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# Effects of Concrete Creep Under Repeated Stresses Superposed on Sustained Stresses

Effets du fluage de béton sous contraintes répétées, superposées aux contraintes permanentes

Betonkriechen infolge Wechsellastungen überlagert mit Dauerspannungen

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It is a well-known fact that the repeated loading of concrete causes irreversible deformations /3/-/7/ called cyclic creep. The experimental knowledge of this phenomenon is still rather limited but yet sufficient for an approximate analysis. No consideration of this effect, however, is required by the actual building codes.

The purpose of the present discussion is to outline briefly the possible effects of cyclic creep and to show that they can become important, particularly with regard to the deflections of very slender prestressed concrete bridges of great span.

The cyclic creep is a nonlinear phenomenon since the principle of superposition in time /2/,/4/ is no longer valid. In the

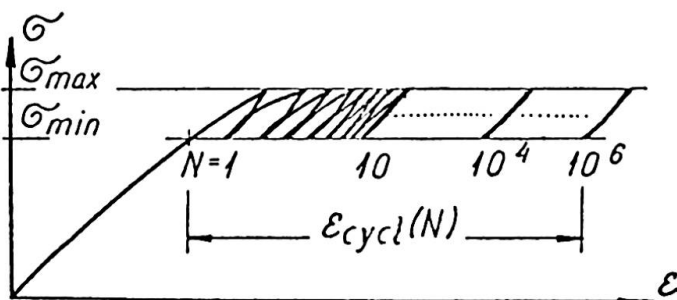


Fig. 1

range of working stresses, however, the final total inelastic deformation caused by compressive stress oscillating between the two limits  $\sigma_{\max}$  and  $\sigma_{\min}$  (Fig. 1) varies almost linearly with  $\sigma_{\max}$ , whereas

the difference  $\sigma_{\max} - \sigma_{\min}$  has little influence and primarily affects the rate of this deformation [3], [5]. The irreversible deformation accumulates with the number of cycles,  $N$ , and after about  $10^6$  cycles the creep achieves approximately the value of the final creep deformation which would appear, after several years, under constant sustained stress  $\sigma = \sigma_{\max}$ . The cyclic creep and the creep under sustained stress are non-additive, e.g., if the concrete is first subjected to a sustained compression  $\sigma_1$  for several years, and then this compression replaced by a subsequent cyclic compression with  $\sigma_{\max} = \sigma_1$ , almost no additional irreversible deformation is produced [7]. This property suggests that the cyclic creep is the same phenomenon as the creep under sustained stress and may thus be regarded as an accelerated creep.

The total stress  $\sigma$  in a structure may be divided into two components; a sustained stress  $\sigma_g$ , due to permanent load and prestressing, and a variable stress  $\sigma_{\text{cycl}} = \sigma - \sigma_g$  due to live loads, oscillating between two limits  $\sigma_{\min}$  and  $\sigma_{\max}$ . The effect of creep  $\epsilon_{\text{cr}}$  due to the sustained stress  $\sigma_g$  may be computed separately, using well-known methods. Therefore we are interested only in the creep  $\epsilon_{\text{cycl}}$  due to the cyclic component  $\sigma_{\text{cycl}}$ . This separation which simplified the analysis, is permissible because of the forementioned linearity with respect to  $\sigma_{\max}$ . The additional irreversible strain caused by  $\sigma_{\text{cycl}}$  may be expressed as

$$\epsilon_{\text{cycl}} = \psi(N) \epsilon_{\text{el}} = \psi(N) \frac{\sigma_{\max} - \sigma_g}{E} \quad (1)$$

where  $\epsilon_{\text{cycl}}$  is the instantaneous elastic deformation due to the stress component  $\max \sigma_{\text{cycl}} = \sigma_{\max} - \sigma_g$ ,  $E$  denotes the corresponding elastic modulus and  $\psi$  is the cyclic creep factor which is a function of the number of cycles  $N$ . It is also a function of the ratio  $\sigma_{\min}/\sigma_{\max}$ , the frequency  $f$ , the age of concrete  $\tau$ , the form of the stress-time curve in a cycle and possibly many other phenomena. As a first approximate, for  $N = 10^6$  cycles we may assume  $\psi = \Phi$  where  $\Phi$  represents the sustained creep factor for a period of several years.

In concrete members subjected to a longitudinal cyclic compressive force of small eccentricity, such that the component  $\sigma - \sigma_g$  (as well as  $\sigma_g$ ) is compressive throughout the entire

cross-section, the irreversible deformation  $w_{cycl}$  of the member (e.g., its deflection) is again related to the instantaneous elastic deformation  $w_{el}$  (according to the equation)  $w_{cycl} = \psi w_{el}$ .

On the other hand, in members subjected to cyclic bending or cyclic longitudinal compression of great eccentricity, such that the component  $\sigma - \sigma_g$  is tensile in one part of the cross section while the total stress  $\sigma$  is compressive throughout the entire cross-section, the bending curvature and deflection is less than, and the shortening of the member axis is greater than, the value indicated by the factor  $\psi$ . This is caused by the fact that  $\epsilon_{cycl}$  is almost totally independent of  $\sigma_{min}$  but essentially dependent upon  $\sigma_{max}$ , so that on one side of the neutral axis of the stresses  $\sigma_{cycl}$  in the cross section, the maximum compressions  $\sigma_{max}$  correspond to the live load maxima  $P_{max}$ , whereas at the other side of the neutral axis  $\sigma_{max}$  corresponds to the live load minima  $P_{min}$ . If  $P_{min}$  is equal to the sustained component  $P_g$ , then on one side of the neutral axis  $\sigma_{max}$  will equal  $\sigma_g$  and because of the introduction of the cyclic component it is necessary that we assume  $\epsilon_{cycl} = 0$  in this part of the cross section. In effect, the creep, due to the sustained stress

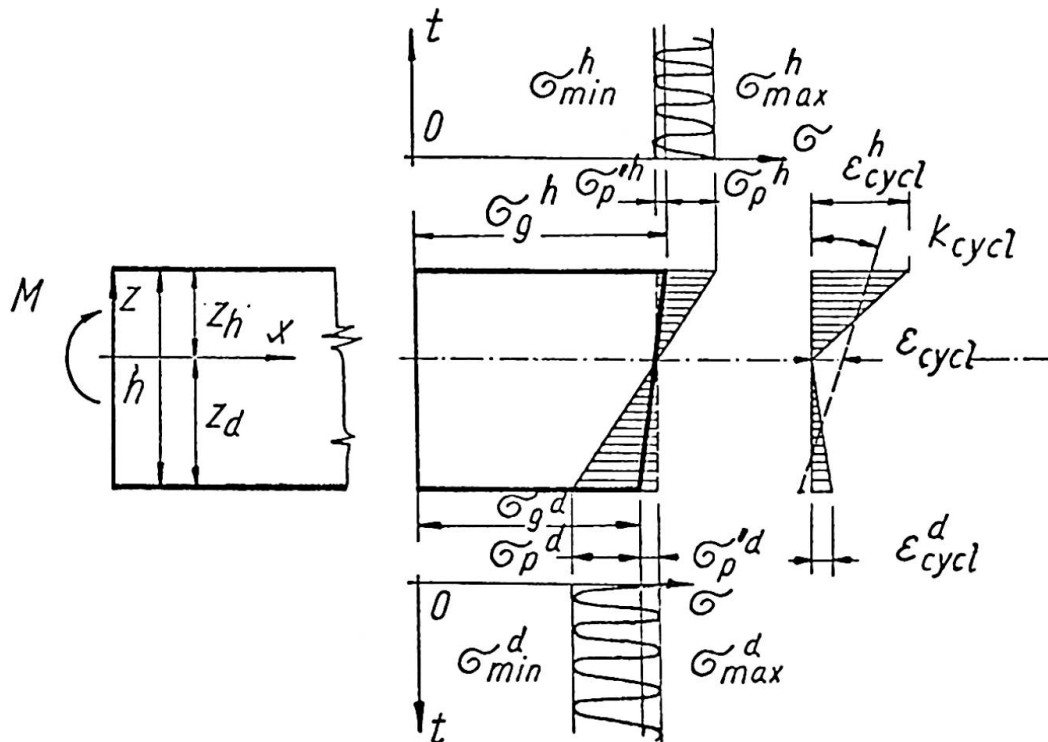


Fig. 2

$\sigma_g$ , which is to be considered in the analysis of the effects of permanent loads, is now accelerated by cyclic load, but its final value may be supposed to be unaffected.

As a consequence of this, in the case of cyclic bending or cyclic compression of great eccentricity, the distribution of the cyclic creep deformation throughout the cross-section would be nonlinear (see Fig. 2). Because the cross-section must remain plane (provided the beam depth-to-span ratio is small enough), a re-distribution of internal forces takes place /1/. The analysis can be performed in a similar way as the analysis of a nonlinear temperature distribution throughout the cross-section or differential shrinkage in composite beams. (For the detailed formulae, using the effective modulus  $E_{ef} = E/(1+\psi)$ , see /1/.)

The practical analysis of one typical cross-section of a prestressed concrete bridge box girder /1/ yielded the value  $w_{cycl} = 0.55 \psi w_{el}$  for irreversible deflection due to live load.

In a member of symmetric cross-section subjected to both a sustained axial compression and a cyclic bending moment which oscillates between equal values of opposite sign, it is found that only an axial shortening results, with no bending being caused by the cyclic load.

A questionable point in practical bridge analysis is what magnitude of the cyclic load component ought to be actually considered. In the analysis of one bridge with two main spans of 102m (at Dolní Kralovice, over the Želívka river, in Czechoslovakia) cast by the cantilever method and with articulations in the midspans, it was assumed that during the service life the vehicles will cause  $2 \times 10^6$  cycles of the magnitude of 1/3 of the total live load prescribed by the code; 10 cycles up to 2/3 of this live load and one cycle of the full live load, (i.e., the loading test). The magnitude of the creep deflections due to vehicles was thus found to be 5.7 cm.

This result may partly explain the excessive deflections observed at many bridges of this type built in the past.

For comparison, some other effects which contribute to excessive deflections should also be quoted /1/:

1. If the prestressing force has, because of greater losses of prestressing, a value 10% lower than assumed, the deflection of the forementioned bridge would be increased by 4.9 cm.
2. The fact that the upper plate of a box cross-section is sealed at the upper face against moisture losses (and often has a different thickness) results in about 3.0 cm of additional deflection.
3. The additional negative bending moments due to the compression force, induced in the bridge floor by the creep shortening of the upper fibres of the girder under prestress, cause an additional deflection of 1.9 cm.
4. Shear deformations give deflection of 0.5 cm. The total difference with respect to the usual analysis of deflections achieves a substantial value of 16 cm. These effects (except point 4), however, practically vanish in frame bridges of about constant beam depth and without articulations at midspan. Therefore this type of structure should be considered as less susceptible to large deflections and should be preferred.

Other effects of creep under cyclic stress are the changes in the statically indeterminate internal forces, the redistribution of stresses between the reinforcement and the concrete and the re-distribution of the compressive stresses in the prestressed cross-section in concrete itself. This last effect results in an increase of the compressive stress in the core of the cross-section and a decrease near the faces.

Similar effects also appear in tall concrete buildings due to wind loads.

For a more exact analysis of the effect of cyclic creep further experimental research is of prime importance.

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## SUMMARY

The effects of cyclic creep of concrete are briefly discussed and a method of their analysis suggested, in which the irreversible deformations due to cyclic stresses are separated from the deformations due to sustained stresses. The influence upon deflections of prestressed concrete bridges may be substantial.

## RÉSUMÉ

Les effets du fluage sous charge répétée sont étudiés et une méthode de calcul proposée, dans laquelle les déformations irréversibles dues aux contraintes répétées sont séparées de celles dues aux contraintes permanentes. L'influence à la flèche des ponts en béton précontraint peut être considérable.

## ZUSAMMENFASSUNG

Der Einfluss des Schwingkriechens von Beton wird untersucht und eine Berechnungsmethode entworfen, bei welcher die irreversiblen Verformungen unter zyklischen Spannungen von den Verformungen unter dauernden Spannungen geteilt werden. Die durch Schwingkriechen verursachten Durchbiegungen können eine bedeutsame Grösse erreichen.