REHABILITATION OF BLAST DAMAGED PRE-STRESSED CONCRETE BEAMS WITH FIBER REINFORCED POLYMERS (FRP)

C S Lewangamage[1], M T R Jayasinghe[2]

[1]Senior Lecturer, Department of Civil Engineering, University of Moratuwa, Sri Lanka,
[1]E-mail: sujeewal@civil.mrt.ac.lk

[2]Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka,
[2]E-mail: thishan@civil.mrt.ac.lk

Abstract: Damage to buildings due to blasts is a somewhat common occurrence in today's context. When such damages occur, one option is to demolish the structure and then to reconstruct. However, a better approach from sustainability point of view is to rehabilitate the damaged structure with suitable means so that a lot of materials and time can be saved while reducing the creation of heaps of construction waste. Since the damages due to blasts are not so common, it is worth reporting sustainability approaches employed in every such occurrence. This paper will present one such rehabilitation work that has been carried out for a complete floor consisting of pre-stressed concrete beams with pre-tensioned wires that suffered heavily due to extremely high loads caused by a blast that occurred directly above it when a small plane carrying explosives was shot down.

***Key words:** Blast damage, Retrofitting, Fiber Reinforced Polymer (FRP), Reinforced concrete beams*

1. Introduction

When the buildings are damaged due to blasts, an option that can be appreciated more from the point of view of sustainability is repair and reuse. However, this is a challenging task due to the need for proper assessment of the effects of blast on short and long term performances. Therefore, the studies carried out using actual situation could be important as the laboratory based experiments. This paper presents one such rehabilitation work that has been carried out for a complete floor consisting of pre-stressed concrete beams with pre-tensioned wires that suffered heavily due to extremely high loads caused by a blast that occurred directly above it when a small plane carrying explosives was shot down.

The blast that is reported here was of very severe nature. It caused extensive cracking in T shaped pre-tensioned beams at both tension face (at the bottom) and also in the flanges that are supposed to be in compression [1]. At the outset, a simple solution for rehabilitation was reconstruction after demolishing the damaged beams. However, due to various other constraints such as time, congested site, difficult access, etc., an alternative was sought though it was a very challenging task for the structural engineer who was supposed to give a solution that can carry a guarantee with respect to durability and strength. The solution was first developed by approaching the solution with analysis based on fundamentals and basic properties of materials such as concrete and pre-stressing wires. The understanding on the behaviour of beams was then extended to cover the behaviour with Fiber Reinforced Plastic system that could be implemented economically. The theoretical model developed can be considered as a good approach that can be adopted not only to the beams damaged by blasts, but also to the structural members subjected to flexure that have suffered some damage due to corrosion of pre-stressing strands and reinforcement. This research paper describes the experimental study on FRP composites for flexural strengthening and also the practical applications of FRP.

2. Role of FRP in sustainable, built environment

Use of fiber reinforced polymer (FRP) composites for construction of new structures and rehabilitation of existing structures has increased significantly over past decades. FRP composites are lightweight, noncorrosive, exhibit high specific strength and specific stiffness, are easily constructed, and can be tailored to satisfy performance requirements [2]. For structural applications, FRP composites are typically fabricated using polymer matrix, such as epoxy, vinylester, or polyester, and reinforced with various grades of carbon, glass and/or aramid fibers. Due to its advantageous characteristics, FRP composites have been included in construction and rehabilitation of structures through its use as reinforcement in concrete, bride decks, modular structures, external reinforcement for strengthening and seismic upgrade. While mechanical advantages of using FRP composites are widely reported in literature, questions remain in regards to the feasibility of FRP composites within the framework of a sustainable environment[2].

The fabrication of constituent materials for FRP composites, namely matrix of fiber, could be areas of concern especially when considering that the primary resources from which polymers are produced; they could be crude oil, natural gas, chlorine and nitrogen [3]. The most commonly used fiber reinforcement in structural applications, can be identified as glass and carbon fibers. When considering only energy and materials resources it appears that the argument for FRP composites in a sustainable built environment is questionable. However, such a conclusion needs to be evaluated in terms of potential advantages present in the use of FRP composites related to consideration such as: high strength, light weight, high performance, longer durability, ability of rehabilitating existing structures and extending their life, seismic upgrades. They may also have applications in defense systems unique requirements, space systems and ocean environments.

It is important to note that the best way to minimize use of resources is to not rebuild in the first place. In this regard, the primary benefit of FRP composites will be its role in the solutions that seek to extend the service life of existing structures and to develop new structures that achieve superior service life with minimal maintenance. Essentially, it involves efficiently maximizing the benefit of potentially limited nonrenewable resources and avoiding the environmental, social and economic impacts associated with replacement and new construction. The benefits of FRP composites can be realized from its physical characteristics and their potential in developing structural systems with service life exceeding traditional materials [2]. The light weight of the composite can result in lower construction costs and increased speed of construction resulting in reduced environmental impacts. FRP composite material’s high strength and stiffness characteristics can require less material to achieve similar performance as traditional materials resulting in minimizing resources use and waste production. In general, the promise of FRP composites is its potential to extent the service life of existing structures and to develop new structures that are far more resistant to effects of aging, wreathing, and degradation in severe environments.

3. Performance of FRP composites with reinforced concrete beams subjected to flexure

An experimental study on behavior of FRP materials which has been used for the flexural strengthening of the beams were carried out. Three numbers of beams were casted and one beam was kept as the control specimen and other two beams were bonded with FRP composites and tested to find out the increment of flexural capacity. The deflection pattern and failure modes have also been checked. Beams were designed to avoid the shear failure with the increment of the loading after bonding with FRP.

3.1 Specimen details

2000 mm long × 150 mm wide × 200 mm deep beams were constructed. Cross section with the reinforcement details of the beams is given in Figure 1

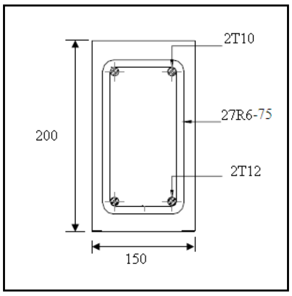

Figure 1: Cross section of the beam with R/F details

Grade of concrete used for beam casting was 30 and the properties of the FRP composites are given in Table 1.

Table 1: Properties of FRP composite

Thickness	**1mm/one layer**
Ultimate Tensile stress	834 N/mm^2
Rupture strain	85%
Modulus of Elasticity	82 kN/mm^2

Figures 2 and 3 show the cross section and the longitudinal section of the beam bonded with FRP, respectively.

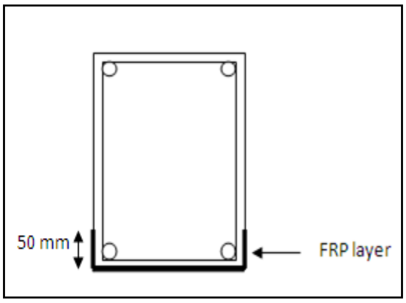

Figure 2: Cross section after bonded with FRP where FRP extends 50 mm on each side.

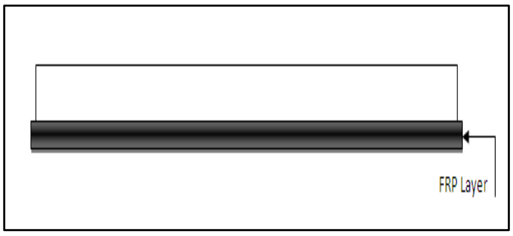

Figure 3: Longitudinal section after bonded with FRP

3.2 Test procedure

The beams were tested in four point bending, being simply supported on a pivot bearing on each end, over a span of 2.0 m. Identical bearing pads were placed at the loading points on top of the beams. A spreader I-beam resting on top of these provided a system for load distribution. Load was applied, by the increments of 5.0 kN throughout the tests. At each load increment, observations of crack development and the deflection of the mid span on the concrete beams were noted. Figure 4 shows the loading arrangement of the beams.

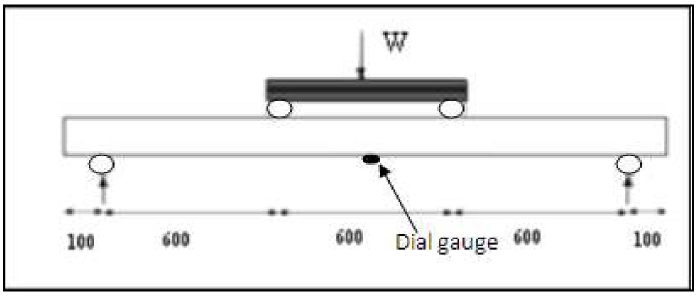

Figure 4: Loading arrangement

The bonding stresses of FRP-concrete interface are mainly shear and normal stresses. FRP on bottom of the beam that is subjected to flexural strengthening carries tensile stresses transferred through interface shear stresses and improves the bending capacity of the beam. The interface normal stresses also have influence on strengthened beam behavior [4]. At the end part of FRP where there is a truncation of FRP, stress concentration occurred and could initiate the FRP de-bonding [5].

Figure 5 shows the flexural cracks were propagated on the control specimen and Figure 6 shows the failure mode of the FRP bonded specimens and finally it can be concluded that the all the beams have failed due to flexure.

Figure 5: Flexural cracks of the control specimen

Figure 6: Concrete crushing and de-bonding of FRP bonded beam

3.3 Results

Deflection pattern of the FRP strengthened beams were almost the same and failure load was doubled compare to the control specimen. Figure 7 indicates the Load Vs Deflection of the mid span.

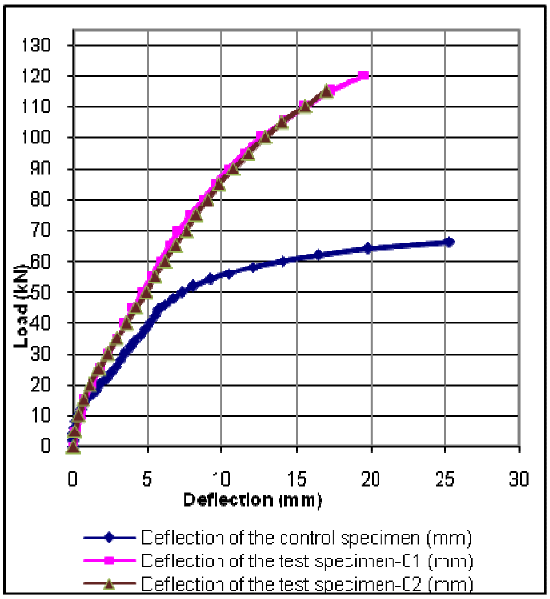

Figure 7: Load Vs deflection curve of the mid span of the beams

Failure load increment was nearly 84%. Summary of the failure loads and the failure modes are given in Table 4.

Table 4: Failure loads and failure modes of beams

Specimen	**Failure Load (kN)**	**Failure mode**
Control Specimen	66	Flexural failure
FRP bonded specimen-01	120	FRP de-bonding Flexural failure
FRP bonded specimen-02	123	FRP de-bonding Flexural failure

It is thus evident that FRP contributes to the beam's flexural capacity by restricting the opening of vertical cracks in the constant bending region. When the load and deformation are further increased, the developed interfacial shear stress at the concrete-FRP interface exceeds its capacity and then separation of the FRP plate could occur.

4. Rehabilitation of blast damaged pre-stressed concrete beams using FRP composites.

This work was part of the refurbishment and reconstruction of Inland Revenue head office building after the blast that occurred in the plane hit by ground fire. It was observed that about 27 number of precast pre-tensioned concrete T- beams (Figure 8) have hair line cracks close to their mid spans. The span of simply supported beams is 10. 6 m. These beams are located at roof terrace which is located at the 4th floor level. The main building has 12 stories.

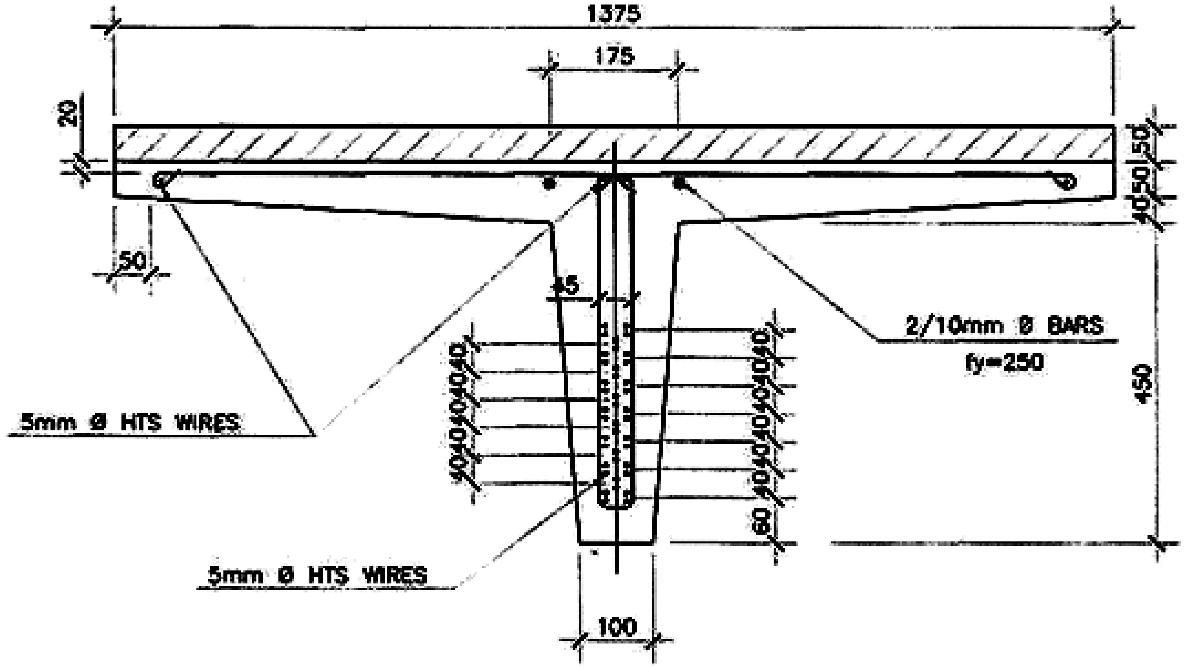

Figure 8: A section of the typical T-beam

During the blast that occurred, the building was hit by the many pieces of a small plane. The blast occurred just before the plane hit the building and hence could have occurred right above the roof slab. Some pieces and the engine of the plane ended up within the building. The location of blast was about 20 m above the roof terrace floor. This blast occurred at about 9.00 pm and a subsequent fire spared within the building. During the period of fire fighting and later, furniture, equipments and debris due to fire have been thrown away from the upper floors of the building on to this roof terrace. The day following the incident, it was observed that roof terrace floor was stacked with debris with over 2.0 m height. The debris consisted of equipments, computers, furniture, etc. which would have exerted significant loads. It was also reported that no such cracks have been observed in floor beams (floor beams in other location are also pre-stressed concrete T-beams) in other locations. Figures 9 and 10 show the details of cracked T-beams. The cracks appeared near the mid span of the beams are hair line cracks with maximum cracks width was about 0.1 mm.

Figure 9: Hair line cracks on T-beams close to mid spans

Figure 10: Cracks at T-beams flanges

The beams have suffered two types of loading that could be of significant nature. The blast that occurred over the 4th floor roof slab as could be seen with images captured by cameras with night vision would have applied a very significant impact load in the downward direction. The other load was due to throwing of various goods during fire fighting and cleaning operations that followed afterward by the security forces. It should be noted that for a heavy slab supported on beams, a gradual built up of debris could primarily over-load the slab and such overloading is most likely to cause few flexural cracks at the centre. However, there could also be few localized damages.

It should be noted that the crack width are as small as 0.1 mm with only few isolated ones reaching 0.2 mm. This is an indication that the steel wires would have suffered some overstress and would have been stressed beyond the 0.2% proof stress, thus inducing some permanent elongation. However, there is one property of steel that can still allow such over-stressed steel to be used further in structures for supporting loads of normal magnitudes. That is if a steel section does not break due to over stressing that induce work hardening, the steel can still be used if it is unstressed to a appreciably lower stress.

In this particular case, the steel tendons are partially unstressed and the actual stress would be as low as 750 – 800 N/mm^2 where as the characteristic tensile strength of original steel was much higher and in the range of 1560 N/mm^2.

5. Remedial measures

It was recommended to strengthening all the beams with cracks to enhance the flexural capacity using carbon fiber reinforcements so that some extra load could be independently carried by the carbon fiber based system. This position can be supported by the following facts. The systems of beams are pre-tensioned. Thus, the energy stored in the system allowed the beams to survive the blast though they could have suffered excessive deflections that led to high strain in steel wires and also some cracks at the very highly reinforced flanges. However, system recovered after the blast and indicated the possibility carrying self weight without noticeable deflections. A load test carried out has also indicated the possibility of carrying some loads without noticeable deflections. Here, bonded system was considered as a secondary system that would give a guarantee on load carrying capacity, both short and long term. Hence, only the additional loads that could induce further deflections were considered for determining the FRP system. The loading considered were the followings: (a).Allowance of 1.0 kN/m^2 is desirable to take account of finishes. (b). Live load on the slab can be considered as 5.0 kN/m^2 The corresponding design bending moments will be about 27 kNm for permanent loads (with a partial factor of safety for loading of 1.4) and 154 kNm for live loads (with a partial factor of safety for loading of 1.6) under simply supported conditions.

When carbon fibers are used, it is possible to determine the flexural capacity with triangular stress block even for ultimate loads. This will be a better approach since inducing high strains in carbon fiber is not prudent from the point of view of brittleness indicated by carbon fibers. Thus, it would be better to rely on a triangular stress block in concrete even at ultimate for the additional loads. This will results in slightly higher use of carbon fibers, but will ensure that there would be a very remote chance for exceeding the strain capacities of carbon fiber even when the beams are overloaded.

The corresponding resisting tensile force due to above loading is 322 kN. Hence required area of carbon fiber reinforcements is 386 mm^2 (corresponding to design tensile strength of carbon fiber and epoxy composite is 834 N/mm^2).

The stresses that will occur in this beam under service conditions have also been determined. The stresses under working condition will be; (a) at the top of the screed is 5.1 N/mm^2, (b) at the top fiber of precast section is 5.06 N/mm^2 and (c) at the bottom fiber of the precast section is -0.93 N/mm^2

It can be stated that the stresses in concrete are within the allowable limits for this 10. 6 m long beam. The allowable value for compressive stress will be 0.33 x f_{cu} = 0.33 x 40 = 13.2 N/mm^2. The allowable tensile stress for a class 2 structure is about 2.0 N/mm^2. Figures 11 and 12 show the repair work of cracks in beams and floor and the beams completed with FRP work.

Figure 11: Repairs to non-structural cracks

Figure 12: The beams completed with FRP work

6. Conclusion

The beams have suffered two types of loading, the blast loading and the loads due to throwing of various goods during fire fighting and cleaning operations. The gradual built up of debris could have over-loaded the slab which would have already suffered heavy overload due to the blast. Hence, it is most likely that the cracks near mid span of the beams would be of flexural nature, and are existing because steel tendons have suffered strain beyond 0.2% proof stress during the blast.

The blast damaged pre tensioned concrete T-beams were successfully strengthened using FRP composites with a carefully selected system that can ensure acceptable behaviour and a safe structure with respect to both short term and long term performance. This could be a solution that can be appreciated very much from sustainability point of view.

Acknowledgement

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