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Knowledge Acquisition of Existing Buildings by Means of Diagnostic Surveying. Case Studies

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Abstract: The issue of assessing the structural safety of existing buildings involves several problems when a unique and reliable strategy of modelling and analyzing is looked for. This is mainly related to the peculiarity of each construction in a context of broad variety. In this light the structural model and consequently the judgment on structural safety should be derived from a process of knowledge of the construction carried through steps of different reliability. This paper focuses on a fundamental step of the knowledge acquisition process, which is the surveying campaign aimed at assessing some of the parameters to implement into the structural model (geometry, detailing and properties of the materials). The main aspects of a proper and effective planning of the diagnostic campaign are issued and discussed also with reference to some case studies. Special emphasis is given to the usefulness of non-destructive testing methods, the criteria underlying their selection and the relevance of their calibration.

Keywords: Existing Buildings, Knowledge Acquisition Process, Survey Planning, Non-Destructive Testing

Introduction

The assessment of the structural safety of existing buildings has become a topic of great interest in recent years, especially in Italy, due to the existing buildings heritage and to the numerous historic buildings that are in need of protection, extraordinary maintenance or consolidation. Not always, also because of the interventions over the years, the original design of the building is available to the engineer and above all, the mechanical properties of the load-bearing materials are not known.

In terms of international regulatory framework, the problem of verifying the persistence of buildings reliability over time is addressed by ISO 13822 (2010). The requirements and procedures outlined in ISO 13822 are based on the principles of structural reliability and the standard also includes specific recommendations for the assessment of buildings belonging to the artistic heritage of a territory.

To confirm the relevance of the topic, at European level, CEN Technical Committee 250 (CEN/TC 250) "Structural Eurocodes" has launched a specific Working Group (WG2) on "Assessment and retrofitting of existing structures", with the long-term goal of emanating a specific Eurocode. The work of WG2, recently published in Report EUR 27128 EN (2015), presents scientific and technical proposals to consider as a basis for further work aimed at achieving a harmonized European approach to the assessment and retrofitting of existing structures and identifies which key issues still require a solution. Among these: (i) the opportunity or not to accept different levels of reliability for existing constructions with respect to new constructions, (ii) the possibility to update the safety coefficients according to the level of knowledge taking into account the uncertainties innate in the updating process, (iii) the opportunity to assess the structural safety on the basis of knowledge levels, as well as required for seismic design (CEN EN 1998-3; 2013), also for other design situations. The work of the WG2 also contains a review of the various national standards and European standards concerning existing structures, which highlights a wide range of different and sometimes diverging positions about the approach to existing structures.

In Italy the Technical Standard for Construction – TSC in the following - (D.M.14/05/2008 and C.M.02/02/2009) includes a whole chapter devoted to the rules for assessing safety and designing interventions on existing buildings. The assessment of structural safety is achieved through a process of knowledge acquisition consisting of different and complementary steps.

This paper outlines some considerations regarding the process of knowledge acquisition proposed by the TSC, with special focus on the step concerning the evaluation of materials properties to use as parameters for implementing the numerical model of a reinforced concrete structure. The main aspects of a proper and effective assessment of these properties are issued and discussed also with reference to some case studies. Special emphasis is given to the usefulness of non-destructive testing methods, the criteria underlying their selection and the relevance of their calibration.

The Process of Knowledge Acquisition

The TSC defines three levels of increasing knowledge of an existing structure: (1) Limited, (2) Adequate and (3) Accurate. Focusing on reinforced concrete structures, the level of knowledge gained is determined by the degree of accuracy of the information relating mainly to three categories of parameters:

- Geometry, that is the layout of the structure (geometric dimensions of beams, pillars and walls, possible eccentricity between beams and pillars, arrangement of floor slabs, etc.)
- Structural details, as the quantity and arrangement of the reinforcements, the thickness of the concrete cover, the constraint conditions, etc.
- Properties of materials, as concrete compressive strength, yield point, tensile strength and ultimate strain of the reinforcements, etc.

The process of knowledge acquisition, as suggested by the TSC, consists of the following three main steps:

1. Research, collection and critical review of existing data and information, such as original designs and so on, in order to reconstruct the building process, the changes the building has undergone over time, the events that have affected the building over time
2. Geometric and structural survey, with the aim of clearly define the geometry of each element and of the overall building, the load-bearing frame, the type and extent of any damage if present
3. Determining the properties of materials, such as strength, stiffness, density.

The above mentioned last two steps and particularly the third, need the implementation of a diagnostic campaign consisting in tests and inspection to carry out both on site and in laboratory.

The achieved level of knowledge determines the method of analysis and the confidence factors *CF* to apply to the properties of the materials that have to be implemented in the numerical model of the structure. For example, the generic on site design strength f_d can be expressed as follows:

$$f_d = f_m / (CF.\gamma) \quad (1)$$

Where:

f_m = The mean value of the on-site strength measured by means of destructive and/or non-destructive testing
γ = The safety factor of the material
CF = The confidence factor directly dependent on the level of knowledge gained (1, 2 or 3).

Confidence factors are basically additional safety factors that take into account deficiencies in knowledge of the parameters of the structural model.

Contrary to the case of new constructions, for existing buildings the evaluation of the strength is not based on the characteristic value but on the on-site mean value. This mainly depends on the fact that the existence of the structure entails the possibility of determining the actual mechanical properties of the materials, which cannot be imposed as design data to obtain at the construction stage, likewise the case for a new construction. Therefore, an accurate knowledge phase reduces the uncertainties inherent in the transition from design data to implementation, typical of new constructions. In addition to this and especially for protected buildings, the number of tests that can be performed on site is generally restricted and does not allow to perform a statistical analysis of results significant enough for the purpose of applying probabilistic or semi-probabilistic methods. The definition of materials properties should therefore be framed in general procedures that allow to attribute significance to a single experimental data at worst.

The evaluation of on-site concrete compressive strength, as well as of reinforcements strength, plays a key role in assessing building safety. It is a quite complex task because strength depends on the materials in use and the technologies available at the time of construction, which may have a profound effect on the physical properties of the concrete and on its state of conservation. The evaluation of concrete compressive strength in existing buildings becomes necessary whenever building residual capacity, even seismic, has to be assessed, but also in cases of simple refurbishment. This evaluation is usually performed by compression tests carried out on specimens extracted from structural elements. Non-destructive tests can be performed additionally, with the aim of deepening the information and limiting the damage resulting from sampling on already degraded or protected structures.

Planning the Diagnostic Campaign

Knowing the building means to obtain analytical and objective data that, when properly and critically interpreted, allow for an integrated, synthetic and concrete reading of the construction, that is a crucial issue for making decision on any future work to carry out on the building.

The diagnostic process is a dynamic process. The results of a test may change the knowledge path and orient it differently depending on the qualitative and quantitative growth of knowledge. Therefore, the key role in the knowledge acquisition process is played by the methodological choices behind the implementation of the experimental tests, which should produce qualitatively and quantitatively data representative of the building. In the light of this, the planning of the diagnostic process becomes a crucial issue.

The methodological process that leads to the planning of a diagnostic campaign can be summarized as in Fig. 1.

More specifically, the planning of a diagnostic campaign requires the following methodological steps, that should be viewed in a dynamic perspective:

- Identify the information needed to overview the situation of the building and define design solutions
- Establish which tests can provide the appropriate answers
- Assess the feasibility of the tests in relation to the specific context and the cost-benefit ratio
- Identify the location of the tests and how the tests have to be carried out
- Assess the limits and approximations within the tests
- Interpret the results and define inputs for further works.

In this context, the designer of the diagnostic campaign assumes also the role of knowledge coordinator, that should be able to interact with the various specialists and technicians at the different stages of the process.

The Role of Non-Destructive Tests

The definition of the number and the location of the experimental tests is a crucial phase due to the need to find a compromise between the desired level of knowledge and the degree of admissible invasiveness of the tests. Test distribution should be statistically representative of the entire construction – or the specific element - but the higher the level of heterogeneity of the structure, the higher the degree of complexity of a reliable estimate of the characteristics of the structure itself starting from a limited sample.

In general, it is advisable to take few samples and make few measurements in the areas where the material is fairly homogeneous, reserving the largest number of samples in the non-homogeneous areas. Sampling must be planned in such a way as to best represent the variability of the construction, identifying areas that are sufficiently homogeneous during the preliminary stages of the knowledge acquisition process.

In this context, the use of non-destructive testing methods - a group of tests and examinations that can be carried out without significant interference with the condition of the tested object – is particularly advisable. These diagnostic methods are able to achieve the highest number of information about materials and structures without altering their condition as is the case, for example, when samples are extracted from the structural elements. The elastic and mechanical parameters of the materials, or the information on structural behavior, are estimated indirectly by correlations with other types of parameters non-invasively measured on site.

The TSC requires to determine the mechanical properties of the concrete by cores extraction (EN 12504-1, 2009), but it also suggests to carry out non-destructive testing methods, which have to be calibrated on the destructive ones. Other Italian standards and regulations (ReLUIS, 2012; C.S.LL.PP., 2017; UNI EN 13791, 2008) provide some guidance on how to perform the major non-destructive tests and the curves to be used to correlate the non-destructive parameter to the concrete compressive strength; the coefficients of these curves are determined by calibration of non-destructive parameters on the results of compression tests carried out on cores. In fact, the relationship between the non-destructive parameter and the concrete compressive strength can only be established after the definition of a specific and univocal correlation determined by means of the compressive strength of specimens properly extracted on site. Empirical or general correlations built in the laboratory on generic concretes different from the one constituting the specific element do not guarantee the correct prediction of the on-site strength.

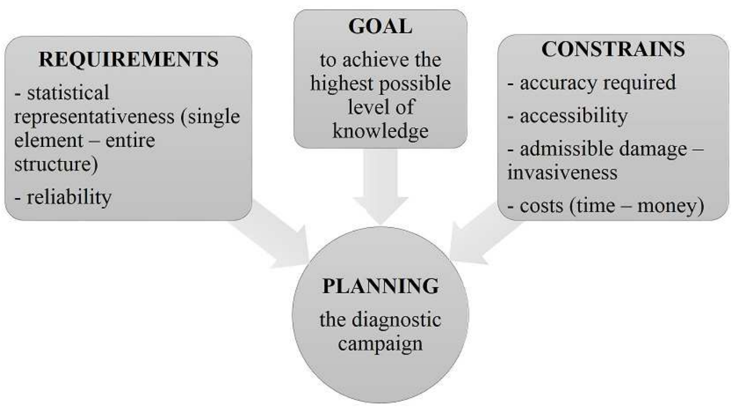

Fig. 1: Methodological process for the planning of a diagnostic campaign

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Among the non-destructive testing methods, the ones most commonly used for the assessment of concrete structures are the following:

- Rebound hammer test (EN 12504-2, 2012)
- Ultrasonic testing method (EN 12504-4, 2004)
- Electromagnetic bars detection (BS 1881-204, 1988)
- Infrared thermography (EN 16714-1; EN 16714-2; EN 16714-3, 2016).

In addition, the pull-out test (EN 12504-3, 2005), that is generally classified as a non-destructive test although it causes slight damage, is used.

The electromagnetic bars detection and the infrared thermography provide information concerning the structural details and the geometry of the structure, whereas the rebound hammer test, the ultrasonic testing method and the pull-out test measure parameters that can be correlated with the concrete compressive strength.

The TSC defines the number of samples or specimens to extract from the structural elements in order to assess the strength as a function of the level of knowledge and the size of the construction (floor's area, number of storeys). Recurring geometric and structural layouts and homogeneity of materials can be taken into account to vary – decreasing or increasing – the number of samples. Moreover, the TSC allows to replace some destructive tests, no more than 50%, with a larger number, at least three times, of non-destructive tests calibrated on destructive ones. According to these regulations, the preliminary in-depth inspection of the structure – visual inspection, geometric survey, analysis of available data, non-destructive testing for defining structural details – allows the planning of the tests (both destructive and non-destructive) according to the specific construction conditions, minimizing the impact on the structure.

Case Studies

The process of knowledge acquisition has been implemented on two reinforced concrete buildings: a hotel (Fig. 2-5) and a council housing building (Fig. 6 and Fig. 7).

In both cases the process has been planned and implemented in order to achieve an adequate knowledge of the structures, that corresponds to a level of knowledge equal to 2 according to the TSC.

Regarding the assessment of concrete compressive strength, the number of concrete specimens to extract from the structural elements and to undergo to compressive test depends on the chosen level of knowledge and the size of the building (floor area), but, as previously mentioned, it can be varied according to the results of some preliminary tests and analysis.

Case 1: The Hotel

After collecting and critical reviewing the existing data and information regarding the building, the construction has been carefully visually inspected and non-destructively tested by the electromagnetic bars detection. The results of this preliminary phase allowed to find out the presence of recurring geometric and structural layouts along with homogeneous areas, for example in terms of concrete age. These findings led to the definition of the number of concrete cores, the type and the number of non-destructive testing and the location of the tests (pillars and beams tested are showed in Fig. 3-5), as summarized in Table 1. The following non-destructive testing methods have been carried out on the building: Ultrasonic Testing (UT), Rebound hammer test (R), Pull-Out test (PO).

It can be inferred from Table 1 that the preliminary phase and the planning of the diagnostic campaign allowed to decrease the number of cores extracted with respect to that expected according to the TSC.

For information, Table 2 shows very briefly the results of the tests.

According to the current standards, the non-destructive tests should be calibrated on the destructive ones to allow their use for estimating the mechanical characteristics of concrete. For this reason, the non-destructive parameters specified in Table 2 have been correlated to the compressive strength of the extracted cores. Three types of correlation have been analyzed: single-variable, double-variable and multiple-variable. Results of the correlation are shown in Table 3.

As can be noted, the coefficient of determination ranges between 0.44 and 0.68 and the highest value is reached by the multiple-variable correlation, in which the concrete compressive strength is estimated by using all three non-destructive parameters.

The correlation formulas allow to estimate the compressive strength of concrete elements for which the cores extraction has not been carried out. As an example, Table 4 reports the values of the concrete compressive strength for the pillars of the basement floor. This floor has thirteen pillars, only two of which have been tested by the core extraction; all of them have been tested by R, two have been tested by UT and four by PO.

Case 2: The Council Housing Building

The knowledge acquisition process and the planning of the diagnostic campaign have been carried out in the same way of the case 1.

Firstly, the existing data and information regarding the building have been collected and critically reviewed, then the construction has been carefully visually inspected and non-destructively tested by means of the electromagnetic bars detection method. The visual inspection highlighted a very high level of damage, that led to increase the number of extracted cores with respect to that expected according to the TSC.

Fig. 2: Front view of the hotel

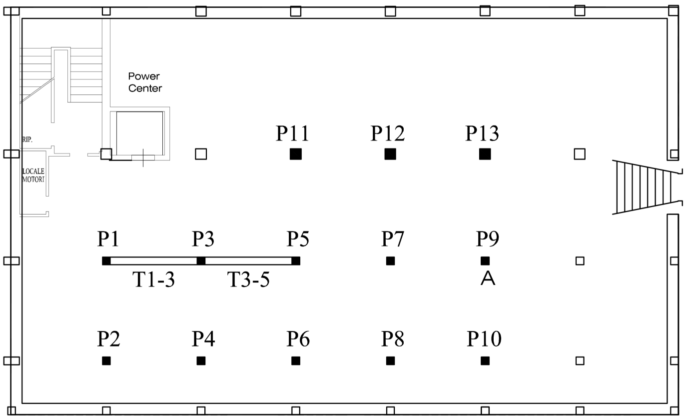

Fig. 3: Basement of the hotel

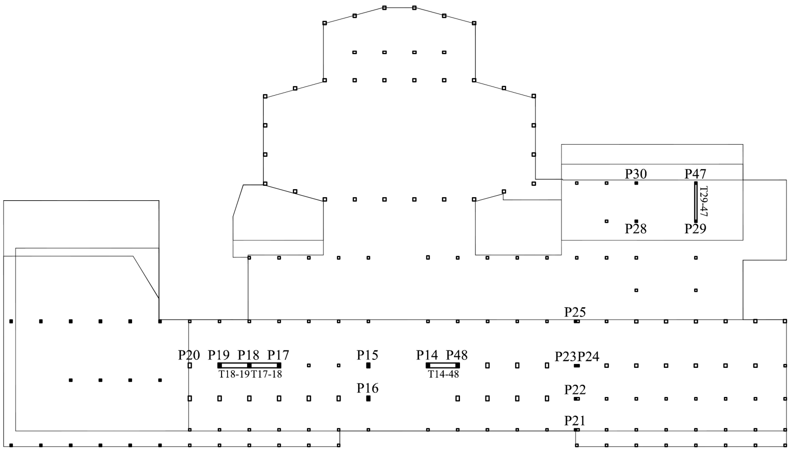

Fig. 4: Ground floor of the hotel

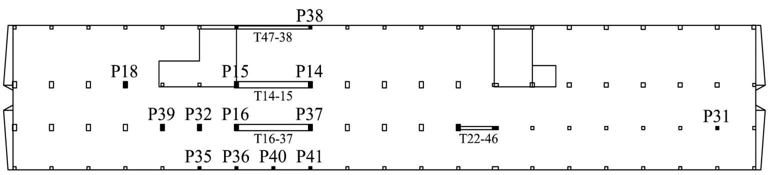

Fig. 5: Type floor of the hotel

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Fig. 6: Front view of the council housing building

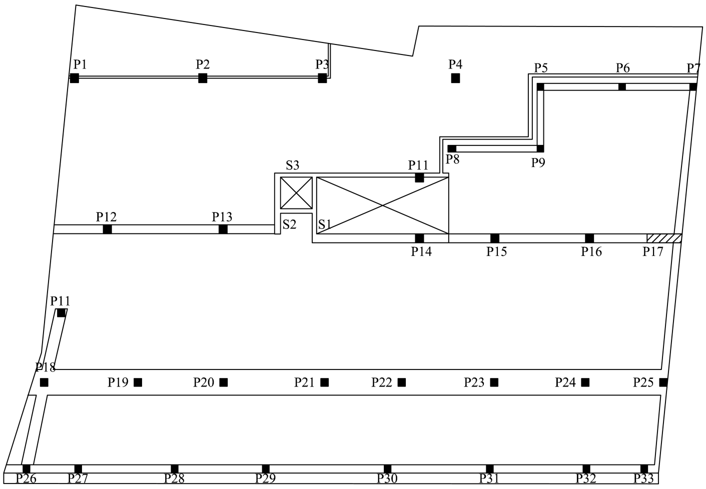

Fig. 7: Type floor of the council housing building

Table 1: Type and number of tests

Floor	Expected concrete samples	Extracted cores	UT	R	PO
Basement	3	3	4	15	4
Ground	12	6	5	18	8
Second	6	2	2	13	1
Third	6	2	2	8	1
Forth	6	2	2	6	1
Total	32	15	15	60	15

Table 2: Summary of the results

Test	Parameter	Mean	Standard deviation	Coeff. of variation
Compressive test on cores	f_c[a]	22.68	5.16	0.23
UT	V[b]	3654.89	276.01	0.07
R	Ir[c]	38.06	4.27	0.11
PO	F[d]	31.06	5.36	0.17

a. f_c (N/mm^2) is the compressive strength
b. V (m/s) is the propagation velocity of ultrasonic signals
c. Ir is the rebound index
d. F (kN) is the extraction force

Table 3: Correlations results

NDT parameter	Correlation formula suggested by Italian standards	r^2
V	$f_{est} = a + e^{b \cdot V}$	0.60
Ir	$f_{est} = a + Ir^b$	0.57
F	$f_{est} = a + b \cdot F$	0.44
V, Ir	$f_{est} = a + b \cdot Ir + c \cdot V$	0.60
V, F	$f_{est} = a + b \cdot V + c \cdot F$	0.67
Ir, F	$f_{est} = a + b \cdot Ir + c \cdot F$	0.59
V, Ir, F	$f_{est} = a + b \cdot V + c \cdot Ir + d \cdot F$	0.68

- f_{est} is the estimated concrete strength
- a, b, c, d are numerical coefficients determined by means of the least squares method
- r^2 is the coefficient of determination

Table 4: Estimated compressive strength

Floor	Pillar	f_c	$f_{est,V}$	$f_{est,Ir}$	$f_{est,PO}$	$f_{est,Comb}$
Basement	1			22.9	23.8	22.9
	2	19.8	19.9	21.7	21.1	19.0
	3			19.4		19.4
	4			22.1		22.1
	5	21.2	20.9	22.0	18.7	20.7
	6			24.4		24.4
	7			21.8		21.8
	8			20.9		20.9
	9			21.0		21.0
	10			23.5		23.5
	11			22.7		22.7
	12			20.5		20.5
	13			20.9	19.7	18.7

- f is in N/mm^2
- $f_{est,Comb}$ is estimated by using the single-variable, the double variable or the multiple variable correlation depending on the number of non-destructive tests carried out on the element

The number of cores, the type and the number of non-destructive testing and the location of the tests are summarized in Table 5.

For information, Table 6 shows very briefly the results of the tests.

Then, non-destructive parameters have been correlated to the concrete compressive strength of the extracted cores by using single-variable, double variable and multiple-variable correlation, as shown in Table 7.

As can be noted, the coefficient of determination ranges between 0.12 for the sole R test and 0.77 for the double-variable correlation by using R and UT.

As stated for the case 1, the correlation formulas allow to estimate the compressive strength of concrete elements for which the cores extraction has not been carried out. As an example, Table 8 reports the values of the estimated concrete compressive strength for some pillars of the ground floor of the building. The sample consists of nine pillars, five of which have been tested by the core extraction; all of them have been tested by R, seven have been tested by UT and seven by PO. It is worth noting that the level of damage pointed out during the preliminary analysis of the building has led to a general increasing, with respect to case 1, of the number - related to the number of elements - of both destructive and non-destructive tests.

Table 5: Type and number of tests

Floor	Expected concrete samples	Extracted cores	UT	R	PO
Ground	2	7	7	9	8
First	3	8	8	15	10
Second	3	6	11	19	15
Third	3	5	9	18	16
Total	11	26	35	61	49

Table 6: Summary of the results

Test	Parameter	Mean	Standard deviation	Coeff. of variation
Compressive test on cores	f_c^a	24.92	6.85	0.27
UT	V^b	3170.72	439.83	0.14
R	Ir^c	32.21	4.74	0.15
PO	F^d	31.70	7.29	0.23

- f_c (N/mm^2) is the compressive strength
- V (m/s) is the propagation velocity of ultrasonic signals
- Ir is the rebound index
- F (kN) is the extraction force

Table 7: Correlations results

NDT parameter	Correlation Formula suggested by Italian Standards	r^2
V	$f_{est} = a + e^{b \cdot V}$	0.66
Ir	$f_{est} = a + Ir^b$	0.12
F	$f_{est} = a + b \cdot F$	0.43
V, Ir	$f_{est} = a + b \cdot Ir + c \cdot V$	0.77
V, F	$f_{est} = a + b \cdot V + c \cdot F$	0.76
Ir, F	$f_{est} = a + b \cdot Ir + c \cdot F$	0.41
V, Ir, F	$f_{est} = a + b \cdot V + c \cdot Ir + d \cdot F$	0.72

- f_{est} is the estimated concrete strength
- a, b, c, d are numerical coefficients determined by means of the least squares method
- r^2 is the coefficient of determination

Table 8: Estimated compressive strength

Floor	Pillar	f_c	$f_{est,V}$	$f_{est,Ir}$	$f_{est,PO}$	$f_{est,Comb}$
Ground	1	33.4	25.1	26.6	28.4	28.5
	9		25.6	27.1	32.6	31.3
	11	28.5		25.1	23.4	23.1
	13		26.1	26.6	30.0	29.5
	15	26.1	25.0	24.9		23.2
	23	19.7		25.6	25.7	25.1
	30	27.3	29.4	25.9	23.5	28.5
	31		26.6	26.6	26.3	29.4
	33		26.5	27.2		31.3

- f is in N/mm^2
- $f_{est,Comb}$ is estimated by using the single-variable, the double variable or the multiple variable correlation depending on the number of non-destructive tests carried out on the element

As can be inferred from Table 8, the variance between f estimated by the correlation formula and f derived from compression tests on concrete cores is evident. This output can be ascribed to the level of damage and the non-homogeneity of the construction.

Concluding Remarks

The considerations presented and the brief analysis of the two case studies allow to draw some concluding remarks:

1. The planning of the diagnostic surveying should follow the acquisition of some preliminary data, such as:

    - General and specific information already available
    - Geometric survey
    - Visual inspection results
    - Identification of homogeneous areas.

2. The selection of the diagnostic testing method should follow the analysis of some aspects, such as:

    - Information available
    - Required accuracy
    - Admissible level of invasiveness
    - Costs.

3. Non-destructive testing methods are powerful tools. They can be used both for qualitative purpose (comparison, preliminary tests for identifying homogeneous areas) and quantitative purpose (mechanical properties of the material); in this last case the calibration is mandatory.
4. The calibration of non-destructive testing methods is an essential step necessary for extending testing results to broader samples and estimating mechanical and physical properties.
5. Finally, it can be stated that the diagnostic campaign is an essential part of the knowledge acquisition process concerning existing buildings and it:

    - Has to be accurately planned
    - Has to be considered, in effect, a design process
    - Claims experienced specialists and sometimes multidisciplinary staff (historical buildings, protected buildings, etc.)
    - Needs a budget proportional to the type and the amount of work.

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Author's Contributions

The authors contributed equally to the work presented in this paper.

Ethics

The Authors declare there is not conflict of interest.

References

CEN Technical Committee 250, 2018. https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:6231&cs=1475B1C21B51CE51CCD000F68519ABE9C
ISO 13822, 2010. Bases for design of structures - Assessment of existing structures.
EUR 27128 EN, 2015. New European Technical Rules for the Assessment and Retrofitting of Existing Structures: Policy Framework, Existing Regulation and Standard, Prospect for CEN Guidance.
CEN EN 1998–3, 2013. Eurocode 8 - Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings. Brussels.
Ministry of Infrastructures, 2008. Ministerial Decree (D.M.14/01/2008). Technical Standard for Construction. Suppl. Ord. n.30 G.U. n.29 4/2/2008 (in Italian).
Ministry of Infrastructures, 2009. Ministerial Circular (C.M.02/02/2009). Instruction for the application of new Technical Standard for Construction. Suppl. or. n.27 G.U. n.47 26/2/2009 (in Italian)
EN 12504-1, 2009. Testing concrete in structures - Part 1: Cored specimens - Taking, examining and testing in compression
ReLUIS, 2012. Linee guida per modalità di indagine sulle strutture e sui terreni per i progetti di riparazione, miglioramento e ricostruzione di edifici inagibili. ISBN 978-88-89972-30-4 (in Italian)
C.S.LL.PP., 2017. Linee guida per la valutazione delle caratteristiche del calcestruzzo in opera. (in Italian)
UNI EN 13791, 2008. Assessment of in-situ compressive strength in structures and precast concrete components.
EN 12504-2, 2012. Testing concrete in structures - Part 2: Non-destructive testing - Determination of rebound number.
EN 12504-4, 2004. Testing concrete - Part 4: Determination of ultrasonic pulse velocity
BS 1881-204, 1988. Testing concrete. Recommendations on the use of electromagnetic covermeters
EN 16714-1, 2016. Non-destructive testing - Thermographic testing - Part 1: General principles
EN 16714-2, 2016. Non-destructive testing - Thermographic testing - Part 2: Equipment
EN 16714-3, 2016. Non-destructive testing - Thermographic testing - Part 3: Terms and definitions
EN 12504-3, 2005. Testing concrete in structures - Part 3: Determination of pull-out force.