Non-destructive method to investigate the hardness - plastic strain relationship in cyclically deformed structural steel elements

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ABSTRACT: A non-destructive hardness testing method is being developed to determine plastic strain in steel elements that have been subjected to inelastic 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, 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: 1) what was the extent of plastic deformation; and 2) what effect does that have on post-earthquake steel properties? To answer these questions a range of actions are being taken. A non-destructive hardness test method is being developed 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 has been hardness and material property tested to determine the changes in the steel, and cyclic testing of active links to defined levels of inelastic demand is underway. Test results to date show clear evidence that the hardness based method is able to give a good relationship between hardness measurements and plastic strain. This paper presents recent significant findings from this project. Principal of these is the discovery that hot rolled steel tested beams, all carry manufacturing induced plastic strains, in regions of the webs, of up to 5%. It is the intention of the overall research project, to establish a robust relationship between measured hardness and plastic strain demand in cyclically deformed steel elements and a comprehensive guideline to assess commonly used seismic-resisting systems will be adopted.

1 INTRODUCTION

During the Christchurch earthquake series of 2010/2011, and in particular the intense earthquake of 22 February 2011, horizontal peak ground accelerations in the CBD were recorded in the range of 0.5g to over 0.8g and peak vertical accelerations were over 1.0g were also measured (Clifton et al., 2012). These accelerations were sufficient to push the active links of the widely used earthquake resisting frame system, the Eccentrically Braced Frame (EBF), into the inelastic range. The buildings all are effectively self-centered, meaning that demolition was not required. Inelastic demand was concentrated into the active links of these frames as intended with the design requirements of the Steel Structures Standard (NZS3404 1997/2001/2007) and steel seismic design procedures (Feeney & Clifton, 2001). This raised the urgent question as to, whether the extent of inelastic demand was sufficient to require replacement of the active links and how to determine this in a non-destructive manner. There are no established criteria either nationally or internationally that provide guidance for checking when the threshold has been reached (or what an acceptable threshold is), or that indicate the remaining life ex-

pectancy and the replacement procedure for damaged active links in the EBFs.

Hardness as a non-destructive method to measure the plastic deformation of metals has been used since early 1900s. During the early development stages of this method, utilising machines that measure hardness by indenting the material to depths of over 1mm, it was realized that this could not be considered as a non-destructive testing method due to the large indentation impressions left on the test surfaces. It was also not practicable for field use due to the size and weight of the testing equipment. Developments of portable hardness testers based on elastic rebound have addressed the portability issues. Hugh O'Neill (O'Neil, 1934) addressed the unrecovered indentation problems after a detailed study of Brinell's Indentation Hardness Testing Method. A wealth of literature is now available concerning the relationship between hardness and monotonic plastic deformation of metallic materials (Pavlina & Van Tyne, 2008). However, the relationship between hardness and plastic deformation of cyclically deformed metals is not available. In the present study, a non-destructive Leeb (portable) hardness tester (model TH170) has been used to measure the hardness in order to determine the plastic strain in the webs of active links and dog-bone tensile specimens, from hot rolled steel universal sections and steel plates.

2 HARDNESS TECHNIQUE

The Leeb test measures the hardness of the material dynamically by elastically impacting a small spherical indenter onto the test surface; the impact and rebounding velocity of the indenter with the test material is measured by the device and converted into a hardness measurement. The TH170 is being widely used because of its speed, light weight, portability, and most importantly its independence from reticulated power or air supply. These properties are essential for use inside an earthquake damaged building. However, the TH170 is prone to inaccurate readings if the test piece is not prepared adequately, with the requirements for the surface preparation and minimum weight of the test piece being specified in the ASTM Standard (ASTM: A956-06, 2011) and instruction manual (Beijing TIME High Technology Ltd, 2007). A minimum test piece weight of 5kg is recommended by the manufacturer. The readings are also very dependent on achieving a smooth surface 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. Specimens were prepared and hardness tests were carried out using the TH170 portable tester and a bench-top Rockwell hardness tester according to the ASTM Standards (ASTM: E18-11, 2012) for Rockwell hardness of metallic materials. The hardness technique presented in this section is based on testing of dog-bone specimens and active links as shown in Figure 1.
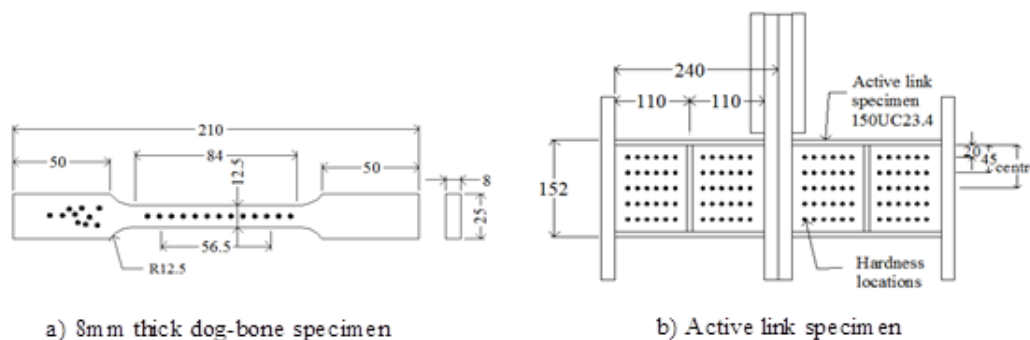

a) 8mm thick dog-bone specimen   b) Active link specimen

Figure 1. Hardness test specimens and locations

In determining the hardness and level of inelastic demand, dog-bone specimens prepared for tensile testing, to generate the monotonic stress-strain characteristics and for hardness testing, were water jet cut from 8mm and 12mm thick hot rolled steel plates. The universal column section 150UC23.4 was used to fabricate the active link specimens. The dog-bone specimen dimensions were determined from the tensile test requirements, given in Standards (AS1391, 2004), (NZS3404, Part 1:1997) and (ASTM: E8/E8M-09, 2009). The active link specimens were designed according to (NZS3404, Part 1:1997) Clause 12.11.1, HERA Report R4-76 (Heavy Engineering Research Association (HERA), 1995) page 11.1-28 and literature by (Popov & Engelhardt, 1988). Limitations on cyclic loading

capability and specimen size restricted the link section to a Grade 300 150UC23.4 section with the clear link length complying with the requirements of NZS 3404 Clause 12.11.1.2 to behave as a shear link. The specimen mass was well above the 5kg minimum weight required by the portable Leeb hardness tester TH170. Hardness was measured at two different locations on the dog-bone specimens and at five locations on the web of the active links, as shown in the diagram (a) and (b) Figure 1.

3 SURFACE ROUGHNESS EFFECTS

For accurate hardness test results, surface roughness has been identified as an important parameter during this study. Test specimens must meet specified criteria for surface roughness according to the American Society for Testing and Materials (ASTM: A956-06, 2011) for hardness determination of metallic materials by rebound based portable machines. Any paint, including undercoat and surface coat, pits and scale must be removed. The TH170 manual (Beijing TIME High Technology Ltd, 2007) states that the surface roughness (Ra) needs to be less than 1.6 micro-meter (μm). Surface preparation techniques used in this study and their comparisons are reported (Nashid et al., 2013).

Figure illustrates the difference in hardness readings between surfaces prepared to Ra = 0.6 microns and unprepared surfaces using the two different hardness methods. It was found that the TH170 does not read when the tested surface is covered with paint or mill scale. Based on these test results, the Powerfile with P120 belts followed by P180 hand sanding was adopted throughout this investigation. Rockwell B hardness (HRB) and Leeb hardness for a prepared surface with grit numbers up to P240 and an unprepared surface of cleaned and mill scale removed is presented in Figure 2. 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.
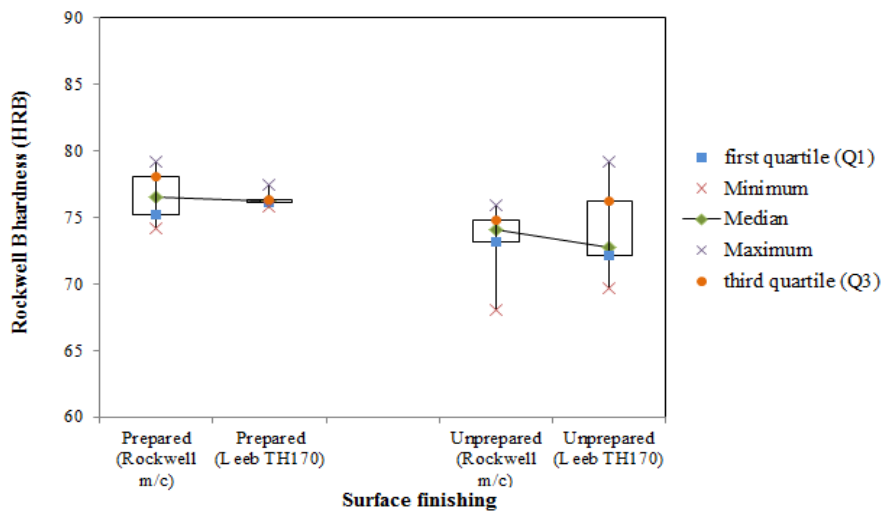

Figure 2. Comparison of hardness between surfaces prepared to Ra < 0.6 microns and unprepared surfaces using a Rockwell B machine and Leeb TH170 hardness tester on a 25mm thick specimen

4 HARDNESS AND PLASTIC STRAIN RELATIONSHIP

4.1 Monotonically strained dog-bone specimens

Uniaxial tensile testing was carried out on 8mm and 12mm thick specimens, followed by Rockwell hardness testing using a bench top Rockwell machine. Targeted plastic strains for tensile 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. Bench top Rockwell hardness was measured at each strain level using the scale B, R_B, with a 100 kgf and a 1.588 mm (1/16″) diameter ball indenter. Both surfaces of all the test specimens were prepared as explained in Section 3. Minimum edge distance was kept more than 2.5 times the indenter diameter and more than 3 times between two indentations according to (ASTM: E18-11, 2012). Measured hardness against plastic strain is presented in Figure 3

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. Prior to tensile testing, zero strain, Rockwell hardness for 8mm thick specimens ranged from 80 to 83 and for 12 mm thick specimens from 82 to 86. The hardness from zero strain to the commencement of plastic strain (i.e. across the yield plateau) was considered to be constant when plotting the hardness versus strain results. The strain corresponding to the end of the yield plateau was determined from the force-displacement diagram. The rationale for this is due to the material strength not increasing until the yield plateau region is exceeded, meaning that the hardness will not increase in that region either. For Grade 300 steel that extends out approximately 2.8% plastic strain. At each strain level, 15 hardness readings were taken and then average, minimum, maximum and median values determined. Hardness gradually increased with increasing plastic strain, in both cases, as shown in Figure 3.
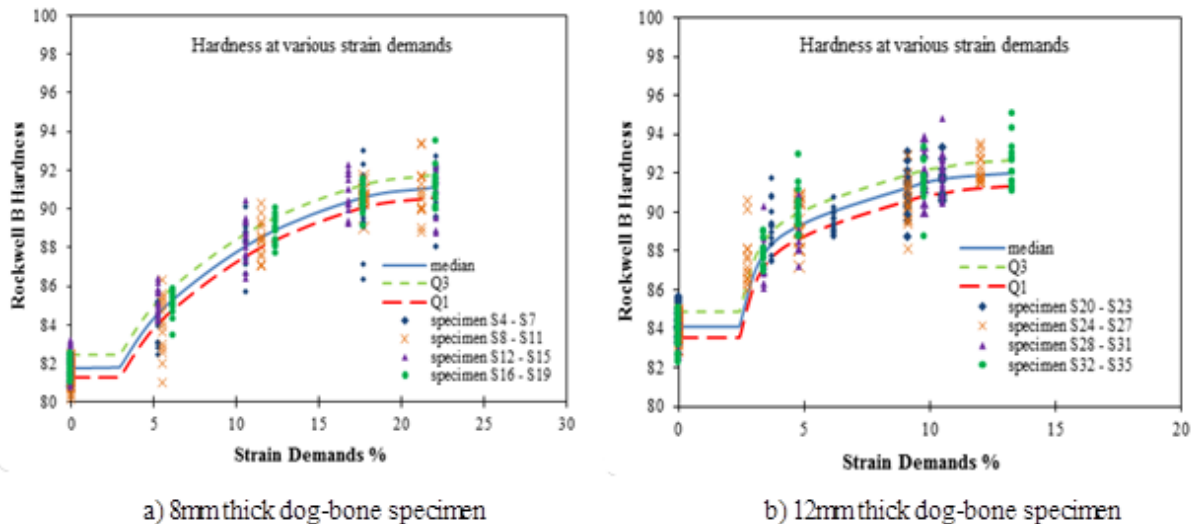

a) 8mm thick dog-bone specimen b) 12mm thick dog-bone specimen

Figure 3. Hardness - tensile relationship for 8 and 12mm dog-bone specimens at various strain demands

Figure 3 shows 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 monotonic plastic strain and hardness can be determined and use to calculate residual plastic strain demand from monotonic loading.

4.2 Cyclically strained active link specimens

A series of cyclic tests have been carried out to determine the link between hardness and cyclic plastic strain. An active shear link specimen as given in Figure 1(b) was designed and fabricated according to the design guidelines discussed in Section 2. Universal column section UC150UC23.4 was used instead of a universal beam section due to the lower shear capacity and greater flexural-torsional stability of the column sections resulting from their geometry compared with the beam sections. UC type sections are typically used in EBF systems in buildings for the same reasons. Figure 4 shows the active shear link setup for full scale cyclic testing.

A digital image correlation (DIC) technique developed at the Centre for Advanced Composite Materials (CACM), University of Auckland, was used to analyse plastic deformation behaviour within the webs of the active links. Portal gauges and strain gauges were used along with the DIC to measure the strain, to compare the accuracy of the DIC method. Initially three sets of identical active links were tested with target strains 3%, 7% and 15%, using dynamic cyclic loading with 5 cycles for each test. Hardness measurements were carried out at various steps of each loading. Active links were tested under a displacement controlled environment to maintain uniformly distribute strain across the webs. Figure 4 (a) and (b) show the specimen at maximum deformation; hardness measurement locations are given in (c) and photogrammetric unit while capturing images is shown in (d).

The designed active link beams show, excellent ductility and efficient energy dissipation capacity. For the 3% plastic strain and it's corresponding hardness, the specimen was pulled up to +8.3mm, then un-

loaded so that the specimen was plastically deformed but not loaded. Hardness was measured. Then the specimen was pushed down to -1.5mm and unloaded to return to approximately the zero displacement position. Hardness was measured again. This was repeated for the reversed loading to -8.3 and +1.5mm, giving 4 sets of hardness tests per cycle. Cyclic loading was repeated and hardness was measured for up to 5 cycles. For the 7% plastic strain, the specimen was pulled and pushed to ±16.3mm and ±1.5mm. For the 15% plastic strain, the deformations were ±32.3mm and ±1.5mm. While the cyclic testing and hardness measurements were being taken, photogrammetric images were being recorded simultaneously at the speed of 1image per second with the pixel density of 3840 x 2764.
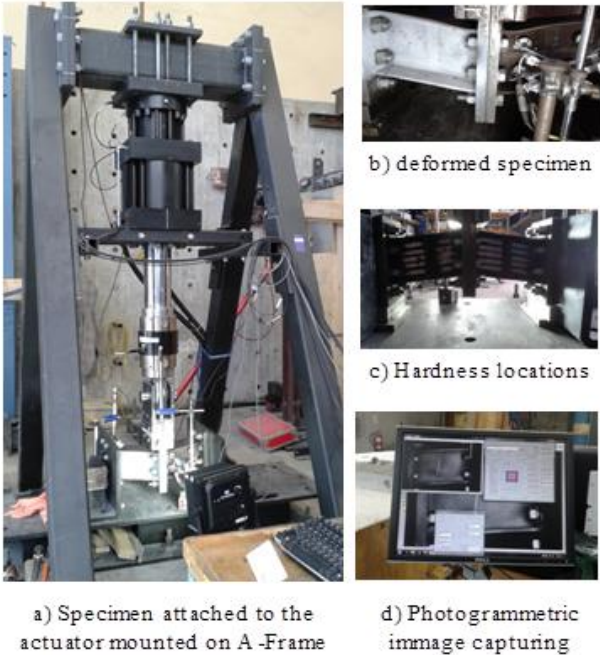

Figure 4. A full scale active link specimen under cyclic loading. Test Hall, University of Auckland

Figure 5 shows that the hardness increases with increasing plastic strain demand and the hardness between three selected strain levels is noticeably different. Hardness measurements presented in Figure are from the test locations give in Figure 1(b). At the centre of the web, the average hardness measured by TH170, before the test was 50. Average hardness value for the 3% plastic strain specimen was 61and for the 7% plastic strain specimen 67. Average hardness for 15% plastic strain was 71 and the 20% trial specimen exhibited 75.8.average hardness.
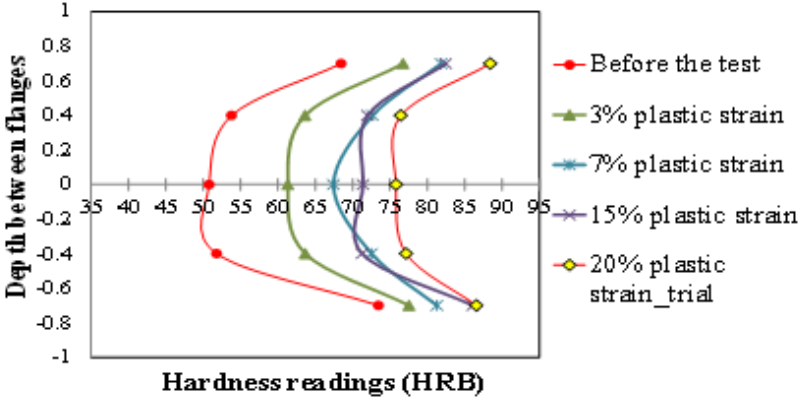

Figure 5. Comparison of average hardness from the five cycles of loading with different cyclic plastic strain levels at normalized link depths using TH170

Note: The depth between the flanges is the clear depth, so 1 represents the underside of the top flange and

-1 the top side of the bottom flange

Hardness at the centre of deformed links was plotted against the cycle number as shown in Figure 6. Upper and lower boundaries of hardness in each cycle were similar between the hardness values. Average hardness increased with increasing plastic strain demand, as observed from Figure 5. At no strain (zero cycle number), hardness range is between 45 to 55. Hardness gradually increases up to the second cycle with no significant increase for subsequent cycles. However, the 15% specimen achieved very little increment in hardness in the second cycle. Neither material softening nor hardening was evident in this study for up to five cycles, for cycles of constant plastic strain. In the future and final stage of this project, active link specimens will be tested under variable cyclic plastic loading to determine the effects of the loading regime on the measured hardness.
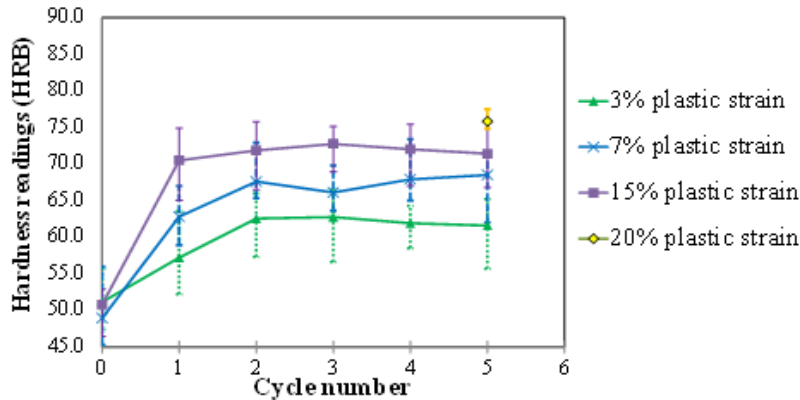

Figure 6. Hardness comparison at the centre of the link versus cyclic number for different strain levels

The hardness results with cyclic loading also showed clear evidence of "pre-earthquake" plastic strains, (i.e. strain prior to any induced deformation) in the top and bottom quadrants of the web, while in the centre of the web, there was no prior plastic strain measured. This is consistent with earlier results (Nashid et al., 2013). These pre-earthquake plastic strains were an initial surprise as it is typically considered that hot rolled sections have zero residual plastic strain but have a complex residual stress distribution within the elastic ranges. This result means that hardness readings on yielded active links must be taken in the centre 1/3 region of the web, so as to capture only the influence of earthquake induced yielding.

Visual inspection of yielded hot rolled active links from Christchurch buildings show 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 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 reported by (Nashid, Ferguson, Clifton, Hodgson, Seal, MacRae, & Choi, 2013). A similar investigation was carried out by Tide (Tide, 2000), Okazaki (Okazaki, 2004) and G.Forceir which was reported by Hajjar et.al and Leon et al. (Hajjar, Leon, Gustafson, & Shield, 1998; Leon, Hajjar, & Gustafson, 1998).

5 PHOTOGRAMMETRY TO INVESTIGATE THE PLASTIC STRAIN DEMAND

The plastic surface strain distribution across the web of active link specimens was analysed using a digital image correlation (DIC) technique incorporated with photogrammetry. The program TRIDENT V3.0, developed by Centre for Advanced Composite Material (CACM) at the University of Auckland, was used in this study. DIC systems have been used by CACM, to investigate plastic strain field of polymer composite materials for approximately 10 years but has not been extended to include monitoring the influence of cyclic inelastic surface strain development in metals. Hence, a trial test was carried out monotonically using two dog-bone specimens extracted from a section as the active links. The strain measured using DIC was compared with extensometer strain to identify the accuracy of DIC method before using it in cyclically deformed active links. Trial test results from both the methods strongly agreed to each other. Hence the DIC technique was adopted to ensure the level of

strain in the active links. Three sets of active links as shown in Figure 1(b) were used to monitor the plastic strain behaviour using DIC system. The test surface of specimens was prepared with a randomly speckled surface pattern of two layers of sprayed paints. Black graphite sprayed on a silver background to ensure the paint uniformly covered the test surface with spaced black speckles.
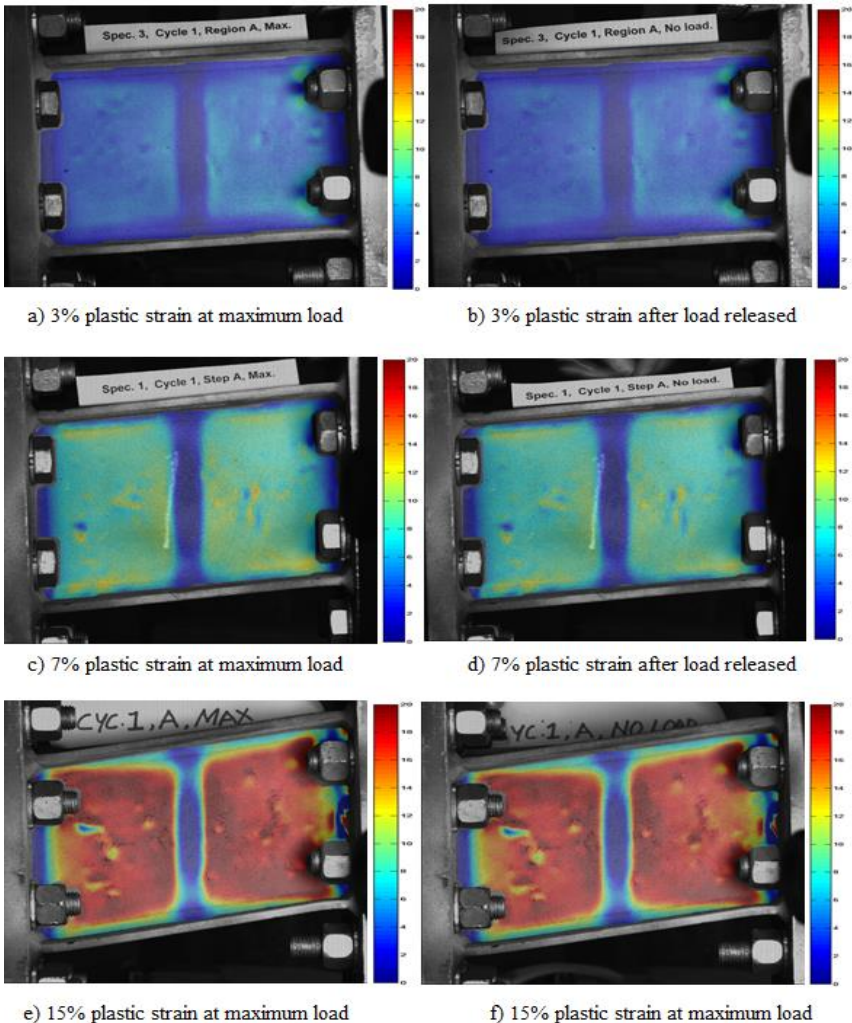

a) 3% plastic strain at maximum load

b) 3% plastic strain after load released

c) 7% plastic strain at maximum load

d) 7% plastic strain after load released

e) 15% plastic strain at maximum load

f) 15% plastic strain at maximum load

Figure 7. Strain contour plots across the web of the active link specimens using DIC by CACM at the University of Auckland

Premature paint flecking as shown in Figure 7 occurred throughout. As a result, the system records the baseline strain approximately 2% higher than the overall strain across the web; as recorded according to the colour scale bar. When the average strain across the web was checked by TRIDENT V3.0 the DIC strains match acceptably the level of plastic strain induced by the deformation controlled loading. Figure 7 (a) represents contour plots where the specimen was fully loaded to 3% strain and (b) is the specimen when the load was released. The influence of the stiffener on the opposite side of the web is clearly picked up by the contour plots. Slight differences in contour plots have been observed between (a) and (b), however strain demand was slightly higher close to the flanges and around the welds as seen from the hardness comparison for 3% plastic strain in Figure 6. Figure 7 (c) and (d) show 7% strain contours when the specimen was loaded and released. Higher contour values are observed than (a) and (b) and they higher close to the flanges and around the welds. An increase in hardness close to the flanges for 7% plastic strain is also significant. In Figure 7 (e) are 15% plastic strain contours when the specimen was at maximum load and (f) when the load was removed. Significant change in contour plots are observed and non-uniform contours due to flecking of paint is noticeable. Plastic strain close to the flanges and around the welds is noticeably increased. High plastic strain near the flanges due to manufacturing induced plastic strain (Nashid et al., 2013) was clearly picked up by both

hardness technique and DIC system. However, interestingly the DIC system showed that the cyclic induced plastic strain develops near simultaneously over the full depth of the web, even though the top and bottom quadrants that have the pre-existing manufacturing induced plastic strain. This is as expected given that the test is displacement controlled.

6 CONCLUSIONS

This paper presents key results from a research project with the objective to develop a non-destructive hardness method for determining the plastic strain of steel elements subjected to seismic loading. Dog-bone specimens, with 8 mm and 12 mm 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 measured from cyclically deformed active links with various strain demands were monitored using a DIC system. Assessment of this experimental work is summarised in the following points:

1. Monotonic plastic tensile strained specimens show a good correlation between hardness and the amount of strain demand, which gives strong evidence that this method can be used to measure the plastic strain of cyclically deformed active links.

2. Monotonic test results show that, a majority of the hardness values fall within the first and third quartile (Q1 and Q3) indicating that the relationship between hardness and monotonically strained steel is within the acceptable limits.

3. The methods and techniques of surface preparation greatly affect the hardness test results for both hardness testing methods.

4. 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.

5. Plastic strain caused by manufacturing was found in the top and bottom quadrants of the web and was detected by both the methods. Hardness is highest near the flanges and lowest in the centre of the web.

6. Energy dissipation capacity of the active links increased with increasing plastic deformation which increased hardness gradually from 50 to 75 points. However the increase in hardness becomes less with increasing plastic strain.

7. Neither material softening nor hardening was significant in this study involving 5 cycles of constant plastic strain.

8. Hardness test results from plastically strained active link specimens shows a good correlation with strain contour plots from the digital image correlation (DIC) system incorporated in the TRIDENT V3.0.

7 ACKNOWLEDGEMENTS

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