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Leeb hardness experimental tests for mechanical characterization of structural steels

Giovanni Chiumiento[a], Gianmaria Di Lorenzo[b], Antonio Formisano[a],
[a] *Università di Napoli "Federico II" Dipartimento di Strutture per l'Ingegneria e l'Architettura (DiSt), Piazzale Tecchio 80, 80125 Napoli (Italia)*
[b] *Università di Napoli "Federico II" Dipartimento di Strutture per l'Ingegneria e l'Architettura (DiSt), Via Forno Vecchio 36, 80134 Napoli (Italia)*

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ABSTRACT
The diagnostic tests on materials and constructional components are commonly classified as destructive, weakly destructive and non-destructive. The destructive and weakly destructive tests provide local quantitative information on the basis of direct measurements of mechanical, physical and chemical parameters, while the non-destructive tests allow for extensive investigations for the detection of indirect magnitudes correlated to the material characteristics of interest. The non-destructive tests for a correct analysis of the artefact degradation status were spread since the 80s aiming at both reducing the number of destructive interventions and operating inside buildings without suspending normal activities of people. With reference to steel buildings, non-destructive tests are not largely diffused as for reinforced concrete ones, but they could be very useful to limit the extraction of members from the structures for tensile tests and the consequent repairing interventions. Therefore, in the current study micro-hardness tests have been carried out on steel samples having different treatment of surfaces in order to evaluate the related hardness and resistance changes. Moreover, the hardness measurements, converted into Brinell and Rockwell scales, have been put in comparison to resistance values extracted from the ASTM standard conversion table for evaluating the trend of the resulting curves useful to setup future correlation laws.

1 INTRODUCTION

Industrial archaeology represents a modern branch which studies, through an interdisciplinary method, all the experiences (material and immaterial, direct and indirect) of the industrialization process in order to deepen the knowledge from the past history to the current techniques. In this architectural and urbanism framework, there are numerous testimonies of historical artefacts, which represent an important social trace of the collective and urban development, becoming witnesses of an epoch. Nowadays, the renewed technical sensitivity is aimed at rediscovering and recovering such evidences with intervention methods having the prerequisites to be eco-sustainable, according to the dictates of bio-architecture, and innovative, according to home automation and intelligent architecture fundamentals (Terracciano et al., 2015; Di Lorenzo et al., 2019). In this context, if the architectural challenge is to adapt volumes to new spaces and activities, the true competition starts at the engineering level in terms of both plants, being the modern functional needs always more specialized, and structures, having to operate on a historic built conceived and erected according to project and executive methodologies often disused or totally in conflict with current design philosophies and relevant regulatory frameworks. Through a project of cognitive investigations, it is possible to find adequate knowledge levels of the structure (OPCM, 2005; NTC, 2018) which allow to identify the used materials, so to carefully simulate the behaviour of structural systems.

On one hand, if it is possible to attain the whole knowledge of these systems by means of surveys and in-situ tests, in order to identify mechanical characteristics and physical properties of materials and their degradation state, it is necessary to perform an adequate campaign of tests. About metal structures, the current regulations allow to use an appropriate number of sampled specimens only (MIT, 2009), achieved from structural zones not too much stressed, to be subjected to destructive laboratory tests able to provide under semi-probabilistic way their mechanical and physical features. Such types of investigative campaigns, however, are often in conflict with the architectural protection constraints of artefacts under consideration, which do not allow to operate the normal sampling of specimens. On the other hand, given the need to pursue minimum levels of knowledge, the use of non-destructive testing methods, instead of destructive investigations, would allow to protect the artefact, without limiting the cognitive framework useful to carry out a proper design intervention. Among non-destructive investigations, the surface hardness measurements of steel specimens performed with portable equipments allow, within certain limits of use, for a supplementary investigation campaign partly substitutive of destructive tests.

Hardness assessment methods are multiple, they being referred to the different reading methods (Brinell - HB, Rockwell - HR, Vickers - HV), related to the type of penetrator adopted, to the value of the applied static force and to the test response value, expressed as the incision energy on the surface of the metal sample. This energy is a function of the shape and size of the impression on the basis of the predetermined load adopted for the test. Micro-hardness or "Leeb" tests are carried out with portable devices equipped with different bits which, providing rebound energy based on their impression on the metal surface, allow to see on the tool display the hardness value to be converted from the Leeb scale (HL) to a predefined more common scale (HB, HR or HV) (Formisano et al., 2018). Compared to the static tests, such investigations are much more affected by a number of factors, such as the sample thickness, the surface cleaning and imperfections, and thus have a reliability degree lower than the traditional hardness tests one.

The objective of the current experimentation is to test the reliability of the Leeb procedure, carried out with a portable equipment, on different types of samples. The inspected procedure results are compared to the nominal hardness values determined by static tests, according to ASTM A956-06 (2006) and UNI EN ISO 18265 (2014) standards, which define in tabular way the transformation and conversion parameters regulating the use of static durometers. The test is carried out in longitudinal direction according to the methodology defined in the ASTM A30-03a code (2003), subsequently evaluating the type of steels according to the UNI EN 10002-1 standard (2001), or using the material accompanying certificates, obtained from acceptance tests. Currently, on the market there are various equipments for Leeb hardness tests, although reliability and compliance with international standards are still being tested (Cavallo et al., 2013).

It should also be noted that for reinforced concrete structures the existing Italian regulations (OPCM, 2005; NTC, 2018; MIT, 2009) allow for the use of non-destructive tests, replacing 50% of destructive tests with at least a double number of non-destructive tests, such as the SONREB (SONic REBound) ones (EN 12504-2, 2012; EN 12504-4, 2005), which are correlated to the compression resistances of cylindrical samples extracted from structural members. On the contrary, for steel structures, current standards do not threat non-destructive tests. It seems, therefore, indispensable to prove the reliability of the Leeb tests in order to integrate and modify the regulatory contents with the purpose to both optimize and improve the goodness of experimental campaigns, working properly on existing artefacts protected by Superintendence rules, and to limit the damage to structures, where latent hazards situations can be hypothesized.

2 TESTING METHODOLOGY

2.1 The hardness tests

Hardness is a measure of the surface resistance of a metal to permanent plastic deformations. The metal specimen hardness is measured through a penetrator, usually with spherical, pyramidal or conical shape, which is pressed against its surface. The penetrator bit is made of tempered or tungsten carbide steel, so that it is tougher than the tested specimen material. Standard hardness tests are based on the slow application of a known force that compresses the penetrator in a perpendicular direction to the metal surface to be tested. After the impression is made, the penetrator is removed from the surface and then an empirical hardness value, based on either the impression area or the imprint depth, is calculated or read directly on the test machine. The hardness value derived from Brinell, Vickers or Rockwell tests depends on both the impression shape and the applied force. Being achieved essentially in conventional way, the hardness values obtained by different methods or with different scales can be compared to each other only by means of purely experimental conversion tables, which are valid for individual classes of materials.

Normally hardness tests use dedicated machines called durometers (Fig. 1), so that each test is calibrated on the force value related to the used penetrator bit type.

The aim of this research work is to verify the reliability of results from non-destructive tests with the Leeb method using portable micro-durometers on steel samples with different shape, nature and origin.

Figure 1. Instrumentations used for Rockwell (a), Brinell (b) and Vickers (c) hardness tests

This allows to both verify the test reliability with respect to the hardness values provided by ASTM A956 and UNI EN ISO 18265 standards and define, whenever possible, the corrective coefficients to be applied to the Leeb tests for the indirect determination of the carpentry steel classes using the tabular expressions defined in ASTM A956 and UNI EN ISO 18265 standards.

2.2 The first experimental activity

The used steel samples, provided by the Tecnolab srl company, an authorised laboratory with headquarter in Naples for investigation tests on construction materials, are represented by specimens having different shape, origin and material type. In particular, the available samples are:

- Plates and sheeting of different thickness (Fig. 2);
- Samples from HE and IPE profiles (Fig. 3);
- Smooth bars with different diameters (Fig. 4).

The above samples have been tested and the achieved test values have been ordered on the basis of the average values of the achieved Brinell hardness. After these non-destructive tests, in the cases where certificates on the steel properties were not available, the various samples have been subjected to destructive mechanical tensile tests in the laboratory, so to classify the steel type (S235, S275 or S355) depending on the yielding stress achieved.

The specimens have been prepared for the execution of the test, assigning an acronym to each of the them. In particular, the used abbreviation is ST-X-N, where ST means mild steel, X indicates the specimen type (P = plate; S = sheet; R = round) and N is the progressive number of samples of the same typology.

Figure 2. Specimens of second experimental activity

Figure 3. Samples from HE and IPE profiles

Figure 4. Samples from smooth round bars having different diameters

The samples have been cleaned by solvents from oils and fats detected on the surface. Each sample has been weighed and the related thickness (Tables 1 and 2 for plates and sheets, respectively) or diameter (Table 3), the latter in the case of round specimens, have been measured. Moreover, the steel class has been determined by destructive tensile tests. On each specimen the area to be used for test has been delimitated by chalk lines. In addition, each sample has been cleaned by means of a bench grinder, bringing the test surface to "white iron".

Subsequently, the specimens have been left to rest for at least 6 hours in a room at standard temperature and humidity, so to allow both any remaining residual stresses and the abrasion heat to be discharged. The preparation lasted about 12 hours. The day after the preparation of specimens, Leeb micro-hardness tests have been performed.

Table 1. Steel type and thickness of plate samples tested

Code	Sample number	Thickness [mm]	Steel class [MPa]
ST-P-01	1	4,7	S235
ST-P-02	2	5,3	S235
ST-P-25	3	10,2	S235
ST-P-09	4	8,0	S235
ST-P-15	5	8,9	S235
ST-P-23	6	10,2	S235
ST-P-24	7	10,2	S235
ST-P-13	9	8,5	S235
ST-P-03	10	5,3	S235
ST-P-08	13	7,9	S235
ST-P-05	14	6,1	S235
ST-P-07	15	7,3	S275
ST-P-26	16	10,2	S235(*)
ST-P-10	17	8,2	S275
ST-P-16	20	8,9	S275
ST-P-12	25	8,4	S275
ST-P-04	26	5,3	S275
ST-P-22	28	10,1	S275
ST-P-06	33	6,5	S275
ST-P-27	37	10,2	S275
ST-P-18	38	9,9	S275
ST-P-31	39	13,0	S275
ST-P-32	40	13,7	S275
ST-P-19	41	9,9	S355
ST-P-17	42	9,3	S355
ST-P-11	43	8,2	S275
ST-P-29	45	11,8	S355
ST-P-28	46	10,2	S355
ST-P-14	48	8,8	S355
ST-P-20	49	9,9	S355
ST-P-34	50	20,4	S355
ST-P-33	53	20,4	S355
ST-P-30	56	12,3	S355

(*) Test not performed, class assigned from the material certification

Table 2. Steel type and thickness of sheet samples tested.

Code	Sample number	Thickness [mm]	Steel class [MPa]
ST-S-01	8	5,0	S235
ST-S-04	11	9,0	S235
ST-S-02	22	7,5	S275
ST-S-05	23	10,0	S275
ST-S-03	29	8,0	S275
ST-S-06	44	15,0	S275
ST-S-08	47	20,0	S355
ST-S-07	52	20,0	S355
ST-S-09	57	9,0	S355

Table 3. Steel type and diameter of round samples tested.

Code	Sample number	Diameter [mm]	Steel class [MPa]
ST-R-02	18	30	S275
ST-R-03	19	30	S275
ST-R-04	21	30	S275
ST-R-05	24	30	S275
ST-R-06	27	30	S275
ST-R-07	31	34	S275
ST-R-08	32	34	S275
ST-R-09	34	34	S275
ST-R-10	35	34	S275
ST-R-11	36	40	S275
ST-R-12	51	40	S355
ST-R-13	54	40	S355
ST-R-14	55	40	S355

The equipment has been calibrated on mild and cast steels, taking care to carry out the test by keeping the device as firm as possible and perpendicular to the impact surface of the sample.

The tests have been conducted in three points of the test area, with a distance among them and from the sample edges not less than 5 mm. For each specimen, the test values have been annotated separately on a laboratory register. Subsequently, the steel class (S235, S275 or S355) has been assigned to each sample according to either the material origin certificate or the result of destructive tensile tests (Tables 1, 2 and 3).

2.3 *The second experimental activity*

The second non-destructive experimental campaign has foreseen hardness tests on carpentry steel specimens in order to both assess a feasible correlation with the steel tensile strengths and evaluate the influence of the surface finishing level of samples on the hardness values.

The tests campaign has been performed by using the Leeb micro-hardness tester on six different samples Si (i=1÷6), namely four plates, one rectangular box profile and one large flange double T member (Figure 5), whose mechanical properties deriving from direct tensile tests were unknown. Also in this case the experimental activity has been conducted at the material test laboratory Tecnolab Srl of Naples.

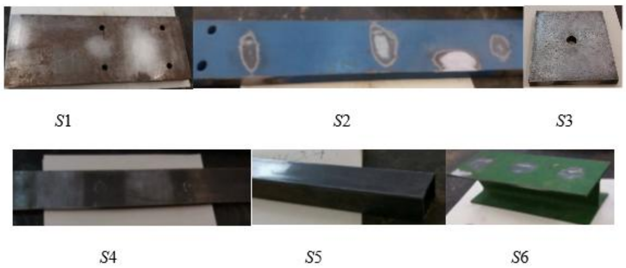

Figure 5. Specimens of the second experimental activity

Strictly speaking, before tests, it has been necessary a thorough cleaning of specimens and the possible removal of paints in order to avoid an excessive surface roughness that can alter the hardness test results. The surface cleaning operations have been executed either by hand or through machineries aiming at creating on the surface of each specimen under examination the following finishing levels:

1. As-is, corresponding to the original condition, where the cleaning of specimens is made with alcohol only;
2. Worked with sandpaper, equivalent to a situation of post-lamination, where abrasive sheets and iron rasps are used;
3. Worked with grinder, to contain the surface roughness within 2 μm.

The measurement of the different thicknesses of specimens, carried out by the calliper, has been conducted after the surface finishing operations has been completed (Table 4).

Table 4. Thickness of tested samples.

Sample	Thickness (mm)
1	3,00
2	10,0
3	20,0
4	3,70
5	1,60
6	8,00

Dynamic hardness tests on the specimens with the above three surface finishing conditions have been carried out by means of the MH100 Leeb Hardness Tester, manufactured by the Mitech CO., LTD company (http://www.mltest.com/PDF/MH100%20Manual_v10.pdf) (Figure 6) and set to convert the obtained HLD rebound values into Brinell and Rockwell hardness ones.

Figure 6. The MH100 Leeb hardness tester.

With the help of this portable and compact instrument, which has a very light weight and it is characterised by limited dimensions (148mm x 33mm x 28mm), in situ tests can be easily made. The used hardness micro tester has a series of advantages, such as a wide measurement range, based on the principle of Leeb hardness steel, large LCD display for viewing the parameters and functions, the possibility to change the inclination angle of the impact tool, the direct reading on the display of the test values in the different scales (HB, HS, HV, HRB, HRC, HRA), a large memory which can contain up to 100 measurement values, information on the impact and angulation, as well as on the impact time, up to 200 hours of continuous work and a software dedicated to transfer the data directly to a PC.

The working conditions, that is work temperature between -10° and 50°, storage temperature between -30° and 60° and relative humidity less than 90%, allow for a very wide use of the instrument, with extreme ease of use even by not highly specialized personnel.

The hardness tests to be performed with the Leeb tester are conditioned by several factors, such as sample surface imperfections, imperfections of the crystalline reticulum, local defects of the material and imperfections due to local preparation and cleaning of impact surfaces, that can compromise the truthfulness of results. In particular, the current provisions require that cleaning of the specimens surface is a necessary condition for the proper execution of hardness tests. In addition, in order to avoid erroneous results, ten measures have been made for each of the three parts of the sample, moving the device along a route, with the purpose to observe how and to what extent the values reported by the test instrument could vary in the vicinity of parts most oxidized and/or painted.

From the ten values recorded, the minimum and maximum results have been discarded, whereas for the remaining eight the average value has been gotten.

3 RESULTS OF THE EXPERIMENTAL ACTIVITY

3.1 *First sequence of tests*

The hardness measurements recorded for the different specimens, have been renumbered in ascending order based on the average value derived from the three tests, taking care to discard the minimum and maximum values from the performed five test readings. Subsequently, the strengths of tested specimens have been derived from conversion tables provided by ASTM and ISO standards, interpolating between two values when test results have not been found in the resistances of reference tables.

Later on, the envelope curves of the obtained data have been determined on the basis of the following formulas:

$$R_m^{ASTM} = 0.0087HB^2 + 1.0286HB + 152.1838$$

(ASTM A370-03a standard) (1)

$$R_m^{UNI} = 0.0007HB^2 + 3.5451HB + 10.0936$$

(UNI EN ISO 18256 standard) (2)

$$R_{m\_avg} = 0.0040HB^2 + 2.2869HB + 71.0451$$

(medium between the two relationships) (3)

where:

R_m^{ASTM} is the tensile strength according to the ASTM standard, expressed in MPa;

R_m^{UNI} is the tensile strength according to the UNI standard, expressed in MPa;

R_{m_avg} is the average tensile resistance, expressed in MPa;

HB is the Brinell scale static hardness.

Considering the conversion tables shown in the UNI EN ISO 18256 (Table 10) and ASTM A370-03a standards, the formulations have been deduced for S235, S275 and S355 metal carpentry steels with nominal ultimate tensile strengths $f_{uk,max}$ in the range from 510 to 530 MPa.

For simplicity, the envelope curves of these strength values for structural carpentry steels have been gotten from the tables of the strength values(?) as a function of the hardness value HB, on the basis of the following expressions:

$$R_m^{ASTM} = 0.0065HB^2 + 1.4910HB + 128.3678$$

(ASTM A370-03a standard) (4)

$$R_m^{UNI} = 0.0008HB^2 + 3.5683HB + 11.9950$$

(UNI EN ISO 18256 standard) (5)

where:

R_m^{ASTM} is the tensile strength according to the ASTM standard, expressed in MPa;

R_m^{UNI} is the tensile strength according to the UNI standard, expressed in MPa.

From the surface hardness measurements, it is possible to achieve the tensile strengths of tested steels.

By implementing all the values contained in the conversion tables, given from both the UNI EN ISO 18256 standard and the ASTM A370-03a one, the envelope formulations, which depends on the measurement of hardness HB, are obtained as:

$$R_m^{ASTM} = 0.0019HB^2 + 2.5495HB + 72.7304$$

(ASTM A370-03a standard) (6)

$$R_m^{UNI} = 0.0006HB^2 + 3.1156HB + 23.8669$$

(UNI EN ISO 18256 standard) (7)

where:

R_m^{ASTM} is the tensile strength according to the ASTM standard, expressed in MPa;

R_m^{UNI} is the tensile strength according to the UNI standard, expressed in MPa.

Comparing the values, obtained from the ASTM A370-03a standard conversion tables, with those achieved from relationships (1), (4) and (6), very similar trends of related curves have been observed (Figure 7).

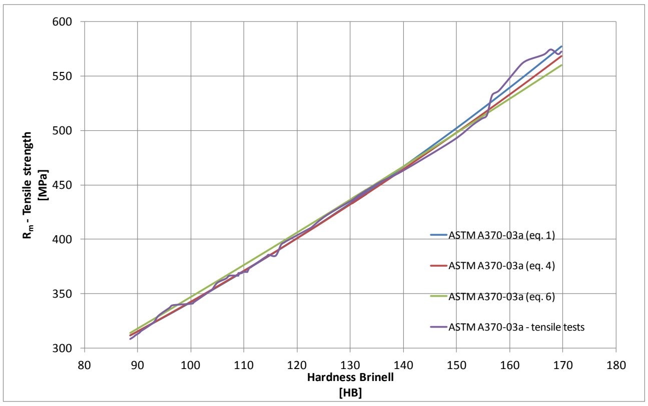

Figure 7. Comparison among hardness-strength curves (Brinell method – ASTM A370-03a standard; tensile tests curve from conversion tables).

The errors committed by using the envelope curve from the whole ASTM table have been evaluated for all the steel classes.

From this comparison it has been observed a maximum negative error $e_{\min(3)}^{ASTM} = -4.37\%$, a maximum positive error $e_{\max(3)}^{ASTMI} = 2.35\%$ and a maximum percentage scatter $\delta_{\max(3)}^{ASTM} = 6.72\%$ (Figure 8). On the contrary, by using the partial tables for structural steels only, a maximum negative error $e_{\min(1)}^{ASTM} = -2.30\%$, a maximum positive error $e_{\max(1)}^{ASTM} = 1.83\%$ and a maximum percentage scatter $\delta_{\max(1)}^{ASTM} = 4.13\%$ have been detected. Analysing separately the errors committed for the different steel classes, it has been observed that errors found for S235 steels (Figure 9) are lower than those obtained with S275 steels (Figure 10).

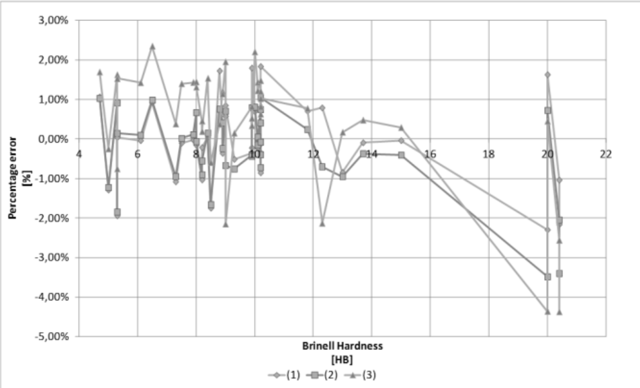

Figure 8. Percentage errors with respect to the envelope curve of the ASTM whole table (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

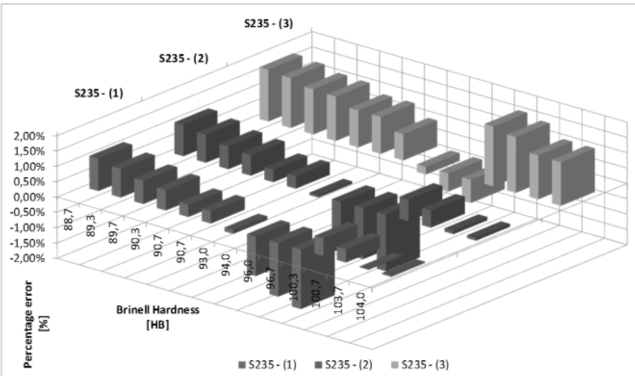

Figure 9. Percentage errors in predicting the Brinell Hardness for S235 steels (ASTM standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

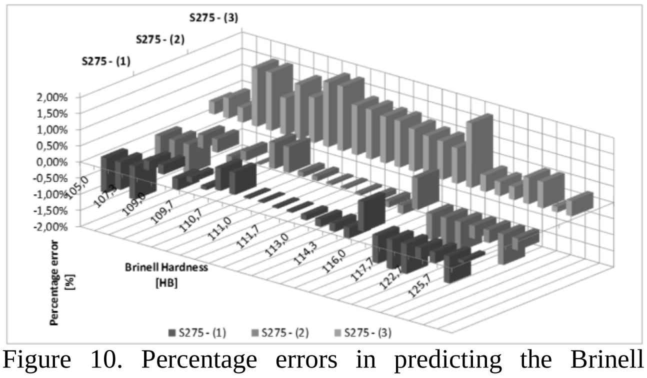

Figure 10. Percentage errors in predicting the Brinell Hardness for S275 steels (ASTM standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

The increase of the resistance class from S275 to S355 (Figure 11) results in errors higher than the ones obtained with lower resistance classes. Comparing the data from non-destructive Leeb tests with the results of tensile tests, it has been observed that for samples ST-P-05 (n.14) and ST-P-07 (n. 15) the passage of class from S235 to the S275 takes place.

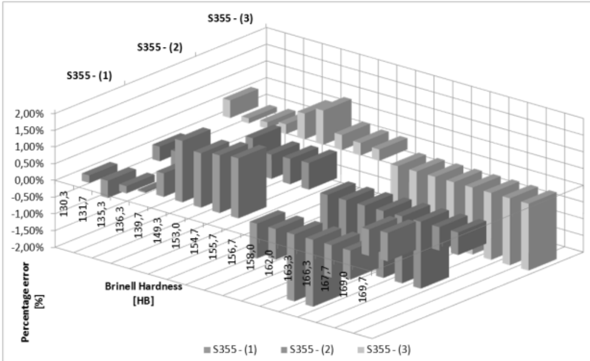

Figure 11. Percentage errors in predicting the Brinell Hardness for S355 steels (ASTM standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

The maximum scatter between the resistances of the two samples Δ_1^{ASTM} is equal to 6.60 MPa. In general, for 1 out of 15 samples of S235 steel class there is an error in identifying a higher resistance class. In particular, there is a percentage error of $e_{S235-S275}^{ASTM} = 6.67\%$,referred to the number of specimens investigated. Regarding the classification between S275 steels and S355 ones, from the data the passage is observed for the samples ST-P-32 (n.40) and ST-P-19 (n.41). The maximum scatter among resistances Δ_2^{ASTM} is equal to 20.9 MPa. In the transition between S275 class and the S355 one, for 1 out of 26 samples made of S275 steel an error $e_{S275-S355}^{ASTM} = 3.85\%$ is committed in the assignment of the class with respect to the higher one.

With regard to the samples ST-P-26, ST-P-11 and ST-S-06, the detected hardness values have been noticed in disagreement with the actual steel class deriving from either tensile test results or origin certificates. Moreover, comparing the resistance values for the different steel classes gotten from the different conversions from Leeb tests, it has been observed for S235 steels a maximum positive error $e_{\max,235}^{ASTM} = 1.75\%$ and a maximum negative error $e_{\min,235}^{ASTM} = -14.31\%$. Therefore, the tests tend to underestimate the resistance values, going on the safe side in terms of classification. For S275 steel, the conversion gives rise to a maximum positive error $e_{\max,275}^{ASTM} = 5.96\%$ and a maximum negative error $e_{\min,275}^{ASTM} = -16.28\%$.

The percentage scatter in terms of stress between the S235 class and the S275 one is defined as:

$$\Delta_{275-235} = \frac{f_{u,S275} - f_{u,S235}}{f_{u,S275}} \tag{8}$$

and herein assumes the value of 16.28%, which is greater than the maximum negative error recorded. However, the test does not imply problems in the class assignment.

For S355 steel class, the conversion provides a maximum positive error $e^{ASTM}_{\max,355} = 12.59\%$ and a maximum negative error $e^{ASTM}_{\min,355} = -14.71\%$.

The percentage scatter between these two steel classes $\Delta_{355\text{-}275}$ is 15.69%, a value greater than the maximum negative error recorded.

The tests conducted on 2 out of the total 19 specimens have provided values with an error $e_{355-275} = 10.52\%$ in the class assignment, while for higher values this problem is not felt.

Analyzing these experimental data, it is clear that the best methodology of data conversion from micro-hardness tests for the determination of the steel class resistance was given by the tables and the formulations of the ASTM standard. In the case of few values to be converted, the most effective method is the manual use of the tables, with an average error of 0.10%. Contrary, with the increase of the number of samples, the manual use has required a significant increase of the working time. In this case, the most reliable conversion method is the formula deriving from the envelope of the entire ASTM table, which provides an average error of 0.42%.

Comparing the results deriving from the relationships for the determination of steel class using UNI ISO methods, the achieved curves have trends very similar to each other (Figure 12).

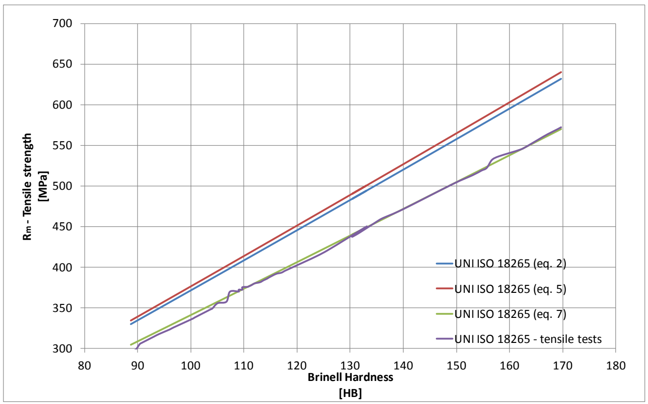

Figure 12. Comparison among hardness-strength curves (Brinell method – UNI ISO 18265 standard; tensile tests curve from conversion tables)

Nevertheless, these values are very far from those gotten from the UNI ISO 18265 standard conversion tables. In particular, when values deriving from the previously mentioned relationships are compared with the UNI complete table ones, it has been recorded a maximum error $e^{UNI}_{\max(6)} = 3.12\%$, a minimum error $e^{UNI}_{\min(6)} = -1.30\%$ and a maximum percentage scatter $\delta^{UNI}_{\max(6)} = 4.42\%$ (Figure 13).

Contrary, in the case of conversion using either only partial tables for carpentry steels or envelope formulas from manual conversion data, it has been noticed that the committed errors are higher than those of the previous case.

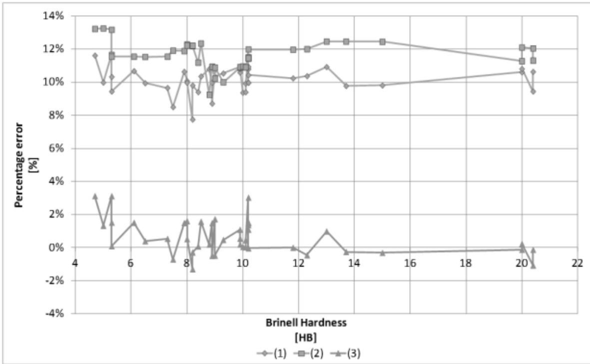

Figure 13. Percentage errors with respect to the envelope curve of the UNI ISO whole table (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

In fact, the maximum error is $e^{UNI}_{\max(5)} = 13.25\%$, the minimum error is $e^{UNI}_{\min(4)} = 7.75\%$ and the maximum scatter is $\delta^{UNI}_{\max(5)} = 4.01\%$. Analysing the error detected for the different steel classes, it has been observed that for S235 (Fig. 14), S275 (Fig. 15) and S355 (Fig. 16) steels, the errors tends to reduce only in the case of the relationship $R^{UNI}_{m} = 0.0006HB^2 + 3.1156HB + 23.8669$ (UNI EN ISO 18256 standard).

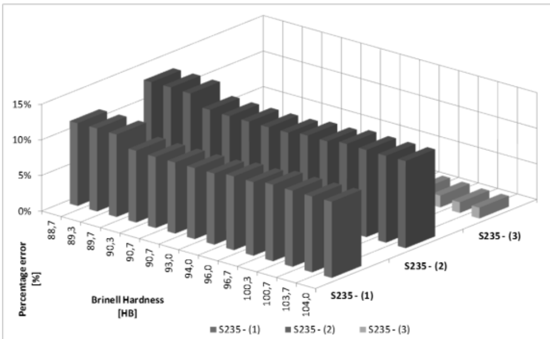

Figure 14. Percentage errors in predicting the Brinell Hardness for S235 steels (UNI ISO standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

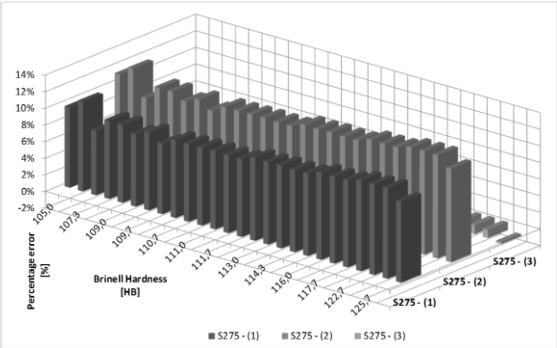

Figure 15. Percentage errors in predicting the Brinell Hardness for S275 steels (UNI ISO standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

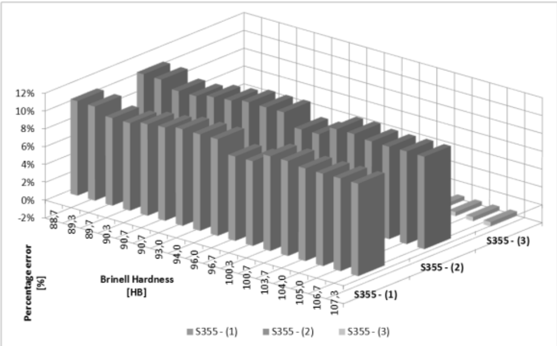

Figure 16. Percentage errors in predicting the Brinell Hardness for S355 steels (UNI ISO standard) (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

Even combining both the ASTM and the UNI standards values, the greatest errors, deriving from the UNI standards, have been obtained. This has led to an increase of the average error in the conversion.

Analyzing the data from non-destructive Leeb tests, the transition from S235 class to S275 class does not take place in a univocal manner, depending on the different assessments made. The error committed is much wider and implies that, according to the criterion used for 9 out of 17 samples of class S235 (samples n.9-17), an error in the identification of a higher resistance class can be made, with a percentage error $e^{UNI}_{S235\text{-}S275} = 52.94\%$. Similarly, in the transition from S275 steel to S355 one, it has been observed that for 10 out of 26 samples the error a percentage error $e^{UNI}_{S275\text{-}S355} = 38.46\%$ is committed in the assignment to a higher class.

Analyzing the resistance values deriving from the different conversions from Leeb tests to the reference values of classes, for S235 steels a maximum error $e^{UNI}_{\max,235} = 12.28\%$ and a minimum error $e^{UNI}_{\min,235} = -17.89\%$ are observed.

The test, therefore, tends to overestimate the resistance values, classifying S235 steel samples as S275 steel ones, and, thus, operating not on the safe side in terms of classification. For S275 class steel the conversion involves a maximum error $e^{UNI}_{\max,275} = 16.45\%$ and a minimum error $e^{UNI}_{\min,275} = -16.84\%$. Given the percentage difference between S235 class and S275 one ($\Delta_{275\text{-}235}$) equal to 16.28%, it is not possible to assign the class in an unambiguous way.

For S355 steel class the conversion involves a maximum error $e^{UNI}_{\max,355} = 25.58\%$ and a minimum error $e^{UNI}_{\min,355} = -17.51\%$. The percentage difference between S275 class and S355 one is $\Delta_{355\text{-}275} = 15.69\%$, higher than the minimum error committed. The tests conducted for 2 out of 19 samples provide limited values, which could lead to an error $e_{355\text{-}275} = 10.52\%$ in the assignment to the samples of a steel lower class.

Using the average values, deriving from formulations provided by ASTM A370-03a and UNI ISO 18265 methods, an intermediate trend between the two curves is achieved (Figure 17).

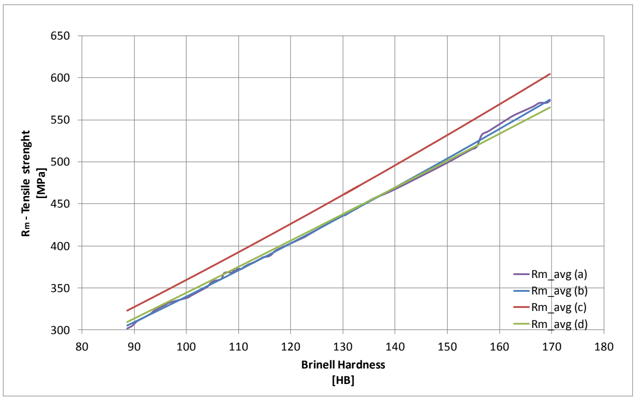

Figure 17. Comparison among hardness-strength curves deriving from average values between ASTM standard and UNI ISO one (Brinell method)

Comparing the values deriving from the different formulas with the average values from the table and evaluating the error committed (Table 5), it is observed (Figure 18) a maximum error $e^{ASTM-UNI}_{\max(8)} = 6.99\%$ and a minimum error $e^{ASTM-UNI}_{\min(9)} = -2.27\%$, with a maximum percentage scatter $\delta^{ASTM-UNI}_{\max(9)} = 4.67\%$.

Analyzing the errors committed for the different steel classes (Table 5), it is observed that the use of average values tends to reduce the errors detected using the UNI ISO tables. As seen before, the use of the envelope curve, obtained from the partial use of the tables for carpentry steels only, entails the greatest errors for all the steel classes.

Table 5. Minimum, maximum and average errors and deviation values with respect to average strengths between the ASTM method and the UNI ISO one

Comparison case	$e_{\min}^{ASTM-UNI}$ (%)	$e_{\max}^{ASTM-UNI}$ (%)	$e_{avg}^{ASTM-UNI}$ (%)	$\delta_{\max}^{ASTM-UNI}$ (%)
(1)	-1,55	1,12	-0,06	2,67
(2)	4,19	6,99	5,65	2,80
(3)	-2,27	2,39	0,48	4,67
S235 - (1)	-0,94	1,06	0,14	2,00
S235 - (2)	4,88	6,99	6,02	2,12
S235 - (3)	0,36	2,39	1,44	2,03
S275 - (1)	-1,55	0,45	-0,22	2,00
S275 - (2)	4,19	6,27	5,57	2,07
S275 - (3)	-0,43	1,36	0,74	1,79
S355 - (1)	-1,09	1,12	0,01	2,21
S355 - (2)	4,21	6,61	5,46	2,40
S355 - (3)	-2,27	0,54	-0,72	2,81

(1) Percentage error between the curves deriving from the average data envelope of ASTM 370-03a and UNI ISO 18265 standards and the average hardness data resulting from the manual conversion from ASTM 370-03a and UNI ISO 18265 tables
(2) Percentage error between the average values from the partial conversion curves for carpentry steels deriving from ASTM 370-03a and UNI ISO 18265 standards and the average hardness data resulting from the manual conversion from ASTM 370-03a and UNI ISO 18265 tables
(3) Percentage error between the average values from the full table curve of ASTM 370-03a and UNI ISO 18265 standards and the average hardness data resulting from the manual conversion from ASTM 370-03a and UNI ISO 18265 tables

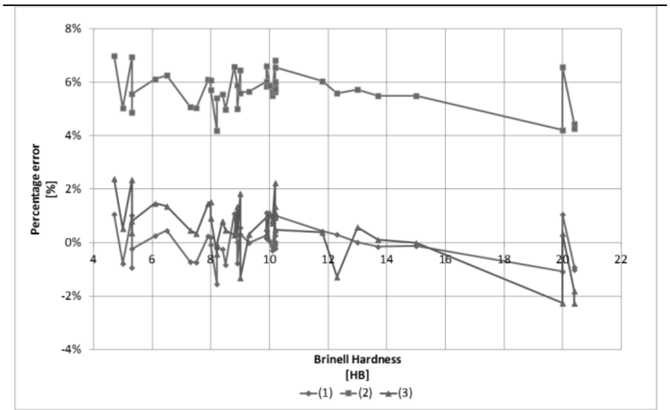

Figure 18. Percentage errors with respect to the envelope curves of the complete tables from ASTM and UNI ISO standards (Legend - 1: envelope from tables; 2: partial envelope; 3: total envelope)

Framing the different samples in steel classes according to either tensile tests or origin certificates, it is noted that for all steel types the use of ASTM standard tables (or of the envelope formulas derived from them) allows to reduce errors obtained from using the UNI standard. In fact, the errors committed with ASTM tables have a maximum value of 6.67%. Contrary, the maximum error detected when using the UNI tables is equal to 52.94%. With regard to the S235 class, the most reliable method is that given by the formulas deriving from the envelope of the ASTM partial tables, which provided error $e_{med-S235-(2)}^{ASTM} = 0.06\%$ and scatter $\delta_{\max-S235-(2)}^{ASTM} = 2.87\%$, respectively, against the corresponding values $e_{med-S235-(3)}^{ASTM} = 1.04\%$ and $\delta_{\max-S235-(3)}^{ASTM} = 2.71\%$ when the complete envelope of tables was used.

Analyzing data from non-destructive Leeb tests due to the use of partial envelope curves, for some samples the passage from S235 class to S275 one takes place from sample ST-S-04 (sample n.11). For 6 out of 16 samples of S235 class a percentage error $e_{S235-S275}^{ASTM-UNI} = 37.5\%$ occurs in the detection of a higher resistance class.

With reference to the transition from S275 steel to S355 one, the change of class is observed for the sample ST-P-27 (sample n.37) when adopting all the evaluation methods. Compared to the total number of S275 class steel samples, for 4 out of 26 samples the assignment to a higher class is committed with a percentage error $e_{S275-S355}^{ASTM-UNI} = 15.38\%$.

Analyzing the resistance values, deriving from the different conversions from Leeb tests to the classes reference values, for S235 steels a maximum error $e_{\max,235}^{ASTM-UNI} = 5.98\%$ and a minimum error $e_{\min,235}^{ASTM-UNI} = -16.1\%$ is gotten. Therefore, the tests do not tend to overestimate the resistance values, but they appropriately classify the samples.

For S275 class steels the conversion involves a maximum error $e_{\max,275}^{ASTM-UNI} = 9.58\%$ and a minimum error $e_{\min,275}^{ASTM-UNI} = -17.38\%$. Major details on the tests performed are reported in Formisano et al. (2019).

Given the percentage scatter $\Delta_{275-235} = 16.28\%$ between S235 class and S275 one, for n.1 sample the assignment to a lower class occurs. For S355 class steels the conversion involves a maximum error $e_{\max,355}^{ASTM-UNI} = 18.52\%$ and a minimum error $e_{\min,355}^{ASTM-UNI} = -17.34\%$. Since the percentage scatter $\Delta_{355-275}$ between the 275 class and the S355 one equal to 15.69%, for n.1 out of 19 samples the assignment on the safe side to a lower steel class occurs with an error $e_{355-275} = 5.26\%$.

In conclusion, passing from the S275 class to the S335 one it is observed that the most reliable method is the envelope of partial tables, where only the data of carpentry steels are present. The detected errors and percentage scatters are respectively 0.16% and 1.93% for S275 steel and 0.91% and 4.54% for S355 one.

3.2 *Second sequence of tests*

The six specimens, having different surface preparation levels, have been subjected to Leeb hardness tests in order to achieve the average rebound values. Subsequently, the ultimate stresses corresponding to Brinell and Rockwell hardness values have been derived from standard conversion tables. Moreover, in order to have a more clear representation and comparison of results, the achieved average tensile stresses for the six samples tested have been diagrammed in growing order of values (Figures 19 and 20). The resistance values of samples have been plotted and the difference among them has been estimated. In particular, for samples 2 and 6 according to the Brinell scale (Figure 19) and for samples 2, 3 and 6 according to the Rockwell scale (Figure 20) there is a significant difference between the stresses of original (as is) specimens and those of samples with the two considered surface treatments. It appears that the detected differences affect steels having tensile strengths in the range between 300 and 500 MPa. Instead, for both hardness methods examined, basically no stress difference between the different surface preparation degrees is detected.

In Figures 21 and 22 the percentage deviations among the resistance values obtained after working with grinder and those achieved from the other two surface treatments (as is and worked with sandpaper) are plotted on the basis of the Brinell scale and the Rockwell one, respectively. From the comparison of values it is seen that the shortest deviations (maximum negative and positive deviations of -1.86% and +2.57%, respectively) are noticed when the Brinell scale is considered. Contrary, the tensile strength values obtained from the Rockwell scale show the highest variability, that is comprised into a range having maximum negative and positive deviations equal to -11.40% and + 12.09%, respectively.

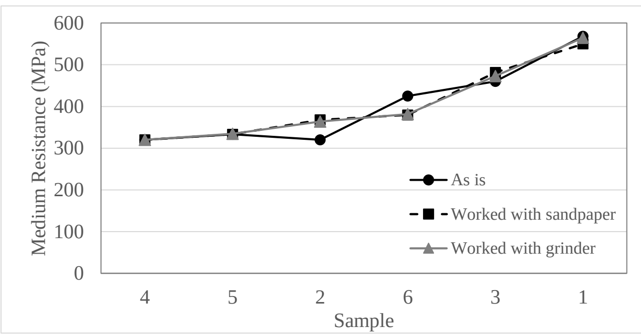

Figure 19. Medium tensile strengths of samples derived from the ASTM A370 standard according to the Brinell scale.

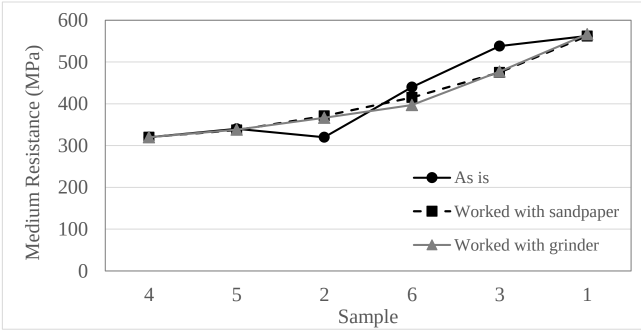

Figure 20. Medium tensile strengths of samples derived from the ASTM A370 standard according to the Rockwell scale.

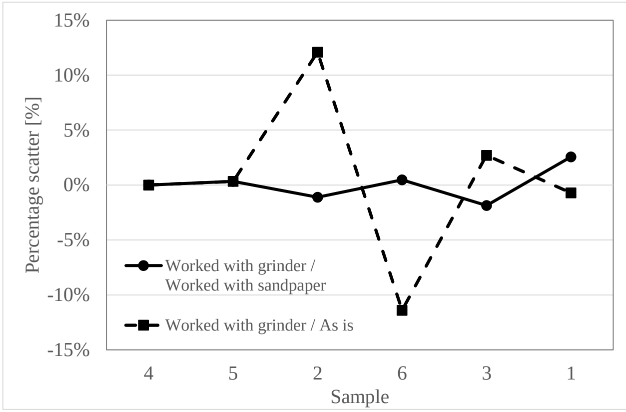

Figure 21. Percentage scatters among medium tensile strengths of samples derived from the Brinell scale.

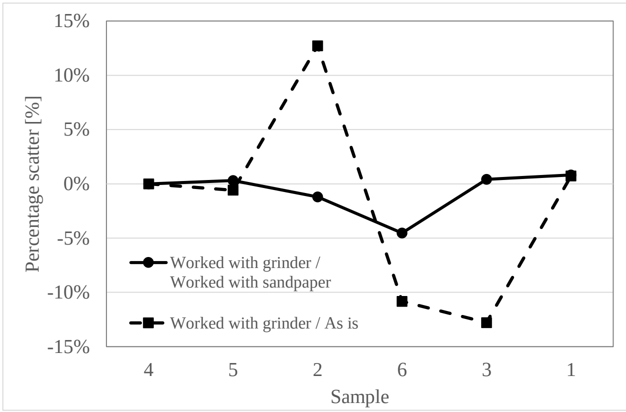

Figure 22. Percentage scatters among medium tensile strengths of samples derived from the Rockwell scale.

Finally, the percentage differences between average tensile strengths values of the Brinell method and those derived from the Rockwell method have been plotted for the samples subjected to the three different polishing treatments of surfaces (Figure 23). From the comparison it appears that the maximum strength percentage deviations occurs for “as is” samples, where the maximum value of 16.96% is recorded for the sample n. 3 due to the numerous oxidized zones. After, the maximum deviations occur for “worked with sandpaper” samples, whose specimen n. 6 shows the maximum deviation of 9.3% due to the presence of paint on the member surface.

Finally, the variation laws among the medium tensile strengths of tested samples and the corresponding hardness values derived from the Brinell scale and the Rockwell one have been reported in Figure 24. From this diagram it is noticed that, while the hardness scales are different in the two examined cases, the corresponding resistance values are similar each other. In addition, as the hardness increases, the average tensile strength variation occurs more quickly when the Rockwell scale is considered. This is testified by the high slope of the Rockwell curve with respect to the Brinell one.

Figure 23. Percentage scatters between resistances derived from the Brinell scale hardnesses and the Rockwell scale ones.

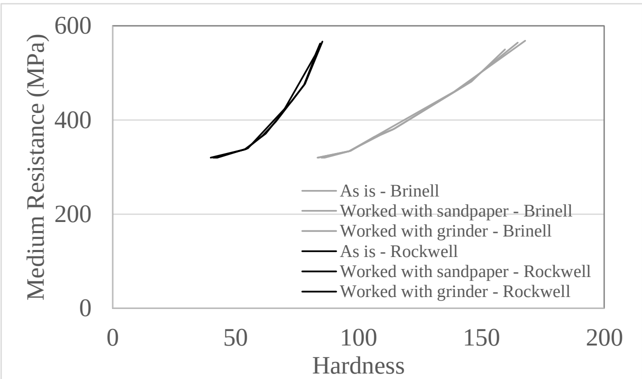

Figure 24. Average tensile strength vs. hardness curves of tested samples.

In order to validate the reliability of the above curves, further hardness data will be collected and experimental tensile tests will be performed on tested samples so to derive a correlation law to predict, starting from non-destructive hardness tests, the tensile strength (or ultimate stress) of carpentry steel members. Moreover, the efficiency of the hardness-stress relationships provided by the standard tables will be additionally proved and supplementary data of such tables, especially for low-carbon content (mild) steels, could be provided.

4 CONCLUDING REMARKS

In the paper the classification of carpentry steels based on non-destructive hardness test was illustrated and discussed.

From the first experimental activity, it was observed that, for the class evaluation of structural steels, the execution of tests required a careful cleaning of the sample surface.

Analyzing the data obtained from the experimentation, it was clear that the best methodology of data conversion from micro-hardness (Leeb method) tests for the determination of the steel class resistance was given by tables and formulations of the ASTM standard. In the case of a few values to be converted, the most effective method was the manual use of the tables, with an average error of 0.10%. However, with the increase of the number of samples, the manual use involved a significant increase of the working time. In this case, the most reliable method for conversion was given by the use of the formula deriving from the envelope of the entire ASTM table, which provides an average error of 0.42%. Even in the case of combined use of the ASTM and UNI standards values, the presence of the greatest errors deriving from the UNI standards leaded to the increase of the average error committed in the conversion.

Dividing the different samples in steel classes, it was noted that for all steel types the use of ASTM standard tables (or of the envelope formulas derived from them) allows to reduce errors obtained from using the UNI standard. In fact, the errors committed with ASTM tables were contained in a limited range, with maximum value of 6.67%. Contrary, the maximum error detected when using the UNI tables for carpentry steels was equal to 52.94%. More in detail, with regard to the S235 class, the most reliable method was that given by the formulas deriving from the envelope of the ASTM partial tables for carpentry steels, which provided error $e^{ASTM}_{med-S235-(2)} = 0.06\%$ and scatter $\delta^{ASTM}_{\max-S235-(2)} = 2.87\%$, respectively, against the corresponding values $e^{ASTM}_{med-S235-(3)} = 1.04\%$ and $\delta^{ASTM}_{\max-S235-(3)} = 2.71\%$ when the complete envelope of tables was used.

In conclusion, passing from the S275 class to the S335 one it was observed that the most reliable method is the envelope of partial tables, where only the data of carpentry steels are present. The detected errors and percentage scatters were respectively 0.16% and 1.93% for S275 steel and 0.91% and 4.54% for S355 one.

However, it is important to remember that tables of both ASTM and UNI standards do not cover a large range of low hardness values. For this reason, further experimental destructive and non-destructive tests steels should be performed in order to complete the standard tables for obtaining reliable conversion formulas from hardness values to tensile strengths.

On the other hand, from the second experimental activity, the following considerations can be done:

– The hardness values recorded by micro-hardness tests tended to increase in the case of samples particularly oxidized and to decrease for painted samples. Therefore, it can be deduced that the presence of the paint caused a sort of "soft layer" that alters the surface resistance value;
– The hardness increased more near to the boundaries of samples due to steel hardening caused by the formation process. So, it is essential to perform measurements at predefined distances from edges and holes to avoid local effects which can distort the results.
– The tests provided a very wide dispersion of results in the case of thin samples (thickness in the order of 5 ÷ 10 mm). In the experimental stages, in fact, it was observed that for the reduced thickness, due to the rebound of the micro-hardness tester, the specimens tended to vibrate, producing a series of unstable readings.
– The major scatters of results in terms of both hardness and tensile strength were recorded for members without surface treatments (as is), whereas the scatters between two worked solutions (with sandpaper and with grinder) were very limited. This suggested to use the technique of working with sandpaper of steel samples before performing hardness tests.
– The trends of average tensile strength-hardness curves for both Brinell and Rockwell scales were derived. On the basis of further hardness tests on steel samples with known mechanical properties, future correlation laws to use hardness tests in partial replacing of destructive tensile tests could be usefully employed.
– Future investigations must be targeted to evaluate how hardness values will be influenced by the distance of readings from edges and/or holes. In addition, further experimental researches should be performed aiming at assessing the influence of the internal stress state of in-situ structural elements on the Leeb hardness values in order to deduce corrective correlation coefficients between destructive tensile tests and the non-destructive ones herein inspected.

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