CHAPTER 5

INVESTIGATIONS ON THE INFLUENCE OF ADHESIVE ON STRENGTHENING

5.1 GENERAL

This chapter reports the performance of the beams retrofitted using Kevlar fabric with different adhesives. The beams include a control RC beam, retrofitted beams with Epoxy, and retrofitted beams with Polymer modified Cement Mortar adhesives. The polymer modified cement mortar has been named as the cement mortar adhesive in this present study. Experimental investigations were carried out to provide a better understanding of the effectiveness of cement mortar based adhesive versus epoxy based adhesive as a means of increasing the load carrying capacity of the reinforced concrete beams. The structural behaviour of concrete structures can be improved by bonding the textile fabrics using epoxy adhesives. It has been reported that the use of epoxy resulted in excellent performances in terms of bonding and resistance to environments but with some drawbacks (Ombres 2011).

To overcome the drawbacks of epoxy adhesive, an alternative bonding agent made of cement mortar based composite can be used. Cement based materials have many advantages such as less or no preparation of a concrete surface required for good bonding, high resistance to fire and high temperatures, resistance to UV radiation, good workability, no emission of odors and toxins during construction or curing, and cost effective in comparison to polymeric resins (Toutanji et al 2006).
The most relevant issue concerned with the bond of the FRP or woven mat in the cement-based mortar is due to the granularity of the mortar and difficulty in the penetration and impregnation of fiber sheets (Smitha et al 2011). An enhancement of the bond can be obtained using fabric meshes or grids of FRP embedded into cementitious mortar. To account for better bonding Kevlar fabric open mesh was used for strengthening.

The results such as strength, stiffness, deflection, failure pattern, and cracking of beams strengthened using Kevlar fabric with the two adhesive systems and varying number of layers were compared.

5.2 LOAD DEFLECTION RESPONSE

Load deflection behaviour of the beams strengthened with epoxy and cement mortar was compared based on the wrapping scheme and the number of layers. Table 5.1 shows the ultimate load and deflection of the strengthened beams with the two adhesive systems.

5.2.1 Ultimate Load of Strengthened Beams vs. Unstrengthened Beam

The epoxy bonded bottom wrapped beams with single layer, two layers, and three layers of Kevlar fabric (KEB1, KEB2, and KEB3) showed an increase in load carrying capacity of 55%, 62%, and 82% respectively, compared to that of the control beam. The increase in the load carrying capacity of the epoxy bonded U wrapped beams with single layer, two layers, and three layers of Kevlar fabric (KEU1, KEU2, and KEU3) was 76%, 101%, and 114% respectively compared to the control beam. The epoxy bonded fully wrapped single layer, two layers, and three layers of Kevlar fabric strengthened beams (KEF1, KEF2, and KEF3), showed an increase in the
load carrying capacity of about 69%, 139% and 152% respectively with respect to the control beam.

Table 5.1 Ultimate Load and Deflection of Strengthened Beams with Two Adhesive Systems

<table>
<thead>
<tr>
<th>Beam ID</th>
<th>Ultimate Load (kN)</th>
<th>Ultimate Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>33</td>
<td>5.90</td>
</tr>
<tr>
<td>KEB1</td>
<td>51</td>
<td>5.65</td>
</tr>
<tr>
<td>KEB2</td>
<td>53</td>
<td>6.34</td>
</tr>
<tr>
<td>KEB3</td>
<td>60</td>
<td>7.43</td>
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<tr>
<td>KEU1</td>
<td>58</td>
<td>7.06</td>
</tr>
<tr>
<td>KEU2</td>
<td>66</td>
<td>10.17</td>
</tr>
<tr>
<td>KEU3</td>
<td>71</td>
<td>11.14</td>
</tr>
<tr>
<td>KEF1</td>
<td>56</td>
<td>5.88</td>
</tr>
<tr>
<td>KEF2</td>
<td>79</td>
<td>12.25</td>
</tr>
<tr>
<td>KEF3</td>
<td>83</td>
<td>13.23</td>
</tr>
<tr>
<td>KMB1</td>
<td>50</td>
<td>8.65</td>
</tr>
<tr>
<td>KMB2</td>
<td>53</td>
<td>8.10</td>
</tr>
<tr>
<td>KMB3</td>
<td>60</td>
<td>10.50</td>
</tr>
<tr>
<td>KMU1</td>
<td>53</td>
<td>16.17</td>
</tr>
<tr>
<td>KMU2</td>
<td>57</td>
<td>14.12</td>
</tr>
<tr>
<td>KMU3</td>
<td>67</td>
<td>13.09</td>
</tr>
<tr>
<td>KMF1</td>
<td>57</td>
<td>10.35</td>
</tr>
<tr>
<td>KMF2</td>
<td>63</td>
<td>11.88</td>
</tr>
<tr>
<td>KMF3</td>
<td>70</td>
<td>13.64</td>
</tr>
</tbody>
</table>
The increment in load carrying capacity of the cement mortar bonded bottom wrapped beams with single layer, two layers, and three layers of Kevlar fabric (KMB1, KMB2, and KMB3) was 52%, 62%, and 82% respectively, compared to the control beam. The cement mortar bonded U wrapped beams with single layer, two layers, and three layers of Kevlar fabric (KMU1, KMU2, and KMU3) attained an increase in load carrying capacity by 62%, 72%, and 102% respectively, compared to the control beam. The cement mortar bonded fully wrapped single layer, two layers, and three layers of Kevlar fabric strengthened beams (KMF1, KMF2, and KMF3), showed an increase in the load carrying capacity by 72%, 92%, and 112% respectively with respect to control beam. It was observed that the response of epoxy and cement mortar bonded Kevlar fabric strengthened beams was quite effective in increasing the flexural strength compared to that of the control beam. This was due to the wavy yarn geometry of the woven fabric structure, which turned out to be an effective anchoring mechanism as reported by Mu and Meyer (2002). Furthermore, the mesh type fabric structure helped in the efficient penetration of the bonding agent into the fabric meshes and improved the bond area between the fabric composite and the concrete surface of the beam.

5.2.2 Load Carrying Capacity Based on Wrapping Scheme

The single layer U wrapped epoxy bonded beam (KEU1) showed an increase in the load carrying capacity by 13% than that of the bottom wrapped beam (KEB1) and 4% than that of the fully wrapped beam (KEF1). The ultimate load of epoxy bonded fully wrapped beam with two layers of Kevlar fabric (KEF2) was 48% more than that of the beam wrapped at bottom with two layers (KEB2). The increase in load carrying capacity of epoxy bonded fully wrapped beam with two layers of Kevlar fabric (KEF2) at the ultimate stage was 19% higher than that of U wrapped beam with two layers
It was observed that the epoxy bonded fully wrapped beam with three layers of Kevlar fabric (KEF3) resulted in 38% higher load carrying capacity than that of the bottom wrapped beam with three layers (KEB3) and 18% higher than that of U wrapped beam with three layers (KEU3) at the ultimate stage. Hence, in the two layers and three layers of epoxy bonded beams, full wrapping scheme attained higher load carrying capacity than that of the bottom wrapping and the U wrapping scheme.

The single layer fully wrapped cement mortar bonded beam (KMF1) showed an increase in load carrying capacity by 13% than that of the bottom wrapped beam (KMB1) and 6% than that of the U wrapped beam (KMU1). The ultimate load of the cement mortar bonded fully wrapped beam with two layers of Kevlar fabric (KMF2) was 19% more than that of the beam wrapped at bottom with two layers (KMB2). The increase in load carrying capacity of the cement mortar bonded fully wrapped beam with two layers of Kevlar fabric (KMF2) was 12% higher than that of the U wrapped beam with two layers (KMU2). It was observed that the cement mortar bonded fully wrapped beam with three layers of Kevlar fabric (KMF3) had resulted in 17% higher load carrying capacity than that of the bottom wrapped beam with three layers (KMB3) and 5% higher than that of the U wrapped beam with three layers (KMU3). Thus, the cement mortar bonded beams of full wrapping scheme showed increased ultimate load in single layer, two layers and three layers of Kevlar fabric.

From Figure 5.1, it is found that the epoxy bonded fully wrapped beams with two and three layers of Kevlar fabric (KEF2 and KEF3) had resulted in higher load carrying capacity than that of the cement mortar bonded fully wrapped beams with two and three layers. But in single layer, U wrapped epoxy bonded beam (KEU1) was effective than that of the cement mortar bonded beams. The large area of the beam was covered with fabric in
U wrapping and full wrapping schemes resulted in the improvement of the bond strength. The effective confinement with the fabric resulted in improving the flexural strength of the beams.

Figure 5.1  Ultimate Load of Epoxy Bonded and Mortar Bonded Beams for Bottom, U and Full Wrapping Schemes with CB

5.2.3  Load Carrying Capacity Based on Number of Layers

From Figure 5.2, it is found that the three layered epoxy bonded and the cement mortar bonded beams had shown higher load carrying capacity in bottom wrapping, U wrapping, and full wrapping schemes than that of two layers and single layer strengthened beams. The ultimate loads of the beams were increased monotonically with increased degree of strengthening. The improvement of the ultimate load in the epoxy bonded bottom wrapped beams by increasing from one layer (KEB1) to two layers (KEB2) was 4%, whereas, it was 18% when increased to three layers (KEB3). In the U wrapped epoxy bonded beams the two layered (KEU2) and the three layered (KEU3) strengthened beams attained 15% and 22% increase in ultimate load over single layered beam (KEU1). The epoxy bonded fully
wrapped beams with two layers (KEF2) and three layers (KEF3) resulted in 42% and 49% higher load than that of the single layer beam (KEF1). So it is found that in all the schemes of wrapping, the strengthening with three numbers of fabric layers had been effective in gaining load capacity.

The improvement of the ultimate load in the cement mortar bonded bottom wrapped beams by increasing from one layer (KMB1) to two layers (KMB2) was 7%, whereas, it was 20% when increased to three layers (KMB3). In the U wrapped cement mortar bonded beams the two layered (KMU2) and the three layered (KMU3) strengthened beams attained 6% and 25% increase in the ultimate load over single layered beam (KMU1). The cement mortar bonded fully wrapped beams with two layers (KMF2) and three layers (KMF3) resulted in 12% and 24% higher load than that of single layer beam (KMF1). From the above results, it was found that the greater the number of Kevlar fabric layers, the greater the gain in load carrying capacity.

**Figure 5.2  Ultimate Load of Epoxy Bonded and Mortar Bonded Beams for Single, Two, and Three Layers of Fabric with CB**
While comparing the effectiveness of adhesive systems for varying number of layers, the three layered epoxy bonded beams in all the schemes of wrapping resulted in higher load carrying capacity than that of the cement mortar bonded beams. The higher effectiveness of the epoxy bonding is attributed to the higher strength of the epoxy compared to that of the cement mortar. This allowed for better stress redistribution in the fibers and hence, higher strength of the epoxy adhesive system was obtained. As reported by Saadatmanesh and Ehsani (1991), the epoxy adhesives have sufficient strength and stiffness to transfer the loads to the fibres. The development of shear stresses at the concrete and fibre matrix interface helped in effective transferring of the load.

5.2.4 Deflection Response of Epoxy vs. Cement Mortar Beams

The load deflection curves for the epoxy and the mortar bonded beams for various wrapping schemes in single layer, two layers, and three layers of Kevlar fabric is shown in Figures 5.3-5.5. The control beam failed at 33kN load with a deflection of 5.9 mm. From the experimental results, it was found that the first crack load of control beam was 11kN. Table 5.2 indicates the deflection values at a load of 11kN for epoxy bonded and cement mortar bonded strengthened beams. To study the deflection response of the strengthened beams over the control beam, the first crack load of the control beam was considered. All the strengthened beams showed increased flexural stiffness than the unstrengthened control beam. The increase in stiffness was proportional to the type of adhesive, wrapping scheme and number of layers or degree of strengthening. From Table 5.2, it is found that the epoxy bonded beams are stiffer than that of the cement mortar bonded beams. Based on the wrapping scheme, the fully wrapped epoxy bonded beams in single layer, two layers and three layers of fabric resulted in higher stiffness than that of the bottom wrapped and the U wrapped epoxy bonded beams.
Table 5.2 Deflections at 11kN Load for Epoxy Bonded and Cement Mortar Bonded Beams

<table>
<thead>
<tr>
<th>Wrapping Scheme with Number of Layers</th>
<th>Deflection @11kN Load (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Epoxy Adhesive</td>
<td>Cement Mortar Adhesive</td>
</tr>
<tr>
<td>B1</td>
<td>0.81</td>
<td>0.90</td>
</tr>
<tr>
<td>B2</td>
<td>0.70</td>
<td>0.84</td>
</tr>
<tr>
<td>B3</td>
<td>0.61</td>
<td>0.73</td>
</tr>
<tr>
<td>U1</td>
<td>0.77</td>
<td>0.82</td>
</tr>
<tr>
<td>U2</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td>U3</td>
<td>0.57</td>
<td>0.64</td>
</tr>
<tr>
<td>F1</td>
<td>0.55</td>
<td>0.78</td>
</tr>
<tr>
<td>F2</td>
<td>0.50</td>
<td>0.68</td>
</tr>
<tr>
<td>F3</td>
<td>0.40</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Further, from Table 5.2 and from Figures 5.6-5.8, it is clear that the three layered epoxy bonded beams with bottom, U and full wrapping schemes were stiffer than that of the single and the two layered bottom, U and fully wrapped schemes. The epoxy bonded strengthened beams resulted in a better performance compared to that of the cement mortar bonded strengthened beams, owing to the superior bond between the epoxy and the fibres. The improved bonding was because of the better penetration of epoxy adhesive into the fabric structure. The individual filament of the fabric was getting fully wet with epoxy, and made the textile fabric structure stiff. This was not done in the case of the cement mortar with fabric because of its granularity structure.
Figure 5.3  Load Deflection Curves for Epoxy and Mortar Bonded Beams for Various Wrapping Schemes in Single Layer

Figure 5.4  Load Deflection Curves for Epoxy and Mortar Bonded Beams for Various Wrapping Schemes in Two Layers
Figure 5.5  Load Deflection Curves for Epoxy and Mortar Bonded Beams for Various Wrapping Schemes in Three Layers

The curve fitting equation of the load deflection curve for KEB2, KEB3, KEU2, KEU3, KEF2, and KEF3 is given by

KEB2 (Epoxy bonded bottom wrapped beam with two layers)

\[ y = 0.0301x^5 - 0.3142x^4 + 1.9590x^3 - 6.3242x^2 + 19.3912x \]  
\[ (R^2 = 0.9984) \]  
(5.1)

KEB3 (Epoxy bonded bottom wrapped beam with three layers)

\[ y = -0.0055x^6 + 0.1274x^5 - 1.1543x^4 + 4.9946x^3 - 11.1740x^2 + 22.1052x \]  
\[ (R^2 = 0.9996) \]  
(5.2)

KEU2 (Epoxy bonded U wrapped beam with two layers)

\[ y = -0.015x^5 + 0.159x^4 - 0.634x^3 - 0.334x^2 + 15.51x \]  
\[ (R^2 = 0.998) \]  
(5.3)
KEU3 (Epoxy bonded U wrapped beam with three layers)

\[ y = 0.0016 \ x^5 - 0.0694 \ x^4 + 0.7314 \ x^3 - 4.1763 \ x^2 + 20.0327 \ x \]

\( R^2 = 0.9989 \) \hspace{1cm} (5.4)

KEF2 (Epoxy bonded fully wrapped beam with two layers)

\[ y = 0.0041 \ x^5 - 0.0754 \ x^4 + 0.7578 \ x^3 - 4.7007 \ x^2 + 22.1689 \ x \]

\( R^2 = 0.9992 \) \hspace{1cm} (5.5)

KEF3 (Epoxy bonded fully wrapped beam with three layers)

\[ y = 0.0190 \ x^5 - 0.3066 \ x^4 + 2.4410 \ x^3 - 10.4452 \ x^2 + 30.0500 \ x \]

\( R^2 = 0.9993 \) \hspace{1cm} (5.6)

Figure 5.6 Load Deflection Curves for Epoxy and Mortar Bonded Beams for Increasing Number of Layers in Bottom Wrapping
The curve fitting equation for mortar bonded strengthened beams is given by

\[ y = 0.0940 \, x^5 - 0.229 \, x^4 + 1.9453 \, x^3 - 7.4163 \, x^2 + 18.3744 \, x \]

\[ (R^2 = 0.9958) \]  

(5.7)
KMB2 (Cement mortar bonded bottom wrapped beam with two layers)

\[ y = 0.0510 \ x^5 - 0.1454 \ x^4 + 1.4073 \ x^3 - 6.5562 \ x^2 + 20.8850 \ x \]

\[ (R^2 = 0.9976) \] \hspace{1em} (5.8)

KMB3 (Cement mortar bonded bottom wrapped beam with three layers)

\[ y = 0.0043 \ x^5 - 0.1192 \ x^4 + 1.2055 \ x^3 - 5.9265 \ x^2 + 19.8213 \ x \]

\[ (R^2 = 0.9937) \] \hspace{1em} (5.9)

KMU1 (Cement mortar bonded U wrapped beam with single layer)

\[ y = 0.0002 \ x^5 - 0.0099 \ x^4 + 0.1784 \ x^3 - 1.7545 \ x^2 + 12.0988 \ x \]

\[ (R^2 = 0.9975) \] \hspace{1em} (5.10)

KMU2 (Cement mortar bonded U wrapped beam with two layers)

\[ y = 0.0134 \ x^5 - 0.0257 \ x^4 + 0.3802 \ x^3 - 2.7377 \ x^2 + 13.7051 \ x \]

\[ (R^2 = 0.9973) \] \hspace{1em} (5.11)

KMU3 (Cement mortar bonded U wrapped beam with three layers)

\[ y = 0.016 \ x^5 - 0.277 \ x^4 + 2.189 \ x^3 - 8.296 \ x^2 + 20.06 \ x \]

\[ (R^2 = 0.998) \] \hspace{1em} (5.12)

KMF1 (Cement mortar bonded fully wrapped beam with single layer)

\[ y = -0.0016 \ x^6 + 0.0514 \ x^5 - 0.6409 \ x^4 + 3.7198 \ x^3 - 10.2828 \ x^2 + 18.5409 \ x \]

\[ (R^2 = 0.9993) \] \hspace{1em} (5.13)
KMF2 (Cement mortar bonded fully wrapped beam with two layers)

\[ y = -0.0010 \ x^4 + 0.0447 \ x^3 + 0.9096 \ x^2 + 11.3602 \ x \]
\[(R^2 = 0.9976) \quad (5.14)\]

KMF3 (Cement mortar bonded fully wrapped beam with three layers)

\[ y = 0.018 \ x^5 - 0.0663 \ x^4 + 0.9206 \ x^3 - 6.0106 \ x^2 + 22.4536 \ x \]
\[(R^2 = 0.9957) \quad (5.15)\]

5.3 SPECIMEN BEHAVIOUR AND CRACK PATTERN

From the load deflection curves of the strengthened beams, it was observed that initially all the strengthened beams had behaved like the control beam with the internal steel bars carrying the majority of the tensile force in the section. When the steel had yielded, the additional tensile force was carried by the fabric and an increase in the load capacity of the member was obtained. The use of fabric could cause delay in the initiation of the cracks in the beam. The failure modes of the strengthened beams were different from that of the conventional reinforced concrete control beam. The fabric strengthened beams behaved in a linear elastic mode up to the failure. Figures 5.9 - 5.17 show the failure pattern of the epoxy bonded and the cement mortar bonded fabric strengthened beams.

In the bottom wrapped epoxy bonded beams, as the degree of fabric reinforcement increased from two layers to three layers, the failure mode was transferred from fabric rupture to debonding of fabric layers from the concrete surface. The beam KEB2 failed by crushing of the concrete within the midspan region and tearing of the fabric under the loading point at the bottom of the beam.
In the beam KEB3, a sudden debonding of the fabric layers was observed after the rupture of fabrics near one of its supports in the shear span, while reaching the ultimate load. The debonding had taken place due to flexural shear failure, indicating that the capacity of fabric with adhesive was not fully utilized. One of the vertical cracks in the shear zone had turned into inclined because of the combined effect of shear and flexure, and further increase in the load resulted in the propagation of the inclined crack towards the top concrete and hence debonding occurred. In addition, the debonding was caused by the failure of epoxy bonding between the concrete and the strengthening layer, which was observed by Grace et al (1999). It should be noted that the thickness of the fabric layer could also affect the debonding. The failures of the beams KEB2 and KEB3 are shown in Figures 5.9 and 5.10.

Figure 5.9 Failure of Beam KEB2

Figure 5.10 Failure of Beam KEB3
The cracks in the U wrapped and the fully wrapped epoxy strengthened beams were concentrated in the midspan region. The failure was because of the rupture of fabric at the bottom width and the sides of the beam combined with the crushing of concrete at the top as shown in Figures 5.11-5.14.

![Figure 5.11 Failure of Beam KEU2](image1)

![Figure 5.12 Failure of Beam KEU3](image2)

![Figure 5.13 Failure of Beam KEF2](image3)

![Figure 5.14 Failure of Beam KEF3](image4)

The cement mortar bonded beams are advantageous over epoxy bonded beams in terms of material compatibility between the adhesive and the beam. The cracks were formed at closed intervals as shown in Figures 5.15-5.22, which indicated the improved ductile behaviour of the cement mortar strengthening systems, as the fabric remained linear. Hence, the cement mortar bonded beams deform more without the rupture of fabric as reported by Bournas et al (2007). This ductile behaviour gave enough warning
before the ultimate failure. The failure of mortar bonded fabric beams was gradual compared to that of the epoxy bonded beams, owing to the slow progress of individual fibre fracture. This helped in controlling the failure of the strengthened beams.

The beam KMB1 failed by the crushing of the concrete as shown in Figure 5.15. In the bottom portion of the beam, more parallel cracks were observed in the fabric layer. The crack pattern of the beam KMB2 resembled the flexure failure of the conventional concrete beam as shown in Figure 5.16. It was observed that for each increment of loading, the crack propagation was one cm and the ultimate failure was due to the crushing of concrete in the constant moment region.

Figure 5.15 Failure of Beam KMB1

Figure 5.16 Failure of Beam KMB2
The three layered mortar bonded beam also showed normal pattern of cracks with some branched cracks as shown in Figure 5.17. For each increment of load, the distance of propagation of the cracks towards the compression zone was less. It was due to the crushing of the concrete that the ultimate failure happened and at this ultimate stage the fabric layers started debonding from the concrete surface.

The beam KMU1 failed by the crushing of the concrete between the loading points as shown in Figure 5.18. It was noted that at each increment of load, larger number of hair cracks were formed. The two layered U wrapped mortar bonded specimens exhibited closely spaced parallel cracks during each stage of loading and at the ultimate stage, the crushing of the compression concrete took place as shown in Figure 5.19.
In beam KMU3, the cracks were randomly distributed with slow propagation towards the top of the beam. The top concrete was crushed and hence from the top, peeling of mortar at the sides of beam was observed as shown in Figure 5.20.

In fully wrapped cement mortar bonded beams, a large number of closely spaced cracks were observed. These cracks were followed by the spalling of the mortar from the fabric during the increment of loading as shown in Figures 5.21 and 5.22. The cement mortar adhesives possess pseudo-plasticity due to the formation of micro-cracks resulting in the improved ductile behaviour of the strengthening system. Furthermore, the clear visibility of cracks in the cement mortar strengthened beams allowed easy inspection and immediate action of the damaged regions.
SUMMARY

The experimental results have shown that the load carrying capacity of the fabric strengthened beam with epoxy and cement mortar as adhesive is more than that of CB. The fully wrapped beams showed better performance than the bottom and the U wrapped beams. The confinement of the beams with fabric composites resulted in improving their strength. It is clear from the experimental results that the increase in the number of layers of the fabric resulted in higher load carrying capacity and stiffness. The epoxy resin matrix beams showed higher strength than that of the cement mortar.
bonding beams. The effectiveness of the strengthening methods will be reported in the next chapter by comparing the experimental test results of the beams retrofitted by externally bonded fabrics and near surface mounted FRP technique.