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Relationship between hardness and plastically deformed structural steel elements

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ABSTRACT

A field based non-destructive hardness method is being developed to determine plastic strain in steel elements subjected to seismic loading. The focus of this study is on the active links of eccentrically braced frames (EBFs). The 2010/2011 Christchurch earthquake series, especially the very intense February 22 shaking, which was the first earthquake worldwide to push complete EBF systems into their inelastic state, generating a moderate to high level of plastic strain in EBF active links for a range of buildings from 3 to 23 storeys in height. Plastic deformation was confined to the active links. This raised two important questions: what was the extent of plastic deformation and what effect does that have on post-earthquake steel properties? A non-destructive hardness test method is being used to determine a relationship between hardness and plastic strain in active link beams. Active links from the earthquake affected, 23-storey Pacific Tower building in Christchurch are being analysed in the field and laboratory. Test results to date show clear evidence that this method is able to give a good relationship between plastic strain and demand. This paper presents significant findings from this project to investigate the relationship between hardness and plastic strain that warrant publication prior to the completion of the project. Principal of these is the discovery that hot rolled steel beams carry manufacturing induced plastic strains, in regions of the webs, of up to 5%.

Keywords: deformed steel; eccentrically braced frames; earthquake; hardness; plastic strain; residual stress; portable hardness tester.

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1. Introduction

Eccentrically braced frames (EBFs) are widely used as earthquake-resisting frames in high seismic regions due to their combination of high elastic stiffness, excellent ductility capacity and overall cost-effectiveness when compared with other conventional seismic-resisting systems such as moment resisting frames (MRF), buckling-restrained braced frames (BRBF) and concentrically braced frames (CBF). Eccentrically braced frames are designed to remain elastic in small to moderate earthquakes, while in severe earthquakes the systems form a mechanism, with inelastic demand being focused into the active link, thereby protecting the braces, columns and beams from damage. During the Christchurch earthquake series of 2010/2011, in particular the intense earthquake of 22 February 2011, peak ground accelerations in the CBD ranged from 0.5g to over 1.0g and peak vertical accelerations were over 1.0g (Clifton et al., 2012). EBFs were pushed into the inelastic range due to this shaking. As intended, the inelastic demand was concentrated into the active links of these frames, consistent with the design requirements of the New Zealand Steel Structures standard (NZS3404., 1997/2001/2007) and steel seismic design procedures (Feeney & Clifton, 2001). There are no criteria established nationally neither internationally to provide guidance for checking when this threshold has been reached, nor to indicate the remaining life expectancy and the repair and replacement procedure for the damaged links beams and frames. In the active links that have yielded, this raised the urgent question about their ability to perform as expected during another design ultimate limit state earthquake, i.e. what extent of inelastic demand was sufficient to require replacement of an active link and how to determine this in a non-destructive manner.

Moment resisting frame system has been used in the buildings in seismic regions for many years. The buildings used steel MRF performed very well during the 1906 San Francisco earthquake, USA and it has been used as an efficient frame system until Managua earthquake in 1972, capital of Nicaragua (Roeder, Popov, American Iron, & Steel Institute, 1977). Analytical and experimental studies on EBFs under cyclic loading began in the early 1970s. However, the Managua earthquake developed strong interest in studying the behaviour of different types of elastic structures in more detail. Research on inelastic behaviour of steel frame systems under cyclic loading has been an active study since late 1960s. As a result different types of steel frame systems with various parameters, different loading and support fixing conditions have emerged. The earliest analytical investigation on steel braced frame systems to study the inelastic behaviour was carried out by Tanabashi (Tanabashi & Taneta, 1962); Veletsos (Veletsos, 1969) and Workman (Workman, September 1969). Their studies were based on the use of slip model behaviour to analyse the dynamic actions of multi-storey steel braced frames. Later, Fujimo et al. (Fujimo, Aoyagi, Ukai, Wada, & Saito, October 1972) carried out several tests analytically and experimentally to study the behaviour of eccentric K-braced frame systems with different parameters. This investigation was identified as the beginning of the research on the field of eccentric brace frame systems. It was recognised as a popular and promising start among the researchers due to excellent energy dissipation capacity of their model under cyclic loading. During this time several other investigations were carried out by different researchers to investigate the performance of framed systems under cyclic loading. These tests confirmed the active links as being able to deform plastically in a stable manner to the large deformations required. However, these tests focused on determining the ductility capacity of the active links and eccentrically braced frames, through testing to destruction, and so did not provide a relationship between plastic strain levels and remaining steel capacity in active links subject to lower levels of inelastic demand, such as seen in most of the EBF buildings in Christchurch.

Research into the relationship between hardness and plastic strain of metals began through practical applications: as a result, different methods and measuring devices were invented. During the early development stages of hardness method, it was realised it could not be considered a non-destructive testing method due to several limitations, mainly the large indentation impressions left on the test surfaces. In 1908, Meyer carried out a detailed study in relation to Brinell's indentation hardness method and proposed an expression relating hardness to plastic strain known as Meyer's Law. Meyer's expression still couldn't resolve the problem of indentation impressions on various metallic materials. O' Neil (O'Neil, 1934) addressed the unrecovered indentation problems of Meyer's expression and carried out a detailed study of Brinell's method combined with Meyer's law. Hugh O'Neill in his book the 'Hardness of Metals and its Measurement, explains the relationship between hardness, deformation and strain-hardening of metals in great detail with the help of experimental studies of various metallic materials. The most commonly used method to stretch or deform metals is stretching them in tension, also known as the tensile test method, which ultimately increases the resistance of the material flow. These methods, indentation hardness and tensile testing increase the flow stress of the material. Hence the hardness test methods introduced by metallurgists have been used since the 1930's to study the behaviour of tensile flow properties of metallic materials. The relationship between hardness and tensile plastic strain of any ductile metal can be summarised as: the more the metal is stretched, the harder it becomes, until it reaches its ultimate tensile stress, after which further plastic strain leads to local necking and fracture.

In recent years, hardness testing has become established as a commonly used practical method to predict mechanical and material properties of steel (Cahoon, Broughton, & Kutzak, 1971; Datsko, Hartwig, & McClory, 2001). As a result, a significant volume of literature is available on this subject. However, established guidelines to identify the amount of plastic deformation in cyclically deformed metals are very limited, especially using techniques that are portable and can be applied to elements within an earthquake damaged building in the field. Pavlina and Van Tyne (Pavlina & Van Tyne, 2008) carried out a numerical analysis to estimate the yield strength and tensile strength of steel based on hardness-strength data from 20 years of research work. Their study was based on two numerical expressions by Cahoon and Cahoon.et al. (Cahoon et al., 1971; Cahoon, 1972). They found that the numerical expression by Cahoon was not suitable to predict the tensile strength at higher hardness values, but the ratio of the two linear regression equations proposed by Cahoon indicates that a linear relationship between tensile strain and hardness can be established.

Matsumoto (Matsumoto, 2009) carried out a comprehensive experimental investigation to study the correlation between plastically strained steel and hardness. This correlation was then used to identify the amount of damage and residual performance of steel structures under severe earthquakes. A series of monotonic and cyclic loading tests on two different steels were carried out to investigate the effect of hardness and tensile strains of the steel. Leeb hardness testers were used to measure the hardness of steel at different loading conditions. It was found that the mass of the specimen plays a vital role in predicting the Leeb's hardness values, and recommended keeping the specimen weight greater than 5kg. A small error of 5% between the experimental and the estimated hardness values indicated a very good correlation between hardness and ultimate tensile strength. The Bauschinger effect of the material was considered by examining the yield point of the material for different loading conditions. In conclusion he confirmed that the correlation between tensile strength and hardness of plastically strained steel is proportional and on-site hardness testing by Leeb's hardness testers can potentially be used to estimate the remaining life of steel structures after a severe earthquake.

In the present investigation, a non-destructive Leeb (portable) hardness tester (model TH170) has been used to measure the hardness in order to determine the plastic strain, in hot rolled steel universal sections and steel plates. A bench top Rockwell hardness testing machine has been used to compare the hardness measured by the TH170. The amount of manufacturing induced plastic strain, in regions of webs identified during this study has been analysed. To the authors' knowledge non-destructive hardness test methods have not been used to determine the amount of manufacturing plastic strain in structural steel sections. However, destructive methods have been reported by several researchers including Chi and Uang (Chi & Uang, 2004); Tide (Tide, 2000) in 2000; Kaufman and Fisher (Kaufmann & Fisher, 2001); and Masui and Okaza (Masui & Okada, 1989).

2. Hardness technique

A portable Leeb hardness tester, series TH170, has been used in these experimental studies. This instrument measures the hardness of the material dynamically by impacting a spherically shaped indenter onto the test surface, so that the impacting and rebounding velocity of the test material is measured as a hardness of the test material. TH170 is being widely used because of its speed, light weight, portability, ease of use and because the Leeb Hardness measurement procedure is covered by an ASTM standard (ASTM: A956-06, 2011) . Fig. 1 shows the portable hardness tester TH170.

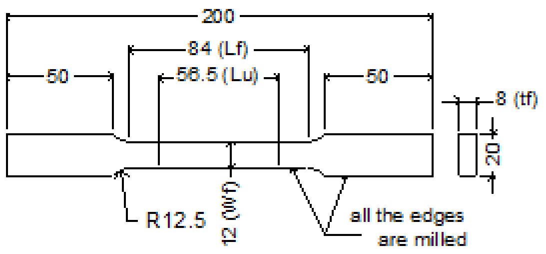
Fig. 1 Integrated portable Leeb hardness tester Th170

Since this is a portable instrument it is very convenient and easy to use in the laboratory as well as inside damaged buildings. However, these devices are prone to inaccurate readings if the test piece is not prepared adequately, especially with the requirements on the surface preparation and minimum weight of the test piece according to the instruction manual of the TH 170 (Beijing TIME High Technology Ltd, 2007). A minimum test piece weight of 5kg is recommended by the manufacturer and surface roughness less than or equal to 1.6 microns has been found by the principal author to be necessary for accurate test results. Hardness tests were conducted on the test specimens prepared according to ASTM Standards (ASTM: E18-11, 2012) for Rockwell hardness of metallic materials.

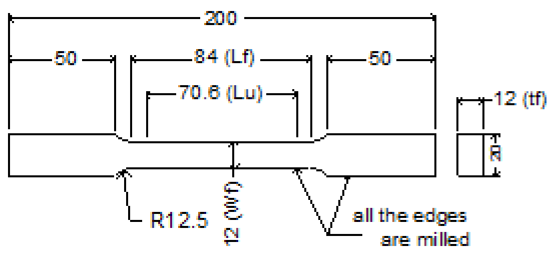
3. Experimental procedure

3.1. Test detail

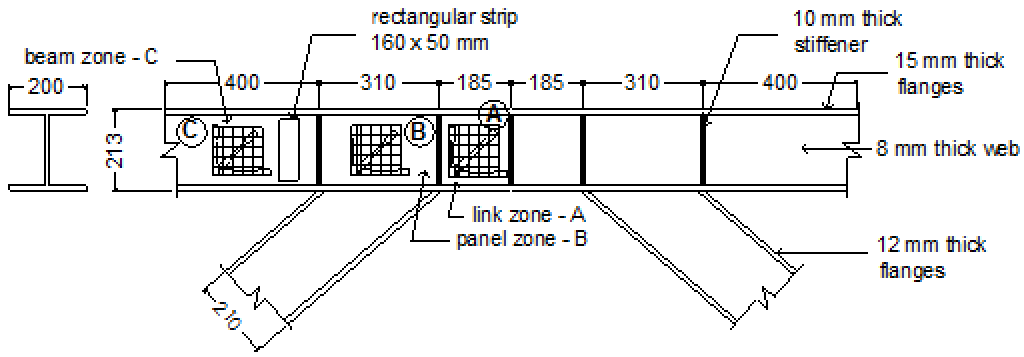
For the purpose of this investigation, hot rolled steel plates and active links from a building affected by the Christchurch earthquake series were tested. Steel plates of two different thicknesses, 8mm and 12mm, with minimum yield strength of 300MPa and complying with the Australian and New Zealand Standards (AS/NZS1365, 1996; AS/NZS3678, 2011; NZS3404, Part 1:1997), were used to make the tensile dog-bone specimens used in this study. The tensile testing was undertaken in accordance with ASTM: E8/E8M-09 (ASTM: E8/E8M-09, 2009). Dog-bone specimen details are given in Fig. 2(a) and (b). The two thicknesses of hot rolled steel for grade 300 MPa were selected as they cover the range of EBF active link webs, which is the target of this research. The minimum thickness of the test specimen was selected by considering 10 times the depth of indentation for the purpose of hardness testing (AS1391, 2004; ASTM: E8/E8M-09, 2009; NZS3404, Part 1:1997). Active link from Christchurch earthquake effected, 23-storey Pacific Tower was tested. The detail of the specimen is given in Fig. 2(c).



(a) 8mm thick specimen



(b) 12 mm thick specimen



(c) active link beam at level 03 on grid 01

Fig. 2 Dog-bone tensile specimens and active link from earthquake affected

(a) 3M flap wheel on hand drill

(b) grit 120P wheel on rotary tool

(a) Powerfile sander by Black & Decker

Fig. 3 Surface preparation tools

3.2. Surface roughness tests

For an accurate hardness test result, surface roughness was identified as an important parameter during this study. Test specimens must be smooth, even and clean enough according to ASTM Standards (ASTM: A956-06, 2011) for hardness determination of metallic materials by this rebound based portable machine. Oxide scale or mill scale and other foreign matter can lead to inaccurate readings. Any paint, including undercoat and surface coat, pits and scale must be removed. Testing on a range of surface roughness as described below established that surface roughness (Ra) needs to be less than 1.6 micro-meter (μm) when using TH170 testers for accurate hardness rest results. Three surface preparation methods were used to carry out a surface test; 3M Flap Wheel on electric rotary tool followed by hand sanding, Two Dremel Wheels on electric rotary tool followed by hand sanding and an electric sander (variable speed Powerfile by Black & Decker) with different sanding belts followed by hand sanding. Different surface preparation instruments and prepared surfaces are shown in Fig. 3 and Fig. 4.

Prepared surfaces were measured for their roughness using a surface roughness tester, Surtronic 3. The test results were then compared to identify the best cleaning method to achieve the best surface roughness for the portable hardness tester TH170. An electric rotary tool, a Dremel with wheel P60 followed by hand sanding with all the grits from P60 to P240 was used for surface preparation and the Dremel with wheel P120 followed by hand sanding with grits from P120 to P240 was also used. A rechargeable hand drill with 3M flap wheel followed by hand sanding using grit numbers P80 to P240 was also used. Like Dremel with wheel P120, a sanding belt P120 was used in an electric Powerfile followed by hand sanding with grits up to P240. Even though different sanding belts were available for the Powerfile, they were not used in this study to maintain consistency with the other two test methods. Rough sanding belts (P60 and P80) were used for initial cleaning and removing of thick paint and mill scales from the test surfaces.

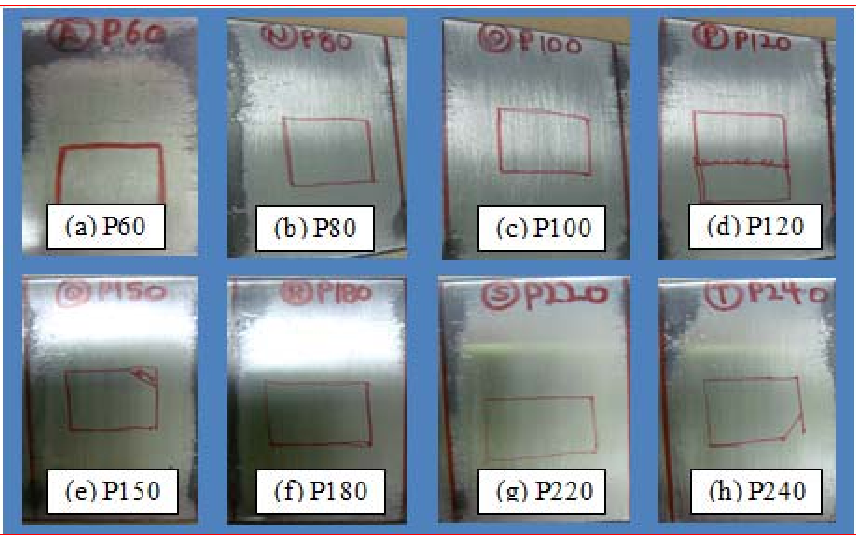


Fig. 4 Surface prepared for roughness testing

4. Monotonic test

Uniaxial tensile testing was carried out on an MTS machine with the capacity of 120kN, followed by Rockwell hardness testing using a bench top Rockwell machine. Targeted plastic strains for loading were 5%, 10%, 15%, and 20% for the 8mm thick specimens and 2.5%, 5%, 10% and 15% for the 12 mm thick specimens. Machine settings for these specimen tests were pre-calculated where targeted strain and test result outputs were pre-set in the MTS station manager software before the experiments: this software controls the machine from start to end of each experiment. During the experiments, load-displacement characteristics of the specimens are displayed graphically. Changes in the specimen were recorded after the testing to identify the following: final gauge length (L_u); parallel length (L_f); width (W_f) and thickness (t_f) of the section. The load- displacement diagrams for each specimen were analysed to investigate the behaviour such as yield load, yield displacement, maximum load, maximum displacement, strain hardening region and failure load. Rockwell hardness was measured at each strain level using the scale B, RB, with a 100 kgf and a 1.588 mm (1/16″) diameter ball indenter. Both surfaces of all the test specimens were prepared according to the ASTM Standards (ASTM: E18-11, 2012), and hand sanding using sandpapers with grit numbers P120 and P220 were used to prepare the test surfaces. No surface alterations were ensured during the surface preparation and also no heating or cold-working while extracting the specimens. Minimum edge distance was kept more than 2.5 times the indenter diameter and more than 3 times between two indentations.

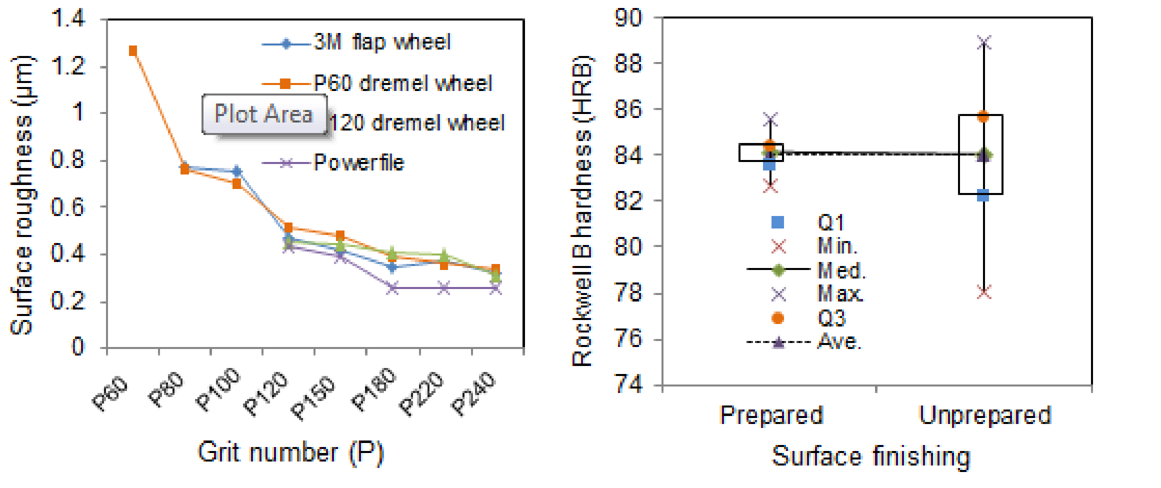
5. Cyclically deformed active link

Cyclically deformed EBFs from Pacific Tower, given in Fig. 2(c), were used to study the relationship between hardness and cyclic plastic strain. This active link beam was divided in to three test zones; link zone (zone A), panel zone (zone B) and beam zone (zone C). Each of these zones was further divided in to 25 small grids to carry out a hardness survey using both the portable hardness tester TH170 and the Rockwell hardness machine, as shown in Fig. 8(a) and (b). Dog-bone specimens for tensile testing were water jet cut from all three zones to avoid heat.

6. Test results

6.1. Surface roughness test results

Surface roughness in microns (μm) is plotted against different grits (P) from the three methods explained in section 3.2, and presented in Fig. 5(a). The test results show the roughness on all prepared surfaces. As all of these are less than the 1.6 microns recommended for the TH170 operation, it can be considered that any roughness below P60 would be sufficient to carry out TH170 hardness measurements accurately as given in Section 3.1. Fig. 5(b) describes the influence of surface preparation on hardness values. Hardness readings from as-received specimens are scattered over a wide range compared to the prepared specimens. This indicates more accurate hardness could be achieved from a specimen properly prepared.



(a) Comparison of surface roughness (b) Influence of surface finishing on hardness

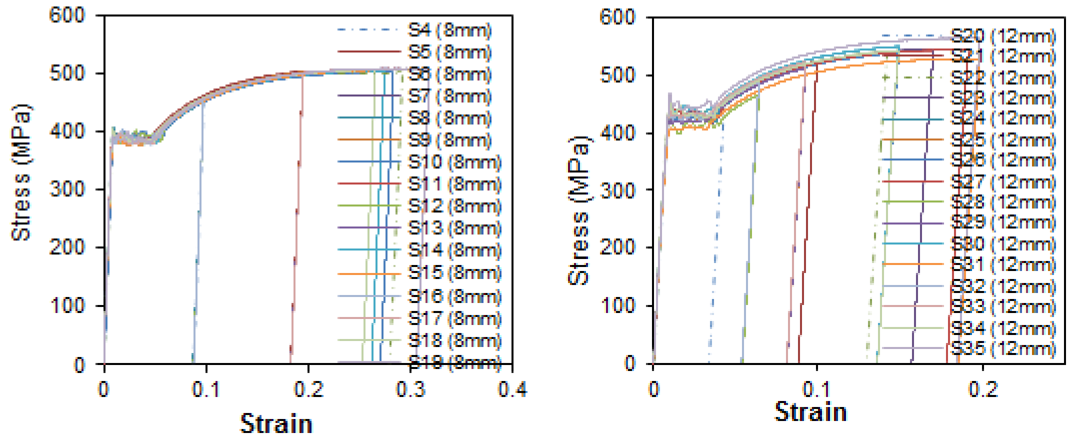
Fig. 5 Surface roughness with different surface cleaning methods and the

In Fig. 5(a), the grit number P60 gives the highest the surface roughness (Ra = 1.27μm) whereas P240 gave the finest surface achieved in this study. The test results were than compared to identify the best cleaning method out of the three discussed in previous section to achieve the most cost and time effective surface roughness for the portable hardness tester TH170. Challenges in adopting the best method involves access to the test site and location, geometry of the sections, availability of appropriate tools and materials and the safety of the building specially in earthquake effected zones and building structures. There is significantly greater variation in the Rockwell and Leeb readings for the unprepared surface and a slight difference in the average value. This highlights the need for surface preparation to achieve a roughness of Ra < 1.6 microns.

7. Monotonic test results

7.1. Tensile test results

This section presents tensile test results for 8mm and 12mm thick dog-bone specimens. For different strain demands, load against the displacement graphs were plotted and the hardness was measured before and after the tensile testing. Load-displacement diagrams for 8mm thick specimens S4-S19 are presented in Fig. 6(a). Specimen S1 was strained to failure in order to determine the overall force-displacement characteristics over the full plastic strain range. Specimens S2 and S3 were used as trial specimens. The target strains were set as 5%, 10%, 15%, and 20%, however, due to test setup flexibility, the strain achieved was slightly different. Other mechanical properties, i.e., yield strength, ultimate tensile strength, yielding and plastic deformation behaviour of all the specimens is same.



(a) 8mm thick dog-bone specimens S4 to S19

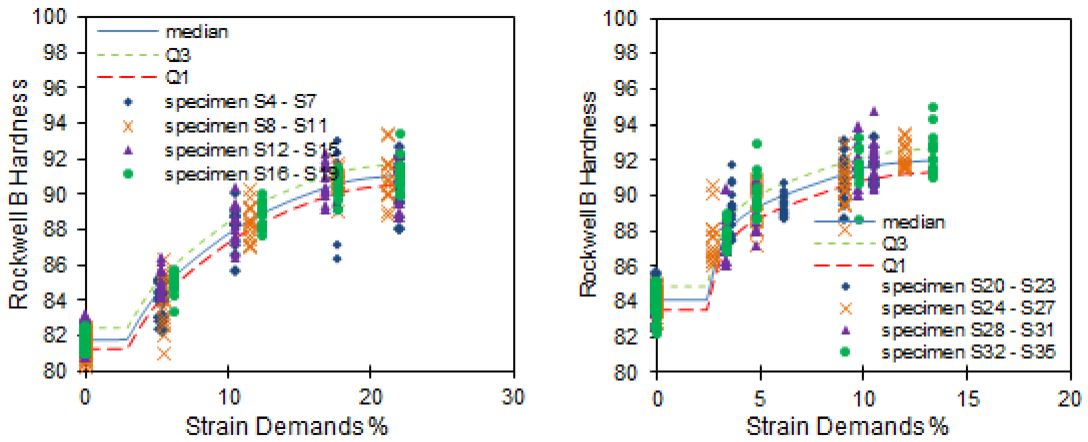
(b) 12mm thick dog-bone specimens S20 to S35

Fig. 6 Load-Displacement diagrams for 8mm and 12 mm thick dog-bone

Fig. 6(b) represents load-displacement graphs for 12 mm thick specimens S20 – S35. Targeted strains set for these specimens were 2.5%, 5%, 10% and 15%; achieved strains were slightly different. The maximum yield load obtained from the 12mm specimens was about 65kN, which is 15kN higher than the maximum yield load of 8mm thick specimens. Unlike the 8mm thick specimens, a small inconsistency was observed within a few 12 mm specimens. Hardness test results in Fig. 7 don't show any dramatic changes due to these minor inconsistencies in plastic behaviour.

7.2. Hardness test results

Measured hardness against plastic strain from the dog-bone specimens is presented in Fig. 7. Hardness measurements were undertaken with the Rockwell B bench top hardness tester, with the readings for different specimens being taken on different days. For the hardness tests, specimens were grouped from lowest to highest achieved strain levels as a set, and this was repeated for up to four sets. At zero strain, Rockwell hardness for 8mm thick specimens ranged from 79.6 to 83.2 and for 12 mm thick specimens ranged from 82.2 to 85.6. Hardness measurements up to the beginning of plastic strain were considered to be constant and it were plotted following the load-displacement diagram shape. At each strain level, 15 hardness readings were taken and recorded in four categories; average, minimum, maximum and median. Hardness gradually increased with increasing plastic strain in both the cases as shown in Fig. 7. It was observed, the majority of hardness values fall between the first and third quartile (Q1 and Q3), indicating that this relationship is within the acceptable limits. Based on monotonically strained specimen test results, the relationship between plastic strain and hardness can be determined and use to calculate residual plastic strain demand.



(a) Tensile-hardness relationship for 8mm thick specimens

(b) Tensile-hardness relationship for 12mm thick specimens

Fig. 7 Hardness - tensile relationship at various strain demands

Fig. 7 shows, curves meeting the zero strain hardness values at the plastic strain corresponding to the end of the yield plateau. This intersection point which is got from the force-displacement diagram in Fig. 6 are based on the fact that the material strength does not increase above yield in the yield plateau region, meaning that the hardness will not increase in that region either. For Grade 300 steel that extends out approximately 2.8% plastic strain

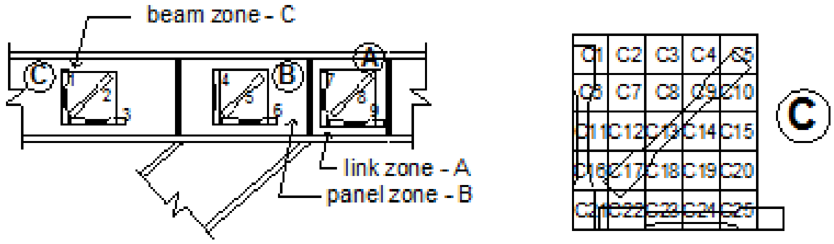
8. Cyclically deformed active link test results

8.1. Hardness test results

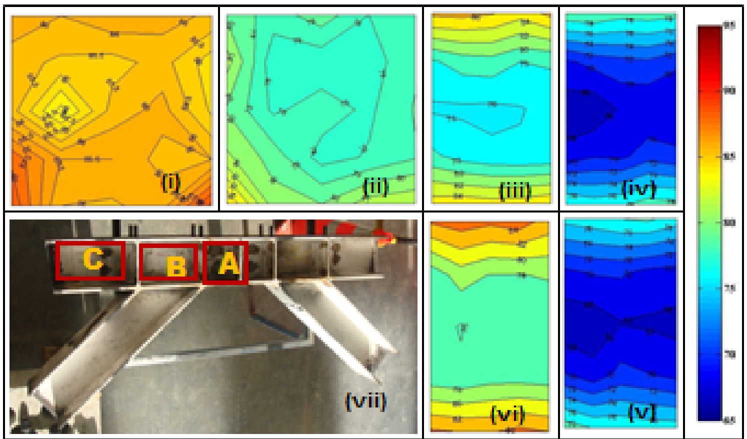
Hardness tests were conducted on EBF from the earthquake affected Pacific Tower, which was observed to be plastically deformed during earthquake events (Gardiner, Clifton, & MacRae, 21-22 February 2013). The test specimens were prepared and tested according to the details given in Section 3.2. The EBF was divided into three test zones; Active Link Zone (Zone-A), Panel Zone (Zone-B) and Beam Zone (Zone-C), see Fig. 8 (a), and the tests were conducted on the web section of each zone. Three tensile specimens were water jet cut from each zone for the tensile tests, and hardness was measured in a grid pattern of 25 test locations as designated in Fig. 8 (b) with a minimum of 6 readings being taken at each grid location. Fig. 8 (c) shows hardness mapping over the three tested zones using the Rockwell B hardness machine and Rockwell B hardness using the portable hardness tester TH170. Hardness mapping was done using MATLAB (MathWorks, 2011) to map the variation in hardness over the three tested zones. Fig. 8 (c) illustrates that the hardness distribution is different for each of the three tested zones. Zone-A exhibits higher hardness readings than Zone-B and Zone-C, indicating more plastic deformation has occurred in Zone-A. Hardness within the same zone by the two testing machines is also noticeably different, with the

Leeb TH170 consistently showing lower hardness results as compared to the bench top Rockwell tester. However, both the instruments clearly picked up changes in hardness and displayed the same trends between the test zones.

They also showed clear evidence of pre-earthquake plastic strains, in the top and bottom 1/4^{t} quadrants of the web, as evidenced by the hardness readings in the panel zones B and C, where little if any plastic strain was noted, being higher than the centre of the web, and similar results were found by the current authors in other studies of new beams (Nashid et al., 2013).



(a) Hardness test grid and tensile specimen locations (b) Hardness test grid details



(i) Zone-A Rockwell B hardness survey; (ii) Zone-A TH170 hardness survey; (iii) Zone-B Rockwell B hardness survey; (iv) Zone-B TH170 hardness survey; (v) Zone-C TH170 hardness survey; (vi) Zone-C Rockwell B hardness survey; (vii) Active link beam at level 05 on grid 01and test zones A,B and C

(c) Hardness mapping over the three tested zones using MATLAB filled contour plots

Fig. 8 Test details and comparison of the results over three test zones

Rockwell B hardness for both testers, as a function of normalized link depth is presented in Fig. 9 (a) to (f) and (g) represents a comparison of hardness over the three zones.

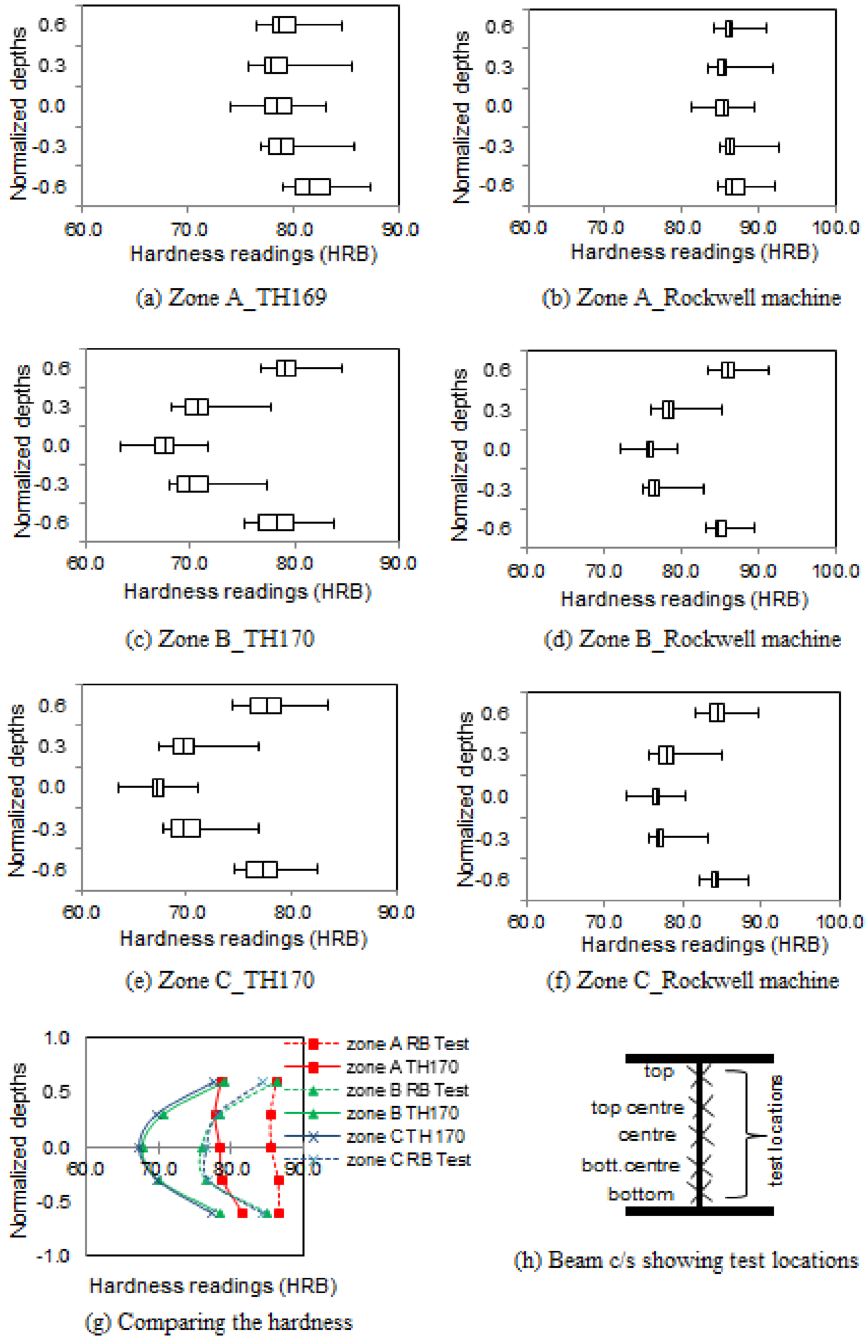


Fig. 9 Normalized link depth versus hardness in three zones of the active link

Accuracy of the hardness method can be predicted by comparing the proximity of the box plots. It is noted that the hardness measurements in these tests were carried out before adopting the proper surface preparation technique discussed in Section 3.2 and 6.1. These normalized link depths clearly demonstrate the difference in hardness between the three test zones using the two test methods as shown in Fig. 9(g). Rockwell B machine values were between 10 to 8 points higher than the Leeb TH170 tester hardness values. The difference in hardness between these two methods could be due to the geometry of the section and the mass effect of the test specimen. Both machines clearly show that Zone-A achieved the highest hardness values for both the methods. Constant high hardness values through the depth of the web in Zone-A indicates that the web of the active link had undergone appreciable in-plane plastic deformation during the earthquake, while the panel and beam zones, B & C, had much lower levels of plastic strain at the midpoints of the webs.

It was observed that the panel and beam zone plastic strain distribution could not be explained by the earthquake actions, hence further studies were required to confirm the initial results and an alternative solution had to be found. Visual inspection of the hot rolled yielded active link in Fig. 10 showed the earthquake induced yielding was concentrated in a band in the middle of the web and either did not extend to the root radius at the web top and bottom or was appreciably less in the top and bottom quadrants. In addition, the paint flecking started approximately at the centre of the web and stopped close to the k-region of the section where the manufacturing plastic strain was measured. This interesting phenomenon was identified during this investigation and is reported by Nashid et. al. (Nashid et al., 2013) and a similar investigation carried out by Tide in 2000 (Tide, 2000).

Fig. 10 Active link beam from Club Tower, Christchurch which has undergone

Further investigation was carried out on active links at different floor levels in Pacific Tower to compare the laboratory test results with onsite test results. Fig. 11(a) to (f) represents the Rockwell B hardness measured at different levels and plotted against the normalized depth of the sections, and the box plots from (a) to (e) indicate the accuracy of the readings. High hardness close to the flanges was observed at all the locations and hardness drops at the centre of the active beams, similar to the laboratory test results. The measured Rockwell B hardness at level 22 was less than that for the other floors. It was observed that two different active links on different grids at the same level were showing different hardness results, because the earthquake demands on the building were different in the two principal axes of the building. The hardness of these beams was previously measured by Holmes Solutions Ltd (HSL) and reported by Gardiner et. al. in 2013 (Gardiner et al., 21-22 February 2013) .The HSL hardness readings and visual observation of yielded links throughout the building were later analysed by the first author and showed inelastic demand in the active links was greatest around levels 5 and 6 and negligible above level 16.

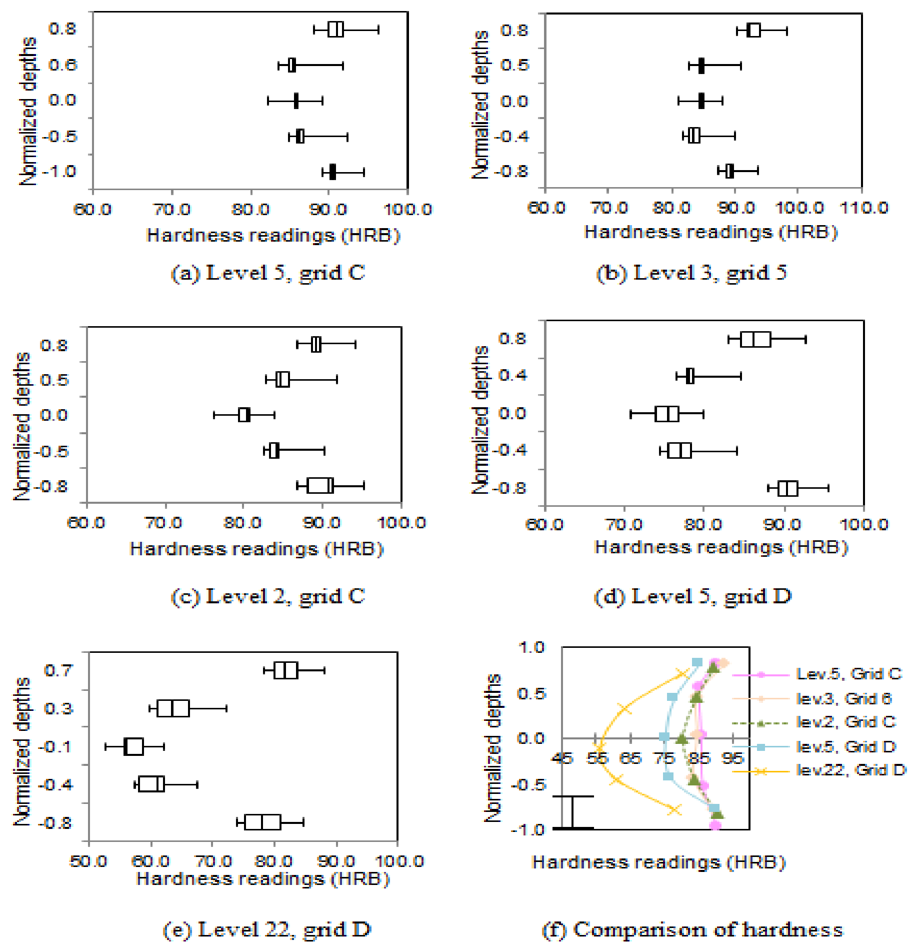


Fig. 11 Hardness versus normalized link depths at different levels at Pacific

9. Tensile test results

Standard dog-bones were cut from the cyclically deformed active link beam from level 3 of Pacific Tower, to carry out tensile tests. Specimens S1, S2 and S3 were extracted from the beam zone (Zone-C), Specimens S4, S5 and S6 from the panel zone (Zone-B) and Specimens S7, S8 and S9 from the active link zone (Zone-A) as shown in Fig. 8(a) and (b). The orientation of the specimens was arranged to investigate the plastic deformation in three positions of the web. The stress-strain curves for the 9 specimens from the three zones of the active link beam are presented in Fig. 12.

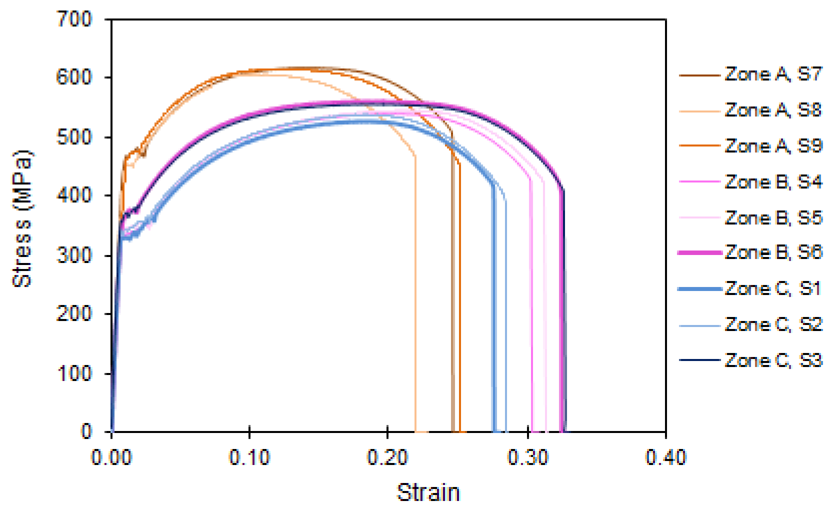


Fig. 12 Stress strain diagrams for three zones of the active link from level 03 on

This shows that all specimens from Zone - A (S7, S8 & S9) have essentially the same shaped curves and yield stresses, which is consistent with the visually observed significant plastic deformation from the earthquake and matches the hardness profile showing similar hardness values across Zone-A. For zones B & C, tests S1, S4, S2 & S5, have similar shaped yield curves and yield stresses, which is to be expected, as the centres of these specimens are in the centre of the web, which for these zones have not yielded. Tests S3 & S6 are near the flange have the same shaped stress-strain curve, but the flow stress has increased over that for tests S1, S4, S2 & S5, showing there has been pre-earthquake plastic deformation in the region of the web near the flange and confirming the hardness results in the Fig. 9. The stress-strain diagram shows that the active link Zone-A has undergone approximately 7-7.5% plastic strain, compared with up to 4% plastic strain in the top and bottom of the webs in Zone-C. The plastic strain in Zone-A is a combination of pre-earthquake strain, termed manufacturing strain, in the top and bottom sections of the webs, and earthquake induced strain across the whole web depth. The results show that the as-received EBF has been plastically deformed due to pre-earthquake straining in the web near the flanges to about 4% prior to the earthquake and this is termed manufacturing plastic strain. This plastic strain is believed to arise from roll straightening at temperatures below 100ºC (Tide, 2000), when the web is held vertical as the flanges are cold bent to within tolerances. Based on these results, it is recommended that the hardness is measured in the centre of the web, where there is no significant influence of manufacturing strain, to check for increase in plastic deformation following an earthquake. Similarly, dog-bone tensile specimens have to be taken in the centre of the web, parallel to the flanges if there is a necessity for tensile testing.

10. Conclusion

This paper presented a non-destructive hardness testing method for determining the plastic strain of steel elements subjected to seismic loading. Dog-bone specimens with 8mm and 12mm thickness were tested monotonically from 2.5% to 20% strain, followed by hardness measurement. An appropriate level of surface preparation method to measure the hardness was established. Hardness and tensile tests were conducted on EBFs from the earthquake affected Pacific Tower in Christchurch, New Zealand and which were observed to be plastically deformed during the 22nd February 2011 earthquake event, one of 8 damaging events in the 2010/2011 earthquake series. Assessment of this experimental work is summarised in the following points:

- Monotonic plastic tensile strained steel shows a good correlation between hardness and the amount of strain demand and the results give strong evidence that this method can measure the plastic strain of cyclically deformed active links.
- Monotonic test results show that, majority of the hardness values fall within the first and third quartile (Q1 and Q3), which indicates that the relationship between hardness and monotonically strained steel is within the acceptable limits.
- The methods and techniques of surface preparation greatly affect the hardness test results for both the hardness testing methods. Hence it is recommended that a proper surface preparation technique or method, especially for the portable hardness tester TH170, be adopted.
- Hardness testing has to be undertaken in the centre of the web, where there is no influence of manufacturing strain, and similarly tensile specimens have to be taken in the centre of the web, parallel to the flanges.
- The hardness number found from the Rockwell method was 8 to 10 points higher than that from the portable hardness tester TH170. The difference near the flanges was less than at the centre of the webs.
- Plastic strain caused by manufacturing was found in the top and bottom quadrants of the web and was detected by both the instruments.
- The active link zone (Zone-A in Figure 15) had undergone significant plastic deformation compared to panel zone (Zone-B) and beam zone (zone-C), and no measurable earthquake induced plastic strain was detected in these two regions. This complies with the expected role of each region of an EBF.
- The stress-strain diagrams clearly show the link zone achieved higher stress with reduced elongation compared to the other zones, indicating the middle of the link zone has undergone plastic strains of up to 7.5%.
- Residual, manufacturing plastic strain was approximately 4%.
- The pattern of onsite test results is similar to that of the laboratory test results. Hardness is highest near the flanges and lowest in the centre of the web. Geometry and mass effects of the EBFs were identified.
- Limited experimental test results were available to confirm the relationship between hardness and plastic strain, for adoption of on-site hardness testing methods using portable hardness testers for estimating the inelastic demand.

The completed testing shows clear evidence that this method can predict the residual plastic strain of cyclically deformed active links. The key differences between this experimental study and on-going investigations by different investigators are: A comprehensive guideline to asses active link repair and replacement can be established based on the relationship between hardness and plastic strain; identifying the degree of surface preparation effects on hardness and the level of strains; establishing the relationship between cyclically deformed specimens in the laboratory and the field; identifying the strain distribution behaviour and the location of peak strains; and identifying the hardness relationship between post-strained and strain-aged specimens.

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