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FLEXURAL STRENGTHENING OF 48-YEAR OLD PEDESTRAIN BRIDGE REINFORCED CONCRETE GIRDERS

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ABSTRACT
As an emerging technology, the use of Fiber-Reinforced Polymer (FRP) reinforcements in the civil infrastructure has seen an exceptionally rapid growth as an alternative replacement to steel reinforcement. FRP reinforcements have been used in various configurations using different techniques for strengthening and repairing concrete bridges to restore or increase their capacity. Externally bonded FRP reinforcements are currently the most commonly used techniques for flexural strengthening of concrete girders and slabs.

This paper provides experimental results of an investigation that evaluated the efficiency and feasibility of various systems for flexural strengthening of large-scale reinforced concrete girders dismantled from a 48-year old deteriorated pedestrian bridge. The strengthening system comprised externally bonded Carbon FRP (CFRP) including strips, plates and sheets. Another material known as Steel-Reinforced Polymer (SRP) was also used as externally bonded sheets. Four beams were strengthened with the above various strengthening systems using the same axial stiffness and tested under static monotonic loading up to failure. Two beams were tested without strengthening. A 25% increase in the yield load and about 32% to 42% increase in the ultimate strength were achieved. the SRP sheets were more effective at increasing the strength and ductility.

KEYWORDS
Carbon fiber reinforced polymer, externally bonded, flexure, girder, plates, sheets, static, steel, strips, strengthening.

1. INTRODUCTION
Forty percent of Canada's bridges were built in the 1950s and 1960s and many are reaching the end of their service design lives and require rehabilitation and strengthening. The civil engineering and construction industry are facing unexpected challenges due to the state of repair of concrete infrastructure worldwide, and Canada is no exception in which $44 billion is required to renovate deteriorated infrastructure. Engineers all over the world are challenged and in search of new and affordable construction materials, cost-effective methods of extending the service live of deficient structures, as well as innovative approaches and systems to problem solving. Fibre-Reinforced Polymers (FRPs) have evolved as a promising form of reinforcement in new construction and rehabilitation projects. Various FRP systems for strengthening concrete structures have been widely accepted as practical substitutes to traditional strengthening techniques such as bonding steel plates, section enlargement, and external post-tensioning steel cables. Strengthening systems utilizing FRP reinforcements (sheets, strips, plates) externally bonded to the tension zone of concrete members are currently the most commonly used techniques for flexural and shear strengthening of concrete beams and slabs. Some FRP strengthening techniques could be more effective than others; however, their cost effectiveness is extremely important and could govern their use. The successful application of FRP for structural upgrade has motivated the development of other novel low-cost materials that exhibit excellent structural properties. One such material is composed of unidirectional knitted ultra high-strength steel wires forming cords (11 times stronger than typical steel plate) that are assembled into a fabric embedded or impregnated within a polymeric resin matrix and is referred to as Steel-Reinforced-Polymer, designated as (SRP). This paper investigates the feasibility and effectiveness of using various externally-bonded systems/materials to strengthen four full-scale G-type conventionally reinforced concrete girders dismantled from a deteriorated bridge near the city of Calgary that were cast in 1958 with 25% less flexural reinforcing steel bars. The structural performance under static loading including the behavior prior to cracking, post-cracking, yielding of steel and mode of failure of the strengthened girders will be evaluated and discussed.

2. EXPERIMENTAL INVESTIGATION

2.1 Specimens Details

A total of six girders provided by Alberta Transportation were tested under static load. The girders were dismantled from a pedestrian bridge near the city of Calgary and were 6.0 m (20 ft) long large-scale pre-cast G-type conventionally reinforced concrete girders fabricated in 1958. A cross-section showing details of the girder is shown in Figure 1. The girders are inverted open box channel with end blocks. The problems identified with these girders include the insufficient number of stirrups, lack of load sharing, and stringer legs spallings at the bottom. Spalling was noticed in the underside of the girders in localized sections, and some larger cracks were found on the girders before testing. Considering the age of these girders and the environment they were exposed to, they were in a decent shape. Though, in some places the clear cover was less than adequate and the flexural steel rebars were corroded.

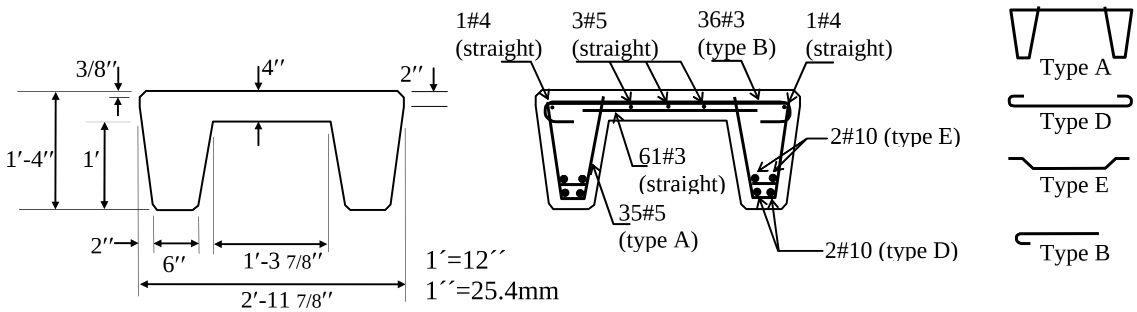

Figure 1: Details of the G-type reinforced concrete pedestrian girders

2.2 Material Properties

Concrete

The concrete compressive strength as specified on the drawings was 28 MPa (4 ksi). Concrete cores were extracted from the control girder and the actual compressive strength of the concrete was found 60 MPa (8.7 ksi). Also, the concrete compressive strength was determined from Schmidt hammer tests and was found to be 58 MPa (8.4 ksi).

Reinforcing Steel

The girders were reinforced with 32mm diameter steel bars with specified yield strength 350 MPa (51 ksi). Three samples of the reinforcing steel were removed from the end of the control girder and tested in uniaxial tension to determine the tensile properties. The yield strength and modulus of elasticity were found 300 MPa (43.5 ksi) and 200000 MPa (290010 ksi), respectively

Strengthening Materials

The externally bonded strengthening systems selected for this study were Carbon-Fiber Reinforced Polymers (CFRP) strips, CFRP sheets, CFRP plates, and Steel-Reinforced Polymer (SRP) sheets. The material properties of the different systems are given in Table 1. A two-part component epoxy adhesive, the main epoxy resin (component A) and the curing agent hardener (component B) was used. Sikadur 330 (mix ratio 4(A):1(B) by weight) was used for bonding the SRP and CFRP sheets, and Sikadur 30 (mix ratio 3(A):1(B) by volume) was used for bonding the CFRP plates and the CFRP strips to the bottom flange of the girders.

Table 1 – FRP material properties as reported by the manufacturers

FRP products (manufacturer and type)	Dimensions	Elastic Modulus (MPa)	Ultimate Tensile Strength (MPa)
Pultruded CFRP Strip (Hughes Brothers Alan 500 CFRP Tape)	t =2.0mm‡ w = 16mm‡‡	124000	2068
Pultruded CFRP Plate (Sika Carbodur® Type S 812)	t =1.2mm‡ w = 80mm‡‡	165000	2800
Unidirectional CFRP Sheet (Sika Wrap® Hex230C)	t= 0.381mm‡	61012	715
Unidirectional SRP Sheet (Hardwire™ 3×2-23-12)	0.44mm^2/mm†	206000	3170

† Net area per width ‡t: thickness ‡‡w: width (as shipped by manufacturer and not necessarily entirely used)

2.3 Test Matrix

Four girders (B1, B2, B3, and B4) were strengthened with various strengthening systems using the same axial stiffness (*AE*) of the strengthening material (where *A* is the cross sectional area of the strengthening reinforcement and *E* is its elastic modulus) so as to achieve a 30% increase in the carrying capacity. The strengthening systems comprise externally bonded FRP reinforcements including different types of CFRP (strips, plates, and sheets) and SRP sheets. Two beams were tested without strengthening and served as unstrengthened control specimens for comparison purposes to compare the effectiveness of each technique in terms of percentage increase of the flexural strength and overall structural performance. Table 2 summarizes the test matrix.

Table 2 – Test matrix for the G-type reinforced concrete girders

Beam #	Externally Bonded Strengthening System
C1	Control beam without strengthening
C2	Control beam without strengthening
B1	Four CFRP strips per web (Hughes Brothers 500 Aslan CFRP Tape)
B2	One 80mm wide CFRP plate per web (Sika Carbodur® Type S 812 Plate)
B3	Seven layers of 105mm wide CFRP sheets per web (Sika Wrap® Hex230C Sheet)
B4	Two layers of 90mm wide SRP sheets per web (Hardwire™ Sheet)

2.4 Surface Preparation and Installation of the Strengthening Systems

The bottom surface of the concrete webs was leveled with a grinder to eliminate any ridges. To ensure good and strong bond, the surfaces were washed with a water pressure blaster and cleaned by air brushing to remove any debris and dust. Large amounts of concrete had spalled off near the ends of the girders and the reinforcing steel was exposed, therefore patching was done in these areas after removing loose concrete and oxidation from the reinforcing steel. The mortar used for the patching repair was a combination of oven-dried sand and the Sikadur 30 epoxy adhesive with a mix ratio of 1:1 by volume. The mortar was allowed to cure for 24 hours before strengthening was performed. Installation of the strengthening systems followed typical field conditions on the bottom flange beneath the girders. The epoxy was allowed to fully cure at room temperature for at least one week before testing the girders to failure. The anchorage system consisted of wrapping U shape unidirectional CFRP sheets (Sika Wrap® Hex230C) bonded to the webs of beams B1, B2 and B3, while for beam B4, the anchor consisted of SRP sheets. The anchors consisted of 28 pieces of 102×762mm and 8 pieces of 305×762mm. The larger sheets were used at the ends of the webs, and the seven sheets were spaced at 600mm center-to-center through the length of each of the webs.

2.5 Test Setup, Procedure and Instrumentation

The girders were simply supported, simulating the majority of pedestrian bridges, with a span of 5.84m and tested under static monotonic loading up to failure. The girders were loaded at four-point bending with 1.2m spacing between the two concentrated point loads. The load was applied using a 500kN capacity actuator through an MTS controller-testing machine operating under displacement control mode at a constant loading rate of 2mm/min. All girders were fully instrumented to monitor their behaviour during testing by measuring the deflection at midspan using Linear Strain Conversion devices (LSCs), strains in the concrete in the compression zone, and strain in the CFRP and SRP reinforcements using electrical resistance strain gauges. Horizontal LSC were also placed at midspan on each side of the girder to determine the strain in the concrete: one at 50mm from top and one at 40mm from bottom approximately at the level of the reinforcing steel bars. Crack widths were measured using crack comparator and their patterns were marked on the girders. Data were automatically collected and electronically recorded using a data acquisition system. Typical test set-up and instrumentation is shown in Figure 2.

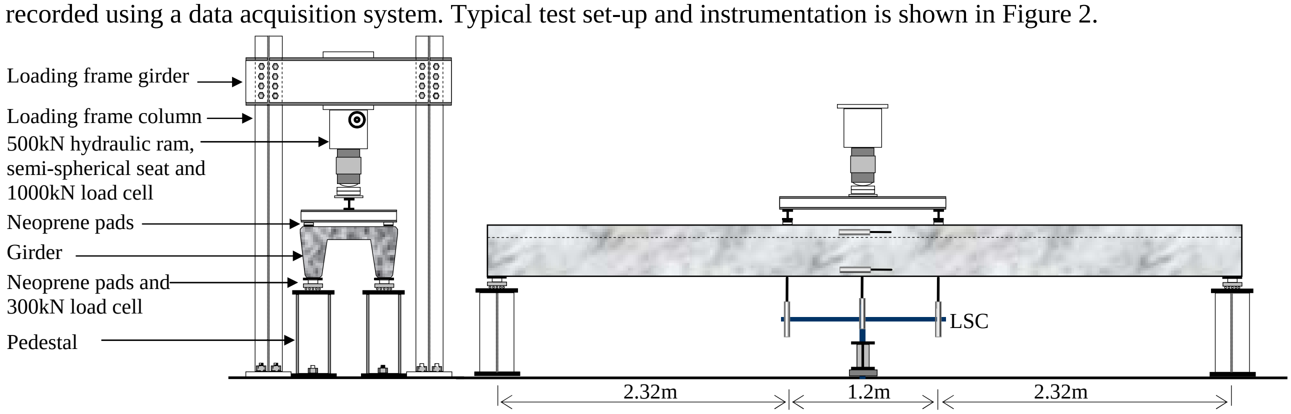

Figure 2: Test set-up and instrumentation of the G-type reinforced concrete girders

2.6 Test Results and Discussion

Beam C1 was loaded until a load of 287 kN which is 63% of the predicted load of 452 kN determined according to the provided information on the girders (Figure 1). Decision was made to test another control beam (C2) and the failure load recoded was 309 kN which is 68% of the predicted load. Testing of the second control beam confirmed the results of the first beam. However, to prove the accuracy of the given specifications and drawings for the theoretical predictions, the concrete cover was hammered off from part of the two webs to expose the reinforcing steel and it was discovered that only three steel bars in two layers were used in each web instead of four bars as shown on the drawings. Thus, these girders were cast with 25% less flexural reinforcing steel. This proved why the control beams yielded significantly lower flexural strength than calculated. The prediction of the ultimate load was recalculated based on the results of the materials (concrete and steel) tests and the accurate locations and number for the reinforcing steel bars and found to be 367 kN indicating 22% and 16% difference for beams C1 and C2, respectively. The load versus midspan deflection curves comparing the flexural behaviour of the beams are presented in Figure 3. The load-deflection behaviour is bilinear until failure. All beams exhibited similar behaviour with regard to cracking and their load-deflection followed almost similar paths until failure. Figure 4 shows the load versus strain in the CFRP and SRP reinforcements at midspan. None of the beams failed by rupture of the strengthening materials; as can be seen in Figure 4 at ultimate load the strain in the strengthening materials were less than the ultimate tensile strains. In beam B1, debonding at the interface of the CFRP strips and the epoxy took place at a load of 400 kN starting at the center of the span and as a result the load decreased slightly. This debonding stopped when it reached the nearest transverse anchor. This allowed the load to increase again as the imposed deflection increased and the FRP was "tightened". Suddenly the anchor would separate allowing debonding up to the next anchor. Afterwards the load would repeatedly slowly increase until the next anchor separated. Finally the CFRP reinforcement tore away from the last anchor and debonded from the beam completely at a load of 417 kN. Similar behaviour was observed in beams B2, B3, and B4, debonding occurred at a load of 380 kN, 407 kN, and 428 kN; respectively, then the CFRP and SRP reinforcement tore away from the anchor at a load of 407 kN, 415 kN, and 435 kN, respectively in beams B2, B3, and B4. The debonding behaviour is illustrated by the jogs in the curves just before failure. The failure of the CFRP strengthened beams with CFRP sheet anchors was dramatic, as it literally tore the anchors off the corner of the web and the CFRP strips, plates, and sheets fell to the ground. The increase in the yield load was about 25% in all beams. After yielding, the strengthened beams continued to resist further increase in the applied load with a more gradual linear slope than the pre-yield portion of the curve. The increase in the load continued until failure. The ultimate strength increased by 35%, 32%, 34% and 42% in B1, B2, B3, and B4, respectively. However, the SRP sheets are more effective at increasing the strength and ductility.

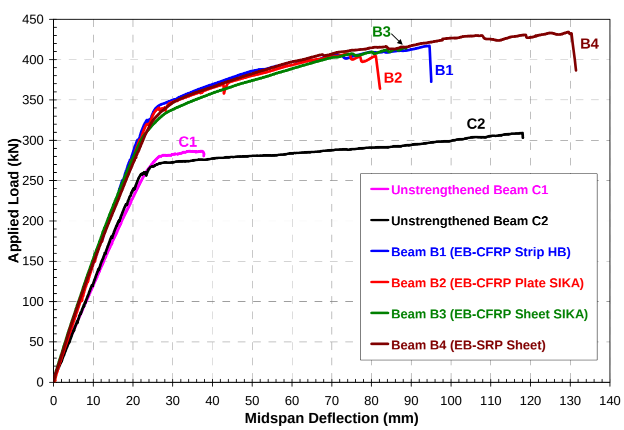

Figure 3: Load-midspan deflection curves for all beams

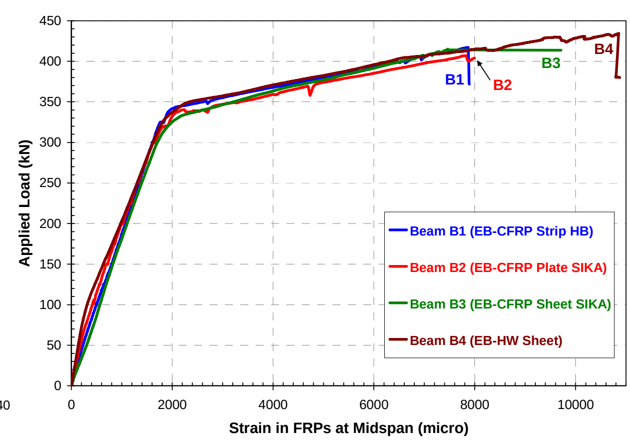

Figure 4: Load-FRP strain curves for all beams

3. CONCLUSIONS

Based on the results of this experimental study the following conclusions can be made:

- The ultimate strength gains achieved by the externally bonded reinforcements exceeded the initial goal of 30%.
- An increase in the yield load and ultimate load of 25% and up to 42%, respectively was achieved.
- All strengthened beams failed in a ductile manner accompanied by large deformation; however the beam strengthened with SRP sheets showed mores ductile behaviour and higher capacity than the other beams.

To summarize, this study has confirmed the structural benefits and feasibility of using externally bonded CFRP and SRP reinforcement to strengthen deficient reinforced concrete girders. However, the CFRP is particularly attractive since it is not susceptible to corrosion, and extremely lightweight making it easy to work with.