Determination of the Post-Earthquake Capacity of an Eccentrically Braced Frame Seismic Resisting System

Paper by G Charles Clifton and George Ferguson
Presentation by Ken Elwood

The University of Auckland

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QuakeCoRE
NZ Centre for Earthquake Resilience

Christchurch Examples

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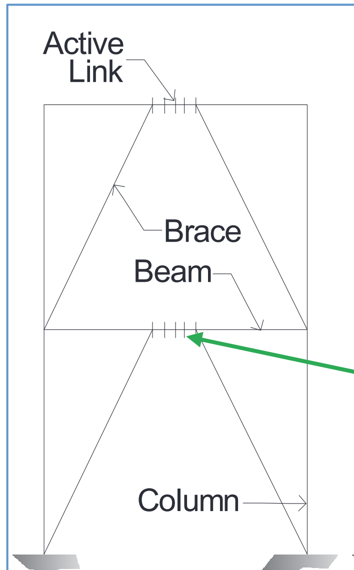
Background and Objective

- 22 Feb 2011 Christchurch EQ pushed EBFs into inelastic range
- Inelastic demand occurred within link
- Minor slab cracking
- Buildings self-centred
- **Question:**
  Do links need replacing because of the inelastic demand?

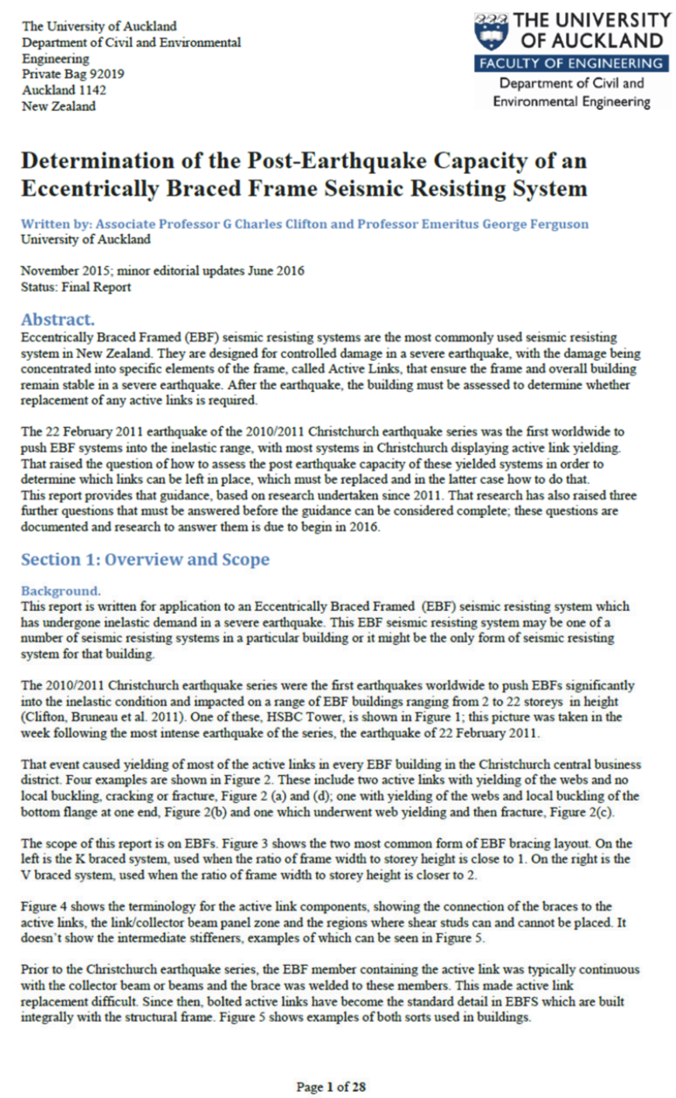


Eccentrically Braced Frame (EBF), K or V-Type

Draft Guidelines Developed

Document covers:

1. Overview and scope
2. **Determination of Post Earthquake Capacity** (the detailed procedure)
3. Guidelines on replacement of damaged active link, where required
4. Design example
   – Fully worked design example for 4 storey building
5. Further research required
6. Acknowledgements and References



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Determination of the Post-Earthquake Capacity of an Eccentrically Braced Frame Seismic Resisting System

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Status: Final Report

Abstract.
Eccentrically Braced Framed (EBF) seismic resisting systems are the most commonly used seismic resisting system in New Zealand. They are designed for controlled damage in a severe earthquake, with the damage being concentrated into specific elements of the frame, called Active Links, that ensure the frame and overall building remain stable in a severe earthquake. After the earthquake, the building must be assessed to determine whether replacement of any active links is required.

The 22 February 2011 earthquake of the 2010/2011 Christchurch earthquake series was the first worldwide to push EBF systems into the inelastic range, with most systems in Christchurch displaying active link yielding. That raised the question of how to assess the post earthquake capacity of these yielded systems in order to determine which links can be left in place, which must be replaced and in the latter case how to do that. This report provides that guidance, based on research undertaken since 2011. That research has also raised three further questions that must be answered before the guidance can be considered complete; these questions are documented and research to answer them is due to begin in 2016.

Section 1: Overview and Scope

Background.
This report is written for application to an Eccentrically Braced Framed (EBF) seismic resisting system which has undergone inelastic demand in a severe earthquake. This EBF seismic resisting system may be one of a number of seismic resisting systems in a particular building or it might be the only form of seismic resisting system for that building.

The 2010/2011 Christchurch earthquake series were the first earthquakes worldwide to push EBFs significantly into the inelastic condition and impacted on a range of EBF buildings ranging from 2 to 22 storeys in height (Clifton, Bruneau et al. 2011). One of these, HSBC Tower, is shown in Figure 1; this picture was taken in the week following the most intense earthquake of the series, the earthquake of 22 February 2011.

That event caused yielding of most of the active links in every EBF building in the Christchurch central business district. Four examples are shown in Figure 2. These include two active links with yielding of the webs and no local buckling, cracking or fracture, Figure 2 (a) and (d); one with yielding of the webs and local buckling of the bottom flange at one end, Figure 2(b) and one which underwent web yielding and then fracture, Figure 2(c).

The scope of this report is on EBFs. Figure 3 shows the two most common form of EBF bracing layout. On the left is the K braced system, used when the ratio of frame width to storey height is close to 1. On the right is the V braced system, used when the ratio of frame width to storey height is closer to 2.

Figure 4 shows the terminology for the active link components, showing the connection of the braces to the active links, the link/collector beam panel zone and the regions where shear studs can and cannot be placed. It doesn't show the intermediate stiffeners, examples of which can be seen in Figure 5.

Prior to the Christchurch earthquake series, the EBF member containing the active link was typically continuous with the collector beam or beams and the brace was welded to these members. This made active link replacement difficult. Since then, bolted active links have become the standard detail in EBFS which are built integrally with the structural frame. Figure 5 shows examples of both sorts used in buildings.

Clifton, G. C. and W. G. Ferguson (2015). Determination of the Post-Elastic Capacity of an Eccentrically Braced Frame Seismic Resisting System. Auckland, New Zealand, The University of Auckland for the Natural Hazards Research Platform

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Detailed Procedure

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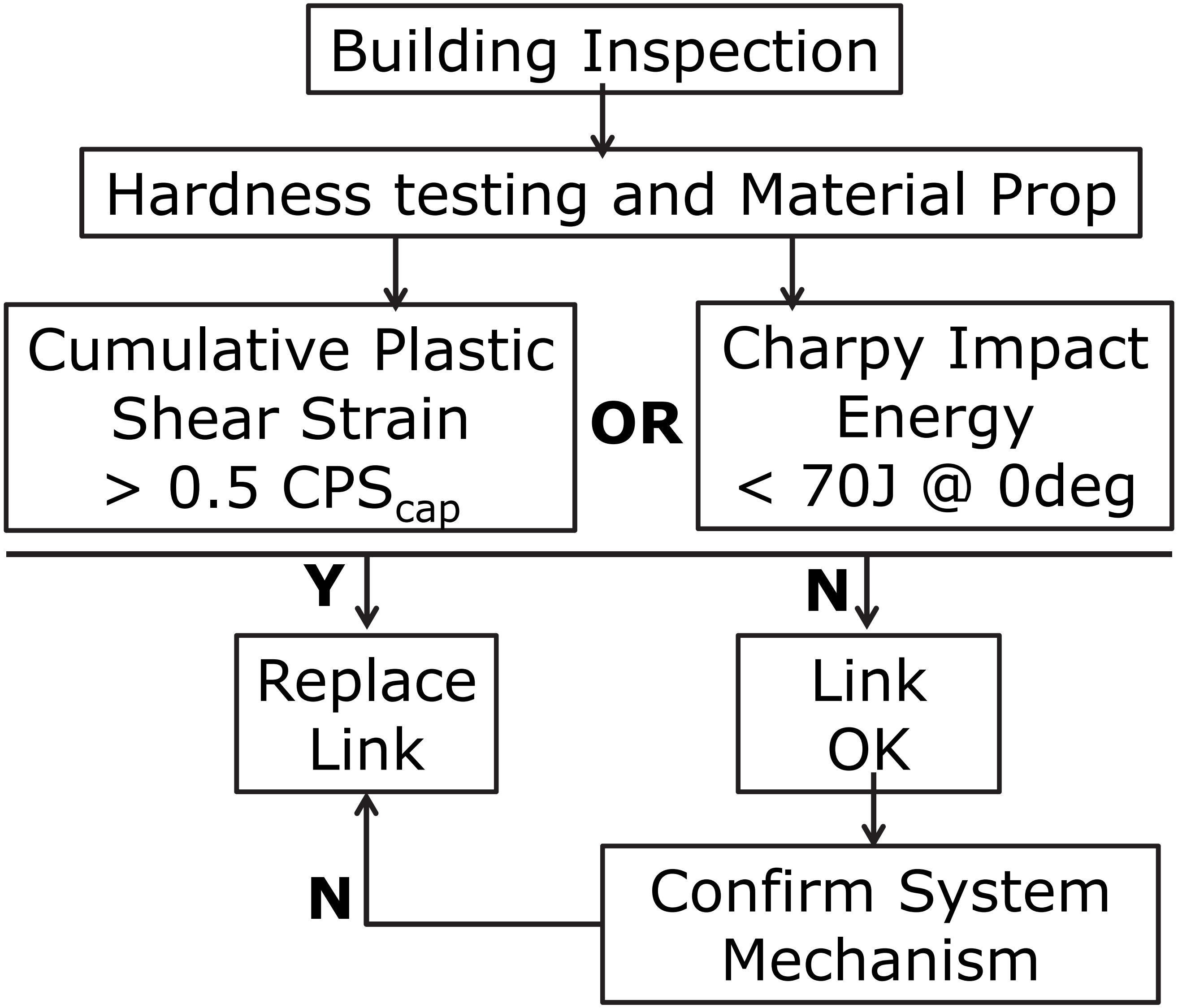

Integrated Portable Leeb Hardness Tester TH170

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Testing of Active Links in Shear: Key part of project

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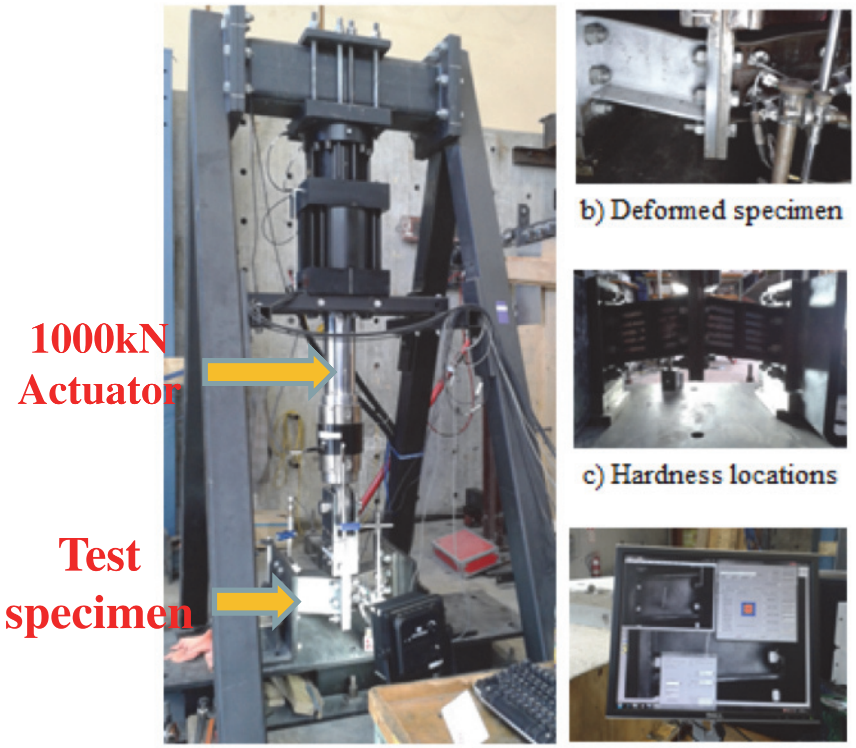


b) Deformed specimen

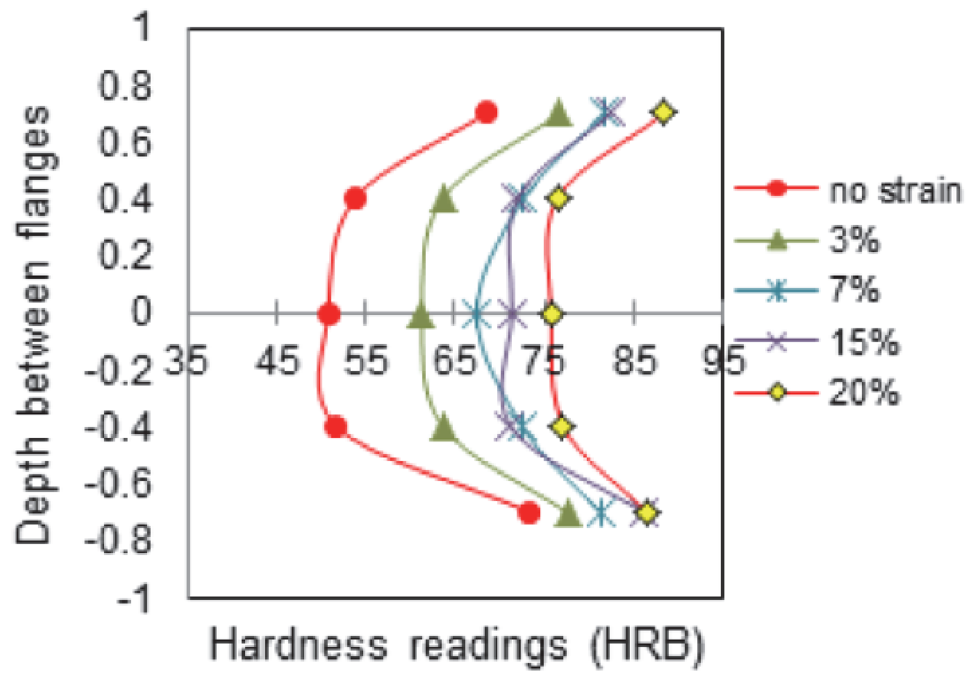
c) Hardness locations

a) Specimen attached to the actuator mounted on A-Frame

d) Photogrammetric immage capturing

- ✓ Cyclic tests at constant plastic strain 3%, 7%, 15% and 20%

Cumulative Plastic Strain Capacity: CPS_{cap} = 280%



Hardness from different plastic strain at normalized link depths

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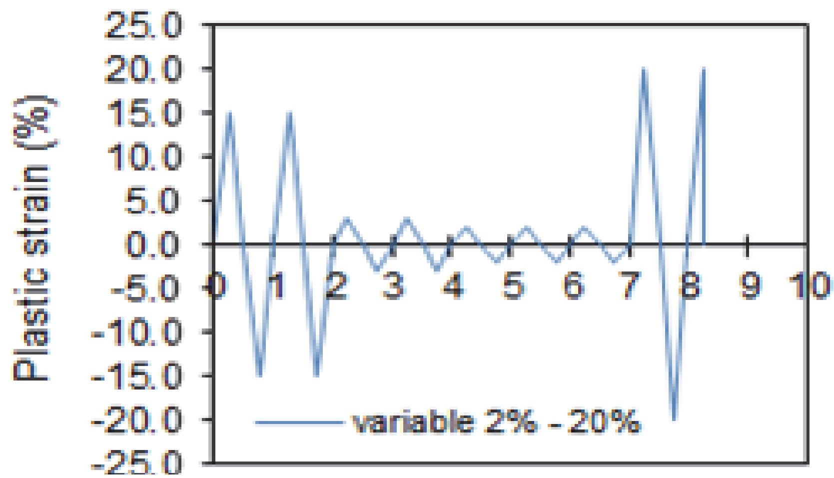
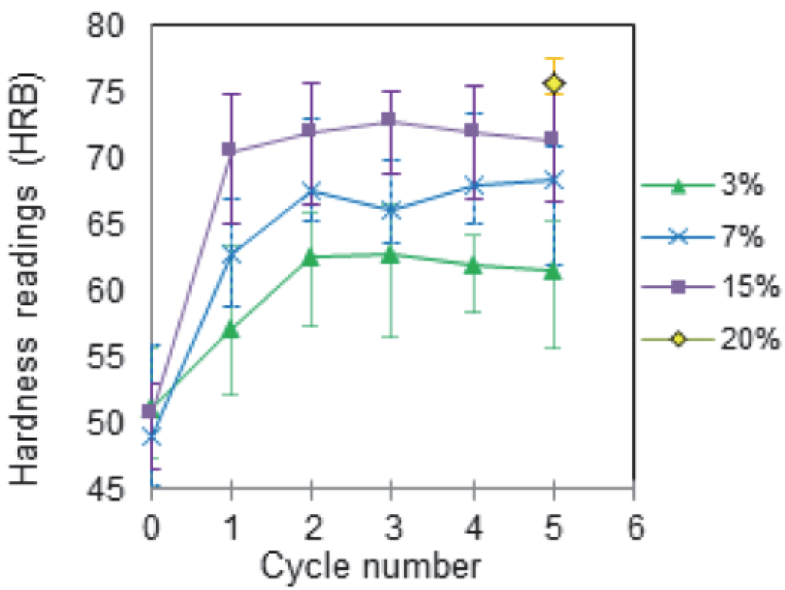
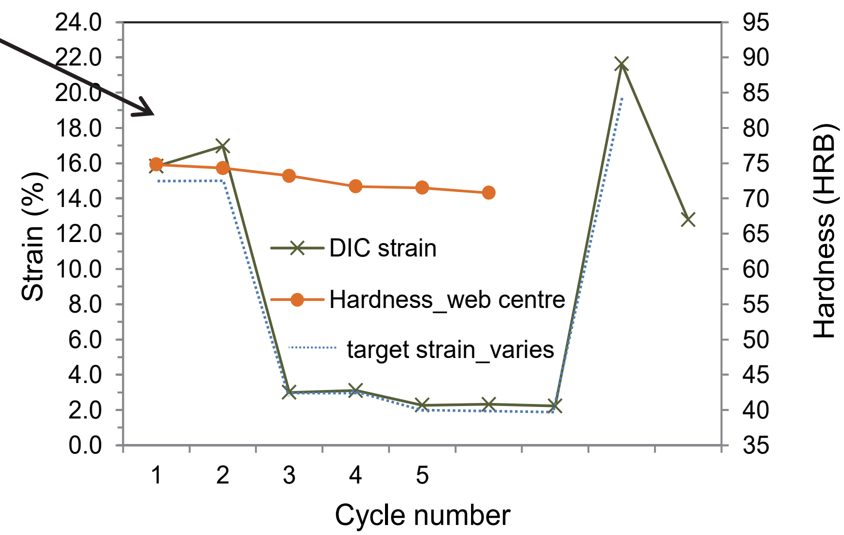
Effect of Loading History on Hardness



Hardness gives estimate of peak plastic strain.





Cyclic Plastic Strain Demand

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Table 1 Relationship Between Number of Cycles of Inelastic Action as a Proportion of the Maximum Cycle (from Choi 2013)

Length of Strong Motion Under 30 Seconds		*Length of Strong Motion Over 30 Seconds*	
N No of Cycles	Proportion of Peak Cycle Plastic Shear Strain (α)	N No of Cycles	Proportion of Peak Cycle Plastic Shear Strain (α)
1	1.00	1	1.00
2	0.80	2	0.80
2	0.65	4	0.65
3	0.50	6	0.50
4	0.30	8	0.30

Cumulative Plastic Strain Demand = $\Sigma\ (N\alpha\gamma_{max})$

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Detailed Procedure

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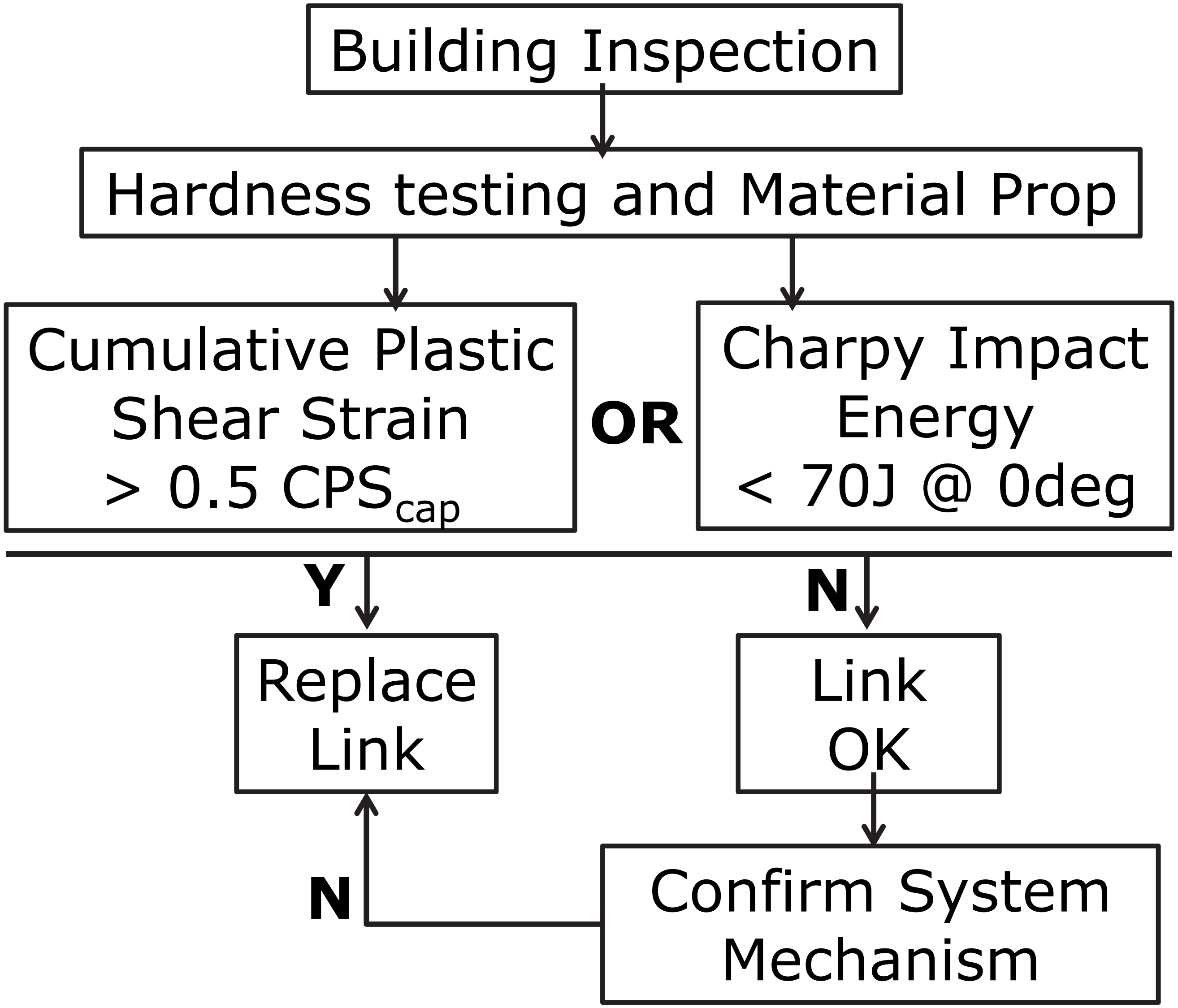

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Further Research Required

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- Effect of **strain ageing** of the shear deformed active link on the future deformation capacity
  - Project currently underway; completion Feb 2017

- Robustness of the **cumulative plastic shear strain limits**
  - Project currently underway; completion Feb 2017

- Influence of **Charpy Impact Energy level** on the inelastic cyclic performance of a well designed and detailed active link
  - Field evidence is that we need both **low CVN** and **poor detailing** to generate brittle fracture
  - What is influence low CVN alone?
  - Study planned for 2017

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Acknowledgements

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Auckland academics (current and former) involved:

Emeritus Professor George Ferguson

Dr Michael Hodgson

Dr Chris Seal (now at University of Manchester, UK)

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New Zealand Natural Hazards Research Platform

QuakeCoRE: NZ Centre for Earthquake Resilience

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Thank you and “Questions”

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Steps Involved:
1 of 2

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Step 1: Initial post earthquake inspection of the building and yielded links

Step 2: Undertake hardness testing of the EBF Active Link yielded webs and of control surfaces

Step 3: Determine change in mechanical properties of the active links

Step 4: Determine the peak plastic shear strain based on the change in hardness and the estimated loading history

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Steps Involved: 2 of 2

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Step 5: Estimate loading history and **cumulative plastic shear strain demand**

Step 6: Consider the change in **Charpy Impact Energy** due to the plastic shear strain demand

Step 7: Determine whether the active links can be left in place or require replacement

Step 8: Maintaining strength balance up the frame when links at only some levels require replacement

Step 9: Determine %New Building Standard for each EBF frame and for the whole building

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Use of DIC to Capture Strains

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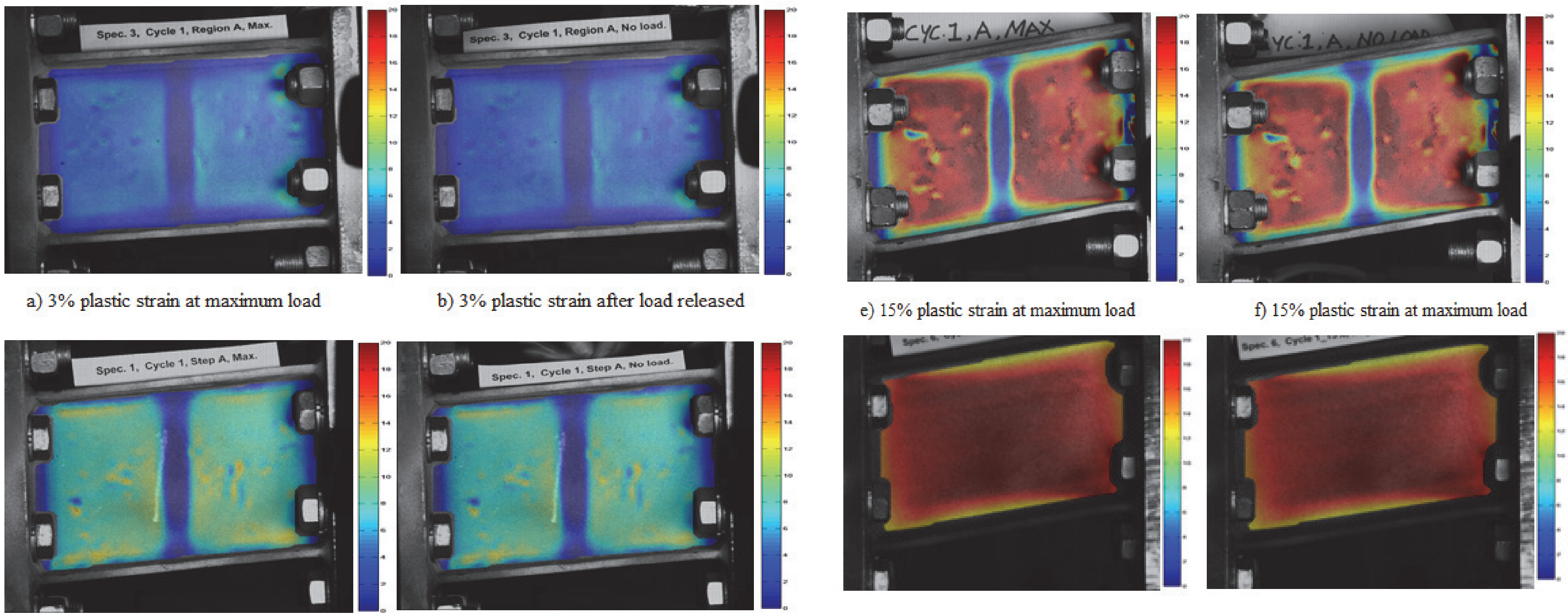

a) 3% plastic strain at maximum load

b) 3% plastic strain after load released

e) 15% plastic strain at maximum load

f) 15% plastic strain at maximum load

c) 7% plastic strain at maximum load

d) 7% plastic strain after load released

g) Link 6, variable loading- at maximum load

h) Link 6, variable loading- after load released

- ✓ Digital Image Correlation (DIC) was used to verify the strain demand achieved then compared with hardness results

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Testing of Active Links in Shear: Key part of project

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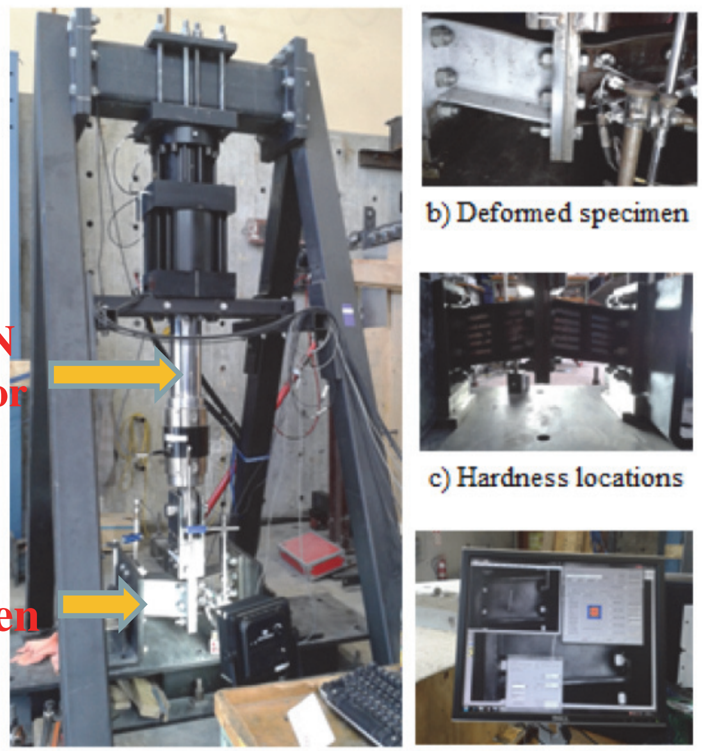
1000kN Actuator

Test specimen



a) Specimen attached to the actuator mounted on A-Frame

b) Deformed specimen

c) Hardness locations

d) Photogrammetric image capturing

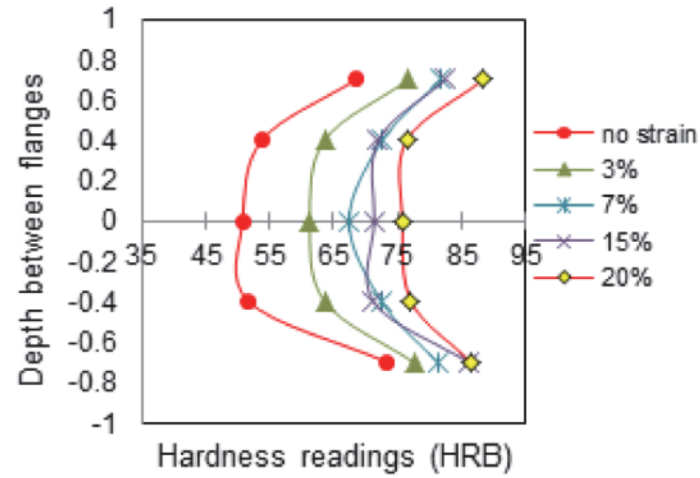


Fig. 5.3 Hardness from different plastic strain at normalized link depths

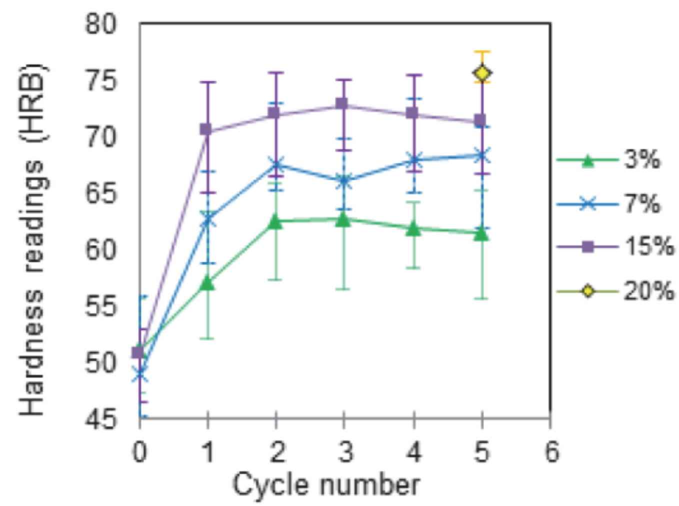


Fig. 5.4 Hardness distribution against cyclic number

- ✓ A series of cyclic tests have been carried out; constant plastic strain 3%, 7%, 15% and 2% being a trial specimen

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Conclusions and Outcomes

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- ✓ Cyclically strained specimens show a good correlation between hardness and strain demand.
- ✓ Surface preparation greatly affect the hardness and it has to be taken in the centre of the web
- ✓ Relationship between hardness and cyclic plastic strain demand has been established
- ✓ Neither material softening nor hardening was significant
- ✓ Proposed method can be used as a guideline to identify the amount of plastic strain demand and replacement criteria.

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