Experimental Evaluation of Transverse Reinforcement Configurations of Earthquake – resistant R/C Shear Walls

I. A. Tegos, K. T. Psarras, D. Kalkinis, I. C. Papadopoulos & N. Legbelos
Aristotle University of Thessaloniki, Department of Civil Engineering, Thessaloniki, Greece

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SUMMARY
The term "transverse reinforcement", used for reinforced concrete (R/C) shear walls, denotes both lateral horizontal web reinforcement related with the shear transfer mechanism, as well as confinement reinforcement at the strengthened boundary regions. Regarding the shear resistance reinforcement, an experimental research is conducted on the evaluation of different anchoring configurations at the boundary regions, according to criteria associated with the ease of construction and the structural performance. For this purpose, a total of three specimens under monotonic lateral loading were tested. Based on the same criteria, seven more specimens were tested under monotonic loading, for the evaluation of different types of confinement reinforcement. The examined configurations were both conventional, differing at the anchoring details, as well as unconventional, as in the case of the incorporation of steel hollow sections filled with concrete in the critical regions. The latter configuration multiplies the confinement effect, increases the bearing capacity of the boundary bending regions against compression (and tension), and drastically reduces the sliding shear failure risk at the base, which is, as known, the "Achilles' heel" as regards to the seismic contribution of earthquake – resistant shear walls. Conclusions are extracted based on the above experimental results. Furthermore, design recommendations are proposed for the enhancement of the seismic performance and the ease of construction of shear walls, which are the most critical structural elements, regarding the earthquake resistance of multistory dual spatial systems. The study is of special interest for both the design as well as the construction process of different applications.

Keywords: Confinement, Shear Wall, Transverse Reinforcement

1. INTRODUCTION

Currently, several experimental investigations [1-8] have been conducted on the behavior of squat RC walls under simulated seismic loading. RC structural walls are frequently used in buildings primarily to resist lateral loads imposed by wind and earthquakes. In recent years, extensive research has been conducted to assess the validity of current design provisions in squat RC walls. These walls are usually detailed according to the current provisions and are aimed at achieving full ductile behavior of structural walls. Presently, various countries have recommendations for confirming reinforcement to ensure that the required ductility demands can be achieved. A high ductility demand can be expected and therefore the required quantities of reinforcements, especially the transverse reinforcement in the web and boundary elements must be effective.

The use of the required quantities of transverse reinforcement could eliminate shear failure. However, the risk of sliding shear at the base of shear walls still exists. Due to sliding shear their ductile behavior can not be achieved. When sliding shear takes place, the cracks at reinforced concrete remain open under cyclic load. In that case, the resistance of the reinforcement at the base of the wall is dramatically reduced, and finally it slides, as the remaining reinforcement can not afford the lateral load. In addition, that type of failure could not be avoided even if the content of transverse reinforcement is great, because of the vertical cracks.

Experimental research has proved that sliding shear failure does not allow the shear wall to use its plastic hinge in order to develop its flexural strength. Also, experiments that took place at the Aristotle University of Thessaloniki, concluded that the use of diagonal reinforcement reduces the possibility that type of failure to take place. Diagonal reinforcement is positioned at the base of the shear wall, in the center of the region. The results, using that type of reinforcement, are positive. However, that method does not solve that problem completely, while the diagonal reinforcement protects the base of the shear wall, and the failure can take place higher, except for shear walls of low height, where its response is better. Other experimental tests on shear walls have proved that great content of transverse reinforcement in the wall boundary elements, could eliminate sliding shear failure, as well as to increase the ductility of those critical regions.

The aim of this work is to recommend methods which could reduce the sliding shear failure, and increase its shear strength respectively. The first method has to do with the evaluation of different anchoring configurations at the boundary regions, and it refers to the lateral horizontal web reinforcement. The second and the third method refer to different types of confinement reinforcement, using innovative anchoring details, as well as steel hollow sections filled with concrete in the critical regions.

2. EXPERIMENTAL RESEARCH

The following experimental work took place at the Aristotle University of Thessaloniki, at the Department of Civil Engineering. The subject of the research has to do with three topics. The first one includes specimens of shear walls, where the horizontal web reinforcement is anchored both conventionally and unconventionally, in order to examine whether the shear capacity of the wall is increased or not. In the second topic, ways of improving the critical regions of a shear wall are examined. The methods include three different ways of anchoring the stirrups on the longitudinal bars. It also examines the performance of the shear wall when the latter has one or two hollow sections respectively, filled with concrete in the critical regions. The last topic has to do with the sliding shear failure of shear walls. Especially, two specimens were constructed, simulating the critical region of a shear wall. By adding a hollow section filled with concrete, the phenomenon of sliding shear is halting.

2.1. Evaluation of different anchoring configurations of the lateral horizontal web reinforcement

Conventionally, the lateral horizontal web reinforcement is anchored behind the stirrups of the critical region, seen in Fig.2.1. The main disadvantage of that method is that the reinforcement bar gets into the concrete cover. However, the reason that such an anchor is preferred is the ease of its configuration. As a result, due the seismic loads, the lateral reinforcement loses its bending capacity while the concrete cover disappears, and the anchorage does not basically exist any more. That phenomenon is more frequent in coastal areas, due to steel carbonation. The methods of anchoring proposed could be characterized as easily applicable.

2.1.1. Description of the three specimens

There were constructed three different specimens of shear walls, dimensioning 0.20x0.20x3.30 m (7.87x7.87x129.92 in.). The aspect ratio of the experiment was 1:2,5. The longitudinal reinforcement of the critical regions consists of 8 bars of a diameter of 16 mm (0.63 in), as well as for the shear reinforcement there were used stirrups Ø4.2@5.5 cm (Ø0.17@2.17 in). The concrete category was C20/25. The first wall is represented in Fig. 2.1. The second one includes lateral horizontal web reinforcement that is anchored behind the longitudinal reinforcement of the critical region, by making an angle of 180^{o} as shown in Fig. 2.2. The last specimen consists of horizontal reinforcement that is anchored at the internal part of the longitudinal reinforcement, as shown in Fig. 2.3. In all three specimens the lateral horizontal web reinforcement is Ø4.2@110 mm (Ø0.17@4.33 in).

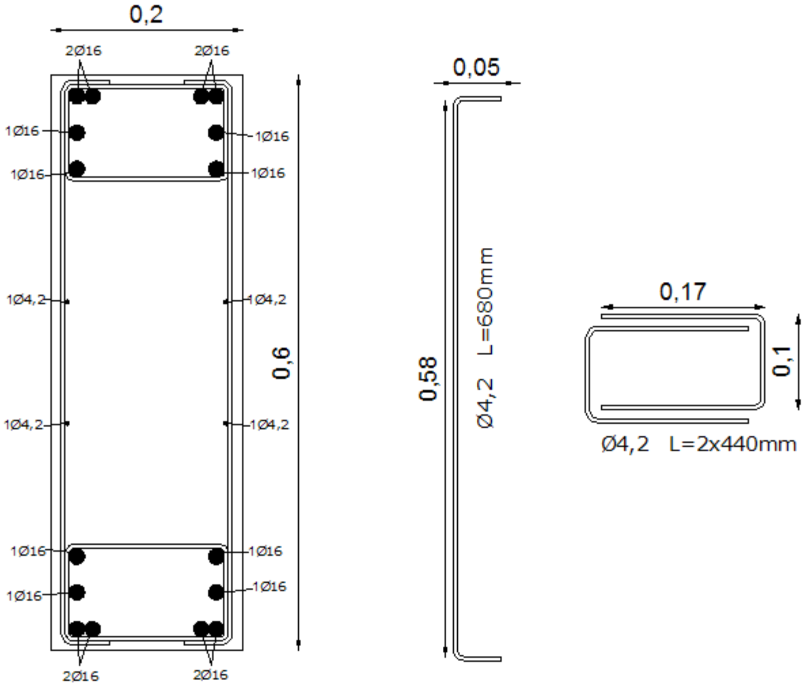

Figure 2.1. Geometrical characteristics and reinforcement of the first (conventional) specimen

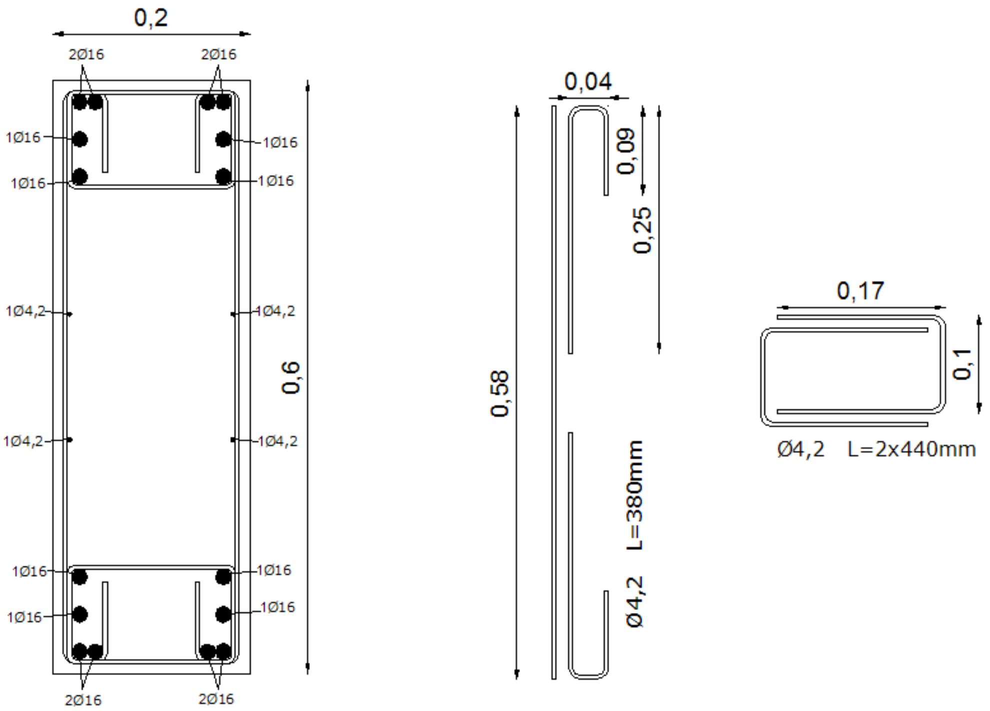

Figure 2.2. Geometrical characteristics and reinforcement of the second specimen

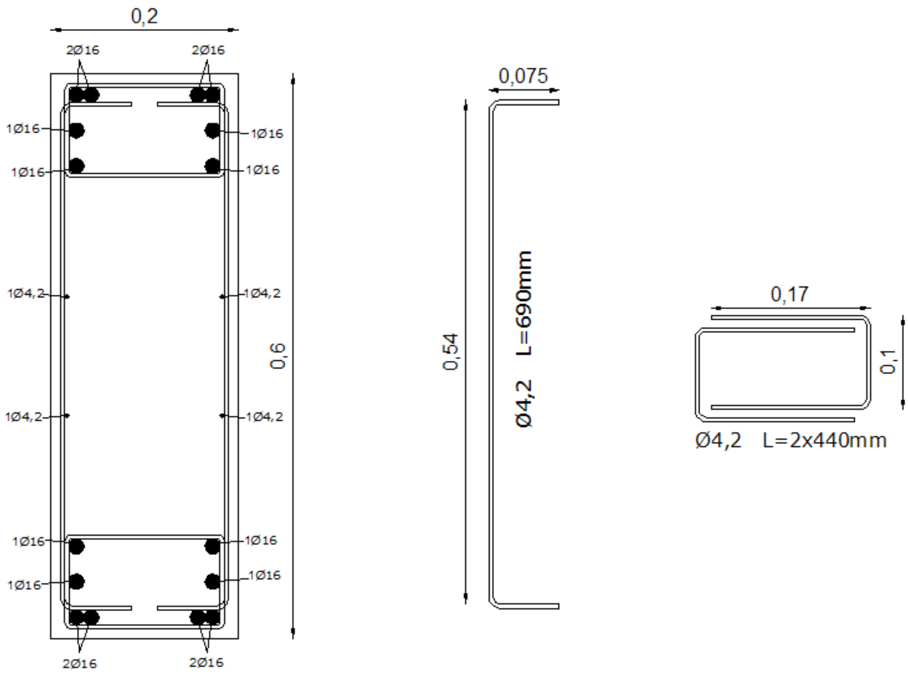

Figure 2.3. Geometrical characteristics and reinforcement of the third specimen

Figure 2.4. Loading of one of the specimens

2.1.2. Loading process and experimental results

After the concreting process the shear walls were loaded up to failure, as depicted in Fig. 2.4. The load was monotonic and subjected on the wall, as a lateral seismic load. The estimated shear capacity of the sentiment was 270 kN (60.7 kip), and the bending capacity of the wall is higher than the shear one. The experimental results are summarized in Fig. 2.5. where the Load – Displacement curve of the shear wall is shown.

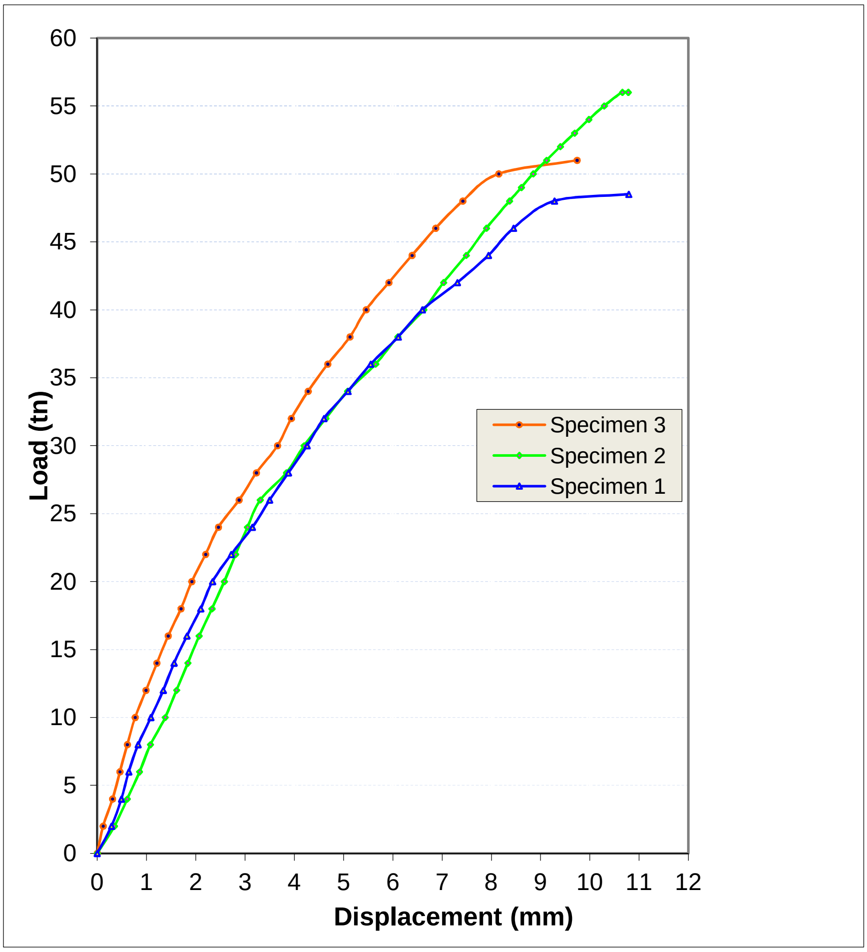

Figure 2.5. Experimental results of the first experiment, load – displacement curve

As we can see from the diagram, the optimal performance is obtained by using the second anchoring method. Quantitatively, the benefit of 20% compared to the usual way is obvious. The third specimen's results are better than the conventional ones' but not impressive. However, considering the steel carbonation, the last solution is preferable than the conventional one. In addition, the high strength concrete is one of the factors that cause the differences between the results, as the maximum anchoring load is been developed before the 90^o turning.

2.2. Evaluation of different types of confinement reinforcement

It is well known that shear capacity of shear walls increases as the confinement of concrete in the critical regions gets stronger. The current topic examines ways of strengthening the confinement in comparison with their shear capacity. The examined specimens were both conventional, differing at the anchoring details, as well as unconventional, by using hollow sections. One of the main aims of that innovation is to avoid sliding shear failure. It is worth noting that even if the specific experiments have to do with the confinement of the concrete of the critical region, the results refer to the whole shear wall.

2.2.1. Description of the five specimens

There were constructed five specimens that each one has different confinement provisions. In Fig. 2.6. the specimen's dimensions are represented, as well as the reinforcement. The longitudinal one consists of 6 bars of a diameter of 16 mm (0.63 in), except for the fourth specimen, where there were used only 4 longitudinal bars. The aspect ratio chosen for the experiment was 1:1.25. The first one is the conventional one, while the stirrups are anchored at the same longitudinal bar of the critical region, as recommended from the codes. At the second specimen, each stirrup is anchored in a different longitudinal bar, so that each bar is used once for four stirrups, and so on. At the third case, the same type of stirrups were used, as those used for torsion. In that case, each stirrup is anchored on two longitudinal reinforcement bars, once for two stirrups. The specimens that described above could be characterized as conventional. The next two ones include hollow sections filled with concrete. The first from those two has a hollow section of 220 mm (8.66 in) x 120 mm (4.72 in). The second one includes two sections of 80 mm (3.15 in) x 120 mm (4.72 in) each.

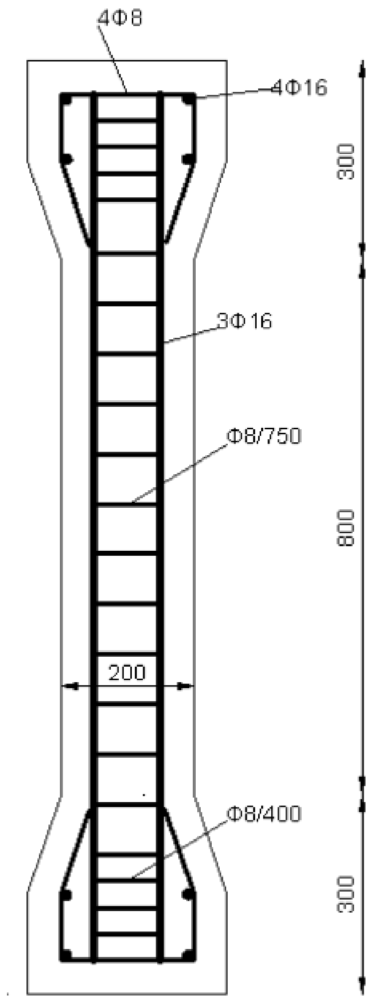

Figure 2.6. Dimensions and reinforcement of the typical speciment

2.2.2. Loading process and experimental results

After the process of concreting, the loading of the specimens followed. The load applied was axial monotonic. In Fig 2.7 the Load – Displacement curve for each case is shown. The first three curves refer to the conventional specimens, and the next two refer to those ones which have hollow sections.

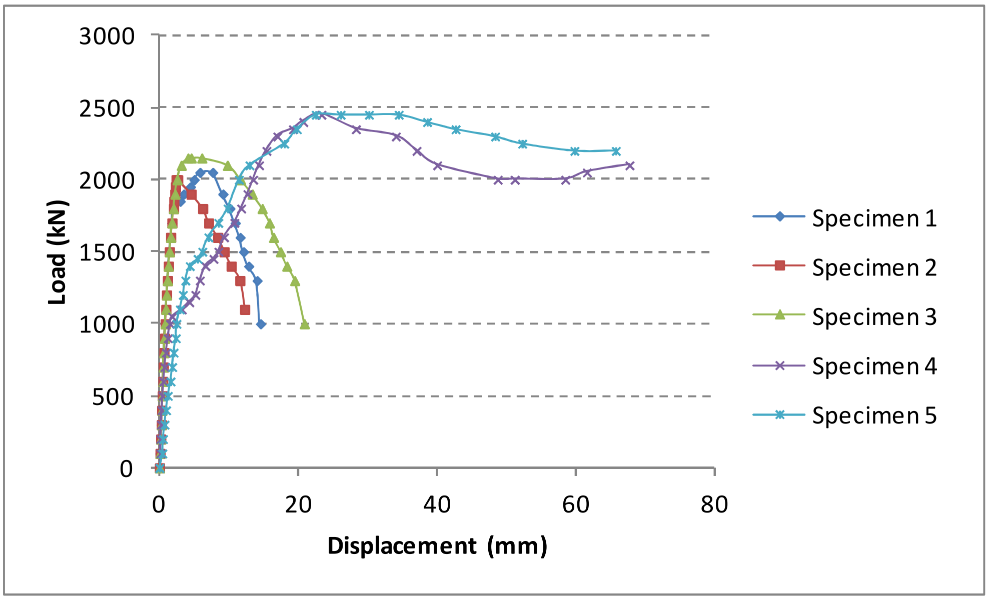

Figure 2.7. Experimental results of the second experiment, load – displacement curve

Regarding the diagram of Fig. 2.7. the stirrups of the first specimen fail, although the steel was of high quality (B500 C). It is obvious that the third anchoring method is more effective than the previous two, as we can see from its general behavior, compared with the others. As for the reason for the conventional specimens' failure, it is the buckling of the longitudinal bars. So, stronger confinement of the critical regions is required, even if it is not recommended from the codes. Alternatively, the use of longitudinal reinforcement bars with diameter upper than 20 mm (0.79 in) is recommended, which is the real type of rebar that is used at the real structure.

As for the evaluation of the confinement response of the critical regions that include hollow sections, the results could be characterized as safe, although the edges of the specimens failed very early. It wouldn't be an exaggeration to claim that the use of hollow sections at the critical regions of shear walls reduces drastically the possibility that the wall fail under sliding shear, while it strengthens the confinement of the specific area.

2.3. Evaluation of innovative critical regions of shear walls

One of the main problems that this work tries to solve, is the sliding shear failure of shear walls, as mentioned above. The experimental research that follows examines the sliding shear phenomenon, and the results refer generally to the behavior of hollow sections under seismic loads. There were constructed two specimens simulating the critical region.

2.3.1. Description of the two specimens

Both specimens have the shape represented in Fig. 2.8. The reinforcement was the same for both of them, and their difference is the hollow section that was placed in the second specimen. The concrete used was conventional.

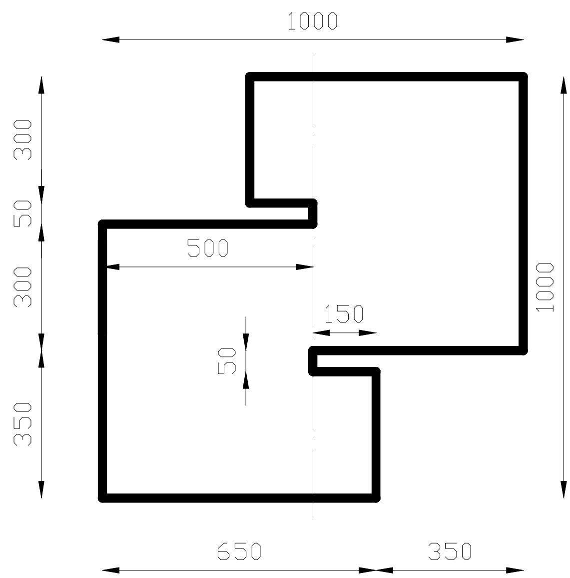

Figure 2.8. Dimensions of the specimen that is used in the third topic

In Fig. 2.9 the reinforcement of the first specimen is shown. The central zone consists of 8 longitudinal bars of a diameter of 14 mm (0.55 in), and 4 stirrups. Two of the stirrups were placed at the edges of the central zone, and the other two at both of the sides of the center, at a distance equal to the quadruple of the longitudinal bars (56 mm – 2.2 in).

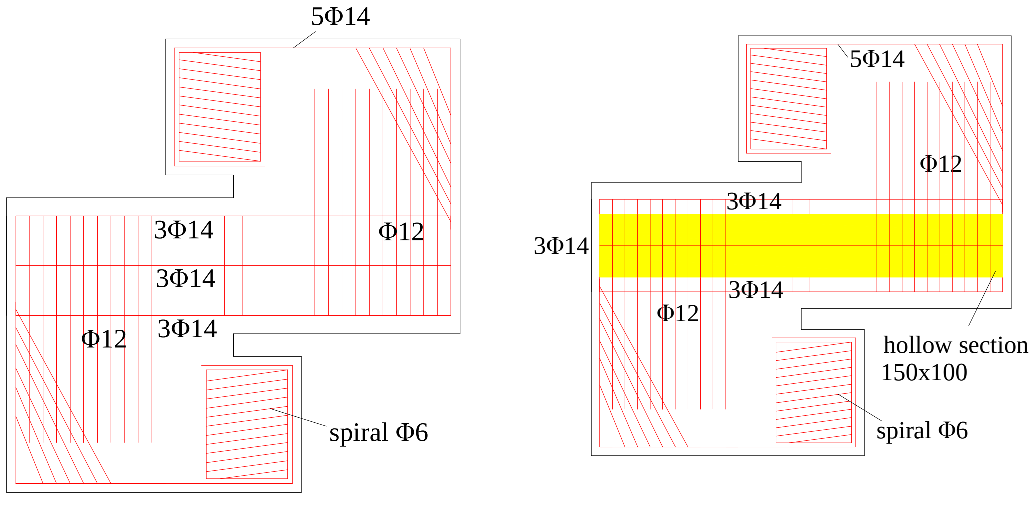

Figure 2.9. Reinforcement of the two specimens

The second specimen is of the same reinforcement as the first one, but in the central zone it includes the hollow section. The region's dimensions are 150 x 100 x 960 mm (5.91 x 3.94 x 37.80 in). It was soldered at the central zone of the specimen, 35 mm (1.38 in) far from the edges, as represented in Fig. 2.9. Finally, it was filled with conventional concrete.

2.3.2. Loading process and experimental results

Both specimens were placed in a special device, and loaded up to failure as represented in Fig. 2.10. The results of the specific experimental research are summarized in the Load – Displacement curve of Fig. 2.11.

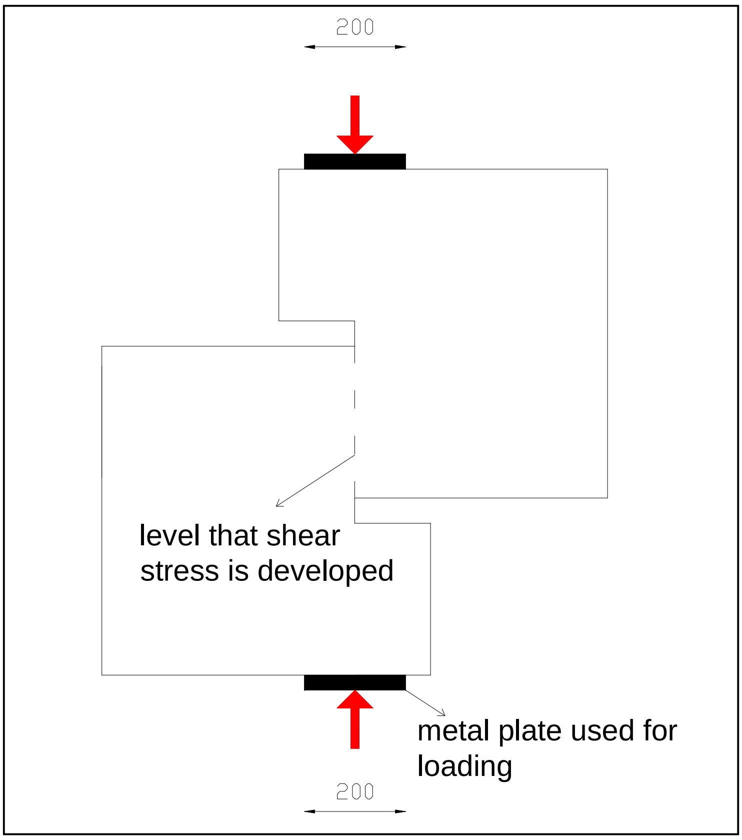

Figure 2.10. Loading of the specimens

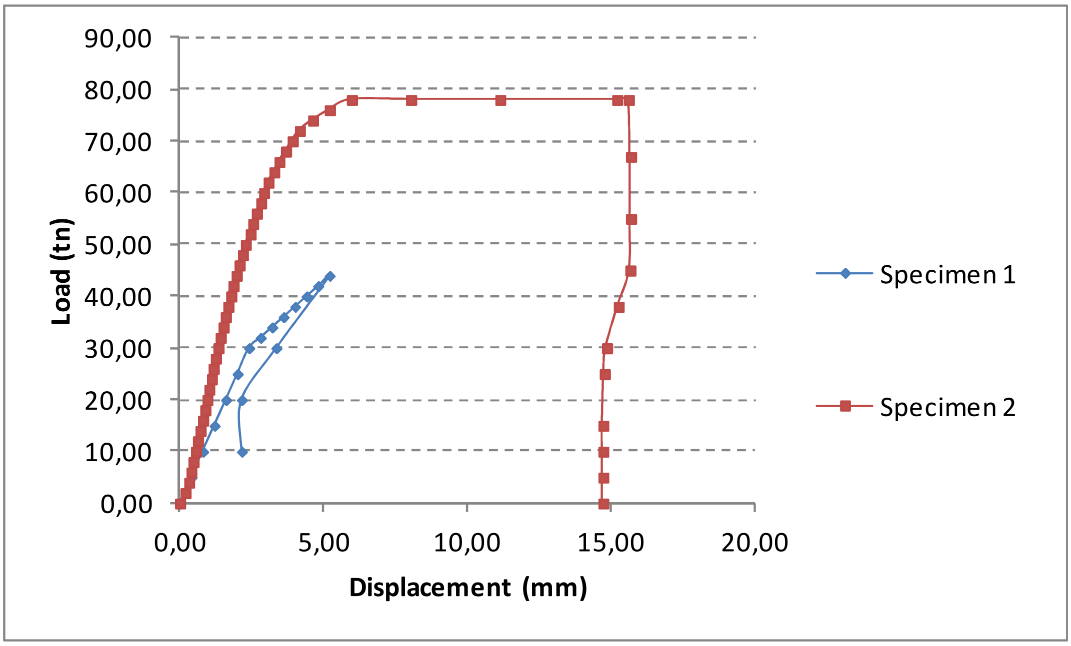

Figure 2.11. Experimental results of the third experiment, load – displacement curve

That experimental research did not examine the whole shear wall, but subtotals of it, in order to find whether hollow sections protect the structure against sliding shear or not. The main conclusion is that its use is an innovation that is according to the principles of reinforced concrete, and it could annihilate the problem of sliding shear. Experimental tests on real shear walls could prove the above results.

3. CONCLUSIONS

That work, consisting of three series of experimental tests, concluded that an improved way of anchoring the transverse reinforcement in the web and boundary elements is of great importance, as they are not usually anchored effectively.

The innovation that enhances drastically the compressive strength of boundary elements, as well as eliminates the sliding shear failure, is the use of hollow sections filled with concrete at the critical regions of shear walls. In that case, the increase of the strength capacity varies from 12% to 40%. However, the results of that work could be a motivation for experimental tests on shear walls of an aspect ratio of 1:1, under cyclic loading.

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