Investigate the relationship between hardness and plastic strain in cyclically deformed structural elements

H. Nashid, W.G. Ferguson, G.C. Clifton, M. Hodgson & C. Seal

The University of Auckland, New Zealand.

G.A. MacRae

University of Canterbury, New Zealand.

2013 NZSEE Conference

ABSTRACT: This paper presents progress on a non-destructive hardness testing method being developed in order to quantify the plastic strain generated in steel elements that have been cyclically deformed by one or more earthquakes. It focuses 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 worldwide to push complete EBF systems into their inelastic state, generating a moderate to high extent of plastic deformation in the EBF active links of a range of buildings from 3 to 23 storeys in height. This raised the very important questions as to what was the extent of plastic deformation and what effect does that have on the post-earthquake steel properties? To determine the magnitude of plastic strain, a non-destructive hardness test method is being used to develop a relationship between hardness and plastic strain in active link beams. For the purpose of this investigation, active link beams at different levels from the earthquake effected, 23-storey Pacific Tower, Christchurch are being analysed. Test results to date show clear evidence that this method is able to give a good relationship between plastic strain and hardness in structural steel elements. The results have also showed that hot rolled steel beams carry a manufacturing induced plastic strain in the webs of up to 5%.

1 INTRODUCTION

The Christchurch earthquake series of 2010/2011, in particular the intense earthquake of 22 February 2011, pushed Eccentrically Braced Steel Frames (EBFs) into the inelastic range. Inelastic demand was concentrated into the active links of these frames, consistent with the design requirements of the Steel Structures Standard (NZS3404 1997/2001/2007) and steel seismic design procedures (Feeney and Clifton 2001). The active link is designed and detailed to deform inelastically in shear, protecting the other parts of the EBF system from damage. In the active links that have yielded, this raises a question about their ability to perform well during another earthquake.

A non-destructive hardness test method is being used to identify the extent of plastic strain in the webs of these active links, which comprise hot rolled universal sections. In determining the level of plastic strain, a portable Leeb hardness tester series TH170 was used to measures the hardness of the materials dynamically. Since this is a portable instrument it is very convenient and easy to use in the laboratory as well as on testing sites. A bench top Rockwell hardness testing machine was used to check the accuracy and reliability of TH170 used on site to measures the hardness. The development of this process is currently underway and this paper gives an overview of progress to the end of 2012. It also highlights and important and unexpected finding from the research to date, which is that the webs of roller straightened hot rolled sections have high levels of manufacturing induced plastic strain in the top and bottom quadrants. A brief background to the development of the EBFs and studies on residual stresses is given, followed by details of the testing procedure used and key findings. The issue of manufacturing induced plastic strains in the webs is then covered followed by the conclusions from this work as of the end of 2012.

2 ECCENTRICALLY BRACED FRAMES AND RESIDUAL STRAINS

2.1 Eccentrically braced frames

The Eccentrically Braced Frame is a seismic resisting system that comprises a braced frame in which the braces meet the beams eccentrically, resulting in a region of beam that is subject to high shear force under lateral loading. A detailed description and design procedure for them is given in (Feeney and Clifton 2001) and the key design concept and detailing requirements are given in Clause 12.11 of NZS 3404 (NZS3404 1997/2001/2007). Figure 2.1 demonstrates the most commonly used seismic resisting system in multi-storey steel framed buildings in New Zealand. Out of these, EBFs are the most widely used due to their combination of high stiffness, good ductility capacity and stable inelastic behaviour.

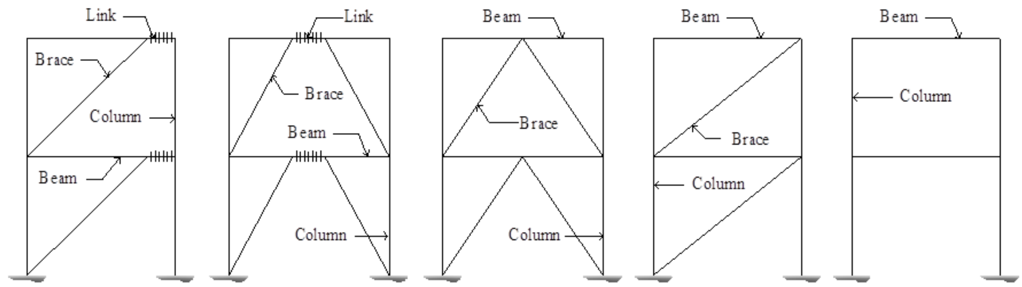

Figure 2.1 Different types of earthquake resisting steel frame systems

Roeder and Popov (1997), Wakabayashi (1970) and Wakabayashi et al (1970 and 1974) studied the cyclic behaviour of braced frames by conducting several tests. Wakabayashi et al (1972); Igarashi and Inoue et al. (1972 and 1973); Fujimoto et al (1973); Nonaka (1973) and Higginbotham (1973) carried out analytical and experimental investigations to study the cyclic behaviour of individual bracing elements. 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 several of the EBF buildings in Christchurch.

2.2 Residual strain

Residual strain can be measured using different methods, most important is the accuracy of the test results in determining the role of the structural steel sections especially in seismic regions. Residual strain distributions in structural beams have been an active study. Papp and Szalai (2005) reported that an accurate residual strain measurement was difficult and complex due to several factors. As a result, chances of accumulation of errors are common and this leads to great uncertainty. Thermal stress distributions generated through the cooling process are the most commonly considered. Yoshida (1984) conducted an experimental investigation using thermo-couples attached before the section was heated up to between 985°C to 1025°C, then the temperature was recorded during the air-cooling process. To the authors' knowledge, non-destructive hardness test methods have never been reported to check the amount of manufacturing plastic strain of structural steel sections. However, destructive methods have been used by several researchers to investigate the residual plastic strain developed due to manufacturing process of the UB and UC sections (Chi and Uang, 2004; Tide, 2000; Kaufman and Fisher, 2001; Masui and Okaza, 1989).

3 EXPERIMENTAL PROCEDURE

3.1 Test details

For the purpose of this investigation, an active link from a building affected by the Christchurch earthquake series was tested and then compared with test results of an identical steel section tested in the laboratory. Hardness and tensile tests were carried out on EBFs of 1800mm length x 200mm width and 213mm deep, 305mm wide x 280mm deep, 250mm wide x 230mm deep, 200mm wide x 180mm deep and 310mm wide x 280 deep sections at different levels of the building. The details of these sections and test locations are given in Figure 3.1.

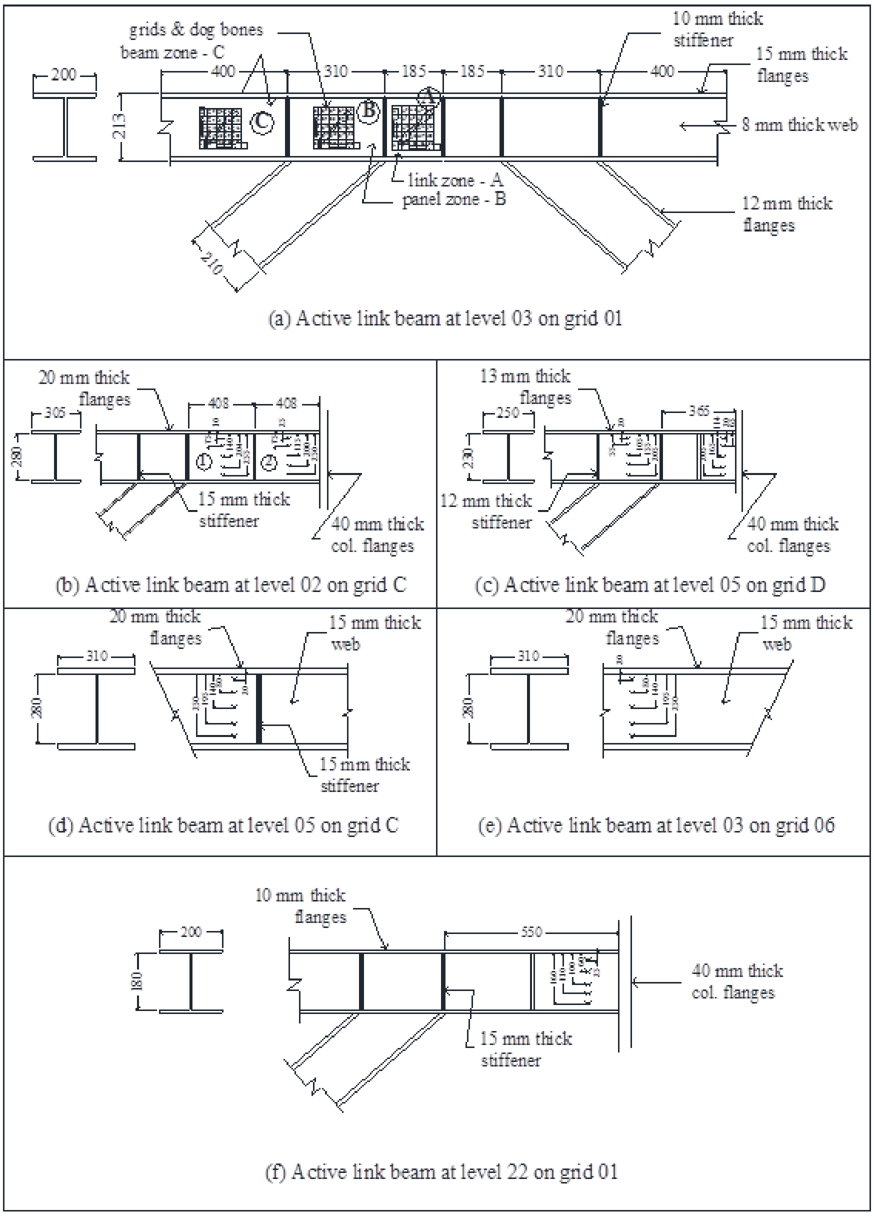

Figure 3.1 Hardness and tensile test locations, grid details with dog-bone specimen's layout

Test results obtained from these links were compared with a 1000mm long x 152mm wide and 152mm deep section. The active link in Figure 3.1 (a) was tested in the Test Hall, University of Auckland. 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 carryout hardness survey using both the portable hardness tester TH170 and Rockwell hardness machine. Dog-bone specimens were extracted from all three zones for tensile testing. The rest of the links were tested onsite. Active links onsite were tested only using the portable Leeb hardness tester TH170.

3.2 **Surface roughness tests**

A portable Leeb hardness tester series TH170 was used in these experimental studies, as it is important that the machine used to determine hardness of earthquake damaged buildings is robust, lightweight, portable and not dependent on reticulated power or air supply. The rebound hardness TH170 tester meets all these criteria. However, this machine is prone to inaccurate readings due to the effects of surface preparation. Therefore, for an accurate hardness test result, proper surface preparation was identified as an important parameter during this study. Test specimens must be clean enough according to ASTM E18-08b for Rockwell hardness of metallic materials. Oxide scale or mill scale and other foreign matter can lead to inaccurate readings in this tester. Any paint, including undercoat and surface coat, pits and scale must be removed. Test surface roughness (R_a) is usually less than 1.6 micron meter (µm) when using TH170 testers (parameters in the Instruction Manual TH170) for accurate hardness rest results. Three methods were used to carry out this 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.

3.3 **Hardness and tensile tests**

The portable Leeb hardness tester series TH170 measures the hardness of the materials dynamically by impacting a spherically shaped indenter onto the test surface. The TH170 is being widely used to measure hardness due to its speed, accuracy and user friendly operational features. The minimum weight of the test piece and surface roughness both contribute to the accuracy of the hardness values of the test specimen. A minimum test piece weight of about 5kg and a surface roughness less than or equal to 1.6 microns was found to be necessary for accurate test results.

A material Testing System (MTS)-810 series electro-mechanical testing machine was used to test extracted tensile test “dog-bone” specimens from three zones of the active links. The MTS testing systems used in these tensile tests are equipped with full real-time digital controls including computerised step-less mode and control channel switching. It is capable of loading the test specimens up to ±500kN. This experimental study focused only uniaxial behavior of the test specimens. The testing of active link webs subject to cyclic shear deformation is the next stage of this study, with testing underway in early 2013.

4 **TEST RESULTS**

4.1 **Surface roughness test results**

Prepared surfaces were measured for their roughness using surfaces roughness tester Surtronic 3. The test results were than compared to identify the best cleaning method to achieve the best surface roughness for the portable hardness tester TH170. The results from the surface roughness tester are shown in Figure 4.1. Challenges in adopting a proper method involves the access of 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.

Surface roughness in microns (µm) plotted against different grit (P) using three methods explained in section 3.2 presented in Figure 4.1. The surface roughness and grit numbers are inversely proportional to each other. Lesser the grit number (P60) lead to higher the surface roughness (Ra = 1.27µm), P240 was the most fine surface achieved in this study. Dremel wheel P60 followed by hand sanding with all the grits from 60 to 240 was used and Dremel wheel 120 followed by hand sanding was done only from grits 120 to 240. 3M flap wheel followed by hand sanding was done from grit numbers 80 to 240. Like Dremel wheel P120, sanding belt 120 was used in the Powerfile followed by different hand sanding up to P240. Even though the different sanding belts were available for Powerfile, they were not used in this study to maintain the consistency with the other two test methods. Rough belts (P60 and P80) were used for initial cleaning of heavily painted and mill scaled test surfaces. Figure 4.1 demonstrates that the Powerfile with different hand sanding achieved the best surface finishes compared to the other two cleaning methods and hand sanding beyond grit 180 shows little effect in all three methods. The sanding belt used in Powerfile gets worn after every cleaning this may be one of the reasons that the Powerfile achieved better test results. Based on these test results, the Powerfile with P120 belts followed by P180 hand was adopted throughout this investigation.

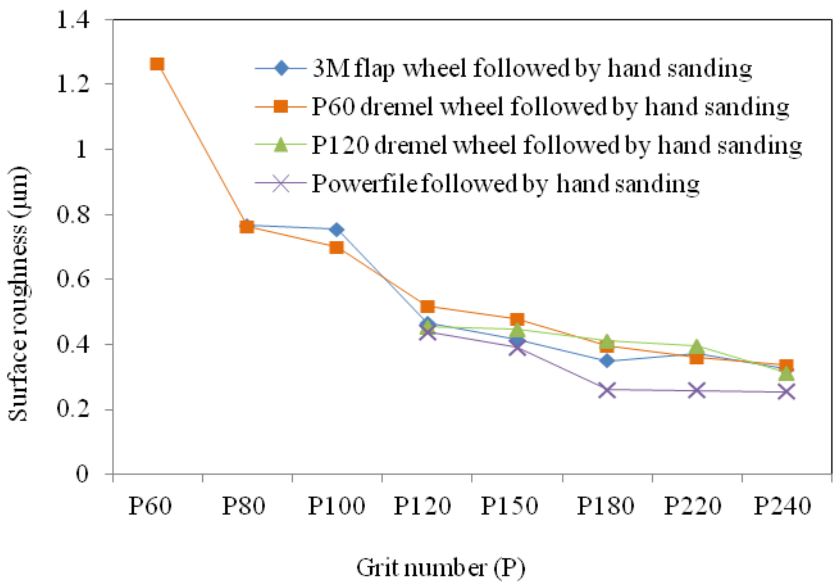

Figure 4.1: Comparison of surface roughness with different surface cleaning methods

4.2 Hardness and tensile test results

The hardness and tensile test results presented in this section are based on the active link components shown in Figure 3.1. In determining the relationship between hardness and the level of inelastic demand, the active link beam in Figure 3.1(a) was tested for both the hardness and the tensile test. Figure 4.2 shows the hardness mapping over the three tested zones using Rockwell B hardness machine (bench top) and Rockwell B hardness using the portable hardness tester TH170. Hardness mapping was done using MATLAB filled contour plots to identify the intensity of the hardness over the tested zones.

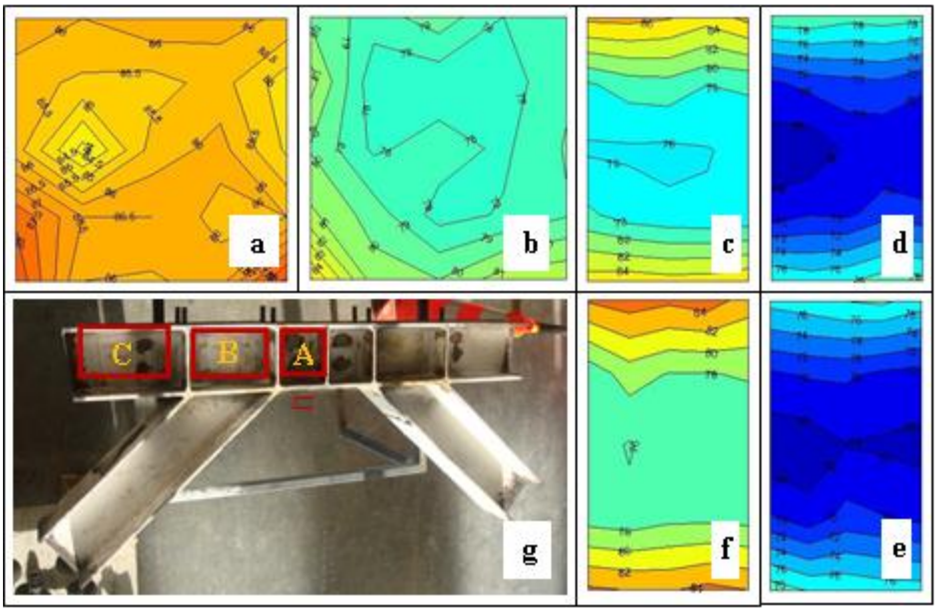

Figure 4.2 (a) Zone A Rockwell B hardness survey; (b) Zone A TH170 hardness survey; (c) Zone B Rockwell B hardness survey; (d) Zone B TH170 hardness survey; (e) Zone C TH170 hardness survey; (f) Zone C Rockwell B hardness survey; (g) Active link beam at level 05 on grid 01and test zones

One of the significant findings of this testing is the difference in hardness over the three zones. Zone A exhibits higher hardness readings than zone B and zone C, indicating more deformation occurred in zone A. Hardness in the same zone between two methods is also noticeably different, being lower with the TH170 compared to Rockwell B machine. Both the instruments clearly picked up the change in hardness over the test zones. They also showed clear evidence of pre-earthquake plastic strains, through the hardness readings in zones B and C being higher when closer to the flanges, and lower at the centre.

Normalized link depths presented in Figure 4.3 clearly shows the difference in hardness between the three test zones using two test methods. Rockwell B machine hardness values were approximately 10 greater than the Leeb TH170 tester hardness. Also in zones B and C, the hardness drops away from the flanges. In this study, zone A achieved the highest hardness values for both the methods, indicating the link zone A has undergone the highest inelastic deformation. However, the increase is minimal when comparing the Rockwell B results, showing that a geometry effect may also be occurring with the TH170 tester.

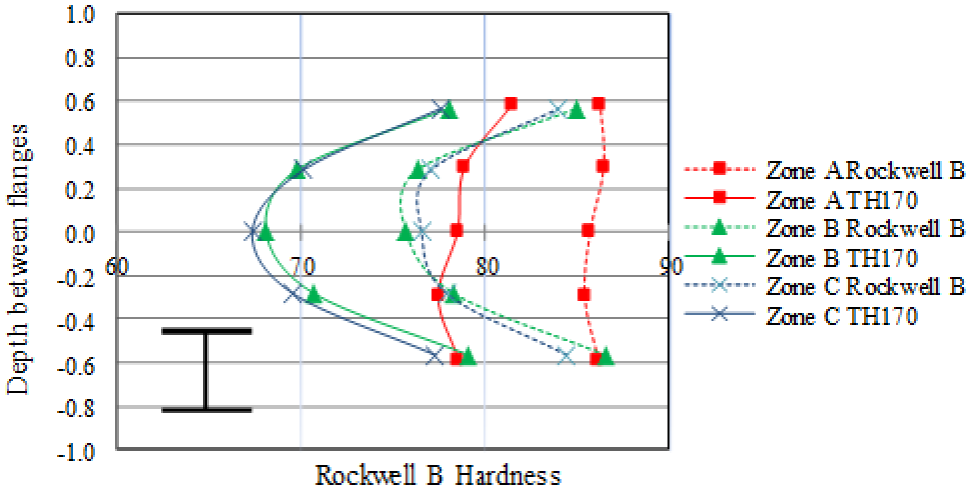

Figure 4.3: Rockwell B hardness versus normalized link depths between flanges in three zones of the active link beam form level 03 on grid 01, Pacific Tower

A further check involved comparing the grid survey. Rockwell B hardness measured from 25 individual grids in three zones (top, centre and bottom).Six hardness readings from each grid were measured using Rockwell B bench top machine and the portable hardness tester TH170. These test results match with the normalized test results in Figure 4.3, indicating that the top and bottom grids next to the flanges achieved highest and hardness drops at the centre grids in zone B and C while zone A maintained the hardness along the depth of the web.

Constant high hardness values throughout 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 had much lower levels of plastic strain in the middle of the webs. However the results also showed significant plastic strain in the top and bottom regions of the webs of all zones. Because the panel and beam zone plastic strains could not be explained by the earthquake actions, further studies were undertaken to confirm the initial results and an alternative explanation had to be found. Furthermore, visual inspection of the yielded active links showed in all cases where these were hot rolled members, the earthquake induced yielding was concentrated into 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. See examples in Figure 4.4, especially 4.4(b). The paint flecking started approximately at the centre of the web and stops close to the k-region of the section where the manufacturing plastic strain was measured. This interesting phenomenon which is considered to be due to flange and web roller straightening of hot rolled sections was identified during this investigation and is reported in section 5.

Figure 4.4 Active link beams undergone plastic strain (a) Active link beam at CDHB building, Christchurch (b) Active link beam at Club Tower, Christchurch

Further investigation was carried out on active link beams in Pacific Tower to compare the laboratory test results with onsite test results. The hardness of these beams was previously measured by Holmes Solutions Ltd (HSL). Figure 4.5 represents the Rockwell B hardness measured at different levels and plotted against the normalized depth of the sections. High stress close to the flanges was observed at all the levels and hardness gradually drops at the centre of the active beams. The measured Rockwell B hardness at level 22 was small compared to that measured at the other floors. The HSL hardness readings and visual observation of yielded links throughout the building by the first author showed inelastic demand in the active links was greatest around levels 5 and 6 and negligible above level 16.

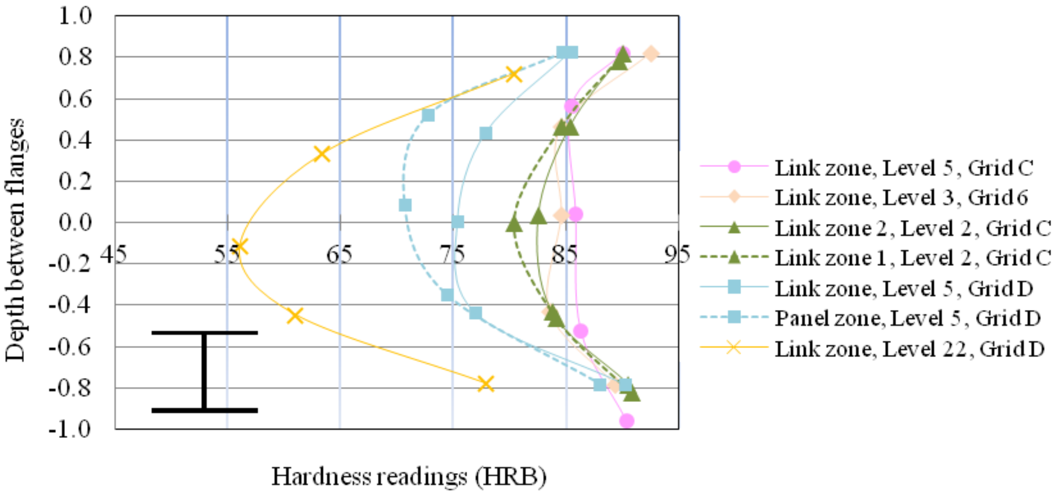

Figure 4.5 Rockwell B hardness versus normalized link depths between flanges in different zones of the active links at different levels, Pacific Tower

Identifying the amount of plastic strain in a cyclically deformed element, using a non-destructive method, is the key objective of this research project. Hardness mapping within the web has been established, with the next step to establish the relationship between hardness and plastic strain. A series of tensile tests in the active link beam from level 3 of Pacific Tower was carried out. Standard dog-bones from each zone were extracted by water-jet cutting to avoid any heat. Specimen 1, 2 and 3 were extracted from the beam zone, Specimens 4, 5 and 6 from the panel zone and Specimens 7, 8 and 9 from the active link zone. The orientation of the specimens were arranged to investigate the plastic deformation in three levels of the web of the beam that is; top, bottom and centre of the web.

Stress-strain diagrams in Figure 4.6 shows the amount of strain experienced in three zones of the active link beam in level 3. All tests from zone A, 7, 8 & 9, have essentially the same shaped cure and flow stress which is to be expected as this web should have been deformed plastically in the earthquake. For zones B & C, tests 1, 4, 2 & 5, have essentially the same shaped yield curve and yield stress, which is to be expected as the centres of these specimens are in the centre of the web which for these zones should not have yielded. Tests 3 & 6 are near the flange, have the same shaped stress-strain curve, but the flow stress has increased over that for tests 1, 4, 2 & 5, showing there has been plastic deformation in the region of the web near the flange and confirming the hardness results.

The stress-strain diagrams shows that the active link zone A has undergone approximately 7-7.5% plastic strain, compared with up to 4% plastic strain in zone C. The plastic strain in zone A is a combination of pre-earthquake straining, termed manufacturing strain, and earthquake induced strain. Manufacturing strain is significant in this context and is covered further in the next section.

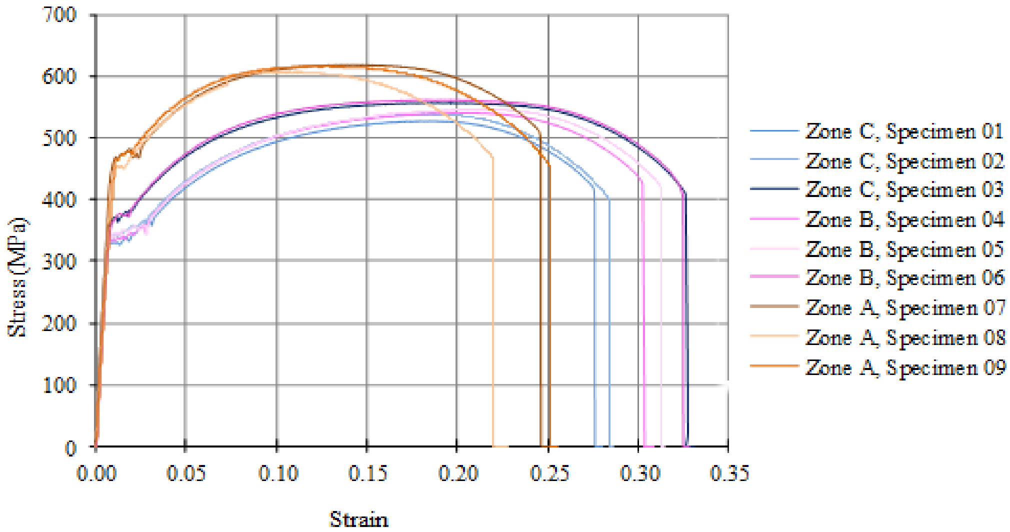

Figure 4.6 Stress strain diagram for three zones of the active link shear beam from level 03 on grid 01, Pacific Tower

5 MANUFACTURING INDUCED PLASTIC STRAIN

As hot rolled sections cool, they deform to the extent that minor straightening at low temperatures is required to bring them within the tolerance envelope required (NZS 3404). In modern steel making plants, this is typically undertaken by roller straightening, as described in section 1.3.4 of HERA Report R4-80 (Clifton 1994). This process is reported to induce a relatively complex pattern of residual stresses into hot rolled sections, with these stresses reaching $0.5f_y$, where f_y = the yield stress of the steel (see for example Figure 1.20 of (Clifton 1994)).

However, the hardness testing undertaken on the Pacific Tower active links showed plastic strains in the top and bottom quadrants of the webs of up to 4% plastic strains. (Hardness testing cannot identify strains lower than yield and so is not suitable for determining residual stresses). This unexpected finding correlates, in both position and magnitude, with limited research undertaken in the USA by Tide (Tide, 2000). The exact reason for it is unclear but a probable cause is the very tight gripping of the webs by the rotary straightening rollers when the web is held vertical to allow the flange tilt to be corrected. It has gone unreported principally because it has generated no adverse structural effects, however it is a significant factor to consider when developing guidelines for field hardness testing to determine earthquake induced plastic strains in damaged structural steel elements, as the testing must be undertaken in locations where earthquake induced plastic strain and not manufacturing induced plastic strain is measured.

6 CONCLUSIONS

Assessment of this experimental work is presented in the following points.

1. The hardness number found from the Rockwell machine was greater than that from the portable hardness tester (TH170). The difference was approximately 10 except near the flanges where the difference was less.
2. Plastic strain from manufacturing in the top and bottom quadrants of the web was evident throughout this investigation and clearly picked up by both the instruments. This appears to correlate closely with the zones of roller impact generated by the roller straightening process.
3. No significant change in hardness was observed close to the stiffener, indicating little influence of welding on the hardness around the stiffeners.
5. The active link zone A Figure 3.1 (a) had undergone significant plastic deformation. Zone A hardness values are approximately 10 higher than zone B and C.
6. Hardness between 'panel and beam zone' was almost the same, indicating no measurable earthquake induced plastic strain in these two regions.
7. The stress-strain diagram clearly shows 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 up to 7.5%
8. Residual and manufacturing plastic strain was approximately 3.5-4%.
9. 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.

Test results shows clear evidence that this method can predict the residual plastic strain of cyclically deformed active links. The detailed relationship between hardness and monotonic plastic strain has been established. The next stage is to determine experimentally the relationship between hardness and cyclic induced plastic shear strain in the webs of active links.

Acknowledgments

The authors would like to gratefully acknowledge Natural Hazard Research Platform (NHRP) the financial supporter for this project. The authors would also like to thank Sean Gardiner, CPG New Zealand Limited and his team for their contribution to conduct onsite as well as the laboratory tests.

REFERENCES:

American Society for Testing and Materials ASTM: E18-08b. *Standard test methods for Rockwell hardness of metallic materials*. ASTM International, Pennsylvania, United States, 2008.

Chi B and Uang Chia M (2004). Effect of straightening method on the cyclic behaviour of k-area in steel rolled shapes, *Engineering Journal*, Vol.41, No.1, pp.15-22

Clifton, G. C. (1994). New Zealand Structural Steelwork Limit State Design Guides Volume 1, *HERA Report R4-80*. Manukau City, New Zealand, New Zealand HERA.

Fujimo M, Aoyagi T, Ukai K, Wada A, Saito K (1972). Structural characteristics of eccentric K-brace frames. *Transactions of the Architectural Institute of Japan (AIJ)*. October 1972: No.195.

Feeney, M. J. and G. C. Clifton (2001). Seismic Design Procedures for Steel Structures including Tips on Seismic Design of Steel Structures. Manukau City, New Zealand, *New Zealand Heavy Engineering Research Association.*

Higginbotham AB (1973). The inelastic cyclic behaviour of axially loaded steel members. *PhD Thesis*, University of Michigan.

Igarashi S and Inoue I (1973). Memorandum on the study of braced frames. *Quarterly Column*, October 1973: No.49.

Igarashi S, Inoue I, Ogawa K, Asano M (1972). Hysteric characteristics of steel braced frames, Part I, The behaviour of bracing members under cyclic axial forces. *Transactions of the Architectural Institute of Japan* (AIJ), 1972: No. 196.

Integrated Hardness Tester TH170 Instruction Manual (V090115), Beijing TIME High Technology Ltd.

Kaufmann EJ and Fisher JW (2001). The effect of straightening method on the k-area loading behaviour of rolled column sections, *ATLSS Report*, No. 01-16, Leigh University 2001.

Masui T and Okada S (1989). A trial to improve size variation in roller straightening of H-beam. *Journal of Japanese Society for Technology of Plasticity*. Vol.30 (343):1141

NZS3404 (1997/2001/2007). Steel structures standard, incorporating Amendments 1 and 2, Wellington [N.Z.] : *Standards New Zealand.*

Roeder CW, Popov EP (1997). Inelastic behaviour of eccentrically braced frames under cyclic loading. *Earthquake Engineering Research Centre*, University of California, Berkeley, California 1977: EERC Report No.77/18.

Szalai J and Papp F (2005). A new residual stress distribution for hot-rolled I-shaped sections, *Journal of Constructional Steel Research*, 61 (6) 845-861.

Tide R.H.R (2000). Evaluation of steel properties and cracking in k-area of W shapes, *Engineering Structures*, 22(2000) 128-134

Wakabayashi M (1970). The behaviour of steel bracing with diagonal bracings under repeated loading. *Proceedings of U.S.-Japan Seminar on Earthquake Engineering with Emphasis on the Safety of School Buildings*, Sendai, Japan 1970: pp. 328-359.

Wakabayashi M, et al. (1970 and 1974). Experimental study on the elastic-plastic stability on steel frames and the restoring force characteristics: *JSCC*, Vol. 6, No. 55, in Japanese.

Wakabayashi M, et al. (1972). Experiment on the Elastic-Plastic Behaviour of Bars Subjected to Cyclic Axial loads. Preprints of Annual Conference , *Architectural Institute of Japan (AIJ)*, October 1972.

Yoshida H (1984). Analysis of residual stress in hot rolled H-beams, *Transaction of the Iron and Steel Institute of Japan* (ISIJ), Vol.24