Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 44 (2023) 886–893

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XIX ANIDIS Conference, Seismic Engineering in Italy

Evaluation of mechanical characteristics of steel bars by non-destructive Vickers micro-hardness tests

Silvia Caprili[a], Francesca Mattei[a], Isabella Mazzatura[a]*, Filippo Ferrari[b], Massimo Gammino[b], Marco Mariscotti[b], Michele Mori[b], Andrea Piscini[b]

[a]Department of Civil and Industrial Engineering (DICI), University of Pisa, Largo L. Lazzarino 1, 56122 Pisa, Italy

[b]*SINA S.p.A., Viale Isonzo, 14/1, 20135 Milano, Italy*

Abstract

Materials' properties evaluation represents a crucial aspect for the static and seismic assessment of existing Reinforced Concrete (RC) structures and infrastructures. While concrete's mechanical characteristics are classically investigated by both destructive tests (DTs) and non-destructive tests (NDTs), for steel reinforcing bars the use of NDTs is not consolidated: a large number of samplings are planned as part of the survey campaign, requiring strong effort to be both extracted and restored and being, moreover, not always sufficient to reliably determine the characteristics of each type of steel grade/rebar used in the structure. Within NTDs, the determination of the hardness value could be a viable way to estimate rebars' tensile strength. Many experimental studies were proposed in the past and current scientific literature, most of them performed through laboratory tests and therefore requiring a strong time and economic effort: the adoption of portable instruments for the determination of the in-situ hardness of rebars can be a good possibility to reduce the impact on the structure/infrastructure and to optimize timing and restoration operations. Of course, the methodology adopted shall be opportunely calibrated and attention shall be paid to the interpretation of the achieved data. The present research work aims at testing the effectiveness of NDT Vickers micro-hardness tests in the estimation of the mechanical properties of steel reinforcing bars. A methodology is proposed to achieve reliable correlations between hardness values and tensile strength of rebars, accounting for parameters affecting in-situ measures and different typologies of steel grades/rebars.

Keywords: *Hardness, Exsting Strucrures, Non Destructive tests, Steel rebars*

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: isabella.mazzatura@phd.unipi.it

10.1016/j.prostr.2023.01.115

1. Introduction

The static and seismic assessment of existing structures and infrastructures is nowadays one the most important goals of civil engineering, considering that a lot of structures have already passed their nominal service life. In Italy, a large part of the building stock was built between the 60s and the 80s, thus designed without modern capacity design rules and adopting materials that are now outdated. A large part of these structures is Reinforced Concrete (RC) type, commonly affected by deterioration of concrete strength, loss of bond between rebars (especially if smooth rebars) and concrete and reinforcements' corrosion. The evaluation of the effective mechanical properties of existing materials is therefore a crucial aspect for the safety assessment of existing structures/infrastructures: according to current codes (NTC 2018, EUROCODE 8), both destructive tests (DTs) and non-destructive tests (NDTs) can be adopted for both concrete and steel reinforcing bars.

Even if DTs are reasonably reliable for defining mechanical properties of the materials, it is often difficult to withdraw enough concrete and steel specimens without strongly impacting on the structure, requiring time and economic effort to restore the state-of-art condition. In particular, while NDTs are widely used for concrete (i.e. rebound and ultrasonic pulse velocity tests), only DTs are adopted for defining steel bars' mechanical properties and NDTs are essentially employed to define the effective position of the bars providing – where possible in relation to the in-situ conditions – an estimation of the diameter. Recently, some NDTs have been also developed to evaluate the residual stresses on the steel cables of prestressed reinforced concrete elements (Morelli et al. 2021). Otherwise, a limited number of DTs should be carried out due to the practical difficulties of extracting rebars, to the potential impact that the removal of many bars could have on the bearing capacity and to the fact that the restoration by welding is not always possible in relation to the chemical composition of rebars, that therefore requires to be determined before the extraction of the sample.

In the last years, in-situ ND hardness tests have been developed as a possible alternative to classical destructive tensile tests, trying to reliably relate the hardness measure to the ultimate tensile strength. The hardness measure can be obtained through portable testers (Borggren, et al, 1999), executing a static or dynamic hardness test; the use of such instrumentation in the field of civil applications essentially aims to evaluate mechanical properties of existing steel elements and rebars, and was widespread only in the last thirty years. If, on one hand, the hardness test is actually the only kind of NDT used on rebars, a lot of uncertainties depending to the tests' procedure affect the achieved measure and therefore the possible correlation with tensile strength, requiring therefore the accurate calibration of the methodology adopted and a deep analysis of the achieved data.

The most popular hardness tester, for its easy use and the relatively low cost, is the Leeb portable tester (Leeb, 1977 and 1978), widely adopted for the evaluation of the mechanical properties of structural steel elements (Formisano et al. 2020) and, more recently, of reinforcing steel bars (Mineo et al. 2019, Cavallo et al. 2013). According to Sonnenberg and Boully (2004) – who performed both laboratory and in-situ tests – the hardness measure can be used to determine both the ultimate and the yielding strength; (Brencich et al. 2019), by applying the procedure to existing bridges, collected a database of hardness values for rebars in existing structures trying to solve some technical issues. The Leeb tester was used also to evaluate the plastic strain deformation from yielding strength coming from the hardness measure (Loporcaro et al. 2014), performing laboratory tests on rebars extracted from damaged structures after Christchurch earthquake.

Considering the limits of the portable hardness testers and related measures, these methods are not yet considered sufficiently reliable for the estimation of the mechanical properties from hardness values, especially if performed in-situ. The present research work, developed within a research grant actually ongoing, proposes a validated procedure to derive reliable correlations between in-situ hardness measures and tensile strength of different typologies of steel reinforcing bars. Differences related to steel grade and chemical components, diameters, production process, presence/lack of ribs and to technical factors potentially affecting the in-situ measures are considered. Correlations will allow to understand by simple non-destructive tests the mechanical properties of reinforcing steels without requiring sampling extraction and tensile tests in laboratory. Preliminary results, to be further updated thanks to additional data, are presented and discussed.

2. Relation between hardness values and mechanical performance

Hardness is the measure of the resistance of a material to localized plastic deformations, induced by an indenter through an impact (dynamic) or an applied force (static). Hardness is not properly a mechanical property of materials but an indirect way to obtain some of them, depending, in general, on different parameters and conditions of the tests. The interest around this kind of measure is essentially for the cheapness, speed, and the easy modality of tests' execution. For steel elements, hardness is related essentially to the Carbon content in the alloy; anyway, different hardness values can be achieved even for the (apparently) same kind of rebars, being different the production process and the finally achieved microstructure.

Several methods were developed since the beginning of the XX century to evaluate the hardness of metallic components. The main distinction among existing methodologies, considering the aims of the present research work, can be made within laboratory or in-situ tests. If we consider laboratory tests, the most common are Brinell (Brinell, 1900), Rockwell (Rockwell, 1920), Knopp (Knopp et al. 1939) and Vickers' methods (Smith and Sandland, 1925), from which the relative well-known hardness scales are derived. All these lab methods are based on the application of a static force on a contained defined shape for a certain time: the force induces, in correspondence of the footprint leaved by the indenter, a plastic deformation. The measure of the depth of the penetration (Rockwell) or of the dimension of the footprint (Brinell, Vickers and Knopp) can be then evaluated allowing to obtain the steel hardness (H) depending on the type of indenter (diamond, metal, etc.) and its geometrical shape (spherical, pyramidal, etc.). The hardness value is then proportionally related to the ultimate tensile strength (σ_u) of the material through a constant parameter k, result of an empirical correlation that, for instance in the case of Brinnell Hardness (HB), is equal to 3.3 (Nicodemi, W. 2007). Over the years, different hardness conversion scales for mechanical strength were developed (e.g. ASTM A370 - Rockwell method; UNI EN ISO 18265 - other methods). For laboratory H measures, a specific preparation of the sample is usually required, leading to time-requiring procedures and cost increase. The achieved measures are accurate, but the procedure cannot be proposed to be commonly adopted in existing constructions to achieve a quick estimation of the mechanical properties of rebars: this is the reason why, in the last years, the interest increased in the determination of instruments and procedures able to provide rapid in-situ estimations of rebars' hardness, to be further related to tensile performance. Looking at in-situ hardness tests, the Leeb tester is the most widely used due to its compactness and low cost. A dynamic measure of hardness is achieved, being the procedure codified according to ASTM E-956, DIN50156 and ISO16859. Trying to simplify, the method measures the rebound speed when a bullet with a carbon or diamond tip is launched from the preloaded spring to the surface to be investigated: a part of the energy is dissipated through plastic deformation, while the remaining part is returned as an elastic rebound. The percentage ratio of impact velocity to rebound velocity is the measure of the dynamic Leeb Hardness (HL) of the specimen. Despite the apparent easiness in performing the tests, some limitations exist when the procedure is applied to steel rebars: above all, to provide adequate restraints for tests' execution, it would be necessary to remove as little concrete as possible, making the test surface's cleaning and the instrumentation's correct positioning highly complicated. This is the reason why, actually, additional instrumentations are under exploration to test their efficiency in providing accurate results.

3. Methodology proposed

Aim of the work is to validate an NDT for the estimation of rebars' mechanical properties from the hardness value. This will be useful for providing reliable correlations between H values – achieved from quick and easy in-situ measurements using portable instrumentation – and tensile strength of different rebars' typologies, accounting for variations related to diameter, presence/lack of ribs, production process, etc. Different experimental tests need therefore to be performed on a selected set of rebars: (1) hardness in-situ tests and (2) laboratory tensile tests. To check the reliability of the portable instrumentations for the hardness measure, several comparisons with traditional laboratory hardness tests – performed on small samples extracted from existing rebars – will be performed. The maximum stress derived from the conversion of the hardness index to the value of the ultimate strength will be then compared to the results of tensile tests (UNI EN ISO 15630-1:2019), allowing to calibrate reliable correlations further employable without the need of extracting samples from existing structure/infrastructures.
Possible disturbing factors, related to methodology, operators, application conditions, etc. will be considered.

The a-priori determination of the typology of steel rebars in terms of components' content and production process is necessary: apparently similar reinforcements can show a wide scattering in mechanical performance in relation to the C-content or the thermal treatments applied during production, factors that cannot be otherwise determined.

The methodology proposed to achieve the above-mentioned correlations therefore foresees the following phases:

Phase 1. Determination of a representative set of rebars, different in terms of diameters, ribs, shape, year of realization (related to the age of construction of the structure/infrastructure), etc. from selected available infrastructures (e.g. viaducts, bridges, buildings, etc.). For each typology/diameter/production process etc. a minimum number of samples, sufficient for allowing a statistical correlation, will be necessary for tests' execution.

Phase 2. Execution of in-situ hardness tests on selected rebars using portable instrumentation. Preliminary check of the reliability of the in-situ measure will be performed by comparing with laboratory tests.

Phase 3. Extraction of samples from selected existing rebars for the execution of the following laboratory tests. Before extraction, the possibility of restoring by welding the reinforcement shall be accurately investigated.

Phase 4. Execution of tensile tests on selected specimens (~60 cm of length) following current standards.

Phase 5. Execution of laboratory tests on small specimens (~2 cm of length) to assess the chemical composition through spectrometer instrumentation; additional metallographic investigations will be performed if needed.

Phase 6. Correlation between tensile strength values derived from hardness and tensile tests.

Stating the inhomogeneity of rebars' typologies normally found in existing RC structures and infrastructures, related to the wide period of realization of the artwork, it's expected to require a huge sample to be tested. Differences concern the nominal diameter (from 8to30 mm), the type of surface finishing, the steel grade (Aq42, Aq50, FeB38k, FeB44k etc.) and the related production process. In the current stage of the research, having defined the methodology above presented, only several operations and tests have been started, whose preliminary results are hereafter discussed.

4. Description of rebars' sample

The experimental campaign for the sampling of existing rebars samples is actually ongoing. Samples have been (and will be) extracted mainly from bridges and viaducts managed by SINA S.p.A (Società Iniziative Nazionali Autostradali), located in Tuscany and Liguria and designed in the period 1960÷1980. All the viaducts are pre-stressed RC with post-tensioned cables. Until today, 99 rebars were collected, and 68 rebars investigated according to Phase 2 (in-situ hardness tests) and 74 according to Phase 4 (tensile tests in laboratory), Table 1. Tests for chemical composition and metallographic investigations (Phase 3) have not been till now executed but will take place in the next future. Fig. 1 summarizes the repartition of collected rebars respect to the type of surface: as expected from the analyses of existing databases, three kinds of rebars were individuated (smooth round rebars, ribbed rebars and RUMI steel rebars), with diameters ranging from 8 mm to 30 mm (both stirrups and longitudinal reinforcements). Approximately the 63% of the above-mentioned sample is made up of ribbed bars (62), with predominant diameters equal to 10 mm (20 bars) and 16 mm (14 bars). Of course, the sample in its actual condition cannot be considered enough wide to provide reliable correlations, especially concerning smooth bars; anyway, it can be usefully adopted to easily present the application of the proposed methodology.

Table 1. Typology of rebars and number of tests carried out according to Phase 2 and Phase 4.

Typology	N° of samples	% on the total	N° of hardness tests (Phase 2)	N° of tensile tests (Phase 4)
RUMI	24	24%	8	16
Smooth	13	13%	7	13
Ribbed	62	63%	53	45

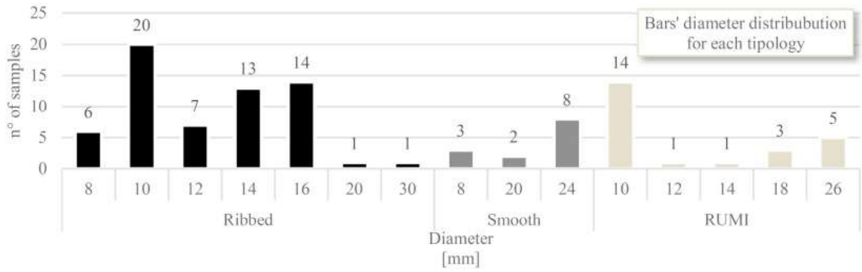

Fig. 1. Repartition of investigated rebars: respect to the type of surface and to diameter.

5. Micro Hardness tests *in situ*

The hardness tester used in the present research is E-Handy Ernst ® (Fig. 2), whose principle of operation is quite different from traditional instruments: it allows to obtain the hardness value through the measure of electrical resistance (DIN 50158, 2008): the diamond tip indenter, which is subjected to a chemical treatment, became a semi-conductive, according to the Chemical Vapor Deposition (CVD). The hardness is related to the electrical resistance: the harder the investigated material, the lower the penetration with a greater resistance. This kind of function, and the fact that the area of the print of the diamond tip is equal only to 2 mm x 2 mm, allows to execute the test even in correspondence of critical areas (such as weld seams, heat affected zones, etc.) and on very small surfaces. The indenter tip has a pyramidal shape; therefore, the Vickers hardness index is achieved. The instrument is equipped with a tablet providing real-time hardness results. The tester presents different kind of support for the diamond tip (Fig. 2), depending on the surface to measure; in particular, rubber support is useful in case of rebars, being very stable, while the metallic one has been specially designed and realised for strands and wires.

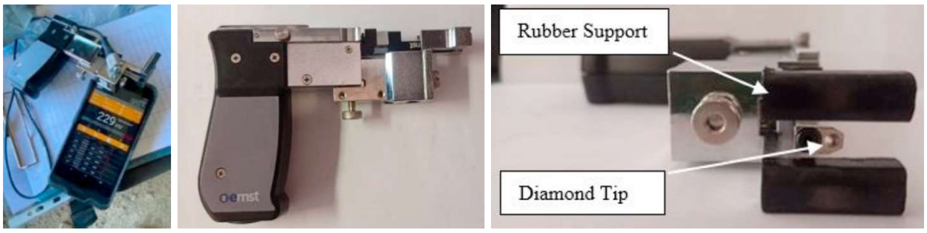

Fig. 2. Portable Micro Hardness Test Ernst® used for in-situ investigations.

5.1. Analysis of parameters affecting the measure

The reliability and applicability of the tester was assessed by investigating potential influence factors such as the surface preparation, the operator dependence and the correspondence between the measures in situ and in laboratory.

Sample surface preparation. The sample's surface preparation is fundamental for the execution of hardness tests providing reliable data; however, there are no codified standards or practical indications about the correct use of the tester. To this purpose, hardness tests were preliminary carried out on some rebars where two different kinds of superficial treatment were applied: "rough" surface, i.e. only slightly levelled using a grinder with a 60-grit disc, and "mirror" surface, i.e. processed using a grinder with abrasive papers with grits of 60, 150, 180, 1000. In both cases, a little part of the surface was removed through the grinder in order to have a planar area for carrying out the hardness measurements. On nine selected samples at least 12 hardness measurements for each tests' group were executed: Fig. 3a shows the results in terms of Coefficient of Variation (CV) for each sample in case of rough and mirror finishes.

It's visible that the "rough" surface greatly affects the dispersion of the measure, with a values of CVs between 5% and 12%, while the "mirror" surface cleaning always leads to a decrease in CV on the single sample; in any case the CV lies between 1% and 5%.

Operator dependence. With the aim to evaluate the repeatability of the measurements, the operator-dependence of the hardness tests was analyzed, through some tests carried out by two operators (with a mirror surface finish). The results expressed in terms of CV,12 measurements on the single sample, show (Fig. 3b) that the difference in the two cases lies in the range of CV equal to 1%, and only in one case is equal to 2%, excluding the operator-dependence.

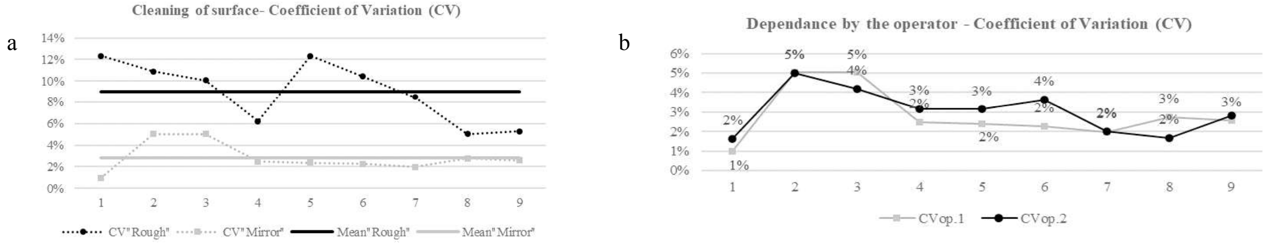

Fig. 3. Influence of cleaning of surface (a) and of different operators (b) on the hardness measures.

Comparison between hardness measures in situ and in laboratory. A set of around 30 tests were carried out both on-site and in the laboratory, with the aim to observe possible influences of environmental and boundary conditions. Fig. 4 shows the HV index and the relative errors, which amplitude is equal to two times the Standard Deviation of each set of measurements: measurements from laboratory are generally affected by lower errors; hence, it is necessary to discard the values of the on-site measurements if the error bars of the pair don't intersect. Because the discarded measurements correspond to a not proper surface preparation on-site, it can be asserted that the environmental conditions don't affect considerably the measurements' results.

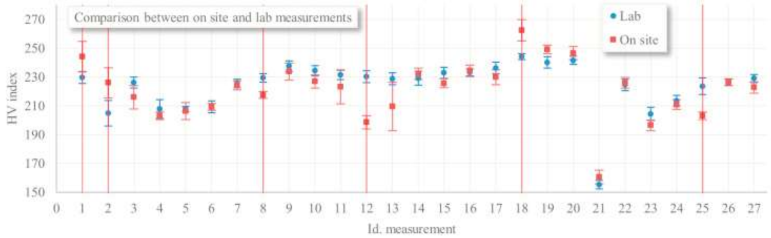

Fig. 4. Comparison between in-situ and lab HV measure; the error bars represent the standard deviation of the set of measures.

5.2. Hardness tests' results

Hardness tests were executed according to the surface preparation procedure. Fig. 5 shows the trend of HV index with the diameter for each typology of rebars: in case of ribbed rebars, for instance, and for the same diameter, there is a considerable variation of the HV index (at most 100 HV in case of 10 mm diameter), that can be related to several factors, i.e. the chemical composition and the manufacturing process. It's evident the need of deeper investigations (Phase 4) of the methodology, since rebars apparently similar for diameter, period of realization of the infrastructure, ribs, etc. can be completely different in terms of mechanical properties.

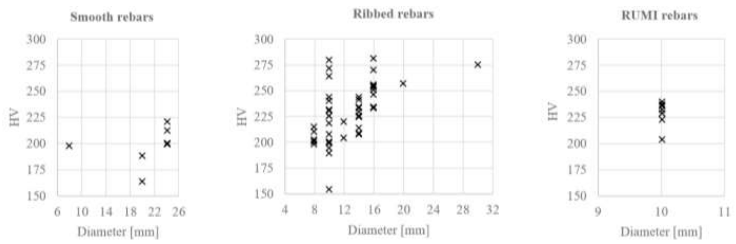

Fig. 5. Values of HV index in relation to the diameter for different types of rebars.

6. Tensile tests on reinforcing bars

Tensile tests were executed both at the Laboratorio per le esperienze sui materiali da costruzione of University of Pisa, and at another Laboratory, according to the provisions of UNI EN ISO 15630:2019. Fig. 6 shows the variability of tensile strength with diameter; the different indicator identifies different laboratory (x-shape for UniPi and the square-shape for the external one). Once again, the high variability of the results highlights the need of performing investigations of Phase 4, with the aim of define those rebars that are effectively associated to a coherent sample.

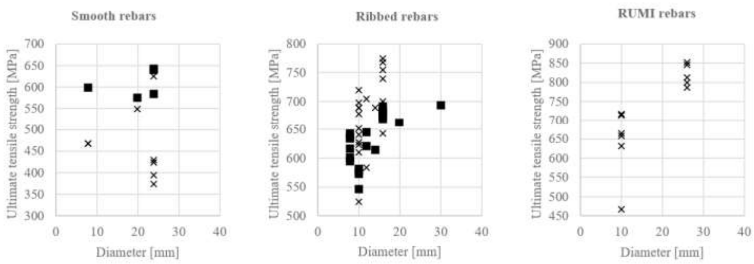

Fig. 6. Variability of tensile strength with diameter (the different indicators refer to the different laboratories that tested the bars).

7. Preliminary correlation between hardness values and tensile strength

The ultimate tensile strength of rebars can be achieved from hardness tests through opportune conversion according to ASTM-A370 (2021) and shall be compared to the ones coming from tensile tests (UNI EN ISO 15630-1:2019). Until now, both the tests (Phase 2, Phase 4) have been carried out on 43 samples, whose major part is made up of ribbed bars (only 7 are smooth). The current number of data cannot be sufficient to provide reliable correlations, even considering that Phase 3 needs to be still started and can lead to a further subdivision of the sample in relation to manufacturing and chemical composition. Considering, in fact, the sample in its entirety (ribbed, smooth, RUMI and diameters from 8 mm to 30 mm) the correlation obtained between actual tensile stress and tensile stress from hardness tests is shown in Fig. 7, where the linear regression gives a coefficient R^2 equal to 0.6602, and therefore not satisfactory. However, considering only the ribbed bars with diameters between 10 mm and 16 mm, an improvement in the regression is observed with a coefficient R^2 that became 0.7065 (Fig. 7). The choice of the diameter ranges from 10 to 16 mm derives from the need to consider a sufficiently large sample (28 elements) but as selected as possible. Finally, it can be observed that the tension from hardness tests is always higher (except in one case) than the actual stress, and in 86% of the cases, the relative error is lower than 20%.

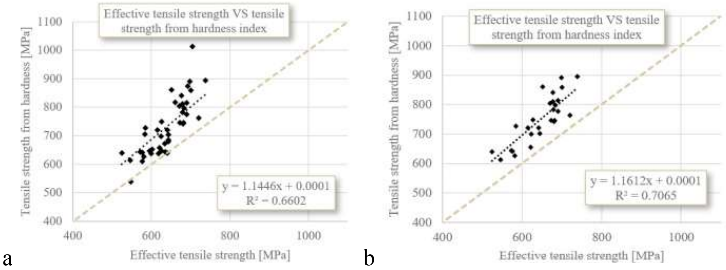

Fig. 7. Correlation between tensile strength obtained from hardness measures and tensile tests. (a) All rebars, (b) ribbed rebars (ϕ10 ÷ 16 mm).

8. Conclusions

The evaluation of mechanical properties of existing steel reinforcing bars is nowadays performed essentially through destructive tests (DTs), through the extraction of the sample from the elements, the restoration by welding and tensile tests. It is desirable to look for other less invasive tests' methodologies, with a lower impact on the infrastructure from an economic, time and safety point of view. A promising *in-situ* NDT, is the hardness test, allowing to evaluate the rebars' hardness and, therefore, the ultimate tensile strength. The present paper proposes a methodology for the elaboration of reliable correlation between in-situ hardness measures on steel rebars and their ultimate tensile strength; final correlations will account for differences in terms of diameter, ribs, chemical composition, and manufacturing process used for rebars' production, with the aim of providing realistic estimations not requiring strong impact on the structure/infrastructure. In the present work, the procedure is widely described, with preliminary results, highlighting the relevance of the amplitude of the rebars' set to have statistical validity of evaluations and the need of performing metallurgical/metallographic investigations to achieve meaningful relationships.

References

ASTM A956-06. Standard Test Method for Leeb Hardness Testing of Steel Products. ASTM International. West Conshohocken. PA. 2006.

ASTM-A370. Standard Test Methods and Definitions for Mechanical Testing of Steel Products. ASTM International. West Conshohocken. PA. 2021.

Borggren, K., Tonder, P., Lorenzen, M.S., Hansen, J.V. and Auerkari, P., 1999. Comparison of portable hardness testers: Performance with ideal samples.

Brencich, A. and Campeggio, F., 2019. Leeb hardness for yielding stress assessment of steel bars in existing reinforced structures. Construction and Building Materials, 227, p.116570.

Brinell, J.A., 1901. Brinell's method of determining hardness and their properties of iron and steel. "II Cong. Int. Methodes d'Essai, Paris" (translated to English by A. Wahlberg). J. Iron Steel Inst., 59, pp. 243-298.

Decree, M., 2008. Technical codes for constructions. Official Gazette of the Italian Republic, pp.1-434.

DIN 50156. Metallic materials – Leeb hardness test, Deutsches Institut fur Normung E.V. (DIN). 2007.

DIN 50158-1. Metallic materials - Hardness testing with portable measuring instruments operating with electrical penetration depth - Part 1: Test method, Deutsches Institut fur Normung E.V. (DIN). 2008.

Eurocode 8. Design of structure for earthquake resistance – Part 3: Assessment and retrofitting of buildings. EN 1998-3. 2004.

Formisano, A. and Davino, A., 2020, July. Hardness vs strength for structural steels: first results from experimental tests. In European Workshop on Structural Health Monitoring (pp. 227-237). Springer, Cham.

Formisano, A. and Davino, A., 2020, July. Hardness vs strength for structural steels: first results from experimental tests. In European Workshop on Structural Health Monitoring (pp. 227-237). Springer, Cham.

ISO 16859. Metallic materials – Leeb hardness test. 2015.

ISO 18265. Metallic materials - Conversion of hardness values. 2013.

Knoop, F., Peters, C.G. and Emerson, W.B., 1939. A sensitive pyramidal-diamond tool for indentation measurements. Journal of Research of the National Bureau of standards, 23(1), p. 39.

Leeb D. et al., 12 July 1977. U.S. Patent n. 4 034 603

Leeb D., 1978. New Dynamic Measurement Techniques for Hardness Testing of Metallic Materials (in German). VDI-Berichte. n. 308.

Loporcaro, G., Pampanin, S. and Kral, M.V., 2014, March. Investigating the relationship between hardness and plastic strain in reinforcing steel bars. In NZSEE conference, Auckland (pp. 21-23).

Morelli F., Panzera I., Piscini A., Salvatore W., Chichi F., Marconi G., Maestrini D., Gammino M., Mori M., 2021. X-Ray measure of tensile force in post-tensioned steel cables. Construction and building materialsDOI: https://doi.org/10.1016/j.conbuildmat.2021.124743

Nicodemi, W., 2000. Metallurgia: principi generali. Zanichelli Editore. Bologna

Rockwell, W.W., 1922. Seeberg's History of Dogma.

Smith, R.L. and Sandland, G.E., 1923. An Accurate Method of Det. ermining the Hardness of Metals with Reference to those of a High Degree of Hardness. Proceedings of the Institution of Mechanical Engineers, 1, pp. 623-641.

Sonnenberg, A. and Boully, G., 2004. Onsite Hardness Testing of Reinforcement. In AUSTROADS BRIDGE CONFERENCE, 5TH, 2004, HOBART, TASMANIA, AUSTRALIA (No. AP-G79/04).

UNI EN ISO 15630-1. Acciaio per calcestruzzo armato e calcestruzzo armato precompresso - Metodi di prova - Parte 1: Barre, rotoli e fili per calcestruzzo armato. 2019