# The cracking behaviour of reinforced concrete beams under static and dynamic loading

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**ABSTRACT:** Following the 2010 and 2011 earthquakes in Canterbury it was observed that many plastic hinge zones in reinforced concrete beams of multi-story buildings performed unexpectedly. It was seen that a few wide cracks developed, rather than the expected large number of hairline cracks. The purpose of this research was to investigate the effect of different loading types and rates on the cracking pattern in the concrete and strain demand along the reinforcing bar within the plastic hinge zone of a typical beam. This was achieved through conducting tests on concrete prisms simulating the conditions around an individual bar in a beam with typical beam reinforcement content under monotonic and cyclic loading at static and dynamic loading rates. A strain hardness relationship was developed in order to obtain the strains along the reinforcing bar post testing. The results from the static and dynamic tests show that faster rates of loading induce a smaller number of cracks then do static loading rates. There was no observed significant difference between monotonic and cyclic loading. The strain along the reinforcing bar was not uniform and this resulted in concentrated strains developing at crack locations. This research shows that the current strategy of repair of damaged concrete buildings needs to be reconsidered due to this markedly non-uniform strain distribution.

## 1 INTRODUCTION

Following the 2011 Christchurch earthquake it was found many beams in moment-resisting reinforced concrete framed buildings performed unexpectedly. When a beam is subject to a significant seismic action it has been expected, based on many previous laboratory tests, that closely spaced distributed cracking will form along the length of the plastic hinge zone. This allows the strain caused by the cracks to be spread evenly over this length and this was assumed for design. The cracking pattern seen in beams in the 2011 Christchurch earthquake was substantially different from what was expected based on previous experimental testing (Bull 2013). Instead of evenly distributed cracking forming in the beams it was observed that only a small number of widely spaced large cracks formed. These large cracks put an increased strain demand on the steel that runs across the crack, reducing the post-earthquake capacity of the structure for a given plastic hinge rotation. This has made understanding why this unexpected cracking behaviour occurred in the Christchurch earthquakes a high priority.

### 1.1 Objectives

The objectives of this research were to;

- Determine how different loading types affect the cracking pattern and the strain profile produced in the plastic hinge zones of reinforced concrete beams.
- Develop a robust strain-hardness relationship for a Grade 500 deformed 12mm reinforcing bar made from straight bar (diameters typically used in full scale beams are made from straight bar not coil and the properties are different).

## 2 METHODOLOGY

The objectives of this research were achieved through two experimental stages. The first stage was developing a robust strain hardness relationship through performing tensile tests on the reinforcing bar at particular strains, and then subsequently testing the hardness of the bar. The second stage included testing reinforced concrete prisms with loading types as follows; monotonic static, cyclic static, monotonic dynamic and dynamic cyclic. Once loaded and unloaded, the longitudinal reinforcing bars were removed from the concrete prisms and hardness tested in a benchtop hardness tester. From the specimens' hardness, a strain profile along the bar for each loading type was developed.

### 2.1 Strain hardness relationship

The direct tension tests of DH12 bars were conducted to predetermined plastic strains. The hardness of these bars was then tested using the Rockwell G Hardness machine, to develop the relationship between plastic strain and hardness of the reinforcing bars. This relationship provided a platform for which the hardness reading results from the concrete prisms tests could be correlated to the associated plastic strains based on the strain-hardness relationships developed. This technique of using a strain-hardness profile to approximate the plastic strain in the reinforcing bar was previously used in research conducted by Van and Patel (2013).

The direct tension tests were performed on the 12mm reinforcing bar in the 100 kN Ingstron tensile testing machine. The reinforcing bar was gripped at each end and each bar strained to 3.5, 7, 10.5 or 15%. The hardness of these bars was then tested and plotted against the known plastic strains in order to develop the robust strain-hardness relationship for DH12 reinforcing bars.

### 2.2 Concrete prism testing

A concrete specimen with cross-sectional area of 100x100mm was constructed and tested axially under pure tension and compression with loading types as follows; monotonic static, cyclic static at an ascending rate, monotonic dynamic and dynamic cyclic at an ascending rate. The reinforcing bar was then removed from the concrete and the hardness along the bar determined. From the specimens' hardness along the bar, a strain profile versus cracking pattern was developed for the different loading types.

The test setup was designed to represent a section of a beam with approximately 2.0% reinforcing content in the plastic hinge zone of a moment resisting frame. In a small segment of the beam close to the column face the forces acting on the element are almost direct tension and compression and it was this environment that was captured in the prism tests. .

**Table 1. Concrete prism construction details.**

| | Concrete Prism |
|---|---|
| Prism Dimensions | 100x100x756 mm |
| Longitudinal Reinforcing Size | DH12 |
| Stirrup Size | R4 |
| Stirrup Spacing | 50mm |
| Concrete Cover | 14mm |
| Aggregate Size | 10mm |
| Concrete Strength | 45MPa |

Eight 100x100mm specimens were cast into formwork and each with 14mm of concrete cover as well as a notch that acted as a crack initiator. The specimens contained one DH12 longitudinal bar and 4mm stirrups at 50mm spacing as can be seen in Figure 1. Due to the specimen containing four free edges, the longitudinal bar had less restraint and was prone to buckling, not normally the case in typical beams. Therefore it was deemed necessary for the stirrups to have a spacing of 50mm. At each end of the concrete specimens the reinforcing bar was welded to a 10mm steel plate which contained 4 bolts. All concrete specimens had a specified concrete strength of 45MPa and 10mm aggregate size. The specimens were set for around 28 days in order to allow strength gain of the concrete.

In the monotonic tests the concrete specimens were subject to increasing tensile loads until the reinforcing bar ruptured. For the cyclic tests, the loading regime began with 1mm displacement followed by 1.5mm and continuing to increase by 25-50% with each increment. Three cycles at each displacement were conducted before incrementally increasing the displacement.

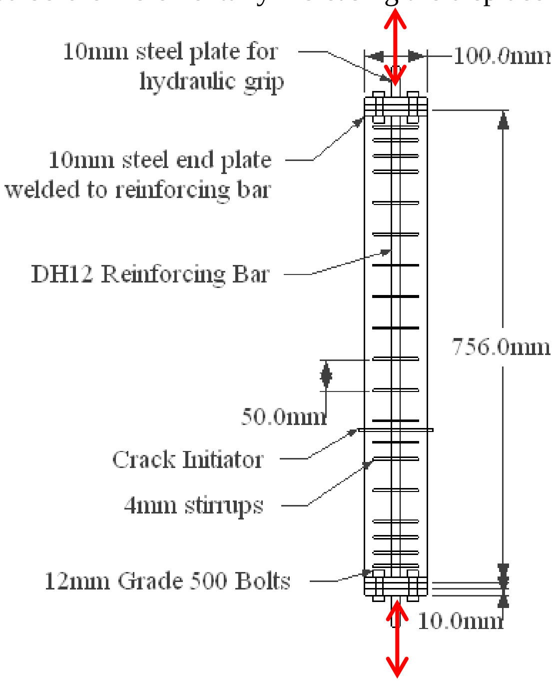


**Figure 1. Concrete prism test setup.**

Each of the loading types in Table 2 represents the different tests that took place. Each of these tests was repeated twice to ensure accuracy of results. The loading rates used in the dynamic tests lie between the middle and upper end of earthquake loading rates while the static tests loading rates are well within the pseudo-static limits (Pajak, 2011).

**Table 2.** ***Loading types and rates***

| Loading Type | Loading Rate | Strain Rate |
|---|---|---|
| Monotonic Static | 0.05mm/s | $10^{-4}$/sec |
| Cyclic Static | 0.05mm/s | $10^{-4}$/sec |
| Monotonic Dynamic | 26.5mm/s | 0.05/sec |
| Cyclic Dynamic | 26.5mm/s | 0.05/sec |

Once the tests were conducted, the reinforcing bar was removed, milled and cut into lengths of less than 100mm while ensuring crack locations remained identified. The hardness along the bar was then tested to determine the plastic strain along the bar and in particular the strain at the crack locations was measured more densely in a micro-hardness traverse. This was done using the Rockwell G hardness machine. The hardness reading obtained was used in conjunction with the strain hardness relationship developed earlier to obtain plastic strain values along the reinforcing bar. The plastic strain values and crack locations were matched and comparisons between different loading types took place in order to determine the effect these loading types have on the crack pattern and ultimately the strain in the reinforcing bar.

## 3 **RESULTS**

### 3.1 **Steel tensile test results**

Figure 2 shows the results from the steel tensile tests. Reinforcement derived from straight bar was used throughout this research, as coiled bar is only available in diameters up to 16mm and beam members typically use bar sizes greater than this. The measured yield point of the steel was 520MPa. The measured ultimate tensile strength of the bar was 620MPa. The bar fractured at a measured strain of 13.8%. As seen in Figure 2, the steel bar used in this research has a small post-yield increase in strength and therefore undergoes limited hardening for a significant increase in plastic strain.

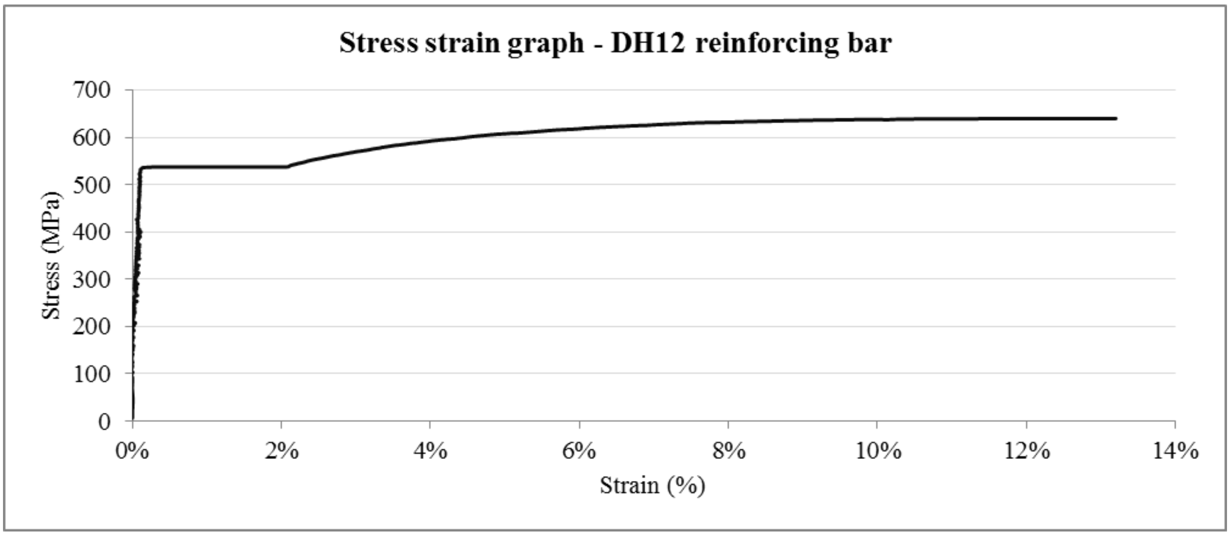


**Figure 2. Stress strain relationship of a DH12 reinforcing bar.**

### 3.2 **Hardness Strain Relationship**

As seen in Figure 3, there is a clear trend showing that an increase strain results in an increase in the hardness of the DH12 reinforcing bar.

A hardness value of 71.5 ± 3% or below gives no indication of the strain in the reinforcing bar. In this region which corresponds to a strain up to 2.5% ± 0.5%, the bar has only undergone elastic deformation and therefore no strain hardening has occurred. This means the hardness in the bar has not changed from its unstrained state. Where a hardness reading is obtained that lies in this region we cannot be sure what extent of elastic or plastic deformation the bar has undergone. As seen in the strain hardness relationship in Figure 3, hardness increases with increasing strain up to failure of the bar at 13.8% strain. Hardness readings indicating a strain higher than this are not valid, so where a hardness reading corresponds to a strain higher than this, the value has been limited to 13.8%.

The error bars from the data relating to the strain hardness relationship as seen in Figure 3 are the maximum and minimum values recorded for hardness. These are large in relation to the total hardness range; however this is within the variability of the measuring procedure.

In the region of strain between 2.5% ± 0.5% and 13.8% ± 0.5% the hardness can be related to the plastic strain for a DH12 reinforcing bar through the equation below:

$$HRG = 2.93 \ln(\varepsilon) + 69.80 \quad (1)$$

Where 2.5% ± 0.5% $< \varepsilon <$ 13.8% ± 0.5%; HRG = Rockwell G Hardness; $\varepsilon$ = Plastic Strain

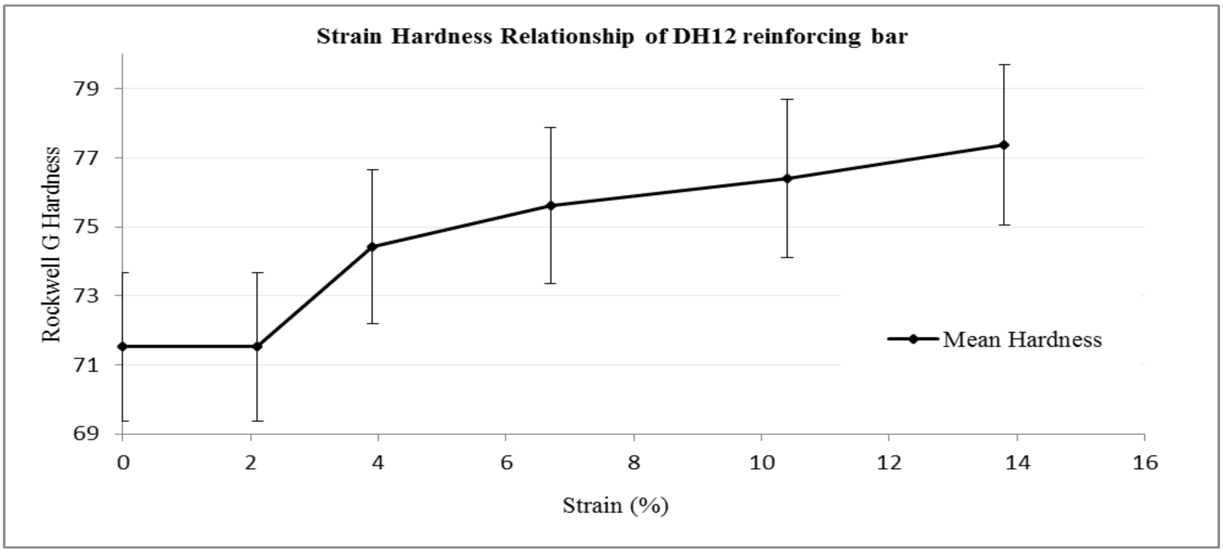


**Figure 3. Strain hardness relationship of DH12 reinforcing bar.**

### 3.3 **Concrete Prism Test Results**

Eight concrete prism tests were conducted. From the compression and split tensile tests it is estimated that the concrete reached an average compressive strength of 36MPa and tensile strength of 4.8MPa. Figures 5 to 8 show the strain profiles along the length of the reinforcing bars and the cracked profile of the specimens for each of the different loading cases. From the strain profiles it can be seen that the bars did not strain uniformly. The peak strains in the bar correspond to the locations of the cracks in the concrete. The strain drops off on either side of the crack location where the load is transferred from the reinforcing bar into the concrete. It was observed that the crack caused by the crack initiator did not match up directly with a peak strain. When cracks form they naturally spread from the reinforcing bar into the concrete and propagate to the surface. It is thought that the crack initiator caused the crack at this location to propagate from the surface of the concrete inwards on a 45 degree angle causing the corresponding peak strain from this crack to be skewed to the side of the crack initiator.

#### 3.3.1 *Static monotonic*

In the static monotonic tests nine primary cracks were observed with secondary cracks developing towards the end of the test. The longitudinal bar fractured in the heat affected zone at a tensile load of 74kN and a displacement of 47mm.

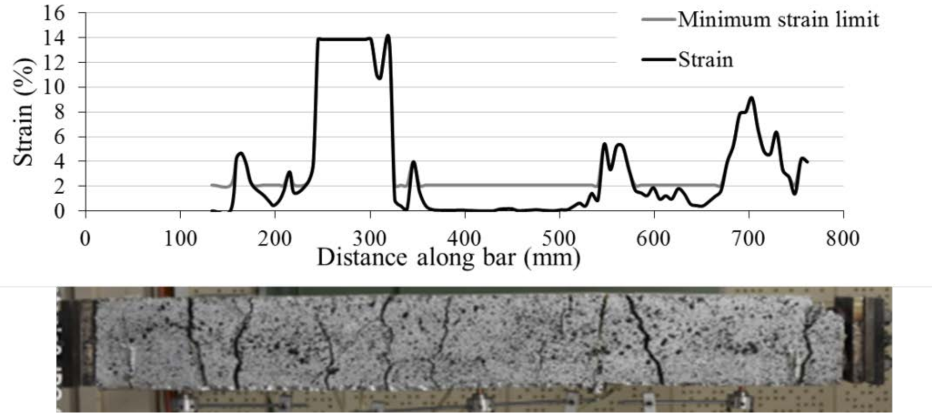


**Figure 4. Static monotonic strain profile and cracking pattern.**

3.3.2 *Static cyclic*

In the static cyclic tests, five to six primary cracks were observed with minor secondary cracks developing along the length of the member subsequent to the primary cracks. The first static cyclic test failed due to the longitudinal bar fracturing in the heat affected zone of the bar. The second test was stopped due to excessive buckling of the member. The maximum displacement reached was 20mm. Both tests underwent approximately 25 cycles before failure of the member occurred.

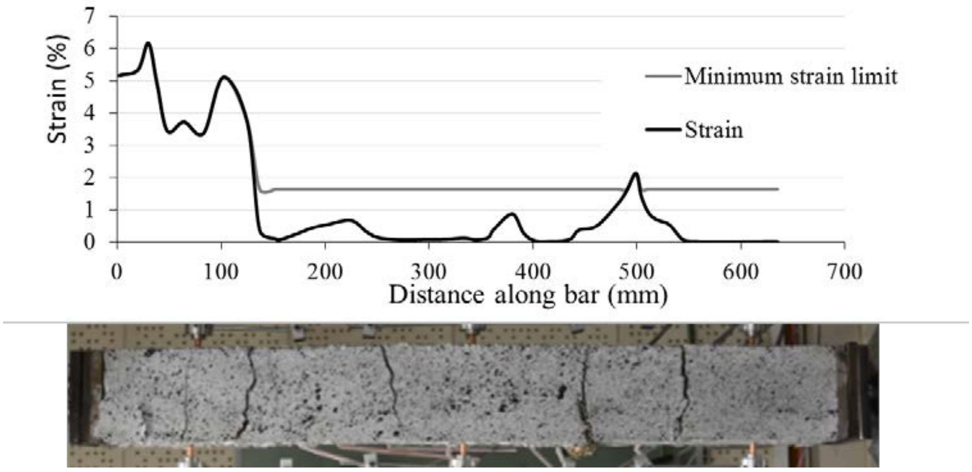


**Figure 5. Static cyclic cracking pattern and strain profile.**

3.3.3 *Dynamic monotonic*

In the dynamic monotonic tests, five to six primary cracks were observed with minor secondary cracks developing along the length of the member. The longitudinal bar fractured on average 43mm from the base of the endplate. The maximum displacement reached was 34-46mm.

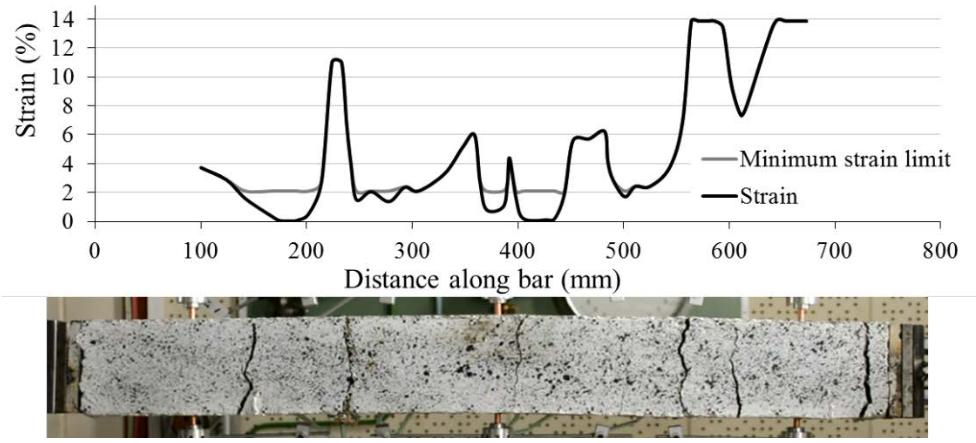


**Figure 6. Dynamic monotonic strain profile and cracking pattern.**

3.3.4 *Dynamic Cyclic*

In the dynamic cyclic tests, five primary cracks were observed with no secondary cracks developing. The first test was stopped due to excessive buckling of the member. The second test was stopped due the maximum compression load of 110kN on the MTS being reached. Before the tests were stopped the maximum increase in displacement reached was 20mm and approximately 25 cycles had been completed.

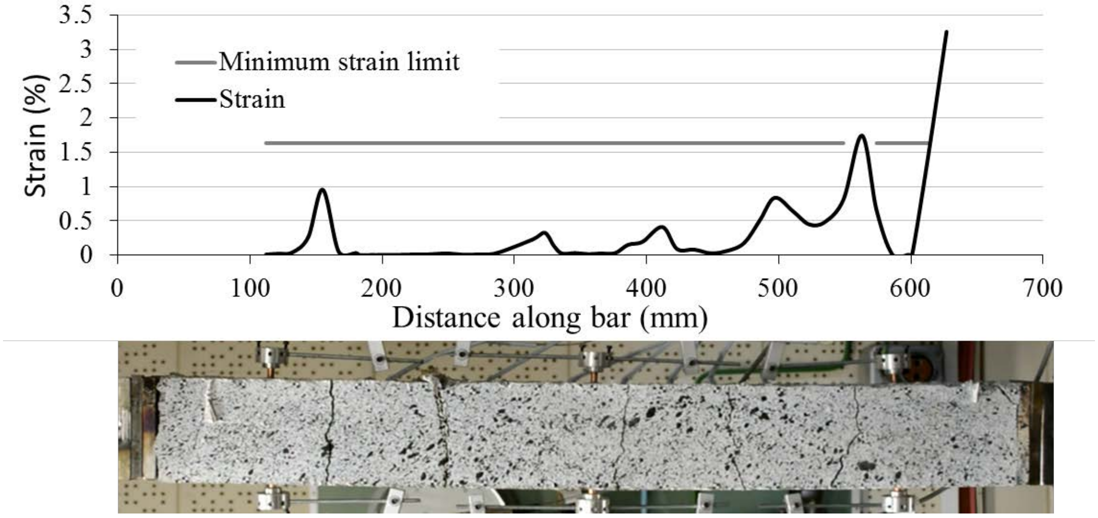


**Figure 7. Dynamic cyclic strain profile and cracking pattern.**

# 4 DISCUSSION

## 4.1 Comparison of static and dynamic tests

From the figures showing strain along the reinforcing bars it is apparent that the static tests had more primary and secondary cracks develop than the dynamic tests. Furthermore the reinforcing bar acted in a more ductile manner in the dynamic tests, in contrast to the findings of Chung and Shah (1989). This was evident in the failure of the reinforcing bar as necking occurred in the dynamic tests as seen in Figure 8. Additionally, both the static and dynamic tests reached a similar total displacement, however the dynamic tests had much fewer cracks form. This would mean that the bar had to elongate more in these few wide cracks, demonstrating a ductile behaviour.

**Figure 8. Bar Fracture – Monotonic Dynamic (Left), Monotonic Static (Right).**

In research conducted by Pajak (2011) it was seen that as the loading rate increases, the concrete tensile strength also increases. This may have contributed to the decreased number of cracks forming in the dynamic tests as it would become increasingly difficult to initially crack the concrete. Degradation of the bond between the concrete and reinforcing bar may have been more prominent in the static tests as it takes time for the bond to break down. When this degradation occurs, it allows the strain to propagate along the reinforcing bar and progressively yield. This is a likely contributing factor to the higher number of cracks in the static tests.

## 4.2 Comparison of monotonic and cyclic tests

In comparing the monotonic tests with the cyclic tests, it can be seen that the monotonic tests had more prolific cracks. This however was due to the cyclic tests only making 20mm displacement before the specimens buckled or the maximum compression load the testing machine could handle was reached. Buckling of the cyclic tests occurred due to a crack forming between the face of the steel plate and concrete. This reduced the end fixity of the specimens and allowed rotation at these points. There appears to very little difference between the cracking patterns in the monotonic and cyclic loading, however further research conducted with greater end fixity to remove the buckling of the specimen is needed. It was observed in the cyclic tests that the stains obtained from the strain hardness relationship are relatively low in comparison to the monotonic tests. This may be due to the reinforcing bar undergoing less extension than the monotonic tests and therefore a lower strain.

### 4.3 **Canterbury Earthquakes**

It was found that the cracking pattern observed in this research was very similar to that seen in the Christchurch earthquakes, whereby, widely spaced large cracks formed in the plastic hinge zone instead of evenly distributed fine cracking forming. As the longitudinal reinforcing bar is strain hardened, the strength of the bar in the cracked region increases, which moves the yield further along the reinforcing bar making it more likely that another crack will form adjacent to the first crack. However, as can be seen in Figure 8, the reinforcing bar used in this research had a very small increase in strength following yielding and therefore underwent very little hardening for a significant increase in strain. This low ratio of $f_u$ to $f_y$, the high tensile strength of the concrete and the high bond strength between the bar and the concrete made it unlikely that a large number of cracks would form along the length of the concrete prism and agrees with the cracking pattern seen in this research.

The strain hardness relationship that has been developed could potentially be used in buildings that have undergone an earthquake as a single reinforcing bar could be carefully removed from the plastic hinge zone of a beam and hardness tested to evaluate the strain in the bar. This would give us a better understanding of the post-earthquake capacity of the beams in a structure.

## 5 **CONCLUSIONS**

The reinforcing bar did not strain uniformly. The strain in the bar was concentrated in the crack locations.

It was observed that there were more cracks in the static tests than there were in the dynamic tests.

The cracking pattern of widely spaced large cracks seen in beams in the Canterbury earthquakes is very similar to what has been observed in these tests.

The central reinforcing bar in the dynamic tests acted in a more ductile manner than in the static tests.

## 6 **REFERENCES**

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