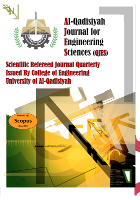
Contents lists available at: http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq



Research Paper

Non-destructive experimental test on the hardness and strength of steel exposed to temperatures of 250°C and 500°C

Zel Citra [1,2] ✉, ***Antonius*** [1], ***Agung W. Biantoro*** [2], ***Han A. Lie*** [3]
and Risma Apdeni [4]

[1] *Doctoral Program in Civil Engineering, Faculty of Engineering, Universitas Islam Sultan Agung (UNISSULA), Semarang, Indonesia.*
[2] *Department of Civil Engineering, Faculty of Engineering, Universitas Mercu Buana, Jakarta, Indonesia.*
[3] *Department of Civil Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, Indonesia.*
[4] *Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang, Indonesia*

ARTICLE INFO

Article history:
Received 15 January 2026
Received in revised form 28 March 2026
Accepted 10 May 2026

keyword:
Steel material
Non-destructive test
Hardness
Steel strength
Post-fire assessment

ABSTRACT

This study evaluates changes in hardness and estimates the reduction in tensile strength of BJ37 structural steel after exposure to elevated temperatures of 250 °C and 500 °C using the Leeb hardness non-destructive testing (NDT) method. Since hardness is closely related to mechanical properties, the Leeb test can be used as an indirect approach to estimate tensile strength without damaging the material. A total of 36 specimens were prepared from the flange and web sections of a WF 300 × 150 × 6 × 9 steel profile. The specimens were heated to 250 °C and 500 °C for 15 minutes and then rapidly cooled by water immersion before testing. The initial hardness was measured at approximately 366.19 HL, corresponding to an estimated tensile strength of about 372 MPa. After heating to 250 °C, the hardness decreased to 352.5 HL, with an estimated tensile strength of 342.5 MPa; at 500 °C, the hardness was 354.7 HL, corresponding to approximately 346 MPa. The reduction in tensile strength ranged from 7.0% to 7.9% relative to the initial condition, with only a small difference between the two temperature levels. These results indicate that the Leeb hardness method can serve as a rapid, non-destructive tool for the preliminary assessment of steel mechanical properties after fire exposure. Further research is recommended to validate these findings through destructive tensile testing, considering a wider range of temperatures, longer heating durations, and a larger number of specimens. The findings provide a practical basis for rapid post-fire evaluation of steel structural integrity.

1. Introduction

The increase in industrial development, such as processing plants, will certainly require more materials, including building materials. Building materials are all materials used for construction, including naturally occurring materials (such as clay, sand, and wood) and artificially produced materials (such as bricks, insulation, metal, and plastic) [1]. Building materials are generally classified into two groups: metal materials and non-metal materials [2]. Steel is widely used in construction due to its high strength, characterized by high yield strength (Fy) and tensile strength (Fu) being high, is ductile (can undergo significant deformation before breaking), and has high toughness, capable of absorbing large amounts of energy [3]. The demand for steel as a construction material is also increasing globally. IISIA projects that national steel consumption (Apparent Steel Consumption-ASC) in 2024 will grow by 5.2%, in line with the average growth rate for the period 2020-2023, reaching 18.3 million tonnes. Production and exports are expected to continue growing at the CAGR for 2020-2023, which is 5.2% and 18.6% respectively, reaching 15.9 million tonnes and 7.1 million tonnes (https://iisia.or.id, 2024). Steel is an alloy of iron (Fe) and carbon (C), with carbon content typically below 2%. The mechanical characteristics of steel are determined by its chemical composition and manufacturing process [4, 5]. Steel is also an isotropic material and has the same properties under both tensile and compressive conditions [6, 7]. Because of these properties, steel can be used in a wide range of applications. Commonly used forms of steel include: Wide flange (W), Channel (C), Angle (L), Tee (WT), and Hollow structural section (HSS). The main components of steel are iron, carbon (0.15–1.7% by weight), and manganese (0.5–1.7% by weight) in Table 1. The mechanical characteristics of steel material required in building planning include yield strength, tensile strength, modulus of elasticity, shear modulus, Poisson's ratio, specific weight, and thermal expansion coefficient [8–11]. The typical values of these properties are as follows:

- Yield strength (Fy): 250 to 690 MPa, depending on steel type
- Tensile strength (Fu): 400 to 900 MPa
- Modulus of elasticity (E): 200,000 MPa
- Shear modulus (G): 77 MPa
- Poisson's ratio (ν): 0.29
- Specific weight (γ): 77 kN/m^3
- Thermal expansion coefficient (α): Normally $11.7 \times 10^{-6}/C$, increasing to $14 \times 10^{-6}/C$ for temperatures above $65C$.

However, a recent problem is that many industrial factory buildings constructed with steel are experiencing fires. Buildings often catch fire for various reasons, such as short circuits, gas cylinder explosions, or arson. Fire temperatures can reach 900°C or higher [12–14].

---

[*] *Corresponding Author.*
E-mail address: zel.citra@mercubuana.ac.id ; Tel: (+62) 856-909 4090 (Zel Citra)

https://doi.org/10.30772/qjes.2026.168669.1871

Nomenclature

a, b	Interpolation constants
$BJ37$	Structural steel grade based on SNI 7506:2011
E	Modulus of elasticity (MPa)
F	Flange
F_y	Yield strength (MPa)
F_u	Tensile strength (MPa)
F_{uo}	Tensile strength (initial condition)
F_{uT}	Tensile strength (post-fire exposure)
G	Shear modulus (MPa)
HL	Leeb hardness value
HL_o	Leeb hardness value (initial condition)
HLO_T	Leeb hardness value (post-fire exposure)
NDT	Non-Destructive test
T	Temperature (Celsius)
W	Web
UTM	Universal testing machine
vr	Rebound velocity
vi	Impact velocity
Greek Symbols	
ν	Poisson's ratio
γ	Specific weight (kN/m^3)

The high incidence of fires needs to be a concern regarding the use of steel as a construction material. Steel is susceptible to temperature effects [15–17]. The effect of temperature on the mechanical properties of steel is that the strength and stiffness of steel decrease as the temperature increases, and this reduction in strength must be carefully considered in the design of steel structures [18,19]. One cause of steel structure collapse in a fire is the reduction in the strength of steel structures and joints at high temperatures. On the other hand, steel is a structural material that is not easily flammable but is very sensitive to heat. It loses its strength with increasing temperature, and its modulus of elasticity decreases rapidly [20,21]. Unprotected steel begins to soften and lose strength at high temperatures, resulting in geometric changes. Therefore, structural steel elements must be protected from fire. High temperatures accompanying fires cause significant changes in the mechanical properties of structural steel elements and substantial expansion as shown in Fig. 1. Experiments show that as temperature increases, the yield point of carbon steel decreases, and above a certain temperature, the structure collapses [22].

Table 1. Chemical composition of medium carbon steel [23].

Element	Maximum limit (%)
Carbon (C)	0.26
Manganese (Mn)	0.85 – 1.35
Phosphorus (P)	0.04
Sulphur (S)	0.05
Silicon (Si)	0.40max
Copper (Cu)	0.2

The influence on steel post-fire strength necessitates a comprehensive inspection or testing of the steel after it has been affected by the fire. However, the large number of industries that use steel as a construction material and experience fires is inconsistent with the limited availability of agencies or parties authorised or competent to conduct structural audits, especially of steel structures, in Indonesia. Post-fire structural assessment of steel is absolutely necessary as a follow-up recommendation for the evaluation and re-utilisation of the building's function. In this study, testing was conducted by creating simulations of several test specimens made from normal-quality steel BJ37, using cut plates from the flange and web sections of $WF\ 300 \times 150 \times 6 \times 9$. This study investigates the reduction in strength of the flange and web sections of the steel due to temperature effects, because the flange functions to bear bending moments and withstand axial tensile and compressive forces, while the web section will bear shear loads. Then, the test specimen was heated at 250 °C and 500 °C, and cooled by immersion in water for 15 minutes. Next, non-destructive testing methods were conducted, including hardness tests, and the hardness values were converted to yield strength (Fy) and tensile strength (Fu). This research also continues the author's previous study, which examined the inspection of coating materials on steel structures affected by fire. This research contributes academically by developing a practical, non-destructive approach to evaluate the residual mechanical properties of structural steel after exposure to elevated temperatures, particularly under post-fire conditions. The study provides a quantitative relationship between Leeb hardness values and the estimated tensile strength of BJ37 steel, which can serve as a reference for similar structural materials. From an industrial perspective, this research offers a rapid and cost-effective method for post-fire structural assessment, eliminating the need for destructive sampling and reducing downtime in industrial facilities. The proposed approach enables engineers, inspectors, and asset managers to quickly estimate residual steel strength and make informed decisions regarding repair, reinforcement, or reuse of fire-damaged structures. This is particularly important in industrial environments, where timely evaluation is critical to ensuring structural safety, minimising economic losses, and supporting sustainable reuse of materials.

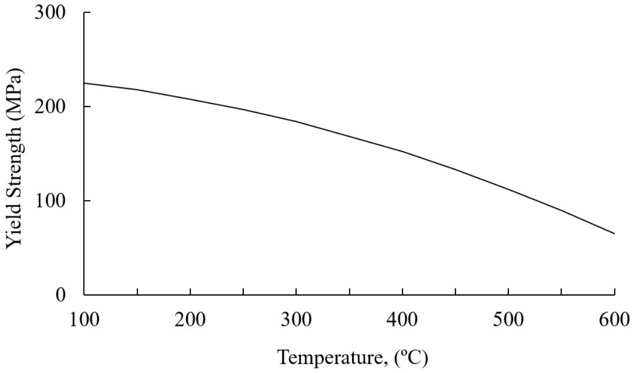


Figure 1. Graph of the decrease in steel strength due to temperature effects [24]

2. Material and Methods

Hardness testing in this study was conducted using a Leeb Hardness Tester Digital, a Non-Destructive Test (NDT) method. This method was chosen because it can measure surface hardness quickly and accurately, without damaging the test object. The working principle of this tool is based on the law of conservation of momentum, which compares the rebound velocity to the impact velocity of the impact body on the steel surface.

2.1 Principles and Testing Instrument

The Leeb method uses a device that projects kinetic force from an impact body shot onto the test object's surface via a spring [25]. The device used is the SNDWAY Leeb Hardness Tester SW-6230, as shown in Fig. 2. After hitting the surface, some of the energy is absorbed by the material, while the rest is reflected. The Leeb hardness value (HL) is calculated from the ratio of the rebound velocity to the impact velocity according to Eq. 1.

$$HL = 1000 \times \frac{vr}{vi} \tag{1}$$

The higher the HL value, the harder the tested material.

Figure 2. SNDWAY SW-6230 Leeb Hardness Tester

Figure 3. IWF Profile of the test sample

In this study, the test sample is BJ37 grade normal-quality carbon-structural steel, commonly used in industrial building construction in Indonesia. Samples were taken from the steel profile at the wing section of the Wide Flange WF 300 × 150 × 6 × 9, which represents main structural elements such as beams and columns, as shown in Fig. 3. The procedures for sampling, cutting, and preparing the samples refer to ASTM A370 (Standard Test Methods and Definitions for Mechanical Testing of Steel Products) [26] and ASTM E8/E8M (Standard Test Methods for Tension Testing of Metallic Materials) [27], to ensure uniformity in specimen shape and reliability of test results. This research is limited to NDT testing to obtain data on steel hardness, yield strength, and tensile strength. This research does not include tensile testing using a Universal Testing Machine (UTM) [28]. The WF profile steel was cut into test specimens in the form of plates with a geometry having a total length of approximately 450 *mm*, a gauge length of 200 *mm*, a middle width of 40 *mm*, and a gripping end width of 60 *mm*, as well as a transition radius of 25 *mm*, as. This specimen geometry was adjusted due to the size limitation of the heating oven: a chamber size of 50 × 50 *cm*. The cutting process is carried out mechanically without excessive heating to avoid changes in the material's mechanical properties. A total of 36 specimens were used in this study, comprising 18 flange and 18 web specimens from the steel profile. The specimens were assigned identification codes based on the treatment temperature variations (F-250, W-250, F-500, W-500). All specimens were heat-treated and divided into two temperature groups. Each section was tested with 9 specimens heated to 250 °C, and another 9 to 500 °C, representing the high-temperature exposure conditions that can occur in steel structures during a fire. As a reference or control, the initial profile steel hardness test was conducted, which showed a hardness of 366.19 HL and a tensile strength of 372 MPa. This standard serves as a baseline for evaluating the potential reduction in the material's mechanical properties after exposure to high temperatures. Next, the specimens were heated to 250 °C and 500 °C, with a 15-minute holding time at each temperature to ensure a relatively uniform heat distribution throughout the specimens' volumes. Each test specimen was then heated in an oven to simulate fire conditions. After heating, the specimens are immediately cooled rapidly by immersion in water for 15 minutes. This research is a continuation of the author's previous study on the temperature-dependent thickness testing of coating materials [29]. Additionally, this research is supported by other studies showing that the Leeb Hardness Test method can be used as a non-destructive approach to estimate the mechanical strength of steel. Research [30] indicates that the tensile strength of steel can be estimated quite accurately from portable Leeb hardness tester measurements, making this method a viable alternative to mechanical testing without damaging the specimen. Additionally, research by [31] shows a relationship between Leeb hardness values and yield strength in structural steel bars, allowing this method to be used for in-situ evaluation of the mechanical properties of steel in operational structures. Experimental studies by [32] also show that the relationship between Leeb hardness values and the tensile strength of steel can be modelled by regression analysis, enabling the estimation of material strength from hardness testing. Another study by [33] indicates that the Leeb rebound hardness method is widely used for testing large metal components due to its portability, speed, and non-destructive nature. Furthermore, recent research [34] on the relationship between hardness and the tensile properties of steel shows a significant statistical correlation between hardness and material strength parameters. In addition, this research is supported by other studies on the Leeb hardness method for measuring the strength of steel after a fire. As many as 120 H-shaped steel parts from China were tested after being exposed to fire. The parameters studied include the duration of fire exposure, cooling mode, steel grade, stress condition, and testing location, as well as research investigating the mechanical properties of structural steel after a fire using experimental data [35]. Based on various studies, the Leeb Hardness Test is an effective non-destructive testing method for estimating the mechanical strength of steel, particularly for evaluating steel structures that have been in service or exposed to high temperatures. This experimental study adopts a fire scenario representative of industrial environments with steel structures, where facilities are typically equipped with fire protection systems such as water storage tanks and hydrant networks. In such scenarios, fire can develop rapidly within the first few minutes after ignition, and the hydrant system serves as an initial fire suppression measure before the arrival of firefighting personnel. This assumption is consistent with standard firefighting operational procedures, which generally indicate a response time of approximately 15 minutes from the time of incident reporting. Accordingly, the heating duration in this study was limited to 15 minutes to represent the early stage of fire exposure. However, in real fire events, structural elements may be subjected to elevated temperatures for longer durations, leading to greater thermal degradation. Prolonged exposure allows more extensive microstructural changes, including recovery, recrystallisation, and potential phase transformations, depending on the temperature level. Therefore, the reductions in hardness and tensile strength observed in this study may represent a lower-bound estimate of material degradation, and more severe deterioration could occur under longer heating durations. Consequently, the effect of heating duration, in addition to peak temperature, should be considered in future studies to better represent real fire conditions. Based on this assumption, the specimens were heated for 15 minutes and subsequently tested using the Leeb hardness method in accordance with ASTM A956/A956M-22 [36].

2.2 Testing Procedure

The testing stages in this research are carried out systematically and follow the standard procedures for Non-Destructive Testing (NDT) Leeb hardness testing, as specified in SNI 8461:2017 (Leeb hardness test method for iron and steel) and ASTM A956/A956M-22 (Standard Test Method for Leeb Hardness Testing of Steel Products). This procedure is designed to minimise the influence of external factors, such as surface conditions and measurement inconsistencies, and to ensure the repeatability and reliability of the obtained data. The testing steps are carried out as follows:

- Surface preparation of the test specimen: the steel surface is cleaned of rust, oil, and dirt to ensure that the test results are not affected by surface irregularities.
- The calibration of the tool is carried out using a reference standard block provided by the manufacturer to ensure the accuracy of the tool before use.
- Determination of test points: each specimen is tested at three different points (left edge, centre, and right edge) with a total of 12 points for one specimen, with a minimum distance between points of 3 times the diameter of the impact ball to avoid the effect of residual impacts.
- Test execution: the Leeb probe is placed and pressed perpendicular to the surface of the test object (body sample). Then the device automatically measures impact and rebound velocity and displays the HL value (the average of the 12 measurement points) on the digital screen.
- Conversion of hardness values: measurement results in HL units can be converted to HB (Brinell), HRB/HRC (Rockwell), or HV (Vickers) units using standard international conversion tables that refer to Hardness Testing ASM Metal Handbook [37], ASTM Designation E140-12b [38], ASTM Designation E29 [39], ASTM Designation E10 [40] as shown in Table 2.
- The above steps are the procedure for the initial testing when the sample has not yet been heated, and then repeated when the sample has been heated to temperatures of 250 °C and 500 °C.

3. Result and Discussion

The initial hardness testing was conducted on BJ37 steel specimens in the non heat-treated condition using the Non-Destructive Test (NDT) Leeb hardness method on 36 samples, with each sample having 12 measurement points, and the hardness value was taken as the average of the instrument readings. The obtained hardness values reflect the steel's mechanical characteristics under normal conditions, providing an indication of the material's quality before exposure to high temperatures. The initial test results serve as a reference (baseline) for comparison with those of specimens heated to 250 °C and 500 °C. Through this comparison, changes in hardness values due to temperature treatment can be quantified, both as a decrease in the Leeb value and as equivalent tensile-strength changes. Thus, the initial test data play an important role in

Table 2. Leeb hardness to tensile strength conversion table.

HV (Vickers)	HBW / BHN (Brinell)	HRC	HRB	HRF	Tensile (MPa)	HK	LEEB (D)
80	76.0	—	—	—	255	—	299
85	80.7	—	41.0	—-	270	—	310
90	85.5	—	48.0	82.6	285	—	320
95	90.2	—	52.0	84.8	305	—	330
100	95.0	—	56.2	87.0	320	112	340
105	99.8	—	59.3	88.8	335	118	348
110	105	—	62.3	90.5	350	124	357
115	109	—	64.5	92.1	370	128	365
120	114	—	66.7	93.6	385	134	373
125	119	—	69.0	95.0	400	139	380
130	124	—	71.2	96.4	415	143	388
135	128	—	73.1	97.7	430	147	395
140	133	—	75.0	99.0	450	155	402
145	138	—	76.9	100.0	465	158	408
150	143	—	78.7	101.4	480	164	415
155	147	—	80.2	102.5	495	168	422
160	152	—	81.7	103.6	510	174	428
165	156	—	83.4	104.6	530	180	434
170	162	—	85.0	105.5	545	185	440
175	166	—	86.1	106.4	560	190	446
180	171	—	87.1	107.2	575	196	452
185	176	—	88.3	108.0	595	201	458
190	181	—	89.5	108.7	610	206	463
195	185	—	90.5	109.4	625	211	469
200	190	—	91.5	110.1	640	216	474
205	195	—	92.5	110.7	660	221	480
210	199	—	93.5	111.3	675	226	485
215	204	—	94.0	111.9	690	230	491
220	209	—	95.0	112.40	705	234	496
225	214	—	96.0	112.90	720	238	501
230	219	—	96.7	113.40	740	—-	506
235	223	—	97.4	113.90	755	246	511
240	228	20.3	98.1	114.30	770	—-	516
245	233	21.3	98.8	114.70	785	258	521
250	238	22.2	99.5	115.10	800	—-	526
255	242	23.1	100.3	—-	820	—-	531
260	247	24.0	101.0	—-	835	272	535
265	252	24.8	101.5	—-	850	278	540
270	257	25.6	102.0	—-	865	283	545
275	261	26.4	103.0	—-	880	—-	549
280	266	27.1	104.0	—-	900	290	554
285	271	27.8	104.5	—-	915	297	558
290	276	28.5	105.0	—-	930	—-	563
295	280	29.2	—-	—	950	—-	567
300	285	29.8	—-	—	965	208	571
310	295	31.0	—-	—	995	318	580
320	304	32.2	—-	—	1030	327	588
330	314	33.3	—-	—	1060	337	596
340	323	34.4	—-	—	1095	—-	604
350	333	35.5	—-	—	1125	355	612
360	342	36.6	—-	—	1155	367	619
370	352	37.7	—-	—	1190	378	627
380	361	38.8	—-	—	1220	389	634
390	371	39.8	—-	—	1255	400	641
400	380	40.8	—-	—	1290	412	648
410	390	41.8	—-	—	1320	424	655
420	399	42.7	—-	—	1350	435	661
430	409	43.6	—-	—	1385	448	668
440	418	44.5	—-	—	1420	460	675
450	428	45.3	—-	—	1455	482	681
460	460	46.1	—-	—	1485	495	687
470	447	46.9	—-	—	1520	—-	693
480	456	47.7	—-	—	1555	—-	699

assessing the degree of degradation in steel's mechanical properties and serve as the basis for the feasibility analysis of steel after exposure to high temperatures. The results of the steel hardness using the Leeb method as the initial test are shown in Table 3. Figures 4 and 5 from the tests show the distribution of Leeb hardness (HL) values for structural steel specimens tested before further mechanical property evaluation, with a total of 36 measurement points: 18 for the 250 °C specimen group and 18 for the 500 °C specimen group. It should be emphasised that all these data represent initial hardness (before heating), with the grouping at 250 °C and 500 °C for marking specimens to be heated in the next stage, not as thermal conditions during the hardness testing. Based

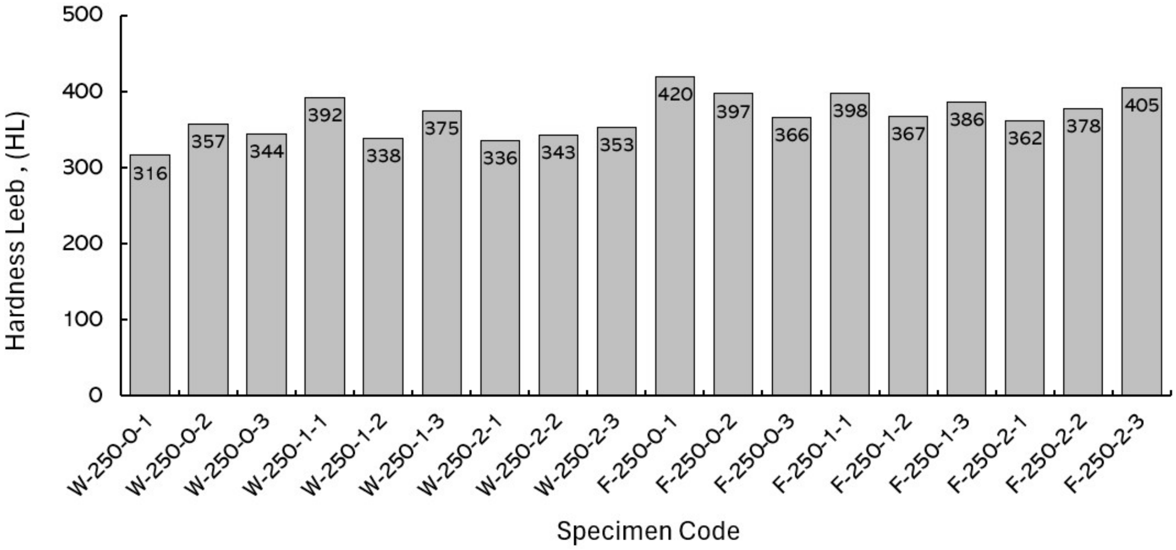


Figure 4. Graph of steel hardness before exposure to a temperature of 250 °C.

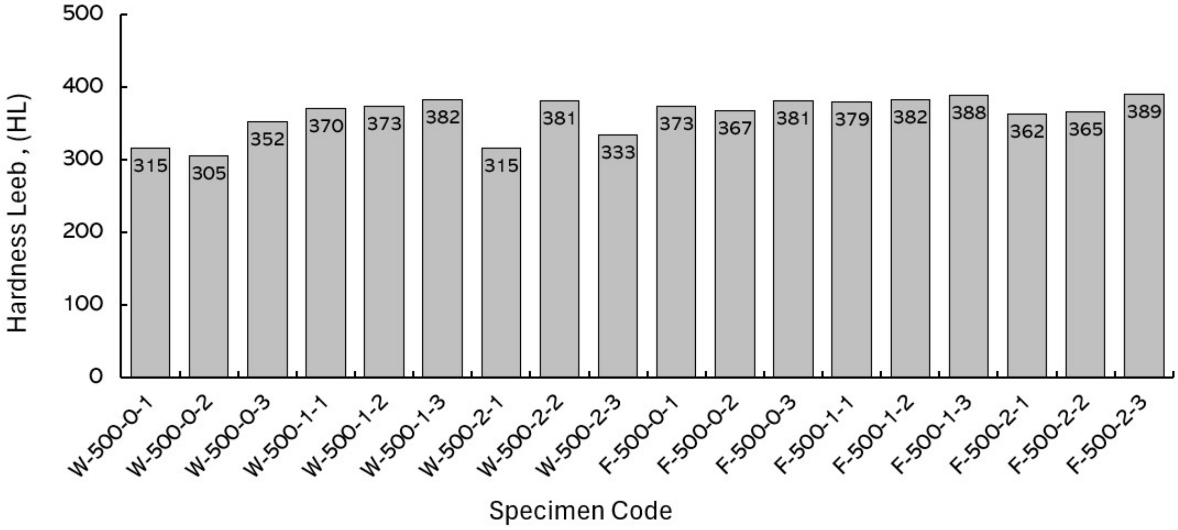


Figure 5. Graph of steel hardness before exposure to a temperature of 500 °C.

on the test results, the Leeb hardness values for the 250 °C specimen group range from 316 HL to 420 HL, both in the flange and web sections. Meanwhile, the Leeb hardness values for the 500 °C specimen group range from 305 HL to 389 HL. The range of values indicates local variations in steel hardness; however, these variations do not show a tendency influenced by differences in cross-sectional area. Therefore, it can be concluded that the thickness or testing position (flange or web) does not significantly affect the steel's initial hardness. The data processing results show that the average Leeb hardness value of the entire 36 samples is 366.19 HL. This average value represents the steel's initial mechanical condition before exposure to high temperatures and serves as a baseline for analysing mechanical property degradation due to heating at 250 °C and 500 °C. The interpolation results indicate that the average Leeb hardness value of 366.19 HL corresponds to a tensile strength of approximately 372 MPa. This value is consistent with the characteristics of BJ37 quality carbon structural steel, which has a minimum tensile strength of 370 MPa; therefore, the material's initial mechanical condition before heating still meets the standard mechanical properties. This equivalent tensile strength value is subsequently used as a baseline to evaluate changes and reductions in material strength due to exposure to 250 °C and 500 °C. Figure 6 shows the results of the steel hardness test after exposure to 250 °C using the Leeb hardness test method on the web and flange sections. The hardness values ranged from 314 to 396 HL, with relatively moderate variation among the specimens. The distribution of these values indicates that heating to 250 °C has affected the material's hardness, although it did not cause a significant difference between the web and flange sections. Thus, it can be concluded that the thickness or testing position (web and flange) is not a dominant factor in determining the hardness value of the steel under these conditions. Based on the data processing, an average Leeb hardness of 352.5 HL was obtained for all specimens after heating at 250 °C. Subsequently, this hardness value was converted to equivalent tensile strength using Table 2., the standard conversion table for the relationship between Leeb hardness and steel tensile strength. According to the table, a value of HL=348 corresponds to a tensile strength of 335 MPa, while HL=357 corresponds to 350 MPa. Since the average hardness falls between these two values, a linear interpolation of the table was performed, yielding an equivalent tensile strength of approximately 342.5 MPa. Compared with the initial condition before heating, which had an equivalent tensile strength of around 372 MPa, this result indicates a reduction of approximately 7.9% in tensile strength due to exposure to 250 °C. This reduction indicates that heating at medium temperatures significantly affects the mechanical capacity of the steel. Figure 7 shows the steel hardness result after heating at 500 °C. The Leeb hardness (HL) value range from 319–362 HL for the web and 357–373 HL for the flange section. This distribution of values indicates that, after exposure to high temperatures, the steel's hardness in both sections of the specimen remains relatively uniform despite variations between testing points. The data processing results show that the average Leeb hardness for all samples at 500 °C is 354.7 HL. This average value is then converted to an equivalent tensile strength estimate using Table 2, the standard conversion table between Leeb hardness and steel tensile strength. Based on linear interpolation

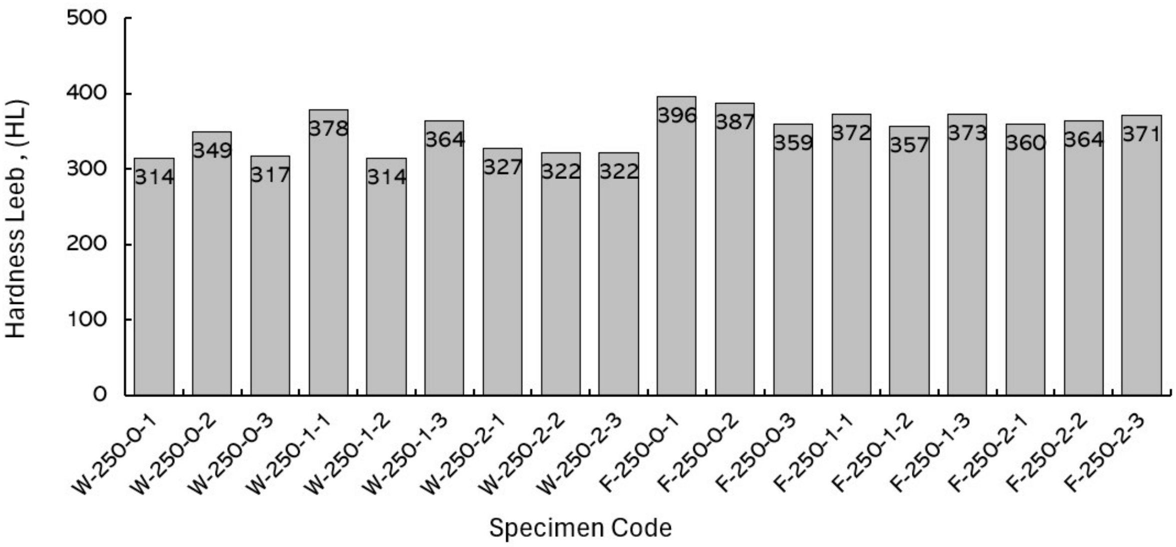


Figure 6. Graph of steel hardness after exposure to 250 °C.

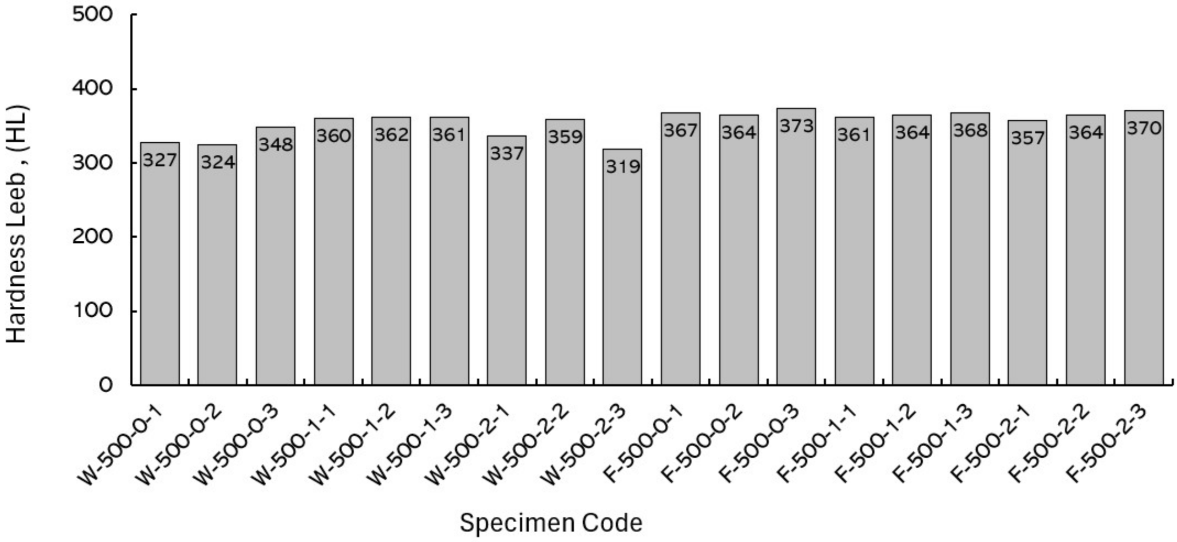


Figure 7. Graph of steel hardness after exposure to 500 °C.

between adjacent HL values in that table, a hardness of 354.7 HL is equivalent to a tensile strength of approximately 346 MPa. When compared to the initial condition of the steel, which has an average hardness value of 366.19 HL and an equivalent tensile strength of approximately 372 MPa, heating to 500 °C reduces tensile strength by about 26 MPa, or approximately 7.0%. The above analysis, supported by previous studies and established theories, indicates that the mechanical properties of steel are influenced by temperature, while very rapid cooling (quenching) can lead to significant changes. The quenching process can modify the steel microstructure, particularly by forming martensite when the material is heated to the austenitization temperature (around 723°C) and then rapidly cooled. Such microstructural changes may result in a noticeable increase in material hardness. However, in this study, the maximum heating temperature is limited to 500 °C, which remains below the austenitization threshold; consequently, the likelihood of martensitic transformation during cooling is relatively low. In addition, this study focuses on evaluating mechanical properties using a non-destructive approach via the Leeb hardness test; as such, microstructural analysis was not conducted. Nevertheless, the influence of cooling rate on microstructural evolution, as well as its relationship with hardness and tensile strength, remains an important aspect that deserves further investigation. At temperatures below the austenitization threshold, increasing temperature can initiate recovery, which reduces dislocation density through the movement and rearrangement of dislocations within the crystal structure. At temperatures around 500 °C, this process becomes active, leading to reduced resistance to dislocation movement and contributing to a decrease in material hardness. In contrast, recrystallisation and grain growth generally occur at higher temperatures and require greater thermal energy, and are therefore not dominant under the conditions considered in this study. Accordingly, the observed reduction in hardness is more likely associated with the early stage of recovery rather than with more significant microstructural transformations. In contrast to the general behaviour of structural steel described in international standards such as Eurocode 3 and AISC, the reduction in tensile strength observed at 250 °C and 500 °C in this study is relatively small, ranging from approximately 7.0% to 7.9%. According to Eurocode 3 (EN 1993-1-2) [41] and AISC provisions [42], structural steel typically begins to experience significant strength degradation at temperatures above 600 °C, and may lose approximately 40–50% of its original strength at temperatures between 500 and 600 °C, depending on the steel grade and exposure conditions. The discrepancy between the experimental results and standard predictions may be attributed to the test specimens' characteristics, particularly the presence of a coating layer on the steel surface. This coating can act as a thermal barrier, reducing heat transfer into the material and limiting direct heat exposure. As a result, the degree of thermal degradation observed in this study is lower than that typically expected for unprotected steel. Therefore, further research is recommended to investigate the combined effects of heating duration, cooling methods, coating conditions, and microstructural changes on the mechanical properties of steel under high-temperature exposure. Based on the results of the Leeb hardness (HL) test and its conversion to equivalent tensile strength, as shown in Table 4, a mathematical relationship can be derived to describe the change in steel's tensile strength (Fu) with exposure to high temperatures. Based on the standard conversion table, the tensile strength of steel can be estimated as a function of Leeb hardness HLEq. 2.

$$F_u = f(HL) \tag{2}$$

For a relatively narrow range of HL values, this relationship can be approached linearly, Eq. 3.

$$F_u = a \times HL + b \tag{3}$$

The gradient (a) is calculated from the change in tensile strength against the change in hardness, using two extreme conditions (initial and 250 °C) so that the sensitivity of the changes is clearly visible Eq. 4.

$$a = \frac{F_{uo} - F_{uT}}{HL_o - HL_T} \rightarrow a = 2.15\ MPa \tag{4}$$

The constant (b) is obtained by substituting one of the data points into the linear equation. Initial conditions are used Eq. 5.

$$b = F_{uo} - a \times HL_o \rightarrow b = -415.31\ MPa \tag{5}$$

And, the final Conversion Equation (Valid & Consistent) can be found by Eq. 6.

$$F_u = 2.15 \times HL - 415.31 \tag{6}$$

The verification of equations (Consistency Test) is listed as follows:
1. Temperature 250 °C, , $F_{u250} = 2.15(352.5) - 415.31 = 342.6\ MPa$
2. Temperature 500 °C , $F_{u500} = 2.15(354.7) - 415.31 = 346\ MPa$
The verification results above are in accordance. Furthermore, the formula for strength reduction due to temperature can be divide to two approaches:

a. Absolute decrease, Eq. 7

$$\Delta F_u = F_{uo} - F_{uT} \tag{7}$$

1. Temperature 250 °C, $\Delta F_{u250} = 372 - 342.5 = 29.5\ MPa$
2. Temperature 500 °C, $\Delta F_{u500} = 372 - 346 = 26\ MPa$

b. Relative decrease (percentage), Eq. 8

$$\Delta F_u(T) = \frac{F_{uo} - F_{uT}}{F_{uo}} \times 100\% \tag{8}$$

1. Temperature 250 °C, $\Delta F_u(250) = 7.9\%$

2. Temperature 500 °C, $\Delta F_u(500) = 7.0\%$

Finally, the general form of the strength reduction model is Eq. 9.

$$F_{uT} = F_{uo}(1 - \delta(T)) \tag{9}$$

Or from hardness Eq. 10.

$$F_{uT} = 2.15HL_T - 415.31 \tag{10}$$

Table 3. Specimen code for all test samples.

Specimen 250°C	**Hardness** (hl)	**Specimen** 500 °C	**Hardness** (hl)
Flange			
F-250-0-1	420	F-500-0-1	373
F-250-0-2	397	F-500-0-2	367
F-250-0-3	366	F-500-0-3	381
F-250-1-1	398	F-500-1-1	379
F-250-1-2	367	F-500-1-2	382
F-250-1-3	386	F-500-1-3	388
F-250-2-1	362	F-500-2-1	362
F-250-2-2	378	F-500-2-2	365
F-250-2-3	405	F-500-2-3	389
Web			
W-250-0-1	316	W-500-0-1	315
W-250-0-2	357	W-500-0-2	305
W-250-0-3	344	W-500-0-3	352
W-250-1-1	392	W-500-1-1	370
W-250-1-2	338	W-500-1-2	373
W-250-1-3	375	W-500-1-3	382
W-250-2-1	336	W-500-2-1	315
W-250-2-2	343	W-500-2-2	381
W-250-2-3	353	W-500-2-3	333

Table 4. . Baseline experimental data

Condition	*HL*	F_u (MPa)
Initial (unheated)	366.19	372.00
Temperature 250 °C	352.50	342.50
Temperature 500 °C	354.70	346.00

Overall, these results reinforce previous findings that the Leeb hardness test effectively captures changes in steel's mechanical properties at elevated temperatures. This method is particularly relevant as a rapid, non-destructive approach for preliminary assessment of steel condition after fire exposure, especially when destructive testing is not feasible. In this study, tensile strength was estimated using standard hardness conversion tables rather than direct tensile testing. While this approach is widely adopted in material inspection due to its efficiency and non-destructive nature, it has inherent limitations, as the estimated values are based on empirical correlations between hardness and material strength. Therefore, to improve the accuracy and reliability of the results, further research is recommended to perform destructive tensile testing using a Universal Testing Machine (UTM). Such tests would enable validation of the consistency between tensile-strength values obtained from hardness conversion and those measured directly on BJ37 steel specimens.

4. Conclusions

Based on the research and analysis conducted, the following conclusions can be drawn:

- The results of the Non-Destructive Test (NDT) using the Leeb Hardness Test indicate that exposure to elevated temperatures affects the mechanical properties of BJ37 structural steel, as reflected by changes in hardness values and estimated tensile strength.
- In the initial (unheated) condition, the average hardness was 366.19 HL, corresponding to an estimated tensile strength of approximately 372 MPa. This value is consistent with the characteristic properties of BJ37 steel and serves as the baseline reference.
- After heating to 250 °C, the average hardness decreased to 352.5 HL, corresponding to an estimated tensile strength of 342.5 MPa. This represents a reduction of 29.5 MPa, or approximately 7.9%, compared to the initial condition.
- At 500 °C, the average hardness was 354.7 HL, corresponding to an estimated tensile strength of approximately 346 MPa. This indicates a reduction of about 26 MPa, or 7.0%, relative to the initial condition. The difference between the 250 °C and 500°C results is relatively small, indicating no significant additional reduction within this temperature range.
- The Leeb Hardness Test can be used effectively as a rapid, non-destructive method for the preliminary evaluation of the mechanical properties of steel after exposure to elevated temperatures.
- Further research is recommended to validate these findings through destructive tensile testing and to consider wider temperature variations, longer heating durations, and a larger number of specimens to improve the correlation between Leeb hardness values and steel mechanical properties.

CRediT authorship contribution statement

Zel Citra: Contributed to writing – review, conceptualization, formal analysis, and laboratory investigation. **Antonius**: Contributed to validation, methodology, and supervision. **Agung Wahyudi Biantoro**: contributed to supervision and validation. **Han Ay Lie**: Contributed review and editing, validation, and methodology. **Risma Apdeni**: Contributed to writing – review, supervision, and validation.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

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

Acknowledgements

The authors would like to acknowledge the support and contributions of all parties involved in this study.

References

[1] M. A. B. Omer and T. Noguchi, "A conceptual framework for understanding the contribution of building materials in the achievement of sustainable development goals (sdgs)," *Sustainable Cities and Society*, vol. 52, p. 101869, 2020. [Online]. Available: https://doi.org/10.1016/j.scs.2019.101869

[2] Q. Yan, F. Jiao, and W. Peng, "Building materials classification model based on text data enhancement and semantic feature extraction," *Buildings*, vol. 14, no. 6, p. 1859, 2024. [Online]. Available: https://doi.org/10.3390/buildings14061859

[3] BCSA & SCI, *Handbook of Structural Steelwork - Eurocode Edition*. British Constructional Steelwork Association and The Steel Construction Institute, 2013, publication No. 55/13.

[4] The Indonesian Iron & Steel Industry Association, "National steel performance projection 2024," 2024. [Online]. Available: https://iisia.or.id/en/news/proyeksi-kinerja-baja-nasional-2024

[5] M. A. Javed, N. Ivanovich, E. Messinese, R. Liu, S. E. Astorga, Y. P. Yeo, S. Idapalapati, F. M. Lauro, and S. A. Wade, "The role of metallurgical features in the microbially influenced corrosion of carbon steel: A critical review," *Microorganisms*, vol. 12, no. 5, p. 892, 2024. [Online]. Available: https://doi.org/10.3390/microorganisms12050892

[6] Y. B. Guo and C. R. Liu, "Mechanical properties of hardened aisi 52100 steel in hard machining processes," *Journal of Manufacturing Science and Engineering*, vol. 124, no. 1, pp. 1–9, 2002. [Online]. Available: https://doi.org/10.1115/1.1413775

[7] Q. Ma, D. Feng, Y. Li, B. Yao, and L. Wang, "Mechanical properties and constitutive model of steel under temperature–humidity cycles," *Buildings*, vol. 15, no. 5, pp. 1–22, 2025. [Online]. Available: https://doi.org/10.3390/buildings15050732

[8] A. Z. Issagulov, S. S. Kvon, V. Y. Kulikov, D. R. Aubakirov, Y. P. Chsherbakova, and A. M. Dostayeva, "Testing experimental parts of metallurgical units for wear and impact in industrial conditions," *IOP Conference Series: Materials Science and Engineering*, vol. 866, no. 1, pp. 6–11, 2020. [Online]. Available: https://doi.org/10.1088/1757-899X/866/1/012054

[9] A. Taqiya, I. N. Aenin, Antonius, and L. Fitriyana, "Perencanaan bangunan gudang dengan struktur baja pada tanah lunak," *Prosiding Seminar Nasional Konstelasi Ilmiah Mahasiswa UNISSULA 7 (KIMU 7) Klaster Engineering*, vol. 7, no. 31, pp. 265–272, 2022. [Online]. Available: https://jurnal.unissula.ac.id/index.php/kimueng/article/view/20576

[10] AISC, *Specification for Structural Steel Buildings (ANSI/AISC 360-16)*. American Institute of Steel Construction, 2016.

[11] BSN, *Spesifikasi untuk bangunan gedung baja struktural*, Std. SNI 03-1729, 2015. [Online]. Available: www.bsn.go.id

[12] W. D. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction*, 10th ed. John Wiley & Sons, 2017.

[13] Antonius, A. Widhianto, D. Darmayadi, and G. D. Asfari, "Fire resistance of normal and high-strength concrete with contains of steel fibre," *Asian Journal of Civil Engineering*, vol. 15, no. 5, pp. 655–669, 2014.

[14] J. Yin, T. Tang, G. Zhang, L. Zhou, and P. Deng, "A probabilistic model for fire temperature rise in high-rise residential buildings under the action of uncertain factors," *Fire*, vol. 6, no. 4, p. 147, 2023. [Online]. Available: https://doi.org/10.3390/fire6040147

[15] A. Zhdanova, R. Volkov, A. Sviridenko, G. Kuznetsov, and P. Strizhak, "Influence of compartment fire behavior at ignition and combustion development stages on the operation of fire detectors," *Fire*, vol. 5, no. 3, p. 84, 2022. [Online]. Available: https://doi.org/10.3390/fire5030084

[16] M. Abdullah, M. A. Muttalib, Z. F. Alam, M. M. Hossain, and Z. Ahsan, "Effects of temperature and water pressure on mild steel strength: A comparative study," *Results in Surfaces and Interfaces*, vol. 17, p. 100328, 2024. [Online]. Available: https://doi.org/10.1016/j.rsurfi.2024.100328

[17] L. Song, Y. Peng, H. Zhao, Y. Cao, and L. Zhao, "Study on dynamic mechanical properties of low-alloy, high-strength steel weld metal at high temperatures," *Materials*, vol. 18, no. 7, p. 1488, 2025. [Online]. Available: https://doi.org/10.3390/ma18071488

[18] C. Fix, L. Borrmann, S. Elixmann, C. Grahe, S. Kurenbach, and D. Senk, "Investigations on decreased high temperature ductility of different continuously cast steel grades," *Steel Research International*, vol. 92, no. 12, 2021. [Online]. Available: https://doi.org/10.1002/srin.202100323

[19] W. Wang, B. Liu, and V. Kodur, "Effect of temperature on strength and elastic modulus of high-strength steel," *Journal of Materials in Civil Engineering*, vol. 25, no. 2, pp. 174–182, 2013. [Online]. Available: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000600

[20] M. M. Tedesco, D. De Caro, P. Rizzi, and M. Baricco, "Effect of composition and thermal treatments on mechanical properties and applications of quenching and partitioning steels," *Metals*, vol. 13, no. 10, p. 1757, 2023. [Online]. Available: https://doi.org/10.3390/met13101757

[21] S. Li, W. Ding, Q. Zhang, X. Xiao, and Q. Zhou, "Experimental study of the mechanical properties of a new duplex stainless steel exposed to elevated temperatures," *Case Studies in Construction Materials*, vol. 17, p. e01683, 2022. [Online]. Available: https://doi.org/10.1016/j.cscm.2022.e01683

[22] L. Huang, G. Q. Li, X. X. Wang, C. Zhang, L. Choe, and M. Engelhardt, "High temperature mechanical properties of high strength structural steels q550, q690 and q890," *Fire Technology*, vol. 54, pp. 1609–1628, 2018. [Online]. Available: https://doi.org/10.1007/s10694-018-0760-9

[23] M. Pop, I.-M. Sas-Boca, D. Frunză, and A. Neag, "The influence of hot deformation on the mechanical and structural properties of mild carbon steel for industrial application," *Metals*, vol. 15, no. 7, pp. 1–24, 2025. [Online]. Available: https://doi.org/10.3390/met15070756

[24] O. F. Kültür, A. Al-Masri, and B. Sayin, "Effect of high temperature exposure on design parameters and collapse behavior of reinforced concrete and steel-framed buildings," *Case Studies in Construction Materials*, vol. 17, p. e01263, 2022. [Online]. Available: https://doi.org/10.1016/j.cscm.2022.e01263

[25] M. Zhi, L. Feng, D. Jingfei, C. Daobin, and N. Tao, "Relation between the bending and temperature of coated steel beam in fire test," *Procedia Engineering*, vol. 84, pp. 840–848, 2014. [Online]. Available: https://doi.org/10.1016/j.proeng.2014.10.504

[26] *Metode uji kekerasan leeb untuk besi dan baja*, Std. SNI 8461:2017, 2017.

[27] *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, Std. ASTM A370 / ASME SA-370, 2016.

[28] *Standard Test Methods for Tension Testing of Metallic Materials*, Std. ASTM E8/E8M-13a, 2013.

[29] M. Gajdzicki and J. Miszczak, "Determining the steel tensile strength based on leeb hardness measurement," *Materialy Budowlane*, vol. 619, no. 3, pp. 18–22, 2024. [Online]. Available: https://doi.org/10.15199/33.2024.03.04

[30] Z. Citra, Antonius, and A. Wahyudi, "Application of ultrasonic and coating material thickness testing on post-fire steel construction," *Rekayasa Sipil*, vol. 19, no. 02, 2025. [Online]. Available: https://doi.org/10.21776/ub.rekayasasipil.2025.019.02.12

[31] A. Brencich and F. Campeggio, "Leeb hardness for yielding stress assessment of steel bars in existing reinforced structures," *Construction and Building Materials*, vol. 227, p. 116570, 2019. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2019.07.296

[32] A. Lahouel, S. Athmani, A. Sedik, A. Saoudi, R. Barille, L. Khezami, A. Guesmi, and M. Fellah, "Predictive correlation between hardness and tensile properties of submerged arc welded api x70 steel," *Materials*, vol. 18, no. 19, p. 4482, 2025. [Online]. Available: https://doi.org/10.3390/ma18194482

[33] R. Hegazy, G. Mohamad, M. Mohamad, K. M. Khaled, and M. I. Mohamad, "Empirical relation between leeb rebound hardness and tensile strength for austenitic ductile cast iron," in *IMEKO 23rd TC3, 13th TC5, and 4th TC22 International Conference*, 2017. [Online]. Available: https://www.imeko.org/publications/tc5-2017/IMEKO-TC5-2017-011.pdf

[34] Q. Z. Sheng, C. C. Li, H. S. Sun, and L. Q. Yu, "Experimental study on in-situ inspection of existing steel structure's steel strength by leeb hardness," *Advanced Materials Research*, vol. 1065-1069, pp. 1770–1775, 2014. [Online]. Available: https://doi.org/10.4028/www.scientific.net/AMR.1065-1069.1770

[35] K. Karolewska, M. Wirwicki, and B. Ligaj, "Evaluation of a method for determining material strength based on hardness measurements: A case study of the ti6al4v alloy," *Materials*, vol. 18, no. 16, p. 3726, 2025. [Online]. Available: https://doi.org/10.3390/ma18163726

[36] K. Maissara, F. Forouzan, P. Åkerfeldt, I. Timokhina, P. Åkerström, E. Vuorinen, and M. Antti, "Effect of tempering on microstructure and tensile properties of ultra-high strength steels for press hardening applications," *Metallurgical and Materials Transactions A*, vol. 56, pp. 2570–2585, 2025. [Online]. Available: https://doi.org/10.1007/s11661-025-07805-5

[37] *Standard Test Method for Leeb Hardness Testing of Steel Products*, Std. ASTM 956/A956M-22, 2022.

[38] H. Kuhn and D. Medlin, Eds., *Mechanical Testing and Evaluation*. ASM International, 2000. [Online]. Available: https://doi.org/10.31399/asm.hb.v08.9781627081764

[39] *Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness*, Std. ASTM E 140-07, 2007.

[40] *Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications*, Std. ASTM E29-13, 2013.

[41] *Standard Test Method for Brinell Hardness of Metallic Materials*, Std. ASTM E10-12, 2012.

[42] *Eurocode 3: Design of Steel Structures*, Std. BS EN 1993-1-2:2005, 2005.

How to cite this article:
Zel Citra, Antonius, Agung W. Biantoro, Han A. Lie and Risma Apdeni, (2026). 'Non-destructive experimental test on the hardness and strength of steel exposed to temperatures of 250 °C and 500°C', Al-Qadisiyah Journal for Engineering Sciences, 19(3), pp. 001- 009. `https://doi.org/10.30772/qjes.2026.168669.1871`