Investigating the relationship between hardness and plastic strain in reinforcing steel bars

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ABSTRACT: It is well known that modern seismic codes are based on capacity design and hierarchy of strength philosophy that allows inelastic response in case of severe earthquakes and thus, in most traditional systems, damage develops at well-defined locations of reinforced concrete (RC) structures. The 2010 and 2011 Christchurch earthquakes have demonstrated that the aforementioned philosophy worked as expected. However, there is a lack of literature on methods to evaluate the residual capacity at specific locations of damaged buildings to sustain subsequent aftershocks and earthquakes. Therefore, in the present paper, a methodology to estimate the level of damage in reinforcing steel bars is investigated. Laboratory-based tensile and hardness tests on a number of steel reinforcing bars were used to develop an empirically-based mathematical relationship correlating plastic strain and hardness above the original baseline. Following a brief overview of hardness testing methods and devices, the results will be presented and critically discussed to identify whether and under which conditions there is a robust relationship between plastic strain and hardness that can be employed to estimate the level of damage in reinforcing steel bars. The influence of strain ageing is integral to the discussion.

1 INTRODUCTION

It is recognized that designing a building to withstand earthquakes elastically is not economical viable, thus modern seismic codes are based on capacity design and hierarchy of strength philosophy. This philosophy promotes the design of ductile structures and encourages the designer to locate “the weakest link of the chain” within the structural system where it will act as ductile “fuse” dissipating energy and preventing unwanted brittle failure mechanisms. (Pampanin, 2012) A structure designed following this approach is expected to sway laterally during an earthquake but not collapse. Most monolithic reinforced concrete (RC) structures rely on the predictable inelastic behaviour of the steel reinforcing material, which is expected to have well-defined strength and ductility. The inelastic mechanism and associated damage is intentionally developed at well-defined locations called plastic hinges. The 2010 and 2011 Christchurch earthquakes demonstrated that the aforementioned philosophy was successful. Plastic hinges formed in beams, coupling beams and at the base of columns and walls. Structures were damaged permanently but did not collapse.

However, due to the lack of information in literature on robust and standardized methods to evaluate the residual capacity of damaged buildings to sustain subsequent aftershocks and on reliable and cost-efficient repairing techniques to restore the structure “at least” as it was before the earthquake, a significant proportion of multi-storey RC buildings were deemed irreparable and demolished. Thus, a minimally invasive technique is desired to evaluate the level of damage and estimate the residual capacity of damaged building.

Soon after the Canterbury seismic events, substantial work was conducted (Ferguson et al., 2013) (HolmesSolution, 2011) to estimate the amount of plastic deformation generated in structural and reinforcing steel. The proposed method is based on measuring hardness in situ then correlating the measured hardness to plastic strain based upon laboratory tensile tests, as it is known that plastic deformation increases yield strength (Dieter, 1976) (Vander Voort, 1984) and that yield strength can be correlated to hardness of metals in deformed regions (Cahoon, Broughton, & Kutzak, 1971). Hardness in metal can be defined as a measure of its resistance to plastic deformation. In engineering applications, hardness measurements can be described as the resistance of a metal against the penetration of a body made by a harder material such as a diamond indenter or a hard steel ball (Dieter, 1976). The most traditional hardness testing method is the static indentation method, which involves the application of an indenter on a sample surface. Hardness is then calculated as the ratio between load applied and area of indentation made on the surface sample, this is the case of the well-known Brinell, Rockwell or Vickers hardness tests. Another testing method is the rebound or dynamic hardness test, in which an impact body is dynamically applied on a metal sample and hardness is measured in terms of energy dissipation during the impact. An example is the Leeb hardness test commonly used in industry.

A methodology to estimate the amount of plastic strain generated in steel structural elements during earthquakes based on the relationship between hardness and plastic strain has been previously investigated by Matsumoto (Matsumoto, 2009). A series of tensile tests and hardness tests was conducted on SN490 structural steel in order to investigate the correlation between hardness and tensile properties. The experimental tests showed that tensile strength increased in proportion to the hardness, and uniform elongation decreased with increase in hardness.

A portable device for minimally invasive “in situ” testing is desirable for the purpose of this research, in this regard experimental tests in order to identify the most suitable portable hardness tester device have been conducted by a research team in Japan (Nakane et al., 2010). Results from a portable Vickers hardness tester, an UCI (Ultrasonic Contact Impedance) hardness tester and a rebound (Leeb) hardness tester were compared with those obtained with a conventional Vickers hardness tester. It was observed that the portable Vickers and ultrasonic hardness testers gave similar results to those obtained with the conventional Vickers, while the rebound hardness device gave slightly higher results.

More recently, damage assessment tests have been carried out on some of the buildings damaged in the Christchurch 2010/2011 earthquakes. Leeb hardness and Rockwell B hardness tests were used, respectively on site and in laboratory, on the Eccentrically Braced Frames (EBF) of the Pacific Tower in Christchurch (Ferguson, et al., 2013). Hardness measurements showed an increase in Leeb and Rockwell B hardness in the web section of the active link beam of damaged EBFs. This increase in hardness was interpreted as a significant plastic deformation of the structural element. Damage assessment of some Christchurch RC buildings have also been conducted by Holmes Solutions (HolmesSolution, 2011), in which Leeb hardness tests were conducted on site on reinforcing steel bars that crossed concrete cracks. Vicinal to crack locations, the bars were exposed by removing covering concrete. The exposed surface was ground flat and finished to facilitate the hardness measurement operations. Leeb hardness readings were obtained at regularly-spaced intervals along a significant length of the bar in order to detect any systematic increase in hardness near cracks that could demonstrate that the elastic limit of a bar has been exceeded. In order to quantify the amount of plastic deformation, a reference relationship between Leeb hardness and steel plastic strain was determined through laboratory-based hardness and tensile tests.

The mechanical properties of strained reinforcing bar have been found subject to a "strain-ageing" phenomenon (Hall, 1951) (Baird, 1971) (Erasmus & Pussegoda, 1977). An example of this phenomenon is illustrated in Figure 1 using Grade 300E supplied by Pacific Steel. Consider the example case where steel with strain-ageing proclivity is strained in tension beyond its elastic limit up to stress A. If the specimen is unloaded and then immediately reloaded, the specimen will show elastic behaviour up to stress A and strain hardening will continue as if the test had not stopped. However, if the specimen is unloaded, aged and reloaded, the upper/lower yield point phenomenon not only reappears but it does so at a higher stress (point B). The strain ageing process occurs due to diffusion of interstitial nitrogen and carbon atoms, which have the function to lock the mobile dislocations in the new positions after the steel has strained. This locking effect is dependent on the interstitial content of nitrogen and carbon, the ageing time and temperature.

For broader acceptance in industry, further study of damage assessment methods is required. Therefore, in the present work, results from laboratory-based tests will be presented and critically discussed to identify whether a relationship between plastic strain and hardness that can be employed to estimate the level of damage in reinforcing steel bars. A series of interrupted tensile tests in conjunction with Vickers hardness tests was conducted on the current seismic Grade 300E and seismic Grade 500E reinforcing steel bars. The main difference between the present work and some previous work is that tensile test interruptions are at refined strain intervals, Vickers hardness measurements were made on polished surfaces at closer spatial intervals, and the materials have full traceability. Perhaps most significantly, strain-ageing effects have also been investigated and discussed in the present context of damage assessment.

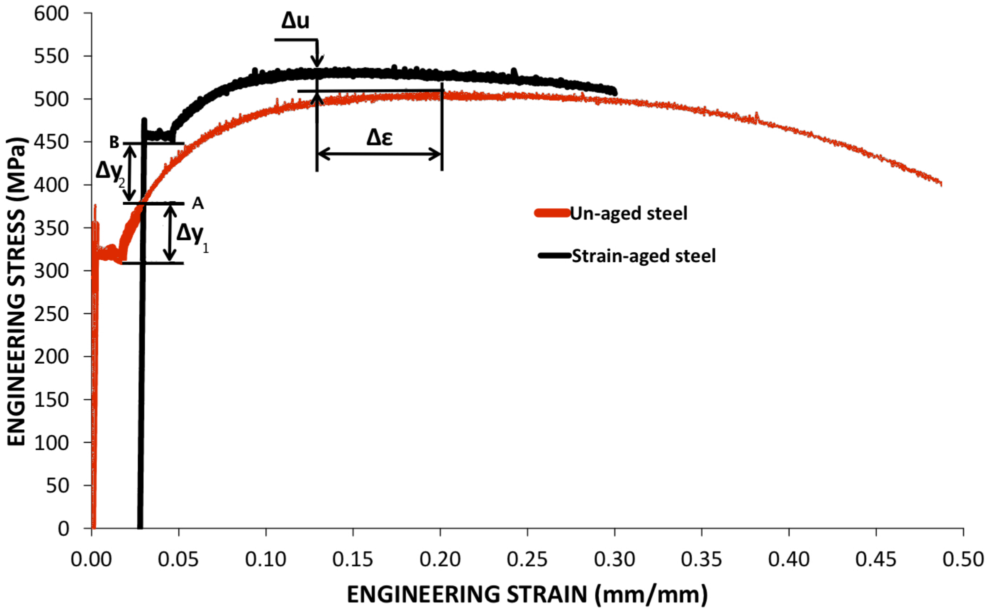

Figure 1. Stress – strain curves of seismic Grade 300 reinforcing steel, as-received (un-aged), and pre-strained to 0.03mm/mm, aged to simulate one year at 15°C and then re-loaded to investigate strain age effects.

2 EXPERIMENTAL PROCEDURES

2.1 Monotonic Tensile tests

25 mm diameter seismic Grade 300E and seismic Grade 500E reinforcing steel bars were obtained from a local supplier. Chemical compositions are shown in Table 1. Three round "dog bone" specimen samples for each Grade were machined to 13 mm diameter and 75 mm gauge length. Tensile tests on round "dog-bone" specimens were performed with a SATEC system with 1000kN load capacity using an MTS 25 mm gauge length extensometer capable of 50% travel in tension. The crosshead displacement rate was 1 mm/min. Resultant average values of the fundamental tensile mechanical properties are shown in Table 2.

Table 1. Chemical composition data (wt%) from Mill Certification Sheet

Material	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Sn	V	Ceq
300E	0.18	0.78	0.22	0.024	0.013	0.09	0.09	0.017	0.28	0.018	0.003	0.36
500E	0.18	1.27	0.35	0.032	0.017	0.07	0.11	0.013	0.26	0.017	0.085	0.46

Table 2. Average Tensile properties of reinforcing steel

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Uniform Elongation (%)
300E	323	515	19.3
500E	524	684	13.1

2.2 Hardness and Interrupted Tensile Tests

In order to find a correlation between hardness and plastic strain, eight samples for each steel Grade were subjected to interrupted tensile testing. Each sample was deformed up to a pre-determined amount of strain: for seismic Grade 300E reinforcing steel 1, 2, 4, 6, 8, 10, 14 and 18% strain, and for seismic Grade 500E reinforcing steel 1, 2, 4, 6, 8, 10, 12 and 14%. At each interruption, Vickers hardness tests were been carried out according ASTM Standard E384 - $11^{\varepsilon 1}$ using a conventional Vickers hardness machine. The Vickers method requires the user to optically measure the diagonal lengths of the indentation produced by a diamond indenter on the sample through a microscope.

To facilitate the hardness testing procedure the shoulder ends of the "dog bone" specimens were cut off and the round surface was ground flat. The flat surface was then sequentially ground from 240 - 600 grit and polished with 9, 3 and then 1 micron diamond paste to reduce errors during the Vickers optical indentation measurements. Vickers indentations were performed on the deformed samples at 5 mm intervals along the gauge length. The mean hardness and standard deviation were calculated and correlated to the amount of true plastic strain, calculated as the logarithms of the ratio between deformed cross sectional area and original cross area.

2.3 Strain ageing

To investigate the effect of strain ageing on the mechanical properties of seismic Grade 300E reinforcing steel a series of experimental tests have been conducted. Another test series was undertaken on seismic Grade 500E, however due to the higher vanadium content (see Table 1), strain ageing effects were not expected to be significant (Erasmus & Pussegoda, 1977).

Five samples were machined and pre-strained up to 1.5, 3, 6, 12 and 18%. Strained samples were immersed in boiling water (100ºC) for four hours, which is intended to simulate the effect of ageing steel at 15ºC for one year (Hundy, 1954). This approximation was validated by comparing the ratio of diffusivities at the 2 temperatures of both carbon and nitrogen in alpha iron. After ageing, the samples were hardness tested and then tension tested until failure. Between tests or in case of delays, samples were stored at -10°C.

3 RESULTS AND DISCUSSION

The main objective of the present work was to determine whether a robust relationship between hardness and plastic strain for current reinforcing steel grades can be employed to estimate the amount of plastic deformation generated by earthquake in damaged reinforcing steel bars and the residual ductility.

As expected, the results showed an increase in hardness with an increase of plastic strain for both materials, see Figure 2 and Figure 3. All data sets were fitted to power law curves. The standard deviation for hardness measurements is approximately 2.5HV for strains over 2% in both steels. The standard deviation for strains as low as 1% (i.e., within the Lüders extension) was 7HV. Therefore, strain is easily and reliably detected using the Vickers hardness testing method under laboratory conditions.

However, the strain ageing effect needs to be considered. In all cases of pre-strain from 1.5 - 18%, the upper-lower yield point phenomenon returned but at a higher stress, the uniform elongation was reduced, as shown in Table 3. In every case but 1.5% pre-strain, the ultimate tensile strength reached a higher value. Figure 1 shows by the example of 3% pre-strain that the strain ageing effect is significant:

$$\Delta\varepsilon = \varepsilon_{SA} - \varepsilon_{UA} = 0.10 - 0.20 = -0.10 \text{ mm/mm}$$

$$\Delta u = u_{SA} - u_{UA} = 540 - 515 = 25 \text{ MPa}$$

$$\Delta y = y_{SA} - y_{UA} = 450 - 323 = 128 \text{ MPa}$$

where the subscripts "SA" and "UA" mean "strain aged" and "un-aged", respectively. The 50% decrease in strain at the ultimate tensile strength ($\Delta\varepsilon$), which is considered the end of uniform elongation and thus the total plastic strain capacity, also accounts for the offset due to the pre-strain of

0.03mm/mm.

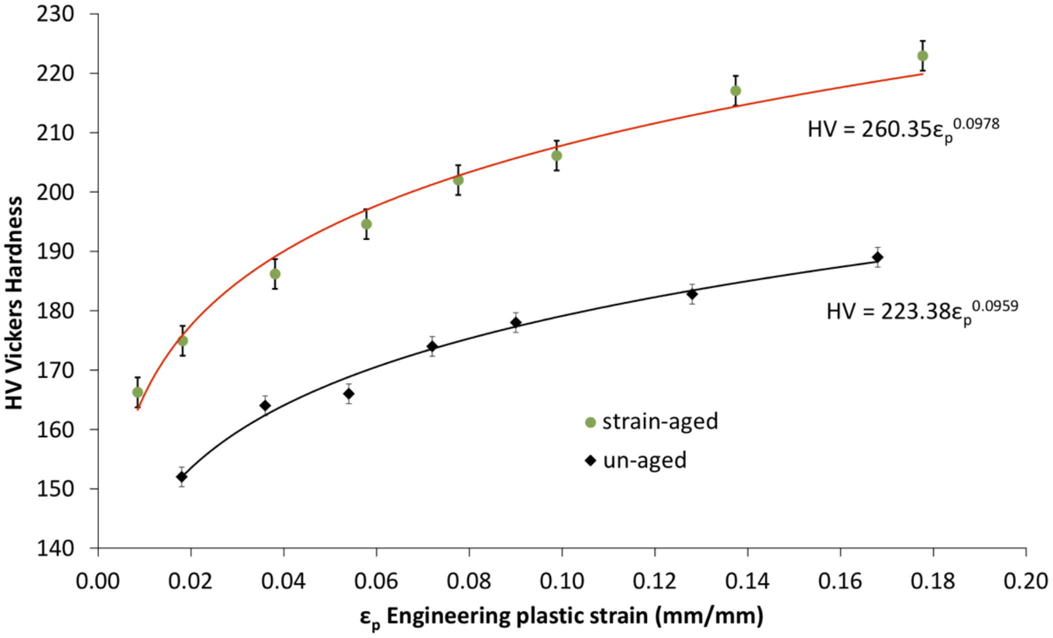

Figure 2. Vickers hardness versus plastic strain for un-aged Grade 300 steel and for Grade 300 steel with simulated strain ageing of one year.

Strain ageing effects were also quantified by correlating strain-aged hardness to pre-strain. Figure 2 shows that strain ageing induces a significant increase in hardness in Seismic Grade 300E but no effects were observed on Seismic Grade 500E. In order to explain in more detail the consequence of this phenomenon in the present context, the following example can be useful (see Figure 2 and Figure 4). Consider the case if a 300E reinforcing steel bar were damaged during an earthquake and the hardness, measured one year after the seismic event, was found to be 170 HV and the baseline hardness was found to be 149 HV. Based on the un-aged correlation HV = 223.38 $\varepsilon_p^{0.0959}$ the plastic strain generated in the seismic event would be $\varepsilon_p \approx 0.06$ mm/mm, the residual strain capacity would be estimated as $\varepsilon_r = \varepsilon_{UA} - \varepsilon_p \approx 0.2 - 0.06 \approx 0.14$. However, if the strain-aged correlation HV = 260.35 $\varepsilon_p^{0.0978}$ is employed, the plastic strain experienced by the bar would be only $\varepsilon_p \approx 0.01$ mm/mm and the residual plastic strain capacity would be estimated as $\varepsilon_r = \varepsilon_{SA} - \varepsilon_p \approx 0.10 - 0.01 \approx 0.09$. Figure 4 illustrates how the residual plastic strain capacity may be underestimated or overestimated from hardness measurements if strain ageing occurs. In the present case of 300E steel with relatively small increases in Vickers hardness above the baseline (in this case from 149 to 185 HV), the residual plastic strain capacity will be overestimated because the strain ageing effect so significantly reduces the strain at the ultimate tensile stress, from ~0.2 for un-aged steel to ~0.1 for strain aged steel that had been pre-strain to 3%. Note that the total plastic strain capacity, in other words the uniform elongation, varied significantly depending on the pre-strain as shown in Table 3.

Table 3. Total plastic strain capacity of strain-aged 300E

%pre-strain	Ultimate tensile strength (MPa)	Uniform Elongation (%)
1.5	499	9.8
3	531	10.2
6	503	7.5
12	546	5.0
18	574	0

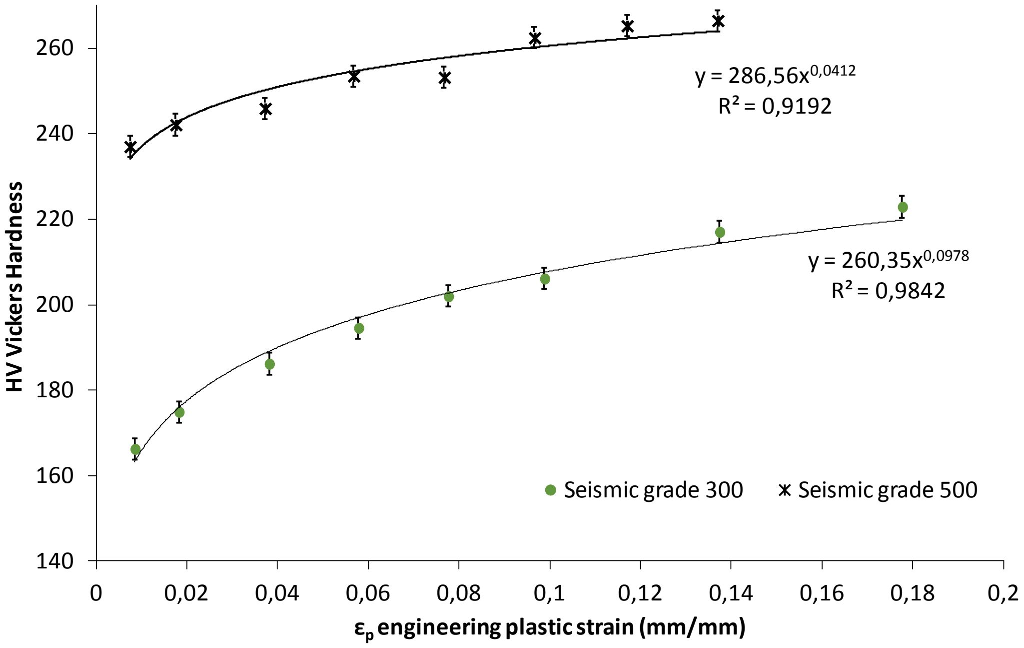

Figure 3. Hardness versus engineering plastic strain for aged seismic Grade 300E and aged seismic Grade 500E, although significant strain ageing effects were not observed for Grade 500E.

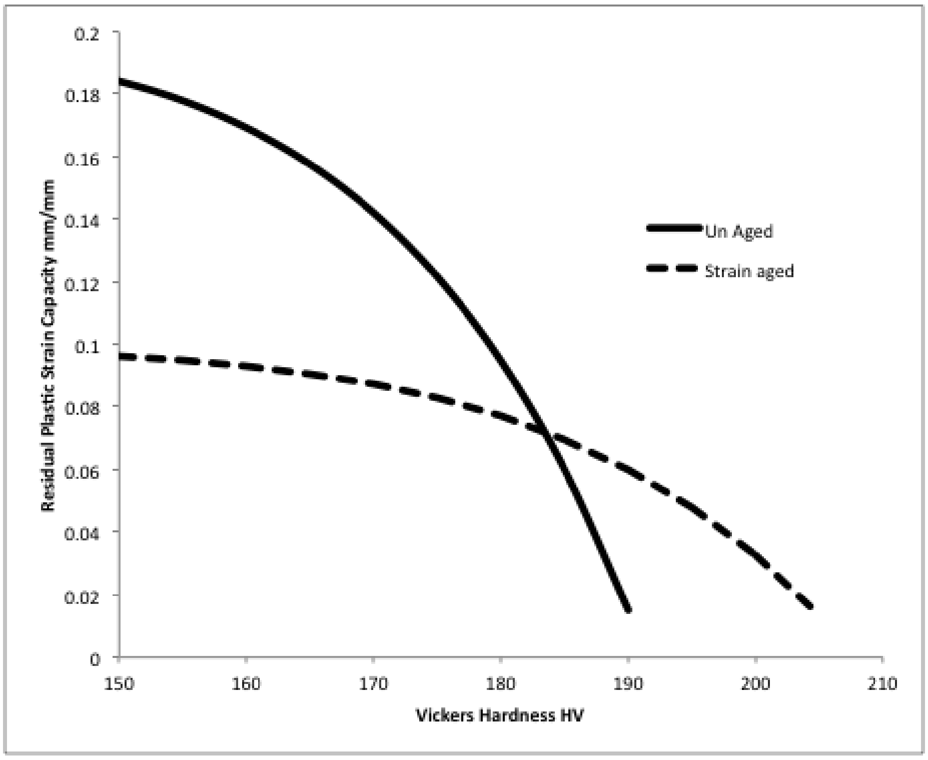

Figure 4. Residual plastic strain capacity for Grade 300E steel for strain aged and un-aged steel.

4 CONCLUSIONS

Based on the experimental tests conducted and reported in this paper the conclusions are:

- The Vickers hardness tests of seismic Grade 300E and seismic Grade 500E gave consistent results: hardness increases significantly with the amount of plastic strain, therefore it is reasonable to use hardness measurement to affirm a bar has exceeded its elastic limit during a seismic event.

- Estimation of the residual plastic strain capacity requires calibration tests to convert hardness to plastic strain, and tensile tests to determine the original plastic strain capacity.
- Seismic Grade 300E used in these experimental tests is prone to strain ageing and this phenomenon affects the mechanical properties of the material. Increases in yield and tensile strength were observed (and can be observed via hardness measurements), but most significantly there was a decrease in plastic strain capacity. The strain ageing phenomenon was not observed in Seismic Grade 500E.
- If a relationship between hardness and plastic deformation is employed to assess damage, then strain-ageing effects must be taken into account.

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