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Autor: Coyne, M.

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Tests on the Slow Buckling of Concrete Sticks.

Versuche über das langsame Knicken an Betonkörpern.

Essais de flambement lent de baguettes en béton.

M. Coyne,
Ingénieur en Chef des Ponts et Chaussées, Paris

When a prism-shaped body is loaded at the end its condition is one of unstable equilibrium if the load equals or exceeds the limit given by *Euler*'s expression $\frac{\pi^2 E I}{l^2}$.

The mechanism of buckling can in fact be visualised as follows: any slight eccentricity of the load gives rise to a bending moment which causes an initial deformation, this deformation has the effect of increasing that moment so as to cause a second deformation, and so on. If the deformations thus obtained constitute a divergent series the piece buckles. This is the meaning of *Euler*'s equation, which further implies that the limit of stability is independent of the amount of initial eccentricity.

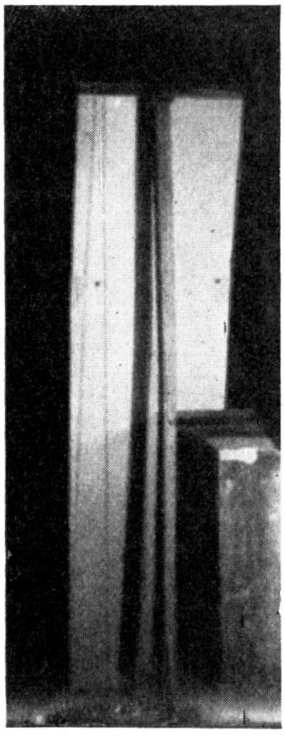

Fig. 1.
Photograph showing the deflection assumed by a test bar 135 · 3 · 3 cm the day before its collapse.

According to the customary rules governing the strength of materials these deformations occur immediately the load is applied, and as a corollary to this the series of phenomena described below take place almost instantaneously, and fracture occurs suddenly without any warning.

Concrete, however, behaves in a different way: the initial deformation is almost instantaneous, but its subsequent growth is slow. There exists, therefore, an *a priori* possibility that under certain values of load the piece may assume a condition of stable equilibrium under the action of the first deformation, and that it is the subsequent of slow deformations which constitutes the divergent series characteristic of buckling. In other words, the reasoning on which *Euler's* formula is based is independent of time, and what takes place is exactly as if the modulus of elasticity E were to decrease as the stress and its duration increased. In order, then, to arrive at the true criterion of buckling, it becomes necessary to introduce the final value of E into *Euler's* formula.

It was thought that the matter might be illustrated in a particularly striking way if it could be reproduced in the laboratory, and attempts were accordingly made to bring about slow buckling in concrete pieces. These pieces took the form of sticks measuring 135 cm by 3 cm by 3 cm, made from fine gravel concrete using 350 kg per cu. m of "superciment" or of aluminous cement (Photograph N° 1). The sticks were loaded by means of a lever-operated press, and the results are given in the following table:

No. of Specimen	Kind of Cement	Age of Concrete when tested (days)	Strength of concrete as measured on 20 cm cubes (kg per sq. cm)	Load Applied kg	Load Applied kg per sq. cm	Results of Tests	Deflection	Modulus of elasticity as calculated from buckling
1	Artificial	130	260	780	86	Instantaneous buckling		210.000
2	do.	130		580	64	A deformation begins to occur, but after 6 days shows no perceptible further increase; the load is then increased:		
				650	72	Buckling at 14 days	3 mm	175.000
3	Superciment	19		1120	124	Instantaneous buckling		300.000
4	do.	19		720	80	Buckling after 15 minutes		195.000
5	Aluminous	3	430 at 3 days	1520	170	Instantaneous buckling		410.000
6	do.	8		1070	118	Buckling after 5 days	4 mm	290.000
7	Aluminous	4	360 at 4 days	1140	126	Instantaneous buckling		310.000
8	do.	4		960	106	do.		260.000
9	do.	4		900	100	do.		240.000
10	do.	4		780	86	Buckling after 5 minutes		210.000
11	do.	5		650	72	Buckling after 7 days	3 mm	175.000

It was found that the piece sometimes broke at once and sometimes resisted the load indefinitely, but between these two extremes it was found possible, after a few attemps, to bring about the desired phenomenon in sticks Nos. 2 (second test) 4, 6, 10 and 11.

These experiments amount to no more than a first approach to the study of a problem which deserves closer attention, and however incomplete the results given above it seemed worth while to publish them as evidence of the existence of this phenomenon of slow buckling and as forming a broad outline of its nature.

It is impossible to lay too much emphasis on the danger that may arise, in practice, from this cause, and on the necessity for adopting a very low value of the modulus of elasticity in applying *Euler's* formula. At the same time, it should be observed that the deformation of a member placed in this condition of unstable equilibrium becomes apparent a short time after the load is applied and then increases progressively to a high value. Since, therefore, failure through slow buckling is preceded by these visible phenomena, it is less dangerous than failure by instantaneous buckling, though the actual occurrence of fracture is in fact equally sudden in both cases.