EXPERIMENTAL STUDY ON THE EFFECTS OF CYCLIC LOADING DURING REPAIRING PERIOD ON THE EFFECTIVENESS OF BONDED CFRP

M. Quiertant 1*, L. Siegert 2, C. Boulay 2, P. Fakhri 2, C. Tourneur 3 and J.-L. Clément 4

1 Division for Structures Behaviour and Durability, Public Works Res. Lab. (Université Paris-Est, LCPC), France. Email: Marc.Quiertant@lcpc.fr

2 Division for Concrete and Cement Composites, Public Works Res. Lab. (Université Paris-Est, LCPC), France.

3 Freyssinet-France, Palaiseau, France.

4 Scientific Direction, Public Works Res. Lab. (Université Paris-Est, LCPC), Paris France.

ABSTRACT

This paper describes a laboratory investigation on the effects of traffic load induced vibrations during the epoxy-curing period on the effectiveness of externally bonded carbon fibre-reinforced polymer in repairing reinforced concrete beams. During this experimental program, four small reinforced concrete beams were tested under three point bending. Except the control beam that was tested monotonically up to failure, all specimens were pre-cracked to be representative of damaged RC structures and then were submitted to a fatigue flexural loading. This cyclic load was intended to simulate the traffic condition. One beam was externally strengthened before the fatigue test while another one was repaired during cyclic loading. Finally beams were loaded monotonically up to failure. The results indicate that although strengthening during cyclic loading produces an efficient retrofitting, the cyclic loading affects the curing process of epoxy and reduces the effectiveness of the repairing. These results indicate that further studies are required to evaluate reliable and conservative safety factor for the design of bonded reinforcement if the bridge is to be subjected to traffic induced vibration during adhesive curing.

KEYWORDS

Carbon fibre-reinforced polymer, flexural strength, cyclic load, fatigue tests.

INTRODUCTION

In most European countries, financial efforts are mainly concentrated in the maintenance and the repair of existing bridges rather than building new structures. Similar situation exists in USA (Frangopol 2002). As a result, the construction companies have focused, in the last few decades, on the improvement of cost-effective and reliable techniques for the repair of Reinforced Concrete (RC) structures. Strengthening and rehabilitation of RC structures by externally-bonded Carbon Fibre-Reinforced Polymer (CFRP) systems is considered one such method as the use of Fibre-Reinforced Polymer (FRP) materials significantly shortens downtime for rehabilitation, which reduces inconvenience to the travelling public and economic loss to area served. Actually, in case of bridge structure, it is often important not to interrupt the traffic or at least to reduce the interruption to a minimum. However, to date, FRP system installation contractors and manufacturers recommend that the bridge remains closed during installation of the FRP system. If traffic interruption is not possible, one solution consists of using heat activated curing prepreg, (Li et al. 2003) to fasten repair damaged concrete structures. Then, curing can be achieved within 40 min to 3h depending on the materials used and the curing process. A major problem associated with prepreg system is that they can only be stored for a short period (approximately 30 days at room temperature) not always in accordance with usual stock management of fabricator and applicator. If an interruption of bridge service is not feasible, even for a short time, special precautions have to be to taken, like prescribing detour routes for trucks and/or diverting traffic away from the lane directly above the FRP installation (Reed et al. 2005). One major problem of such decision is that, effects of traffic on the effectiveness of the repairing are not completely established. Although bonded FRP systems have been extensively used, the lack of information concerning the effects of traffic load during and after strengthening are limitations that would be desirable to overcome. With this intention, a laboratory investigation on the effects of cyclic loading during the epoxy-curing period on the effectiveness of externally bonded CFRP in repairing RC beams has been conducted. The present paper describes the experimental program, details and discusses obtained results.
Review of previous work

One key factor to be considered in any repairing design when bridge remains open to traffic is the in-service mechanical condition: the magnitude of the sustaining load as well as magnitude and frequency generated by load cycles. Much research has been conducted on the topic of the effect of sustained load at strengthening on the flexural behaviour of strengthened reinforced concrete beams (e.g. Bonacci and Maalej 2000; Shahawy et al. 2001; Yeong-Soo and Chadon 2003; Takahashi and Sato 2005; Wenwei and Guo 2006).

Very few investigations, however, have been performed on the effectiveness of externally bonded FRP when the strengthened structure is subjected to significant transient loads during epoxy curing. Barnes and Mays (2001) have demonstrated that vibration during cure causes a progressive reduction in strength with increasing strain level of the lap joint. Their experimental program involved tests on two forms of joint, namely a CFRP single lap joint and RC beams with representative scale (Barnes and Mays tests on steel adhesion are not reported here). Two plate/adhesive systems were employed. Joints were vibrated during curing and compared to control specimen (non-vibrated during curing). For CFRP single lap joints, a 19 % strength reduction for one plate/adhesive system and 3 % for this other system was reported. However, each vibrated beam specimen failed at the same load as its respective control beam. It must be underlined that, in none of the beams tested was the failure of the adhesive. Moreover, in the same paper, Barnes and Mays underlined that this result is similar to the one obtained with concrete slab tested at the Swiss Federal Laboratories for Materials Testing and Research (EMPA 1998) where the ultimate load capacity of the externally strengthened slabs was not affected by vibration. Reed et al. (2005) describe a study conducted on eight beams (one half scale model of one girder of the War Memorial Bridge, Alabama) tested up to failure. Seven of the beams were strengthened with carbon-fibre of procured laminate strip. Test variables included the intensity and frequency of load cycles applied during the epoxy-curing period. Failure of all strengthened specimens initiated with FRP debonding. For all the traffic load regimens applied during and after installation, no reduction in the effectiveness of the strengthening was observed.

Finally although external bonding of FRP is generally installed to rehabilitate or restore the strength of deteriorated structural members, to the authors’ knowledge there is no experimental research data available for pre-damaged beams that are upgraded while under cyclic load. The other original aspect of the presented work lies in the use of sheets for the strengthening rather than plates. This permits to study the effect of vibrating during adhesive and polymer matrix curing (rather than only adhesive curing) on the effectiveness of the strengthening.

DESCRIPTION OF THE TESTS

Specimens

For this research program, four small-scale beams (15x20x70 cm³) were fabricated. All beams had identical rectangular cross-sections, size and internal steel reinforcement. Two of the four beams were strengthened with respect to flexural behavior using one layer of bidirectional carbon fiber sheet externally bonded to the tension face. The typical geometry and internal steel configuration of the specimens are shown in Figure 1.

Material characteristics of concrete have been identified on cylinders cast from the same concrete batch as the beams. They were measured at the period of the beam tests. Concrete properties are listed in Table 1.

<table>
<thead>
<tr>
<th>Material characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>31.8</td>
</tr>
<tr>
<td>Poisson’s ratio (MPa)</td>
<td>0.19</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>3.1</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>41.2</td>
</tr>
</tbody>
</table>

Table 1. Average mechanical properties of concrete (3 specimens)

Figure 1. Concrete beam geometry and reinforcement details
Specimen ES1 and ES2 were externally strengthened using an optimized scheme, consisting of one layer of CFRP that was externally bonded along the soffit of the beam for flexural strengthening and a second layer that was cut into U-shaped straps bonded transversely on the beams sides and soffit, as shown in Figure 2. The use of U-shaped transverse CFRP straps helps to anchor the longitudinal CFRP layer to the bottom of the RC beam. The width and locations of the transverse straps were established on the basis of a previous damage survey conducted at the LCPC (Wu et al. 2002).

The dry fiber sheets were applied following the specifications of the material system manufacturers. This include compliance with resin proportioning, mixing, application and, for ES1, curing. A two-component epoxy resin was used as the matrix and bonding agent for this composite system. Following preparation by sandblasting of the concrete beam surface, a first layer of impregnating resin was applied before application of the sheet, and application of the second layer of impregnating resin. Then, U-shaped straps were placed before the cure of the previous layer of resin.

The CFRP system manufacturer’s reported material properties are shown in Table 2. The woven sheet is a bidirectional fabric (70% of fibres are in wrap direction). The CFRP strengthening configuration of beams ES1 and ES2 is shown in Figure 2.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Fibers (12 k, Torayca)</th>
<th>Tensile modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x 0.43</td>
<td>230-221</td>
<td>4,900-4,510</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
<td>1,700</td>
</tr>
</tbody>
</table>

Test setup

The specimens were tested under a 3-point bending configuration with central concentrated load. The beams spanned 600 mm and were pin-roller supported. The loading was applied with a 500 kN Tinuis Olsen servo-hydraulic actuator controlled by TestwareSX software. The load was distributed equally by a stiff steel spreader beam to two points along the bottom of the beams. These loading points were also the pin-roller supports. The reaction was located at mid-span on the upper side of the beam. The experimental setup, location of load points and reaction are shown in Figure 3. During the tests, the loading, the deflection, the strain in the steel rebar at the middle of beam and the widths of the crack were measured. One gauge was glued at mid-span on CFRP for externally strengthened beams, below the first crack.
Experimental program

Four RC beams were tested in three point bending. The first and second RC beams (respectively labeled NES1 and NES2) were not externally strengthened. Except the control beam (NES1) that was tested monotonically up to failure, all specimens were pre-cracked to be representative of damaged RC structures and then were submitted to a fatigue sinusoidal flexural loading. Finally all beams were loaded monotonically up to failure. For monotonic loading, the deflection was used as the servo-control parameter, that helps recording post-peak behavior, provided the failure is ductile enough.

Monotonic and cyclic tests were performed using the same loading configuration. Fatigue test loading consisted in applying a total of 2,000,000 cycles with a load level varying from 40 % to 100 % of the load producing a 0.35 mm opening of the crack at midspan. The value of this load level, intended to simulate service condition of a bridge that needs to be repaired, was achieved by loading beam NES1 to the load level of 48.5 kN.

Although a frequency of 1 Hz was identified to be representative of highway traffic conditions (Macdonald 1981, Barnes and Mays 2001), beams NES2 and ES1 were loaded in fatigue at 4 Hz to shorten the testing program. The third beam (labeled ES1) was externally strengthened, after pre-cracking and before fatigue test, with no loading during epoxy-curing period. Following a further 7 days curing, fatigue flexural loading was undertaken. Beam ES2 was first cycled at 1 Hz during one week to allow for application and curing of the CFRP reinforcement. The rest of fatigue loading program of ES2 was achieved at 4 Hz. During cyclic loading, the servo-control parameter was the measured load.

Adhesion of the FRP sheets on ES2 was conducted by working under the specimen as it would be done in the field for the repair of the lower side of a bended member (Figure 4 b) while the beam ES1 was strengthened in laboratory conditions (Figure 4 a). Due to frequency of loading and conditions of CFRP applications, in the authors’ point of view, the external strengthening of the specimen ES2 is representative of the practical cases where strengthening is performed without removing the service load.

Following the 2 millions cycles program a static load test was undertaken on beam NES2, ES1 and ES2 up to failure.

The specimens and the steps of their test conditions are summarized in Table 3.

![Table 3. Summary of experimental program](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 5</th>
<th>Step 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NES1</td>
<td>No</td>
<td>No</td>
<td>X</td>
<td>None</td>
<td>Yes</td>
</tr>
<tr>
<td>NES2</td>
<td>Yes</td>
<td>No</td>
<td>X</td>
<td>2,000,000 cycles</td>
<td>Yes</td>
</tr>
<tr>
<td>ES1</td>
<td>Yes</td>
<td>Yes</td>
<td>One week with no loading</td>
<td>2,000,000 cycles</td>
<td>Yes</td>
</tr>
<tr>
<td>ES2</td>
<td>Yes</td>
<td>Yes</td>
<td>One week with 604,800 cycles of loading during epoxy-curing period</td>
<td>1,395,200 cycles</td>
<td>Yes</td>
</tr>
</tbody>
</table>

a) Reinforcement of beam ES1 in laboratory condition
b) CFRP applied as in situ (working under the beam)

Figure 4. External reinforcement of specimens

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TEST RESULTS

Specimen NES1 failed by rupture of one of its longitudinal bars below the mid-span stirrups, at the location of the initiation of the first crack. The initial crack formed a large flexural crack at failure. Similar failure mode was observed for beam NES2. Failure of the specimen ES1 occurred with tensile rupture of the longitudinal CFRP at the location of the crossing of this longitudinal layer with U-jacket, near the central part of the beam (Figure 6 a). Tensile failure of the CFRP was triggered by the large opening of a diagonal crack. Specimen ES2 failed by tensile rupture of CFRP below the central crack (Figure 6 b).

Performance of the beams are evaluated considering the load-deflection behaviour (other measured values are not considered in this paper). Experimental results are presented on Figure 5 and summarized on Table 4. Test on beam ES1 was stopped before complete failure of the specimen when the linear potentiometer employed for measuring deflection reached its maximum capacity (20 mm).

As a first result, it can be clearly observed that despite the fatigue cycles, the load-carrying capacity of the cycled specimen NES2 was still 7% higher than that of the non-cycled specimen NES1.

For all specimens, there was an increase in the load-carrying capacity when CFRP external reinforcement was added. The external reinforcement gave beams ES1 and ES2 strength gains of 49% and 17% respectively, over the specimen NES2.

When the load-deflection response of specimen ES1 is compared with that of specimen ES2, it is apparent that the efficiency of CFRP external reinforcement was reduced as a result of the cyclic loading during repairing period. It was observed during fatigue loading of ES2, that due to the cyclic opening of the crack, curing process of epoxy was never achieved, and no matrix was formed below the initial crack. Consequently, the external reinforcement at this exact location appeared to be just non-impregnated carbon sheet. Then the stress concentration on CFRP below the initial crack was critical and local failure occurred prematurely. It is also clear from this results that the fatigue load during repair, to which specimen ES2 was subjected, affected the deflection capacity of this repaired beam, noticeably lowering it.

It is interesting to note that NES1, NES2 and ES2 had similar deflection capacities at failure.

![Figure 5. Load-deflection behaviour of beams during static load.](image_url)

![Figure 6. Observed failure modes of strengthened beams.](image_url)
Table 4. Experimental results for loads and deflection.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum load (kN)</th>
<th>Failure mode</th>
<th>Ultimate deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NES1</td>
<td>133.7</td>
<td>Tensile rupture of one of the longitudinal bars</td>
<td>9.46</td>
</tr>
<tr>
<td>NES2</td>
<td>143.8</td>
<td>Tensile rupture of one of the longitudinal bars</td>
<td>9.16</td>
</tr>
<tr>
<td>ES1</td>
<td>215.0</td>
<td>Tensile rupture of the CFRP due to diagonal crack</td>
<td>x</td>
</tr>
<tr>
<td>ES2</td>
<td>168.6</td>
<td>CFRP rupture at mid-span below the initial crack</td>
<td>9.73</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The experimental program reported here included two externally strengthened beams that were tested up to failure. For comparison purpose one beam was not exposed to fatigue loading during bonding and curing while the other specimen was repaired while applying live load representing the expected service load of the member. For this beam, the CFRP was applied as in situ (i.e., working under the beam). Prior to the test of the two strengthened specimens, two unstrengthened beams were tested up to failure for comparison purpose. One of the unstrengthened beams was submitted to a fatigue flexural loading. Before fatigue tests, all cycled beams were precracked.

Obtained results indicate that although strengthening during cyclic load produces an efficient retrofitting in terms of load capacity, the cyclic loading affects the curing process of epoxy and reduces the effectiveness of the repairing especially in terms of additional ductility. Further studies are then required to evaluate reliable and conservative safety factor for the design of bonded reinforcement if the bridge is to be subjected to traffic vibration during adhesive curing.

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REFERENCES


