Effect of plasticity of concrete and steel on the stability and endurance of reinforced concrete

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Effect of Plasticity of Concrete and Steel on the Stability and Endurance of Reinforced Concrete.

Der Einfluß der Plastizität des Betons und des Stahles auf Stabilität und Dauerhaftigkeit des Eisenbetons.

Rôle de la plasticité du béton et de l'acier sur la stabilité et la durée du béton armé.

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Before investigating how the endurance of structures is affected by the plasticity of their materials — particularly as regards reinforced concrete — it may be well to consider exactly what is meant by "plasticity" and what influence this property has on variations in stress. In an earlier paper the author has attempted, by means of a simple mathematical theory, to show that the magnitude of elastic and plastic strains depends not only on the momentary load but also on antecedent conditions other than loading. The theory cannot pretend to finality, but consists merely of a series of syllogisms which derive from certain simple experimental premises and which lead to conclusions that are difficult to establish experimentally.

If a sample of steel be subjected to a load in excess of its elastic limit the steel will suffer a permanent deformation and if the load remains constant the deformation will continue to increase, to a greater or less extent, with the passage of time, according to a law of creep which depends on the quality of the steel and on the temperature. This creep, while extremely small in the case of loads close to the creep limit, is nevertheless not zero. If the load fluctuates between two definite limits the permanent deformation grows very appreciably in course of time, and if the upper limit of the varying load exceeds the critical fatigue load (or natural limit of elasticity as defined by *Bauschinger*) this phenomenon takes place even below the limit of elasticity (yield point]: it is the result of an exchange of energy which arises from the elastic and plastic hysteresis between the elastic and plastic strains. A rapidly applied load may, therefore, produce contrary effects according to its mode of application: thus a single shock may cause diminution of the plasticity, whereas repeated loading, sustained vibration or slowly applied loads may bring about an increase in this quality.

The practical importance of this phenomenon appears when alternating or pulsating loads are applied to reinforced concrete members which have been pre-stressed in accordance with the system of *Freyssinet.* When this occurs the steel bars may be observed gradually to extend, and at the same time the pre-imposed compression in the concrete is reduced; in certain cases, where the amount of the pre-stressing is small by comparison with the load applied, cracks may appear in the concrete under tension. The destructive effects produced by the repeated loadings on the steel bars becomes greater in proportion as the bars are irregular, embrittled or rusted; and the fatigue limit is much lower for the hook at the end of a bar than for the straight portion.

There appears to be no method, other than experiment, of determining the stress-strain curve for a sample of concrete beforehand, for this material has no fixed elastic limit; the latter varies according to age and depends on the rate at which loads are applied. Everything which has been said above regarding the plasticity of steel is applicable even more strongly to concrete. The constants of hysteresis which define the plastic and elastic viscosity are small, and the amount of such hysteresis large. Hence, in calculations relating to reinforced concrete, the concept of a "coefficient of elasticity" has no meaning unless it is associated with constants which define the conditions of plasticity, creep and hysteresis. That is why agreement has never been reached as to the proper value for the modular ratio m.

The effect of accelerated creep under repeated loading is found also in concrete, to a very high degree. The phenomenon of plastic creep is attended by phenomena of irreversible friction; these are additive, and tend to hasten adaptation because of the effect of bond on the elastic strain, to which the author has referred in his earlier paper.[1] Moreover this process of adaptation is associated with all those factors which usually accompany ageing: increased stiffness, increased strength, and reduced shrinkage, etc. The concrete is liable to exhibit all those phenomena of fatigue after repeated loading which occur in the metal. For instance, a concrete which has a breaking strength of 350 kg per sq. cm and is subjected to loads varying 500 times a minute between 50 and 300 kg will break at the end of one hour; during this time its modulus of elasticity will have changed and the length of the specimen will have decreased. For any such specimen there is a fatigue limit which determines the pulsating load that will cause breakage after a limited number of alternations; but below this limit, on the other hand, the effect of repeated loading is to bring about an increase in the statical strength.

A number of experiments on the behaviour of bent beams subjected to repeated loads have been carried out in the laboratoires[2] in Paris to which the author is attached, and it has been observed that even in these cases there exists a characteristic fatigue limit, so that by making successive experiments on a series of similar beams it becomes possible to construct a *Wöhler* curve in which the first limb is much more steeply inclined than would be the case for concrete or steel by itself. Finally, it has been noticed that the principal effect produced by successive loadings was to accelerate the occurence of plastic strain, and it has been possible to devise a method of accelerated experiment for the study of the adaptation that takes place in a reinforced concrete member under load, the effects

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[1] See Theme I.

[2] Laboratoires du Bâtiment et des Travaux Publics.

of the repeated loadings being practically equivalent to an artifical ageing of the work in question. This has led to the observation that adaptation does not take place equally in the parts under tension and those under compression. Again, it appears that the fatigue limit in relation to the static breaking load is much lower for concrete in tension than for concrete in compression. Account must also be taken of those mutual forces between steel and concrete which constitute the bond: the experiments go to show that bond is very sensitive to repeated loadings, and a large number of beams failed through slipping of the bars, probably because the latter had been unable to adapt themselves to the deformations caused by plasticity. In yet other cases the stabilisation of the bar, after its first slip, brought about a considerable degree of cracking in the concrete without actually leading to failure of the member.

The upshot of these considerations is that any attempt to calculate the strain in a piece of concrete by referenec to elementary data must be a very complex matter, and can, in the present state of our knowledge, be attempted only as a rough approximation. When all is said and done, the scope for the occurrence of adaptation appears very great, and however rough this approximation may be its effect is to suggest that when the earliest designers of reinforced concrete introduced the idea of partial continuity they came nearer to the truth than do all the hyperstatical calculations which have since been developed.