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Invention: Seismic Retrofitting by Exterior Steel Brace Structural Building Jacketing System

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Abstract

Structural Building Jacketing System is a new technique for the retrofitting of reinforced concrete structures. It involves the application of jacketing to the whole structure exterior using steel braces connected to the RC frame by anchorages. This invention is especially used retrofitting of existing important building structures such as hospitals, schools, factories, communication and power buildings. The main advantage is to retrofit the existing buildings without disturbing their serviceability. A new modern architectural appearance will also be provided to existing structure if a cladding is done. Three-dimensional scaled models of RC buildings with and without the jacketing system were tested under static cyclic pushover loading to understand three-dimensional behavior. Experimental and analytical results were compared to verify the models. The results indicate that structures retrofitted with the jacketing system increase seismic capacity by a factor of four. Application of this system to a 10-story housing in Istanbul is discussed.

Key words: Structural building jacketing system, retrofitting, seismic performance, steel bracing, experimental test

1. Introduction

Many reinforced concrete buildings including critical facilities like hospitals, schools, factories, and power and telecommunication buildings are not retrofitted for seismic loads because of the inconvenience of interrupting their serviceability during the retrofitting construction. For example, if a factory building needs to be strengthened for seismic safety, construction is likely to stop production for three to six months, resulting in expense not only for the construction but also in lost revenue. In the case of some telecommunication buildings, it is not possible to perform seismic retrofitting inside the building without disturbing the thousands of communication cables and thus, the serviceability. To address this critical need, the author has developed a seismic retrofitting system that is constructed on the outside of the building structure. The structural building jacketing system consists of steel braces (Fig. 1) that are connected to the whole perimeter of exterior reinforced concrete (RC) frame by anchorages. Once installed, the system behaves as a composite structure, absorbing most of the seismic loads. Structural elements inside the building are mainly subjected to gravity loads. As such, the jacketing increases seismic performance and torsional capacity. It can be applied to any type of RC structure that has an accessible exterior.

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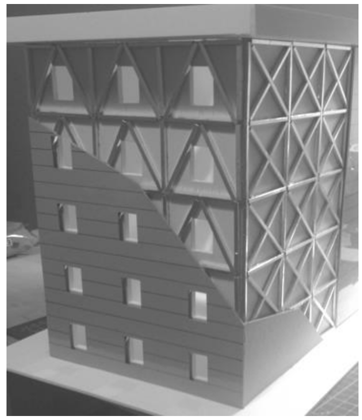


Figure 1. Architectural exterior view of retrofitting by using structural building jacketing system

Experimental studies were carried out to test and verify the structural building jacketing system. Three-dimensional models of three-story scaled RC buildings with and without the jacketing system were tested under static cyclic pushover loading to understand 3D behavior, lateral load capacities, crack patterns, and collapse mechanisms under earthquake loads. Experimental and analytical results were compared to verify the models. The experimental studies were performed in the laboratory at Erciyes University Sumer Earthquake Research Center in Kayseri, Turkey, and were supported by the Turkish National Science Foundation.

This paper discusses the design of the structural building jacketing system and the results of experimental and analytical studies. It then reviews, as a case study, the analysis related to the seismic retrofitting of the 10-story TCDD housing building in Istanbul, Turkey. Seismic performances of the TCDD existing and retrofitted building project were evaluated according to TEC-2007 [1] and ATC-40 [2].

2. Methods

2.1. Structural building jacketing system

The structural building jacketing system (Patent No.: TR2008 08886B) [3] is a method of seismic retrofitting for RC buildings that involves the application of a jacketing to, and from, the whole exterior of the structure using steel braces (Fig. 1). By applying the jacketing from the exterior, serviceability interruptions are avoided. The steel braces are connected to the exterior RC frame by anchorages, and the new system behaves as a composite structure. The effect is similar to that of a shear wall around the perimeter of a building. Thus, earthquake loads are taken at the new outer composite frames, and earthquake loads on the structural elements inside the existing structure are minimized. Lateral forces are uniformly distributed along the joints and structural elements at the façade. This load distribution prevents overloading of the joints of the existing building structural system. Most of the lateral loads as earthquake loads as well as wind loads are taken from the new structural system at perimeter. The interior structural elements are mainly subject to gravity loads. Seismic and torsional capacities of the existing RC structures are increased because of the composite behavior and 3D behavior of the jacketing system. If necessary, foundation systems can be retrofitted as a continuous foundation system from the outside.

The experimental tests indicate that the ductility level will be relatively high in the case of seismic loads. The additional mass to the existing structural system due to seismic retrofitting will be less, and the mass distribution will be uniform. However, if retrofitting were done using conventional techniques, with additional infill shear walls in the existing frames, the result would be a more rigid and heavily retrofitted structure that was subjected to more earthquake forces.

The application of the structural building jacketing system from the exterior is relatively quick, straightforward, and economical. Anchorages are used between the structural steel and the RC exterior frame located not only at beam–column connections but also at the interior points of beams and columns (Fig.2).

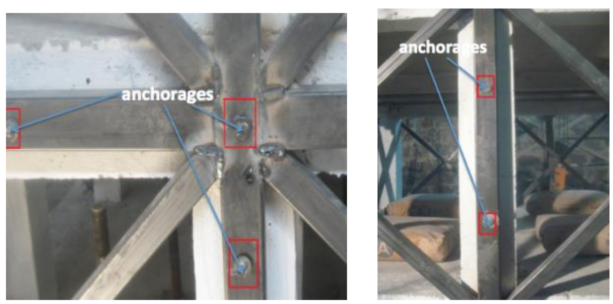
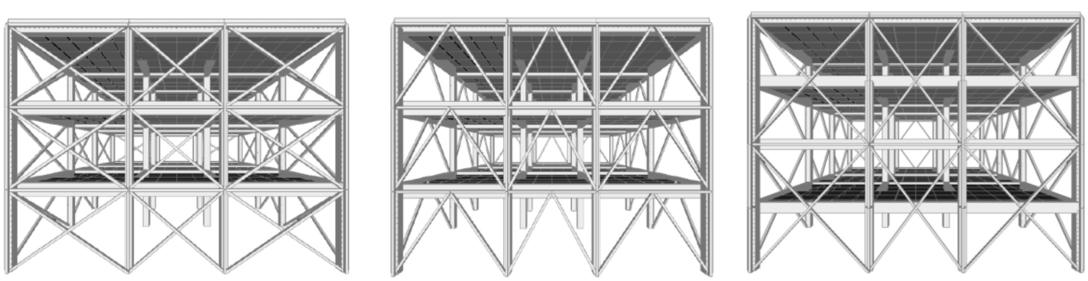


Figure 2. Steel brace to concrete frame connections by using anchorages



a) X-braces b) Inverted V c) X-braces at two stories

Figure 3. Types of steel braces depending on openings

Different types of steel braces can be used as shown in Fig. 3. The selection of a brace depends on architectural openings such as door and windows. If there is an opening, inverted V-type steel braces are used. If there is no opening, X cross-braces are preferred for a relatively high lateral resistance.

3. Experimental and Analytical Studies

3.1. Experimental studies

Experimental studies were carried out to test and verify the structural building jacketing system.

3D models of three-story scaled RC buildings with and without the jacketing system were tested under static cyclic pushover loading to understand the 3D behavior, lateral load capacities, crack patterns, and collapse mechanisms under earthquake loads [4].

3.1.1. Existing RC Model

A 3D, 1/3-scaled, three-story existing RC model was constructed in the Lab. (Fig. 4). The building model had three spans in the application of the seismic load direction and two spans in the transverse direction. The span lengths and story heights were 1 m. The dimensions of the structural elements shown in Fig. 4 were as follows: columns, 15 × 15 cm; beams, 10 × 15 cm; and floor and foundation thicknesses, 5 and 20 cm, respectively. The material properties of concrete and steel were selected to represent the existing RC building stock in Turkey, and the concrete material type used was C12. The ductility level was considered normal. Stirrup spacing was not changed around the structural joints in the existing structural columns and beams. The stirrups used were Ø4/10 in beams and columns. Reinforcements were 4Ø8 StI (S220) in columns and StI (S220) 4Ø6 in beams. RC slabs had top and bottom Ø6/20 straight reinforcements. In the foundation, top and bottom Ø12/20 StIII (S420) reinforcements were used in longitudinal and transverse directions.

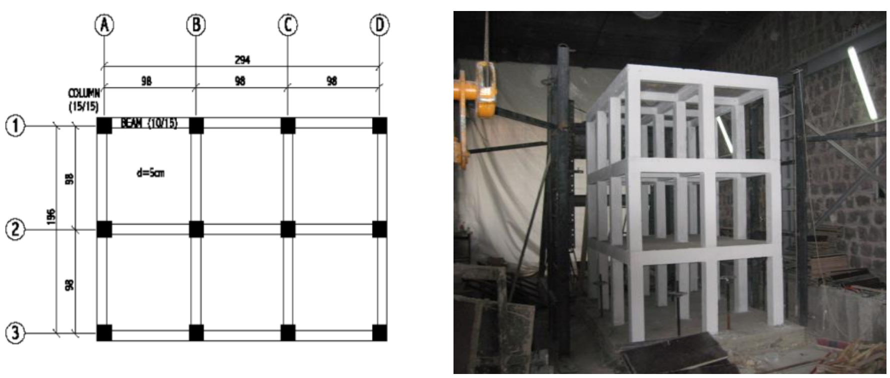


Figure 4. 3-Story scaled existing RC building plan and model

Seismic loads were applied as pushover loading, and the load cell platform (Fig. 5) was arranged to transfer the load to the top two floors by pushing 2/3 of the load to the upper floor and 1/3 to the lower floor. For the pushover test on the back of the structure, the plate and four tie bars were provided on the floor levels to transfer the pulling loads.

Figure 5. Loading platform

Before applying pushover forces, we applied 50 kg/m² loading on each floor slab as additional vertical load, using cement bags. The linear variable differential transformers (LVDTs) were placed on each floor, including locations of rotation and foundation movement, to measure the basic displacements corresponding to the pushover loads. Horizontal seismic loads were applied to the structure in the form of static cyclic pushover loads. Loads were applied up to the collapse of the structure.

Cracks started in the system after applying a force of three tons. The seismic capacity of the existing model was determined to be eight tons. The load-deflection curve of the existing RC model is shown in Fig. 6 for the top-story displacements under static pushover forces.

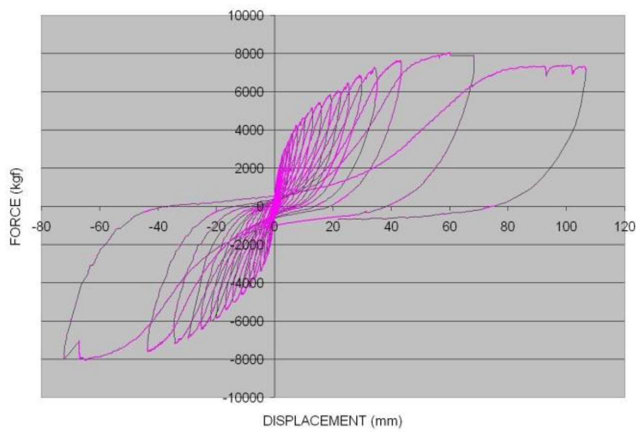


Figure 6. Load-deflection curve of existing experimental model

3.1.2. Exterior steel brace structural building jacketing retrofitted model

For the retrofitted model, the RC model was re-constructed with the same material qualities as the model of the existing structure, and then, the jacketing system was applied as shown in Fig. 7. For the steel brace system, steel box profiles of 40 × 60 × 2 mm were used for columns and beams. For cross braces, steel profiles of 40 × 40 × 2 mm were used. The steel members and their connections were welded, and anchor bolts were used at the foundation connection. Anchorages were constructed, with epoxy at the joints and around 30 cm spacing on reinforced columns and beams. The total number of frame anchorages was 200.

The same vertical forces were applied to the retrofitted model before applying the pushover lateral forces. At forces up to seven tons, a few cracks occurred in three locations. At around 34 tons, major cracks started at the columns and joints. The seismic capacity of the retrofitted model was determined to be 37.5 tons. The load-deflection curves for the top floor under static pushover forces are shown in Fig. 8. The curves indicate that the retrofitted system is behaving as a composite structure, and 3D behavior is such that the system has a higher seismic capacity than the RC model without steel bracing.

Figure 7. Retrofitted by exterior steel brace system model

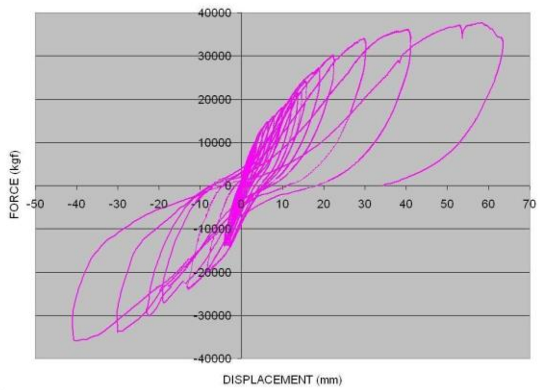
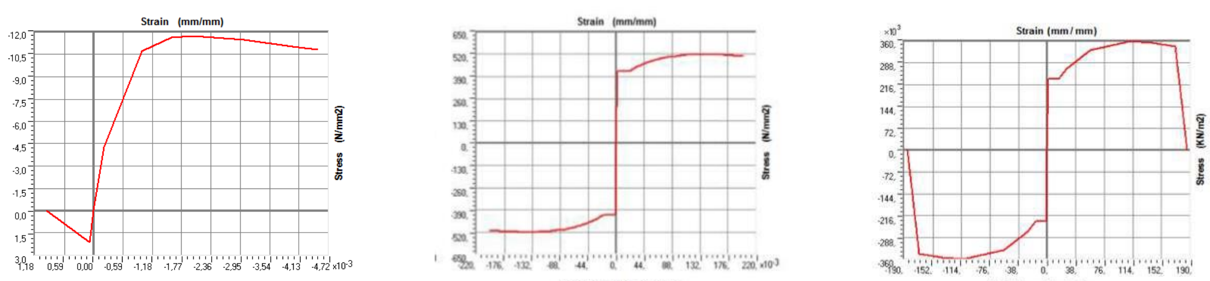


Figure 8. Load-deflection curve for retrofitted model

3.2. 3-D nonlinear FEA and comprasion of results

The 3D model of the existing structure was modeled by using SAP2000 [5] structural analysis software. For the nonlinear FEA, the foundation was modeled as a fixed base. In the model, geometric nonlinearity was not taken into account. The response spectrum was set on the basis of TEC-2007 [1] for the first-degree earthquake region Ao= 0.40, and Z2-type soil. Hinge mechanisms were defined according to FEMA-356 [6], which is P, M2, M3 for columns, and M3 for beams. Pushover analyses are performed.



(a) concrete (C12) (b) anchorages (St52) (c) steel profile (St37)

Figure 9. Nonlinear material properties.

For the integration of the structural steel to the RC structure, the anchorages were modeled as rigid members. Nonlinear material properties are given in Fig. 9. The class of the retrofitting steel was St37 and that of the anchorages was St52. The concrete class was C12, and the steel class was S220. The Mander unconfined concrete model [7] was used. Dynamic analysis and pushover analysis were conducted. In the analyses, an extra 50 kg/m² was imposed on the structure in addition to the dead load of the structure itself. Pushover curves and load capacities obtained from the experimental and analytical studies were similar.

4. Case Study: Application of structural building jacketing system

The application of the structural building jacketing system to the retrofitting of the TCDD housing building is presented as a case study [8]. This RC housing building has 10 stories and is located in Istanbul, Turkey. The existing RC building view and typical structural plan are shown in Fig. 10. The structural system consists mainly of the RC frame structure and shear walls in the y-direction. Existing building material and soil characteristics are given in Table 1.

Table 1. Existing building material and soil characteristics

Concrete Class	C14
Reinforcement Steel Class	StI (220 MPa)
Soil Type	Z2
Soil Characteristic Periods	Ta = 0.15s, Tb = 0.4s
Effective Ground Acceleration	Ao=0.4 g
Earthquake Region	Region I
Allowable Soil Stress	21 ton/m^2
Soil Spring Constant	3000 ton/m^3

Steel brace types around the building were selected by considering the openings in the architectural plan and views. A 3D view of the structural jacketing system from the outside is shown in Fig. 11. For the retrofitting steel, class St52 was used. Column and beam sections were 2*U200 welded face-to-face. The braces selected from a 100 × 100 × 8 mm hollow box section. All the connections were welded.

Figure 10. Existing RC building view and structural plan

A 3D computer model and analysis were completed for both the existing and the retrofitted buildings using SAP2000. To find the performance points of the existing and the retrofitted structures, procedures indicated in TEC-2007 and ATC-40 were used as shown in Fig.12 and Fig.13 respectively.

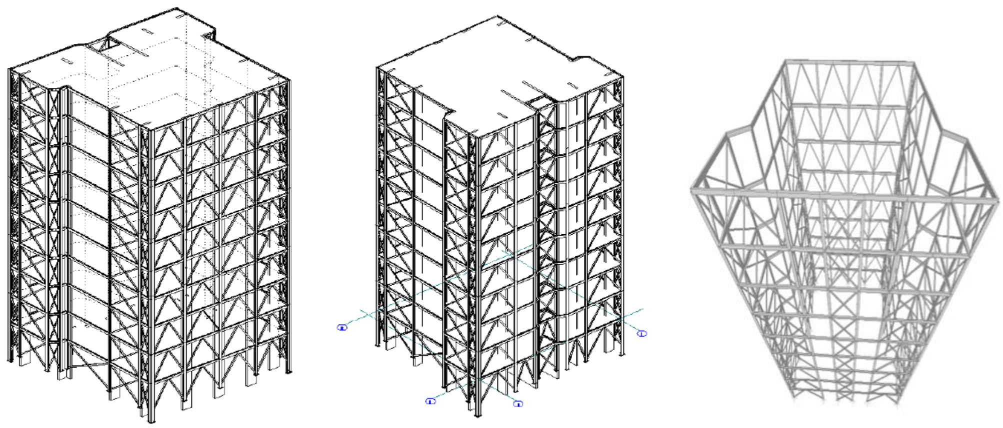


Figure 11. 3D views of the structural jacketing system of TCDD Building

Table 2. Modes of the existing and retrofitted structure

Existing Structure			Retrofitted Structure		
	Mode	Period(sec)		Mode	Period(sec)
1	x-direction	1.32	1	x-direction	0.74
2	Torsion	1.20	2	y-direction	0.55
3	y-direction	0.66	3	Torsion	0.46

When the fundamental periods are compared in Table 2, there is a huge stiffness increase in the x-direction with the retrofitted structure. The fundamental period in the x-direction reduced from 1.32 to 0.74 s. Since the torsional rigidity increased, the period of torsion mode decreased from 1.20 to 0.46 s with the retrofitted structure. Due to the existing shear walls in the y-direction, the fundamental period in the y-direction was reduced from 0.66 to 0.46 s in retrofitted structure.

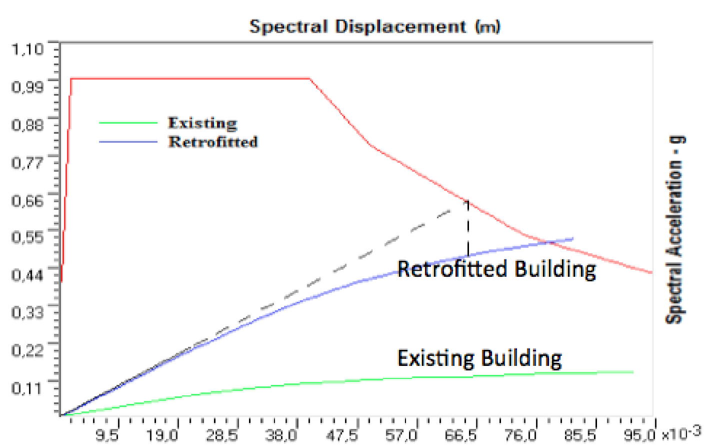
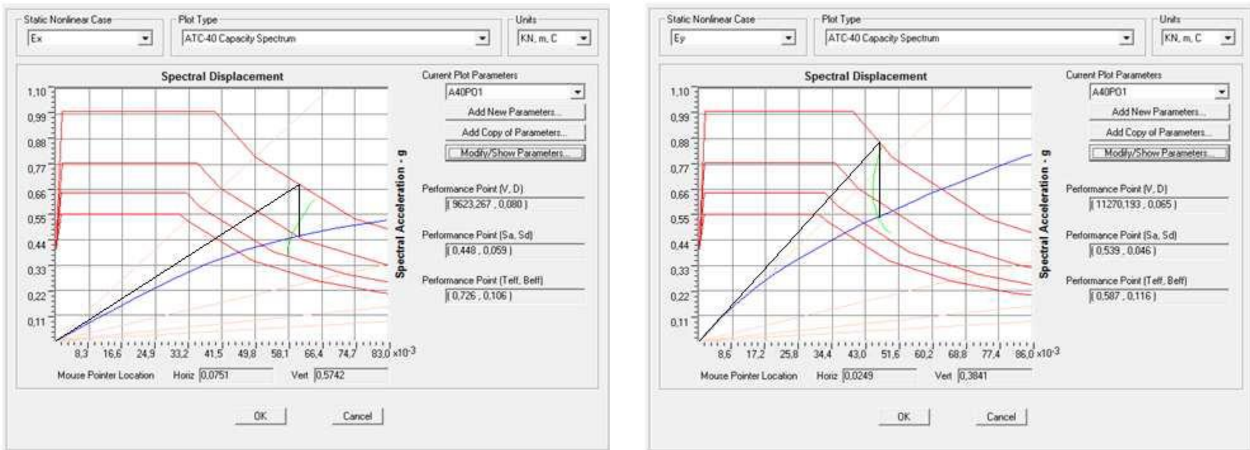


Figure 12. Performance evaluation of existing and retrofitted models in x-direction according to TEC-2007



a) x-direction b) y-direction

Figure 13. Performance evaluation of retrofitted building model according to ATC-40

It can be seen from Fig. 12 & 13 that the comparison of the performance evaluation of the existing and retrofitted structures reveals a gradual increase in the seismic performance of the retrofitted structure. The steel jacketing system has a great influence on the dynamic response of the building. While there is no performance point for the existing structure, the performance point of the retrofitted structure satisfies the 'Life Safety' criterion according to Turkish Earthquake Code-2007 (TEC-2007) and ATC-40 requirements. Performance points are found similar in TEC-2007 and ATC-40 for retrofitted building model. Since the retrofitting was done from outside the building, additional foundation works were also done from outside.

Conclusions

This paper described a new technique for the seismic retrofitting of RC buildings, which is an exterior steel brace structural building jacketing system. 3D models of the existing RC buildings and RC buildings retrofitted with the jacketing system were tested under pushover loading to show 3D behaviour and seismic performance. The seismic capacity of retrofitted model increased up to 37.5 tons, as compared to the eight tons by the existing building model. Seismic loads were mainly taken at the outer perimeter, so structural elements inside the building were mainly subjected to gravity loads.

The advantage of the structural building jacketing system for the retrofitting of RC buildings can be summarized as structural, economic, and architectural advantages.

- Structurally, seismic performance and torsional rigidity are increased. Earthquake loads and additional weight due to retrofitting are uniformly distributed along the perimeter and the exterior joints of the buildings. Most of the earthquake loads are taken at the outside perimeter of the new composite structure. If necessary, foundation retrofitting can be constructed from outside. Steel brace retrofitting adds less weight than RC shear walls.
- From an economic perspective, retrofitting from outside allows the building to remain in service, thereby saving money in terms of both construction budget and lost revenue or service.

The costs of exterior cladding could be reduced by 30%–40% by using the steel brace system that is part of the building jacketing system. The cost of finishing works (painting, electrical, and mechanical works) could also be reduced by performing the work from outside. The system also provides the opportunity to promote energy efficiency by introducing insulation between the steel braces and cladding.

- Architecturally, the opportunity to apply exterior cladding to the steel braces provides a new, modern appearance to an existing structure.

This study suggests that the structural building jacketing system is a promising solution for the earthquake retrofitting of RC buildings that need to remain in service without interruption.

Acknowledgements

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