The Development of Strain Penetration in Lightly Reinforced Concrete Shear Walls

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ABSTRACT

A well reinforced (ductile) shear wall is likely to have multiple cracks formed along its height when subjected to lateral loading. On the other hand, a lightly reinforced concrete shear wall which has been detailed poorly can have a single crack formed at its base. The deformation of such a wall may well be attributed mainly to the localization of strains surrounding the crack. Bond-slip relationship between the deformed reinforcing rebars and the concrete on both sides of the crack can have a significant effect on the lateral drift capacity of the wall, and particularly so if the wall is lightly reinforced. The strain profile of reinforcing rebars surrounding the crack was the subject of investigation in the study. Concrete specimens were subject to reversed loading up to the limit when the reinforcement bars ruptured. Reinforcing bar size and concrete grades were amongst the factors that have been analysed.

Keywords: ribbed bar, bond-slip behavior, yield penetration, slip displacement, slender shear walls, drift capacity.

1. INTRODUCTION

Concrete shear walls are categorised, in terms of their aspect ratio and hence lateral displacement behaviour, into slender and squat walls. For instance, it has been postulated that an aspect ratio (H/L) ≥ 3.0 is for slender walls, and an aspect ratio (H/L) ≤ 1.5 for squat walls (FEMA-356 2000). Numerous experimental studies (Bimschas 2010; Riva, Meda & Giuriani 2003; Salonikios 2002) showed that the total lateral displacement of shear walls comprised contributions from four deformation mechanisms; namely flexural, yield penetration, shear and sliding shear. The former two mechanisms were found to be more dominant in slender shear walls whereas the latter two more dominant in squat shear walls.

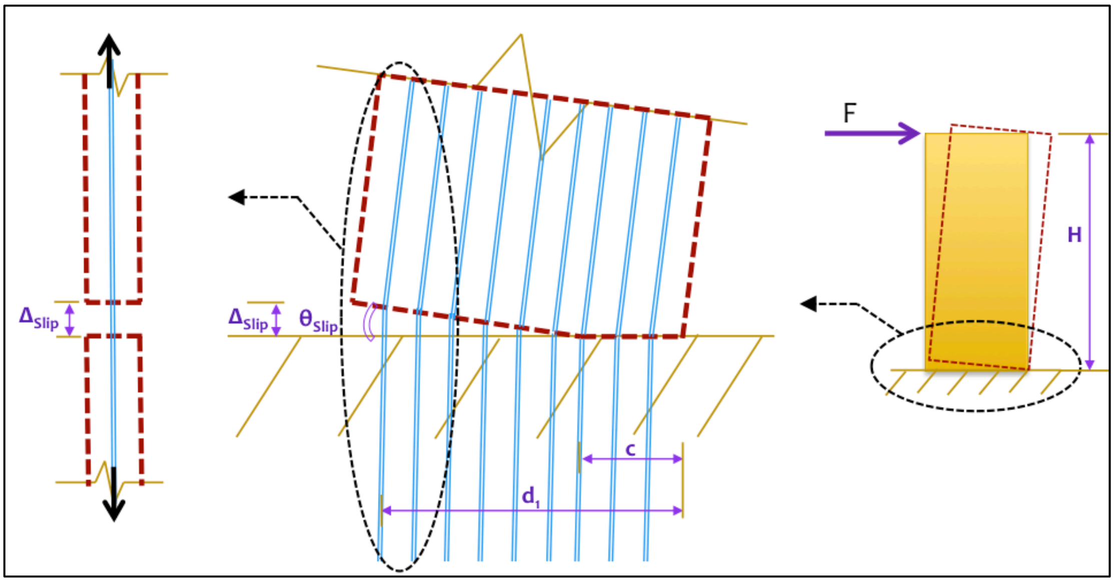

Fig. 1: The Development of The Yield Penetration Displacement Near The Wall Base.

When a non-ductile shear wall is subjected to a marginal axial load ratio, in which the cracking moment is greater than the ultimate moment of the member, it is expected to have one main crack formed down the base of the wall as opposed to having multiple cracks formed over the wall height (Davey & Blaikie 2005). This type of failure has been reported in counterpart walls in the Canterbury earthquakes 2010/2011 (Henry 2013). In those walls, some of the outermost longitudinal bars were fractured prior to the formation of a second crack.

In this paper a reinforced concrete (RC) element, which represents an outermost strip of a RC wall, has been tested under uniaxial cyclic loading with the aim of investigating the development of rebar strain over the length of the structural element (Fig. 1). Unlike other comparable experimental procedures such as direct rebar pull-out test (Engström 1992; Engstrom, Magnusson & Huang 1998) or testing of reinforcing rebar welded to an external steel plate (Fronteddu 1992), the specimen herein was successfully fabricated to simulate the nearest loading condition so that the embedded rebar would be loaded indirectly while maintaining robust boundaries (Fig. 2).

The ultimate objectives of the joint experimental/analytical research program between the University of Melbourne and Swinburne University of Technology are to quantify the displacement capacity of the lightly (non-ductile) RC shear walls up until the axial collapse limit state and assess the potential seismic performance of those walls utilising a displacement-based procedure.

2 EXPERIMENTAL PROGRAM

2.1 DESCRIPTION OF THE SPECIMEN

In order to achieve comparable strain development of the outermost longitudinal bars, the specimens were embedded with a single rebar along the specimen centreline in the loading direction. A series of specimens with various bar sizes (10, 12 and 16 mm) and concrete grades (ranging between 40 and 65 MPa) were tested. Details of only one example specimen #A (N10) is presented herein.

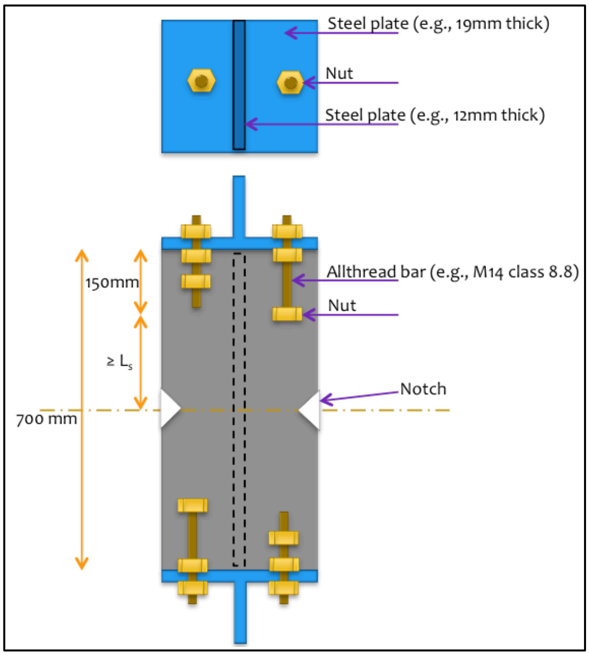

Fig. 2: Experimental Specimen #A (N10).

2.2 MATERIAL PROPERTIES

The concrete compressive strength was measured from a series of 100×200 mm cylinder tests which were carried out on the same day of the specimen test (at a concrete age of 20 days). The average concrete compressive strength f_c' was found to be 40.60 MPa.

The embedded reinforcing rebar was of the Australian type D500N (deformed-normal ductility bar, grade 500 MPa). Bar N10 was tested in the laboratory and the stress-strain relationship is shown in Fig. 3. The yield and ultimate mechanical properties are summarised in Table 1. All the threaded bars

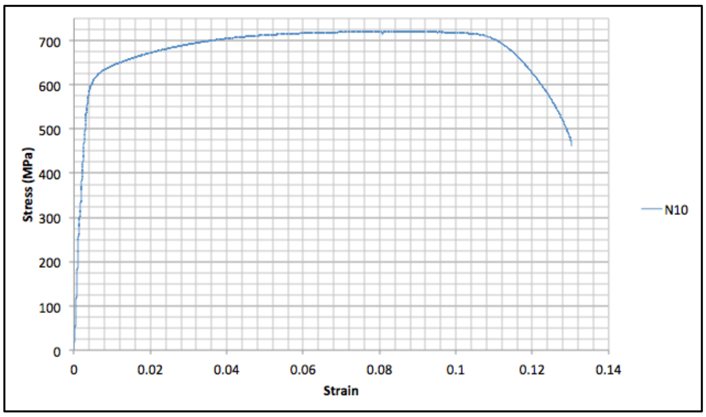

Fig. 3: The Stress-Strain Relationship (σ-ε) for Bar N10.

(M14-class 8.8), which were utilised to transfer the applied load between the steel plates and the reinforcing bar, were high-tensile steel with stress area of 115 mm^2 and minimum tensile strength of 800 MPa.

Table 1: The Mechanical Properties of Bar N10.

Bar dia (mm)	Yield		Ultimate		Rupture
	Strain (ε_y)	Stress (f_y) (MPa)	Strain (ε_u)	Stress (f_u) (MPa)	Strain (ε_{rup})
10	0.0029	500	0.1	720	0.13

2.3 SPECIMEN GEOMETRY AND TEST SETUP

The specimen has a cross-section of 175×175 mm and a height of 700 mm. The specimen was designed and cast so that the reinforcing bar (N10) is in alignment with the centreline of the specimen. A couple of all-threaded bars were embedded by 150 mm into the concrete and were orientated parallel to the reinforcing bar at both ends of the specimen in order to transfer the cyclic loading between the steel plates and the reinforcing bar (Fig. 2). A triangular notch (12 mm deep) was made all around the side of the cross-section at mid-height of the specimen. High-tensile nuts were used to ensure that that the all-threaded bars were in alignment and to enhance load transfer (bearing over the nuts).

Reversible loads were applied to the specimen using a servo-hydraulic universal testing machine (MTS) with a total capacity of 1 MN (Fig. 4). The load was displacement-controlled at a rate of 1 mm/min, with dead end at the lower jaw and active end at the upper jaw. This setup was found to be satisfactory given that only a single crack occurred at the notch plane up until the termination of the test.

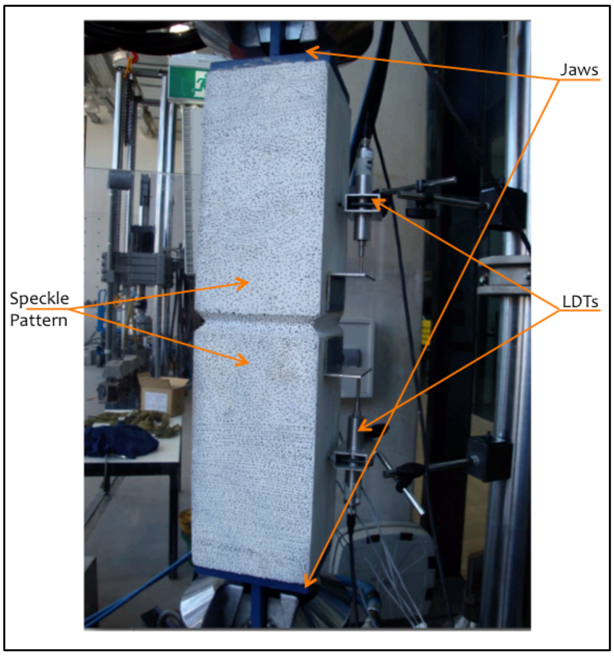

Fig. 4: Test Setup.

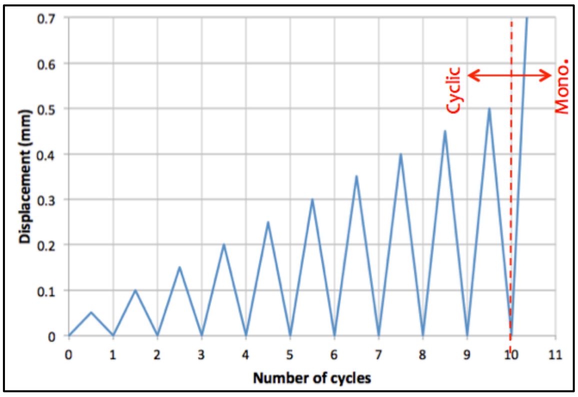

Fig. 5: Applied Loading Regime.

2.4 INSTRUMENTATION

The parameters of interests were the load applied, the total axial displacement, the crack width and the strain profile of the steel bar measured adjacent to the crack. The first two parameters were measured directly using the servo-hydraulic testing machine (MTS). The localised crack width was measured using two Linear Displacement Transducers (LDTs), with a gauge length of 50 mm. The strain profile was measured using 5 post-yield strain gauges (TML–YEFLA-2-1L).

The strain gauges were distributed at -83, -40, 0, +20 and +60 mm from the mid-height of the specimen (i.e., notch). It should be noted that the bar cross-sectional area was marginally reduced due to flattening of the strain gauge sticking spots.

To validate the result, speckle pattern image correlation technique (Correlated Solutions) was employed to measure the localised gap displacement (Fig. 4).

2.5 LOADING REGIME:

The applied loading regime was displacement controlled with a mean loading rate of 1 mm/min. That mainly consists of two loading series: cyclic loading with 10 incremental cycles up to 0.5 mm and monotonic loading up to the limit of steel bar rupture (Fig. 5).

3 TEST RESULTS

3.1 FORCE-DISPLACEMENT RELATIONSHIP (F-Δ)

The force displacement relationship for the entire specimen (jaw displacement) was plotted alongside the two direct sources of the localised gap displacement (LDTs and speckle pattern displacements), as shown in Fig. 6. As expected, the jaw displacement was found to be always the largest because of the larger gauge length and additional contributions from elastic deformation of the specimens and the steel plates. On the other hand, fairly good matches were found between the LDTs and the speckle pattern results.

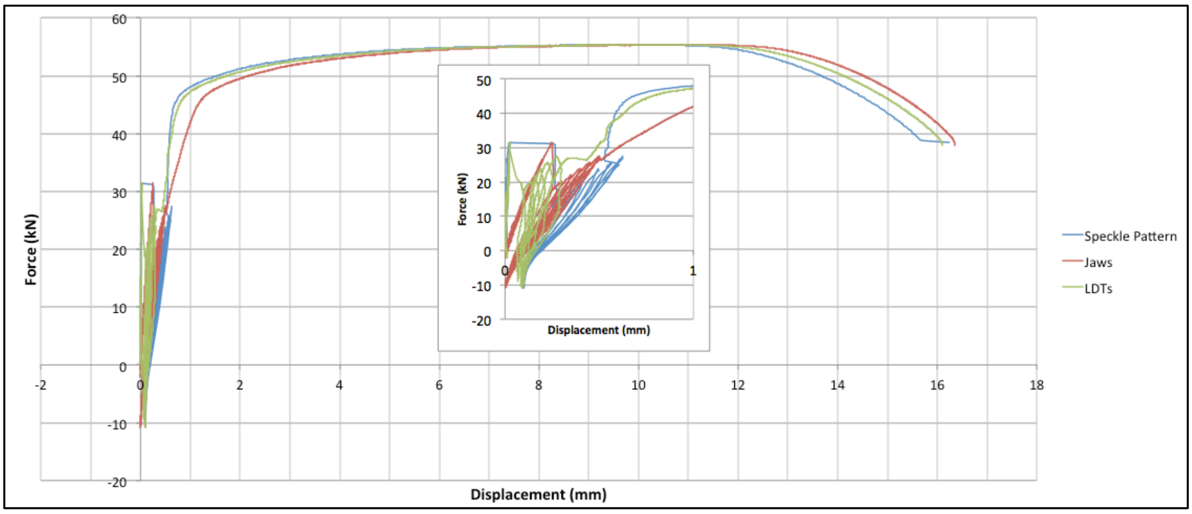

Fig. 6: The Force-Displacement From The Jaw, LDTs and Speckle Pattern Readings.

3.2 STEEL BAR STRAIN PROFILE

The readings obtained from the 5 post yield strain gauges were initially adjusted to account for strain gauge nonlinearity. Subsequently, five readings were integrated and plotted on one side for improved visibility and hence extrapolation of the missing part of the strain profile.

The values of the strain penetration length (L_s) were inferred by extending from the lines representing the outermost strain gauge readings. In the post yield stage, however, some of the strain gauge readings were estimated by equating the area under the strain profile curve (strain gauge displacement) with the corresponding LDTs displacement value (Fig. 7).

Each of the developed strain profiles was integrated over the strain penetration length (L_s) for calculation of the total displacement values which were then correlated with direct measurement of the total displacement by the LDTs (Fig. 8).

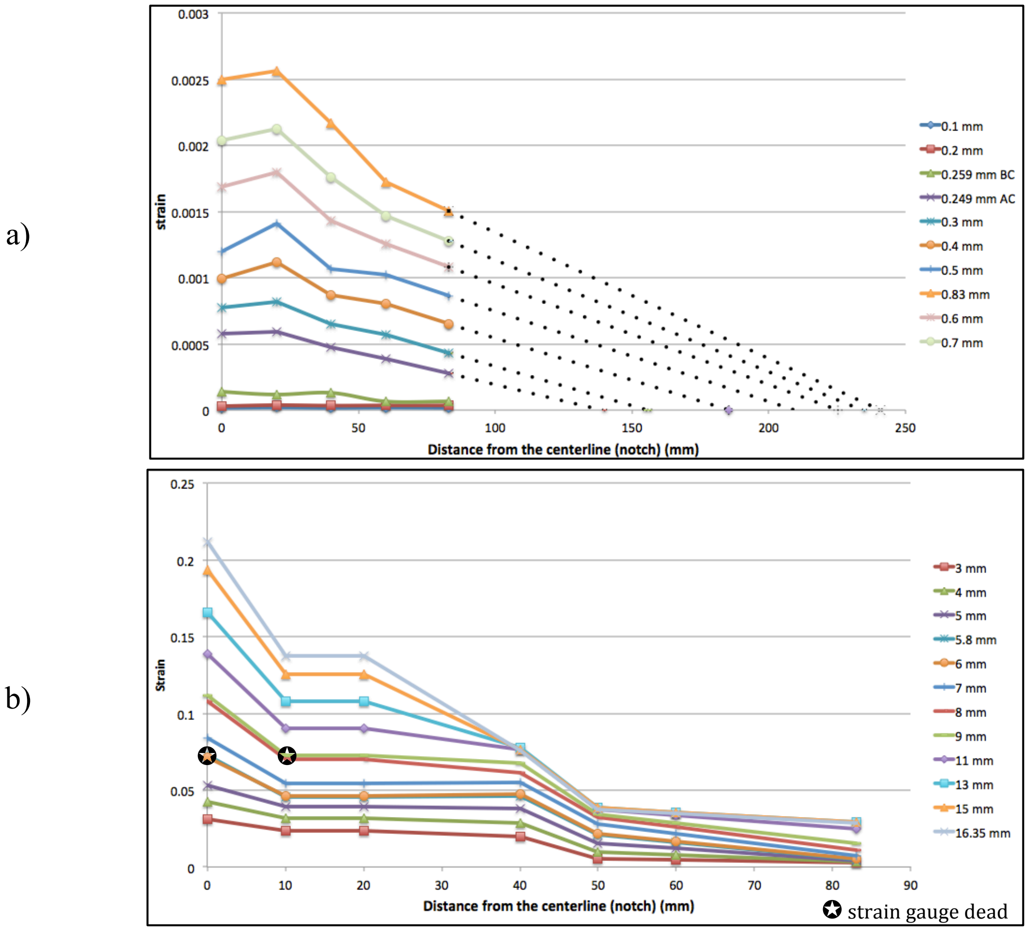

Fig. 7: The Developed Steel Strain Profile Up to: a) Yield Limit State and b) Post-Yield Limit State.

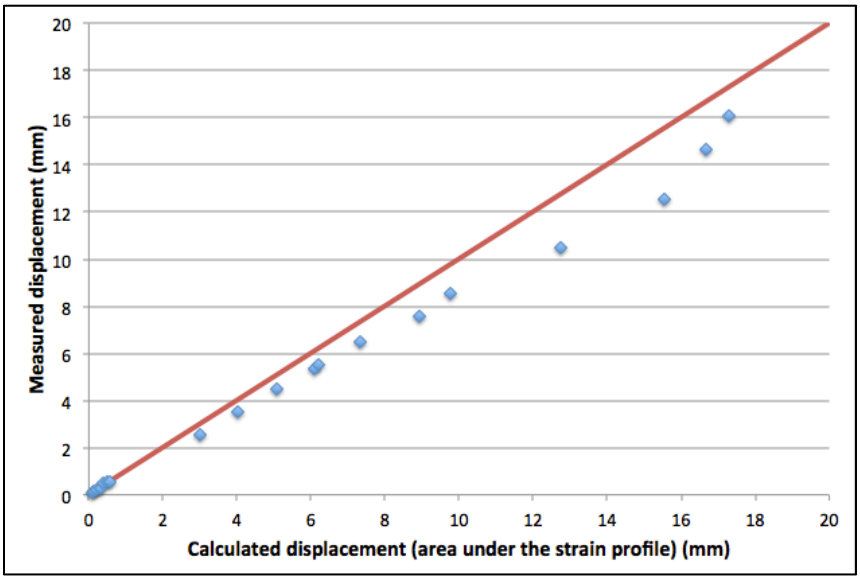

Fig. 8: The Measured Gap Displacement (LDTs Displacement) Versus The Calculated Gap Displacement (Integrated Area Under The Strain Profile).

4 CONCLUSION

- The main objective of this study was to gain a good understanding of the development of strain penetration displacement component in a lightly reinforced concrete element by miniature experimentations.
- The tested concrete specimen was designed and fabricated to match well with the conditions of strain penetration of the rebar down the bottom of a non-ductile shear wall. The test setup was found to be representative of real conditions given that only one crack was formed along the notch plane.
- The gap displacement was recorded employing two techniques: LDTs and speckle pattern. The recorded results were found to be matching well up until the steel rupture.
- The steel strain profile was precisely constructed using 5 post yield strain gauges which were distributed around the preformed crack (notch). It should be noted that the measured gap displacement readings (LDTs) were utilised to compensate for missing readings from the damaged strain gauges at the latest loading stage.

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