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Behavior of Reinforced Concrete Walls with Mesh Reinforcement Subjected to Cyclic Loading

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Abstract:

This work forms part of a research program to assess existing non-conforming reinforced concrete walls, namely walls designed according to older seismic codes that do not meet the modern seismic provisions. An experimental study undertaken to assess the seismic behavior of reinforced concrete shear walls (SWs) constructed prior to the introduction of seismic design requirements of Turkey. For this purpose, a SW test specimen, representing typical medium-rise walls, was designed and tested as cantilever under static cyclic loading. The test data documenting the global and local behavior of the test unit can serve as a reference point for the research community. Lightly reinforced concrete SW test specimens formed only a single crack in the plastic hinge region as opposed to the expected distributed cracking. This type of failure takes place due to rupturing of longitudinal reinforcement with crushing of concrete therefore is of particular interest in emphasizing the mode of failure that is not routinely considered during seismic design of reinforced concrete SW.

Key words: Reinforced concrete, seismic design, shear-wall, minimum vertical reinforcement

1. Introduction

Modern seismic design is based on the ductile response of the structure. With this premise modern seismic codes give great attention to the seismic detailing of reinforced concrete members, trying to secure the flexural behavior of the member and to reach adequate ductility levels. In a lot of countries with high seismic exposure there is a significant number of existing structures, designed according to older seismic regulations, which include SWs non-compliant to modern seismic design and detailing provisions. These non-conforming SWs do not include confined boundary elements and they are characterized by low ratios of shear reinforcement [1-6]. In design, reinforced concrete walls are intended to develop a ductile flexural behavior consistent with the strength reduction factor R, and hence, brittle modes of failure should be avoided [7]. Reversed cyclic lateral loading was performed on reinforced concrete SW test specimen having distributed mesh reinforcements. Full scale reinforced concrete SW test specimen subjected to low axial load was tested under reversed cyclic lateral loading. Reinforced concrete buildings constructed prior to the 1975s in Turkey [8] were not designed and detailed to undergo a ductile mode of failure. This work forms part of a research program to assess existing non-conforming reinforced concrete SWs, namely walls designed according to older seismic codes that do not meet the modern seismic provisions. The objective of the current study is to investigate, how the level and distribution of vertical reinforcement can influence the wall failure mechanism.

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2. Details of Test Specimen

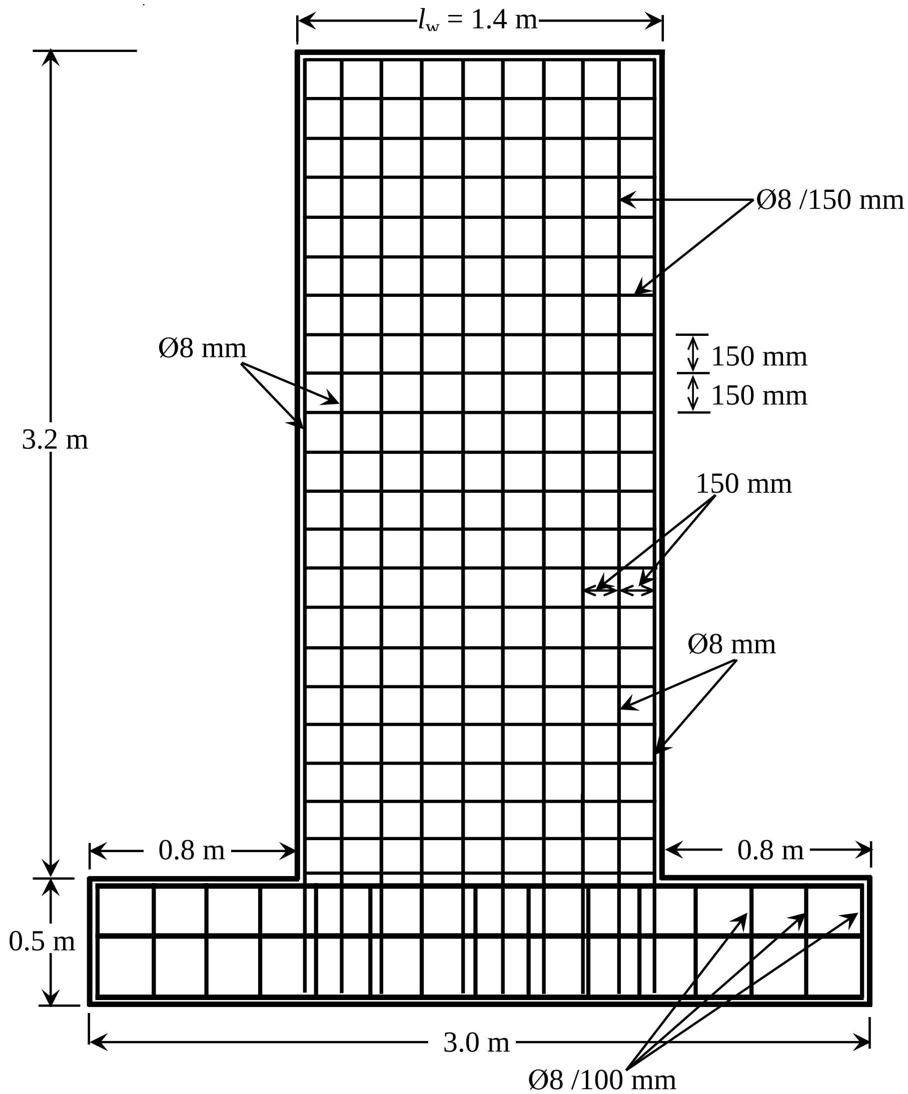

Figure 1. Elevation view of the reinforcement layouts of foundation and SW test specimen

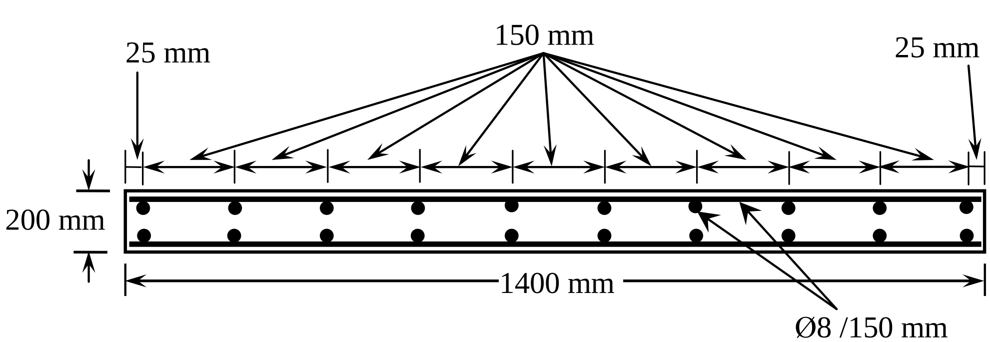

Figure 2. Plan view of the reinforcement layouts of the SW test specimen

Figure 3. General view of the SW test specimen in the construction stage

Figure 4. Pouring the concrete of the SW test specimen

The experimental work described herein involves the testing of a full scale SW. The test specimen was designed to represent the lower stories of structural walls in high-rise buildings. Testing program consisted of lateral reversed cyclic loading. Reinforced concrete wall specimen was designed and labeled as SW. The SW was 3.2m tall, 1.4m length, 0.2m thick and had an aspect ratio (height-to-width ratio) of 2.285. The dimensions of the elevation view of the SW specimen are illustrated in Figure 1. The wall was located on the building perimeter next to a stairway shaft. The applied gravity loads produced a compressive stress of 1% of the nominal concrete compressive strength and were therefore ignored in the test program. A detailed description of the experiments and a compilation of all test data are available elsewhere [9]. Mesh reinforcement for the walls consisted of 8 mm diameter deformed bars. The SW was constructed with normal-strength concrete having a nominal compressive strength f_c = 30Mpa and reinforcing steel with a nominal f_y of 500Mpa and f_u of 550 MPa. Double-layer mesh reinforcement was placed in the SW test specimen. Bar spacing in the vertical and horizontal directions were 150 mm. Figure 2 shows the plan view of the reinforcement layouts of the shear-wall test specimen. The ratio of wall reinforcement along each orthogonal direction was 0.0036. SW test specimen was monotonically constructed and manufactured on the foundation having 0.7m width, 3.0m length, and 0.5m thickness. The rigid foundation was clamped to the laboratory strong floor by high-strength steel bolts. The photograph in Figure 3 shows the general view of the shear wall test specimen in the construction stage. Figure 4 shows the pouring the concrete of the SW test specimen.

3. Instrumentation and Test Procedure

The testing was performed to determine the inelastic seismic behavior of the SW test specimen. The specimen included the test wall portion and a strong foundation block used to reproduce realistic base condition. The foundation block was purposely designed significantly thicker than the test wall to limit cracking in the foundation. The wall and foundation portions were cast continuously without cold joints. The specimen was mounted vertically on the strong floor of the laboratory and the load was applied by a 500 kN actuator with pinned end conditions.

Figure 5 shows the test setup used in the experimental program. The testing system consisted of strong floor, reaction wall, loading equipment, instrumentation and data acquisition system. The lateral loading system consisted of a load cell, hydraulic jack and hinge. Instruments were used to measure loads and displacements for the SW test specimen. Load cell measured the lateral loads applied to the specimen. Strain gage-based linear variable differential transformers (LVDTs) were used to measure the displacements. Five LVDTs were mounted to measure the lateral displacements over the wall height. An LVDT was mounted horizontally on the foundation to monitor any horizontal slip of the foundation along the reaction floor.

Figure 5. Test setup, loading system and instrumentation of SW test specimen

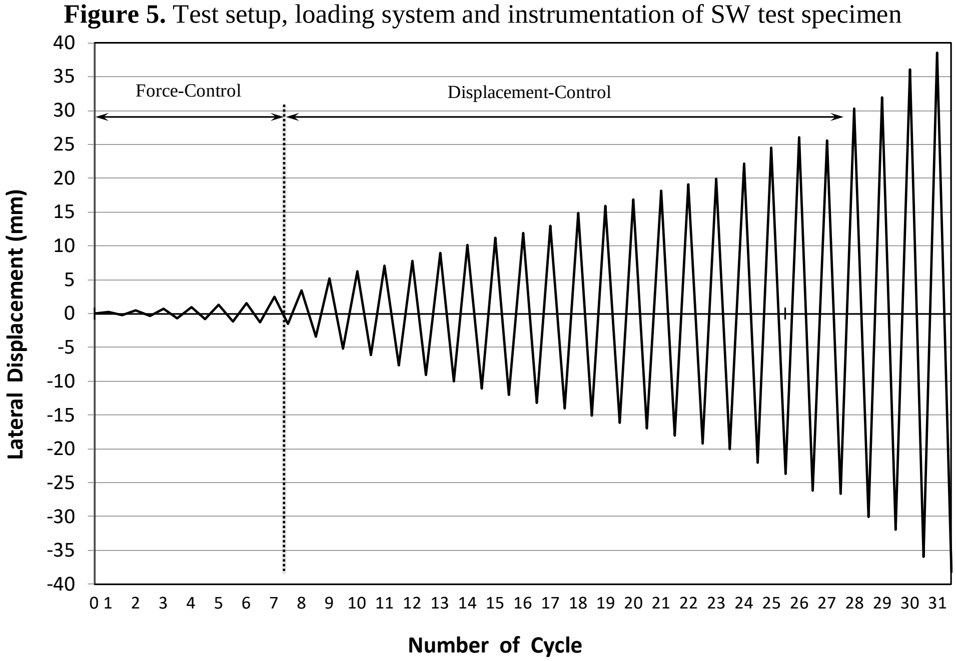

Figure 6. Reversed-cyclic lateral displacement history

Test was conducted by controlling the horizontal top displacement imposed by the actuator. The specimen was subjected to reversed-cyclic lateral loading. A reversed-cyclic lateral displacement history shown in Figure 6 was applied to SW test specimen. The measurements were recorded by a computer data acquisition system. During the tests, cracks and failures were observed carefully and recorded by hand. Movements of the foundation block and actuator resisting system was monitored and removed to obtain the wall deformations relative to the foundation. The test, however, was interrupted to allow for observation of damage and photos to be taken.

4. Experimental Results

The initial cracks in the concrete occurred at an average measured lateral load of +/-60 kN of the SW. The cracks were nearly horizontal and formed from the edges of the SW. Being that the cracks are mostly horizontal, it can be concluded that the response of the SW is governed by bending. As the loads increased, the edge cracks progressed toward the centre of the wall. This was followed by the crushing of the concrete and buckling of longitudinal reinforcement in the boundary regions. Figure 7 shows the cracking patterns of SW at 16 mm lateral displacement. The performed test showed an expected flexure-dominant behavior in accordance with the design process, crushing of the compressed concrete and the tearing of the tensioned steel reinforcement. Buckling of longitudinal reinforcements can be seen in Figure 8. The final stage was buckling of the boundary reinforcement and tearing of all the mesh reinforcements at the foundation level. The test was stopped due to tearing of the all the vertical reinforcements and buckling of the boundary reinforcement. Collapse of SW characterized by the existence of a wide crack at the base level (Figure 9), thus showing a higher tendency to localize plastic deformations in mesh reinforcement. All the longitudinal bars just above the foundation level were broken. The concrete in the boundary regions were crushed. Figure 9 shows overall condition of SW test specimen at end of test. Figure 10 shows the horizontal lateral force - lateral top displacement curves for the SW. Maximum lateral top displacement was 38.5mm and the maximum lateral load capacity of the SW was 108 kN. Lateral force versus - lateral displacement at 2.0m and 1m above the foundation levels were presented in Figure 11 and Figure 12, respectively. Maximum lateral displacement at 2.0m above the foundation levels was 27.4mm. The lateral load- drift ratio relationship of the wall specimen is plotted in Figure 13. Maximum lateral top drift ratio was 1.26 for SW test specimen. Lightly reinforced concrete SW wall test specimens formed only a single crack in the plastic hinge region as opposed to the expected distributed cracking. Because of the lack of distributed cracks, the inelastic deformation of the SW test specimen was concentrated in a significantly reduced plastic hinge length, resulting in the premature fracture of vertical reinforcement, as shown in Figure 9. Furthermore, large crack openings at the wall base can cause additional problems, such as large axial elongations, wall sliding and early reinforcement buckling. In response to the observed performance of lightly reinforced concrete SW to ensure that yielding of reinforcement can extend beyond the immediate vicinity of a single primary crack.

Figure 7. Cracking patterns of SW at 16 mm lateral displacement

Figure 8. Buckling of longitudinal reinforcements

Figure 9. Overall condition of SW test specimen at end of test

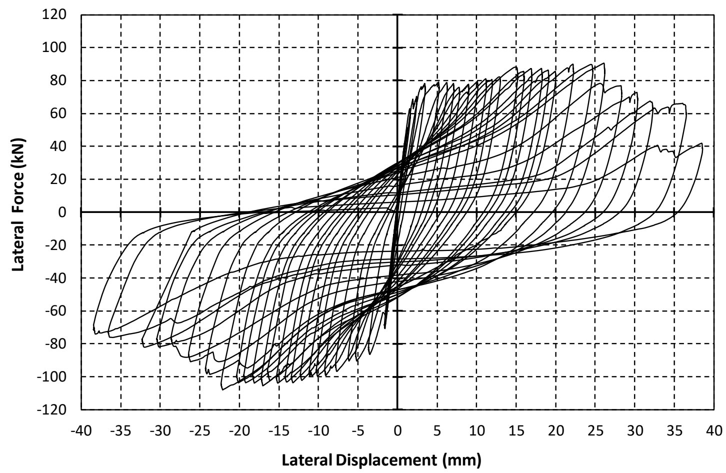

Figure 10. Lateral force versus lateral top displacement relationships of SW

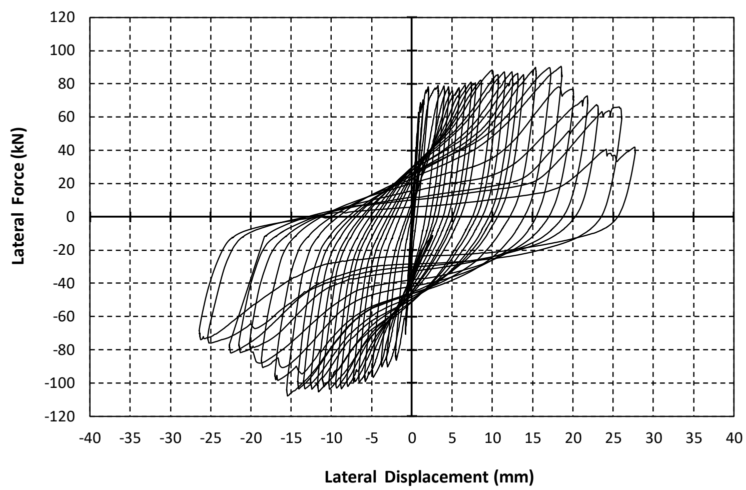

Figure 11. Lateral force versus - lateral displacement relationships 2.0m above the foundation level

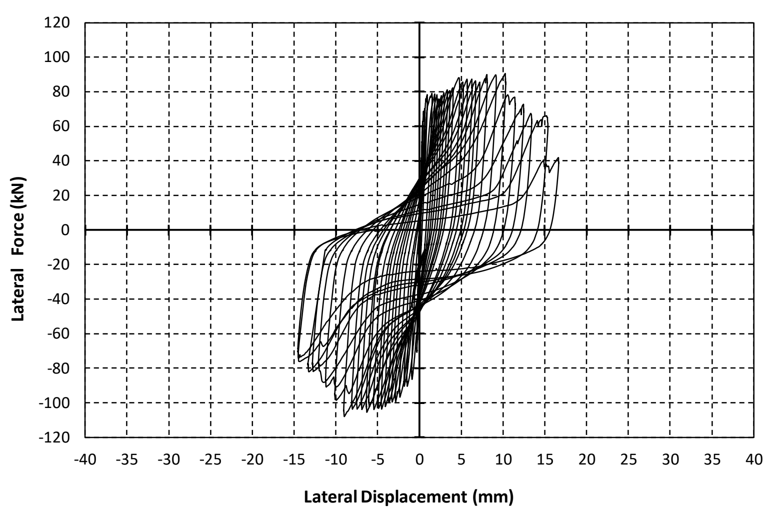

Figure 12. Lateral force versus - lateral displacement relationships 1.0m above the foundation level

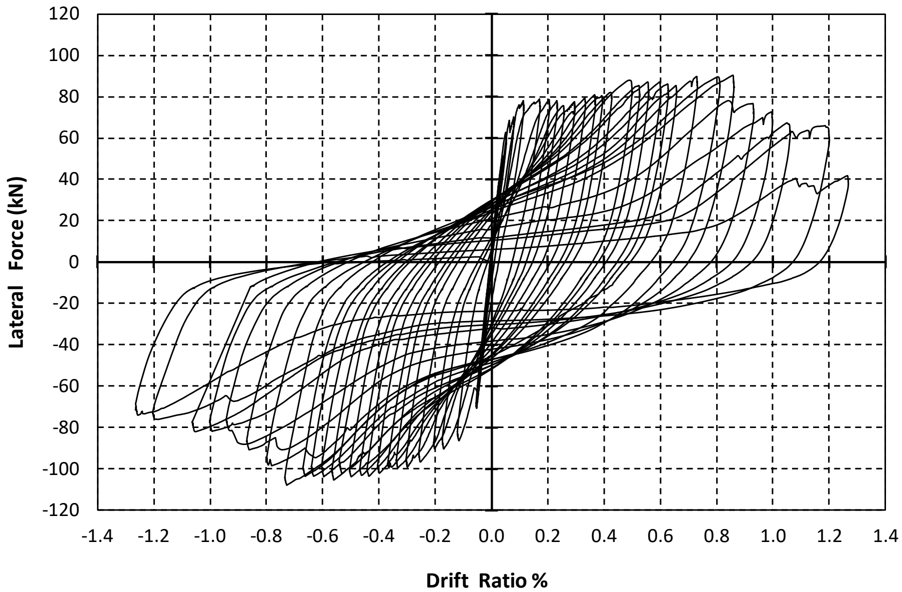

Figure 13. Lateral force versus lateral top drift relationships of SW test specimen

Results and Conclusions

In a lot of countries with high seismic exposure there is a significant number of existing structures, designed according to older seismic regulations, which include shear walls non-compliant to modern seismic design and detailing provisions. Flexure dominant reinforced concrete SW test specimen with two layers of distributed vertical reinforcement was tested. The lateral-load response of the SW test specimen was controlled by one main large flexural crack at the wall base. This behaviour greatly reduced the spread of plasticity and resulted in several potential issues, such as limited drift capacity and premature reinforcement buckling or fracture. Therefore, to achieve a high ductility capacity during earthquakes, reinforced concrete SWs should be designed to form a large number of distributed primary and secondary flexural cracks in the plastic hinge region. If insufficient vertical reinforcement is provided in RC walls, the cracking moment may exceed the nominal flexural capacity of the wall, and sudden loss of strength and failure could occur [10-11]. Primary cracks occur as a result of the flexural cracking strength of the wall being exceeded, whereas secondary cracks occur based on the local tensile stresses induced by the reinforcement into the surrounding concrete. Additionally, the tension force generated by the reinforcement may not be sufficient to develop secondary flexural cracks in the surrounding concrete, resulting in a limited number of cracks. Previous researches also to confirm that [3,4,5,9,10,11] reinforced concrete SWs with minimum distributed vertical reinforcement may be susceptible to sudden failure unless a significant axial load was applied. This finding was supported later by other researchers who highlighted the potential deficiencies of the current minimum vertical reinforcement requirements [12]. The rotational capacity of the plastic hinge is dependent on the distribution of cracking, with a greater number of flexural cracks allowing the vertical reinforcement to yield over a significant length.

Acknowledgements

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