Repairing and Seismic Strengthening of Damaged Reinforced Concrete Structures with External Steel Shear Walls

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ABSTRACT

In this study, a new strengthening technique for earthquake-damaged reinforced concrete (RC) structures was experimentally investigated. Within the scope of the study, three-dimensional, two-storey RC model was constructed. During the production of this model, some of the common structural inadequacies in existing RC structures were taken into consideration. For this purpose, initially a reference model was exposed to lateral loads up to 1.7 % drift. Then, the damaged structure was repaired with epoxy injection. Finally, the repaired model was strengthened with External Steel Shear Walls (ESSW) and subsequently tested under the same load pattern. Chevron braced system is selected as ESSW. The results show that existing RC structures damaged under earthquake effects can be strengthened rapidly by proposed strengthening technique and the lateral load capacity and stiffness of these structures can be increased significantly.

***Keywords**: Earthquake, Repairing and strengthening, External steel shear wall, Chevron braced system.*

INTRODUCTION

Several techniques were developed for strengthening of the existing buildings [1-5]. Increasing the lateral load capacity and stiffness of the structures are the common aims of those techniques, which contribute to the performance of the structure by limiting the lateral drifts. Seismic strengthening of structures is mainly based on two strengthening schemes: Element-Based and System-Based. The former, bases on the strengthening of the structural elements, which are expected, undergo a brittle failure. The latter involves introduction of new structural elements to the system, such as reinforced concrete shear walls to improve the overall structural performance.

Element-based techniques may not always be sufficient to increase the seismic performance of the strengthened structure [3]. In this case, it is better to introduce system-based strengthening methods, which improve base shear capacity as well as lateral stiffness. These methods usually compensate for the local deficiencies, which reduce the structural performance before strengthening, by decreasing the displacement demand.

The use of RC infill walls has a wide range of applications for the strengthening of earthquake-damaged structures. Its efficiency was proved by numerous experimental studies [6-14] showing that strengthening with RC infill increases the lateral load capacity and stiffness while it reduces lateral drifts. In previous studies, the effect of connection capacity between existing and new concrete [9] and the effect of wall openings [8] were investigated. According to these studies, properties of reinforced concrete frames (column reinforcement ratio, column and beam transverse reinforcement and column compressive strength) and connection between frame and infill walls were effective in strengthened frame behavior. The use of external RC shear walls was also tested on RC specimens. External wall schemes that are perpendicular [15-17] or parallel [18] to the side of the building were examined. As found in these studies, external RC walls behaved like monolithic walls. Only minor cracks were observed between wall and connecting elements after 2 % drift ratios.

Additionally, many theoretical and experimental studies were carried out on the use of steel shear walls as an alternative method of strengthening [19-22]. Most of the experimental studies on the use of steel braced shear walls were performed on single-storey and single-span frame models. According to the studies, strengthening the structures with steel shear walls increased the strength of the structure and better performance was achieved considering the ductility and energy dissipation. The performance of the technique was directly related to that of the dowels [14].

In this study, seismic performance improvement of earthquake-damaged RC structures with External Steel Shear Walls (ESSWs) was investigated experimentally. The reference and repaired and strengthened models were tested under imposed lateral sway to simulate seismic behavior. Chevron braced system is selected as external steel shear wall for strengthening. Repaired and strengthened model was tested under lateral loads again. The results obtained were compared with the results of un-strengthened reference model. The results of the study, demonstrate that reinforced concrete structures damaged in earthquakes can be strengthened with external steel shear walls after being repaired.

EXPERIMENTAL STUDY

Within the scope of this study, two-storey three dimensional RC structural models were produced in one-third scale and tested under lateral loads. The prepared RC model structure (Reference Model-RM) was tested, after then the damaged structure was repaired by epoxy injection and strengthened with ESSWs. Subsequently, the repaired and strengthened model was subjected to deformation.

Production and Properties of Reference Model

A one-third scale RC Reference Model was constructed as two-storey, one bay at one side, and three bays at the other side. The plan view and sections of the model are shown in Fig. 1. Structural deficiencies, which are widely observed in many existing RC structures in Turkey, like strong beam-weak column, cold joints with low sliding shear capacity and inadequate development length, were duplicated in the reference model. The final view of reference structure is given in Fig. 2.

The details of column and beam sections in the reference model are given in Fig. 3. Column dimensions were chosen to be 200×200 mm and Ø6 (S220) steel bars were used for reinforcement. End regions of the columns and beams were poorly confined by 90^{o} hooked stirrups. At the upper ends of the second storey columns, steel bars were placed straight without providing necessary development length. The beam dimensions were chosen to be 140×200 mm, see Fig. 3. Similar to the columns, Ø6 steel bars (S220) were used as reinforcements. Meanwhile, 2Ø8 plain bars were used as top and bottom reinforcements in the longitudinal direction. At the supports, an additional Ø8 steel bar was used for top reinforcement. Like the columns, poor confinement was evident.

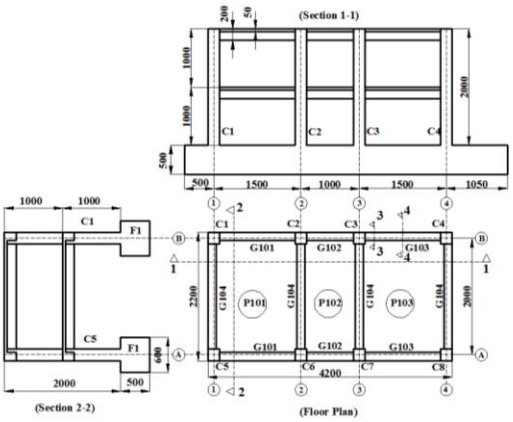


Figure 1 Plan view and sections of the RC structure model

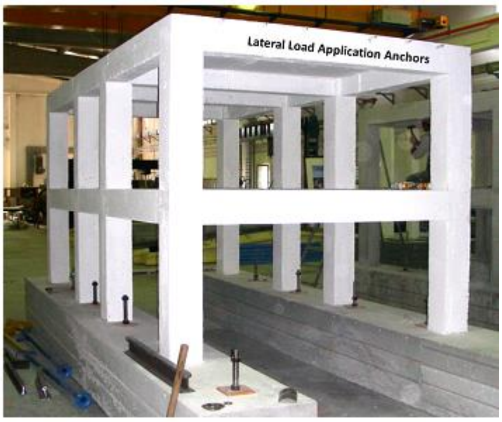


Figure 2 Final view of the RC Reference Model (RM)

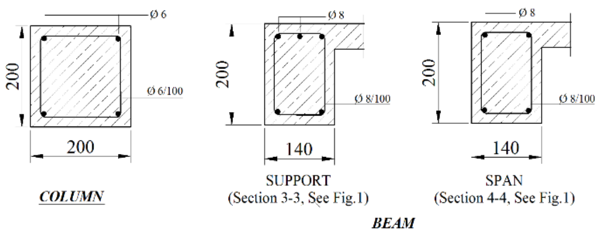


Figure 3 Details of the column and beam section

Material Properties

The properties of materials, concrete and steel bars, were also investigated in this study. Concrete samples taken during the production of the RC model were subjected to the uniaxial compression tests. Compressive strength was found to be 29.60 MPa and 32.18 MPa for the first and second storey, respectively. While, S220 reinforcement steel bars were used for the construction of RC models. S235 steel was used for SSW elements. Strength characteristics of these reinforcements and steel sections obtained from the tensile tests are given in Table 1. The technical properties of epoxy used for injection and anchor bonding are given in Table 2.

Experimental Setup

Experimental models fixed to the rigid floor with anchor bolts were loaded laterally by a servo-hydraulic actuator supported by the reaction wall. Fig. 4 illustrates the side view of the loading setup. Displacement of various points and deformation of some sections were measured to observe the behavior of the models. Linear Variable Differential Transformers (LVDT) and Linear Position Transducers (LPT) were used for measuring the displacements. They were also utilized for curvature measurements of RC elements and elongation of bracing elements.

Table 1 Strength characteristics of reinforcement steel bars and SSW members

Material Type	f_{sy} (MPa)	f_{su} (MPa)
Ø6 Reinforcement	328.30	398.70
Ø8 Reinforcement	386.50	532.00
St 37 (S235)	293.00	395.00

Table 2 Specifications of epoxy and anchorage resin, [23].

Material	Epoxy	Anchorage cement
Mixing ratio	A /B	A /B /C
Percentage by weight	60 /40	30 /20 /50
Percentage by volume	57 /43	40 /27/ 33
Mixing density (g/cm3, at 20^0C)	1.0 – 1.1	1.70 ± 0.10
Mixing race (min., 25^0C, 25^0 g)	60- 90	50- 70
Color	Colorless	Gray
Desiccation duration (23^0C)		
Dust holding (min.)	120- 180	50- 60
Touching (hour)	5- 7	3- 4
Full hardening (date)	7	7

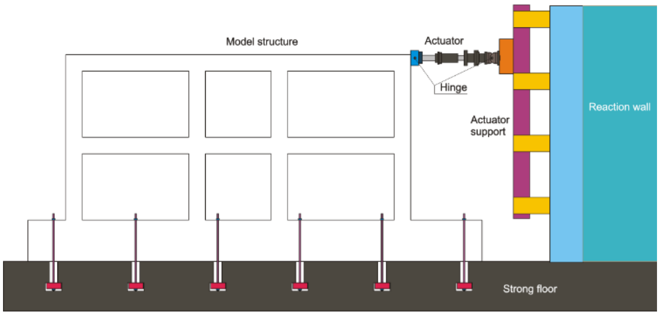
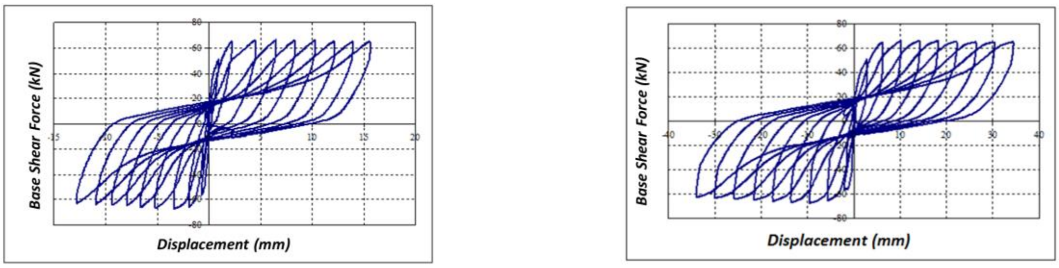


Figure 4 Side view of the loading setup

The Reference Structure Experiment

Reference model was tested under cyclic lateral load as shown in Fig. 4. The model was pushed up to 1.72% second floor drift level. At the end of the experiment, extremely smooth "load-displacement" conversion curves were obtained for the first and second floors of the structure (Fig.5). Until the end of the experiment, there was no significant decline in load carrying capacity of the structure. At the end of the experimental study, the second floor roof displacement of the model reached 34.40 mm, and capacity reached 67.35 kN (Fig.5). Damages mainly occurred in the upper and lower ends of the column. The cracks in the lower end of the column, shifted to floor joints expressed as cold joints and occurred in the form of a straight line. The cracks on the second floor column emerged as larger than the cracks on the first floor columns. The formation of cracks observed in the reference model after the experiment is shown in Fig.6.



a) First Floor b) Second Floor

Figure 5 Reference Structure "Load-Displacement" Conversion Curve

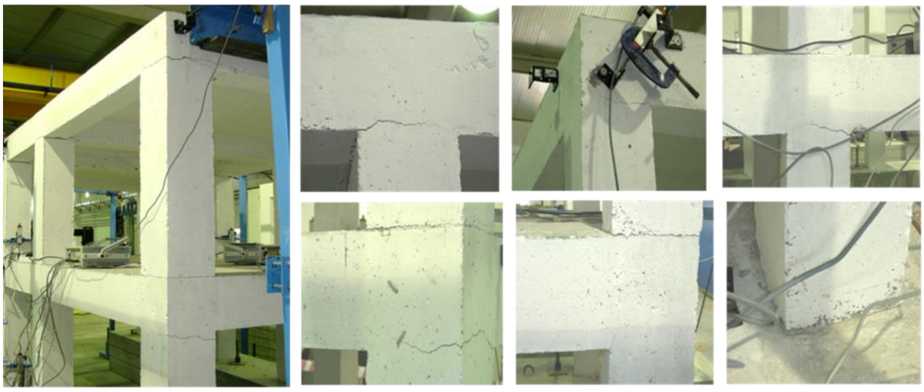


Figure 6 Particular cracks on the RC reference model

Repairing of the Damaged RC Reference Model

The reference model damaged by pushing the second storey to drift ratio of 1.72 %, was repaired by injection of bi-component epoxy material to the RC structure in order to fill and repair the cracks formed on the RC members (Fig.6).

In order to repair the deformed model, initially, damaged zones were immobilized and all the cracks including micro fissures were enlarged and cleaned by oil-free dry compressor. Then, packers were placed into the holes which were perforated to the lower and upper parts of the cracks forming a 45° angle with the concrete surface for epoxy injection. Afterwards, cracks were closed completely with repair cement and epoxy material was pierced to the cracks under pressure (maximum with 5 bar pressure). This treatment continued to the point where the epoxy material goes out of the control packer. At this stage, it was understood that micro fissures were completely filled when epoxy left the control packers. Details of the repairing procedure for the reference model and the appearance of the repaired model are given in Fig.7 and Fig.8, respectively.

Figure 7 Repairing of the damaged RC reference model with epoxy injection

Figure 8 Repaired RC reference model before strengthening

Strengthening of the Repaired RC Reference Model

The repaired RC model was strengthened by SSW externally. External SSW strengthening system made out of circular hollow sections was designed and produced as a diagonally braced frame. Elements of the SSW were connected to each other with bolts to allow a prefabricated production. The aim of use of the existing structures was taken into consideration and braces of the SSW were arranged as reverse V (Λ). Fig. 9 illustrates the side view of the SSW and connection of the joints. As seen in section (1-1) of this figure, bolted joint connections of steel elements were constructed by squeezing the ends of circular hollow sections. Section properties of the steel elements used in SSW are given in Table 3, where As is cross-sectional area of steel, D is the diameter of circular tube section, ix is the radius of gyration, Ix is the moment of inertia, Skx is the buckling length and Wx is the section modulus.

The connection between the RC model and SSW needs a carefull design to achieve load transfer from model to SSW elements. Therefore, the space between the strengthening system and RC system was minimized to provide a better connection. The connection elements (R), which provide the connection between SSW and the reference model, were designed such that they transfer shear forces safely. Connection element linked to other elements with fillet welds is designed as 50x50x5 box section. Anchor holes were drilled into the RC model by using a template that fits the prefabricated SSW. The holes were cleaned by oil-free air and anchor bolts were fixed to the columns, beams and foundations. The connection details and the installation stages of External SSW to the RC structures are shown in Fig.10 and Fig.11 respectively.

Table 3 Sectional properties of the steel shear wall elements

Steel member types (See Fig. 10)	Section		As (mm2)	ix (mm)	Wx (mm3)	Ix (mm4)	Skx (mm)
	D (mm)	t (mm)					
D1	33.70	3.0	289	10.90	2040	34400	860
D2	33.70	3.0	289	10.90	2040	34400	960
U1	60.30	3.0	868	19.60	11100	334800	930
U2	60.30	3.0	868	19.60	11100	334800	930
V1	60.30	5.0	868	19.60	11100	334800	880
V2	60.30	5.0	868	19.60	11100	334800	1000

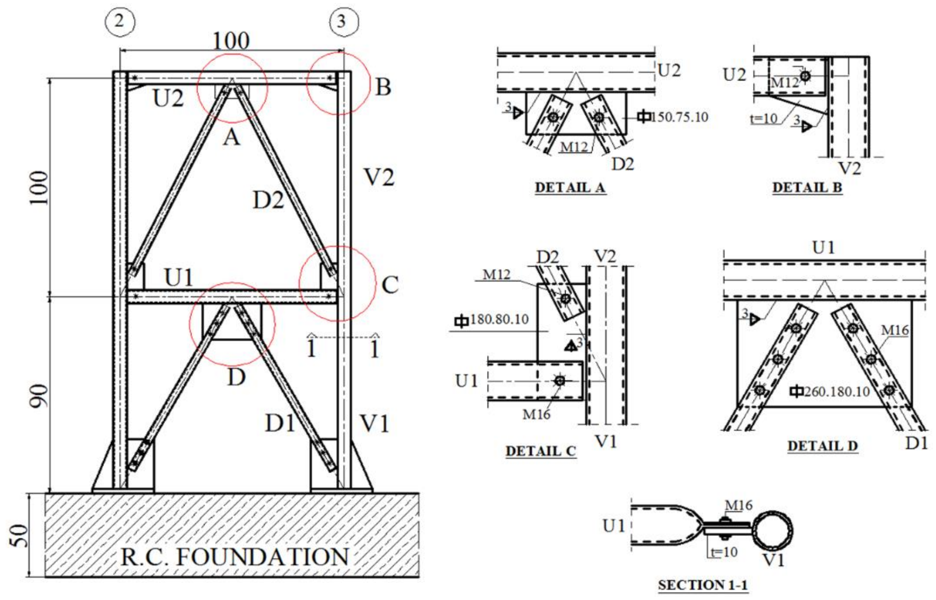


Figure 9 Connection details of the SSW

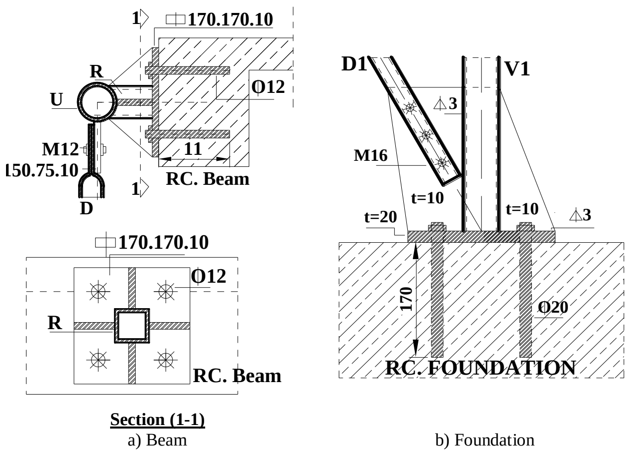


Figure 10 Details of the connection between the external SSW to the RC structure

Figure 11 Installation of the External SSW to the RC structure.

Repaired and Strengthened Structure Experiment

The reference model was repaired and strengthened with External SSW, and then tested under lateral load applied to the second floor level. The experiment continued until the second floor displacement rate reached 3.13%. At the end of the experiment, the second floor peak displacement reached 62.55 mm and the maximum base shear reached 178.26 kN. Until the end of experiment, no significant decrease was observed in the carrying capacity of the structure.

For the strengthened model, initial damages in the RC system occurred at the upper ends of the second floor columns. The damage at the lower and upper ends of the columns became intense in the final stage of loading. Like the reference model, the cracks formed at the lower ends of the columns moved along cold joints and appeared as a straight line. The view of the damage formations at the RC system of the repaired and strengthened model is given in Fig. 12. Most cracks on the RC structure formed nearby the repaired cracks.

When the second storey drift ratio reached 0.8 %, diagonal member (D2) of the SSW buckled about the weak connection point, i.e. squashed end, due to the presence of compressive force. Meanwhile, crushing was observed as a result of the tensile force around the bolt hole of the other diagonal member (D2), see Fig.13.

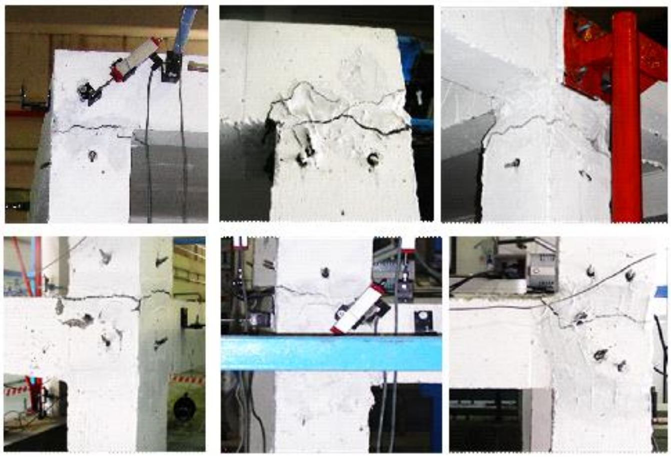


Figure 12 Particular cracks on the repaired and strengthened model

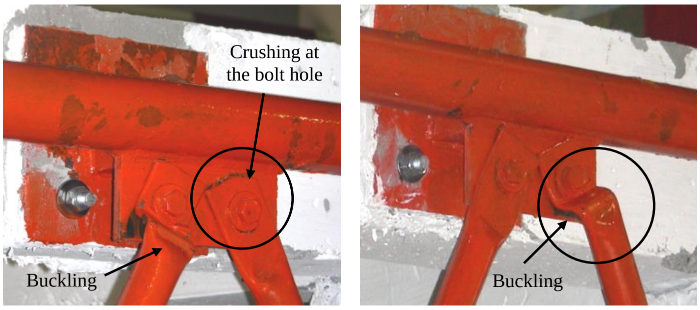


Figure 13 Damages formed in the strengthening SSW system

conclusion

In this study an alternative technique for strengthening of the earthquake-damaged RC structures with external SSWs was proposed. The experimental study was based on two models, namely reference model and repaired-strengthened model. The reference model was tested under lateral loads. The damaged reference model was repaired with epoxy injection and strengthened with external SSWs and then tested under incrementally reversed cyclic lateral loads. Here, it was aimed to increase the lateral load capacity of the structure to a sufficient value by new SSWs connected to the exterior surface of the system. For this purpose, the strengthening was performed externally. Compared to the conventional techniques, functionality of the structure was slightly affected and duration of construction was very short. Apart from these, the loss of space, architectural functional failures and repair costs are at a minimum level. For these reasons, the use of external SSW in strengthening to the damaged RC structures offers an economical and practical alternative. The main results of this study are as follows:

1. The application of external SSWs increased the lateral load capacity and stiffness of the reference structure substantially. The lateral load capacity of the model strengthened with SSW reached to the value of 178.26 kN showing 265 % increase in the capacity with respect to the reference model (67.35 kN). Similarly, initial stiffness of the strengthened model also increased by 315 % relative to the reference model.
2. Repaired and strengthened model was forced approximately to 3.0 % drift level during which no significant capacity loss occurred.
3. In the reference model, there is no considerable difference between the first and the second floor displacement ratio throughout the experiment. In contrast to that, in the strengthened model, the ratio of the second floor displacements to that of the first floor showed 100% increase. This was observed as shear walled system behavior and loading pattern were effective.
4. When the second storey drift ratio of the strengthened system reached 0.8 %, diagonal member (D_2) of the SSW was buckled about the squeezed end due to the compressive force. Besides, around the bolt hole of the other diagonal member (D_2), crushing occurred because of the tensile force. These demonstrate that, diagonal elements and their connections should be designed carefully.
5. In order to minimize the forces at the intermediate members (R) connecting SSW and RC structure, the exterior SSWs were positioned close to the RC structure, eliminating damage of the elements.
6. There was no damage at the anchorages, which successfully conducted the load transfer between RC system and SSWs.

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