The Use of Advanced Composite Technology for Mitigating Blast Risk in Structures

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Introduction
Recent world events have exposed the vulnerability of civilian infrastructure under the extreme effects of accidental or man-made explosions with respect to protecting the lives and safety of occupants. Accordingly, there exists a need to develop new retrofit strategies to mitigate the effects that explosions have on structures. To date, a great deal of research has focused on the use of fibre reinforced polymer (FRP) materials for the retrofit of seismically deficient structures and structures suffering from corrosion related problems. Recently, research has begun focusing on the application of FRP retrofits for blast resistant structures. The advantages of FRP – including adaptability and high strength-to-weight ratio – offer tremendous potential for retrofitting existing structures against potential blasts threats. However, FRP retrofitted structures subjected to impulsive loading are susceptible to premature failure caused by FRP debonding. Consequently, the Blast Research Group at the University of Ottawa is actively investigating the innovative use of FRP anchors to increase the blast capacity of FRP retrofitted reinforced concrete structures.

Technical Analysis
The predominant failure mode of FRP retrofitted structures is the premature failure of the chemical bond between FRP and concrete causing delamination of the FRP. This bond failure causes a loss of composite action between the reinforced concrete member and the externally bonded FRP. This results in a significant loss of strength and, ultimately, leading to structural failure. However, if mechanical anchorage of FRP sheets is provided, delamination of FRP may be prevented or delayed and the capacity of the reinforced concrete member may be significantly increased. FRP anchors are designed to prevent premature debonding failure of externally bonded FRP retrofits subjected to blast pressures. These anchors, placed at the ends of FRP sheets, provide end-anchorage against delamination by supplementing the primary mechanism of bond between of chemical adhesion between the concrete and the FRP’s epoxy resin.

Anchor preparation and installation is described in detail by Ozbakkaloglu and Saatcioglu [1] and summarized below; anchors are prepared from the same materials used to strengthen individual members. Sections of FRP sheets are cut to the desired width and length and then rolled to form a tube of desired diameter. The tubes are folded at midlength and tied at the desired length of embedment, shown in Figure 1(a). Depending on the application, FRP anchor diameter ranges from 1/2” to 3/4” and fan length of at least 4” to ensure proper bond between anchor and longitudinal FRP sheet.

Holes with the same diameter as the anchors are drilled in the concrete substrate prior to the application of externally bonded FRP sheets. Holes are drilled perpendicular to the concrete surface to a depth of 1” to 4”, depending on the required anchorage strength. Holes are cleaned of dust and debris and the externally bonded FRP sheets are applied to the concrete surface. FRP anchors are the inserted and epoxy glued into the holes. The fan portion of the anchors is then epoxy glued to the externally bonded FRP sheets, as seen in Figure 1(b).
Anchorage strength of FRP anchors is influenced by the anchor diameter, embedment depth, workmanship and angle of inclination relative to concrete surface [1]. Generally, anchors with larger diameter and embedment length exhibit greater pullout capacities than smaller anchors. Furthermore, preparation of the hole and application of epoxy resin are critical to ensuring full development of anchor strength.

An experimental program designed to evaluate the benefit of FRP anchors in increasing the blast resistant capacity of externally bonded FRP retrofits is currently underway at the University of Ottawa. A total of six one-way simply supported reinforced concrete slabs, divided in two companion sets, are currently being subjected to simulated explosive testing. All slabs are nominally identical, with a clear span of 6'-8" and a width of 17.3". Three slabs from one companion set were constructed with a thickness of 3.1" while the remaining slabs were 4.7" thick. The specimens were each reinforced with four \( \frac{1}{4} \)" diameter undeformed steel bars in the longitudinal direction, on both faces. Concrete strength at the time of testing was 8.4 ksi and the yield strength of steel was 81.1 ksi.

One slab from each companion set was not retrofitted to serve as a baseline to judge the performance of the retrofits. Another slab from each set was retrofitted with one-ply of the FYFE-CO SCH-41 unidirectional carbon fibre reinforced polymer (CFRP) laminate on the unloaded face. The third slab from each set is currently under construction; these specimens will be retrofitted with one-ply of unidirectional CFRP laminate with four FRP anchors on each end of the laminate sheet. The anchors will have a diameter of 5/8" and be embedded a depth of 3" at an angle of 90° to the surface of the slab.

Simulated blast loading of these specimens is conducted using the University of Ottawa’s Shock Tube Testing Facility. Designed to accurately and economically allow for large scale testing of structural elements to shock wave loading, while eliminating the dangers and costs associated with live explosive testing, the full capabilities of the pneumatically-driven shock tube are described in [3, 4, 5]. Figure 2(a) shows a typical slab prior to simulated blast testing. All slabs were subjected to two identical simulated explosions. The first blast was intended to determine slab response at negligible levels of damage. This was followed by a large blast, simulating the detonation of approximately 2200 lbs of TNT at a stand-off of 90 ft causing significant damage to both the control slab and slab retrofitted with FRP shown in Figures 2(b) and (c), respectively.
The peak reflected blast overpressure developed on the face of the slabs was equivalent to 390 psi with a positive phase duration of 17.2 ms.

![Image of slabs](image)

(a) Typical slab prior to simulated blast testing  
(b) Unretrofitted control slab after simulated blast testing  
(c) CFRP retrofitted slab (without FRP anchors) after simulated blast testing

**Figure 2: One-way RC slabs prior to and after being subjected to simulated shock loading.**

The experimental testing performed to-date has confirmed that there is insufficient bond between FRP and concrete to fully realize the capacity of an externally bonded FRP retrofit system to resist blast loading. This implies that additional anchorage is required. The displacement time histories recorded during blast response for the 3.1" thick companion slabs are shown in Figure 3. The 3.1" thick unretrofitted control specimen experienced a peak midspan displacement of 6.6" and underwent extensive plastic deformation. Although the midspan displacement of the FRP retrofitted specimen without anchors was reduced to 5.7" under the same simulated blast loading, premature bond failure prevented the retrofit from achieving its full capacity. This experimental result reinforces the need for the development of secondary anchorage systems to ensure the full potential of FRP retrofits is realized.

Currently, development of the FRP anchorage technology applied to mitigate explosive effects of blast on structures is at the research and development stage. An experimental programme investigating its performance is currently underway at the time of writing this document. Current experimental research has shown that relying on the bond between FRP laminate sheets and concrete alone is insufficient to develop the full potential of externally bonded FRP retrofits. Existing research into the application of FRP anchors under static loading conditions and subjected to seismic (earthquake) loading has shown that this technology has the ability to
increase overall retrofit performance by preventing and/or delaying premature FRP delamination failures.

Figure 3: Experimental pressure-time history and midspan displacement curves for the 3.1” thick FRP retrofitted RC slabs.

Market Analysis
Key facilities forming the backbone of North American infrastructure are vulnerable to the hazards caused by explosive blasts. These structures include hospitals, fire stations, industrial complexes, and electrical and telecommunications facilities. The destruction of these facilities could potentially result in the loss of a significant number of lives and affect the economic well-being of countless citizens. Therefore, the FRP anchorage retrofit system is targeted towards Government, property owners/managers and engineers tasked with protecting critical infrastructure. By incorporating this technology into existing FRP retrofit systems, the likelihood of unwanted premature structural failure may be reduced, if not eliminated.

Industry Analysis
Several methods of preventing delamination of externally bonded FRP sheets are currently in use, with varying degrees of success. One method that has been successful at preventing delamination and increasing the capacity of reinforced concrete members is the use of metal bolts to mechanically clamp between the anchorage device and concrete [6]. As FRP sheets have low shear resistance, localization of stresses around metal end-anchorages tend to result in localized shear failure of FRP sheets. Another retrofit technique involves machining a groove in concrete at the ends of the FRP sheets, running parallel to the principle direction of the fibres. The FRP sheets are then extended into the groove and the groove filled with resin [7]. However, the large-scale installation of these end-anchorages is costly and extremely labour intensive.

The advantages of using FRP end-anchorages over other anchorage systems include:

- FRP anchors have identical physical characteristics to the rest of the strengthening system
- Reduced material cost; anchors may be fabricated on-site and are constructed from the same material as the rest of the strengthening system
• Minimal installation requirements lowers labour costs and reduces building downtime, allowing building occupants to return to work sooner than similar systems

• Increase retrofit capacity by promoting tension membrane behaviour and not inducing shear failure of the FRP sheets

Recommendations
Externally bonded fibre reinforced polymers have tremendous potential to increase structural capacity for structural members considered deficient under explosive loading. Many benefits may be realized from proper use of this advanced composite material including increased strength, stiffness, and ductility, all of which can contribute to mitigating the risk of casualties or structural damage. In order to achieve the potential benefits of the FRP, proper care must be given to ensuring that premature failure does not occur in the polymer bond that joins the retrofit material to the concrete member. The use of FRP anchors is recommended to increase the bond capacity and prevent premature delamination of the FRP. These anchors must be strategically placed in critical members such that the maximum capacity of the retrofit is achieved.

FRP anchor technology for blast risk mitigation is currently at the system development phase; large-scale testing of actual specimens retrofitted with FRP laminates and incorporating FRP anchors subjected to simulated blast pressures is currently being performed. Future development will require a parameterized experimental and analytical study to develop design guidelines governing the implementation of FRP anchor technology to mitigate blast risk for use by Government, property owners/managers and engineers. As the Shock Tube Testing Facility at the University of Ottawa is fully equipped to perform simulated blast testing, the development of these guidelines will only require a modest operating budget to fund expenses associated with construction of test specimens.

References


