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A proposed improvement to the crushing test of concrete specimens

Irvin Luker

A method is proposed to determine from any compression test on a concrete specimen the strength that the specimen would have had if it had been tested in a 'perfect' machine capable of uniformly straining the specimen. The method requires the measurement of strains in the specimen and total load on it during the test. A parabolic curve is assumed to represent the stress-strain behaviour of the concrete when uniformly strained, and the form of the parabola is fixed from the strain and load measurements. The peak stress of the parabola is then the maximum strength that the specimen could have had if uniformly strained.

IRVIN LUKER graduated in civil engineering from Bristol University in 1969. After working at a consultancy and a local authority in England he emigrated to South Africa in 1971 where he was employed by Roberts Construction to work on site construction, soils investigation and structural design. In 1977 he enrolled at the University of the Witwatersrand to do research and was awarded a PhD for a thesis on soil anchors. His teaching and research interests are wide-ranging, and currently include concrete and the behaviour of laminated glass in bending.

INTRODUCTION

The practice of compression testing hardened specimens of representative samples of concrete stretches back into dim history. In this testing, the necessity for a freely rotating load-application platen on the testing machine to accommodate non-parallelism between the loaded faces of the specimen has long been appreciated, but it was only in 1954 (Tarrant) that it was realised that if this freedom of rotation persisted throughout the whole test, the maximum resistance force produced by a cube would in most cases be significantly reduced because of non-uniform straining.

The reduction is caused by some parts of the specimen reaching their maximum stress while others are still climbing towards their maximum or are falling away from theirs. The resulting average stress produces the maximum resistance force for the cube. Because of the inhomogeneity of concrete, even if all parts of a specimen were uniformly strained in compression, there would still be non-uniform compressive stress. However, if a platen is able to rotate in the latter stages of a test, or if other instability of machine components also cause non-uniform straining, then the average stress at maximum load on the cube will be reduced.

A solution to this problem which was proposed by Foote (1970), and adopted into a national standard (BSI 1983), was to use a strain-gauged steel cylinder to check the platen's initial rotational freedom and the stability under load of the whole testing machine.

With improvements since then in instrumentation and computing power, it is now proposed to improve the compression test of concrete by including the measurement of strain on four sides of the specimen throughout the test, and to automatically interpret the results in the manner described in the following section.

INTERPRETATION OF STRAIN MEASUREMENTS

The objective of the interpretation is to obtain a value for the strength of a concrete specimen that can be said to be the strength that it would have had if it had been uniformly strained throughout the compression test.

If such a uniform strain test could be done, the graph of average stress against known strain for a specimen could be drawn. An assumption of the shape of this graph needs to be made for the interpretation of the strains from a real test. For reasons explained in appendix A, a parabolic shape is assumed, having the equation:

$$\sigma = k[1 - (\varepsilon - h)^2/h^2] \qquad (1)$$

where h is the strain at which the peak stress k occurs. (Refer to figure 1.)

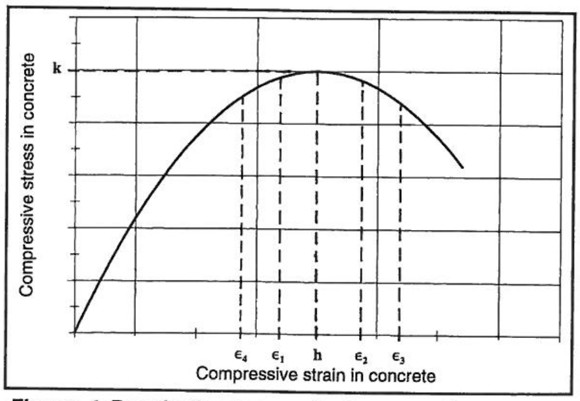

Figure 1 Parabolic stress-strain curve for concrete in compression with examples of measured strain values at peak load an the specimen

From measurements made during the test, the strains on four sides of the specimen at the point of maximum load on the specimen are determined. If it is assumed that each strain value is representative of one quarter of the specimen, and that a single parabolic stress-strain graph can adequately represent all parts of the specimen, then the stresses given by the parabolic function on all quarters at the instant of the maximum load resistance of the whole specimen can be calculated. Using these parabolic function stress values and the observed maximum load on the specimen, the peak value of the function and therefore the value of load that the specimen could carry if the peak function value occurred simultaneously across it (ie if it were uniformly strained at failure) can be found.

The procedure is as follows:

(i) Find the value of strain, h, where the peak of the concrete's parabolic-shaped stress-strain graph must occur to give the maximum mean value of the stresses corresponding to the four measured strains, ε_1 to ε_4. (Refer to figure 1.). This is given by:

$$h=(\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2+\varepsilon_4^2)/(\varepsilon_1+\varepsilon_2+\varepsilon_3+\varepsilon_4) \quad (2)$$

The derivation of equation 2 is given in appendix B.

(ii) The peak value k of the parabolic shaped stress-strain graph is then determined from the following equation:

$$k = 4 \times \sigma_{meas} / (f_1 + f_2 + f_3 + f_4) \quad (3)$$

Where: σ_{meas} = the actual maximum load on the specimen divided by its area.

f_1 to f_4 = values of the square bracketed term in equation 1 for each of the measured values of strain ε_1 to ε_4 at maximum load on the specimen.

The derivation of equation 3 is given in appendix C.

(iii) The theoretical maximum load that the specimen could have carried is then k multiplied by the area of the specimen.

EXAMPLES OF APPLICATION

Strains have been measured during compression tests in three machines and the results are presented in table 1.

Table 1 Results of analysis of concrete compression tests using the proposed theory

Type of machine	Specimen size	Compressive strength		Observed/Theoretical %
		Observed	Theoretical	
Machine A, 2 000 kN, universal compression testing m/c	150 cube	33,9	34,0	100
	150 cube	30,8	31,6	97
	150 cube	30,9	31,7	97
	150 cube	35,3	35,4	100
	100 cube	42,2	42,4	100
Machine B, 2 000 kN, dedicated concrete testing machine	100 cube	33,5	33,8	99
	100 cube	30,2	30,7	98
	100 cube	30,9	31,2	99
	100 cube	35,3	36,3	97
	100 cube	36,9	37,5	98
	100 cube	39,0	39,2	99
Machine C, 1 500 kN, hand-pump operated, dedicated concrete testing machine	100 cube	48,0	57,5	83
	100 cube	53,0	63,9	83

DISCUSSION AND CONCLUSIONS

Machine A is an old but very well-made machine which had come close to passing the strain cylinder test three years prior to the time the present compression tests were done.

Machine B is less than two years old, and had passed the strain cylinder test when new. It has not been assessed since.

Machine C is of a simple and inexpensive type. It is not expected to be of sufficiently high quality to pass the strain cylinder test, and has never been assessed with it.

The visual appearance of the specimens at crushing in machines A and B was of cracking appearing almost simultaneously on all four sides, whereas with machine C one side crushed first, distinctly before the one opposite to it.

The relative values of the ratio (observed strength:theoretical strength) seen in table 1 are consistent with what one might expect from a brief quality assessment of the three machines, and with the specimen behaviour in the test.

It is concluded that the measurement of strains during the concrete compression test and their interpretation using the theory proposed in this paper has the potential for enabling the result of a test done in any machine to be adjusted to the value the strength would have been if the specimen had been tested in an excellent quality testing machine.

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APPENDIX A: Choice of the shape of the stress-strain relationship for concrete in compression

The shape of the overall compressive stress-strain relationship for a concrete specimen is affected by rate of straining, value of peak strength, lateral restraint, types of constituents and uniformity of straining by the test machine. Published sources of stress-strain graphs (Rusch 1960, Barnard 1964, Sigvaldason 1964, Spooner & Dougill 1975, Ford *et al* 1981, Kyohiro Ikeda *et al* 1997, Lee & William 1997), despite variations between them in these factors, show very similar shapes up to the peak stress, but greater variation in the post peak region. For example, figure 2 shows the reported eight graphs of Barnard (1964) (where each line is the average of three tests and is normalised to a common peak point), which are typical of the test results reviewed. It can be seen that the rate of fall of the stress after the peak is less steep than the rate of rise before the peak, and there is significant variation in the post-peak slope.

Ideally, when interpreting a compression test result by the method proposed in this paper, the most likely shape of overall stress-strain relationship should be chosen for the specimen, having regard to the influencing factors mentioned here. However, it is suggested by the present author that this is impractical and that a single stress-strain graph shape must be chosen for interpretation of all concrete compression tests.

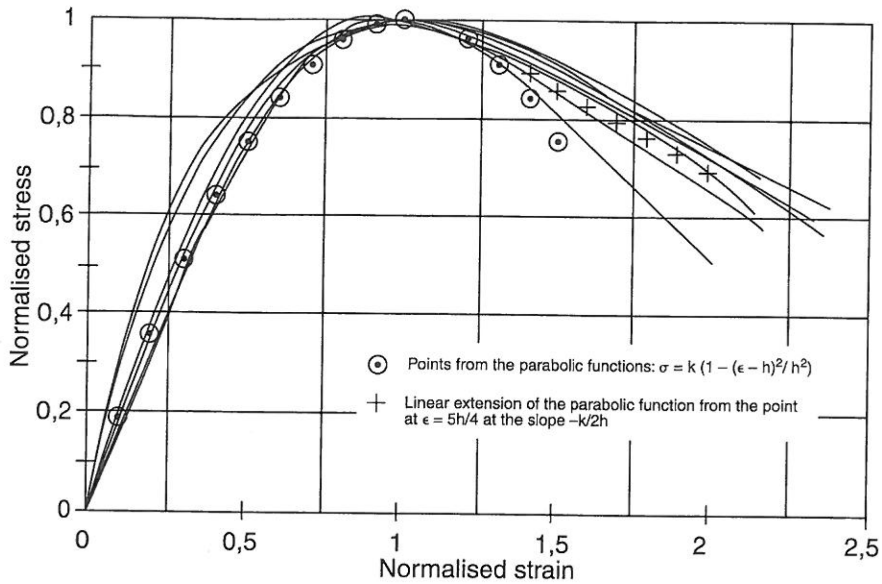

Figure 2 Measured stress-strain curves for concrete from Barnard1964, normalised to common peak points

Kemp (1998), after his review of curve shapes, chose a three-part graph consisting of a rising straight line, a power curve and a falling straight line. However, this would be inconvenient for the present purpose because the discontinuities between the parts increases the complexity of the calculations needed to use the shape to interpret a test result. The most convenient for the present purpose is the parabolic function: $\sigma = k[1 - (\varepsilon - h)^2/h^2]$, where k is the maximum height and h is the strain at maximum height. Points from this function are shown in figure 2, and it can be seen that it represents well the test results up to the peak, but it falls steeper than the test results after the peak.

The implication of this steeper fall of the parabolic function is that if the measured strains in a test are widely spread, the interpreted theoretical maximum stress from a test will be higher than if the assumed curve were flatter after the peak.

A possible compromise to improve the fit of the theoretical line to the test results is to use the parabola up to the point on the falling stress side where the slope is $-1/4$ of the initial slope at the origin, then to have a straight line thereafter at that slope. This is shown by crosses in figure A, starting from the point where the strain is 1,2h (h in figure 2 is 1). In the tests quoted in table 1, none of the measured strains at peak load on the specimens fell beyond this value of 1,2h, ie all points would have fallen on the parabolic part of a two-part graph.

It is therefore concluded that the two-part graph may not be necessary, and the parabola alone may be sufficient for the interpretation of test results. It is hoped that as further experience with the use of this interpretation is gained on a bigger variety of testing machines, the number of occurrences where measured strains fall beyond 1,2h will be noted and discussed.

APPENDIX B: Determination of the value of h in the parabolic stress-strain function for a concrete specimen: $\sigma = k\,[1 - (\varepsilon - h)^2/h^2]$

In figure 1, ε_1 to ε_4 are the measured strains on the four sides of a concrete specimen at the instant the maximum load on the specimen is reached. If it is assumed that each of the four stresses given by the parabolic function for each of these strains acts over one quarter of specimen, then the position of the peak of the parabola must be such as to give the maximum average value of the four stresses. Ie, the sum of σ_1 to σ_4 must be a maximum.

This sum S, is then given by:

$$S = k\,\{[1 - (\varepsilon_1 - h)^2/h^2] + [1 - (\varepsilon_2 - h)^2/h^2] + [1 - (\varepsilon_3 - h)^2/h^2] + [1 - (\varepsilon_4 - h)^2/h^2]\} \qquad \text{(B1)}$$

Setting the differential dS/dh equal to zero gives the following expression for the value of h giving the maximum sum, S:

$$h = (\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 + \varepsilon_4^2)/(\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4) \qquad \text{(B2)}$$

Note that the value of h is independent of the maximum height k of the curve.

APPENDIX C: Use of the parabolic stress-strain curve for a concrete specimen to determine its theoretical maximum strength

The theoretical maximum strength is the parameter k in the parabolic function shown in figure 1. Making the assumption stated in appendix B, the value of k must be such that the stresses σ_1 to σ_4, each acting on a quarter of the area of the specimen, give the measured maximum load on the specimen.

The parabolic function values (equation 1) for the four stresses can be written:

$$\sigma_1 = kf_1, \quad \sigma_2 = kf_2, \quad \sigma_3 = kf_3, \quad \sigma_4 = kf_4 \qquad \text{(C1)}$$

Where f1 to f4 are the values of the square-bracketed term in the parabolic function for each of the measured strain values.

The measured maximum load on the specimen, M, is then given by:

$$M = k\,(f_1 + f_2 + f_3 + f_4)A/4 \qquad \text{(C2)}$$

where A is the area of the specimen. Knowing M, the value of k (the theoretical maximum concrete strength) can then be determined from equation C2.