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An experimental study on the within-member variability of in situ concrete strength in RC building structures

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HIGHLIGHTS

- Knowledge of in situ concrete strength is crucial in the structural assessment.
- The reliability of the most usual NDT methods is discussed.
- The results of an experimental program on as-built structural members are reported.
- The role of the main factors influencing in situ strength estimation is examined.
- Suggestions for sampling and evaluation of test results are provided.

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ABSTRACT

Reinforced Concrete (RC) buildings can require the determination of in situ concrete strength during the execution of new structures to investigate low-strength results from acceptance tests and, especially, in the capacity assessment of existing structures. Most structural codes and technical recommendations indicate that in situ concrete strength should be estimated by means of drilled cores (Destructive Test, DT), possibly supplemented by non-destructive tests (NDTs). Besides contributing to the identification of homogenous concrete areas and thus indicating locations where cores have to be extracted, NDTs can significantly reduce the total amount of cores needed to adequately estimate concrete strength in an entire structure. The paper firstly reports a brief review of the most usual NDT methods (rebound number and ultrasonic pulse) and DT methods (cores) and discusses the role of the main factors influencing in situ strength estimation. It then reports and analyses the results of a wide investigation carried out on an RC beam member extracted from an existing structure. The results show a low variability of rebound number and direct velocity values along the beam, and a high variability for surface velocity values and, especially, core strengths. The wide scatter in some test results has been seen in relationship to the micro-cracking condition arising from past applied loads. Suggestions for test location and interpretation of in situ and laboratory test results are provided.

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1. Introduction

Knowledge of the in situ mechanical properties of constituent materials is a key issue in the evaluation of the structural capacity of both existing (i.e. after critical loads such as earthquakes or explosions, increase of live loads and assessment) and new constructions (i.e. in the case of non-conformity of the strength obtained from standard test specimens). The first and foremost aspect of the estimation of material properties in Reinforced Concrete (RC) structures is the determination of concrete strength, especially compressive strength as other mechanical properties such as tensile strength and elastic modulus can be derived from this.

Knowledge of the in situ strength is mainly required for existing constructions where it is crucial in the assessment phase and, where needed, in the design of the consequent strengthening intervention. An idea of the size of the problem in Italy is shown by the number of public buildings (about 75,000) currently located in seismically classified zones but originally designed without seismic criteria. Moreover, these buildings are often found to have poor quality concrete [1], which makes the execution of accurate assessment and strengthening programs even more urgent. It was in such a context, that, following the tragic collapse of a school building during the 2002 Molise earthquake [2], the Italian Government undertook an exhaustive mitigation policy issuing the Ordinance of the President of the Ministers' Council n. 3274 [3]. Specifically, a prominent national plan was set up with the purpose of defining actions to assess and mitigate the seismic risk of all buildings and infrastructures designed without earthquake

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resistant criteria and whose integrity during earthquakes is of vital importance for civil protection (e.g. hospitals) or that are significant in view of the consequences associated with their collapse (e.g. schools).

The specific role of concrete strength on the seismic vulnerability of existing RC buildings has been studied by many authors (e.g. [4,5]). Moreover, especially for buildings located in seismic areas, the most important codes and recommendations (e.g. [6–8]) provide criteria to estimate concrete properties and, specifically, its compressive strength. In the European code for existing buildings (EC8-3, [6]) the estimation of concrete strength contributes to the determination of the knowledge level (KL) of the structure under study. Three KLs are defined (limited, normal and full knowledge) in order to choose the appropriate confidence factor (CF) value to be adopted in the evaluation process. CF deals with the incompleteness of knowledge that is always present in the evaluation of existing structures. To this end, CF applies to the mean strength obtained from in situ tests and from the additional sources of information (e.g. original design specifications) to determine the design strength to be used in the calculation of the structural capacity. The recommended values of CF are 1.35, 1.2 and 1 for limited, normal and full KL, respectively. Although a certain KL regarding material properties can be achieved on the basis of original design specifications or test reports, complementary in situ tests must be provided. Tests are mandatory because concrete strength is difficult to estimate and because it is a function of component properties and mixture (cement, aggregates, water), casting operations, various maturity phases, interactions between them and, finally, possible deterioration due to environmental impact. Besides, the amount and nature of past loads as well as the shape (cube, cylindrical) and aspect ratio of the specimens used for testing also increase variability in strength estimation.

Although further studies are needed to provide reliable and inexpensive procedures which take all the above factors into account, especially in the case of poor quality concrete, different kinds of approach have been developed to estimate the concrete strength and the role of the main influencing factors. In situ concrete strength can be estimated through destructive tests (DTs) or non-destructive tests (NDTs), or through a combination of both types. The most widespread methods for RC structures include core testing among DTs, rebound number and ultrasonic pulse velocity among NDTs.

The number and extension of tests of the in situ survey campaign has to fulfil the requirements of a quantitative assessment of the structural safety level in compliance with relevant national and international codes. However, campaigns are usually carried out on limited areas of the structure under study and not many destructive and non-destructive test points can be selected to estimate concrete strength. Among the variables affecting the planning of an in situ survey campaign, the budget requirements and, with regard to DTs, the need to reduce possible negative effects on the structural stability during and after the tests [9] have an important role in limiting the extension of the investigation. Because of this, in [10] a preliminary execution of NDTs is suggested in order to identify homogeneous areas in terms of concrete properties, thus effectively addressing locations of DTs while limiting their number. Whereas studies performed so far have analysed the variability of data collected in RC structures as a whole, less attention has been devoted to investigating the variability within single structural members.

In this paper the within-member variability has been studied carefully carrying out an extensive experimental program on a beam member extracted from an existing old RC structure due for demolition, originally designed only for gravity loads. All the experimental tests were performed at the Laboratory of Structures of the University of Basilicata, Potenza, Italy. Principle and application criteria of the NDTs mainly used in real practice (rebound number, ultrasonic pulse) and of the combined SonReb method have been described briefly. The extensive set of experimental results (tens of core tests, hundreds of NDTs) has been analysed to highlight the role of some factors influencing in situ concrete strength. Suggestions for selection of test locations and interpretation of in situ and laboratory test results have been provided to gain more accurate knowledge of the actual in situ concrete properties.

2. Review of destructive and non-destructive testing methods

Broad research on the estimation of in situ concrete strength through DT and NDT methods has already been carried out. A comprehensive study on the evaluation of concrete strength is reported in [11]. On the basis of an extensive review of the technical literature, the use of the most diffuse NDT methods to assess concrete strength, alone or in combination, is analysed, with emphasis on variability and uncertainty of measurements. Furthermore, the main aspects involved in the calibration process of NDT results by means of core tests are also discussed.

The most widespread testing methods for determining in situ concrete strength in existing RC structures, that is core testing, rebound number, and ultrasonic pulse velocity are briefly presented with the focus being on combined methods and on criteria to correlate NDTs and core test results.

2.1. Core testing

Core testing is widely used in professional practice because it is the most direct and accurate method of estimating concrete strength in RC structures. Specifications to apply this method in testing concrete in structures are given in several standards [12,13].

Some scatter is generally found in test results which is mainly due to random variation of concrete characteristics and in situ stress conditions, both within one batch and among various batches, as well as to systematic variation of in situ properties along a member or throughout the structure. Some studies (e.g. [10,14]) have discussed the difference between in situ and core strength. Size and geometry of core specimens, coring direction, presence of reinforcing bars or other inclusions, and effect of drilling damage can influence test results on core specimens and thus determine such difference. With regard to this issue, some relationships to convert the compressive strength of a core specimen f_{core} into the equivalent in situ value f_c have been proposed in the technical literature. Specifically, in [10] the following expression is proposed:

$$f_c = (C_{h/D} \cdot C_{dia} \cdot C_a \cdot C_d) f_{core} \quad (1)$$

where:

- $C_{h/D}$ = correction for length/diameter ratio h/D, equal to $C_{h/D} = 2/(1.5 + D/h)$; due to restraint from the compression test machine platens the strength decreases for ratios $h/D > 1$ [15], therefore, in accordance with [16], it is assumed $C_{h/D} = 2/(1.5 + D/h)$ that provides $C_{h/D}$ equal to 1 and 0.8 for h/D, respectively, equal to 2 and 1.
- C_{dia} = correction for diameter of core D, equal to 1.06, 1.00 and 0.98 for D, respectively, equal to 50, 100 and 150 mm, as suggested in [12].
- C_a = correction for the presence of reinforcing bars, equal to 1 for no bars, and varying between 1.03 for small diameter bars (ϕ 10) and 1.13 for large diameter bars (ϕ 20); C_d = correction for damage due to drilling. In [12] a constant value equal to 1.06 is suggested, whereas in the technical literature also

$C_d = 1.10$ is proposed if the extraction is carefully carried out by experienced operators. However, taking into account that the lower the as-built concrete quality the larger the drilling damage, it appears more accurate to put $C_d = 1.20$ for $f_{core} < 20$ MPa, and $C_d = 1.10$ for $f_{core} \in$ [20,30] MPa and $C_d = 1.00$ for $f_{core} \geqslant 30$ MPa [17–19].

It is worth specifying that the strength obtained from Eq. (1) does not correspond to the standard strength given in codes for the design of new structures, due to the different ageing and casting conditions between the standard specimens and the in situ concrete, as well to the age of the core specimens which is usually much greater than the 28-days of standard specimens.

2.2. NDT methods

The rebound number is the simplest and least expensive NDT method. Specifications to apply this method in testing concrete in structures are given in several standards [20,21] and handbooks [22]. The method consists in measuring the rebound distance of a plunger pulled by a spring against the surface of the concrete member or specimen under test. Because the test only investigates the surface layer, the results may not represent the interior concrete. For example, the carbonation process typical of old concrete has a significant impact on rebound determinations, providing high values, which do not correspond to actually high strengths. In spite of these limitations, rebound number is often used to estimate concrete strength through correlation curves, provided in device manuals or in other references (e.g. [23]), whose prediction capacity is quite poor.

Another commonly used NDT method is based on the ultrasonic pulse velocity. Recommendations are given in several standards (e.g. [20,24]) and a complete overview of the method is presented in [25]. The test requires the determination of the velocity of propagation of ultrasonic longitudinal waves on the specimen or structural member at hand, using two transducers placed at a known distance (transmitting → receiving). These values are then correlated to the concrete properties by using curves, provided with the test device or in other references (e.g. [23]), whose prediction capacity is quite poor. Measurements can be made by placing the two transducers on opposite sides (direct transmission), on adjacent sides (semi-direct transmission), or on the same face (indirect or surface transmission) of the structural member. Direct measurements are preferable, whenever possible, due to their higher reliability. From the physics of elastic wave propagation, the pulse velocity V is proportional to the square root of Young's modulus of elasticity E. Assuming that E is, in turn, proportional to the square root of the compressive strength as suggested in [26], V can be assumed as proportional to the fourth root of the compressive strength. In actual fact the correlation may be affected by a number of factors, such as water/cement ratio, moisture content, presence of reinforcement and age. For this reason, a general correlation cannot be proposed, but the specific characteristics and conditions of the concrete under test have to be taken into account, as recommended in international standards [20]. On the contrary, the ultrasonic method can be effectively used in isolation for detecting local damage or defects (cracks, voids, casting joints, etc.) particularly through surface measurements.

2.3. Combined methods

Guidance for the use of combined NDT methods for the estimation of in situ concrete strength is provided in recommendations, standards and handbooks [15,27,28]. Combined methods aim at increasing the accuracy of the estimation, compared with that from any single method. SONREB method, based on the combination of ultrasonic pulse velocity V and rebound number S measurements, is the best known and most widely used among the combined methods. The underlying concept is that as some factors affect both V and S measurements but in opposite ways, their combined use may result in a balancing effect that can improve the accuracy of the estimated strength. Specifically, whereas V increases with moisture content and decreases in older concretes, the contrary happens to S. By combining results from the two testing methods, a multiple correlation can be established. For example, in [28] iso-strength curves for a reference concrete are suggested, where the compressive strength can be estimated through knowledge of the rebound number and pulse velocity values. When estimating the strength of a specific in situ concrete, in order to improve the accuracy of prediction, a number of correction coefficients need to be considered and applied to the iso-strength values. These coefficients of influence account for the main differences in composition with respect to the reference concrete including differences in cement type and content, aggregate types and size, presence of admixtures. In practice knowledge of the composition of the concrete under test is very rare, thus a total coefficient of influence needs to be estimated by using the results of some core tests.

2.4. Combination of DT and NDT methods for strength estimation

On the basis of the previous sections, it can be stated that NDT methods should not be used in isolation to achieve reliable estimates of concrete strength, but that calibration is required by means of core tests. On the other hand, NDT methods can be used effectively as a means of determining the uniformity of concrete properties in structures, as suggested in [10,20].

Table 1 offers a comparison among the testing methods under consideration in terms of their cost, speed of execution, destructiveness, capability of adequately representing in-structure variability, reliability and ease of use. Core tests are more reliable the more intrusive and expensive they are, therefore only a limited number of them can be carried out in practice resulting in estimates which can be unrepresentative of the within-structure property variations. On the contrary, NDTs are very simple and inexpensive, but they can provide unreliable predictions of concrete strength. A suitable combination of cores and NDTs appears to be the best solution to effectively plan the testing program, to define sampling in terms of size and location of measurements and, finally, to achieve reliable in situ concrete strengths. Indeed, it can be stated that estimate, reliability increases when core extraction points are selected effectively and widespread NDT measurements are made throughout the structure.

Table 1
Comparison between destructive and non-destructive tests.

Method	Cost	Speed of execution	Damage	Representation of in-structure variability	Reliability	Ease of use
Core test	High	Low	High	Moderate	Good	Low
Rebound method	Very low	High	Low	Good (surface)	Low	High
Ultrasonic velocity	Low	High	Low	Good	Moderate	Moderate
Combined methods	Moderate	Moderate	Low	Good	Good	Moderate

With regard to the calibration process of NDT results through core tests, in the RILEM standards [28] a procedure based on the determination of a total coefficient of influence has been proposed to correlate non-destructive and destructive test results. An alternative procedure can be used to obtain the relationship between in situ strength f_c and NDT measurements (rebound number S and ultrasonic velocity V):

$$f_c = aS^bV^c \tag{2}$$

where the coefficients a, b and c are experimentally derived for the specific concrete under test [10,19]. The first step is the execution of an extensive non-destructive testing campaign in N_{NDT} points, with the primary objective of identifying the homogeneity of the concrete under examination. In this way the possible presence of portions of structure representing different concrete batches can be detected. The distribution of S and V values permits an adequate definition of the homogenous areas thus indicating a targeted selection of the points where cores should be extracted. In a limited number of points $N_{core} \subset N_{\mathrm{NDT}}$, selected to ensure that each homogeneous area is appropriately sampled, some cores are extracted and tested in compression to evaluate their cylinder strength f_{core}. Core test values are then converted into the equivalent in situ values f_c by using Eq. (1) and, working within each homogeneous area, a multivariable regression is performed to compute the values of coefficients a, b and c that provide the best correlation between destructive and non-destructive results, i.e. determining the Eq. (2) specifically applicable to the concrete under examination. Finally, by applying the obtained Eq. (2), the in situ concrete strength f_c can also be estimated in the points where only non-destructive measurements have been made, thus leading to a determination of the design strength value in a more representative and reliable way. The location of measurement points along the structural elements is crucial in the setting up of *ad hoc* relationships, such as Eq. (2). Therefore, some remarks and suggestions have been reported on the basis of an extensive experimental investigation made up of DTs and NDTs carried out on a beam member extracted from a real structure.

3. The experimental investigation

A beam member (width b = 40 cm, height h = 62 cm) extracted from an RC school building due for demolition, was investigated carefully. The structure was originally designed and constructed in the '50s in the small town of Aulla (Tuscany, Italy) taking into account only gravity loads in accordance with an old Italian code in force at the time [29]. In Fig. 1 a layout of the school building with the location of the extracted beam is displayed.

The beam member was extracted and handled taking care to avoid as much damage to it as possible through the use of purposely designed steel jackets which were applied to the beam before the extraction operations, as shown in Fig. 2. Possible damage due to the cutting and transport of the beam can be excluded, as confirmed by the stringent examination of the specimen on arrival in the Laboratory of the University of Basilicata where all the experimental tests were performed.

Non-destructive (rebound number and ultrasonic velocity) and destructive (cores) tests were carried out using instrumentation and testing procedures typically adopted in practice and strictly following the rules given in the relevant European Standards, that is EN 12504-1 [13] for core testing, EN 12504-2 [21] for rebound number, and EN 12504-4 [24] for ultrasonic velocity.

Tests were made in several uniformly distributed points along the beam and a reference grid was drawn along the four sides of the beam to ensure their correct identification. Specifically, on each lateral side two alignments (upper and lower) were determined, each one made up of 13 cells. Similarly, on the superior and inferior base of the beam a reference grid perpendicular to the one along the lateral sides was drawn. A local reference system was placed at one of the end sections in order to determine the distance of the test points (Fig. 3).

The beam surface was prepared following the recommendations provided in the international standards [12,20]. Following this, before performing DTs and NDTs, a precise survey was carried out using a pacometer to locate the longitudinal and transverse reinforcing bars (see white lines in the photos in Fig. 3 top, which represent the position of the stirrups). In this way it was possible to avoid the steel bars during core extraction and, if necessary, account for them when analysing test results.

Twelve readings were made inside each grid cell during the application of the rebound test. The maximum and minimum values were subsequently eliminated from each set of local readings and, for each cell, the representative rebound number was computed as the mean of the remaining 10 values. Ultrasonic tests were carried out on the same cells by direct and indirect (surface) transmission, using standard 54 kHz frequency transducers typically used for medium-size concrete specimens [25]. At least three measurements were obtained for each cell, assuming the

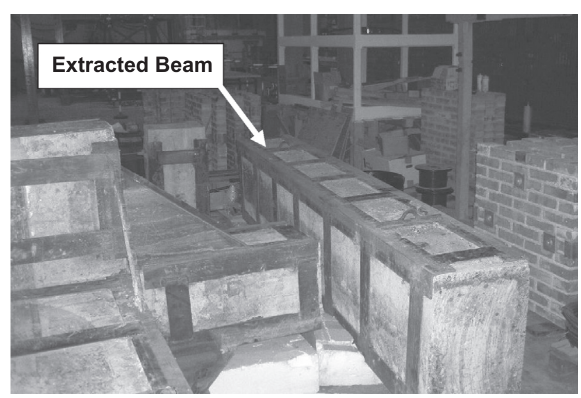

Fig. 2. Steel jackets applied to avoid damage to the beam specimen during the extraction and transport operations.

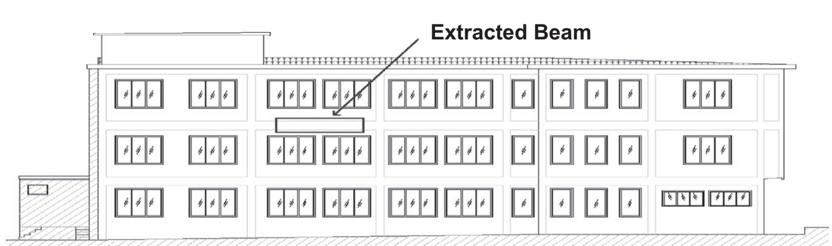

Fig. 1. Layout of the structure with the location of the extracted beam.

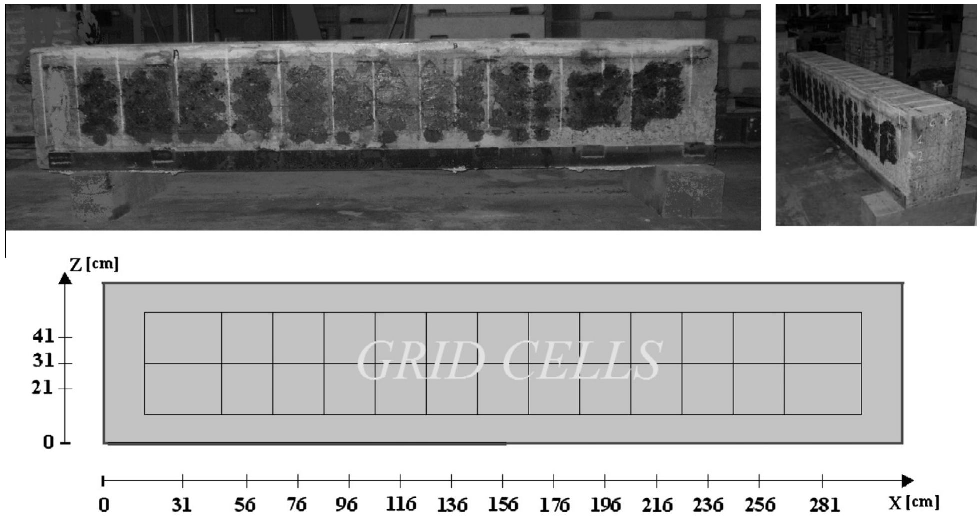

Fig. 3. Views of the beam member. In the photos (top) the white lines mark the stirrups' location while the reference grid is not visible but it is displayed in the drawing (bottom) for one of the lateral side (h = 62 cm) of the beam.

computed mean value as representative for the cell. With respect to surface velocity, the value associated to each cell was assigned by considering the measurements performed when the transducers (transmitter and receiver) were placed in the cells (approximately distant 40 cm) adjacent to the one under consideration. Finally, the cores were extracted along the beam taking, as a rule, one specimen from each cell as shown in Fig. 4.

Most of the cores were extracted from the lateral sides of the beam, where the drilling conditions were the same as those usually employed in real structures, and others were extracted along the superior base and from the end sections. Specifically, as can be seen in Fig. 4, six cores were extracted vertically (i.e. with axis parallel to the direction of concrete casting) along the superior base, and eight cores were extracted horizontally at the end sections of the beam specimen (i.e. with axis parallel to the beam axis). The latter drilling mode is clearly not viable during real in situ testing campaigns as it is only possible on structural members extracted from buildings to be demolished, as in the present study. However, because the direction along which the concrete of structural members is actually stressed is parallel to their axis, it is appeared of some interest to compare the strength values of the cores extracted at the end sections with those generally achieved in real practice.

4. Test results

The main results of the experimental investigation are reported in this section. The results, in relation to the cell grid drawn along the beam, have been plotted as a function of the location of each test point, organized in eight data sets as shown in the scheme displayed in Fig. 5.

The results of DTs and NDTs were firstly analysed by considering the measurements carried out along the vertical sides (A, B, C, D) that provide, values perpendicular to concrete casting. in conformity with real practice. Secondly measurements along the other sides (parallel to concrete casting: E and F, parallel to the beam axis at the end sections: G and H) were analysed and compared.

The results of the rebound test are displayed in Fig. 6. Remarkably low values were found along the exterior lateral side of the beam (zones A and B) with respect to the interior one (zones C and D), while smaller differences were found between the upper and lower lateral alignments (i.e., A *vs* B, and C *vs* D). The measurements carried out along the beam bases (superior and inferior sides, E and F fields) show very low scatter, with higher values generally found along the inferior base F. This result was somehow expected because the direction of concrete casting can affect the rebound test and determine higher values at the lower part of cast-in place members where the compaction effect is greater.

Fig. 7 reports the direct and surface ultrasonic velocity values measured along the four sides of the beam. The values collected along the interior (C, D) and superior (E) sides are not reported due to their unreliability caused by some defects on the beam surface, such as the presence of emerging stirrups and spalling of concrete cover. The surface velocity determinations (Fig. 7, on the right) show very high differences both within the various alignments and between the upper (A) and lower (B) alignments. Specifically, a remarkable decrease of velocity values along the central part of B alignment can be observed, possibly due to the increase of the positive flexural moment in this part of the beam.

Fig. 8 shows the compressive strength values of the cores extracted along the upper (A–C) and lower (B–D) alignment. Specifi-

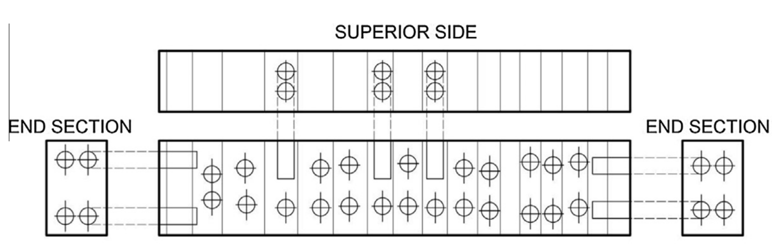

Fig. 4. Location of core extraction points along the beam.

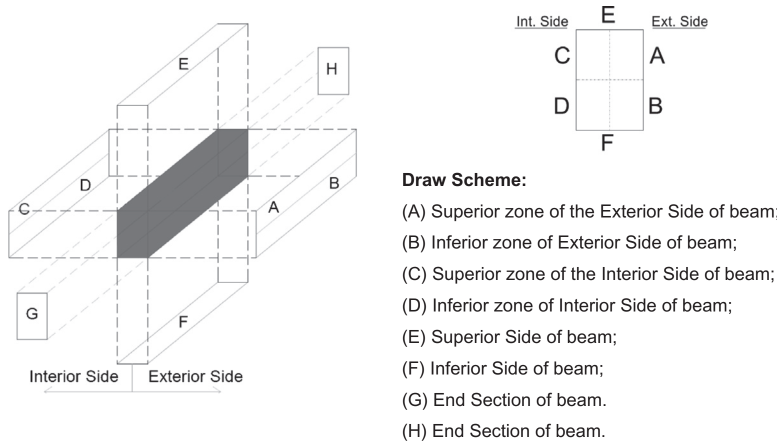

Fig. 5. Scheme adopted to organize the results of the destructive and non-destructive tests performed along the beam ("Interior Side" indicates the lateral beam side facing the inside of the building).

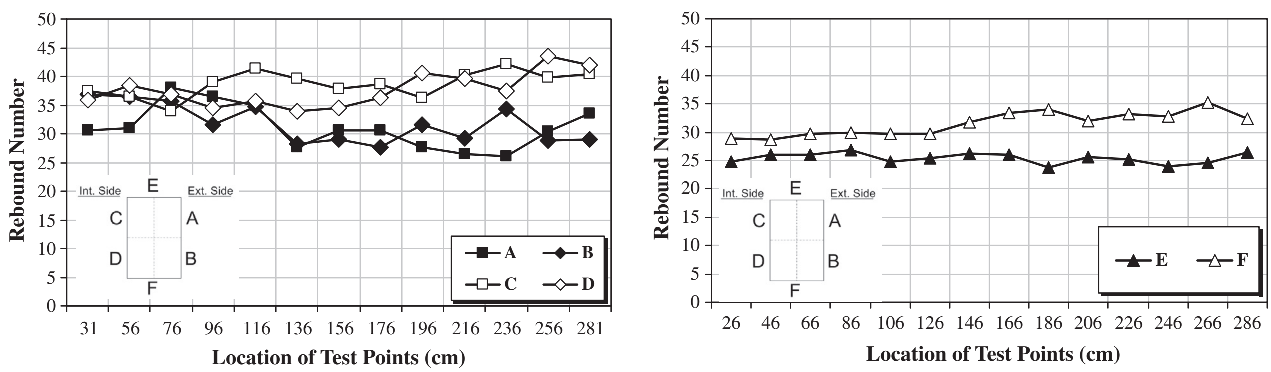

Fig. 6. Rebound number determinations along the beam sides (vertical sides on the left, and horizontal sides on the right).

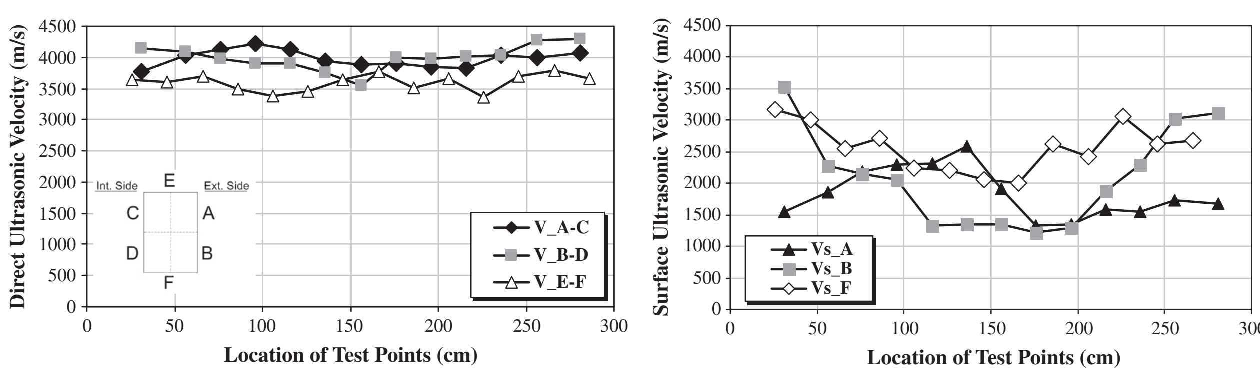

Fig. 7. Direct (on the left) and surface (on the right) pulse velocity measurements along the beam sides; for the direct velocity three datasets are plotted including the horizontal upper (A–C) and lower (B–D) alignments and the vertical direction (E–F).

cally, the diagram on the left displays the strength values as directly found on core specimens, while the diagram on the right displays the equivalent in situ compressive strength values as modified according to Eq. (1). The cores extracted along the lateral side of the beam show a highly variable trend of strength values, with a max–min range around 20 MPa in terms of in situ strength.

In Tables 2 and 3 the in situ strength values found on the cores extracted along the vertical (i.e. parallel to concrete casting direction) and horizontal (i.e. at the end sections parallel to the beam axis) direction are reported, respectively. At the end sections, as a consequence of cracking due to flexural moment, there were some difficulties in extracting core specimens with a standard height of 200 mm, therefore these cores frequently have heights of less than 200 mm. For this reason, the in situ strength values computed applying Eq. (1) are directly reported in both Tables.

In Table 2 the in situ strength values of cores extracted along the upper portion of the beam in direction parallel to the concrete casting (E–F) are compared with those provided by the cores extracted in the lower portion along the lateral side (B–D).

Remarkable differences between the two groups of strength values were found, although a clear trend cannot be recognized. This might be partially ascribable to the contrasting action due to bleeding and consolidation effects on test results [16]. On one hand, bleeding can reduce the compressive strength transverse to

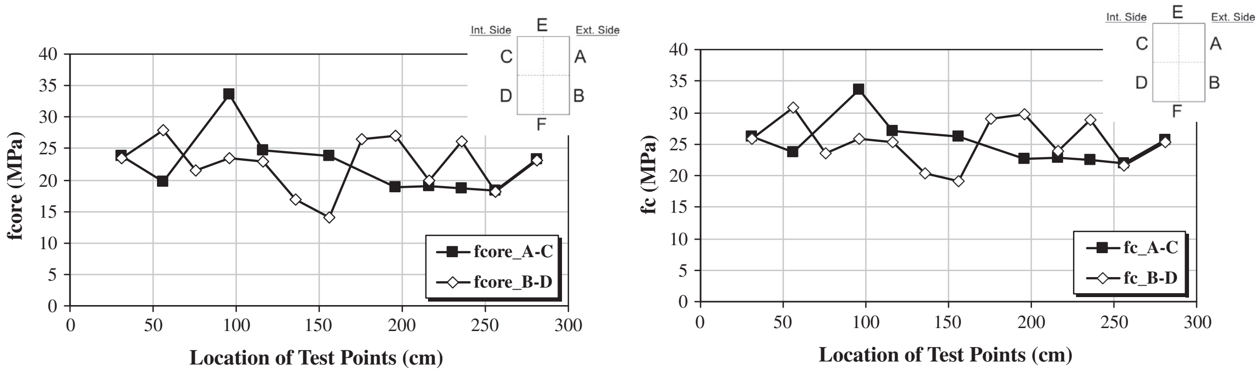

Fig. 8. Compressive strength of the extracted cores along the beam (on the left) and related in situ strength values (on the right) computed using the correction coefficients reported in Eq. (1).

Table 2
In situ strength values of the cores extracted along the direction parallel to concrete casting (E–F) and NDT results obtained along the same direction compared to the related values of cores extracted in adjacent locations along the lateral side (B–D).

Distance (cm)	Superior side			Lateral side		
	S (E)	*V* (E–F) (m/s)	f_c (E–F) (MPa)	*S* (B)	*V* (B–D) (m/s)	f_c (B–D) (MPa)
76	26	3595	13.3	35	4087	24.6
156	26	3700	25.1	29	3553	20.3
216	25	3515	20.2	29	4023	29.1

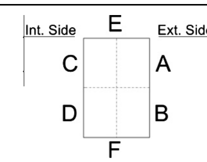

Table 3
In situ strength values of the cores extracted at the end sections of the beam (G, H) compared with those obtained by the cores extracted along the lateral side (A–C, B–D) nearby the end sections.

	ID	H (mm)	D (mm)	f_c (G–H) (MPa)	f_c (A–C, B–D)
G	S1	140	100	15.2	26.1 (A–C)
	S2	*Unusable specimen*			
	S3	200	100	23.2	25.9 (B–D)
	S4	163	100	14.8	
H	S5	170	100	15.8	25.7 (A–C)
	S6	160	100	17.4	
	S7	180	100	17.2	25.3 (B–D)
	S8	*Unusable specimen*			

the direction of casting. On the other hand, due to consolidation pressures, the lower portion of vertical cast members can have relatively greater strengths. A comparison shows that, in two out of three cases, cores with axis perpendicular to the casting direction return strength values higher than those with axis parallel to the casting direction, which might be interpreted as the prevalence of the effect of consolidation over bleeding. This result is not found in a comparison of the strength values of the cores extracted at distance 156 cm, presumably because the strength value f_c(B–D) = 20.3 MPa is measured in the beam portion where the higher values of positive bending moment due to past applied loads caused the greater cracking, therefore the lower values of compressive strength.

Table 3 shows that the strength values relevant to the cores extracted at the end sections of the beam specimen are generally lower than those found at the lateral sides near the end sections. Specifically, the very low values found at the end sections are not easily explained, but they could partially derive from local damage caused by the cutting of the beam when it was removed from the building. It is worth noting that the f_c values found at the lateral sides (A–C, B–D) are very similar (min–max range 25.3–26.1 MPa), in contrast with the large variations detected along the beam specimen (Fig. 8). This can be explained by considering that the values in Table 3 are relevant to cores extracted from beam zones with very low or null values of bending moment, as will be better discussed in Section 4.2.

4.1. The within-member variability of test results

The distributions of test results have highlighted a low variability in the rebound number *S* and in the ultrasonic velocity values measured by direct transmission *V*. In contrast, high variability has been found for the core strength and surface velocity values. Table 4 offers an analysis of this trend by reporting some simple statistics, namely minimum, maximum, mean value, standard deviation and coefficient of variation (CV) of the test results.

The results of the rebound test, although affected by the local surface conditions of the area under test, show a low difference between the minimum and maximum value, with respect to the mean of all values. The same is found for the velocity measured by direct transmission *V*, while far higher deviations are computed for the surface velocity values V_s. However, in spite of the occasionally noted high variability, the results in Table 4 shows that the mean values in the upper (A–C) and lower (B–D) portions of the beam, are practically coincident for the in situ strength f_c and the direct velocity *V*, and slightly different for the weight density SW. The coefficient of variation CV is definitely low for the weight density, emphasizing the homogeneity of concrete composition in the beam under examination, although the mean value relevant to the lower portion of the beam is slightly higher showing a limited consolidation effect. Larger differences among the various zones where tests were performed can be noted for the rebound number with respect to mean values, and for the surface velocity V_s with respect to CV values. High values of CV are found for the in situ strength relevant to specimens extracted along the lateral sides of the beam (i.e. A–C and B–D fields), that is equal to 14%. As an example, the minimum (19.2 MPa) and the maximum value (33.7 MPa) of the in situ strength have percent deviations, compared to the mean of all values (25.3 MPa) equal to −25% and +32%, respectively. With respect to the cores extracted along the other "non-conventional"

Table 4
Minimum, maximum, mean value and coefficient of variation of the main test results.

Method	Sample	*N.* values	Min–max	Mean	St. Dev.	CV (%)
Rebound test (S)	A	13	26–38	31	4	12
	B	13	28–37	32	3	9
	C	13	34–42	39	2	5
	D	13	34–44	38	3	8
	E	14	24–27	25	1	4
	F	14	29–35	32	2	6
	ALL	80	24–44	33	5	15
Direct Ultrasonic Pulse Velocity (V) (m/s)	A–C	13	3771–4227	3984	136	3
	B–D	13	3553–4290	3996	199	5
	E–F	14	3370–3792	3596	136	4
	ALL	40	3370–4290	3852	245	7
Surface ultrasonic pulse velocity (Vs) (m/s)	A	13	1337–2588	1837	397	22
	B	13	1221–3534	2066	776	38
	F	13	2010–3175	2568	373	15
	ALL	39	1221–3534	2385	650	27
In situ strength (f_c) (MPa)	A–C	10	22.0–33.7	25.2	3.5	14
	B–D	13	19.2–30.7	25.3	3.6	14
	E–F	6	12.8–29.1	19.5	6	31
	G–H	6	14.8–23.2	17.2	3.1	18
	ALL	35	12.8–33.7	23.1	5.0	21
Weight density (SW) (kN/m^3)	A–C	10	22.56–23.15	22.83	0.20	1
	B–D	13	22.98–23.54	23.23	0.15	1
	E–F	6	22.45–23.43	23.09	0.36	2
	G–H	6	21.77–23.93	22.69	0.70	3
	ALL	35	21.77–23.93	23.00	0.29	1

directions, only some preliminary remarks regarding the detected differences can be made at this stage of the study.

Finally, as shown in Table 4, which reports the statistics on all collected data, higher CV values were found for the indirect pulse velocity (27%) and in situ compressive strength (21%), while the other NDTs returned low CV values, especially for the direct pulse velocity.

Generally speaking, some scatter in the test results may be expected, taking into account the normal within-concrete, within-member and within-test variations. In [12,14] estimates of the overall variability of in situ concrete strength are provided in terms of coefficient of variation CV (Table 5), considering variability dependent on the number of structural members and concrete batches. It should be emphasized that the values reported in Table 5 are relevant to cast-in-place concrete produced and placed according to normal practice and standards. The difference between the CV values of the in situ strength reported in Table 4 and the corresponding value reported in Table 5 (CV = 7% for one member and one batch) can be ascribed to many factors but the main one appears to be the stress conditions due to past applies loads, as will be discussed further in Section 4.2. In any case, the detected high variability of concrete strength along the beam raises an important and delicate question: in the present experimental study it was possible to conduct a large number of measurements on a single structural member, thus possible outliers could be detected and appropriately accounted for in the estimation of concrete properties. On the contrary, in practical situations only one measurement is usually made on a member of the structure under examination, therefore its value could be unrepresentative of the average properties, with an aggravating circumstance deriving from single values higher than the mean value in the member which would determine non-conservative design values.

Table 5
CVs due to in situ strength variation within-structure (cast-in-place construction) adapted from (ACI, 2010).

Structure composition	CV (One member) (%)	CV (Many members) (%)
One batch	7	8
Many batches	12	13

To better quantify the relation between destructive and non-destructive test results, Pearson's linear and Spearman's rank correlation coefficient were measured. Tables 6 and 7 report respectively Pearson's and Spearman's correlation coefficients among the f_c, S, V, V_s and S_W values collected along the lateral sides of beam. The association of the weight density S_W, measured on the cores before the compression test, was also considered provided that investigations [30] showed that it has some correlation with the compressive strength. There are some small differences between the Pearson and Spearman results. Rebound number S appears to be the ND parameter which is better correlated to the in situ concrete strength f_c, particularly along the upper portion of the beam. Actually, all parameters show a better correlation in the upper zone with respect to the lower zone where the correlation is generally low or null. S_W also shows a good correlation with f_c in the upper part of the beam, while it appears to be badly correlated in the lower zone.

Table 6
Pearson's correlation coefficients between DT and NDT results found along the lateral sides of the beam.

	f_c	S	V	V_s	S_W
Upper portion					
f_c	1.00	0.82	0.56	0.75	0.78
S	0.82	1.00	0.71	0.83	0.47
V	0.56	0.71	1.00	0.75	0.21
V_s	0.75	0.83	0.75	1.00	0.37
S_W	0.78	0.47	0.21	0.37	1.00
Lower portion					
f_c	1.00	0.65	0.32	0.01	0.45
S	0.65	1.00	0.07	0.14	0.19
V	0.32	0.07	1.00	0.78	−0.24
V_s	0.01	0.14	0.78	1.00	−0.46
S_W	0.45	0.19	−0.24	−0.46	1.00
All data					
f_c	1.00	0.73	0.41	0.21	0.45
S	0.73	1.00	0.35	0.37	0.38
V	0.41	0.35	1.00	0.74	0.06
V_s	0.21	0.37	0.74	1.00	0.16
S_W	0.45	0.38	0.06	0.16	1.00

Table 7
Spearman's correlation coefficients between DT and NDT results found along the lateral sides of the beam.

	f_c	S	V	V_s	S_W
Upper portion					
f_c	1.00	0.82	0.38	0.66	0.74
S	0.82	1.00	0.65	0.78	0.42
V	0.38	0.65	1.00	0.64	0.21
V_s	0.66	0.78	0.64	1.00	0.20
S_W	0.74	0.42	0.21	0.20	1.00
Lower portion					
f_c	1.00	0.75	0.21	0.08	0.36
S	0.75	1.00	−0.08	−0.03	0.42
V	0.21	−0.08	1.00	0.84	−0.45
V_s	0.08	−0.03	0.84	1.00	−0.55
S_W	0.36	0.42	−0.45	−0.55	1.00
All data					
f_c	1.00	0.74	0.26	0.30	0.45
S	0.74	1.00	0.34	0.28	0.33
V	0.26	0.34	1.00	0.76	0.06
V_s	0.30	0.28	0.76	1.00	0.05
S_W	0.45	0.33	0.06	0.05	1.00

4.2. The influence of cracking

As has already been mentioned, the scatter in the detected values of f_c and V_s highlights the fact that some test results can be significantly influenced by the cracking distribution along the beam. There are many causes for this, including:

- The extraction operations of the beam specimen from the structure, particularly during the cutting process separating it from the building slab, which is carried out throughout the entire length of the specimen.
- Other accidental circumstances, particularly determining the observed major cracks.
- The distribution of stresses along the beam, particularly of bending moment, due to past gravity loads.

Great care was taken during beam extraction and transport, as well as in the drilling and preparation of the cores, so that cracking would not result from rough handling of the specimens (both beam and cores). Therefore, the role of past gravity loads needs to be examined in depth.

Fig. 9a shows the longitudinal view of the whole beam with the bending moment diagram that can be expected from past vertical loads. As can be observed, it is probable that the extracted part of the beam was prevailingly stressed by positive moment. Consequently, it is likely that micro-cracking due to tension stresses occurred along the lower part of the beam during its service life.

Fig. 9b shows the distribution of the measurements performed along the lower portion of the beam, arranged at the same scale of the drawing at Fig. 6a in order to better visualize the effect of bending moment on the test results (velocity values have been divided by 100 for representation needs). It should be noted that no measurements were made where major cracks were detected. Fig. 9b highlights an almost constant trend of V values and high variations of V_s along the beam. Specifically, the V_s values measured along the lower part of the beam have the same trend as the moment diagram. In fact, cracking due to flexure (perpendicular to the beam axis) interferes strongly with the propagation of ultrasonic waves in the longitudinal direction, thus influencing the velocity measured by surface transmission: the higher the moment values then the expected cracking, the lower the velocity values. On the other hand, there is no influence on the velocity measured by direct

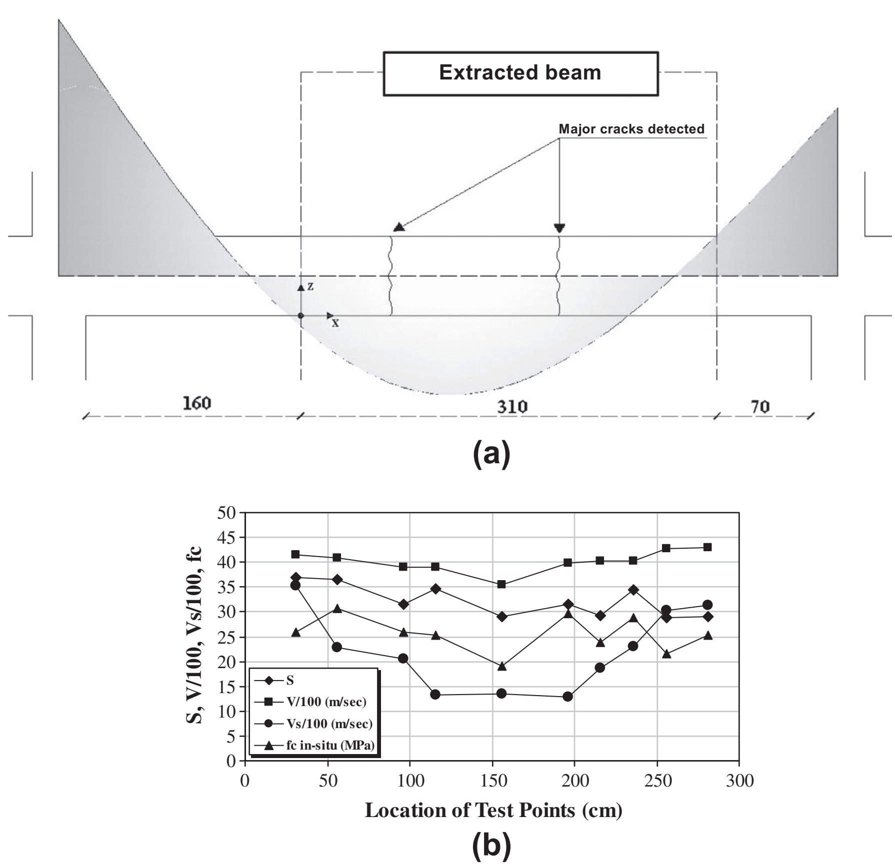

Fig. 9. (a) Qualitative bending moment due to vertical loads and (b) test results along the lower alignment (B–D)

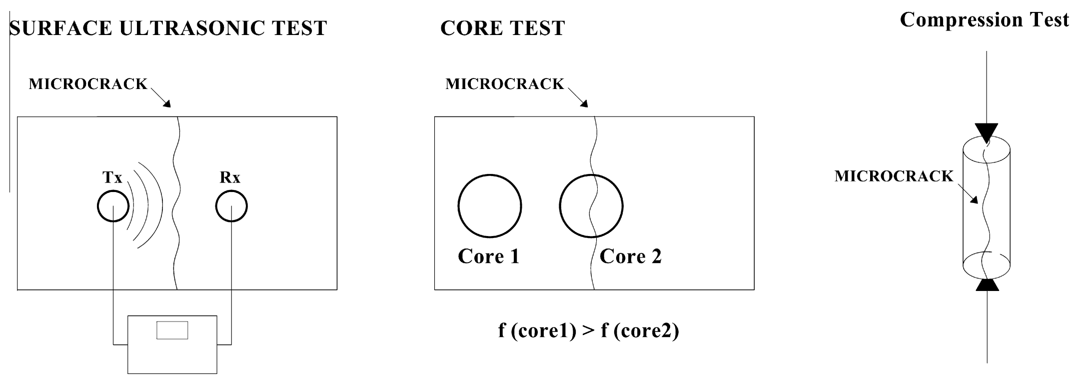

Fig. 10. Effects of micro-cracking on surface velocity values and core strengths.

transmission as the wave's direction is parallel to the cracking plane.

Finally, and more importantly, cracking can also be expected to impact on concrete strength, provided that cores are usually extracted perpendicularly to the beam axis: as the cracks are parallel to the principal axis of the compressive stress in the laboratory test (Fig. 10), test results can be affected determining variable strength values. However, in contrast with what was observed for V_s this effect does not show a regular trend because core strength is conditioned by the specific local conditions of the concrete inspected.

5. Conclusions

The present study reports and analyses the results of a wide experimental program carried out on a beam member extracted from an existing RC building structure due for demolition. The main goal of the study is the estimation of in situ concrete strength recognized as a crucial step in the structural assessment process. Specifically, the study is focused on investigating "real" structural members that can provide quite different results from those achieved on "realistic" specimens purposely prepared in laboratory. This approach merits great attention given its remarkable effects on the development of reliable code recommendations.

The role of some factors influencing the estimation of in situ strength is initially discussed with the main objective of defining criteria for this estimation through DT (core testing) and NDT (rebound number, direct and surface ultrasonic velocity) methods.

The experimental results show a low variability of the rebound number and direct velocity values along the beam member, with high within-member variability being detected for both surface velocity values and drilled core strengths. The wide scatter in some test results has been seen in relationship to the micro-cracking condition arising from past applied loads. On one hand, cracks due to flexure, which develop perpendicularly to the beam axis, do not affect the velocity measured by direct transmission (wave direction parallel to the crack plane). On the other hand, cracks interfere significantly with the propagation of ultrasonic waves in the longitudinal direction, thus decreasing the velocity measured by surface transmission. Besides, transverse cracking also affects core strength, provided that cores are usually extracted perpendicularly to the beam axis, thus tested under compression loads parallel to the micro-cracks plane.

The results confirm that estimating in situ concrete strength can be extremely difficult. Even the use of core testing can produce highly variable results largely as a consequence of local micro-cracking conditions. Because of this, a suitable combination of cores and NDTs appears to be the best solution to achieve reliable in situ concrete strengths.

Furthermore, the results emphasize the need to take great care in the location of measurement points within the structural members. They have to be placed in zones: (i) without apparent damage and/or cracking, (ii) at the points of lowest stresses due to applied loads, and (iii) representative of the average conditions of the concrete taking into account casting and ageing effects. In the beams that have only been subjected to gravity loads during their service life, the best points are located in the lower part of the member ends, provided that the presence of the adjacent RC slab does not permit drilling in the central upper part.

Finally, before drilling, detection of the possible presence of damage or cracking by carrying out surface velocity measurements is recommended.

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