On-site experimental evaluation of the elastic characteristics of large concrete structures

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Abstract

The present research aims to develop a new experimental approach for the estimation of the elastic characteristics of large existing structures and infrastructures. To this end, an experimental program was carried out using fibre-reinforced concrete specimens. The elastic modulus of the material was evaluated through two non-destructive procedures, referred to as the "impulse method" and "pull-out method", which offer several technical and economic advantages. The results achieved are seen to be in good agreement with those obtained from standard laboratory tests. Therefore, such procedures appear to be suitable for on-site material characterization and monitoring, especially if used jointly to minimize the number of tests.
Keywords: elastic modulus, impulse method, pull-out method, non-destructive evaluation, material assessment.

1 Introduction

The knowledge of the elastic characteristics of existing structures is of great importance within the process of safety assessment of the latter. However, the on-site evaluation of such characteristics is a complex task which, in most cases, does not yield satisfactory results. In fact, the determination of the elastic characteristics is usually made by means of preliminary laboratory tests [1], while the available on-site techniques have significant drawbacks: for example, the coring method [2] is fairly accurate but must be limited to a small number of points and, on the other hand, ultrasonic techniques [3] may be used extensively but are deeply affected by test conditions. Therefore, the need to precisely map the elastic characteristics of large structures is increasingly felt by designers and repair and maintenance professionals, in order to evaluate the actual safety level and plan possible future maintenance works.

For these reasons, in the paper a new experimental approach for the on-site evaluation of the elastic modulus is presented. It uses two experimental procedures: the first one, referred to as "impulse method", is based on the acquisition of the force vs. time curve resulting from the impact of a known mass against the surface of the material tested; the second one is based upon a modification of the well-known pull-out test, aimed at detecting the displacement of the insert for increasing extraction forces and subsequently the stiffness of the system. Both methods offer significant technical and economic advantages: in particular, they are non-destructive and therefore can be repeated over time; besides they are fast and easy to perform, which makes them suitable to test large surfaces, such as tunnels, viaducts, etc.

This approach was applied to fibre-reinforced concrete specimens, having elastic characteristics similar to those of many existing structures. The theoretical principles, the experimental steps and the main results achieved are depicted in the following sections.

2 Theoretical models

2.1 Impulse method

The "impulse method" [4-5] can be used on-site to determine the elastic modulus of a material based on a quasi-static theory of the contact between a body and a semi-infinite space, applied in accordance with Hertz's theory of frictionless contact [6]. The physical principles of the method can be resumed as follows.

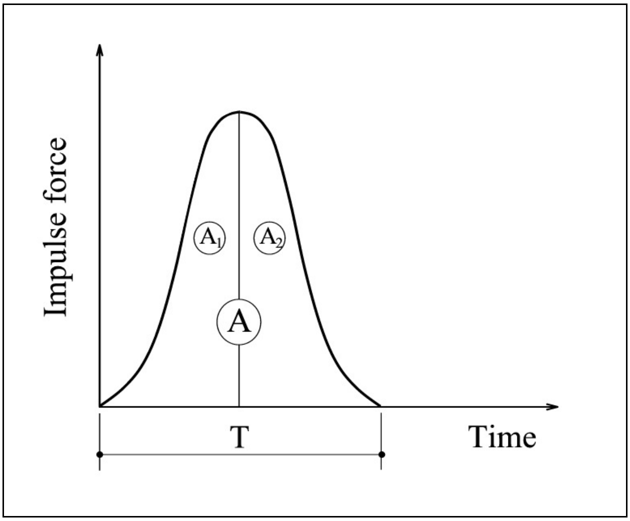

Figure 1: Contact force vs. time.

Let “m” be a mass with a hemispherical surface characterised by: radius R, Young’s modulus E_0 and Poisson’s ratio ν_0. Let us consider the impact of such a mass against the plane surface of a semi-infinite space, characterised by Young’s modulus E and Poisson’s ratio ν. Let the direction of the impact be perpendicular to such a surface and the velocity of all the points in the mass at the time of contact be the same as that of the centre point. With these assumptions, the contact force, F, evolves in time according to fig. 1 and the relative displacement between the surfaces, δ, is given by:

$$\delta = \left[\frac{9F^2}{16R\left(E^*\right)^2} \right]^{\frac{1}{3}}$$

where

$$\frac{1}{E^*} = \frac{1-\nu_0^2}{E_0} + \frac{1-\nu^2}{E}$$

Since the impact is assumed to be perfectly elastic, the total contact time, T, is given by:

$$T = 2T^*$$

T* being the contact time corresponding to the maximum deformation δ_{max}.

T* can be obtained imposing $\frac{d\delta}{dt} = 0$ and finally T can be expressed as follows:

$$T = 2.87\left(\frac{m^3}{RA_1} \cdot \frac{1}{\left(E^*\right)^2} \right)^{\frac{1}{5}}$$

Consequently, E* is given by:

$$E^* = \sqrt{\left(\frac{2.87}{T} \right)^5 \cdot \frac{m^3}{A_1}}$$

and the unknown value of the elastic modulus E is obtained through the formula:

$$E = \frac{E^* E_0 \left(1-\nu^2\right)}{E_0 + E^*\left(\nu_0^2 - 1\right)}$$

It should be remarked that the value of ν is also unknown; however, since its influence on the value of E is negligible, it can be assigned a nominal value, which amounts to introducing a negligible error.

2.2 Pull-out method

The pull-out method [7-8], which is commonly used for the evaluation of concrete strength, has been recently improved by Bocca et al. [9-10] in order to determine, in addition, the elastic modulus of the material.

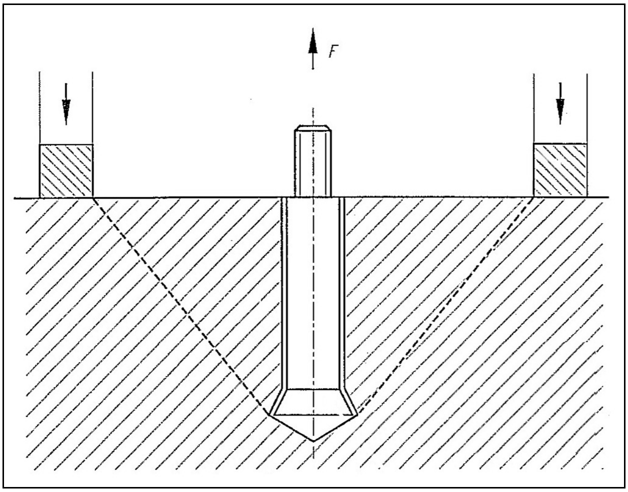

Figure 2: Outline of the geometric configuration of the pull-out test.

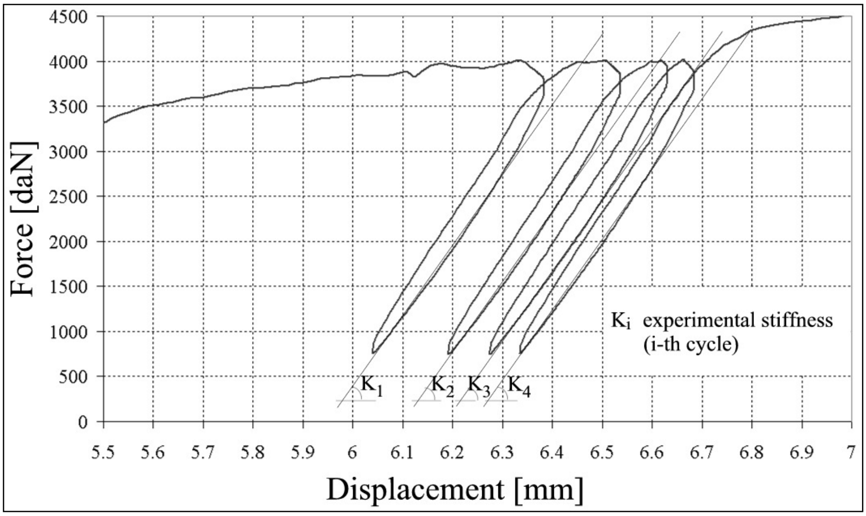

Figure 3: Force vs. displacement curve resulting from a pull-out test.

The method consists in drilling a hole into the concrete mass, embedding a geometric expansion metal insert and gradually extracting it (fig. 2). A few loading-unloading cycles are required to eliminate possible phenomena of mutual sliding between the mechanical parts of the equipment and stabilize the system.

The experimental observation of the force vs. displacement curve makes it possible to determine the pull-out stiffness, i.e. the slope of the curve during the loading-unloading cycles (fig. 3). Finally, a correlation curve worked out through finite elements simulations makes it possible to evaluate the actual value of the elastic modulus based on the experimentally observed stiffness.

3 Experimental program

3.1 Preliminary tests

In the present research, one slab and six prism-shaped specimens were tested. They were made of high-strength fibre-reinforced concrete, whose characteristics are summarized in table 1.

Table 1: Characteristics of the material.

Cement type	CEM II A-L 42.5 R
Cement proportion	450 kg/m^3
Water/cement ratio	0.47
Fibre proportion (°)	40 kg/m^3
Cube compressive strength R_{ck} (°°)	45 MPa

(°) Hooked steel fibres, 50 mm long, 0.50 mm in diameter.
(°°) Design value.

Table 2: Elastic characteristics of the material

Specimen no.	Elastic modulus [MPa]
1	38˙804
2	41˙871
3	40˙009
4	38˙384
5	38˙617
6	37˙900
Average	39˙264
Standard deviation	1˙457
Variation coefficient	3.71%

The high strength of the cement matrix is typical of the high performance concretes often used in bridge decks, prefabricated structures and prestressed members, to which this research is especially dedicated. It should be remarked that steel fibres play a marginal role in resisting compressive loads and hence their presence does not sensibly affect the elastic modulus of the material.

The secant modulus of elasticity was determined through compressive tests according to UNI 6556, with the aid of a 250 kN servo-controlled testing machine and electrical extensometers. The tests were performed on six prism-shaped specimens sized 16x16x48 cm^3 and yielded the results reported in table 2.

3.2 Impulse tests and pull-out tests

After the preliminary characterization tests, the specimens described in the previous section were subjected to impulse tests and pull-out tests in keeping with the theoretical models illustrated in section 2.

As far as impulse tests are concerned, the testing apparatus consisted of an impulse hammer of specified constant energy, equipped with an amplifier and having a ball-shaped iron tip, rigidly linked to a piezoelectric impulse transducer (fig. 4).

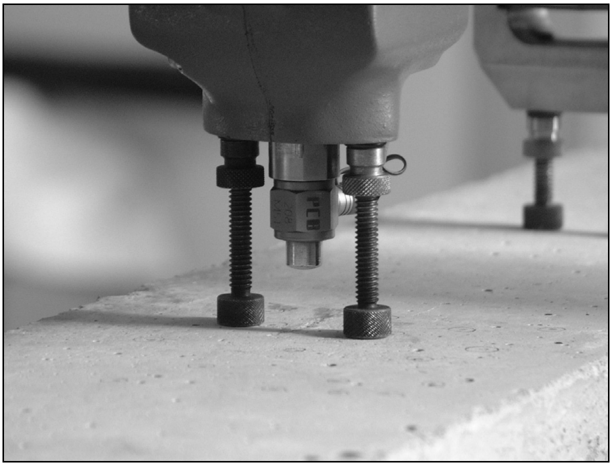

Figure 4: Impulse hammer. Detail of the tip.

The impulse forces measured by the transducer were acquired through a digitizing oscilloscope and subsequently processed. Special care was devoted to ensure that the direction of application of the impact was perfectly perpendicular to the surface tested: this was done by adjusting the four spacers of the hammer. Moreover, a special hammer fastening framework was adopted in order to apply the appropriate pressure to the hammer, so that it would not vibrate.

By means of the above-described equipment, each point was subjected to twenty consecutive vertical impacts. Such a procedure was followed with the purpose of stabilizing the material response: indeed, as can be seen in fig. 5, it can be observed that the shape of the impulse curves, as well as the maximum contact force and the contact time, have a high variability at the beginning of the test, but after approximately a dozen of impacts they tend to stabilize, because the effect of the material's surface conditions gradually vanishes due to local compaction and the result reflects the elastic behaviour of the underlying layers. Therefore, a stable value can be easily identified per each impact point. The results of eleven impulse test at different points are reported in the following section.

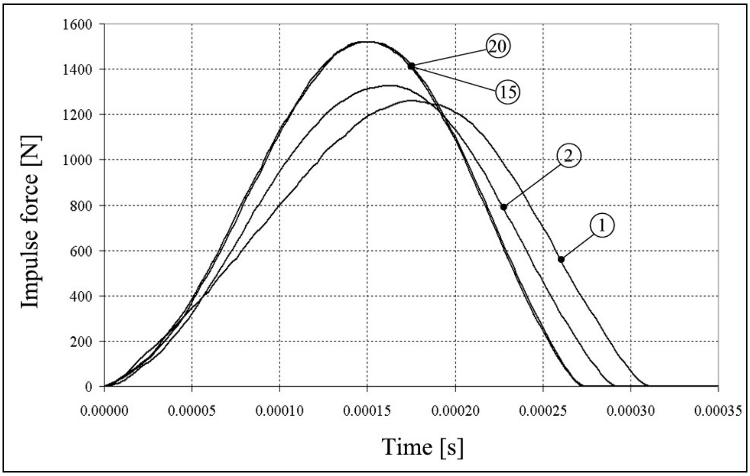

Figure 5: Impulse curves as a function of the number of consecutive impacts.

As far as pull-out tests are concerned, the testing apparatus consisted of a hydraulic jack connected to a manual pump which applied the required traction force to the extractor reacting against a bearing ring. The load was measured by means of a pressure cell, while the displacement of the insert was detected by means of three inductive bridge transducers connected to the extractor.

Particular care was devoted to avoid the onset of cracking phenomena that might alter the elastic behaviour of the material: consequently, the traction force applied was a small percentage of the pull-out strength.

The results of eleven pull-out test at different points are given below in section 4.

4 Results

The preliminary compressive tests for the determination of the secant modulus of elasticity (table 2) revealed a variation coefficient of 3.71%. This figure was assumed as a reference value for the scatter associated with the material, whether due to experimental errors or to the heterogeneity of the material itself. Any alternative on-site testing method that yields, on the same material, a variation coefficient not exceedingly higher than the afore-mentioned reference figure can be rated as acceptable for the purposes of a first approximation evaluation. The results obtained with the impulse method and the pull-out method must be evaluated in this perspective. They are summarized in fig. 6.

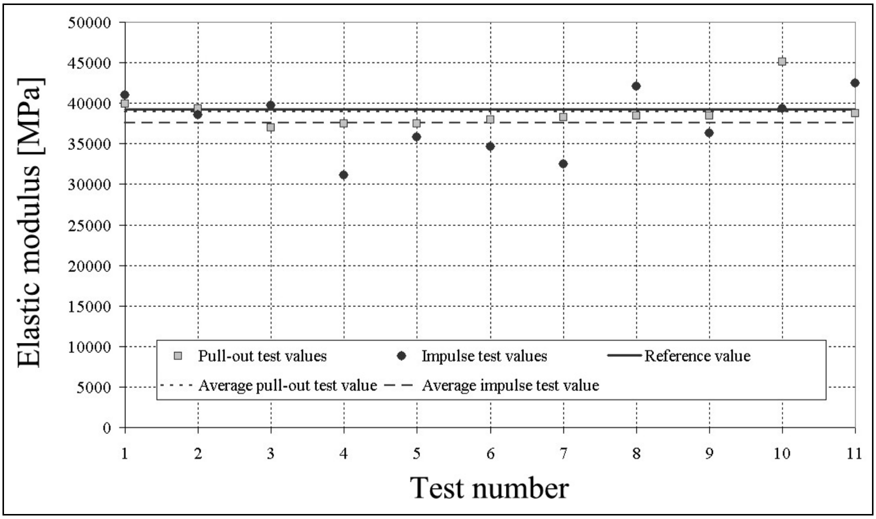

Figure 6: Outline of the experimental results

The evolution of the variation coefficient is similar in both techniques: at the same point, it tends to decrease with increasing number of consecutive impacts or loading-unloading cycles until stabilization.

As can be seen, both methods provide good estimates of the unknown elastic parameter. The relative scatter obtained in the impulse tests (i.e. 9.70%) is higher than in the pull-out tests (i.e. 5.46%); however it is still quite small, considering the reference variation coefficient determined through the standard tests. The pull-out method, instead, reveals a relative scatter which is very close to the scatter as determined through the standard tests.

5 Conclusions

Impulse method and pull-out method prove to be effective for the on-site determination of the elastic modulus of concrete and are particularly suitable to be used in conjunction with traditional methods, especially in order to evaluate the deformability characteristics of huge structures through a quick procedure. On high-strength fibre-reinforced concrete the impulse method yields a relative scatter of about 10%, which is somewhat higher than the scatter observed in standard compressive tests performed on the same material; on the other hand, the method offers several advantages: it is non-destructive and therefore can be repeated over time; it is fast and easy to perform; the testing apparatus is portable and sturdy enough to be used on-site, even in difficult conditions; it makes it possible to test large surfaces in a very short time and get sufficiently accurate results.

When, based on the values obtained through the impulse method, it is deemed appropriate to further investigate, extra information can be obtained using the pull-out method. This one, indeed, can still be rated as non-destructive, since the damage caused by the possible extraction of the insert is negligible and can be easily repaired; furthermore, it is quite fast and easy to perform (albeit less so than the impulse method); finally, its relative scatter is comparable to that arising from standard laboratory tests. In conclusion, the impulse method and the pull-out method can be used jointly in the on-site evaluation of the deformability characteristics of reinforced and prestressed concrete so as to minimise core drilling and the use of costlier and more time-consuming laboratory tests.

Acknowledgement

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References

[1] UNI 6556, Prove sui calcestruzzi. Determinazione del modulo elastico secante a compressione, Unificazione Italiana, Milano (1976).
[2] UNI EN 12504 -1, Prove sul calcestruzzo nelle strutture. Carote: prelievo, esame e prova di compressione (2002).
[3] UNI 8555 Prove non distruttive. Controlli mediante ultrasuoni: termini e definizioni (1984).
[4] Bocca P., Lucchese A., Munari G., Scavia C., Valutazione statica delle strutture murarie mediante il metodo ad impatti a energia costante, *Proc. of the Int. Conf. "Danneggiamento e Diagnosi di Materiali e Strutture"*, ed Pitagora, Bologna, pp. 51-67, 1991.
[5] Bocca P., Lucchese A., Munari G., Scavia C., Metodo ad impatti per la valutazione delle caratteristiche elastiche del calcestruzzo, *Proc. of the Int. Conf. "Danneggiamento e Diagnosi di Materiali e Strutture"*, ed Pitagora, Bologna, pp. 68-74, 1991.
[6] Johnson K. L., *Contact Mechanics*, Cambridge University Press, Cambridge 1985.
[7] UNI 10157, Calcestruzzo indurito. Determinazione della forza di estrazione mediante inserti post-inseriti ad espansione geometrica e forzata (1992).
[8] Bocca P., The application of pull-out test to high strength concrete estimation, *Materials and Structures*, **17(99)**, pp. 211-216, 1984.
[9] Bocca P., Crotti M., In situ mechanical determination of the elastic modulus of concrete, *Proc. of the Int. Conf. "Challenges of Concrete Construction",* eds. R. K. Dhir, M. R. Jones, L. Zheng, Thomas Telford, London, pp. 267-276, 2002.
[10] Bocca P., Grazzini A., Optimised mechanical method for in situ determination of the elastic modulus, *Proc. of the 1st Int. Conf. on Concrete Repair "Concrete Solutions"*, eds. M. Grantham, F. Rendell, R. Jauberthie, C. Lanos, London, vol. 1, pp. 363-371, 2003.