ASSOCIAZIONE NAZIONALE ITALIANA DI
INGEGNERIA SISMICA
ANIDIS
Italian National Association of Earthquake Engineering

XVIII CONVEGNO ANIDIS
L'ingegneria sismica in Italia
ASCOLI PICENO 2019
15-19 Settembre

Assessment of concrete compressive strength using non-destructive test measurements

Andrea Miano[a], Fatemeh Jalayer[a], Andrea Prota[a]

[a] *Università degli Studi di Napoli Federico II, Dipartimento di Strutture per l'Ingegneria e l'Architettura, Via Claudio 21, 80125 Napoli, Italy*

Keywords: Existing RC buildings, knowledge levels, destructive and non-destructive tests, Bayesian updating

ABSTRACT

Evaluation of the uncertainty related to concrete compressive strength is one of the important aspects in the seismic assessment of an existing RC building. This works aims to characterize the compressive concrete strength based on both in-situ destructive and non-destructive test measurements. A large database of the (destructive) core tests and SONREB (hammer rebound and ultrasonic pulse measurements) non-destructive test results for the same structural elements has been gathered from different existing RC buildings mainly located in Campania region, Italy and constructed in the last century between the decades 30' and 90'. A regression model is employed in order to derive predictive expressions for calculating the compressive concrete strength based on the ultrasonic test measurements. The paper further investigates the quantification in terms of relative weights of the concrete strength based on ultrasonic test results for seismic performance assessment of existing RC buildings. The calculated relative weights for ultrasonic tests are compared with the NTC 2018 code recommended relative weights of 1 and 1/3 for destructive and non-destructive tests, relatively.

1 INTRODUCTION

The knowledge process, particularly in a seismically active zone, is the one of the most important steps in the assessment of existing buildings. This process is generally realized through a campaign of in situ tests on the structural members. The goal of this detailed experimentation campaign is to have a complete characterization of the existing structure. This work focuses on the estimation of the in situ compressive concrete strength for existing RC buildings. The compressive strength of concrete, which has a key role in the seismic performance of the building, is usually difficult and expensive to estimate. The principal test categories for the structural concrete are non-destructive and destructive methods. The most common methods for existing buildings include core testing as destructive test and rebound number and ultrasonic pulse velocity (generally obtained in the same tests through SONREB technique) as non-destructive tests. The non-destructive methods can be performed directly on in-situ concrete without removal of a sample, although removal of surface finishes is likely to be necessary. Specifications to execute and apply them in concrete structures are given in several standards (e.g. in Italy UNI EN 12504-2, 2001; UNI EN 12504-4, 2005). The destructive tests are instead in the category of methods requiring sample extraction. Samples are most commonly taken under the form of cylinders extracted from the structure. Such samples are tested in the laboratory for evaluating strength and performing chemical analysis. Some chemical tests may be performed on smaller drilled powdered samples taken directly from the structure, thus causing substantially less damage, but the risk of sample contamination is increased and precision may be reduced (Bungey and Grantham, 2014). Specifications to execute and use core testing are given in several standards (e.g. in Italy UNI EN 12504-1, 2002).

The mechanical properties of the structural concrete have been heavily investigated in the past. Many studies in different parts of the world presented various methods for investigation and processing of the related results, based on their experimental studies. Important studies were conducted in the 1980s by Facaoaru in Europe (eg 1984) and later from Bartlett and McGregor in the United States (e.g., 1996, 1997). However, the results of these research efforts are not directly applicable to the Italian buildings stock, given the differences with that of the countries where these studies have been developed. With specific reference to Italy, there is a vast literature on the topic starting from 1980s (e.g., Bocca and Cianfrone, 1983), 1990s (e.g., Braga et al., 1992; Di Leo and Pascale, 1994) and more recently (e.g., Del Monte et al., 2004; Masi, 2005; Masi et al., 2007; Masi and Vona 2009). Using the ultrasonic velocity and rebound number, the compressive concrete strength is estimated using nonlinear regressions. Such regressions are provided in the RILEM standard (1993) with reference to a concrete of standard features and can also be found in several works in literature (for example, Gasparik, 1992; Di Leo and Pascale, 1994; Del Monte, 2004).

This works aims to (a) characterize the compressive concrete strength based on in-situ non-destructive test measurements; (b) calculate their relative weight with respect to the destructive tests.

A large database of the (destructive) core tests and SONREB (rebound number and ultrasonic pulse measurements) non-destructive test results for the same structural elements has been gathered from different existing RC buildings mainly located in Campania region, Italy and constructed in the last century between the decades 30' and 90'. A regression model is employed in order to derive predictive expressions for calculating the compressive concrete strength R_c based on the ultrasonic velocity V and on the rebound number S measurements. In particular, both linear ln(V)-ln(R_c) and multilinear ln(V)-ln(S)-ln(R_c) regressions are derived, using the ultrasonic velocity and rebound number values in order to obtain the compressive concrete strength based on the available database. The paper further investigates the implementation of the concrete strength based on ultrasonic test results and the relative measurement error in a probabilistic framework for seismic performance assessment of an existing construction (see also Ebrahimian et al. 2019). Then, the relative weights of non-destructive tests for the compressive concrete strength calculation are calculated based on this probabilistic framework and compared with the relative weights of 1 (destructive tests) and 1/3 (non-destructive tests) recommended in the NTC2018 Commentary (Circolare 2019).

The work shows that linear logarithmic regression (V-R_c) can be used instead of the multilinear logarithmic regression (V-S-R_c) without significant loss of accuracy. Moreover, the results show that the effective weights of the non-destructive tests can be significantly different from the code-recommended values.

2 METHODOLOGY

2.1 Linear and multilinear logarithmic regressions based on a large database of in-situ non-destructive tests

This section is related to the methodology applied to the large database of tests collected. Later on, Section 3.1 describes in detail the typology of the considered tests and the specifications/recommendations for their application.

2.1.1 Converting the strength of a core specimen f_{core} into the equivalent in-situ values f_c and R_c

The specifications to use core testing are given in several standards (e.g. in Italy UNI EN 12504, 2002). Although core testing is the most direct and reliable method to estimate concrete strength in a structure, it has to be taken into account that there are many differences between the strength measured on core specimens and the actual in-situ strength. The main factors are the size and geometry of the cores, the coring direction, the presence of reinforcing bars or other inclusions, the effect of drilling damage (Dolce et al. 2006, Masi et al. 2009). To this purpose, a relationship to convert the strength of a core specimen f_{core} into the equivalent in-situ value fc is given in Dolce et al., (2006):

$$f_c = (C_{H|D} \cdot C_{dia} \cdot C_a \cdot C_d) \cdot f_{core} \tag{1}$$

where:

− $C_{H/D}$ is the correction for height/diameter ratio H/D, equal to 2/(1.5+D/H);

− C_{dia} is the 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;

− C_a is the 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 is the correction for damage due to drilling.

The correction coefficient C_d asks for particular attention. As described in Masi et al. 2009, considering that the lower the original concrete quality, the larger would be the drilling damage, it appears more suitable to put C_d = 1.20 for f_{core} < 20 MPa, and C_d = 1.10 for f_{core} > 20

MPa, as suggested in Dolce et al. (2006). More recent results are provided in Masi et al. (2008), where the possible reduction in core specimen strength due to drilling damage has been examined on the basis of a wide experimental database. Finally, it is to note that with respect to the Italian guidelines for the assessment of in situ concrete strength (Linee Guida 2012 and Linee Guida 2017), the factor that takes into account the humidity of the specimen is neglected, due to absence of data about the conservation of the specimen after the extraction.

A factor of 0.83 is suggested from NTC 2018 to convert cylinder to cube strength for normal strength concrete:

$$R_c = f_c \cdot 0.83 \tag{2}$$

This conversion is particularly useful because almost all the literature regression expressions, that correlate the ultrasonic velocity and the rebound index to the concrete strength, use the cube strength for concrete. It has to be mentioned that there a large amount of literature on f_c to R_c mapping (e.g., Braga 1992, Faella et al., Collepardi 2002). However, we have adopted herein the conversion presented in Eq. 2 which is based on the proposals from (Masi 2005) and ACI 214.4-R03. It is note that, given the linear relationship in Eq. 2, the standard deviation and coefficient of determination of the logarithmic regression remain invariant with respect to the use of f_c or R_c (see the following section for more details).

2.1.2 Linear and Multilinear Logarithmic Regressions

Linear least squares regression is a mathematical procedure for finding the best-fitting line (a.k.a., *the linear regression prediction*) to a given set of points by minimizing the *sum of the squares* of the *residuals* (offsets) of the data points from the line. The *sum of the squares* of the residuals is used instead of the (sum of) offset absolute values since it allows the residuals to be treated as a continuous differentiable quantity. Conventional linear regression with least square is used herein to find the relationship between the equivalent in-situ compressive concrete strength R_c and the ultrasonic velocity V. However, since the concrete strength is a positive definite number, we have chosen to apply the regression in the natural logarithmic scale. This is a widely used approach in literature (Jalayer et al. 2017, Miano et al. 2018). This is equivalent to fitting a power-law curve to the R_c-V response in the original (arithmetic) scale. This results in a curve in arithmetic scale that predicts the median R_c value for a given value of the velocity V:

$$\ln R_c = \ln(a) + b \cdot \ln(V) = \ln(\mathrm{a}\mathrm{V}^{\mathrm{b}}) \tag{3}$$

$$R_c = a \cdot V^b \tag{4}$$

where $\ln(a)$ and b are the linear regression constants. The logarithmic standard deviation $\beta_{Rc|V}$ can be estimated as the root mean sum of the square of the logarithmic residuals with respect to the regression prediction:

$$\beta_{Rc|V} = \frac{\sqrt{\sum_{i=1}^{n} (\ln \frac{R_{ci}}{a \cdot \mathrm{V}_i^b})^2}}{n-2} \tag{5}$$

where R_{ci} and V_i are the the equivalent in-situ compressive concrete strength values and the corresponding ultrasonic velocity values used inside the regression. It is to note that the standard deviation of the regression is constant with respect to the ultrasonic velocity over the entire range of the ultrasonic velocity values.

One of the most well-known measures, that indicate how well the sample regression line fits the data, is called *coefficient of determination* or the R-square (R^2). The R^2 is defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(\ln R_{c,i} - \overline{\ln R_c \,|\, V} \right)^2}{\sum_{i=1}^{n} \left(\ln R_{c,i} - \overline{\ln R_c} \right)^2} = 1 - \frac{\sum_{i=1}^{n} \left[\ln R_{c,i} - \left(\ln a + b \ln \mathrm{V}_i \right) \right]^2}{\sum_{i=1}^{n} \left(\ln R_{c,i} - \overline{\ln R_c} \right)^2} \tag{6}$$

R^2, which varies between zero and one, provides a measure of variance reduction provided by means of the regression. In particular, if we have a perfect fit, $R^2 \approx 1$. If $R^2 \approx 0$, we have a poor fit.

In many applications, there is more than one factor that influences the response. Thus, the multilinear regression model describes how a single variable R_c depends linearly on a number of predictor variables. In this case, the rebound index (S) and the ultrasonic velocity (V) are used as predictor (a.k.a., independent) variables:

$$\ln R_c = \ln(a) + b \cdot \ln(S) + \mathrm{c} \cdot \ln(V) = \ln(\mathrm{a} \cdot \mathrm{S}^{\mathrm{b}} \cdot \mathrm{V}^{\mathrm{c}}) \tag{7}$$

2.2 *Weights of non destructive tests for the compressive concrete strength calculation*

The procedure for calculating the relative weight of non-destructive test respect to a destructive test performed on the same building (or same floor) is presented in Ebrahimian et al. 2019. The basic underlying concept is to obtain a weight to be applied to a non-destructive test so that it acquires the same reliability of the destructive test. The procedure relies on a logarithmic regression model of the ultrasonic resistance $R_{ultrasonic}$ versus the destructive test resistance R_c measured at the same location. This helps in characterizing the conditional probability of $R_{ultrasonic}$ given R_c. The equivalent weight of a given ultrasonic test with respect to the non-destructive test is calculated as the ratio of the likelihood of observing the ultrasonic test results –calculated based on the conditional probability described right above-- and the likelihood of observing the ultrasonic test results assuming that it has no measurement error (i.e., essentially treating it as a destructive core test).

3 APPLICATION

3.1 *The database*

The database of test results consists of 193 data points. These data have been taken from 16 different buildings. The buildings have been built in the past century in a range of time spanning from the 1930's to the 1990's in the Campania region. The classes of use of the buildings are different and are mainly related to Class II and III of use defined in NTC 2018. The tests have been performed on RC beams, columns and walls. Table 1 summarizes the data (for reasons of privacy, more specific information about the buildings cannot be shared). BI is the abbreviation for Building Information; CP is the abbreviation of Construction Period. It is to note that for the tests related to building 8, the information about the year and the type of structural member is not available (however, it is confirmed that the tests refer to an existing RC frame structure). Moreover, the CP for buildings 7 and 12 is not available. The data for the most part is taken from personal communications of different engineers. A small amount of the data is related, instead, to tests available in literature (in particular, Building 3 is related to the data from Masi et al. 2007, Building 8 is related to the data from Brognoli 2007, Building 12 is related to the data downloaded from (www.mot1.it/sistemi/documenti/indagini_materiali/.../11_SonReb_Combinato.xlsm). It is to note that the majority of the ultrasonic tests are direct tests. Finally, the number of the tests corresponding to the same building is less than or equal to 30.

Table 1: The database of the used tests.

BI	CP	Total number of tests	Number of tests on beams	Number of tests on columns	Number of tests on walls
1	60'-70'	18	8	10	0
2	60'-70'	21	11	10	0
3	70'	3	3	0	0
4	70'	9	4	5	0
5	80'-90'	26	0	5	21
6	70'-80'	21	19	2	0
7	-	3	3	0	0
8	-	10	-	-	-
9	80'	17	0	0	17
10	60'-70'	7	5	1	1
11	30'-40'	3	1	2	0
12	-	4	1	3	0
13	90'	30	3	21	6
14	30'-40'	4	2	2	0
15	30'-40'	3	1	2	0
16	30'-40'	14	6	8	0

For all the 193 data points, f_c from destructive core tests, ultrasonic velocity V and rebound number S from non-destructive tests are available. They are obtained from the same structural member.

3.2 *Results and comparisons*

3.2.1 *Regression predictive equations*

In this section, the linear and the multilinear logarithmic regressions applied to the 193 data points are presented. It is to note that given the building-to-building variability in in-situ concrete properties, it would be more appropriate to use a random effects type of regression for characterizing both the intra-building and the inter-building variabilities in the concrete properties. This preliminary work instead applies the simple linear regression; hence, the resulting error of regression encompasses both the intra-building and inter-building variabilities. Strictly, speaking, the regression prediction is not applicable to a single building as each building might have a different and distinct characterization of non-destructive parameters versus the concrete strength. However, in lieu of building-specific calibration of the non-destructive versus destructive tests, the regression prediction –albeit imperfect-- is going to prove quite useful.

Figure 1 shows the scatter plots for tests data={(V_i , $R_{c,i}$), i=1:193}. The different sets of data (for a specific building) are represented with different colours and numbers (the numbers correspond to the building IDs in Table 1). Moreover, the figure illustrates the regression prediction model (i.e., regression line in dark grey solid line and the estimated parameters, a, b, and β, see Equations 3-5) fitted to the data. The coefficient of determination or the R-square is also reported in the figure. Figure 2 shows the linear regression between the cylindrical compressive concrete strength f_c (not used hereafter in favour of having a direct comparison with the literature regressions in terms of R_c) and the velocity.

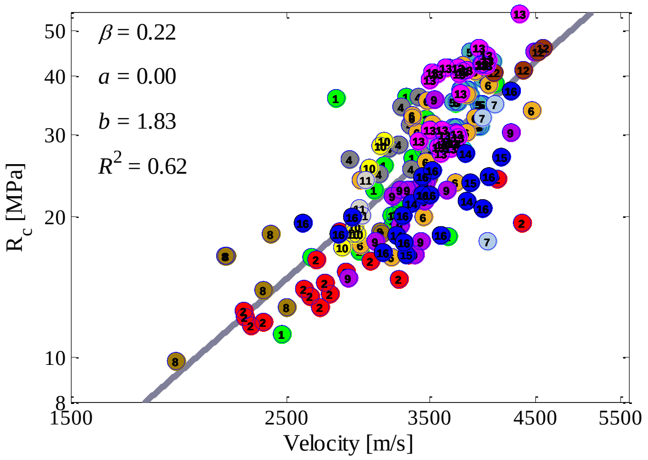

Figure 1: The linear logarithmic regression between Rc and ultrasonic velocity V.

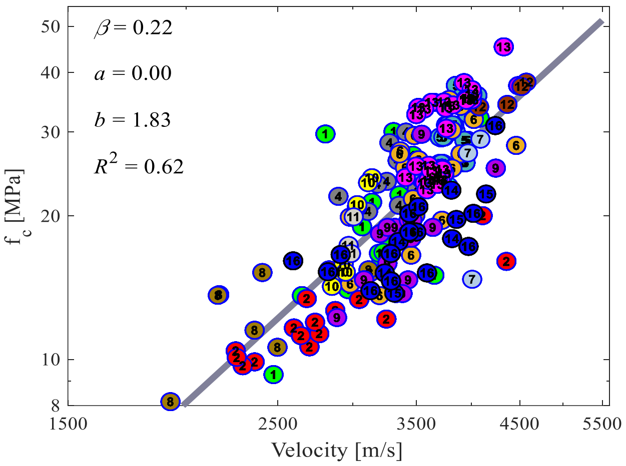

Figure 2: The linear regression between fc and ultrasonic velocity V.

Figures 3 and 4 show the scatter plots for test data={(S_i, V_i, $R_{c,i}$), i=1:193} on natural logarithmic scale. In Figure 3, the plot is for a constant rebound number S, equal to 40.8, i.e., mean of the 193 data. In Figure 4, instead, the plot is obtained for a constant the ultrasonic velocity V, equal to 346 m/s, that is, the mean of the 193 data. The different sets of the data are represented with different colours (the numbers correspond to the number of the building in Table 1). Moreover, the figure illustrates the regression prediction model (i.e., regression line in blue solid line and the estimated parameters, a, b, c and β, see Equation 7) fitted to the data. Finally, the coefficient of determination or the R-square is presented in the figure. Figure 5, instead, presents the 3D plot of the multilinear logarithmic regression.

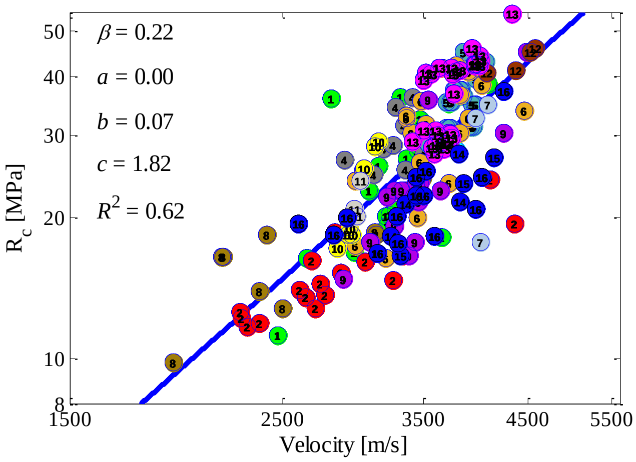

Figure 3: The multilinear regression shown with constant S=40.8.

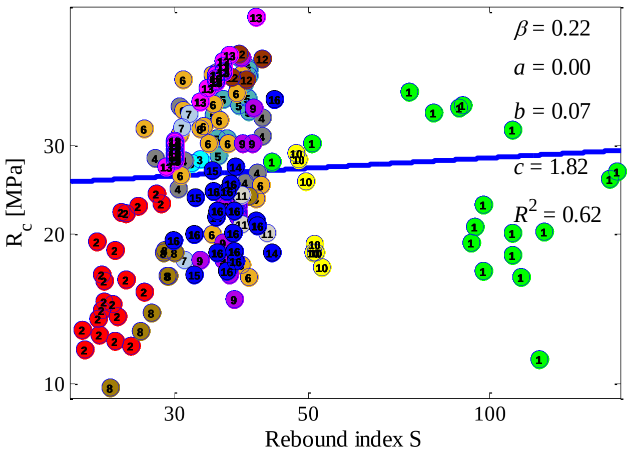

Figure 4: The multilinear regression shown with constant V=346 m/s.

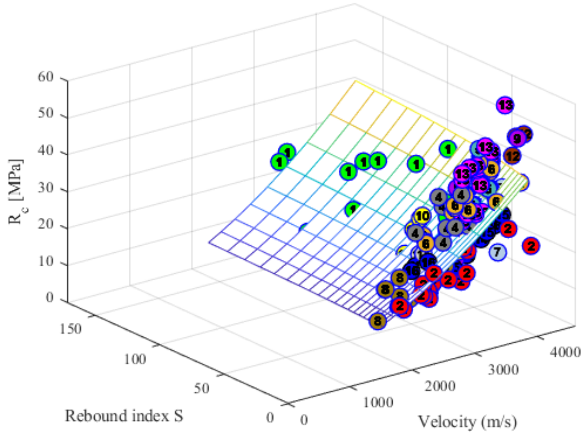

Figure 5: The multilinear logarithmic regression in the 3D space.

In order to check the significance of the rebound index S in the regression, a one-sided p-value test is performed (Rice, 1995, Jalayer, 2003). This test is performed herein on the possible trend between the two sets of residuals: a) logarithmic residuals of R_c given V, based on the original linear regression between R_c and V; b) logarithmic residuals of Rebound Index S (considered as a potential independent variable) on ultrasonic velocity V. One way for measuring significance of the trend between the two sets of logarithmic residuals is to test the following hypothesis: *"The slope of the regression line is zero"* (i.e., test of hypothesis, see Rice, 1995). The significance of the slope is usually measured by a quantity known as the p-value, assuming that the slope of the regression line is a random variable described by Student's t-distribution (see Rice, 1995). The hypothesis is rejected (i.e., the slope is non-zero) if the p-value is smaller than a certain (small) value, e.g., 0.01. Figure 6 shows the logarithmic residual-residual plot, considering S as a (potential) independent variable and checking its significance (i.e., checking whether S can help in describing a part of variability –in regression residuals-- that is not already captured by ultrasonic velocity). The p-value turns out to be quite high, therefore, the rebound index S is low is not statistically significant as a second independent regression variable. This conclusion is also corroborated by the very small R-squared value reported for the logarithmic residual-residual plot. Therefore, for the rest of the paper, we are going to use the linear logarithmic regression based on ultrasonic velocity V as the only independent variable.

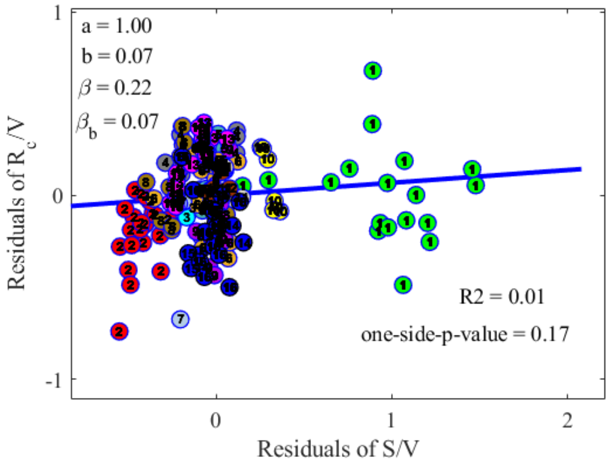

Figure 6: Logarithmic residual-residual plot normalized with respect to V.

Figures 7-10 illustrate comparisons of the presented multilinear regression with some of the regression models proposed in literature. The figures show the scatter plots for test data={(S_i, V_i, $R_{c,i}$), i=1:193}, considering a constant the rebound number S (equal to the average of rebound number values for the dataset). The different sets of the data are represented with different colours, as previously defined. It is to note that the coefficients a, b and c of these regressions, shown on the Figures, are calculated based on a nonlinear relation in the arithmetic scale, as defined herein:

$$R_c = a \cdot S^b \cdot V^c \tag{8}$$

Moreover, the standard deviation is calculated as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left[R_{ci} - \left(\mathrm{a} \cdot \mathrm{S}_{\mathrm{i}}^{\mathrm{b}} \cdot \mathrm{V}_{\mathrm{i}}^{\mathrm{c}}\right)\right]^2}{n-2}} \tag{9}$$

Finally, also R^2 is calculated in the arithmetic scale:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left[R_{c,i} - \left(\mathrm{a} \cdot \mathrm{S}_{\mathrm{i}}^{\mathrm{b}} \cdot \mathrm{V}_{\mathrm{i}}^{\mathrm{c}}\right)\right]^2}{\sum_{i=1}^{n}\left(R_{c,i} - \overline{R_c}\right)^2} \tag{10}$$

Then, the figures illustrate the regression prediction model (i.e., regression line in blue solid line and the parameters, a, b, c and σ) overlaid on our 193 test data points. It should be noted that although σ and R^2 are calculated based on Eq. 9 and 10, they are not least squares error estimates. That is, the reported σ and R^2 are simply representing the goodness of fit of a prescribed regression model (herein, alternative regressions with constant rebound number *S* equal to the average of rebound numbers for the 193 data points).

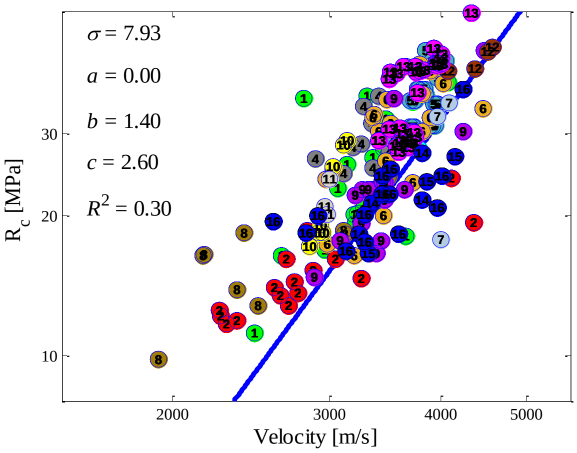

Figure 7: The regression proposed by RILEM 1993 and shown with constant S=40.8.

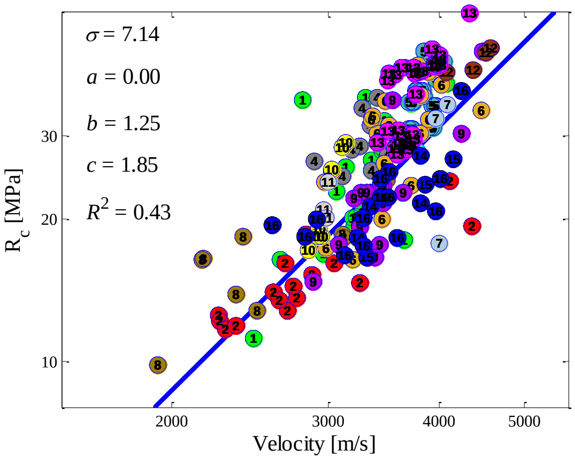

Figure 8: The regression proposed by Gasparik 1992 and shown with constant S=40.8.

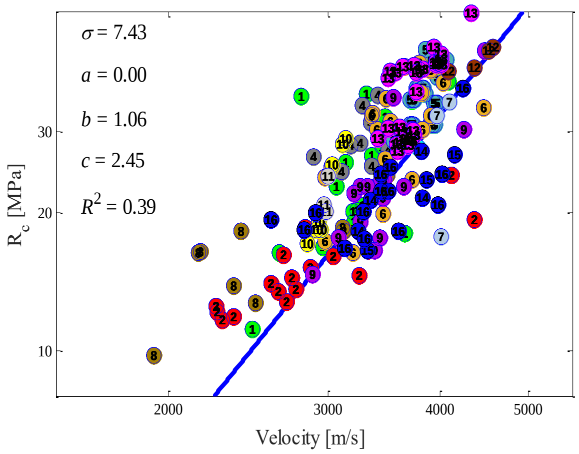

Figure 9: The regression proposed by Di Leo and Pascale 1994 and shown with constant S=40.8.

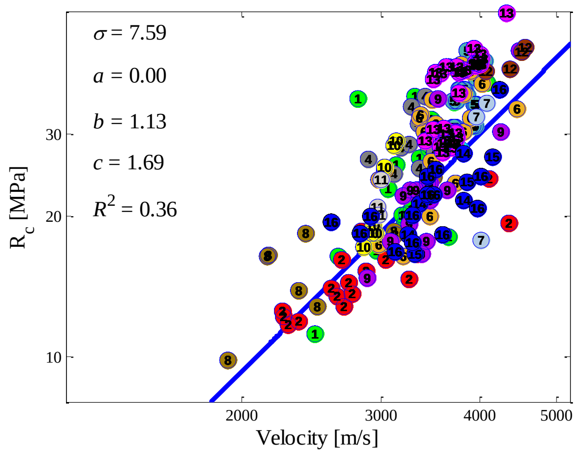

Figure 10: The regression proposed by Del Monte et al. 2004 and shown with constant S=40.8.

The literature comparison shows that the presented multilinear regression reaches a higher value of R^2 with respect to all the other literature regressions. Of course, this was to be expected as the proposed regression prediction is the logarithmic linear least squares fit to the same data. Nevertheless, in lieu of a building-specific test calibration model, the presented linear logarithmic regression is going to be useful in estimating the concrete compressive strength to be associated to the non-destructive tests for RC buildings in Campania Region. The large *p*-value for the second predictor variable (*S*) and comparable coefficients of determination R^2 (i.e., amount of variance reduction) between the multi-variable (*V* and S) and mono-variable (only V) regressions provide evidence in support of using only *V*. Later on, we are going to refer to the mono-variable regression prediction as a function of V only.

3.2.2 Relative weights of non-destructive tests for the compressive concrete strength calculation

This paragraph presents the results obtained from the calculation of the weights of the non-destructive tests, based on the results of the destructive tests in the same structural members. Generally, these weights have a large influence on the calculation of the weighted average of the compressive concrete strength for an existing RC building. In fact, the practice is to perform numerous non-destructive tests to substitute the more invasive destructive tests. In this case, the calculation of the final compressive concrete mean should be done based on the NTC (2018) indications for the relative weight of the non-destructive tests with respect to the core tests.

According to code's indications, the weighted average compressive strength of concrete specimens extracted from columns and beams at each floor have to be calculated by considering weight 1 for destructive tests and weight 1/3 for non-destructive ones.

This section presents the investigation on the calculation of the weight of ultrasonic test results based on their relative measurement error calculated in a Bayesian probabilistic framework (Ebrahimian et al. 2019). The basic concept is to obtain a weight to be applied to each of non-destructive tests in order to have the overall likelihood of a destructive test. As mentioned before, the procedure for calculation of the relative weight relies on a logarithmic linear regression relationship built between the ultrasonic resistance $R_{\text{ultrasonic}}$ and the core resistance R_c measured at the same point (or same structural element). Figure 11 shows the linear regression between R_c and $R_{\text{ultrasonic}}$.

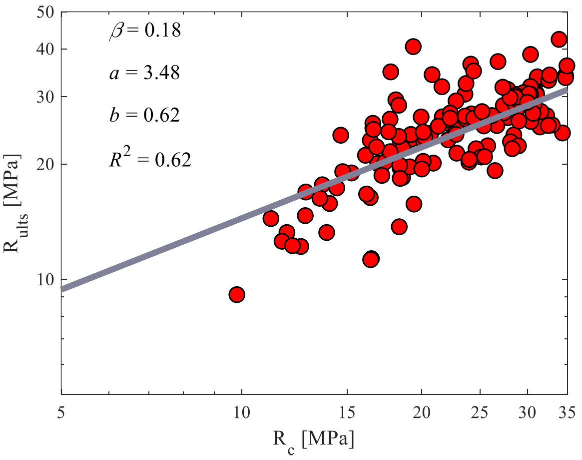

Figure 11: The linear logarithmic regression of Rultrasonic versus Rc.

Figure 12 presents the histogram and statistics of the 193 relative weights calculated based on the procedure presented in Ebrahimian et al. (2019). The calculation of the statistics for the relative weights is based on the first two moments of the set of weights. In particular, the expected value is calculated as follows:

$$E(W) = \sum_{i}^{N} \frac{W_i \cdot R_i}{\sum_{i}^{N} R_i} \tag{11}$$

where E(W) is the expected value of the weights; W_i is the relative weight for each of the 193 data; R_i is the corresponding cubic concrete strength obtained from the non-destructive test ($R_{ultrasonic}$); N is the total number of weights. Moreover, the standard deviation on the set of the weights can be calculated as follows:

$$\sigma_W = \sqrt{E(W^2) - E(W)^2} \tag{12}$$

$E(W)$ has been defined in Eq. 11; $E(W^2)$ can be calculated as follows:

$$E(W^2) = \sum_{i}^{N} \frac{W_i^2 \cdot R_i}{\sum_{i}^{N} R_i} \tag{13}$$

The $E(W)$ and $E(W) \pm \sigma_W$ values calculated from Eqs. 12 and 13 above are reported in Figure 12 as blue solid, dashed and dotted lines, respectively. The figures also illustrates as a red line the code-based value of W=1/3.

It can be observed from Figure 12 that the influence of non-destructive tests with lower strength is less important with respect to the higher strength values. The expected value of the weights calculated according to Eq. 11 is 0.56, while the confidence band of 1 standard deviation around the expected value, calculated according to Eq. 12-13, is represented by the couple of points 0.45-0.67. The code weight corresponds to the 8th percentile of the data and it is outside the confidence interval of 1 standard deviation around the expected value. Moreover, it can be seen that it is also outside the confidence interval of 2 standard deviation around the expected value.

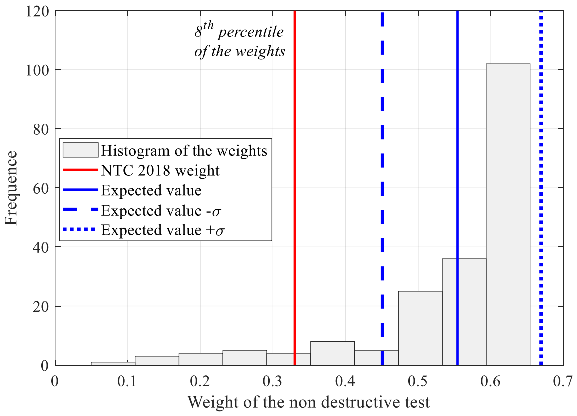

Figure 12: Histogram and statistics of the 193 weights calculated based on the presented procedure, and NTC 2018-based W=1/3.

4 CONCLUSIONS

This works characterizes the compressive concrete strength based on in-situ non-destructive test measurements. Moreover, the weights of the non-destructive tests with respect to the destructive tests are calculated. A large database of the core tests and SONREB non-destructive test results for the same structural elements has been gathered from different existing RC buildings. A regression model is employed in order to derive predictive expressions for calculating the compressive concrete strength R_c based on the ultrasonic velocity V and on the rebound number S measurements. In particular, both linear (V-R_c) and multilinear (V-S-R_c) regressions are derived, using the ultrasonic velocity and rebound number values in order to obtain the compressive concrete strength based on the available database. The paper further investigates the implementation of the concrete strength based on ultrasonic test results and the relative measurement error in a probabilistic framework for seismic performance assessment of an existing construction. Then, the relative weights of non-destructive tests for the compressive concrete strength calculation are calculated based on this probabilistic framework and compared with the relative weights of 1 (destructive tests) and 1/3 (non-destructive tests) recommended in the NTC2018 Commentary.

The work shows that linear logarithmic regression (V-Rc) can be used instead of the multilinear logarithmic regression (V-S-Rc) without significant loss of accuracy. Moreover, the results show that the effective weights of the non-destructive tests can be significantly different from the code-recommended values. In particular, the code weight corresponds to the 8th percentile of the data and it is outside the confidence interval of 1 sigma around the expected value of the calculated weights.

ACKNOWLEDGEMENTS

This work is supported by the Project POR CAMPANIA FESR 2014-2020 DIGIBETON. This support is gratefully acknowledged. Moreover, this study is partially supported by DCP-reluis 2018 joint program and PE 2019-2021; joint program DPC-Reluis.

REFERENCES

ACI 214.4R-03, 2003. Guide for Obtaining Cores and Interpreting Compressive Strength Results. American Concrete Institute (ACI), 214.4R-03, Detroit.

Bartlett, F.M., MacGregor, J.G., 1996. Statistical Analysis of the Compressive Strength of concrete in Structures, *ACIMaterials Journal*, **V. 93**, N. 3, March-April 1996.

Bartlett, F.M., 1997. Precision of in-place concrete strengths predicted using core strength correction factors obtained by weighted regression analysis. *Structural Safety*, **V. 19**, N. 4, pp. 397-410.

Bocca, P., Cianfrone, F., 1983. Le prove non distruttive sulle costruzioni: una metodologia combinata. *L'Industria Italiana del Cemento*, n. **6**.

Braga, F., Dolce, M., Masi, A., Nigro, D., 1992. Valutazione delle caratteristiche meccaniche dei calcestruzzi di bassa resistenza mediante prove non distruttive, *L'Industria Italiana del Cemento,* **3**/92.

Bungey, J.H., Grantham, M.G., 2014. Testing of concrete in structures, Crc Press.

CEB, 1989. Diagnosis and Assessment of Concrete Structures - State of Art Report. *Bulletin d'Information*, **192**, gennaio 1989.

CEN- Eurocode 2, 2004. Eurocode 2: Design of concrete structures-Part 1-1: General rules and rules for buildings. EN 1992-1-1, Brussels.

CEN- Eurocode 8, 2004. Eurocode 8 - Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings (draft n. **6**), EN 1998-3, Brussels.

Circolare, 2019. NTC 2018 Commentary: Supplemento ordinario alla Gazzetta Ufficiale, n. 35 del 11 Febbraio 2019. Ministero delle Infrastrutture e dei Trasporti, Circolare 21 Gennaio 2019 "Istruzioni per applicare dell' «Aggiornamento delle Norme tecniche per le costruzioni».

Del Monte, E., Lavacchini, G., Vignoli, A., 2004. Modelli per la previsione della resistenza a compressione del calcestruzzo in opera. *Ingegneria Sismica,* **3**, settembre-dicembre 2004.

Di Leo, A., Pascale, G., 1994. Prove non distruttive sulle costruzioni in c.a.. *Il giornale delle prove non distruttive*, n. **4**-1994.

Dolce, M., Masi A., Ferrini M., 2006."Estimation of the actual in-place concrete strength in assessing existing RC structures. *The Second International fib Congress*, June 5-8, 2006, Naples, Italy.

Ebrahimian H., Jalayer F., 2019. In-situ tests and inspections for reliability assessment of RC buildings: How accurate? *XVIII Convegno l'ingegneria sismica in Italia (ANIDIS),* Ascoli Piceno, 15-19 September.

Facaoaru, I., 1984. Romanian Achievements in Nondestructive Strength Testing of Concrete. *In Situ/Nondestructive Testing of Concrete,* ACI Publication SP-82.

Gasparik, I., 1992. Prove Non Distruttive nell'Edilizia, Quaderno Didattico AIPND. Brescia, 1992.

Jalayer, F., 2003. Direct Probabilistic seismic analysis: implementing non-linear dynamic assessments. Ph.D. dissertation, Stanford University, California.

Jalayer, F., Ebrahimian, H., Miano, A., Manfredi, G., Sezen, H., 2017. Analytical fragility assessment using unscaled ground motion records. *Earthquake Engineering and Structural Dynamics*, **46**(15), 2639-2663.

Linee guida per modalità di indagine sulle strutture e sui terreni per i progetti di riparazione, miglioramento e ricostruzione di edifici inagibili, 2012, DPC-Reluis, Doppiavoce Editore, Napoli.

Linee guida per la valutazione delle caratteristiche del calcestruzzo in opera, 2017, Consiglio Superiore dei LL.PP n. 80/2016, 30 marzo 2017.

Masi, A., 2005. La stima della resistenza del calcestruzzo in situ mediante prove distruttive e non distruttive. *Il giornale delle prove non distruttive*, **1**-2005.

Masi, A., Vona, M., 2007. Prove distruttive e non distruttive su materiali ed elementi strutturali di edifici esistenti in cemento armato. *Conferenza Nazionale sulle PnD, Monitoraggio e Diagnostica, 12° Congresso Nazionale dell'AiPnD, Biennale PnD-MD*, Milano, 11 – 13 ottobre 2007.

Masi, A., Dolce, M., Vona, M., Ferrini, M., Pace, G., 2007. Indagini sperimentali su elementi strutturali estratti da una scuola esistente in ca. *Atti del XII Convegno Nazionale L'Ingegneria Sismica in Italia*.

Masi, A., Vona, M., Nigro, D., Ferrini, M., 2008. Indagini sperimentali per la stima della resistenza del calcestruzzo in-situ basata su metodi distruttivi e non distruttivi. *Proc. Reluis2Rm08 Valutazione e riduzione della vulnerabilità sismica di edifici esistenti in c.a.*, Roma, E. Cosenza, G. Manfredi, G. Monti Eds., Polimetrica International Scientific Publisher, ISBN 978-88-7699-129-5 (in Italian).

Masi, A., Vona, M., 2009. La stima della resistenza del calcestruzzo in-situ: impostazione delle indagini ed elaborazione dei risultati. *Progettazione sismica*, **1**/2009, IUSS Press, ISSN 1973-7432 (in Italian).

Miano A., Sezen H., Jalayer F., Prota A., 2018. Performance Based Assessment and Retrofit of Non ductile Existing Reinforced Concrete Structures. *Structures Congress 2018: Blast, Impact Loading, and Response; and Research and Education - Selected Papers from the Structures Congress 2018*, Fort Worth, Texas, April 2018.

NTC, 2018. D. M. Infrastrutture Trasporti 17 gennaio 2018, Norme tecniche per le Costruzioni, G.U. 20 febbraio 2018 n. 42 - Suppl. Ord.

Rice, J.A., 1995. Mathematical statistics and data analysis. Duxbury Press, Second Edition.

RILEM, 1993. NDT 4 Recommendations for in situ concrete strength determination by combined non-destructive methods. *Compendium of RILEN Technical Recommendations*, E&FN Spon, London.

UNI EN, 2001. UNI EN 12504 – 2: Prove sul calcestruzzo nelle strutture – Prove non distruttive – Determinazione indice sclerometrico. Dicembre 2001.

UNI EN, 2002. UNI EN 12504 – 1: Prove sul calcestruzzo nelle strutture – Carote – Prelievo, esame e prove di compressione. Aprile 2002.

UNI EN, 2005. UNI EN 12504 – 4: Prove sul calcestruzzo nelle strutture – Parte 4: Determinazione della velocità di propagazione degli impulsi ultrasonici. Gennaio 2005.