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RESEARCH ARTICLE

Non-Destructive Tests on Carpentry Steels

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Abstract:

Background:

Industrial archaeology represents a modern branch of urbanism and architecture that studies, applying an interdisciplinary method, all the evidence inherent the process of industrialization from its origins to the actuality.

Aim:

Looking at the cities of our epoch, more and more are the testimonies of these historical artefacts, which in fact represent our cultural identity and are often intended to be recovered and converted into modern destinations of use.

Methods:

If the identification of constructive schemes is based on direct essays and surveys, the definition of material properties requires material testing and investigation. For metal structures, the standards involve destructive investigations only, with a sampling of specimens, which often conflict with the protection requirements of the artefact. This leads to the need to refine and make reliable non-destructive investigations using the Leeb method, by means of portable micro-durometers, for *in-situ* characterization of carpentry steels, so to suggest new regulatory guidelines for existing structures surveys.

Results:

In the paper, the classification of carpentry steels based on non-destructive hardness test was illustrated and discussed. Firstly, for the evaluation of the resistance class of a structural steel, it was recorded that the execution of tests required a careful cleaning of the surface of samples.

Subsequently, 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 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%.

Conclusion:

In conclusion, it should be remarked that differently from the reinforced concrete structures, where the non-destructive tests are allowed by the current Italian technical code on, for metallic structures only, destructive tests are permitted, so that the use of non-destructive ones should be encouraged, especially when interventions on cultural heritage constructions are of concern.

Keywords: Steel structures, Mechanical tests, Hardness, Brinell tests, Leeb tests, Micro-durometers.

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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 evidence 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 [1, 2]. In this context,

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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 [3, 4], 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 [5], 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 equipment 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) [6]. 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 piece of 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 [7] and UNI EN ISO 18265 [8] 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 [9], subsequently evaluating the type of steels according to the UNI EN 10002-1 standard [10], or using the material accompanying certificates, obtained from acceptance tests [3 - 5]. Currently, in the market, there are various types of equipment for Leeb hardness tests, although reliability and compliance with international standards are still being tested [11].

It should also be noted that for reinforced concrete structures, the existing Italian regulations [3 - 5] 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 [12, 13], which are correlated to the compression resistances of cylindrical samples extracted from structural members. Contrary, for metallic structures, current standards do not envisage 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. So, the innovation of the present work is to set up appropriate theoretical relationships for carpentry steels able to put in relationship Leeb hardness test values with experimental tensile strengths. In this way, it will be possible to indirectly evaluate, starting from Leeb hardness values measured *in-situ* on carpentry steels, the strengths of those materials to be used for their mechanical characterization in the field of seismic assessment of steel artefacts.

2. TESTING METHODOLOGY

2.1. The Hardness Test

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 a 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.

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

Fig. (2). Samples from plates and sheets with different thickness.

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. This allows to:

− Verify the test reliability with respect to the hardness values provided by ASTM A956 [7] and UNI EN ISO 18265 [8] standards;
− 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. Specimens

The used steel samples, provided by the Tecnolab srl company, an authorised laboratory 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**);
- 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, to classify the steel type (S235, S275 or S355) depending on the yielding stress achieved.

2.3. Test Equipment

For the purpose of the tests, a durometer type MH100 Leeb Hardness Tester, manufactured by the Mitech CO. Ltd company, is used (Fig. **5**).

Fig. (3). Samples from HE and IPE profiles.

Fig. (4). Samples from smooth round bars having different diameters.

Fig. (5). MH100 Leeb Hardness Tester manufacturer by the Mitech CO. Ltd company.

No.	Type of impact device	Hardness value of Leeb standard hardness block	Error of displayed value	Repeatability
1	D	760±30HLD 530±40HLD	±6 HLD ±10 HLD	6 HLD 10 HLD
2	DL	878±30HLDL 736±40HLDL	±12 HLDL	12 HLDL
3	C	822±30HLC 590±40HLC	±12 HLC	12 HLC

- Measuring range：HLD（170～960）HLD
- Measuring direction：0°~360°
- Hardness Scale：HL、HB、HRB、HRC、HRA、HV、HS
- Display：segment LCD
- Data memory：100 groups max.（relative to impact times 32～1）
- Battery: 3.7V Li-Ion, Rechargeable
- Battery charger: 5V/500mA
- Continuous working period：about 200 hours（With backlight off, no printing）
- Communication interface：USB1.1

Fig. (6). Technical specifications of the MH100 Leeb Hardness Tester.

Such an instrument has a lot of useful advantages, such as:

- Easiness of measurement, since the tester is portable and compact, with the impacting tip integrated into the instrument main body;
- Large measuring range, based on the principle of steel Leeb hardness;
- Large LCD display for viewing parameters and functions, with direct reading of test values in HB, HS, HV, HRB, HRC and HRA scales;

- Possibility to vary both the angle of inclination of the impact surface and the type of test to be carried out;
- Large memory, that can hold up to 100 measurement, impact, angle information and impact time values;
- Software for transferring data directly to a PC;
- Simplicity of use, due to the limited geometrical dimensions (148mm x 33mm x 28mm).

From the technical specifications (Fig. **6**), the working conditions are described, allowing for very wide use of the device, which is extremely easy to be used even by not highly specialized workers.

The instrument use conditions are:

- Working temperature: -10°C ÷ 50°C;
- Storage temperature: -30°C ÷ 60°C;
- Relative humidity: <90%;
- Preparation of the contact surfaces.

With reference to the last issue, the manufacturer requires the preliminary preparation of the test surfaces for the elimination of residues of oil or fat, traces of rust and/or varnishes. Therefore, the specimens are preliminarily cleaned using a counter-top grinder (Fig. **7**), so to make the surface perfectly flat and free from oxidation spots.

This operation is particularly important and delicate, since the durometer support ring must adhere orthogonal to the surface to properly perform the measurement. Otherwise, the device returns default values only, which require to repeat the test. The test consists of three measurement gauges, carried out at different points of the sample, spaced according to the manufacturer's specifications (Table **1**).

Table 1. Specifications of the manufacturer for Leeb tests.

Type of Impact Device	Distance Between Centres of Two Indentations	Distance from the Centre of the Indentation to the Sample Edge
	Not Less Than (mm)	Not Less Than (mm)
D	3 1.5	5 6,2-20
DL	3 0,6-1,1	5 11-32
C	2 1.35	4 12

Initially, the loading test is carried out by pushing the loading column in contact with the surface and slowly releasing it to the rest position, so as to control the efficiency of the column stroke, paying close attention to check that the test surface adheres to the micro-durometer head ring. After positioned the tool, the release button is pressed, marking the load direction coincident with the device axis.

For each sample five tests are carried out, checking that the result data do not have values that deviate from ± 1.5HL. Excluding the largest and smallest test values, the arithmetic mean of the remaining three test values is performed.

Generally, the device has memorized a number of materials, which there are already conversion ratios in terms of hardness (Table **2**) or resistance (Table **3**) for, to be selected before testing. Contrary, if it is required to correlate Leeb hardness values to another hardness values for special materials (aluminium alloys, steels with different carbon content or special steels), it is necessary to execute a new static hardness test campaign to get the conversion ratios.

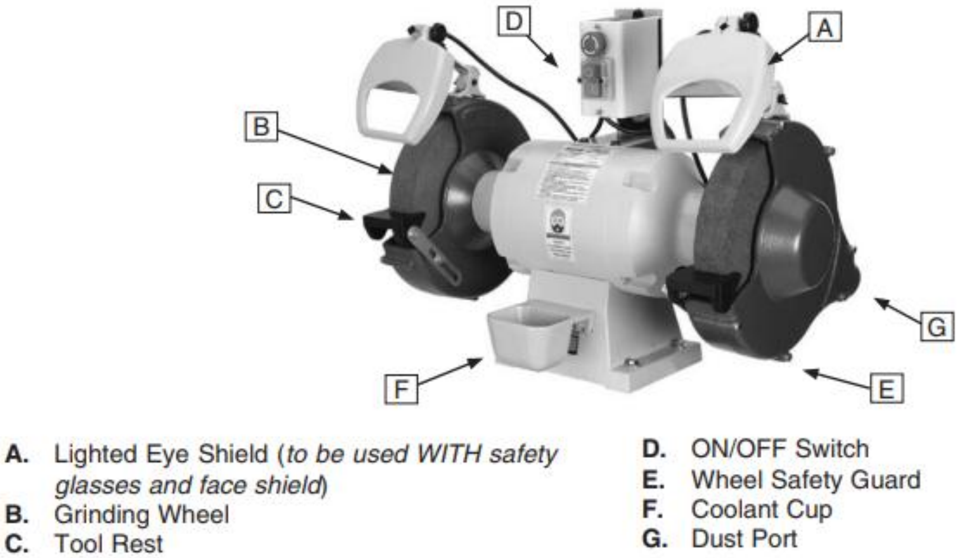

Fig. (7). Bench grinder for preparation of samples (https://cdn0.grizzly.com/manuals/g0596_m.pdf).

Table 2. Different material types for conversion in terms of hardness.

Index	Material
0	Steel and cast steel
1	Cold work tool steel
2	Stainless steel
3	Gray cast iron
4	Nodular cast iron
5	Cast aluminum alloys
6	Copper-Zinc alloys
7	Copper –Aluminum alloys
8	Wrought copper
9	Wrought steel

3. THE EXPERIMENTAL ACTIVITY

3.1. Preparation of Samples for Leeb Test

The specimens have been prepared for the execution of the test, assigning an acronym to each of 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.

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 **4** and **5** for plates and sheets, respectively) or diameter (Table 6), 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".

Table 3. Different material types for conversion in terms of strength.

Index	Material
0	Mild steel
1	High carbon steel
2	Cr steel
3	Cr-V steel
4	Cr-Ni steel
5	Cr-Mo steel
6	Cr-Ni-Mo steel
7	Cr-Mn-Si steel
8	Super strenght steel
9	Stainless steel

Table 4. Numbering, steel type and thickness of plate samples.

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

(Table 4) contd.....

Code	Sample Number	Thickness [mm]	Steel Class [MPa]
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 5. Numbering, steel type and thickness of sheet samples.

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-06	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-05	57	9,0	S355

Table 6. Numbering and steel type of round samples.

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

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. The equipment has been calibrated on mild and cast steels (with index 0 in Tables **2** and **3**), 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 (Table **1**). 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 **4**, **6**).

3.2. Classification of Samples According to the Leeb-HB 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 (Table **7**). 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 (Table **8**).

Table 7. Leeb hardness values resulting from tests.

Code	Sample Number	Leeb - HB Hardness Conversion					Average HB Hardness
		HB_{min}	HB_1	HB_2	HB_3	HB_{max}	HB_{avg}
ST-P-01	1	78,0	81,0	87,0	98,0	99,0	88,7
ST-P-02	2	80,0	82,0	94,0	92,0	95,0	89,3
ST-P-25	3	91,0	93,0	86,0	90,0	93,0	89,7
ST-P-09	4	91,0	91,0	98,0	82,0	85,0	90,3
ST-P-15	5	87,0	92,0	82,0	98,0	101,0	90,7
ST-P-23	6	80,0	82,0	96,0	94,0	97,0	90,7
ST-P-24	7	94,0	97,0	89,0	93,0	96,0	93,0
ST-S-01	8	94,0	95,0	91,0	96,0	99,0	94,0
ST-P-13	9	91,0	92,0	95,0	101,0	104,0	96,0
ST-P-03	10	85,0	86,0	107,0	97,0	100,0	96,7
ST-S-04	11	97,0	99,0	102,0	100,0	102,0	100,3
ST-R-01	12	90,0	92,0	107,0	103,0	105,0	100,7
ST-P-08	13	105,0	108,0	98,0	105,0	107,0	103,7
ST-P-05	14	97,0	98,0	112,0	102,0	104,0	104,0
ST-S-06	15	105,0	107,0	105,0	120,0	122,0	110,7
ST-P-07	16	121,0	123,0	95,0	97,0	99,0	105,0
ST-P-26	17	106,0	108,0	105,0	107,0	109,0	106,7
ST-P-10	18	101,0	103,0	120,0	99,0	101,0	107,3
ST-R-02	19	99,0	100,0	112,0	115,0	117,0	109,0
ST-R-03	20	115,0	117,0	101,0	109,0	111,0	109,0
ST-P-16	21	101,0	104,0	108,0	115,0	117,0	109,0
ST-R-04	22	115,0	120,0	106,0	103,0	105,0	109,7
ST-S-02	23	113,0	117,0	116,0	96,0	98,0	109,7
ST-R-05	24	115,0	117,0	97,0	118,0	120,0	110,7
ST-P-12	25	112,0	113,0	117,0	103,0	105,0	111,0
ST-P-04	26	102,0	106,0	110,0	118,0	120,0	111,3
ST-R-06	27	115,0	119,0	110,0	106,0	108,0	111,7
ST-P-22	28	107,0	110,0	114,0	112,0	114,0	112,0
ST-S-03	29	121,0	124,0	106,0	109,0	111,0	113,0
ST-P-21	30	107,0	111,0	116,0	114,0	116,0	113,7
ST-R-07	31	130,0	132,0	100,0	111,0	113,0	114,3
ST-R-08	32	97,0	100,0	124,0	120,0	122,0	114,7
ST-P-06	33	114,0	117,0	124,0	107,0	109,0	116,0
ST-R-09	34	112,0	115,0	114,0	122,0	124,0	117,0
ST-R-10	35	122,0	125,0	127,0	101,0	103,0	117,7
ST-R-11	36	115,0	118,0	123,0	113,0	115,0	118,0
ST-P-27	37	115,0	116,0	123,0	129,0	131,0	122,7
ST-P-18	38	119,0	124,0	119,0	125,0	127,0	122,7
ST-P-31	39	116,0	117,0	124,0	136,0	137,0	125,7
ST-P-32	40	126,0	127,0	133,0	139,0	140,0	133,0
ST-P-19	41	125,0	128,0	124,0	139,0	140,0	130,3
ST-P-17	42	137,0	140,0	125,0	130,0	131,0	131,7
ST-P-11	43	128,0	129,0	130,0	147,0	148,0	135,3
ST-S-06	44	135,0	136,0	129,0	144,0	145,0	136,3
ST-P-29	45	142,0	143,0	147,0	129,0	130,0	139,7
ST-P-28	46	142,0	144,0	157,0	147,0	148,0	149,3
ST-S-08	47	145,0	147,0	160,0	152,0	153,0	153,0
ST-P-14	48	151,0	153,0	146,0	165,0	166,0	154,7
ST-P-20	49	147,0	148,0	164,0	155,0	156,0	155,7
ST-P-34	50	162,0	162,0	168,0	140,0	141,0	156,7
ST-R-12	51	159,0	160,0	152,0	162,0	163,0	158,0

(Table 7) contd.....

Code	Sample Number	Leeb - HB Hardness Conversion					Average HB Hardness
		HB_{min}	HB_1	HB_2	HB_3	HB_{max}	HB_{avg}
ST-S-07	52	160,0	162,0	160,0	164,0	165,0	162,0
ST-P-33	53	174,0	175,0	153,0	162,0	163,0	163,3
ST-R-13	54	164,0	166,0	159,0	174,0	175,0	166,3
ST-R-14	55	159,0	159,0	175,0	169,0	170,0	167,7
ST-P-30	56	170,0	171,0	167,0	169,0	170,0	169,0
ST-S-05	57	172,0	173,0	186,0	150,0	152,0	169,7

Table 8. Conversion from tensile test values to Leeb hardness ones.

–				Tensile Strength R_m			
Code	Sample Number	Steel Class [MPa] (*)	Average HB Hardness HBmed	ASTM A370-03a [MPa]	UNI ISO 18265 [MPa]	$R_{m,avg}$ [MPa]	Average Deviation [%]
ST-P-01	1	S235	88,7	308,5	295,6	302,1	-4,27
ST-P-02	2	S235	89,3	310,6	297,7	304,2	-4,24
ST-P-25	3	S235	89,7	312	299	305,5	-4,26
ST-P-09	4	S235	90,3	314,0	305,3	309,7	-2,81
ST-P-15	5	S235	90,7	315,7	306,7	311,2	-2,89
ST-P-23	6	S235	90,7	315,7	306,7	311,2	-2,89
ST-P-24	7	S235	93,0	323,5	314,5	319,0	-2,82
ST-S-01	8	S235	94,0	330,0	317,8	323,9	-3,77
ST-P-13	9	S235	96,0	337,0	323,4	330,2	-4,12
ST-P-03	10	S235	96,7	339,5	325,7	332,6	-4,15
ST-S-04	11	S235	100,3	341,0	336,7	338,9	-1,27
ST-R-01	12	S235	100,7	342,4	338,0	340,2	-1,29
ST-P-08	13	S235	103,7	352,4	348,1	350,3	-1,23
ST-P-05	14	S235	104,0	353,4	349,1	351,3	-1,22
ST-P-07	15	S275	105,0	360	355,7	357,9	-1,20
ST-P-26	16	S235	106,7	364	357,6	360,8	-1,77
ST-P-10	17	S275	107,3	366,6	370	368,3	0,92
ST-R-02	18	S275	109,0	366,6	370	368,3	0,92
ST-R-03	19	S275	109,0	366,6	370	368,3	0,92
ST-P-16	20	S275	109,0	369	372,4	370,7	0,92
ST-R-04	21	S275	109,7	369	372,4	370,7	0,92
ST-S-02	22	S275	109,7	370	375,4	372,7	1,45
ST-S-06	23	S275	110,7	370	375,8	372,9	1,56
ST-R-05	24	S275	110,7	370	375,8	372,9	1,56
ST-P-12	25	S275	111,0	373,4	376,8	375,1	0,91
ST-P-04	26	S275	111,3	374,4	377,8	376,1	0,90
ST-R-06	27	S275	111,7	375,7	379,1	377,4	0,90
ST-P-22	28	S275	112,0	376,7	380,2	378,5	0,92
ST-S-03	29	S275	113,0	380,1	381,6	380,9	0,39
ST-P-21	30	S275	113,7	382,4	384	383,2	0,42
ST-R-07	31	S275	114,3	384,5	386	385,3	0,39
ST-R-08	32	S275	114,7	385,8	387,4	386,6	0,41
ST-P-06	33	S275	116,0	385	391,8	388,4	1,75
ST-R-09	34	S275	117,0	395	393,3	394,2	-0,43
ST-R-10	35	S275	117,7	397,3	395,6	396,5	-0,43
ST-R-11	36	S275	118,0	398,4	396,6	397,5	-0,45
ST-P-27	37	S275	122,7	410,7	410,6	410,7	-0,02
ST-P-18	38	S275	122,7	410,7	410,6	410,7	-0,02
ST-P-31	39	S275	125,7	422,4	420,7	421,6	-0,40

(Table 8) contd.....

–				Tensile Strength R_m			
Code	**Sample Number**	**Steel Class [MPa] (*)**	**Average HB Hardness HBmed**	**ASTM A370-03a [MPa]**	**UNI ISO 18265 [MPa]**	**$R_{m,avg}$ [MPa]**	**Average Deviation [%]**
ST-P-32	40	S275	133,0	443,3	450	446,7	1,50
ST-P-19	41	S355	130,3	435	437,7	436,4	0,62
ST-P-17	42	S355	131,7	440,7	442,4	441,6	0,39
ST-P-11	43	S275	135,3	451,7	457,8	454,8	1,34
ST-S-06	44	S275	136,3	454,3	461,2	457,8	1,51
ST-P-29	45	S355	139,7	462,3	470,7	466,5	1,80
ST-P-28	46	S355	149,3	490,8	502,7	496,8	2,40
ST-S-08	47	S355	153,0	505	513,4	509,2	1,65
ST-P-14	48	S355	154,7	510,6	519,1	514,9	1,65
ST-P-20	49	S355	155,7	513,9	522,4	518,2	1,64
ST-P-34	50	S355	156,7	532,4	532,4	532,4	0,00
ST-R-12	51	S355	158,0	536,8	536,8	536,8	0,00
ST-S-07	52	S355	162,0	560	545	552,5	-2,71
ST-P-33	53	S355	163,3	564,5	549,4	557,0	-2,71
ST-R-13	54	S355	166,3	569,5	561,0	565,3	-1,50
ST-R-14	55	S355	167,7	574,2	565,7	570,0	-1,49
ST-P-30	56	S355	169,0	570	570,1	570,1	0,02
ST-S-05	57	S355	169,7	572,3	572,5	572,4	0,03
–	(*)	Classification by destructive tensile tests					

Table 9. Conversion among hardness values for mild and alloy steels according to the ASTM A370-03a code.

HV	**HRC**	**HV**	**HRC**	**HV**	**HRC**	**HV**	**HRC**	**HV**	**HRC**
2270	85	1950	81	1633	77	1323	73	1004	69
2190	84	1865	80	1556	76	1245	72	940	68
2110	83	1787	79	1478	75	1160	71	920	67,5
2030	82	1710	78	1400	74	1076	70	900	67
HRC Diamond cone	**HV Vickers 30**	**HBBrinell 29400 N**	**HRA Diamond cone**	**R_m (MPa)**	**HRB Sphere 1/16”**	**HV Vickers 30**	**HB Brinell 29400 N**	**HRA Diamond cone**	**R_m (MPa)**
68	940	/	85,6	/	100	240	*240*	*61,5*	*800*
67	900	/	85,0	/	99	234	*234*	*60,9*	*785*
66	865	/	84,5	/	98	228	*228*	*60,2*	*750*
65	832	739	83,9	/	97	222	*222*	59,5	715
64	800	722	83,4	/	96	216	216	58,9	705
63	772	706	82,8	/	95	210	210	58,3	690
62	746	688	82,3	/	94	205	205	57,6	675
61	720	670	81,8	/	93	200	200	57,0	650
60	697	654	81,2	/	92	195	195	56,4	635
59	664	634	80,7	2420	91	190	190	55,8	620
58	653	615	80,1	2330	90	185	185	55,2	615
57	633	595	79,6	2240	89	180	180	54,6	605
56	613	577	79,0	2160	88	176	176	54,0	590
55	595	560	78,5	2070	87	172	172	53,4	580
54	577	543	78,0	2010	86	169	169	52,8	570
53	560	525	77,4	1950	85	165	165	52,3	565
52	544	512	76,8	1880	84	162	162	51,7	560
51	528	496	76,3	1820	83	159	159	51,1	550
50	513	482	75,9	1760	82	156	156	50,6	530
49	498	468	75,2	1700	81	153	153	50,0	505
48	484	455	74,7	1640	80	150	150	49,5	495

(Table 9) contd.....

HV	HRC	HV	HRC	HV	HRC	HV	HRC	HV	HRC
47	471	442	74,1	1580	79	147	147	48,9	485
46	458	432	73,6	1520	78	144	144	48,4	475
45	446	421	73,1	1480	77	141	141	47,9	470
44	434	409	72,5	1430	76	139	139	47,3	460
43	423	400	72,0	1390	75	137	137	46,8	455
42	412	390	71,5	1340	74	135	135	46,3	450
41	402	381	70,9	1300	73	132	132	45,8	440
40	392	371	70,4	1250	72	130	130	45,3	435
39	382	362	69,9	1220	71	127	127	44,8	425
38	372	353	69,4	1180	70	125	125	44,3	420
37	363	344	68,9	1140	69	123	123	43,8	415
36	354	336	68,4	1110	68	121	121	43,3	405
35	345	327	67,9	1080	67	119	119	42,8	400
34	336	319	67,4	1050	66	117	117	42,3	395
33	327	311	66,8	1030	65	116	116	41,8	385
32	318	301	66,3	1010	64	114	114	41,4	/
31	310	294	65,8	970	63	112	112	40,9	/
30	302	286	65,3	950	62	110	110	40,4	**370**
29	294	279	64,6	630	61	108	108	40,0	/
28	286	271	64,3	900	60	107	107	39,5	/
27	279	264	63,8	880	59	106	106	39,0	**360**
26	272	258	63,3	860	58	104	104	38,6	/
25	266	253	62,8	850	57	103	103	38,1	**350**
24	260	247	62,4	820	56	101	101	37,7	/
23	254	243	62,0	810	55	100	100	37,2	**340**
22	248	*237*	*61.5*	*790*	54	/	/	36,8	/
21	243	*231*	*61.0*	*770*	51	/	**94**	35,5	**330**
20	238	*226*	*60.5*	*760*	49	/	**92**	34,6	**320**

Legend:
Bold values are reliable, but out of the ASTM table. Italic values are due to the passage from Table 2 to Table 3 of the ASTM A 370 standard.
HRA: Rockwell hardness with diamond cone - load: 588 N - duration: 30”
HRB: Rockwell hardness with 1/16” sphere - load: 980 N - duration: 30”
HRC: Rockwell hardness with 120° diamond cone - load: 1470 N-duration: 30”
HB: Brinell hardness with 10 mm diameter sphere - load: 29400 N-duration: 15”
HV: Vickers hardness with 136° diamond pyramid - load: 294 N-duration: 15”
Rm: Tensile strength (MPa)

Later on, the envelope curves of the obtained data (Table **9**) have been determined, as shown in Fig. (**8**), on the basis of the following (Eq. 1-3) :

$$R_m^{ASTM} = 0.0087HB^2 + 1.0286HB + 152.1838 \quad \textbf{(1)}$$

(ASTM A370-03a standard)

$$R_m^{UNI} = 0.0007HB^2 + 3.5451HB + 10.0936 \quad \textbf{(2)}$$

(UNI EN ISO 18256 standard)

$$R_{m\_avg} = 0.0040HB^2 + 2.2869HB + 71.0451 \quad \textbf{(3)}$$

(medium between the two relationships)

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.

3.3. Determination of Hardness Conversion Curves (Brinell Method)

Considering the conversion tables shown in the UNI EN ISO 18256 (Table **10**) and ASTM A370-03a (Table **9**) standards, the formulations encompassing the values of these tables (Fig. **8**) 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.

Table 10. Conversion of hardness-to-hardness or hardness-to-tensile-strength values for unalloyed and low alloy steels and cast steels according to the UNI EN ISO 18265 standard.

Tensile Strength MPa	Vickers Hardness HV10	Brinell Hardness HB*	Rockwell Hardness							
			HRB	HRF	HRC	HRA	HRD	HR15N	HR30N	HR45N
255	80	76	–	–	–	–	–	–	–	–
270	85	80,7	41	–	–	–	–	–	–	–
285	90	58,5	48	82,6	–	–	–	–	–	–
305	95	90,2	52	–	–	–	–	–	–	–
320	100	95	56,2	57	–	–	–	–	–	–
335	105	99,8	–	–	–	–	–	–	–	–
350	110	105	62,3	90,5	–	–	–	–	–	–
370	115	109		–	–	–	–	–		
385	120	114	66,7	93,6	–	–	–	–	–	–
400	125	119		–	–	–	–	–		
415	130	124	71,2	96,4	–	–	–	–	–	–
430	135	128	–	–	–	–	–	–	–	–
450	140	133	75	99	–	–	–	–	–	–
465	145	138	–	–	–	–	–	–	–	–
480	150	143	78,7	(101,4)	–	–	–	–	–	–
495	155	147	–	–	–	–	–	–	–	–
510	160	152	81,7	(103,6)	–	–	–	–	–	–
530	165	156		–	–	–	–	–		
545	170	162	85	(105,5)	–	–	–	–	–	–
560	175	166		–	–	–	–	–		
575	180	171	87,1	(107,2)	–	–	–	–	–	–
595	185	176	–	–	–	–	–	–	–	–
610	190	181	89,5	(108,7)	–	–	–	–	–	–
625	195	185	–	–	–	–	–	–	–	–
640	200	190	91,5	(110,1)	–	–	–	–	–	–
660	205	195	92,5	–	–	–	–	–	–	–
675	210	199	93,5	(111,3)	–	–	–	–	–	–
690	215	204	94	–	–	–	–	–	–	–
705	220	209	95	(112,4)	–	–	–	–	–	–
720	225	214	96	–	–	–	–	–	–	–
740	230	219	69,7	(113,4)	–	–	–	–	–	–
755	235	223	–	–	–	–	–	–	–	–
770	240	228	98,1	(114,3)	20,3	60,7	40,3	69,6	41,7	19,9
785	245	233	–	–	21,3	61,2	41,1	70,1	42,5	21,1
800	250	238	99,5	115,1)	22,2	61,6	41,7	70,6	43,4	22,2
820	255	242	–	–	23,1	62	42,2	71,1	44,2	23,2
835	260	247	(101)	–	24	62,4	43,1	71,6	45	24,3
850	265	252	–	–	24,8	62,7	43,7	72,1	45,7	25,2
865	270	257	(102)	–	25,6	63,1	44,3	72,6	46,4	26,2
880	275	261	–	–	26,4	63,5	44,9	73	47,2	27,1
900	280	266	(104)	–	27,1	63,8	45,3	73,4	47,8	27,9
915	285	271	–	–	27,8	64,2	46	73,8	48,4	28,7
930	290	276	(105)	–	28,5	64,5	46,5	74,2	49	29,5
950	295	280	–	–	29,2	64,8	47,1	74,6	49,7	30,4
965	300	285	–	–	29,8	65,2	47,5	74,9	50,2	31,1
995	310	295	–	–	31	65,8	48,4	75,6	51,3	32,5
1030	320	304	–	–	32,2	66,4	49,4	76,2	52,3	33,9
1060	330	314	–	–	33,3	67	50,2	76,2	52,3	33,9
1095	340	323	–	–	34,4	67,6	51,1	77,4	54,4	36,5

(Table 10) contd.....

Tensile Strength MPa	Vickers Hardness HV10	Brinell Hardness HB*	Rockwell Hardness							
			HRB	HRF	HRC	HRA	HRD	HR15N	HR30N	HR45N
1125	350	333	–	–	35,5	68,1	51,9	78	55,4	37,8
1155	360	342	–	–	36,6	68,7	52,8	78,6	56,4	39,1
1190	370	352	–	–	37,7	69,2	53,6	79,2	57,4	40,4
1220	380	361	–	–	38,8	69,8	54,4	79,8	58,4	41,7
1255	390	371	–	–	39,8	70,3	55,3	80,3	59,3	42,9
1290	400	380	–	–	40,8	70,8	56	80,8	60,2	44,1
1320	410	390	–	–	41,8	71,4	56,8	81,4	61,1	45,3
1350	420	399	–	–	42,7	71,8	57,5	81,8	61,9	46,4
1385	430	409	–	–	43,6	72,3	58,2	82,3	62,7	47,4
1420	440	418	–	–	44,5	72,8	58,8	82,8	63,5	48,4
1455	450	428	–	–	45,3	73,3	59,4	83,2	64,3	49,4
1465	460	437	–	–	46,1	73,6	60,1	83,6	64,9	50,4
1520	470	447	–	–	46,9	74,1	60,7	83,9	65,7	51,3
1555	480	456	–	–	47,7	74,5	61,3	84,3	66,4	52,2
1595	490	466	–	–	48,4	74,9	61,6	84,7	67,1	53,1
1630	500	475	–	–	49,1	75,3	62,2	85	67,7	53,9
1665	510	485	–	–	49,8	75,7	62,9	85,4	68,3	54,7
1700	520	494	–	–	50,5	76,1	63,5	85,7	69	55,6
1740	530	504	–	–	51,1	76,4	63,9	86	69,5	56,2
1775	540	513	–	–	51,7	76,7	64,4	86,3	70	57
1810	550	523	–	–	52,3	77	64,8	86,6	70,5	57,8
1845	560	532	–	–	53	77,4	65,4	86,9	71,2	58,6
1880	570	542	–	–	53,6	77,8	65,8	87,2	71,7	59,3
1920	580	551	–	–	54,1	78	66,2	87,5	72,1	59,9
1955	590	561	–	–	54,7	78,4	66,7	87,8	72,7	60,5
1995	600	570	–	–	55,2	78,6	67	88	73,2	61,2
2030	610	580	–	–	55,7	78,9	67,5	88,2	73,7	61,7
2070	620	589			56,3	79,2	67,9	88,5	74,2	62,4
2105	630	599	–	–	56,8	79,5	68,3	88,8	74,6	63
2145	640	608	–	–	57,3	79,8	68,7	89	75,1	63,5
2180	650	618	–	–	57,8	80	69	89,2	75,5	64,1
–	660	–	–	–	58,3	80,3	69,4	89,5	75,9	64,7
–	670	–	–	–	58,8	80,6	69,8	89,7	76,4	65,3
–	680	–	–	–	59,2	80,8	70,1	89,8	76,8	65,7
–	690	–	–	–	59,7	81,1	70,5	90,1	77,2	66,2
–	700	–	–	–	60,1	81,3	70,8	90,3	77,6	66,7
–	720	–	–	–	61	81,8	71,5	90,7	78,4	67,7
–	740	–	–	–	61,8	82,2	72,1	91	79,1	68,6
–	760	–	–	–	62,5	82,6	72,6	91,2	79,7	69,4
–	780	–	–	–	63,3	83	73,3	91,5	80,4	70,2
–	800	–	–	–	64	83,4	73,8	91,8	81,1	71
–	820	–	–	–	64,7	83,8	74,3	92,1	81,7	71,8
–	840				65,3	84,1	74,8	92,3	82,2	72,2
–	860	–	–	–	65,9	84,4	75,3	92,5	92,7	73,1
–	880	–	–	–	66,4	84,7	75,7	92,7	83,1	73,6
–	900	–	–	–	67	85	76,1	92,9	83,6	74,2
–	920	–	–	–	67,5	85,3	76,5	93	84	74,8
–	40	–	–	–	68	85,6	76,9	93,2	84,4	75,4

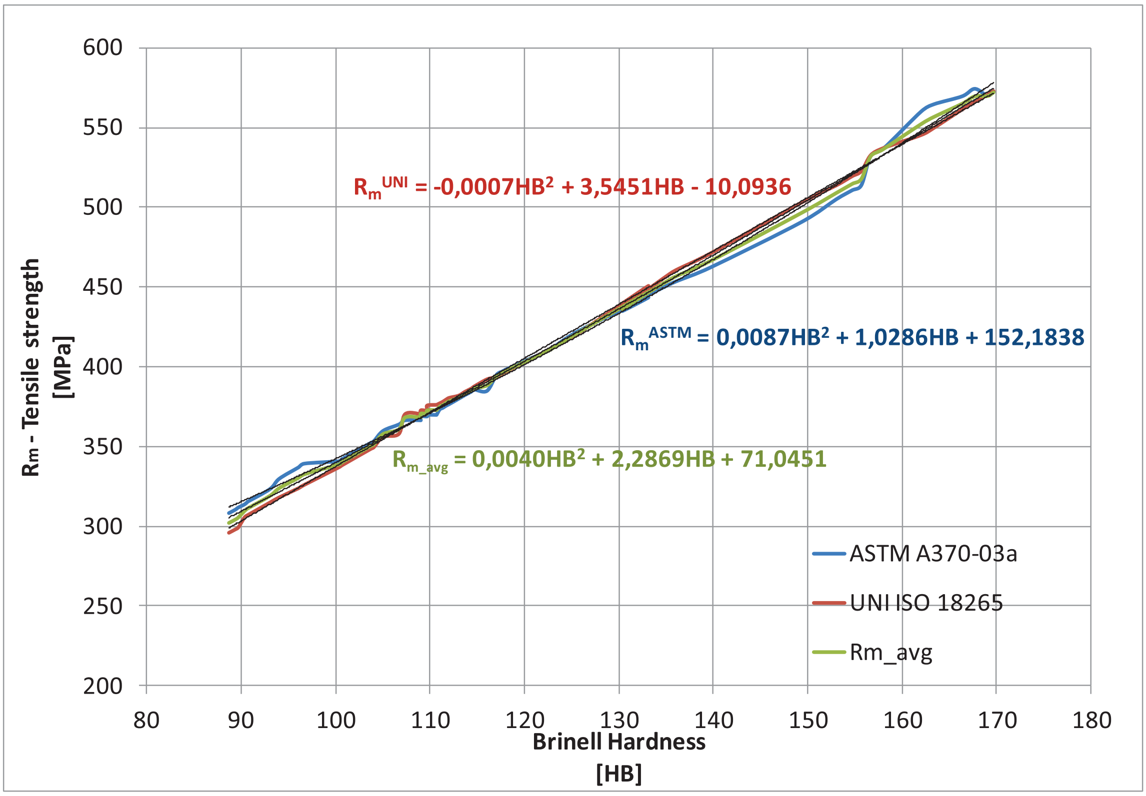

Fig. (8). Hardness-strength curves (Brinell method) achieved from conversion tables.

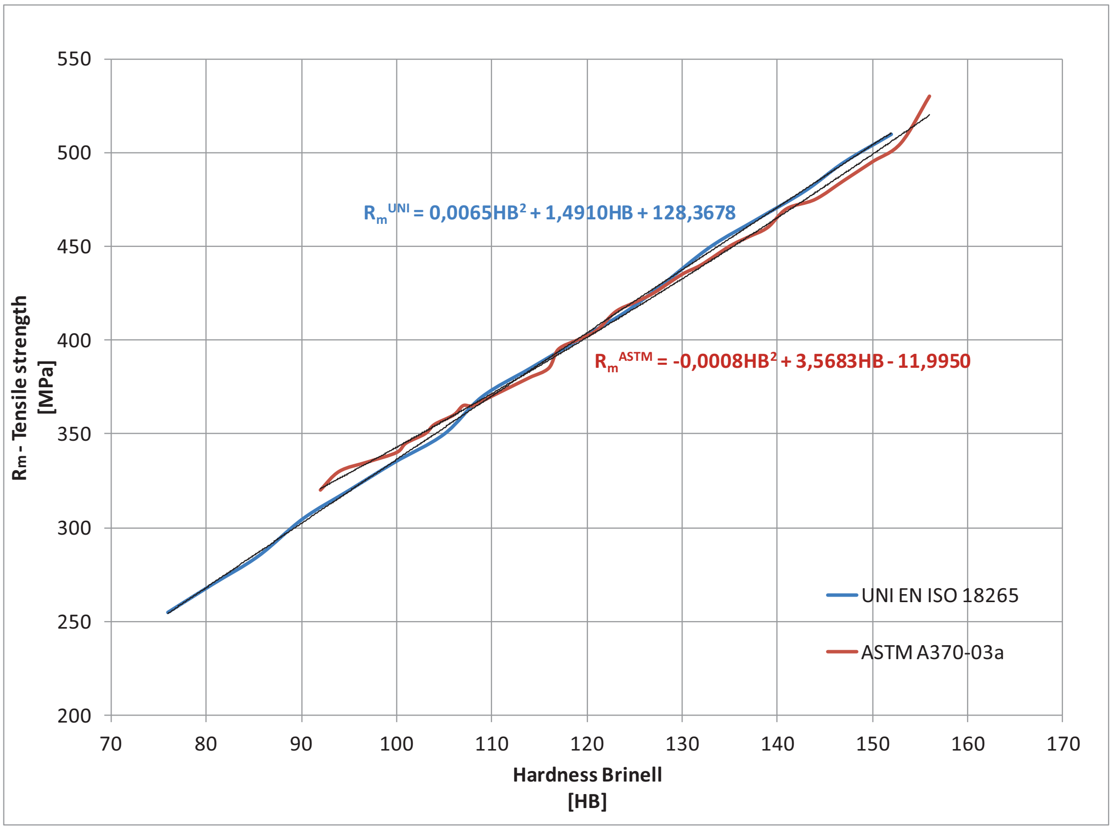

Fig. (9). Hardness-strength curves (Brinell method) achieved from conversion tables for structural steels.

For simplicity, the envelope curves of these strength values for structural carpentry steels have been obtained from the tables as a function of the hardness value *HB* on the basis of the following expressions (Eq. 4 and 5) (Fig. **9**):

$$R_m^{ASTM} = 0.0065HB^2 + 1.4910HB + 128.3678 \quad \text{(ASTM A370-03a standard)} \tag{4}$$

$$R_m^{UNI} = 0.0008HB^2 + 3.5683HB + 11.9950 \quad \text{(UNI EN ISO 18256 standard)} \tag{5}$$

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.

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

3.4. Hardness Estimation by the Complete Conversion Curves (Brinell Method)

By implementing all the values contained in the conversion tables given from both the UNI EN ISO 18256 standard (Table **10**) and the ASTM A370-03a one (Table **9**), the envelope formulations (Fig. **10**), depending on the measurement of hardness *HB*, are obtained as: Eq. (6 and 7).

$$R_m^{ASTM} = 0.0019HB^2 + 2.5495HB + 72.7304 \quad \text{(ASTM A370-03a standard)} \tag{6}$$

$$R_m^{UNI} = 0.0006HB^2 + 3.1156HB + 23.8669 \quad \text{(UNI EN ISO 18256 standard)} \tag{7}$$

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.

4. DISCUSSION

4.1. Determination of Steel Class Using ASTM Methods

Comparing the values deriving from the ASTM A370-03a standard conversion tables (Table **9**) with those achieved from relationships (1), (4) and (6), very similar trends of related curves have been observed (Fig. **11**).

The errors committed by using the envelope curve from the whole ASTM table have been evaluated for all the steel classes (Table **11**).

From this comparison it has been observed a maximum negative error $e_{\min(3)}^{ASTM} = -4.37\%$, a maximum positive error $e_{\max(3)}^{ASTM}$ =2.35% and a maximum percentage scatter $\delta_{\max(3)}^{ASTM}$ =6.72% (Fig. **12** and Table **12**). Contrary, using the partial tables for structural steels only, a maximum negative error $e_{\min(1)}^{ASTM}$ =-2.30%, a maximum positive error $e_{\min(1)}^{ASTM}$ =1.83%, and a maximum percentage scatter $e_{\min(1)}^{ASTM}$ =4.13%, have been detected. Analysing separately the errors committed for the different steel classes (Table **12**), it has been observed that errors found for S235 steels (Fig. **13**) are lower than those obtained with S275 steels (Fig. **14**).

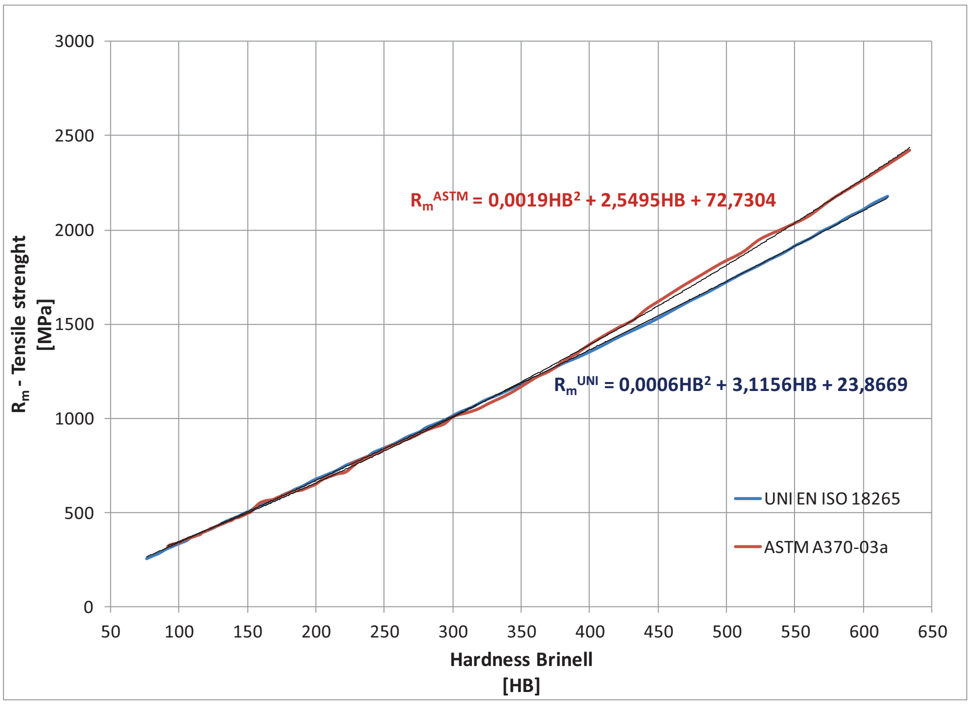

Fig. (10). Hardness-strength curves (Brinell method) achieved from the complete conversion tables.

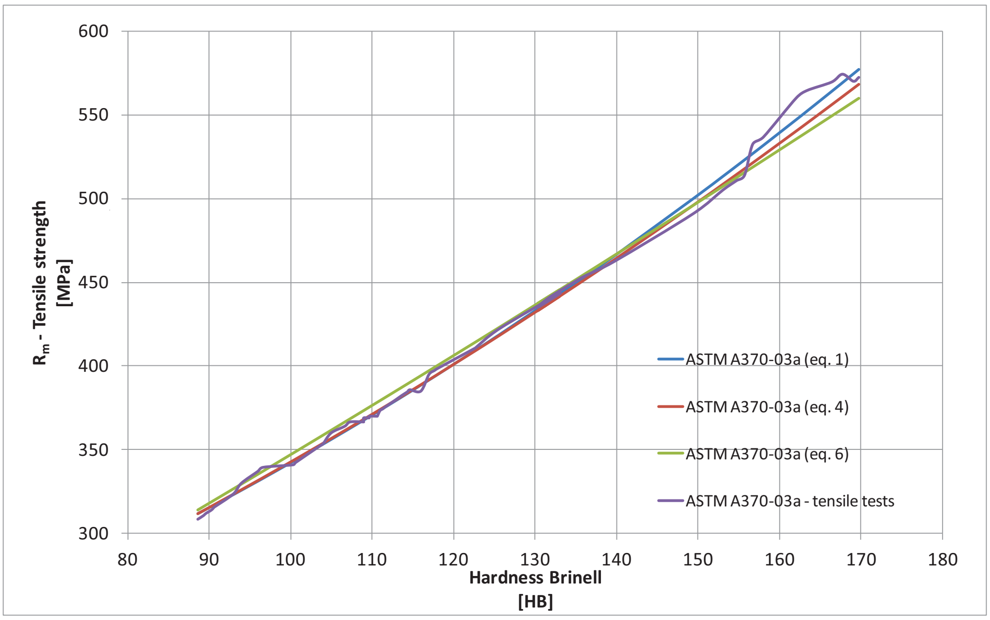

Fig. (11). Comparison among hardness-strength curves (Brinell method – ASTM A370-03a standard; tensile tests curve from conversion tables).

Table 11. Comparison among mechanical strengths obtained by hand conversions and data envelopes and relative percentage errors with respect to the ASTM whole table values.

Code	Sample n°	HB_{avg}	$R_{m(test)}^{ASTM}$ (*) [MPa]	$R_{m(eq.1)}^{ASTM}$ [MPa]	$R_{m(eq.4)}^{ASTM}$ [MPa]	$R_{m(eq.6)}^{ASTM}$ [MPa]	$e_{(eq.1-test)}$ (%) (1)	$e_{(eq.4-test)}$ (%) (2)	$e_{(eq.6-test)}$ (%) (3)
ST-P-01	1	88,7	308,5	311,8	311,7	313,7	1,06	1,03	1,69
ST-P-02	2	89,3	310,6	313,5	313,4	315,6	0,93	0,91	1,63
ST-P-25	3	89,7	312	314,4	314,3	316,6	0,76	0,74	1,48
ST-P-09	4	90,3	314,0	316,1	316,1	318,5	0,67	0,67	1,45
ST-P-15	5	90,7	315,7	317,0	317,0	319,5	0,40	0,41	1,20
ST-P-23	6	90,7	315,7	317,0	317,0	319,5	0,40	0,41	1,20
ST-P-24	7	93,0	323,5	323,1	323,2	326,3	-0,13	-0,08	0,86
ST-S-01	8	94,0	330,0	325,7	326,0	329,2	-1,29	-1,23	-0,25
ST-P-13	9	96,0	337,0	331,1	331,4	335,0	-1,75	-1,66	-0,60
ST-P-03	10	96,7	339,5	332,9	333,2	336,9	-1,94	-1,84	-0,76
ST-S-04	11	100,3	341,0	343,0	343,4	347,7	0,58	0,70	1,95
ST-R-01	12	100,7	342,4	343,9	344,3	348,6	0,44	0,56	1,82
ST-P-08	13	103,7	352,4	352,3	352,8	357,4	-0,02	0,11	1,43
ST-P-05	14	104,0	353,4	353,3	353,7	358,4	-0,04	0,10	1,42
ST-P-07	15	105,0	360	356,1	356,6	361,4	-1,08	-0,95	0,38
ST-P-26	16	106,7	364	360,9	361,4	366,3	-0,86	-0,72	0,63
ST-P-10	17	107,3	366,6	362,8	363,3	368,3	-1,03	-0,90	0,45
ST-R-02	18	109,0	366,6	367,7	368,1	373,2	0,29	0,41	1,80
ST-R-03	19	109,0	366,6	367,7	368,1	373,2	0,29	0,41	1,80
ST-P-16	20	109,0	369	367,7	368,1	373,2	-0,36	-0,24	1,14
ST-R-04	21	109,7	369	369,6	370,1	375,2	0,17	0,29	1,67
ST-S-02	22	109,7	370	369,6	370,1	375,2	-0,10	0,01	1,40
ST-S-06	23	110,7	370	372,6	373,0	378,1	0,69	0,80	2,20
ST-R-05	24	110,7	370	372,6	373,0	378,1	0,69	0,80	2,20
ST-P-12	25	111,0	373,4	373,6	374,0	379,1	0,04	0,15	1,54
ST-P-04	26	111,3	374,4	374,5	374,9	380,1	0,04	0,14	1,53
ST-R-06	27	111,7	375,7	375,5	375,9	381,1	-0,05	0,06	1,44

(Table 11) contd.....

Code	Sample n°	HB_{avg}	$R_{m(test)}^{ASTM}$ (*) [MPa]	$R_{m(eq.1)}^{ASTM}$ [MPa]	$R_{m(eq.4)}^{ASTM}$ [MPa]	$R_{m(eq.6)}^{ASTM}$ [MPa]	$e_{(eq.1-test)}$ (%) (1)	$e_{(eq.4-test)}$ (%) (2)	$e_{(eq.6-test)}$ (%) (3)
ST-P-22	28	112,0	376,7	376,5	376,9	382,1	-0,05	0,05	1,44
ST-S-03	29	113,0	380,1	379,5	379,8	385,1	-0,16	-0,07	1,31
ST-P-21	30	113,7	382,4	381,5	381,8	387,1	-0,23	-0,15	1,22
ST-R-07	31	114,3	384,5	383,5	383,8	389,1	-0,26	-0,18	1,19
ST-R-08	32	114,7	385,8	384,5	384,8	390,1	-0,33	-0,26	1,10
ST-P-06	33	116,0	385	388,6	388,8	394,0	0,93	0,98	2,35
ST-R-09	34	117,0	395	391,6	391,8	397,0	-0,85	-0,81	0,51
ST-R-10	35	117,7	397,3	393,7	393,8	399,0	-0,91	-0,88	0,43
ST-R-11	36	118,0	398,4	394,7	394,8	400,0	-0,93	-0,90	0,41
ST-P-27	37	122,7	410,7	409,3	409,1	414,1	-0,35	-0,40	0,82
ST-P-18	38	122,7	410,7	409,3	409,1	414,1	-0,35	-0,40	0,82
ST-P-31	39	125,7	422,4	418,8	418,4	423,1	-0,84	-0,95	0,17
ST-P-32	40	133,0	443,3	442,9	441,6	445,4	-0,09	-0,37	0,48
ST-P-19	41	130,3	435	434,0	433,1	437,3	-0,22	-0,43	0,53
ST-P-17	42	131,7	440,7	438,4	437,4	441,4	-0,51	-0,76	0,15
ST-P-11	43	135,3	451,7	450,7	449,2	452,6	-0,21	-0,55	0,19
ST-S-06	44	136,3	454,3	454,1	452,5	455,6	-0,04	-0,41	0,29
ST-P-29	45	139,7	462,3	465,6	463,4	465,9	0,70	0,24	0,77
ST-P-28	46	149,3	490,8	499,8	496,0	495,8	1,83	1,05	1,02
ST-S-08	47	153,0	505	513,2	508,6	507,3	1,63	0,72	0,45
ST-P-14	48	154,7	510,6	519,4	514,5	512,5	1,72	0,76	0,37
ST-P-20	49	155,7	513,9	523,1	518,0	515,6	1,79	0,79	0,34
ST-P-34	50	156,7	532,4	526,9	521,5	518,8	-1,04	-2,05	-2,56
ST-R-12	51	158,0	536,8	531,9	526,2	523,0	-0,91	-1,97	-2,57
ST-S-07	52	162,0	560	547,1	540,5	535,6	-2,30	-3,48	-4,35
ST-P-33	53	163,3	564,5	552,3	545,3	539,8	-2,16	-3,40	-4,37
ST-R-13	54	166,3	569,5	564,0	556,2	549,4	-0,97	-2,33	-3,54
ST-R-14	55	167,7	574,2	569,2	561,1	553,6	-0,87	-2,28	-3,59
ST-P-30	56	169,0	570	574,5	566,0	557,9	0,79	-0,70	-2,13
ST-S-05	57	169,7	572,3	577,1	568,5	560,0	0,85	-0,67	-2,15

(*) Tensile strength from conversion tables
(1) Percentage error from the comparison between the curves deriving from the ASTM A370-03a data envelope (eq. 1) and the hardness data resulting from manual conversion with ASTM A370-03a tables (test values)
(2) Percentage error from the comparison between the ASTM A370-03a partial conversion curves for carpentry steels (eq. 4) and the hardness data resulting from manual conversion with ASTM A370-03a tables (test values)
(3) Percentage error from the comparison between the ASTM A370-03a full table curve (eq. 6) and the hardness data resulting from manual conversion with ASTM A370-03a tables (test values)

Table 12. Minimum, maximum and average errors and deviation values among achieved strengths determined according to ASTM methods.

Comparison Case	e_{min}^{ASTM} (%)	e_{max}^{ASTM} (%)	e_{avg}^{ASTM} (%)	δ_{max}^{ASTM} (%)
(1)	-2,30	1,83	-0,10	4,13
(2)	-3,48	1,05	-0,33	4,54
(3)	-4,37	2,35	0,42	6,72
S235 - (1)	-1,94	1,06	/	3,01
S235 - (2)	-1,84	1,03	0,06	2,87
S235 - (3)	-0,76	1,95	1,04	2,71
S275 - (1)	-1,08	0,93	-0,22	2,01
S275 - (2)	-0,95	0,98	-0,16	1,93
S275 - (3)	0,17	2,35	1,17	2,18

(Table 12) contd.....

Comparison Case	$e_{\min}^{ASTM}$ (%)	$e_{\max}^{ASTM}$ (%)	e_{avg}^{ASTM} (%)	$\delta_{\max}^{ASTM}$ (%)
S355 - (1)	-2,30	1,83	/	4,13
S355 - (2)	-3,48	1,05	-0,91	4,54
S355 - (3)	-4,37	1,02	-1,24	5,39

(1) Percentage error between the ASTM A370-03a data envelope curves and the hardness data resulting from manual conversion with ASTM A370-03a tables
(2) Percentage error between the ASTM A370-03a partial conversion curves for carpentry steels and the hardness data resulting from manual conversion with ASTM A370-03a tables
(3) Percentage error between the ASTM A370-03a full table curve and the hardness data resulting from manual conversion with ASTM A370-03a tables

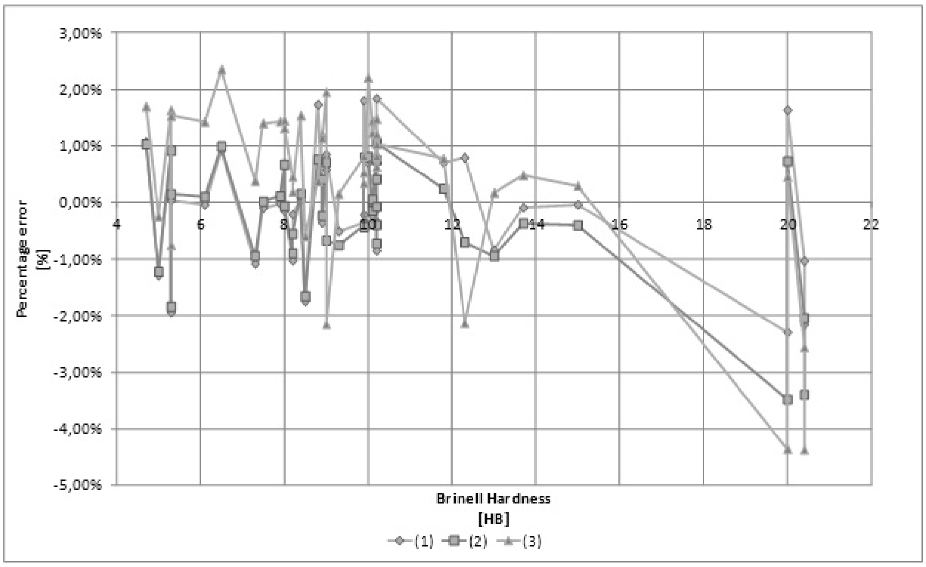

Fig. (12). Percentage errors with respect to the envelope curve of the ASTM whole table.

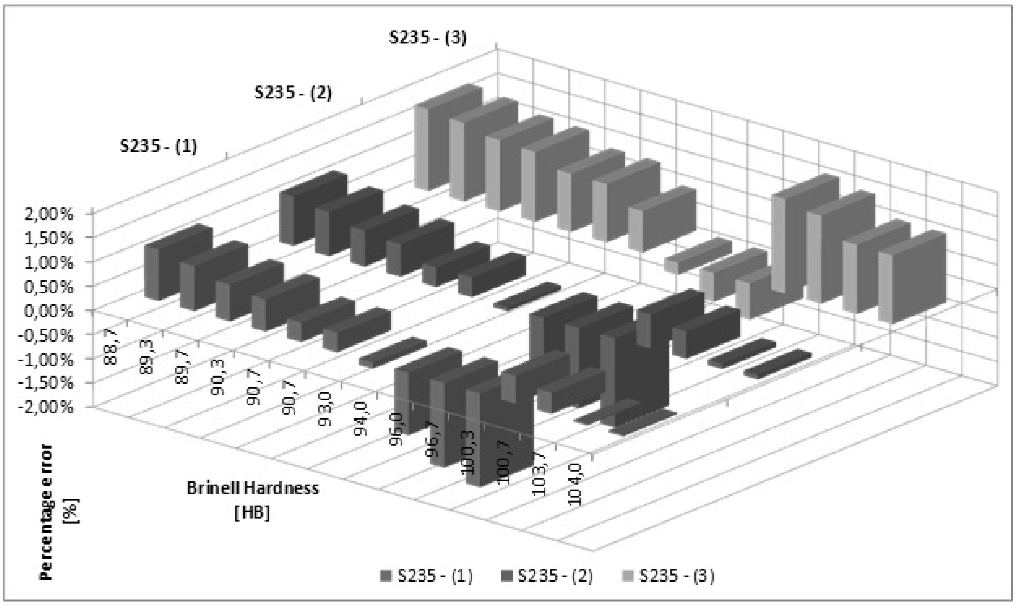

Fig. (13). Percentage errors in predicting the Brinell Hardness for S235 steels (ASTM standard).

The increase of the resistance class from S275 to S355 (Fig. **15**) results in errors higher than the ones obtained with lower resistance classes. Comparing the data from non-destructive Leeb tests (Table **11**) 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.

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 the identification of a higher resistance class, with a percentage error $e_{S235-S275}^{ASTM} = 6.67\%$ referred to the number of specimens investigated. Regarding the classification between S275 steels and S355 ones, from the data (Table **11**) 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.

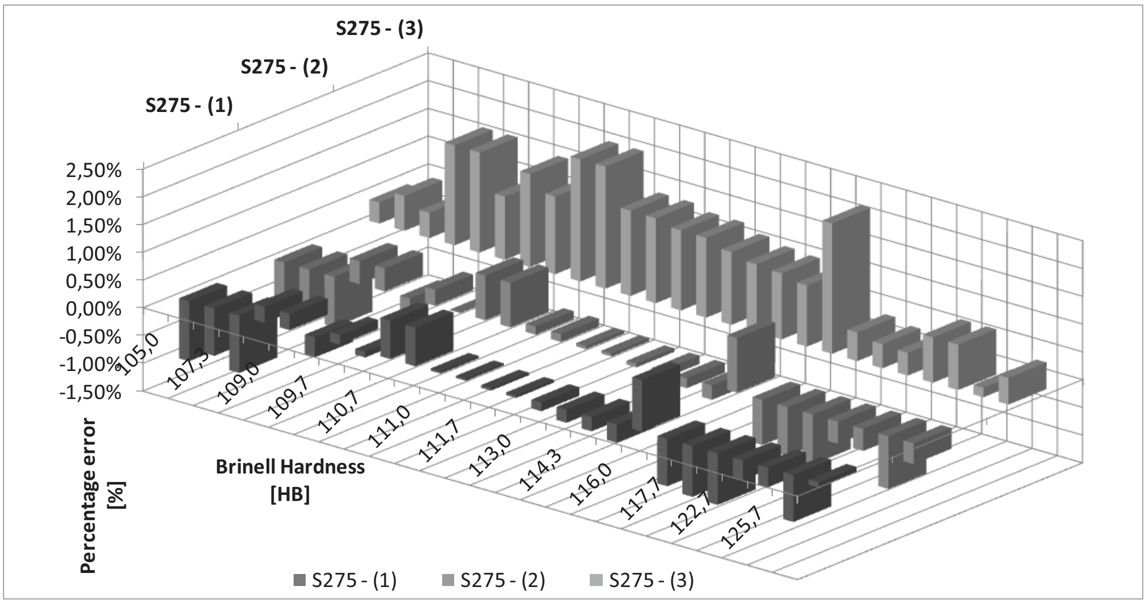

Fig. (14). Percentage errors in predicting the Brinell Hardness for S275 steels (ASTM standard).

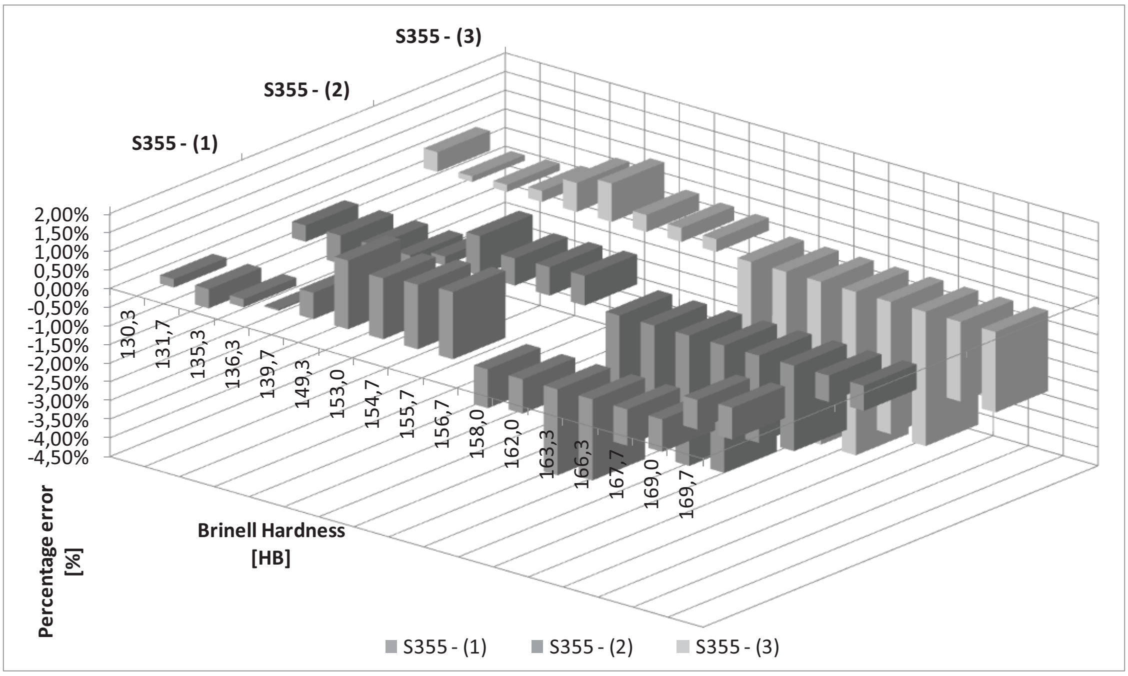

Fig. (15). Percentage errors in predicting the Brinell Hardness for S355 steels (ASTM standard).

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 $e_{\min,235}^{ASTM} = -14.31\%$ (Table **13**). Therefore, the tests tend to underestimate the resistance values, going on the safe side in terms of classification. For S275 steel (Table **14**), the conversion gives rise to a maximum positive error $e_{\max,275}^{ASTM} = 5.96\%$ and a maximum negative error $e_{\min,275}^{ASTM} = -16.28\%$ ..

Table 13. Comparison among strength values obtained from ASTM tables and envelopes and mechanical resistances for S235 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-01	1	-14,31	-13,39	-13,42	-12,85
ST-P-02	2	-13,72	-12,92	-12,93	-12,32
ST-P-25	3	-13,33	-12,68	-12,69	-12,05
ST-P-09	4	-12,78	-12,20	-12,20	-11,52
ST-P-15	5	-12,31	-11,96	-11,95	-11,25
ST-P-23	6	-12,31	-11,96	-11,95	-11,25
ST-P-24	7	-10,14	-10,25	-10,21	-9,37
ST-S-01	8	-8,33	-9,52	-9,46	-8,56
ST-P-13	9	-6,39	-8,03	-7,94	-6,95
ST-P-03	10	-5,69	-7,52	-7,43	-6,41
ST-S-04	11	-5,28	-4,73	-4,61	-3,43
ST-R-01	12	-4,89	-4,47	-4,35	-3,16
ST-P-08	13	-2,11	-2,14	-2,00	-0,71
ST-P-05	14	-1,83	-1,87	-1,74	-0,44
ST-P-07	15	/	-1,08	-0,95	0,38
ST-P-26	16	1,11	0,25	0,38	1,75
–	$e_{\max,235}^{ASTM}$	1,11	0,25	0,38	1,75
–	$e_{\min,235}^{ASTM}$	-14,31	-13,39	-13,42	-12,85
–	$e_{avg,235}^{ASTM}$	-7,64	-7,78	-7,72	-6,76
–	$\delta_{\max,235}^{ASTM}$	15,42	13,64	13,80	14,60

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Table 14. Comparison among strength values obtained from ASTM tables and envelopes and mechanical resistances for S275 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-07	15	-16,28	-17,19	-17,07	-15,96
ST-P-26	16	-15,35	-16,07	-15,96	-14,82
ST-P-10	17	-14,74	-15,62	-15,52	-14,36
ST-R-02	18	-14,74	-14,50	-14,39	-13,21
ST-R-03	19	-14,74	-14,50	-14,39	-13,21
ST-P-16	20	-14,19	-14,50	-14,39	-13,21

(Table 14) contd.....

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-R-04	21	-14,19	-14,04	-13,94	-12,75
ST-S-02	22	-13,95	-14,04	-13,94	-12,75
ST-S-06	23	-13,95	-13,36	-13,26	-12,06
ST-R-05	24	-13,95	-13,36	-13,26	-12,06
ST-P-12	25	-13,16	-13,13	-13,03	-11,83
ST-P-04	26	-12,93	-12,90	-12,81	-11,60
ST-R-06	27	-12,63	-12,67	-12,58	-11,37
ST-P-22	28	-12,40	-12,44	-12,35	-11,14
ST-S-03	29	-11,60	-11,74	-11,66	-10,45
ST-P-21	30	-11,07	-11,28	-11,20	-9,98
ST-R-07	31	-10,58	-10,81	-10,74	-9,52
ST-R-08	32	-10,28	-10,58	-10,51	-9,29
ST-P-06	33	-10,47	-9,64	-9,58	-8,36
ST-R-09	34	-8,14	-8,92	-8,89	-7,67
ST-R-10	35	-7,60	-8,45	-8,42	-7,20
ST-R-11	36	-7,35	-8,21	-8,18	-6,97
ST-P-27	37	-4,49	-4,82	-4,87	-3,71
ST-P-18	38	-4,49	-4,82	-4,87	-3,71
ST-P-31	39	-1,77	-2,60	-2,70	-1,60
–	$e_{\max,275}^{ASTM}$	5,65	5,61	5,22	5,96
–	$e_{\min,275}^{ASTM}$	-16,28	-17,19	-17,07	-15,96
–	$e_{avg,275}^{ASTM}$	-8,92	-9,13	-9,12	-7,99
–	$\delta_{\max,275}^{ASTM}$	21,93	22,79	22,30	21,92

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Table 15. Comparison among strength values obtained from ASTM tables and envelopes and mechanical resistances for S355 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-19	41	-14,71	-14,90	-15,08	-14,26
ST-P-17	42	-13,59	-14,03	-14,24	-13,46
ST-P-11	43	-11,43	-11,62	-11,92	-11,26
ST-S-06	44	-10,92	-10,96	-11,28	-10,66
ST-P-29	45	-9,35	-8,71	-9,14	-8,65
ST-P-28	46	-3,76	-2,00	-2,75	-2,78
ST-S-08	47	-0,98	0,63	-0,26	-0,53
ST-P-14	48	0,12	1,84	0,88	0,49
ST-P-20	49	0,76	2,57	1,56	1,11
ST-P-34	50	4,39	3,31	2,25	1,72
ST-R-12	51	5,25	4,29	3,18	2,55
ST-S-07	52	9,80	7,28	5,98	5,02
ST-P-33	53	10,69	8,29	6,92	5,85
ST-R-13	54	11,67	10,58	9,06	7,72

(Table 15) contd.....

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-R-14	55	12,59	11,61	10,02	8,55
–	$e^{ASTM}_{\max,355}$	12,59	13,17	11,46	9,80
–	$e^{ASTM}_{\min,355}$	-14,71	-14,90	-15,08	-14,26
–	$e^{ASTM}_{avg,355}$	0,85	0,82	-0,14	-0,55
–	$\delta^{ASTM}_{\max,355}$	27,29	28,06	26,54	24,06

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

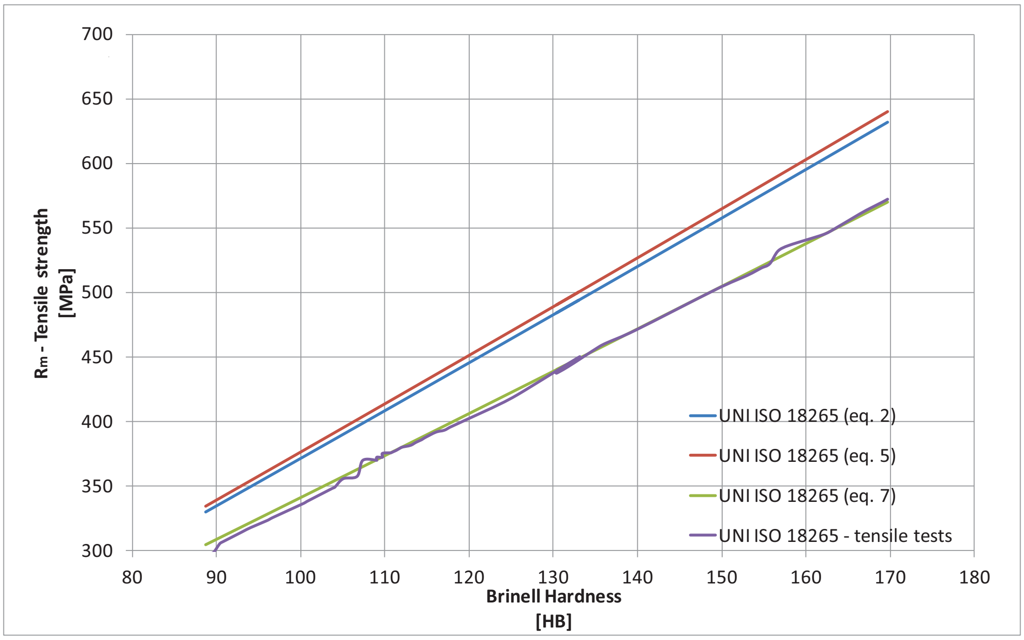

Fig. (16). Comparison among hardness-strength curves (Brinell method – UNI ISO 18265 standard; tensile tests curve from conversion tables).

Table 16. Comparison among mechanical strengths obtained by hand conversions and data envelopes and relative percentage errors with respect to the UNI ISO whole table values.

Code	Sample n°	HB_{avg}	$R^{UNI}_{m(test)}$ (*) [MPa]	$R^{UNI}_{m(eq.2)}$ [MPa]	$R^{UNI}_{m(eq.5)}$ [MPa]	$R^{UNI}_{m(eq.7)}$ [MPa]	$e_{(eq.2\text{-}test)}$ (%)	$e_{(eq.5\text{-}test)}$ (%)	$e_{(eq.7\text{-}test)}$ (%)
							(1)	(2)	(3)
ST-P-01	1	88,7	295,6	329,9	334,7	304,8	11,61	13,22	3,12
ST-P-02	2	89,3	297,7	332,4	337,1	307,0	11,65	13,25	3,12
ST-P-25	3	89,7	299	333,6	338,4	308,1	11,57	13,17	3,03
ST-P-09	4	90,3	305,3	336,0	340,9	310,2	10,07	11,65	1,61
ST-P-15	5	90,7	306,7	337,3	342,1	311,3	9,97	11,54	1,49
ST-P-23	6	90,7	306,7	337,3	342,1	311,3	9,97	11,54	1,49
ST-P-24	7	93,0	314,5	345,8	350,8	318,8	9,97	11,53	1,37
ST-S-01	8	94,0	317,8	349,5	354,5	322,0	9,98	11,54	1,33
ST-P-13	9	96,0	323,4	356,9	361,9	328,5	10,35	11,91	1,58
ST-P-03	10	96,7	325,7	359,3	364,4	330,6	10,32	11,88	1,52

(Table 16) contd.....

Code	Sample n°	HB_{avg}	$R^{UNI}_{m(test)}$ (*) [MPa]	$R^{UNI}_{m(eq.2)}$ [MPa]	$R^{UNI}_{m(eq.5)}$ [MPa]	$R^{UNI}_{m(eq.7)}$ [MPa]	$e_{(eq.2-test)}$ (%)	$e_{(eq.5-test)}$ (%)	$e_{(eq.7-test)}$ (%)
							(1)	(2)	(3)
ST-S-04	11	100,3	336,7	372,8	378,1	342,5	10,73	12,29	1,72
ST-R-01	12	100,7	338,0	374,1	379,3	343,6	10,67	12,22	1,65
ST-P-08	13	103,7	348,1	385,1	390,5	353,3	10,64	12,18	1,49
ST-P-05	14	104,0	349,1	386,4	391,8	354,4	10,67	12,22	1,51
ST-P-07	15	105,0	355,7	390,0	395,5	357,6	9,66	11,19	0,54
ST-P-26	16	106,7	357,6	396,2	401,7	363,0	10,79	12,34	1,52
ST-P-10	17	107,3	370	398,7	404,2	365,2	7,75	9,25	-1,30
ST-R-02	18	109,0	370	404,8	410,4	370,6	9,41	10,93	0,16
ST-R-03	19	109,0	370	404,8	410,4	370,6	9,41	10,93	0,16
ST-P-16	20	109,0	372,4	404,8	410,4	370,6	8,71	10,22	-0,48
ST-R-04	21	109,7	372,4	407,3	412,9	372,8	9,37	10,89	0,10
ST-S-02	22	109,7	375,4	407,3	412,9	372,8	8,50	10,00	-0,70
ST-S-06	23	110,7	375,8	411,0	416,7	376,0	9,36	10,88	0,06
ST-R-05	24	110,7	375,8	411,0	416,7	376,0	9,36	10,88	0,06
ST-P-12	25	111,0	376,8	412,2	417,9	377,1	9,40	10,92	0,08
ST-P-04	26	111,3	377,8	413,5	419,2	378,2	9,44	10,95	0,10
ST-R-06	27	111,7	379,1	414,7	420,4	379,3	9,39	10,90	0,04
ST-P-22	28	112,0	380,2	415,9	421,7	380,3	9,40	10,91	0,04
ST-S-03	29	113,0	381,6	419,6	425,4	383,6	9,97	11,49	0,52
ST-P-21	30	113,7	384	422,1	427,9	385,8	9,92	11,44	0,46
ST-R-07	31	114,3	386	424,6	430,4	387,9	9,99	11,51	0,50
ST-R-08	32	114,7	387,4	425,8	431,7	389,0	9,91	11,43	0,42
ST-P-06	33	116,0	391,8	430,7	436,7	393,4	9,94	11,46	0,40
ST-R-09	34	117,0	393,3	434,5	440,4	396,6	10,46	11,99	0,84
ST-R-10	35	117,7	395,6	436,9	442,9	398,8	10,45	11,97	0,80
ST-R-11	36	118,0	396,6	438,2	444,2	399,9	10,48	12,00	0,82
ST-P-27	37	122,7	410,6	455,5	461,7	415,1	10,93	12,46	1,09
ST-P-18	38	122,7	410,6	455,5	461,7	415,1	10,93	12,46	1,09
ST-P-31	39	125,7	420,7	466,6	473,0	424,9	10,92	12,44	0,99
ST-P-32	40	133,0	450	494,0	500,7	448,9	9,77	11,27	-0,25
ST-P-19	41	130,3	437,7	484,0	490,7	440,1	10,58	12,10	0,55
ST-P-17	42	131,7	442,4	489,0	495,7	444,5	10,53	12,05	0,47
ST-P-11	43	135,3	457,8	502,7	509,6	456,5	9,80	11,31	-0,28
ST-S-06	44	136,3	461,2	506,4	513,3	459,8	9,80	11,31	-0,31
ST-P-29	45	139,7	470,7	518,9	526,0	470,7	10,24	11,74	/
ST-P-28	46	149,3	502,7	555,1	562,7	502,5	10,42	11,94	-0,04
ST-S-08	47	153,0	513,4	568,9	576,7	514,6	10,81	12,32	0,23
ST-P-14	48	154,7	519,1	575,1	583,0	520,1	10,80	12,32	0,19
ST-P-20	49	155,7	522,4	578,9	586,8	523,4	10,82	12,34	0,19
ST-P-34	50	156,7	532,4	582,7	590,7	526,7	9,44	10,94	-1,07
ST-R-12	51	158,0	536,8	587,7	595,8	531,1	9,48	10,98	-1,06
ST-S-07	52	162,0	545	602,8	611,1	544,3	10,60	12,12	-0,12
ST-P-33	53	163,3	549,4	607,8	616,2	548,8	10,63	12,15	-0,12
ST-R-13	54	166,3	561,0	619,1	627,7	558,7	10,36	11,88	-0,41
ST-R-14	55	167,7	565,7	624,2	632,8	563,1	10,34	11,86	-0,46
ST-P-30	56	169,0	570,1	629,2	637,9	567,5	10,37	11,89	-0,45
ST-S-05	57	169,7	572,5	631,7	640,4	569,8	10,35	11,87	-0,48

(Table 16) contd.....

Code	Sample n°	HB_{avg}	$R^{UNI}_{m(test)}$ (*) [MPa]	$R^{UNI}_{m(eq.2)}$ [MPa]	$R^{UNI}_{m(eq.5)}$ [MPa]	$R^{UNI}_{m(eq.7)}$ [MPa]	$e_{(eq.2-test)}$ (%)	$e_{(eq.5-test)}$ (%)	$e_{(eq.7-test)}$ (%)
							(1)	(2)	(3)

(*) Tensile strength from conversion tables
(1) Percentage error from the comparison between the curves deriving from the UNI ISO 18265 data envelope (eq. 2) and the hardness data resulting from manual conversion with UNI ISO 18265 tables (test values)
(2) Percentage error from the comparison between the UNI ISO 18265 partial conversion curves for carpentry steels (eq. 5) and the hardness data resulting from manual conversion with UNI ISO 18265 tables (test values)
(3) Percentage error from the comparison between the UNI ISO 18265 full table curve (eq. 7) and the hardness data resulting from manual conversion with UNI ISO 18265 tables (test values)

The percentage scatter in terms of stress between the S275 class and the S235 one is defined as Eq. (8):

$$\Delta_{275-235} = \frac{f_{u,S275} - f_{u,S235}}{f_{u,S275}} \quad \textbf{(8)}$$

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 (Table **15**), 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 $\Delta_{355-275}$ 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.

4.2. Determination of Steel Class Using UNI ISO Methods

Comparing the results deriving from relationships (2), (5) and (7), the achieved curves have trends very similar to each other (Fig. **16**).

Nevertheless, these values are very far from those gotten from the UNI ISO 18265 standard conversion tables (Table **16**). 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 $\delta^{UNI}_{\max(6)} = 4.42\%$ (Fig. **17** and Table **17**).

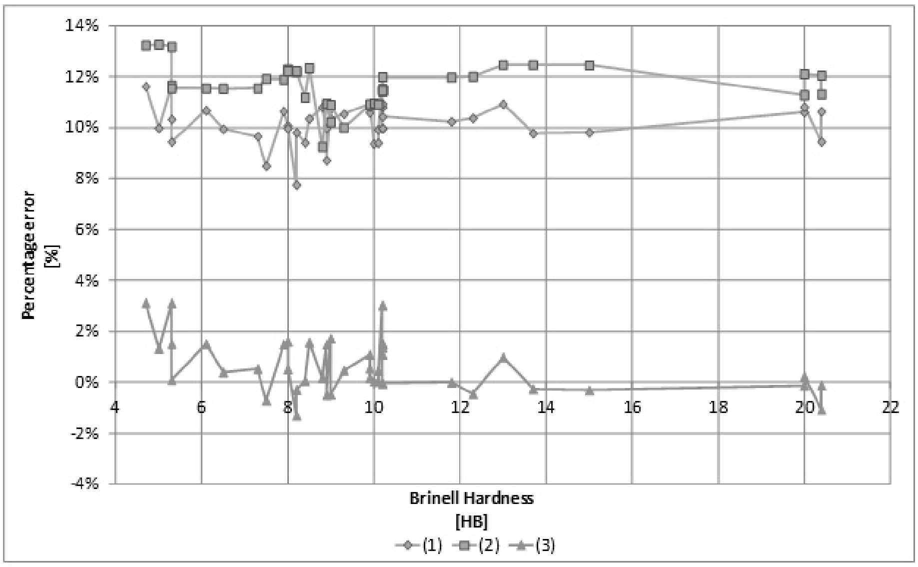

Fig. (17). Percentage errors with respect to the envelope curve of the UNI ISO whole table.

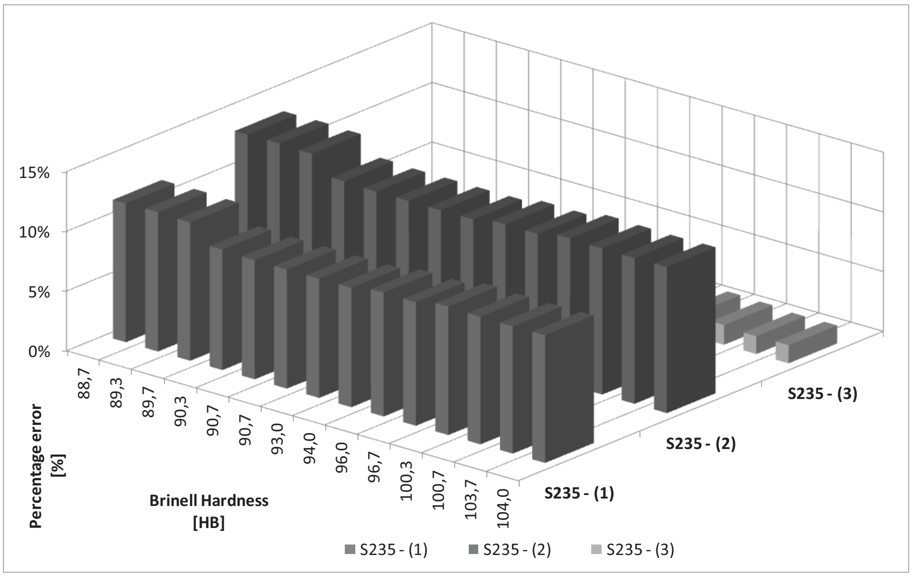

Fig. (18). Percentage errors in predicting the Brinell Hardness for S235 steels (UNI ISO standard).

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 the previous case (Table **17**). 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 (Table **17**), it has been observed that for S235 (Fig. **18**), S275 (Fig. **19**) and S355 (Fig. **20**) steels, the errors tends to reduce only in the case of relationship (7).

Analyzing the data from non-destructive Leeb tests (Table **18**), 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 (Table **18**), with a percentage error $e^{UNI}_{S235\text{–}S275} = 52.94\%$. Similarly, in the transition from S275 steel to S355 one, it is observed that for 10 out of 26 samples a percentage error $e^{UNI}_{S275\text{–}S355} = 38.46\%$ is committed in the assignment to a higher class (Table **19**).

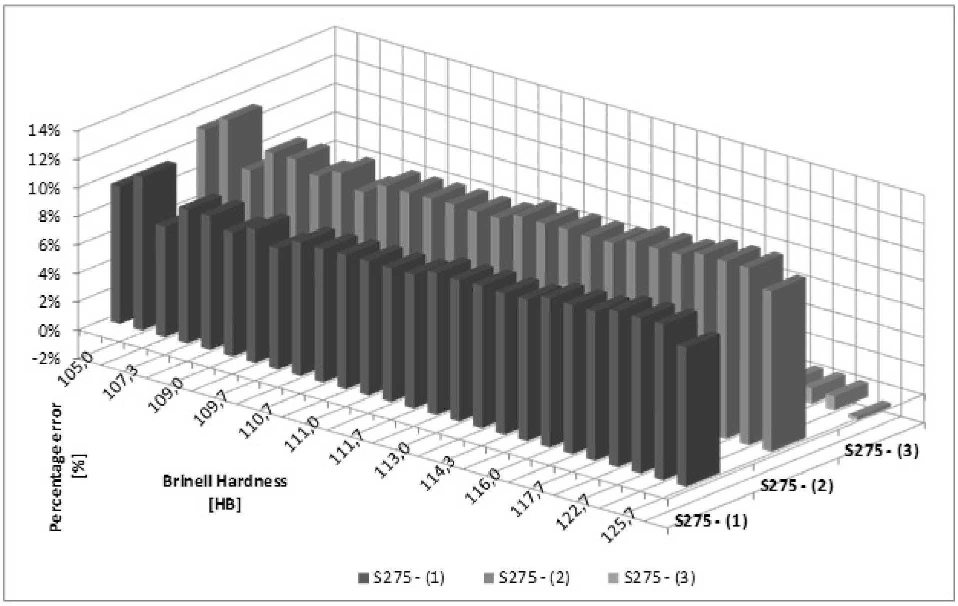

Fig. (19). Percentage errors in predicting the Brinell Hardness for S275 steels (UNI ISO standard).

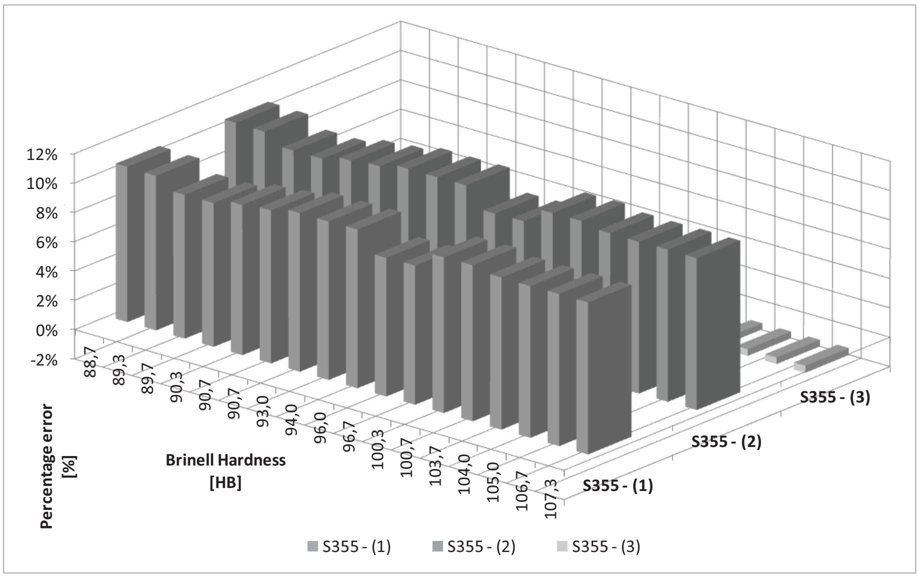

Fig. (20). Percentage errors in predicting the Brinell Hardness for S355 steels (UNI ISO standard).

Table 17. Minimum, maximum and average errors and deviation values among achieved strengths determined according to UNI ISO methods.

Comparison Case	e_{min}^{UNI} (%)	e_{max}^{UNI} (%)	e_{avg}^{UNI} (%)	e_{max}^{UNI} (%)
(1)	9,79	12,41	11,06	2,62
(2)	8,23	10,88	9,54	2,65
(3)	-3,03	1,32	-0,53	4,35
S235 - (1)	9,79	10,55	10,11	0,76
S235 - (2)	8,23	9,02	8,56	0,79
S235 - (3)	-3,03	-1,32	-1,82	1,71
S275 - (1)	10,59	11,56	10,93	0,97
S275 - (2)	9,07	10,05	9,42	0,98
S275 - (3)	-1,49	1,32	-0,30	2,81
S355 - (1)	11,48	12,41	12,04	0,93
S355 - (2)	9,98	10,88	10,52	0,90
S355 - (3)	-0,55	1,08	0,19	1,63

(1) Percentage error between the UNI ISO 18265 data envelope curves and the hardness data resulting from manual conversion with UNI ISO 18265 tables
(2) Percentage error between the UNI ISO 18265 partial conversion curves for carpentry steels and the hardness data resulting from manual conversion with UNI ISO 18265 tables
(3) Percentage error between the UNI ISO 18265 full table curve and the hardness data resulting from manual conversion with UNI ISO 18265 tables

Table 18. Comparison among strength values obtained from UNI ISO tables and envelopes and mechanical resistances for S235 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-01	1	-17,89	-8,35	-7,04	-15,32
ST-P-02	2	-17,31	-7,67	-6,35	-14,73
ST-P-25	3	-16,94	-7,33	-6,00	-14,43
ST-P-09	4	-15,19	-6,65	-5,32	-13,83
ST-P-15	5	-14,81	-6,31	-4,97	-13,53

(Table 18) contd.....

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-23	6	-14,81	-6,31	-4,97	-13,53
ST-P-24	7	-12,64	-3,93	-2,56	-11,44
ST-S-01	8	-11,72	-2,91	-1,53	-10,55
ST-P-13	9	-10,17	-0,87	0,53	-8,75
ST-P-03	10	-9,53	-0,19	1,22	-8,15
ST-S-04	11	-6,47	3,56	5,02	-4,86
ST-R-01	12	-6,11	3,91	5,36	-4,56
ST-P-08	13	-3,31	6,98	8,47	-1,86
ST-P-05	14	-3,03	7,32	8,82	-1,56
ST-P-07	15	-1,19	8,35	9,86	-0,66
ST-P-26	16	-0,67	10,06	11,59	0,84
ST-P-10	17	2,78	10,74	12,28	1,44
–	$e_{\max,235}^{UNI}$	2,78	10,74	12,28	1,44
–	$e_{\min,235}^{UNI}$	-17,89	-8,35	-7,04	-15,32
–	$e_{avg,235}^{UNI}$	-9,35	0,02	1,44	-7,97
–	$\delta_{\max,235}^{UNI}$	20,67	19,09	19,32	16,76

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Table 19. Comparison among strength values obtained from UNI ISO tables and envelopes and mechanical resistances for S275 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-26	16	-16,84	-7,86	-6,58	-15,58
ST-P-10	17	-13,95	-7,29	-6,00	-15,07
ST-R-02	18	-13,95	-5,85	-4,55	-13,81
ST-R-03	19	-13,95	-5,85	-4,55	-13,81
ST-P-16	20	-13,40	-5,85	-4,55	-13,81
ST-R-04	21	-13,40	-5,28	-3,97	-13,31
ST-S-02	22	-12,70	-5,28	-3,97	-13,31
ST-S-06	23	-12,60	-4,42	-3,10	-12,56
ST-R-05	24	-12,60	-4,42	-3,10	-12,56
ST-P-12	25	-12,37	-4,13	-2,81	-12,30
ST-P-04	26	-12,14	-3,85	-2,52	-12,05
ST-R-06	27	-11,84	-3,56	-2,23	-11,80
ST-P-22	28	-11,58	-3,27	-1,93	-11,55
ST-S-03	29	-11,26	-2,41	-1,06	-10,79
ST-P-21	30	-10,70	-1,84	-0,48	-10,29
ST-R-07	31	-10,23	-1,26	0,10	-9,78
ST-R-08	32	-9,91	-0,98	0,39	-9,53
ST-P-06	33	-8,88	0,17	1,55	-8,52
ST-R-09	34	-8,53	1,04	2,43	-7,77
ST-R-10	35	-8,00	1,61	3,01	-7,26
ST-R-11	36	-7,77	1,90	3,30	-7,01

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-27	37	-4,51	5,93	7,38	-3,47
ST-P-18	38	-4,51	5,93	7,38	-3,47
ST-P-31	39	-2,16	8,52	10,01	-1,19
ST-P-32	40	4,65	14,88	16,45	4,38
–	$e^{UNI}_{\max,275}$	4,65	14,88	16,45	4,38
–	$e^{UNI}_{\min,275}$	-16,84	-7,86	-6,58	-15,58
–	$e^{UNI}_{avg,275}$	-10,13	-1,34	0,03	-9,85
–	$\delta^{UNI}_{\max,275}$	21,49	22,74	23,03	19,96

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Analyzing the resistance values deriving from the different conversions from Leeb tests to the reference values of classes, for S235steels a maximum error $e^{UNI}_{\max,235} = 12.28\%$ and a minimum error $e^{UNI}_{\min,235} = -17.89\%$ is observed (Table **18**).

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 (Table **19**) the conversion involves a maximum error $e^{UNI}_{\max,275} = 16.45\%$ and a minimum error $e^{UNI}_{\min,275} = -16.84\%$. Given a percentage difference between S235 class and S275 one, defined by h) is equal to $\Delta_{275-235} = 16.28\%$, it is not possible to assign the class in an unambiguous way.

For S355 steel class (Table **20**) 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 $\Delta_{355-275} = 15.69\%$, higher than the minimum error committed. The tests conducted for 2 out of 19 samples provide limited values, which could lead to an error $e_{355-275} = 10.52\%$ in the assignment to the samples of a steel lower class.

4.3. Relationship Between the Two Conversion Methods

Using the average values deriving from formulations provided by ASTM A370-03a and UNI ISO 18265 methods (Table **21**), an intermediate trend between the two curves ones is achieved (Fig. **21**).

Table 20. Comparison among strength values obtained from UNI ISO tables and envelopes and mechanical resistances for S355 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-31	39	-17,51	-8,50	-7,25	-16,69
ST-P-32	40	-11,76	-3,14	-1,82	-11,99
ST-P-19	41	-14,18	-5,09	-3,79	-13,70
ST-P-17	42	-13,25	-4,12	-2,81	-12,85
ST-P-11	43	-10,24	-1,43	-0,09	-10,49
ST-S-06	44	-9,57	-0,70	0,66	-9,85
ST-P-29	45	-7,71	1,74	3,13	-7,70
ST-P-28	46	-1,43	8,84	10,33	-1,47
ST-S-08	47	0,67	11,55	13,07	0,90
ST-P-14	48	1,78	12,77	14,32	1,98
ST-P-20	49	2,43	13,51	15,07	2,63
ST-P-34	50	4,39	14,25	15,82	3,28
ST-R-12	51	5,25	15,23	16,82	4,14
ST-S-07	52	6,86	18,19	19,81	6,73
ST-P-33	53	7,73	19,18	20,82	7,60
ST-R-13	54	10,00	21,40	23,07	9,55

(Table 20) contd.....

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-R-14	55	10,92	22,39	24,07	10,41
ST-P-30	56	11,78	23,37	25,08	11,28
ST-S-05	57	12,25	23,87	25,58	11,72
–	$e^{UNI}_{max,355}$	12,25	23,87	25,58	11,72
–	$e^{UNI}_{min,355}$	-17,51	-8,50	-7,25	-16,69
–	$e^{UNI}_{avg,355}$	-0,61	9,65	11,15	-0,76
–	$\delta^{UNI}_{max,355}$	29,76	32,37	32,82	28,41

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Table 21. Comparison among mechanical strengths obtained by hand conversions and data envelopes and relative percentage errors with respect to the average values between the UNI ISO whole table values and the ASTM whole table ones.

Code	Sample n°	HB_{avg}	$R^{ASTM-UNI}_{(test)}$ (*) (a)	$R^{ASTM-UNI}_{(eq.1-eq.2)}$ (b)	$R^{ASTM-UNI}_{(eq.4-eq.5)}$ (c)	$R^{ASTM-UNI}_{(eq.6-eq.7)}$ (d)	$e_{(b-a)}$%	$e_{(c-a)}$%	$e_{(d-a)}$%
			[MPa]	[MPa]	[MPa]	[MPa]	(1)	(2)	(3)
ST-P-01	1	88,7	302,1	305,3	323,2	309,3	1,06%	6,99%	2,39%
ST-P-02	2	89,3	304,2	307,3	325,3	311,3	1,02%	6,95%	2,36%
ST-P-25	3	89,7	305,5	308,3	326,4	312,3	0,90%	6,83%	2,24%
ST-P-09	4	90,3	309,7	310,3	328,5	314,4	0,20%	6,08%	1,53%
ST-P-15	5	90,7	311,2	311,3	329,5	315,4	0,02%	5,89%	1,35%
ST-P-23	6	90,7	311,2	311,3	329,5	315,4	0,02%	5,89%	1,35%
ST-P-24	7	93,0	319,0	318,3	337,0	322,5	-0,21%	5,65%	1,11%
ST-S-01	8	94,0	323,9	321,4	340,2	325,6	-0,78%	5,04%	0,53%
ST-P-13	9	96,0	330,2	327,5	346,7	331,7	-0,83%	4,99%	0,47%
ST-P-03	10	96,7	332,6	329,5	348,8	333,8	-0,94%	4,88%	0,36%
ST-S-04	11	100,3	338,9	340,8	360,7	345,1	0,57%	6,46%	1,84%
ST-R-01	12	100,7	340,2	341,8	361,8	346,1	0,47%	6,36%	1,74%
ST-P-08	13	103,7	350,3	351,1	371,6	355,4	0,24%	6,11%	1,46%
ST-P-05	14	104,0	351,3	352,1	372,7	356,4	0,26%	6,12%	1,47%
ST-P-07	15	105,0	357,9	355,3	376,0	359,5	-0,72%	5,08%	0,46%
ST-P-26	16	106,7	360,8	360,5	381,5	364,7	-0,09%	5,75%	1,07%
ST-P-10	17	107,3	368,3	362,6	383,7	366,7	-1,55%	4,19%	-0,43%
ST-R-02	18	109,0	368,3	367,8	389,3	371,9	-0,12%	5,70%	0,98%
ST-R-03	19	109,0	368,3	367,8	389,3	371,9	-0,12%	5,70%	0,98%
ST-P-16	20	109,0	370,7	367,8	389,3	371,9	-0,77%	5,01%	0,32%
ST-R-04	21	109,7	370,7	369,9	391,5	374,0	-0,20%	5,61%	0,88%
ST-S-02	22	109,7	372,7	369,9	391,5	374,0	-0,74%	5,04%	0,34%
ST-S-06	23	110,7	372,9	373,1	394,8	377,1	0,06%	5,88%	1,12%
ST-R-05	24	110,7	372,9	373,1	394,8	377,1	0,06%	5,88%	1,12%
ST-P-12	25	111,0	375,1	374,2	395,9	378,1	-0,25%	5,56%	0,80%
ST-P-04	26	111,3	376,1	375,2	397,1	379,1	-0,23%	5,57%	0,81%
ST-R-06	27	111,7	377,4	376,3	398,2	380,2	-0,29%	5,50%	0,74%
ST-P-22	28	112,0	378,5	377,4	399,3	381,2	-0,29%	5,51%	0,73%
ST-S-03	29	113,0	380,9	380,5	402,6	384,3	-0,08%	5,72%	0,92%

Code	Sample n°	HB_{avg}	$R^{ASTM-UNI}_{(test)}$ (*) (a)	$R^{ASTM-UNI}_{(eq.1-eq.2)}$ (b)	$R^{ASTM-UNI}_{(eq.4-eq.5)}$ (c)	$R^{ASTM-UNI}_{(eq.6-eq.7)}$ (d)	$e_{(b-a)}$%	$e_{(c-a)}$%	$e_{(d-a)}$%
			[MPa]	[MPa]	[MPa]	[MPa]	(1)	(2)	(3)
ST-P-21	30	113,7	383,2	382,7	404,9	386,4	-0,14%	5,66%	0,84%
ST-R-07	31	114,3	385,3	384,8	407,1	388,5	-0,12%	5,68%	0,84%
ST-R-08	32	114,7	386,6	385,9	408,2	389,5	-0,19%	5,60%	0,76%
ST-P-06	33	116,0	388,4	390,1	412,7	393,7	0,45%	6,27%	1,36%
ST-R-09	34	117,0	394,2	393,4	416,1	396,8	-0,20%	5,57%	0,68%
ST-R-10	35	117,7	396,5	395,5	418,4	398,9	-0,23%	5,53%	0,62%
ST-R-11	36	118,0	397,5	396,6	419,5	399,9	-0,23%	5,54%	0,61%
ST-P-27	37	122,7	410,7	411,8	435,4	414,6	0,27%	6,03%	0,95%
ST-P-18	38	122,7	410,7	411,8	435,4	414,6	0,27%	6,03%	0,95%
ST-P-31	39	125,7	421,6	421,6	445,7	424,0	0,01%	5,73%	0,58%
ST-P-32	40	133,0	446,7	446,0	471,2	447,1	-0,15%	5,49%	0,11%
ST-P-19	41	130,3	436,4	437,1	461,9	438,7	0,16%	5,85%	0,54%
ST-P-17	42	131,7	441,6	441,5	466,5	442,9	-0,01%	5,66%	0,31%
ST-P-11	43	135,3	454,8	453,8	479,4	454,5	-0,21%	5,42%	-0,05%
ST-S-06	44	136,3	457,8	457,2	482,9	457,7	-0,13%	5,49%	-0,01%
ST-P-29	45	139,7	466,5	468,5	494,7	468,3	0,42%	6,04%	0,38%
ST-P-28	46	149,3	496,8	501,8	529,3	499,2	1,01%	6,56%	0,49%
ST-S-08	47	153,0	509,2	514,6	542,7	510,9	1,06%	6,57%	0,34%
ST-P-14	48	154,7	514,9	520,4	548,7	516,3	1,09%	6,58%	0,28%
ST-P-20	49	155,7	518,2	524,0	552,4	519,5	1,12%	6,61%	0,26%
ST-P-34	50	156,7	532,4	527,5	556,1	522,7	-0,92%	4,45%	-1,81%
ST-R-12	51	158,0	536,8	532,2	561,0	527,0	-0,85%	4,51%	-1,82%
ST-S-07	52	162,0	552,5	546,5	575,8	540,0	-1,09%	4,21%	-2,27%
ST-P-33	53	163,3	557,0	551,3	580,7	544,3	-1,02%	4,27%	-2,27%
ST-R-13	54	166,3	565,3	562,1	591,9	554,0	-0,56%	4,72%	-1,99%
ST-R-14	55	167,7	570,0	566,9	596,9	558,4	-0,53%	4,73%	-2,03%
ST-P-30	56	169,0	570,1	571,8	601,9	562,7	0,30%	5,59%	-1,29%
ST-S-05	57	169,7	572,4	574,2	604,5	564,9	0,31%	5,60%	-1,32%

(*) Average tensile strength between ASTM 370-03a standard resistance and UNI ISO 18265 standard one
(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

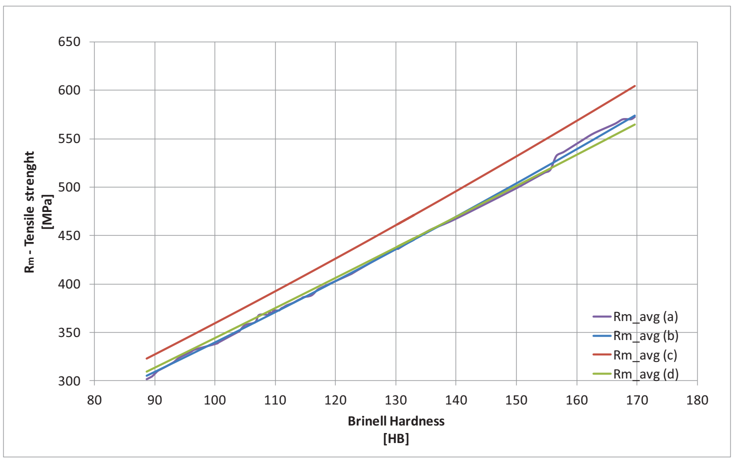

Fig. (21). Comparison among hardness-strength curves deriving from average values between ASTM standard and UNI ISO one (Brinell method).

Table 22. 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

Table 23. Comparison among strength values obtained from ASTM and UNI ISO tables and envelopes and mechanical resistances for S235 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-01	1	-16,10	-15,20	-10,23	-14,09
ST-P-02	2	-15,51	-14,65	-9,64	-13,52
ST-P-25	3	-15,14	-14,37	-9,35	-13,24
ST-P-09	4	-13,99	-13,81	-8,76	-12,67
ST-P-15	5	-13,56	-13,54	-8,46	-12,39
ST-P-23	6	-13,56	-13,54	-8,46	-12,39
ST-P-24	7	-11,39	-11,58	-6,39	-10,41
ST-S-01	8	-10,03	-10,73	-5,49	-9,55
ST-P-13	9	-8,28	-9,04	-3,70	-7,85
ST-P-03	10	-7,61	-8,48	-3,11	-7,28
ST-S-04	11	-5,87	-5,34	0,20	-4,14
ST-R-01	12	-5,50	-5,06	0,51	-3,86
ST-P-08	13	-2,71	-2,47	3,24	-1,29
ST-P-05	14	-2,43	-2,18	3,54	-1,00
ST-P-07	15	-0,60	-1,31	4,45	-0,14
ST-P-26	16	0,22	0,14	5,98	1,29
–	$e_{max,235}^{ASTM-UNI}$	0,22	0,14	5,98	1,29
–	$e_{min,235}^{ASTM-UNI}$	-16,10	-15,20	-10,23	-14,09
–	$e_{avg,235}^{ASTM-UNI}$	-8,88	-8,82	-3,48	-7,66
–	$\delta_{max,235}^{ASTM-UNI}$	16,32	15,34	16,21	15,38

(Table 23) contd.....

Code	**Sample n°**	**e_1 (%)**	**e_2 (%)**	**e_3 (%)**	**e_4 (%)**
		(1)	**(2)**	**(3)**	**(4)**
Conversion with: (1) Manual use of the table (2) Envelope from manual conversion values (3) Envelope from partial tables for carpentry steels (4) Envelope from the complete table					

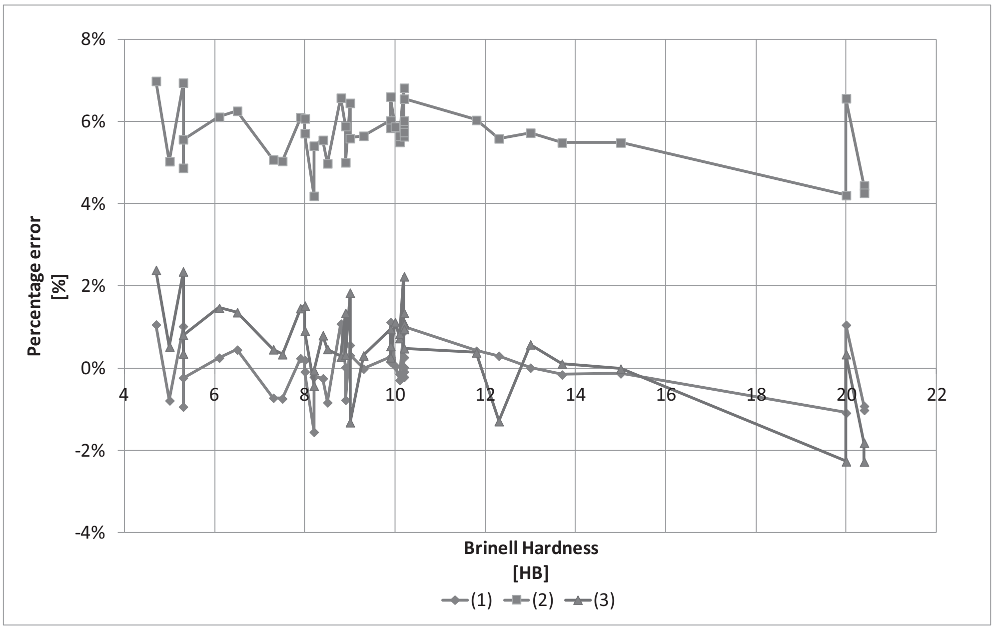

Fig. (22). Percentage errors with respect to the envelope curves of the complete tables from ASTM and UNI ISO standards.

Comparing the values deriving from the different formulas with the average values from the table and evaluating the error committed (Table **22**), it is observed (Fig. **22**) a maximum error $e_{\max(8)}^{ASTM-UNI} = 6.99\%$ and a minimum error $e_{\min(9)}^{ASTM-UNI} = -2.27\%$, with a maximum percentage scatter $\delta_{\max(9)}^{ASTM-UNI} = 4.67\%$.

Analyzing the errors committed for the different steel classes (Table **22**), 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.

Analyzing data from non-destructive Leeb tests due to the use of partial envelope curves (Table **16**), 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) 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 $e_{S235-S275}^{ASTM-UNI} = 37.5\%$.

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 (Table **23**). 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 $e_{\max,355}^{ASTM-UNI} = 18.52\%$ and a minimum error $e_{\min,355}^{ASTM-UNI} = -17.34\%$ (Table **24**).

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 $e_{\min,355}^{ASTM-UNI} = -17.34\%$ (Table **25**).

Table 24. Comparison among strength values obtained from ASTM and UNI ISO tables and envelopes and mechanical resistances for S275 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-07	15	-16,78	-17,38	-12,55	-16,40
ST-P-26	16	-16,09	-16,16	-11,27	-15,20
ST-P-10	17	-14,35	-15,68	-10,76	-14,71
ST-R-02	18	-14,35	-14,46	-9,47	-13,51
ST-R-03	19	-14,35	-14,46	-9,47	-13,51
ST-P-16	20	-13,79	-14,46	-9,47	-13,51
ST-R-04	21	-13,79	-13,97	-8,95	-13,03
ST-S-02	22	-13,33	-13,97	-8,95	-13,03
ST-S-06	23	-13,28	-13,23	-8,18	-12,31
ST-R-05	24	-13,28	-13,23	-8,18	-12,31
ST-P-12	25	-12,77	-12,98	-7,92	-12,07
ST-P-04	26	-12,53	-12,74	-7,66	-11,83
ST-R-06	27	-12,23	-12,49	-7,40	-11,58
ST-P-22	28	-11,99	-12,24	-7,14	-11,34
ST-S-03	29	-11,43	-11,50	-6,36	-10,62
ST-P-21	30	-10,88	-11,01	-5,84	-10,14
ST-R-07	31	-10,41	-10,51	-5,32	-9,65
ST-R-08	32	-10,09	-10,26	-5,06	-9,41
ST-P-06	33	-9,67	-9,27	-4,02	-8,44
ST-R-09	34	-8,34	-8,52	-3,23	-7,72
ST-R-10	35	-7,80	-8,02	-2,70	-7,23
ST-R-11	36	-7,56	-7,77	-2,44	-6,99
ST-P-27	37	-4,50	-4,24	1,26	-3,59
ST-P-18	38	-4,50	-4,24	1,26	-3,59
ST-P-31	39	-1,97	-1,95	3,65	-1,40
ST-P-32	40	3,87	3,71	9,58	3,99
–	$e_{\max,275}^{ASTM-UNI}$	3,87	3,71	9,58	3,99
–	$e_{\min,275}^{ASTM-UNI}$	-16,78	-17,38	-12,55	-16,40
–	$e_{avg,275}^{ASTM-UNI}$	-10,62	-10,81	-5,64	-9,97
–	$\delta_{\max,275}^{ASTM-UNI}$	20,65	21,09	22,13	20,38

Conversion with:
(1) Manual use of the table
(2) Envelope from manual conversion values
(3) Envelope from partial tables for carpentry steels
(4) Envelope from the complete table

Table 25. Comparison among strength values obtained from ASTM and UNI ISO tables and envelopes and mechanical resistances for S355 grade steels.

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-P-31	39	-17,34	-17,33	-12,60	-16,86
ST-P-32	40	-12,42	-12,56	-7,61	-12,33
ST-P-19	41	-14,44	-14,30	-9,44	-13,98
ST-P-17	42	-13,42	-13,43	-8,52	-13,15
ST-P-11	43	-10,83	-11,02	-6,00	-10,88

(Table 25) contd.....

Code	Sample n°	e_1 (%)	e_2 (%)	e_3 (%)	e_4 (%)
		(1)	(2)	(3)	(4)
ST-S-06	44	-10,25	-10,36	-5,31	-10,25
ST-P-29	45	-8,53	-8,14	-3,00	-8,18
ST-P-28	46	-2,60	-1,62	3,79	-2,12
ST-S-08	47	-0,16	0,90	6,40	0,18
ST-P-14	48	0,95	2,05	7,60	1,24
ST-P-20	49	1,60	2,74	8,32	1,87
ST-P-34	50	4,39	3,43	9,04	2,50
ST-R-12	51	5,25	4,36	10,00	3,34
ST-S-07	52	8,33	7,16	12,90	5,88
ST-P-33	53	9,21	8,09	13,87	6,72
ST-R-13	54	10,83	10,22	16,06	8,63
ST-R-14	55	11,75	11,16	17,04	9,48
ST-R-30	56	11,77	12,11	18,03	10,33
ST-S-05	57	12,24	12,59	18,52	10,76
–	$e_{\max,355}^{ASTM-UNI}$	12,24	12,59	18,52	10,76
–	$e_{\min,355}^{ASTM-UNI}$	-17,34	-17,33	-12,60	-16,86
–	$e_{avg,355}^{ASTM-UNI}$	-0,72	-0,73	4,69	-1,41
–	$\delta_{\max,355}^{ASTM-UNI}$	29,58	29,92	31,12	27,62

Conversion with:
Manual use of the table
Envelope from manual conversion values
Envelope from partial tables for carpentry steels
Envelope from the complete table

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 $e_{355-275} = 5.26\%$.

CONCLUSION

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

Firstly, for the evaluation of the resistance class of structural steel, it was recorded that the execution of tests required a careful cleaning of the surface of samples.

Subsequently, 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 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 in the number of samples, the manual use involved a significant increase in the working time. In this case, the most reliable method for conversion was given by 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 led to the increase of the average error committed in the conversion.

By dividing the different samples according to the steel classes deriving from either tensile tests or origin certificates, it was noted that for all types of steel, 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 a 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 $e_{avg-S235-(2)}^{ASTM} = 0.06\%$ and scatter $\delta_{\max-S235-(2)}^{ASTM} = 2.87\%$, respectively, against the corresponding values $e_{avg-S235-(3)}^{ASTM} = 1.04\%$ and $\delta_{\max-S235-(3)}^{ASTM} = 2.71\%$ when the complete envelope of tables was used.

Passing to the S275 and S335 classes, the most reliable method derived from the envelope of partial tables, where only the data of carpentry steels were present. The detected errors were 0.16% and 0.91% for S275 steel and S355 one, respectively. Moreover, percentage scatters of 1.93% and 4.54% were achieved when S275 steels and S355 ones, respectively, are of concern. However, it is important to remember that tables of both ASTM and UNI standards do not cover a large range of low hardness values and, therefore, in these cases a linear interpolation process to find intermediate values is often required. For this reason, further experimental destructive and non-destructive tests on carpentry steels should be performed in order to complete the tables of the used reference standards for obtaining reliable conversion formulas from hardness values to tensile strengths.

In conclusion, it should be remarked that, differently from reinforced concrete structures, where non-destructive tests are allowed by the current Italian technical code, for metallic structures, only destructive tests are permitted. Therefore, in this framework, to know the reliability of Leeb tests appears to be indispensable in order to both integrate and modify the regulatory contents with the purpose of completing the experimental campaign so to work properly also on existing artefacts protected by Superintendence rules, where the damage to structures must be either avoided or limited as much as possible.

Definitely, in the present work, the introduction of theoretical relationships for carpentry steels able to put in relationship Leeb hardness test values with experimental tensile strengths represents a very novel application in the field of seismic assessment of historical metal structures. In this way, it will be possible to indirectly evaluate, starting from Leeb hardness values measured *in-situ* on carpentry steels, the strengths of those materials to be used for their mechanical characterization when seismic analysis and improvement/ retrofitting of steel artefacts are of concern.

LIST OF ABBREVIATIONS

e	=	Percentage error;
$\mathbf{e_{355\text{-}275}}$	=	Percentage error in the assignment of the S355 class instead of the S275 one;
$\mathbf{e_{max}}$	=	Maximum positive error;
$\mathbf{e_{min}}$	=	Maximum negative error;
$f_{uk,max}$	=	Nominal ultimate tensile strength;
HB	=	Brinell Hardness;
HB	=	Brinell Hardness with 10 mm diameter sphere – load: 29400 N – duration: 15”;
$\mathbf{HB_{avg}}$	=	Brinell Hardness average value;
HL	=	Leeb Hardness;
HR	=	Rockwell Hardness;
HRA	=	Rockwell Hardness with diamond cone – load: 588 N – duration: 30”;
HRB	=	Rockwell Hardness with 1/16” sphere – load: 980 N – duration: 30”;
HRC	=	Rockwell Hardness with 120° diamond cone – load: 1470 N – duration: 30”;
HV	=	Vickers Hardness;
HV	=	Vickers Hardness with 136° diamond pyramid – load: 294 N – duration: 15”;
$\mathbf{R^{ASTM\text{-}UNI}}$	=	Average tensile strength between ASTM 370-03a standard resistance and UNI ISO 18265 standard one;
$\mathbf{R_{m,avg}}$	=	Medium value between ASTM A370-03a strength value and UNI EN ISO 18256 one;
$\mathbf{R_m}$	=	Tensile strength (MPa);
$\mathbf{R_m^{ASTM}}$	=	Steel average strength according to the ASTM A370-03a standard;
$\mathbf{R_m^{UNI}}$	=	Steel average strength according to the UNI EN ISO 18256 standard;
SONREB	=	SONic REBound test;
$\mathbf{\Delta_{275\text{-}235}}$	=	Percentage scatter in terms of stress between the S275 class and the S235 one;
$\mathbf{\delta_{max}}$	=	Maximum positive scatter;
$\mathbf{\delta_{min}}$	=	Maximum negative scatter.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data that support the findings of this study are available from the corresponding author upon request.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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