CAUSES OF ELONGATION IN REINFORCED CONCRETE BEAMS SUBJECTED TO CYCLIC LOADING

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ABSTRACT: Elongation in the plastic hinge regions of reinforced concrete beam has a significant influence on the integrity of the structure. This paper describes the research carried out to examine the key mechanisms that contribute to the elongation in plastic hinges. The effect of axial forces on the mechanisms that causes elongation is also investigated. A finite element program is employed to simulate the experimental work reported in literature. The analytical predictions are compared with the experimental results. It is found that elongation in plastic hinges is associated with two key factors: (1) unrecoverable stretching of compression reinforcement, and (2) plastic strains in reinforcement due to plastic rotation. The contributions of these factors to elongation are found to be markedly different for different types of plastic hinge.

KEYWORDS: Beam elongation, reinforced concrete, shear deformation, compression reinforcement extension, uni-directional/ reversing plastic hinge.

1. INTRODUCTION

Experimental research in New Zealand in the last two and a half decades has shown that elongation of plastic hinges can have a very significant influence on the seismic performance of reinforced concrete buildings. Typically, in seismically designed ductile structures, the elongation in plastic hinges at the design displacement is of the order of 2 to 5 percent of the member depth [1]. Although it is commonly known that the elongation occurs as a result of accumulation of plastic strains in the reinforcing bars when RC structures undergo large cyclic flexural deformation, other mechanisms contributing to the elongation of plastic hinge are not well understood. Mechanisms such as diagonal compression struts and shear deformation within the plastic hinge zone also have a major influence on elongation.

Two types of plastic hinges, namely reversing and uni-directional plastic hinge [1], are examined in this paper. Experimental results are compared with the analytical predictions to corroborate the reliability of the finite element program. The analytical results are then scrutinized to identify the main mechanisms that contribute to the elongation in plastic hinges. The effect of axial force on the contribution of these mechanisms is also examined.

2. EXPERIMENTAL SET-UP

Experimental results were extracted from a series of beam tests conducted by Fenwick and Megget [1], Issa [2], Matti [3], and Fenwick et al. [4]. The standard test set up is shown in Figure 1. Three tests with axial loading of 0kN, 500kN in compression and 75kN in tension are considered in this paper. The loading sequence started with two elastic cycles in which the load was cycled to ± approximately

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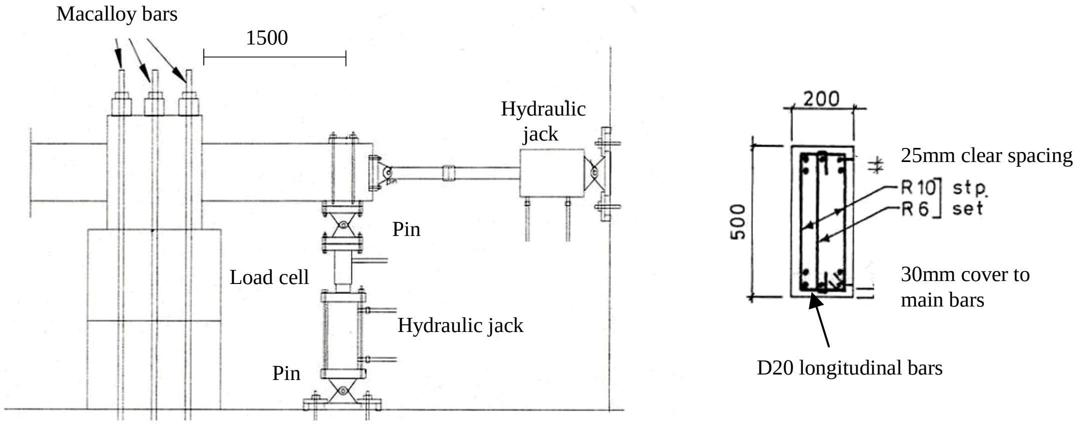
75% of the theoretical flexural strength of the beam (neglecting strain hardening). From these cycles, the yield displacement at displacement ductility of 1 was assessed. The loading history after these elastic cycles became displacement-controlled. The general displacement sequence was to apply two complete cycles to ± displacement ductility of two, (D2) followed by two cycles at displacement ductility of four (D4) and two cycles at displacement ductility of six (D6), as illustrated in Figure 2. The theoretical strength and the yield displacement of the beams are summarised in Table 1.



(a) Test set up (b) Cross section of beam

Figure 1 – Test configuration for beam

Table 1 – Theoretical strength of beams and their yield displacement

Experiment	**Axial Load (kN)**	**Average f_y (MPa)**	**Average f'_c (MPa)**	**M_n (kNm)**	**Yield displacement (mm)**
2A	0	306	37.6	202	8.0
S1B	-500	332	37	305	9.1
M2	75	318	29.4	193	9.0

Note that negative axial load means compression.

3. ANALYTICAL STUDY

A non-linear finite element program, UC-win [5], was used for the analyses. The program is based on non-linear path-dependent material models, which combines uni-axial stress-strain relationship of reinforcing bars and biaxial stress-strain relationship of concrete to form a generalized constitutive relationship for reinforced concrete element using a smeared crack approach.

Sensitivity analyses were performed to determine the suitable mesh sizes, support conditions and load increments for the analyses. The layout and the mesh setting for the analysis is shown in Figure 3. Given that the beam was symmetric about the centre of the central block, the model only consists half of the central block where it is fixed around the circumference. The lighter areas represent reinforced concrete elements and the darker areas represent the elastic plates. The thicker line between the beam and the central block represents the joint elements, which take into consideration the opening and closing of the interface. The height of the top and bottom elements was chosen to ensure the centroid of the mesh would coincide with the centroid of reinforcing bars in the tests. The horizontal spacing of each element is 100mm since the transverse reinforcement spacing in the experiment was 100mm. Ten loading steps were applied in each 1/4 of load cycle.

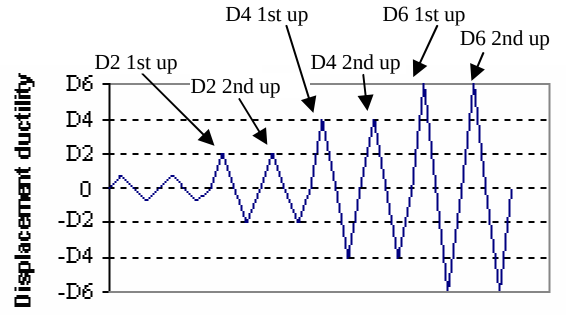


Figure 2 – Loading history

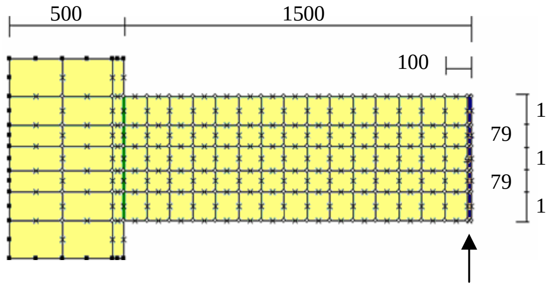
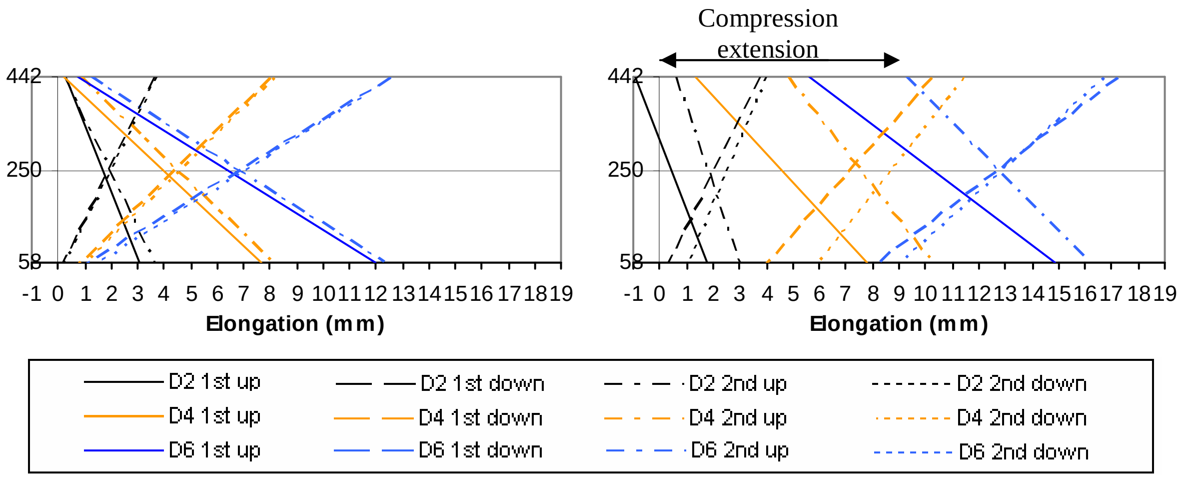


Figure 3 – Analytical beam layout

4. ANALYTICAL PREDICTION AND COMPARISON WITH EXPERIMENTAL RESULTS

4.1 NO AXIAL FORCE

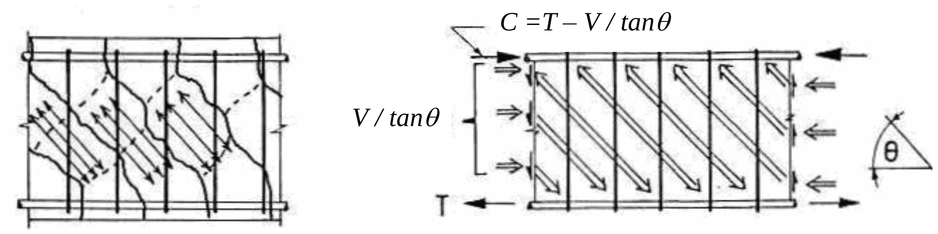
Elongations at the centroid of top and bottom reinforcement were tracked at maximum/minimum displacements of each cycle over the region containing the plastic hinge. The displacement profiles of the centroid of the reinforcing bars at three different displacement ductility levels (D2, D4 and D6) are plotted in Figure 4. One key observation can be made from this comparison. The compression reinforcement in the analysis fully yields back to the original position each time the load reverses, whereas this reinforcement in the tests did not fully yield back. Two reasons have been identified for the observed behaviour in the tests [1]. Firstly, intersecting diagonal cracks in the plastic hinge region destroy the shear resistance provided by the concrete. Consequently, all the shear is resisted by the shear reinforcement and the diagonal compression forces in the web, as illustrated in Figure 5. The diagonal compression forces in the web result in the flexural tension force being greater than the flexural compression force at the same section, which results in additional tensile strains in the tension reinforcement rather than additional compressive strains in the compression reinforcement. Secondly, aggregate particles become dislodged at the cracks. This leads to dilation which restrains the cracks in the compression zone from closing completely. Both of these actions result in unrecoverable elongation of reinforcement in the compression zone as observed in Figure 4(b), unless either a significant axial compression load is applied or the area of tension reinforcement in any half cycle is appreciable greater than the area of compression reinforcement.



(a) Analytical elongation of reinforcement in PH

(b) Experimental elongation of reinforcement in PH

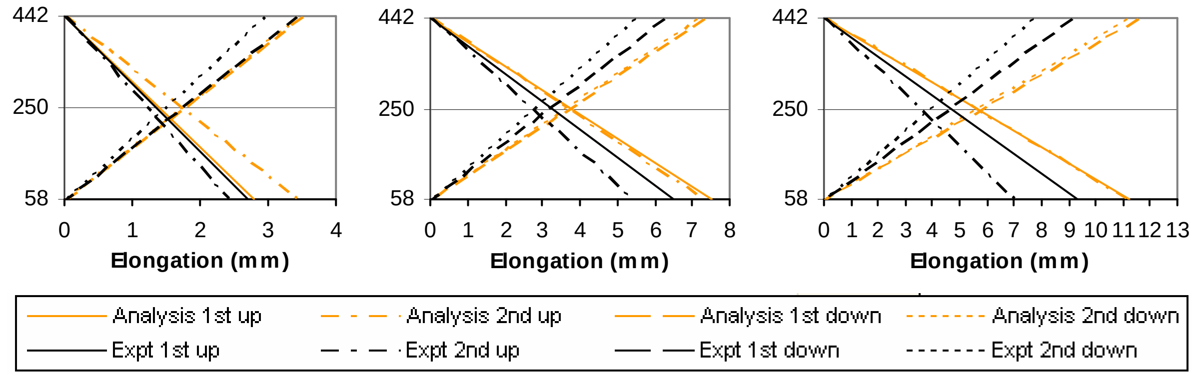
Figure 4 – Elongation of reinforcement in plastic hinge region



(a) Diagonal compression (b) Truss action

Figure 5 – Truss action in plastic hinge zone [1]

Removing the compression extension effect from the experimental results and comparing with the analysis show that when the applied displacement is small, the predicted elongation matches well with the experiment (Figure 6). However, as displacement and number of cycles increase, the differences between the analysis and the experimental results increase. The curvature in the experiment is noticeably smaller than in the analysis at large displacement cycles. This difference was due to underestimation of shear deformation in the analysis, which resulted in a larger predicted curvature in the plastic hinge zone than those deduced from the tests.

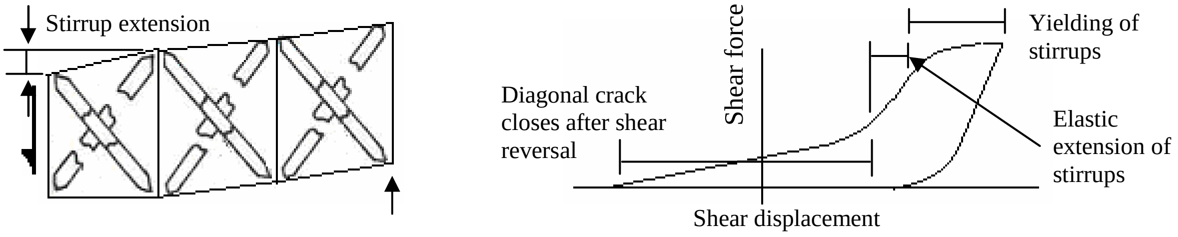


(a) Ductility 2 (b) Ductility 4 (c) Ductility 6

Figure 6 – Comparison between analysis and experiment at each displacement ductility

The role of shear deformation in such cases has been described by Fenwick and Megget [1]. In a reversing plastic hinge zone, the diagonal compression struts carry diagonal compression forces in the web. If the curvature reaches a critical limit, the shear reinforcement yields and wide diagonal cracks form in the plastic hinge. The shear resistance depends on diagonal compression forces being sustained in the web of the beams as illustrated in Figure 7(a). When the shear force reverses the direction of the diagonal forces changes. For these new diagonal forces to develop, the cracks must close. This results in appreciable displacement occurring when the direction of applied shear force changes, which gives the pinched shear force displacement relationship illustrated in Figure 7(b). The pinching effect increases each time the critical curvature limit is exceeded as this causes additional yielding of the stirrups with consequent increase in diagonal crack width.

In uni-directional plastic hinges, the effect of compression extension would not occur as this type of loading ensures that reinforcing bars on one side of the member does not yield in tension. The amount of shear deformation in the uni-directional hinge is also relatively small as the stirrups generally do not yield in tension. Consequently, the pinching effect is small and it does not occur unless the shear force reverses. In this situation, elongation can be calculated from the rotation which is imposed on plastic hinge zone [6].

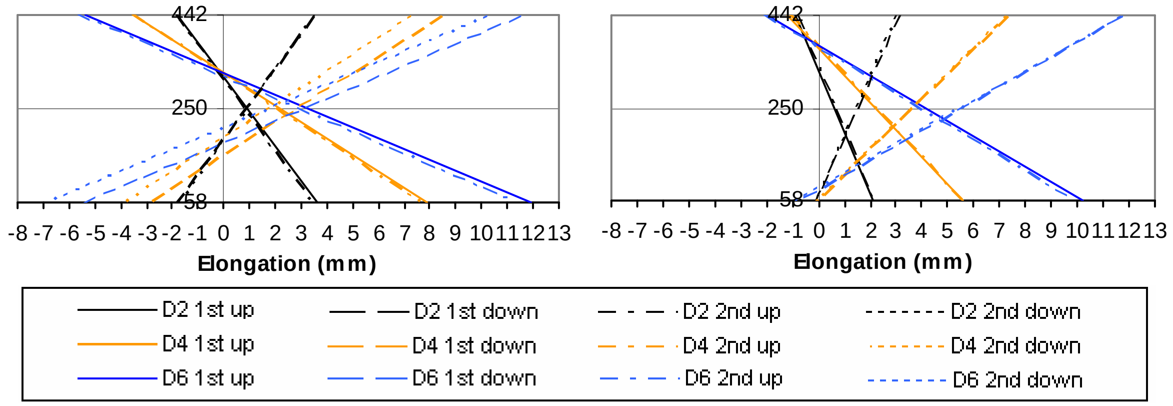


(a) Deformation of truss (b) Shear force versus shear displacement in reversing hinge

Figure 7 – Shear deformation mechanism in reversing plastic hinge region [4, 7]

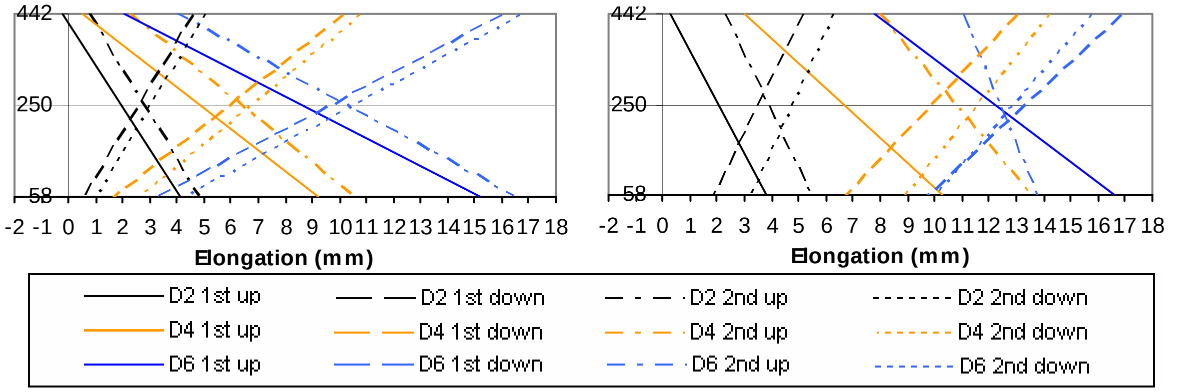
4.2 AXIAL COMPRESSION AND TENSION EFFECT

With the introduction of axial compression force to the beam, the magnitude of the flexural compression force increases and the flexural tension force reduces. Provided the axial force is sufficient, the compression reinforcement yields back enabling the cracks to close in the compression zone, thereby reducing elongation. The test results in Figure 8(b) illustrate the expected influence of axial compression. Comparison of the analytical and experimental values in Figure 8 show the plastic hinge in the test beam sustained smaller curvatures than the predicted values. This highlights the importance of shear deformation mechanisms on the modelling accuracy of the finite element analysis.



(a) Analytical elongation of reinforcement in PH (b) Experimental elongation of reinforcement in PH

Figure 8 – Elongation of reinforcement in plastic hinge region in beam with 500kN axial compression load



(a) Analytical elongation of reinforcement in PH (b) Experimental elongation of reinforcement in PH

Figure 9 – Elongation of reinforcement in plastic hinge region in beam with 75kN axial tension load

With the introduction of axial tension force, the elongation was slightly greater due to an increase in compression extension of the reinforcing bars. Note that the inclination of the diagonal compression struts is expected to be steeper in this case which would cause the transverse reinforcement to yield at an earlier stage. This could be expected to result in an increased portion of applied displacement being carried by shear deformation. Consequently, the curvature reduces markedly at large displacement cycles. This effect can be observed in Figure 9.

5. DISCUSSIONS AND CONCLUSIONS

Based on the outcome of this study, the following conclusions can be drawn:

1) Elongation of plastic hinges during large inelastic deformation occurs mainly from:
    i) Plastic rotation within the plastic hinge zone.
    ii) Unrecoverable extension of compression reinforcement.

2) As the reinforcing bars in one side of a uni-directional plastic hinge do not yield, the elongation in uni-directional plastic hinges is contributed by the plastic rotation only, where as in reversing plastic hinges, both the plastic rotation and compression reinforcement extension contribute to elongation.

3) The axial force applied to the member was found to have a major influence on the magnitude of elongation in reversing plastic hinges. Under an axial compression force, the magnitude of the flexural compression force increases and the flexural tension force reduces. This allows the compression reinforcement that yielded in tension in the previous half cycle to yield back, which leads to a reduction in the compression reinforcement extension. Consequently, elongation in the plastic hinge reduces. Conversely, under an axial tension force, the flexural compression force reduces and the flexural tension force increases. This results in a larger elongation due to an increase in the compression extension of the reinforcing bars.

6. REFERENCES

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