FRP versus Traditional Strengthening on a Typical Mid-Rise Turkish RC Building

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ABSTRACT: Strengthening with the traditional methods is usually applied in most projects, as ordinary construction materials and no specialized workmanship are required. However, in cases of tight time constraints, architectural limitations, durability issues or higher demands for ductile performance, a different technology, namely the FRP material, is preferred since it is able to meet such strict requirements. The most recent Turkish Earthquake Code allows engineers to employ this advanced-technology product to overcome the lack of ductility or shear capacity problems that arise in seismic strengthening projects of existing reinforced concrete buildings. This paper compares strengthening of a characteristically typical mid-rise Turkish RC building by using two methods: traditional column jacketing and FRP strengthening. The requirements of the Turkish Earthquake Code have been used for both cases comparing at the end the two methods in terms of technical capabilities, direct and indirect costs, as well as the time-cost effectiveness. Due to the input into the paper from the industry, the authors were able to use real cost estimates to better compare the two methods.

1 INTRODUCTION

Earthquake is a common threat for many Mediterranean countries. The building stocks in European-Mediterranean region is exposed to earthquakes shocks of different magnitude, many of which have been proved quite destructive. The prohibitive cost of substituting all structures that suffered moderate damage, in conjunction with associated legal issues and complicated bureaucratic procedures, encourages owner or the authority to proceed with the strengthening of the building so that it meets the standards of safety set by the relative codes.

Several solutions have been developed for seismic strengthening of existing RC frame structures, usually based on conventional material and construction techniques. However, in the last years, due to the increased demands for ductility and durability and in a continuous effort to reduce the time and application cost, new techniques and materials have emerged offering comparatively advantageous solutions especially in cases where the architectural limitations are governing.

The aim of this paper is to evaluate the merits of two different methods of strengthening, i.e. column jacketing and FRP application, through the employment of a characteristic RC building commonly met in Turkey that needs to be demolished unless retrofitted under the current code requirements in vigor.

Composite materials are of common practice in repair and strengthening works due to their competitiveness in speed, cost, low profile and ease in application. The area of composite materials has shown a great improvement in the last two decades, leading thus to more developed and easy engineering applications in the most complicated real-life problems. FRP material and relevant materials such as ordinary and special epoxies, fire protection systems, anchors, blast and impact preserving systems, and finishing materials are being used, inside our outside of structures, in ordinary or aggressive environments with high level of confidence in terms of strength and durability. Research and development studies led engineers to be more aware and confident about the possible use of the material.

In summary this design exercise focuses on (i) assessing a RC frame building category, examples of which were exposed to several earthquakes, (ii) applying FRP and valid traditional strengthening methods to reach a specific performance level, and (iii) comparing FRP solution with the traditional solution in terms of technical features, feasibility and cost.

2 ANALYSES PARAMETERS

The case-study structure was selected to be relatively simple and regular in plan and height in order to eliminate a number of uncertainties from our analyses. It is a typical building, possessing similar plan with some of the typical standard designs of state buildings constructed in several regions of the country in large numbers during the last 40 years (see Figure 1 for some examples). The typical standard structures belong to a common practice in Turkey. The time and cost of design of typical state structures (such as dormitories, schools or residential apartment units) is minimized by using a standard design. This practice leads several identical buildings, in terms of dimensions and plans, to be constructed in several different earthquake regions throughout the country. The reason why a typical building is chosen in this study is to have an example which is an average ordinary RC building built several times and experienced several different earthquakes. The authors aim the conclusions to be valid for many similar structures in this way.

The plan and the 3D view of the example structure are given in Figure 2. The concrete and rebar quality were C16 and S420 respectively. The fundamental period corresponding to a lateral mode is estimated after eigenvalue analysis as 0.54sec. The lateral load coefficient c is taken equal to 0.18, though the structure was initially designed for c=0.08-0.10 according to the 1968 aseismic design code.

Figure 1. Some examples of the standard state structures built as residential apartments

The structure was modelled in SeismoStruct (SeismoSoft, 2011), an internet-downloadable software of distributed plasticity that can successfully model the 3D nonlinear behaviour of RC frame structures. The assessment of the structure is conducted by using the regulations of the Turkish Earthquake Code (TEC, 2007). The seismic demand spectrum is used as given for the 1st degree earthquake zone with the effective ground acceleration of 0.4g.

Starting point for the methodology followed for the assessment of the structure is the determination of the target displacement accepting the fundamental rule of equal displacement or equal energy depending on the position of the fundamental period of the structure as compared to the corner period of the acceleration spectrum. Thus, when the target displacement is reached, the individual element performances will be defined on which in sequence the overall performance level of the structure will be based. It should be noted that the Turkish Earthquake Code (TEC, 2007) defined the member-level damages based on the material strains.

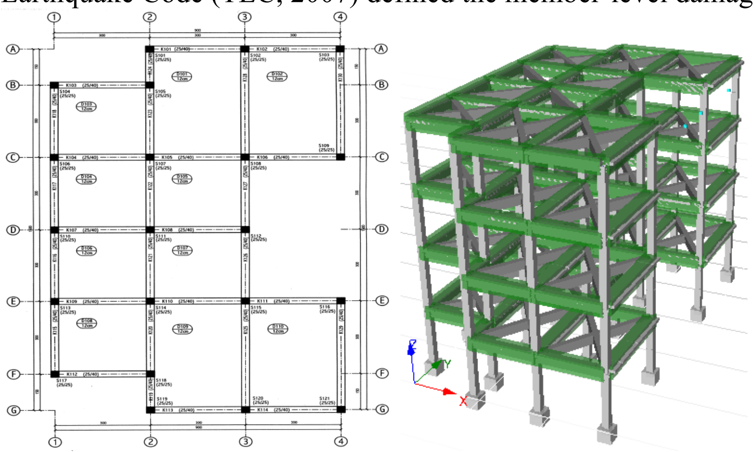


Figure 2. Formwork plan of the structure (left) and 3D view of the SeismoStruct model (right), details of which can be found in Başaran (2006)

A first-mode pushover, where the loading profile through the height of the structure, follows the first mode shape of the structure, is conducted to get the capacity curve in base shear-top displacement format (see Figure 3). The Turkish Earthquake Code allows this rather simple pushover method only if the mass contribution of the relevant mode is more than 70% in the designated direction, which is the case for the case study structure. The multi-degree-of-freedom response is then translated to the representative single-degree-of-freedom (SDOF) response by multiplying the forces and the displacements with the modal participation and displacement-at-effective-height coefficients. The SDOF response is then plotted over the Acceleration Displacement Response Spectrum (ADRS) in order to compare the demand with the capacity, as shown in Figure 3.

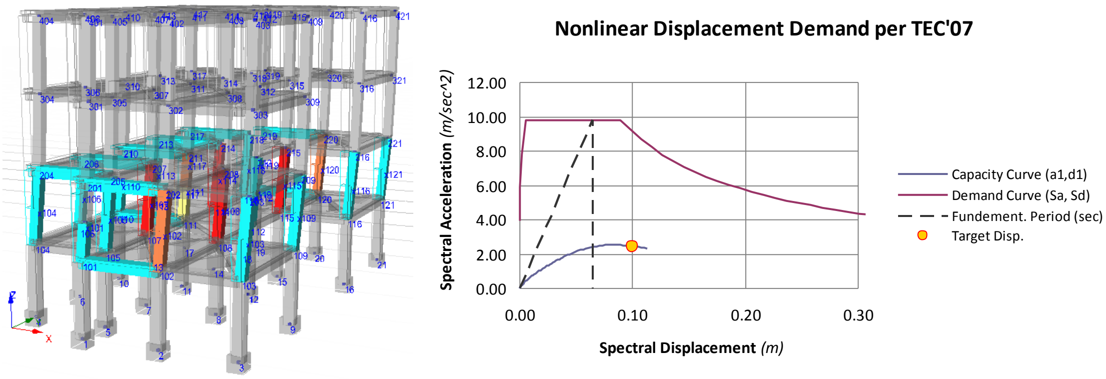
As explained above, the damage states in member level are defined by using the material strains. The material strain limits in the Turkish Earthquake Code are 0.0035 and 0.010 for the LS1, 0.0035 and 0.040 for the LS2 and 0.0040 and 0.060 for the LS3 for concrete and reinforcement, respectively.

3 ASSESSMENT RESULTS AND STRENGTHENING WITH FRP OPTION

The case study structure is assumed to be on soft soil, which corresponds to Type C in NEHRP classification (NEHRP, 1997). Type C soil in the Turkish Earthquake Code (named Z3 in the TEC) has a corner period of 0.60sec. Given the fact that the case-study structure belongs to the equal- energy range of periods (T=0.54sec<060sec) and for the demand spectrum of the Turkish Earthquake Code (2007), the target displacement is estimated approximately 0.10m (Figure 3) for the SDOF representative system, which corresponds to 12cm top displacement in the real 3D structure.

As first analyses results showed for such a displacement, a failure mechanism is formed in the 1st floor (Figure 3). The reason why the mechanism did not occur in the ground floor but in the first floor is that the structure was designed mainly against the dead loads, which renders the ground floor columns significantly larger (i.e. %35-40 more sectional area in average), something that leads the 1st floor columns to be more vulnerable.

As per the damage distribution, in particular, the reinforcement of the columns of the 1st floor reaches LS1 while the concrete material has already attained LS2 and LS3 in the columns of the same floor. These strains occur in both ends of the columns resulting in the soft-story mechanism which is primarily attributed to the abrupt change in stiffness and strength caused by the reduction of columns dimensions in the upper floors, a characteristic feature of frame structures designed for gravity in the countries of the European- Mediterranean region.



Blue: LS1 of rebars

Orange: LS2 of concrete

Red: LS3 of concrete

Figure 3. Damage distribution when the target displacement is reached (left), and the definition of the target displacement as per TEC (right) before FRP wrapping

In the TEC, the Limit State 2 and 3 for the core concrete is function of the level of confinement. The stirrup ends are closed 90^{o} (not 135^{o}) in the old construction practice in Turkey, similar to the practice in European Mediterranean building stock. This fact leads to zero confinement according to the TEC regulations, which causes very small strain limits (i.e. 0.0035 and 0.004) for core concrete for LS2 and LS3. The lack of proper confinement, in combination with the low quality of reinforcement, reveals the low deformation capacity of the elements, enhancement of which would limit the problem in the 1^{st} floor. An improvement in this situation can be achieved with the application of FRP materials.

In case an FRP-based solution needs to be developed, a full wrapping of the column ends only in the first two floors will sufficiently increase the concrete confinement and consequently the concrete compressive strength, as well as the compressive strains of confined concrete (Figure 4). Thus, the damage on the columns can be eliminated or at least limited, pulling the structure to “Minimum Damage” performance level. The effectiveness of such a solution has been confirmed by analyses results that demonstrate that only few columns in 1^{st} problem pass to LS1.

It should be noted that the target displacement has increased slightly after the FRP wrapping of the columns, as shown in Figure 6. The reason behind this is the small improvement in the post-yield response of the structure.

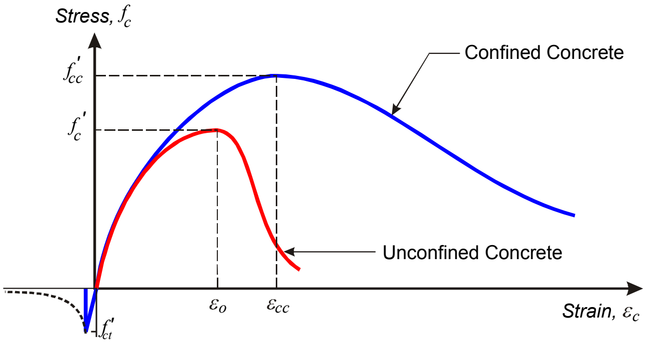


Figure 4. Effect of the full FRP wrapping on concrete behaviour

4 STRENGTHENING WITH RC JACKETING

The traditional strengthening method preferred in this study is the concrete jacketing of some of the columns, an application that needs to be done in all floors as the analyses proved. The scheme of the column jacketing is shown in Figure 5. In particular, applying 10cm RC jacketing in 2/3rd of the columns (total number per floor equal to 13) gives an equivalent result as long as the RC jacketing is continuous along the height of the structure. In a case that the jacketing of the columns does not cover all the floors, the soft-story mechanism is simply pushed towards the upper floor at which the jacketing of the columns is interrupted. The assessment results, as obtained after analyses, showed that only four columns in the 2nd floor would exceed LS1 entailing that the performance of the structure belongs to the "Minimum Damage" category.

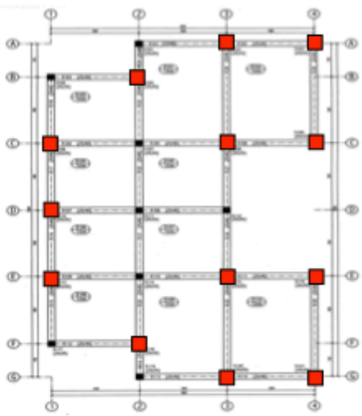
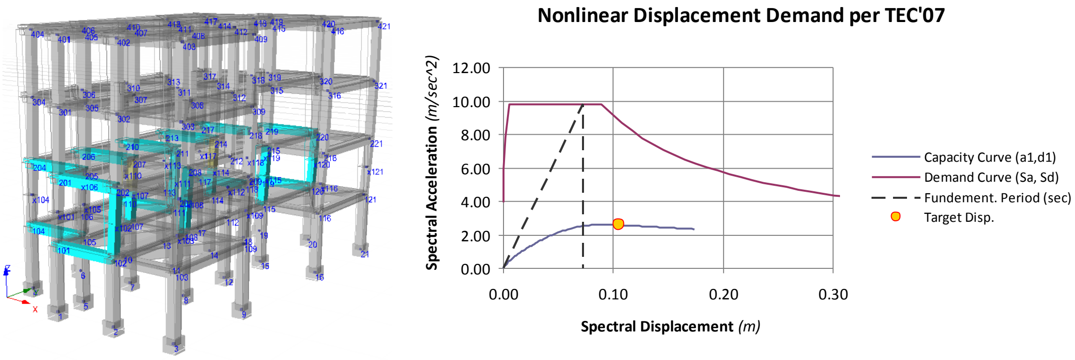


Figure 5. Scheme of the column concrete jacketing used in this study

5 STRENGTHENING OF BEAMS

Another issue that needs to be examined is the shear capacity of beams. Though their lack of flexural capacity is overlooked, in line with most of the modern assessment codes that have adopted capacity design concepts, shear failure is not allowed in the beams. This is a major disadvantage for the common strengthening with RC walls since no feasible measures regarding beams can be taken. Note also that in the case of the jacketing option, 16 out of 30 beams of the first three floors (48 beams in total corresponding to 154lm of jacketing) require shear strengthening, an application that is extremely difficult if feasible at all when it is done with conventional methods. As far as the FRP option is concerned, 26 out of 30 beams in the first two floors and 24 out of 30 beams in the 3rd floors (76 beams in total corresponding to 122lm of jacketing) are estimated that demand shear strengthening (see an example application in Figure 7). Note that FRP jacketing does not cause any change in beam member stiffness, thus can be limited only to the required length from the beam-ends.



Blue: LS1 of rebars

Figure 6. Damage distribution when the target displacement is reached (left), and the definition of the target displacement as per TEC (right) after FRP wrapping

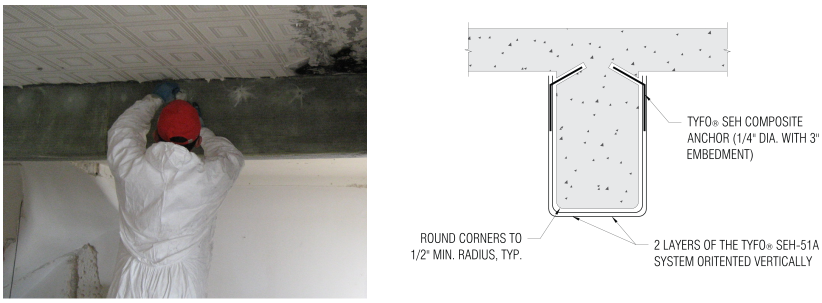


Figure 7. Application of anchors for shear strengthening of beam (courtesy of Fyfe Europe)

The RC jacketing should be applied at all beam length for obvious reasons. For this scenario, the application of shear strengthening with FRP is much easier and faster since tailor-made design is used. FRP materials can be accompanied by appropriate anchors that are especially developed and certified after extensive research work and laboratory tests and are absolutely essential for avoiding a failure due to debonding.

6 COMPARISONS OF THE TWO SOLUTIONS

Comparing the pushover curves for the two scenarios examined is rather illustrative clearly showing that the FRP strengthening does not alter the stiffness but definitely improved the overall ductility of the structure in contradistinction to the RC jacketing that increased both stiffness and strength of the structure regardless, however, of whether it was needed or not (see

Figure 8). The base shear with the RC jacketing is 40% higher than with FRP strengthening, resulting in 40% higher induced seismic forces in the building and its content. This may cause damages and failures to the contents of the structure. Level of induced seismic forces is very important in cases like industrial, telecommunication, hospital, hardware, high-tech, nuclear structures, where the value of the contents is many times higher than the structure itself.

During the application of the FRP solution, wrapping the total number of the first two floors, i.e. 21 columns, at the ends for a length of 80cm using three layers of Tyfo SCH-41. Thus, the desired ductility will be achieved. U-shaped wrapping of the beams of the first three floors, i.e. 76 beams in total, until a length of 2h from the ends, using two layers of Tyfo SEH-51A and the corresponding Tyfo Glass Fiber Anchors. Thus, the shear capacity of the beams will be sufficiently upgraded. De-installation and installation of the same window/door frames (no dimension changes), plastering, as well as some other small repair works, corresponds to a reconstruction cost per plan surface square meter of 15% of a new construction cost.

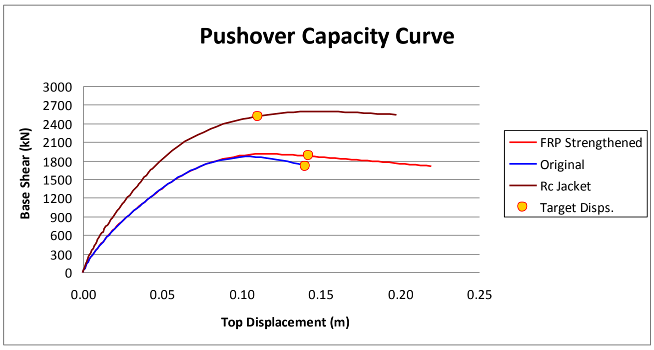


Figure 8. Comparison of the pushover capacity curves for 3 cases

Table 1. Cost analysis for the two solutions

Item	Description	Cost Units	Total	Unit Cost & Total Cost
FRP Strengthening Option				
1	Direct Strengthening	30	50	approximately €150-200/m^2 floor area
2	Finishing reconstruction @ 3 floors (135m^2/floor)	20		
Total Project Cost for total building surface of 4 floors 540 m^2				€81,000- €108,000
RC Columns and Beams Jacketing Option				
Item	Description	Cost Units	Total	Unit Cost & Total Cost
1	Direct Strengthening	50	100	approximately €300-350/m^2 floor area
2	Finishing reconstruction @ 4 floors (135m^2/floor)	50		
Total Project Cost for total building surface of 4 floors 540 m^2				€162,000- €189,000

Similarly, in case of RC jacketing, the application requires full RC jacketing of the 12 columns per floor at all four floors, construction of small foundations for the column jackets, beam jacketing (in whole length) at the first three floors (48 beams in total) and changing of window/door frames (dimension changes due to RC jacketing), demolition and reconstructing of walls, flooring, plastering, painting all inside and outside of the building and other repair works, turn a reconstruction cost per plan surface square meter of 30% of a new construction cost.

In terms of cost, the interventions described previously should be taken into account for each solution in order to reach a realistic estimation of the cost. Quantities have been calculated and for the current prices in Turkey for workmanship and materials the following cost analysis has been conducted (see Table 1). Though the purchase of FRP materials is more expensive as compared to the traditional materials, and their application entails the availability of specialized crew, the FRP solution excels in terms of cost as due to its effectiveness less quantities are required and the works of reconstruction are local and thus the relative cost limited. Specifically with the FRP solution, no work is needed in the fourth floor, thus no reconstruction cost for the fourth floor is generated.

7 CONCLUSIONS

Strengthening of an existing RC structure may be in several ways, depending not only on technical parameters but also on other parameters such as cost, legal issues, shutdown time and disturbance. In case an extra stiffness is not needed in strengthening, something that may be the case up to 3 to 4-story ordinary RC frame structures, as shown in this study, FRP could be a stand-alone solution with competitive advantages. FRP could be particularly useful in increasing the ductility through increasing confinement and/or shear capacity, an option that could be used complimentary to the traditional RC wall option.

The results found in this study are, in summary, given below:

- In small residential buildings with less than 5 floors, FRP can be used as a stand-alone solution for seismic improvement, obviously depending on the case
- Traditional methods may have limitations resulting construction of unnecessary RC walls and jackets, and furthermore, shear strengthening of beams is a major problem

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