INNOVATIVE, INTELLIGENT CONCRETE STRUCTURES USING FIBER REINFORCED POLYMER (FRP) MATERIALS

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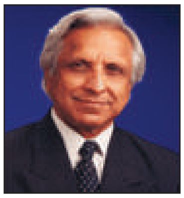


ABSTRACT**:** ISIS Canada intends to significantly change the design and construction of civil engineering structures through the use innovative new technologies and materials. For these structures to be accepted by the engineering community, they must be monitored and the findings reported to the engineering community as well as incorporated into civil engineering codes. Through the development of the new discipline of civionics, which has integrated *civi*l engineering and electr*onics*, ISIS has been able to monitor intelligent structures and harvest the data. This paper discusses some of the innovations that have been implemented in various ISIS research projects across Canada.

1. ISIS INNOVATIVE TECHNOLOGIES

For infrastructure owners, one of the greatest values of ISIS Canada research lies in its practical application; increasingly, new opportunities have arisen for applying ISIS Canada technology. This is evidenced by the growing number of field demonstration projects underway. These projects range from a concrete steel-free bridge deck for the Salmon River Bridge in Nova Scotia [2] to the strengthening of a nuclear containment structure in Quebec [3]. At least fifty projects are currently being monitored for health in Canada, several of which are discussed in the following sections.

1.1. Beddington Trail Bridge, Calgary, Alberta

In 1992, the Beddington Trail Bridge in Calgary [4], Alberta (**Figure 1.1a**), was the first bridge in Canada to be outfitted with FRP tendons and a system of structurally integrated optical sensors for remote monitoring. The bridge opened in 1993 before ISIS Canada was established. However, it is significant to the ISIS network because, for the group of researchers involved, it confirmed the need for an organization like ISIS Canada that could spearhead transferring this new technology to industry.

The Beddington Trail Bridge is a 2-span, continuous skew bridge of 22.83 and 19.23-m spans, each consisting of 13 bulb-Tee section, pre-cast, prestressed concrete girders. Two different types of FRP tendons were used to pretension six precast concrete girders. Carbon fiber composite cables produced by Tokyo Rope of Japan were used to pretension four girders, while the other two girders were pretensioned using Leadline rod tendons produced by Mitsubishi Kasei.

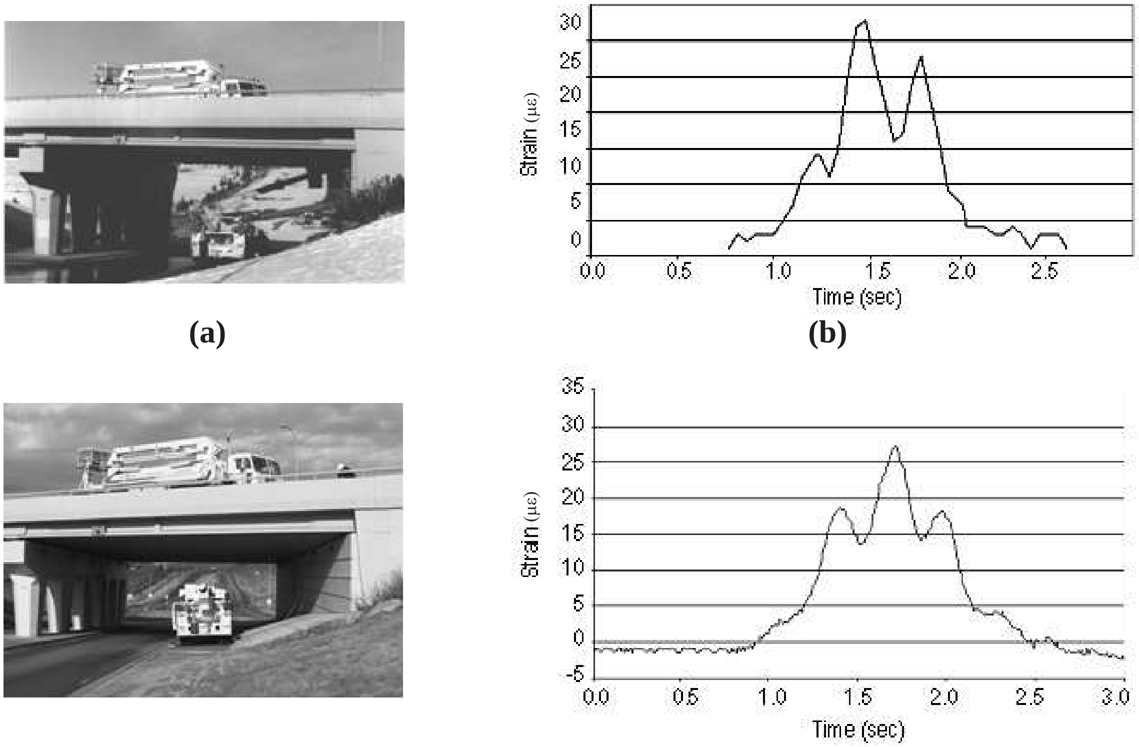
Fiber optic Bragg grating strain and temperature sensors were used to monitor structural behaviour during construction and under serviceability conditions. The 4-channel Bragg grating fiber laser sensing system was developed for this purpose at the University of Toronto Institute for Aerospace Studies. Before constructing the bridge, an experimental program was conducted at the University of Manitoba's W.R. McQuade Structures Laboratory to examine the behavior of scale model beams pretensioned by the same type, size, and anchorage of the two different tendons used for the bridge girders.

Prestressing of carbon FRP was adapted by coupling the carbon fiber composite cables and Leadline rods to conventional steel strands. Couplers helped to minimize the length of carbon FRP tendons and were staggered to allow the use of the same spacing for the conventional steel reinforcing tendons. The Leadline rods were cut at the site, and two rods were used for each tendon. The carbon fiber composite cables were delivered pre-cut to the specified length with 300 mm die cast at each end to distribute the stresses at the anchoring zone. Construction of the bridge and handling of the girders at the site was typical.

A 4-channel Bragg grating fiber optic sensor system was used at different locations along the bridge girders that were pretensioned by the carbon FRP. Each fiber optic sensor was attached to the surface of the tendon after pretension to serve as a sensor. The sensors were connected, through a modular system, to a laptop computer used at the construction site to record the measurements at different stages of construction and after completion of the bridge. The optic sensor system measures the absolute strain rather than a strain relative to an initial calibration value similar to electric resistance strain gauges and mechanical gauges.

In 1999, the bridge was tested statically and dynamically to assess the durability of the fiber optic sensors. After six years, all FOSs were functioning (**Figure 1.1a and 1.1b**). This finding validates the view that FOSs are durable and reliable for long term monitoring.

In November 2004, the bridge was tested again with the same vehicle and weight. **Figure 1.1c and 1.1d** indicates that the FBG sensors are durable and are providing accurate results, and that the CFRP is performing as designed in 1993.



(a) **(b)**

(c) **(d)**

Figure 1.1 On-site monitoring. **(a)** Accessing the fiber optic junction box – 1999. **(b)** Dynamic FBG response to a three-axle truck load – 1999 **(c)** Accessing fiber the optic junction box – 2004 **(d)** Dynamic FBG response to a three-axle truck load – 2004.

2. FIRST GENERATION CORROSION FREE BRIDGE DECKS

In the quest for lighter, stronger, and corrosion-resistant structures, the replacement of ferrous materials by high-strength fibrous ones is being actively pursued in several countries around the world, both with respect to the design of new structures as well as for the rehabilitation and strengthening of existing ones. In the design of new highway bridges in Canada, active research is focused on a number of specialty areas, including the replacement of steel reinforcing bars in concrete deck slabs by randomly distributed low-modulus fibers, and the replacement of steel prestressing cables for concrete components by tendons comprised of super-strong fibers. Research is also being conducted to repair and strengthen existing structures with the use of FRPs.

FRPs have perceived disadvantages compared to steel. These are ductility and low thermal compatibility between FRP reinforcement and concrete. The majority of our construction projects in Canada are in non-seismic zones. Ductility is an important characteristic of steel as it allows large deformations and dissipation of energy. Concrete structures reinforced with FRPs at ultimate loads give large deformations. Therefore, reinforced concrete structures, whether reinforced with steel bars or FRPs, give the same order of deformability. Research to show that concrete structures with FRPs, if properly designed, can dissipate energy is in progress. The design of the proper concrete cover eliminates low thermal compatibility between FRP reinforcement and concrete. It should be noted that Glass Fiber Reinforced Polymer (GFRP) material has a modulus of elasticity comparable to concrete. Therefore, concrete does not feel any intrusion and performs well in resisting fatigue under dynamic loading. The foregoing concepts have been implemented to develop corrosion free bridge decks, several of which have been constructed in Canada and one in Iowa, USA.

2.1. Salmon River Highway Bridge, Nova Scotia

The first generation steel-free deck-slab in Canada was cast on the Salmon River Bridge, part of the Trans Canada 104 Highway in Nova Scotia [2]. Construction of the bridge, which consists of two 31-m spans, includes a steel-free deck over one span and a conventional steel reinforced deck over the other. Internal arching in the slabs helps transfer the loads to the girders. Although the cost of the steel-free side was 6% more than the steel-reinforced side, the overall design tends to be less expensive than conventional decks. This is because steel-free decks do not suffer from corrosion, so traditional maintenance costs are greatly reduced. This concept has won six national and international awards, including the prestigious NOVA award from the Construction Innovation Forum (CIF) of the United States.

The deck contains no rebar. Instead, longitudinal beams or girders support it. The load is transferred from the deck to the supporting girders in the same way that an arch transfers loads to supporting columns. Although steel straps are applied to tie the girders together, because they are not embedded in the concrete, they can be easily monitored and inexpensively replaced.

The SHM of the steel-free bridge deck was conducted by installing sensors (**Figure 2.1)**. SHM indicates that the load sharing of the Salmon River Highway Bridge is similar to conventional decks (**Figure 2.2**).

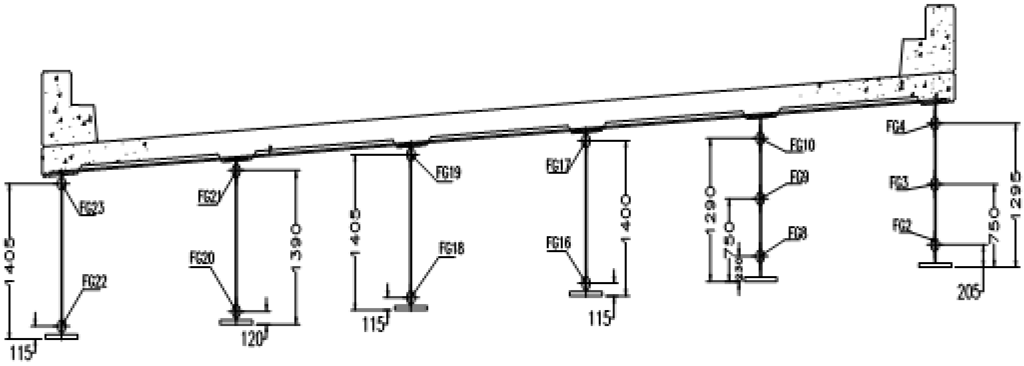


Figure 2.1 Sensor locations.

Figure 2.2 Load sharing for the Salmon River Bridge.

A pictorial view of the casting of the steel free deck for the bridge structure is shown in **Figure 2.3**. With no reinforcing mild steel inside the concrete (**Figure 2.3**), no unnecessary weight is added to the deck slab, thus resulting in relatively thinner deck slab designs. The steel straps are welded to the top flanges of the girders, thereby providing resistance to any lateral movement. The Salmon River steel-free bridge deck has withstood a number of Canadian winters. Based on the performance of this steel free bridge deck, it appears that an alternate design approach to the conventional approach for building steel-reinforced bridge decks has significant merit. Currently eleven steel free bridge decks have been constructed in various regions of Canada in a variety of environmental conditions.

Figure 2.3 Pictorial view of the casting of the steel-free deck.

3. SECOND GENERATION STEEL-FREE BRIDGE DECKS BASED ON WINNIPEG PRINCIPLES

The second-generation steel-free deck slab exhibits the same behavior as the first-generation steel-free deck slab, with the exception of the longitudinal crack at the mid-point between the girders. External steel straps located below the deck provide structural integrity for the slab. To reduce the width of the longitudinal crack that developed on first-generation steel-free decks, researchers at the University of Manitoba (U of M) [5] concluded that a bottom mat of GFRP reinforcement with a reinforcement ratio of 0.25% was required. In addition, recent fatigue tests have also been undertaken at the U of M to replicate actual service life conditions for the deck slab. These tests have confirmed that a steel-free deck slab reinforced with a crack-control grid of nominal GFRP reinforcement exhibits a maximum crack width of 0.34 mm, a limit implicitly acceptable by the Canadian Highway Bridge Design Code, CHBDC (2000) [6,7].

3.1. Red River Bridge, North Perimeter Highway, Winnipeg, Manitoba

This 10-span bridge is 347 m long and consists of steel plate girders spaced at 1.8 m and a composite, cast-in-place, steel reinforced concrete deck. It is located on the north half of the Perimeter Highway that encircles the City of Winnipeg. Because the Perimeter Highway forms part of the Trans-Canada Highway system, this bridge is subjected to significant daily traffic with approximately 20% being truck traffic.

One span utilizing the second-generation steel-free deck technology was designed and cast using a concrete deck slab thickness of 200 mm. GFRP reinforcement was used for both the top and bottom mats in the internal deck panels. The top and bottom transverse and longitudinal reinforcement was comprised of #3 bars spaced at 200 and 600 mm, respectively (**Figure 3.1**). CFRP reinforcement was used as main reinforcement in negative moment regions for both the vehicular and pedestrian cantilevers. This transverse reinforcing consisted of two #4 bars spaced at 200 mm.

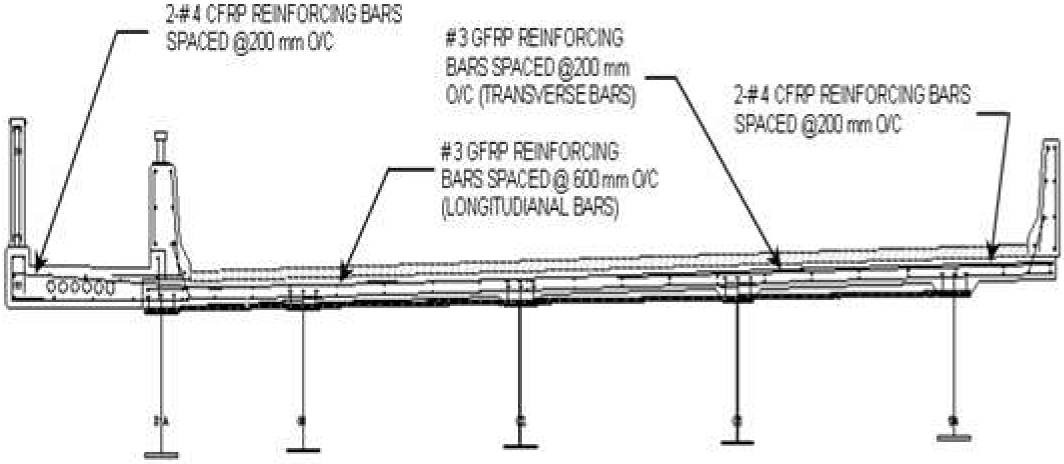


Figure 3.1 Top and bottom transverse and longitudinal reinforcement.

Transverse confinement of the deck slab was provided by steel straps, measuring 50 mm in width by 30 mm in depth, that were tack welded to the top flanges of the steel plate girders at a spacing of 1.2 m. To ensure that the steel straps would perform integrally with the deck slab, steel Nelson studs were added to the straps in the portion that passed over the girders.

For the Red River Bridge, the integrated SHM / civionics system was designed and installed to monitor the components of the steel-free deck slab and provide data on the stresses in the GFRP reinforcement and the transverse steel straps. Stresses in the steel plate girders and the CFRP reinforcement in the negative moment regions for the cantilever sections are also monitored. The system is comprised of a combination of various types of sensors, namely conventional electric strain gauges, fiber optic Bragg sensors, accelerometers, and thermocouples. A portion of the civionics system for the Red River Bridge North perimeter is shown in **Figure 3.2.** Some of the civionics instrumentation installed by Vector Construction prior to the casting of the bridge deck for the Red River Bridge North perimeter is shown in **Figure 3.3.**

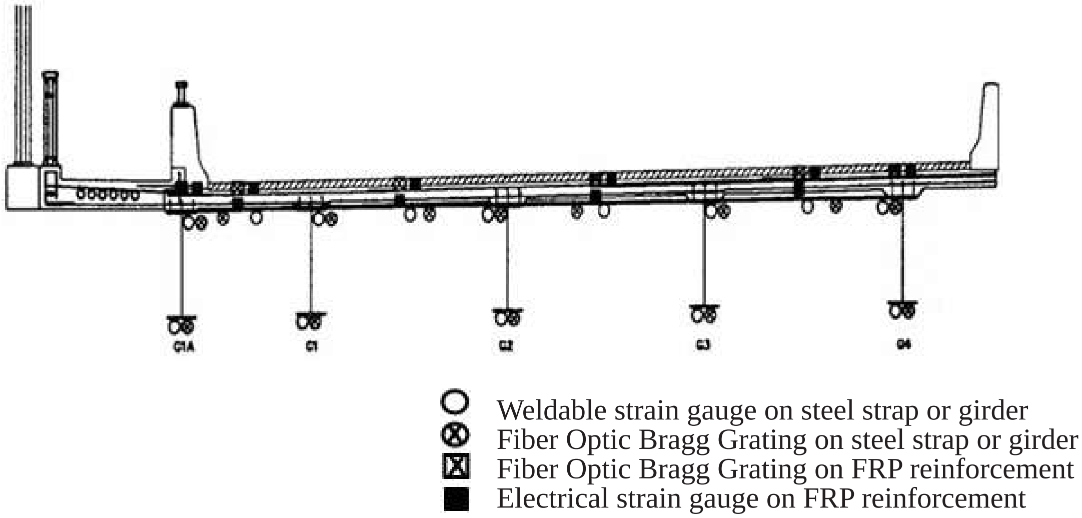


Figure 3.2 Civionics system for the Red River Bridge North Perimeter.

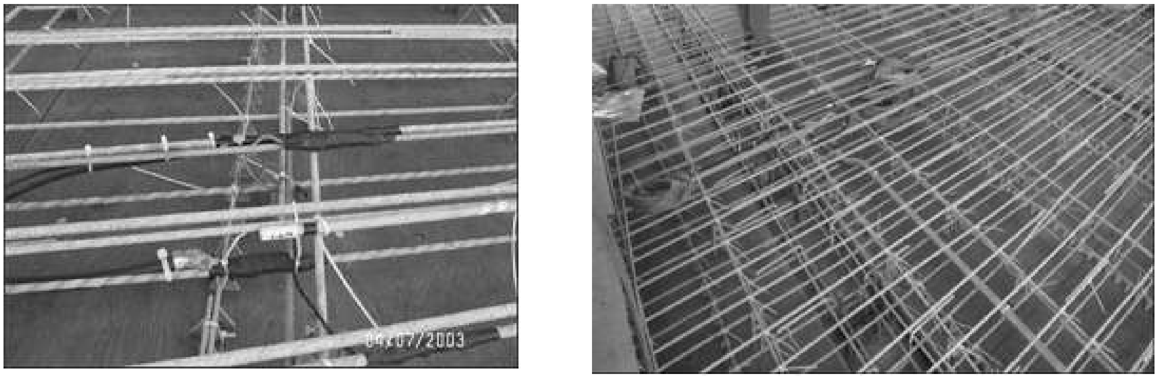


Figure 3.3 Installed civionics instrumentation.

Each sensor is connected to an on-site data acquisition system capable of storing the data. A video camera and weigh-in-motion device were also installed to gather additional information regarding the frequency, configuration, and axle loading of truck traffic on the bridge.

One major concern of a civionics system is the enormous quantity of data that can be generated and which must be stored in a short period of time. Sensors typically take up to 100 readings per second, resulting in 8.64 million readings per sensor in a single day. The Red River Bridge contains 64 sensors, which translates into 0.5 billion readings per day. ISIS Canada, in conjunction with IDERS Incorporated, is currently developing an automated system that can be incorporated in the SHM unit. The readings will be scanned for pre-determined strain readings that will initiate a “red flag” notification to the design engineer. The automated system will greatly reduce the time and cost required to review the entire load history of the deck span.

4. FATIGUE STUDIES OF SECOND GENERATION CORROSION-FREE BRIDGE DECKS

This section describes the fatigue behavior of cast-in-place second generation corrosion-free bridge decks. Although cast monolithically, the bridge deck was divided into three segments (A, B and C). Segment A was reinforced according to conventional design with steel reinforcement. Segments B and C were reinforced internally with a carbon fiber reinforced polymer crack control grid and a glass fiber reinforced polymer crack control grid, respectively, and externally with steel straps. The hybrid CFRP/GFRP and steel strap design is called a second generation corrosion-free concrete bridge deck. All three segments were designed with an almost equal ultimate capacity so that a direct comparison between the segments under fatigue loading conditions could be made. A performance comparison of all three segments for the first bridge deck under 588 kN (60 ton) cyclic loads is reported in this paper.

4.1 Fatigue Testing

4.1.1 Bridge Deck Details

Although cast monolithically, the slab was conceptually divided into three segments, A, B and C (**Figure 4.1**).

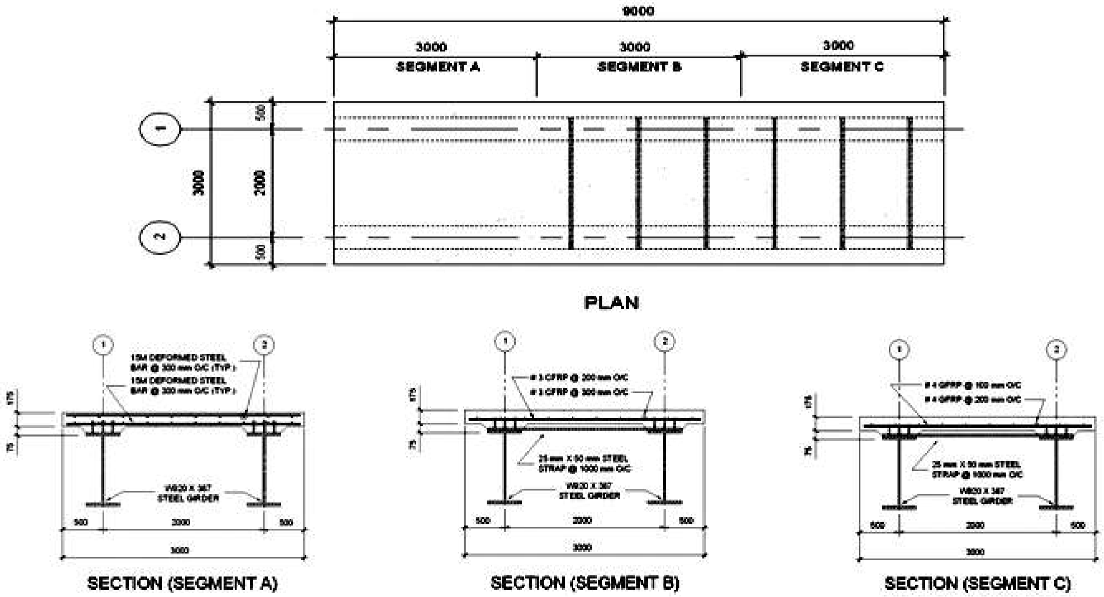


Figure 4.1 Bridge deck reinforcement details.

Figure 4.2 illustrates indirectly the crack width behavior for all three bridge deck segments under the 588 kN load level. The results show that deck Segment A fatigued approximately twenty times as fast as deck Segment C, and deck Segment B fatigued approximately twice as fast as deck Segment C. All three segments failed in fatigue and via a punching shear failure mode, as shown pictorially in **Figure 4.3**.

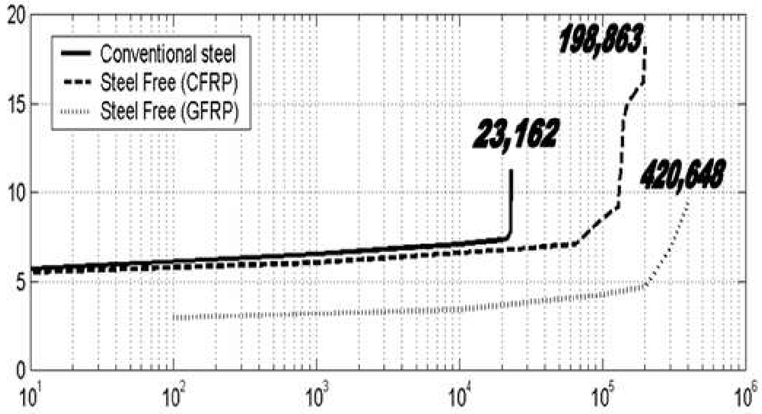


Figure 4.2 Plot of deflection versus number of cycles at 60 tons.

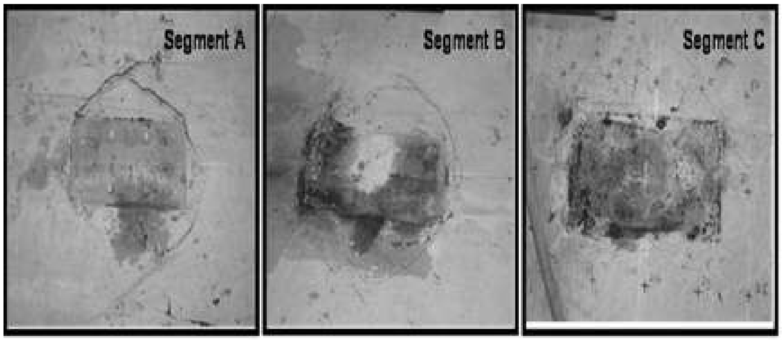


Figure 4.3 Punching modes of fatigue failure for Segment A, Segment B and Segment C.

5. CONCLUSIONS AND RECOMMENDATIONS

As mentioned earlier, ISIS Canada intends to significantly change the design and construction of civil engineering structures. For changes in design and construction to be accepted, it is necessary that innovative structures be monitored for their health. To assist in achieving this goal, ISIS Canada is developing a new discipline that integrates civil engineering and electronics under the combined banner of civionics.

The new discipline of civionics must be developed by civil structural engineers and electronics engineers to lend validity and integrity to the process. Civionics will produce engineers with the knowledge needed to build "smart" structures containing SHM equipment to provide much needed information related to the health of structures before things go wrong. This discipline will, thereby, assist engineers and others to realize the full benefits of monitoring civil engineering structures.

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