Effect of concrete and bond strength on the behavior of RC beams retrofitted with FRP sheets

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ABSTRACT

Many concrete structures in the Arab countries and Iran located near the Persian Gulf are suffering from early deterioration. This is caused by aggressive environment in the region, poor quality concrete made with contaminated materials and lack of good workmanship and curing. A comprehensive survey of the concrete structures in the south coasts of Iran has been conducted in the last 15 years. Results of visual inspections and tests show that the dominant deterioration problem is the corrosion of reinforcement in the concrete structures that need to be strengthened. Sulfate attack, salt weathering, alkali aggregate reaction and environmental cracking were also responsible for some damages to the concrete structures. Among the retrofitting systems, the use of FRP sheets in concrete retrofitting industry is attracting more attentions worldwide. Since the retrofitted concrete structures have concrete with different strength, the behavior of FRP sheets can be different in different structures. Therefore, in this paper behavior of reinforced concrete beams with different concrete and bond strength, retrofitted with FRP sheets are reported. Experimentally obtained results are compared with those obtained from modeling by ABAQUS. Using five different concrete strengths, 15 reinforced concrete beams were constructed. For each concrete strength, two beams were strengthened using FRP sheets and one beam was left to be tested as a control beam. The concrete surface strength and the FRP bond strength were measured using new twist-off method. This new method can be used under laboratory and site conditions. The results tend to indicate that, increase in the concrete strength and the bond between the FRP layer, increases the ultimate load carrying capacity of the retrofitted reinforced concrete beams. Therefore, when opting for retrofitting with FRP sheets, the surface strength and the interfacial adhesion of FRP/concrete, should be given enough thoughts.

Key words: FRP, concrete strength, RC beam, flexural behavior, bond, twist-off method.

Introduction

Concrete is the most used construction material in the Gulf States. This material is more durable against severe conditions compared to other construction materials. However, due to the use of unsuitable components, poor workmanship, lack of curing, and lack of knowledge about the mechanism of deterioration, many structures (predominately those exposed to aggressive environments) show early deterioration.

The Persian Gulf region has a very severe exposure condition for reinforced concrete when compared to other marine environments. In the last couple of decades, the region has experienced significant growth in construction (e.g., industrial and urban construction). Most of this construction uses reinforced concrete. Many structures are showing signs of durability governed distress. Lack of understanding of durability factors in the initial design and construction is the prime cause.

The synergistic effects of physical and chemical mechanisms (e.g., corrosion of steel rebar, sulfate attack, carbonation of concrete, crystallization pressure of salts in pores, hydraulic overload, etc.) have contributed to the deterioration of concrete structures in the Gulf. In addition to these factors, climatic factors that involve large fluctuations in temperature and humidity affect concrete durability in the Persian Gulf states. Extreme temperature and relative humidity with daily and monthly variation intensify some mechanisms of deterioration.

Externally bonded FRP systems have been used to strengthen and retrofit existing concrete structures around the world since the mid 1980s. The number of projects utilizing FRP systems worldwide has
Increased dramatically, from a few in 10 years ago to several thousand today [1,4,2,11]. Structural elements strengthened with externally bonded FRP systems include beams, slabs, columns, walls, joints/connections, chimneys and smokestacks, vaults, domes, tunnels, silos, pipes, and trusses [12,15,17]. Externally bonded FRP systems have also been used to strengthen masonry, timber, steel, and cast-iron structures [9]. Externally bonded FRP systems were developed as alternates to traditional external reinforcing techniques like steel plate bonding and steel or concrete column jacketing [25,6,7,8]. In order to recognize different aspects of this retrofitting system, the effect of bed concrete and its surface strength on the behavior of the retrofitted elements under load is discussed in this paper. Therefore, FRP retrofitted beams were prepared using different concrete strengths and their flexural behavior were monitored. In order to measure the bond of the FRP sheets and the concrete surface strengths, the newly developed twist-off method was used [13,24,23].

Twist-off method:

It is often necessary to test concrete structures after the concrete has hardened to determine whether the structure is suitable for its designed use. Ideally such testing should be done without damaging the concrete. The tests available for testing concrete range from the completely nondestructive, where there is no damage to the concrete, through those where the concrete surface is slightly damaged, to partially destructive tests, such as core tests, pullout and pull off tests, where the surface has to be repaired after testing [16,5]. The destructive methods, which provide the most reliable strength estimates, involve removal of parts of the concrete, by coring or sawing, and testing them in a laboratory in a standard manner. The chief disadvantages of these systems include: considerable damage to the structure, safety problems (especially when prestressed tendons are involved), limited number of non-repeatable tests that can be performed on a member without seriously reducing its strength, and the high cost of performing the tests (including work stoppage, preparation, etc.). It is due to these disadvantages that destructive tests are generally only used in a fault diagnosis situation when other methods of assessing in situ strength are unsuitable or do not yield conclusive results [19,20].

The range of properties that can be assessed using non-destructive tests and partially destructive tests is quite large and includes such fundamental parameters as density, elastic modulus and strength as well as surface hardness and surface absorption, and reinforcement location, size and distance from the surface. In some cases it is also possible to check the quality of workmanship and structural integrity by the ability to detect voids, cracking and delamination. These methods can normally be performed quickly and inexpensively. Although large numbers of results can be obtained from a single member, it is often difficult to estimate the compressive strength of the concrete accurately, due to the highly indirect nature of the tests and the non-unique relationships between the properties measured and compressive strength [21]. The advantages and disadvantages of nondestructive methods are widely known.

Partially destructive tests involve destructive forces, the damage only takes place on a small scale so that repair work, if required, is superficial and the member under test is not significantly weakened. All of these methods employ calibration relationships to estimate compressive strength but, as some strength parameter is usually measured, they are regarded as being more reliable than nondestructive alternatives. As they are generally less expensive than destructive tests they tend to provide a better balance of advantages and disadvantages than any of the traditional in situ methods.

The twist-off method is one such partially destructive method, which can be undertaken in the laboratory and on site [28,26,14,10]. As is shown in Fig.1, the method involves bonding a 40 mm diameter metal probe (Fig.2) to the surface of concrete under test and an ordinary torquemeter is then situated on the preformed groove on the probe and a gradually increasing torque is applied by hand. Using the shear stress–torque relationship, the failure torsional shear stress is calculated. This can be used to estimate the concrete’s equivalent cube compressive strength by means of a previously prepared calibration graph. Some advantages of this method are simplicity, low cost, low damage, no need to expert technician and etc. By applying this method, we can also obtain the bond strength of different layers such as FRP sheets used for retrofitting RC concrete structures.

Fiber Reinforced Polymer (FRP):

FRP comprises of continuous fibers of high tensile strength within a polymer matrix. The matrix has two functions in which it enable the loads to be transferred among the fibers and the matrix also acts to protect the fibers against environmental attacks and mechanical damage during handling. These fibers have beneficial properties such as high stiffness to weight ratio, high strength to weight ratio, superior environmental durability, resistance to corrosion, high durability, ease of application and low maintenance. The properties have made them a competing alternative to the conventional strengthening and repair materials. FRP has been used and studied in different configurations, techniques and environment to utilize the material effectively and to prolong the service life of selected structural system [1,2].
The most common types of fiber reinforcement used in composite applications particularly in civil engineering are glass, carbon (Fig. 3), and aramid. Other fibers that are being used are Boron, silicon carbide, alumina. However, the decision on using which types of fiber for a particular application depends on the desired mechanical and environmental properties, as well as the cost of the fibers. Hence, proper materials selections is necessary for engineers in redesigning of existing product and applying to new products for better performance and also to obtain the maximum cost and weight benefits [11].

Fig. 1: Twist-off method.

Fig. 2: Steel probe used in Twist-off method.

Fig. 3: Retrofitting a beam with FRP.

**Materials and Methods**

**Experimental procedure:**

Reinforced concrete beams of 1200×150×100 mm size with concrete compressive strengths of 15, 25, 35, 45 and 55 MPa were manufactured. After initial curing for each concrete strength, two beams were strengthened using CFRP sheets and one beam was left to be tested as a control beam. The concrete surface strength and the FRP bond strength were measured using new twist-off method. This new method can be used under laboratory and site conditions (Fig. 4, 5 and 6). Concrete mix designs
are shown in Table 1. Ordinary cement which is used for common constructions was used. In order to place concrete easily and avoid creation of voids, with considering our dimensions, maximum size of aggregates and concrete’s slump were selected as 10 mm and 75 mm respectively.

**Fig. 4:** Dimensions of the RC beams used.

**Fig. 5:** Section and the reinforcing details of the RC beams used.

**Table 1:** Mix designs for different strengths ($\frac{Kg}{m^2}$).

<table>
<thead>
<tr>
<th>Strength</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>362</td>
<td>439</td>
<td>510</td>
<td>593</td>
<td>714</td>
</tr>
<tr>
<td>Water</td>
<td>215</td>
<td>217</td>
<td>218</td>
<td>220</td>
<td>222</td>
</tr>
<tr>
<td>Sand</td>
<td>987</td>
<td>893</td>
<td>721</td>
<td>762</td>
<td>688</td>
</tr>
<tr>
<td>Gravel</td>
<td>776</td>
<td>792</td>
<td>758</td>
<td>762</td>
<td>716</td>
</tr>
</tbody>
</table>

After preparation of reinforcing mesh and concreting the specimens, they were kept in a water tank for curing for 2 months. For bonding the FRP sheets, the weak laitance were removed by wire brushing and the dusts were cleaned properly. Properties of the applied epoxy resin glue are shown in Tables 2 and 3. Table 4 shows the properties of the CFRP employed.

**Table 2:** Typical properties of resin used.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxide Equivalent Weight $^1$</td>
<td>g/eq</td>
<td>185-192</td>
<td>ASTM D1652</td>
</tr>
<tr>
<td>Viscosity @ 25°C $^2$</td>
<td>P</td>
<td>110-150</td>
<td>ASTM D445</td>
</tr>
<tr>
<td>Color</td>
<td>Gardner</td>
<td>1 max.</td>
<td>ASTM D1544</td>
</tr>
<tr>
<td>Density @ 25°C</td>
<td>g/ml</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>Physical form</td>
<td>Clear liquid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor pressure at 77°C</td>
<td>mm Hg</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Refractive index @ 25°C</td>
<td></td>
<td>1.573</td>
<td></td>
</tr>
<tr>
<td>Specific heat</td>
<td>BTU/lb/°F</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Epoxy group content</td>
<td>mmol/kg</td>
<td>mmol/kg</td>
<td></td>
</tr>
<tr>
<td>Epoxy molar mass *</td>
<td>g</td>
<td>184-190</td>
<td></td>
</tr>
<tr>
<td>Viscosity at 25°C</td>
<td>Pa.s $^2$</td>
<td>12.0–14.0</td>
<td>ASTM D445</td>
</tr>
<tr>
<td>Color</td>
<td>Pt-Co</td>
<td>100 max</td>
<td>ASTM D1209</td>
</tr>
<tr>
<td>Density at 25°C</td>
<td>kg/L</td>
<td>1.16</td>
<td>SMS 1347</td>
</tr>
<tr>
<td>Flash point (PMCC)</td>
<td>°C</td>
<td>&gt;150</td>
<td>ASTM D93</td>
</tr>
</tbody>
</table>

$^1$ ASTM D1652 (Epoxy Content of Epoxy Resins – Perchloric Acid Method)

$^2$ ASTM D445 (Kinematic Viscosity - Determination of the Viscosity of Liquids by Ubbelohde Viscometer).

$^*$ no. of grams of resin containing 1g-equivalent of epoxide. (Weight per equivalent, WPE, is an alternative term).

$^**$ 1 Pa.s = 10 poise.
Table 3: Typical Properties of the used curing agent.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic nitrogen content</td>
<td>% m/m</td>
<td>6.0-8.0</td>
<td>ASTM D2896</td>
</tr>
<tr>
<td>Viscosity at 25 °C</td>
<td>Pa.s</td>
<td>0.5-0.7</td>
<td>ASTM D445</td>
</tr>
<tr>
<td>Colour Gardner</td>
<td></td>
<td>2 max</td>
<td>ASTM D1544</td>
</tr>
<tr>
<td>Hydrogen equivalent weight</td>
<td>g/eq</td>
<td>102-106</td>
<td>calculated</td>
</tr>
<tr>
<td>Recommended proportion</td>
<td>phr</td>
<td>58</td>
<td>calculated</td>
</tr>
<tr>
<td>Density at 25 °C</td>
<td>kg/l</td>
<td>1.04</td>
<td>ASTM D792</td>
</tr>
</tbody>
</table>

In the next step FRP sheets with properties shown in Table 4 stuck on concrete with epoxy resin glue.

Table 4: Properties of CFRPs.

<table>
<thead>
<tr>
<th>Property</th>
<th>Width</th>
<th>Thickness</th>
<th>Tensile elastic modulus (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Ultimate strain</th>
<th>Percentage of final extension of fibers*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid CFRP</td>
<td>50 mm</td>
<td>1.2 mm</td>
<td>165000</td>
<td>3050</td>
<td></td>
<td>1.7</td>
</tr>
</tbody>
</table>

* The thickness, modulus, and strength of the flexible composite are based on the dry fiber area rather than the “FRP” cross-sectional area.

Fig. 6: Retrofitted RC beams after being tested for FRP bond and the concrete surface strength.

In order to see the effect of the FRP/concrete bond and the concrete surface strength on the behavior of the retrofitted beams under the load, the beams were loaded in flexure and the deflection at different loads were monitored until failure took place.

Results and Discussions

As it is shown in Fig. 7, increasing the concrete strength tend to increase the final load carrying capacity of the non-retrofitted beams under flexural loading.

Examination of the results shown in Fig. 8 also shows the positive effect of the concrete strength on the ultimate load capacity of the retrofitted beams that were tested in flexure.

The measured deflections of the non-retrofitted beams are shown in Fig. 9. Examination of this figure tends to show that as the concrete strength increases, the mid-span deflection decreases under flexural loading.

For comparison, the mid-span deflections of the retrofitted beams are shown in Fig. 10. From this figure it appears that no clear relationship can be defined between the concrete strength and the mid-span deflections of the tested retrofitted beams. The reason for this may be the hardening effect of the FRP sheets on the deflections of the beam that may be independent of the concrete strength.

In figure 11 the deflections of the tested retrofitted beams are shown for comparison.
Fig. 7: Load bearing capacity of non-retrofitted beams with different concrete strength under flexural loading.

Fig. 8: Load bearing capacity of retrofitted beams with different concrete strength under flexural loading.

Fig. 9: Mid-span deflections of non-retrofitted beams under flexural loading.

Fig. 10: Mid-span deflections of retrofitted beams under flexural loading.
Fig. 11: Comparison of final mid-span deflections of retrofitted beams.

In order to see the effect of the concrete strength on its bond with FRP sheets, Fig. 12 is prepared. Examination of this figure shows that, as expected, the increase in the concrete strength tends to increase the FRP/concrete bond strength.

![Comparison of final mid-span deflections of retrofitted beams.](image)

Fig. 12: Relationship between FRP/concrete bond strength and the concrete compressive strength.

The relationship between the ultimate load bearing capacity and the FRP/concrete bond strength of the retrofitted beams are shown in Figure 13. The results shown in this figure shows that increasing the FRP/concrete bond strength tends to increase the ultimate load carrying capacity of the retrofitted beams.

![Relationship between the ultimate load bearing capacity and the FRP/concrete bond strength.](image)

Fig. 13: Relationship between the ultimate load bearing capacity and the FRP/concrete bond strength.

Modeling by ABAQUS software which is a collection of powerful modeling programs based on finite element method, can solve different problems from a simple linear analysis to a complex nonlinear modeling. This software has broad elements to model various geometries virtually. This also has many
engineering material models for modeling different materials with different properties and behaviors such as metals, rubbers, polymers, composites, reinforced concretes, spring and brittle foams, and materials in earth such as soil and stone [27,22].

In order to see the accuracy of the experimentally obtained results, one of the retrofitted RC beams with concrete strength of 15 MPa was modeled using ABAQUS software. As it is shown in Fig. 14, elements of concrete, longitudinal bar and stirrup, and FRP have chosen to be C3D8R (Solid element family), B31 (Beam element family), and S4R (Shell element family), respectively. Also, meshing is a structure type with the following element dimensions:

- Concrete: 0.015
- FRP: 0.02
- Longitudinal bar: 0.11
- Stirrup: 0.011

After completion of the construction of the model and applying the real conditions, analyses were carried out which resulted in the outputs shown in Figures 15-18.

According to Fig. 15 to 19, the outputs of the modeled retrofitted RC beam using ABAQUS software, shows good similarities between the experimental (Fig. 19) and analytical behavior of the beam considered. Comparison of different related parameters are shown in Table 5.
Fig. 17: Damage model of DAMAGEC.

Fig. 18: Damage model of DAMAGET.

Fig. 19: Failure of retrofitted RC beam with 15 MPa concrete strength, under flexural loading.

Table 5: Comparison of experimentally obtained results with those obtained from FE analysis.

<table>
<thead>
<tr>
<th></th>
<th>Ultimate load (KN)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>47</td>
<td>5.75</td>
</tr>
<tr>
<td>Modeling</td>
<td>47.6</td>
<td>5.81</td>
</tr>
</tbody>
</table>

Conclusion:

Based on the results discussed above, the following conclusions may be drawn:

1) By increasing the concrete strength, the load bearing capacity of the non-retrofitted and the retrofitted RC beams tends to increase.

2) Any increase in the concrete strength, decreases the mid-span deflection of both non-retrofitted and the retrofitted RC beams.

3) Increasing the concrete strength tends to have positive effect on the FRP/concrete bond strength.
4) Any increase in the bond strength, tends to increase the ultimate capacity of the retrofitted beams.  
5) Good agreements were observed between the experimentally obtained results and those resulted from the application of ABAQUS program.

Acknowledgment

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