Sustainable Solution for Deteriorated and Aged RCC Structures: A Review of Buildings, Bridges and Pavements

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Abstract. Sustainability is an important topic worldwide. The sustainable design will reduce the consumption of energy, water, land and raw materials. This ought to be taken into account when designing new structures and strengthening and renovating of existing deteriorated structures. This paper deals with the sustainable solution for the strengthening and renovating of the deteriorated or impaired structures. This is usually done through the use of FRP strips / sheets or bars that is bonded outside the member. Many researches have been conducted on this technique to observe its behaviour and ultimate strength. The materials used in research are steel, glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP), aramid fibre reinforced polymer (AFRP) sheets or bars. These were used as side bonding, U-jacketing and wrapping of the members. A significant improvement in strength was observed in the strengthened members. Accordingly, these techniques have been suggested as a sustainable solution. Based on the investigations, different countries propose different design codes and standards. Some of them provide reliable predictions, but more research is needed for an accurate and consistent predictive model.

1. Introduction

Construction of RCC structures involves use of raw materials, land and other resources. The raw materials include wood, metal, glass, sand, cement, aggregates, chemical admixtures etc. The production of the materials requires some energy and this emits CO2 gas in the air, which affects the greenhouse gas. Thus it has some direct and indirect effects on the environment, economy and society. Researchers are looking for a solution to reduce this effect. Sustainable design is an option to offset these issues through a combined methodology to create balanced design solutions. The main goals of this design methodology are to reduce or eliminate the consumption of resources such as energy, water, land and raw materials; avoidance of environmental damage from facilities and infrastructures during their service life; and construct environment that are safe, relaxed, livable and useful.

In addition to the inclusion of sustainable design conceptions in new buildings, proponents of sustainable design often call for the retrofitting of current buildings instead of new ones. Retrofitting a current building can be usually cheaper than constructing a new one. Planning the most important renovations and refinement of current buildings with sustainable design features decreases operating costs and environmental impact, and can improve the resilience of buildings. The resource cost, including manpower and materials, expended throughout the construction and use of the building is wasted when the building deteriorates or is demolished [1].
There are many buildings and infrastructures including bridges and RCC pavements are decaying and not fully functional. This deterioration can be due to the long time use (fatigue), environmental changes such as extreme temperature fluctuations, natural disasters, deficiency in the design, construction faults or weak construction technique, corrosion in reinforcement, improper maintenance, change in intended/planned use of the structures such as use of office buildings as residential buildings, and increase in traffic in case of bridges. Figure 1 shows some examples of deteriorated buildings. Figure 2 presents damages occurs in super structure and sub structure of bridges. Different types of cracks occurs in RCC pavement are shown in Figure 3. These RCC structures may need to be demolished or repaired to meet their expected service life. Demolition and rebuilding create environmental problems and require critical resources. Strengthening and rehabilitation is a preferred solution sustainability in mind.

Figure 1. Some deteriorated structures, (a) A nine story building damaged by earthquake [2], (b) spalling of concrete due to corrosion in reinforcement, and (c) cracking in column due to excessive loadings or faulty design.

Figure 2. (a) Bridges deteriorated by the corrosion of steel reinforcement [3], (b) deterioration in bridge deck and [4] (c) damages in bridge piers [5]

Figure 3. (a) reinforcement exposure in RCC pavement [6], (b) Durability cracking [7] and (c) longitudinal crack in rigid pavement [8]

Many RCC structures in Bahrain as well as around the world need to be repaired or strengthened to make them sustainable and safe or to avoid collapse. To the best knowledge of the authors’, however, no significant work has been done on this subject. Therefore, the purpose of this paper is to examine the techniques for strengthening and rehabilitation of existing deteriorated structures for a sustainable solution. The paper is described in the following order. First some of the existing work of this technique is explained, followed by the potential areas of application. It then identifies some future work and finally draws some conclusions.
2. Strengthening methods

Structural deterioration can be caused in different ways. This may be due to the normal wear and tear or cracking/spalling of concrete due to excessive loadings. The cracks can occur due to flexure or shear. For flexural cracks, surface level is usually the same on both sides of the crack formation. In case of shear cracks, however, the levels can be different, as shown in Figure 4. Therefore, the flexural crack repair might be more effective than shear crack repair. In addition, the performance of the repair depends on the bond strength between the laminate and the concrete.

![Figure 4. Effect of cracks, (a) shear and flexural cracks and (b) punching crack [9].](image)

There are several types of materials and techniques available for strengthening and rehabilitating weak structures. The materials can be steel sheet, fiber reinforced polymer (FRP) sheets, and FRP bars. However, steel is susceptible to corrosion and therefore not a suitable option for a sustainable solution. The FRP materials can be used as externally bonded sheet with concrete or FRP bars mounted close to the surface. For flexural strengthening, it can only be used at the bottom side of the members, however, various techniques such as FRP is bonded to the side of the members, sides and soffit of the members like U-jackets or complete wrapping of the FRP around the members are applicable for shear strengthening (Figure 5). This bond can be discrete or continuous. The FRP also can be used for rehabilitation of RCC pavements as shown in Figure 6.

![Figure 5. Different shear strengthening techniques.](image)
3. Existing studies on strengthening and rehabilitation

The flexural and shear capacities of beams and the axial load bearing capacity of columns can be increased by using FRP. Before applying the FRP for strengthening, the bond characteristics with concrete should be fully understood. In addition, many full-scale studies have been conducted to investigate strength and deformation characteristics. Several studies have been done to understand the bond behavior. Alam et al. [9] examined the influence of different crack surfaces on the shear-peeling bond strength between the FRP and concrete. The authors used Carbon and Aramid sheet laminates for strengthening. It has been observed that a difference in the level on both sides of crack opening has a great influence on the bond capacity. The effect of the fiber types on the bond behavior between fiber laminates and concrete is investigated by Nakaba et al. [12]. The authors mentioned that the bond strength increases as the concrete strength increases. Yuan et al. [13] examined the full range bonded joint behavior between FRP laminate and concrete. The authors explain the debonding process and proposed a bi-linear model to predict the debonding process. The model is applicable for joints made of steel / aluminum and concrete. Similarly, a non-linear bond-slip model is proposed by Savoia et al. [14]. The authors mentioned that the concrete cover layer is important to calculate the stiffness of the members.

Numerous investigations were carried out for strengthening of concrete members, in particular for shear strengthening using FRP materials. Triantafillou [15] investigated the shear strengthening of concrete beams with different area fractions and fiber configurations made of carbon fiber reinforced polymer (CFRP). The author reported that the efficiency of the process increases approximately linearly with increasing axial stiffness of CFRP. The use of CFRP sheets bonded on both sides of the beam led to an increase in the shear capacity that was 1.3 to 1.8 times larger than that of the control beams without any treatment [16].

Extensive damage / failure of bridge piers in 1995 Earthquake in Japan necessitated the determination of the best retrofitting technique. Mutsuyushi et al. [17] reported that the FRP sheet can be a viable solution for retrofitting. Accordingly, a new design method was proposed for retrofitting the bridge piers and columns damaged by the earthquake.

Kachlakev and McCurry [18] conducted a practical study by replicating beams from a deficient bridge caused by an increase in traffic. The beams were deficient in shear. The authors utilized both CFRP and GFRP to retrofit the beams. It was observed that retrofitting the beams resulted in an increase in strength of around 150%. Similar studies were conducted by other researchers [19-23] and observed that the FRP retrofitted members gained strength. Similarly, the shear strength of retrofitted T-beam with externally bonded FRP sheet also increased from 77.0 to 117.0% compared to the control specimens with no FRP sheet [24].

On the other hand, the use of near surface mounted (NSM) FRP bars also enhances the shear and flexural capacity of strengthened beams [25, 26]. In this method, the bars are inserted into the groove and filled.
with epoxy resin. De Lorenzis & Nanni [27] investigated the shear capacity of NSM-FRP reinforced members without transverse reinforcement. The authors reported that the NSM-FRP bars were effective in improving shear strength. Similarly, Nanni et al [28] utilized both NSM-CFRP rectangular bars for shear strengthening and pre-cured CFRP laminate bonded on the outside for flexural strengthening of pre-stressed concrete bridge girders. The girder was removed from an overloaded bridge in Kansas. The authors reported that the performance of the technique is very effective in increasing shear strength.

4. Design approach

The shear design approach for FRP-retrofitted concrete members follows the traditional method that is used in usual members. In this method, the total shear strength is considered to be the combination of concrete components ($V_c$), internal shear reinforcement components ($V_{s-int}$) and external FRP-strengthened components ($V_{f-ext}$). As a result, the total shear resistance ($V$) of FRP-strengthened members can be write as:

$$ V = V_c + V_{s-int} + V_{f-ext} $$

The amount of shear supported by concrete and internal shear reinforcement can be calculated using the same methods that are used in normal design. However, this technique is questionable because the maximum values of steel stirrups and FRP component may not occur at the same time. It is therefore recommended to use the maximum combined values instead of the individual maximum values [34]. The amount of shear that is carried by external FRP reinforcement can be determine using a truss analogy. This technique assumes the effective stress in FRP strips that intersect the cracks. The calculation of this effective stress is different in different methods. Some authors reported that the effective stress could be influenced by the presence of FRP.

The design codes and guidelines proposed in different countries are based on this approach. Some of the existing design codes and guidelines for strengthening and rehabilitation of structures are proposed by American Concrete Institute (ACI 440) [29], Canadian Standard Association (CSA S806) [30], International Federation for Structural Concrete, Switzerland (fib Bulletin No. 14) [31], Japan Society of Civil Engineers (JSCE) [31], and Italian CNR-DT200 [32]. However, there is some variation in the predictions using these methods. Pellegrino and Vasic [33] assessed the performance of the models proposed by different countries and authors using historical databases. The authors reported that the CNR-DT200 [32] and Pellegrino and Modena [33] methods gave more accurate and consistent results than the other methods investigated. The authors used a data set of 215 samples of rectangular and T-beams with different strengthening techniques. The authors also reported that the angle of the diagonal crack has a significant influence on the accuracy of the prediction of some models. It is worth mentioning that the effectiveness of the FRP-shear strengthening was significantly influenced by the steel stirrups [33]. It has been found that the performance of FRP-strengthening is decreased by increasing the ratio of axial stiffness of interior steel stirrups and exterior FRP sheets. This was attributed to the possibility of a non-yielding behaviour of the interior stirrups [33]. However, there are still some limitations remain in the prediction of the shear strength. When developing the model, the effective stress in the FRP-strap based on the strain distribution was taken into account. In the test results, however, the different strain distributions such as parabolic, linear and uniform were observed, although the number of tests is relatively low. Another limitation is the crack angles. The crack angles vary widely, but the design methods used a conservative approach taking into account the 45° angle. Therefore, further investigation is warrant to refine some of the design methods for FRP-strengthened structures.

5. Case studies

There are many companies in the US and around the world for strengthening and rehabilitation work. They implemented numerous techniques to strengthen and rehabilitate buildings, bridges, silos, and other structures. A school namely Jiangsu Xuzhou Mine Road Primary School can be mention as an example. The was built in 1983, after 25 years of its construction, it was noticed that the concrete compressive strength was lower than the design concrete strength. The slab and beams of this building

$$ \text{Shear strength of concrete: } V_c, \text{ internal shear reinforcement: } V_{s-int}, \text{ external FRP: } V_{f-ext} \text{.} $$
were reinforced with CFRP laminate as shown in Figure 7 [34]. The repair of I-65 expressway in Jefferson County, KY, USA can be mentioned as a case study of RCC bridge at this instance where the pre-stressed concrete girder was wrapped with CFRP fabrics at the crack location to prevent excessive deformation and increase their capacity (Figure 8) [35].

![Figure 7. Images of a repaired school building [34]](image)

![Figure 8. (a) Damage of RCC column of I-65 bridge, (b) repairing the columns with CFRP and (c) CFRP being applied on girder [35]](image)

6. Conclusions

The paper presents the possibility of a sustainable solution for deteriorated or damaged reinforced concrete structures without demolition. The literature suggests that there are different techniques are available for flexural and shear strengthening. These are U-jacketing, side bonding and wrapping for building and bridges. In addition to these, FRP sheet bonding and near-surface-mounted (NSM) bars are also sustainable options. Some of the techniques are utilized successfully for strengthening and renovating the existing structures. For pavement, patching and overlays are suitable remedy. The techniques have proven to be more effective and viable solutions. In order to determine the capacity of the strengthening members, several design methods based on the design methods of regular members have been developed. The design methods simply added the additional contribution of shear strength obtained due to the strengthening with the regular methods. While the available models are understandable, but they are not consistent. More researches are needed to develop an accurate and consistent predictive model.

7. References

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