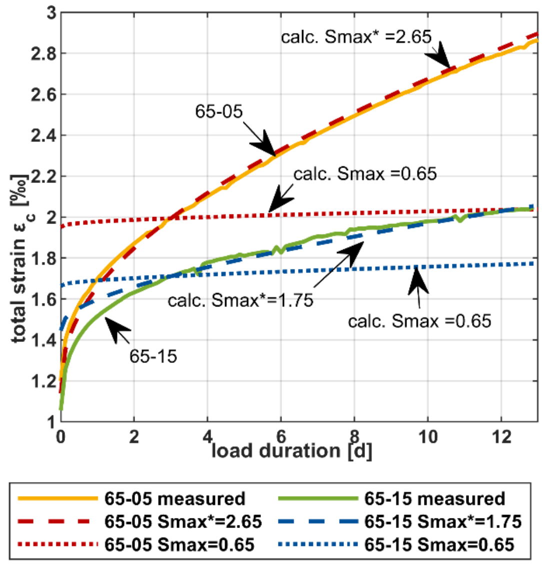

Figure 5: comparison of slopes in strain of exemplary specimen (S_{max}–S_{min} and calc. devt. of strain hinged at measured maximum total strain value of day 3)

progression of a creep specimen with the same upper load-level.

The measured lines in Figure 5 confirm, that cannot describe strain development properly, even if $\varphi(t,t_0)$ was replaced by a suitable non-linear factor $\varphi_\sigma(t,t_0)$.

With the higher σ_{mean}, which directly influences the slope of the strain development in Equation (4), higher total strains could be expected for the latter test. Conversely, the test with the lower σ_{mean} (0.65-0.05) shows higher strains and a higher increase in strain over time. This could be due to the fact that the amplitude and therefore the degradation of the stress is higher. This again shows that for non-linear creep and non-linear cyclic creep damage, induced strains must be treated separately from viscous components.

In future, a new approach is needed in the transition region from linear creep loading to non-linear creep and fatigue. It needs to take the following thoughts into account:

- Viscous strains develop over time, with decreasing gradient.
- Plastic strains caused by micro-cracking develop linearly with the number of cycles increasing. Therefore, the multiplicative approach of

Model Code 2010 [3] and Eq. (2) cannot be suitable.

- To extract damage induced strains from measured curves, development of stiffness can be applied using Equation (5):

$$\varepsilon_{pl,damage}(t_i,t_0)=\frac{S_{max}\cdot f_{cm}(t_i)}{E_{ci}(t_i)-E_{ci}(t_0)} \qquad (5)$$

- However, to calculate the total strain, viscous strains and damage induced strains need to have the same basis (time-wise or LC-wise). Therefore, $E_{ci}(t_i)$ and $E_{ci}(t_0)$ are given in time-scale in Eq. (5). Using the loading frequency, number of loading cycles and loading duration are directly interconnected.
- As described in section 4, additional effects on the development of stiffness such as the loading frequency have to be accounted for. It is further shown in [21,22], that the moisture content and changes in moisture of the concrete has to be considered.

5 SUMMARY AND CONCLUSIONS

In this contribution, a series of creep-tests is compared to cyclic-creep tests at comparable stress-levels. The focus are the stress-levels in the transition from linear creep (below about 45 % of the compressive strength) to non-linear creep and fatigue. These tests are part of a larger joint research project between the Leibniz University Hannover and the University of Wuppertal.

It is firstly shown, that the estimation of strains induced by cyclic loading of Model Code 2010 significantly underestimates the measured values. This is due to the mean stress-level being applied as relevant stress-level. In contrast, the tests show measured strains being only little lower than creep at upper stress-level S_{max}.

It has been shown, that using the non-linear creep coefficient φ_σ of Model Code 2010 does not estimate the strains in non-linear cyclic creep properly. Measured strains are significantly underestimated. Therefore, the development of stiffness throughout cyclic tests is proposed to differentiate between viscous strains and strains induced by structural damage. For stress-levels below 0.45 of the compressive strength, the stiffness initially decreases in a range between 5 % and 10 %. Afterwards it stabilizes at this level or even regains some percent. This confirms that no micro-cracking occurs, strains are purely viscous.

For stress-levels of 0.55 and higher a continuous decrease in stiffness is found. This indicates an ongoing micro-cracking resulting in structural damage. This damage can be quantified using the stiffness reduction.

Finally, an approach is outlined to extract strains induced by micro-cracking from the total measured strain, using the stiffness development. In future, this enables an additive combination of viscous strains on the basis of usual multiplicative models and damage induced strain in a model accounting for the different characteristics of the deformation mechanisms.

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