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TESTING A BINARY CRACK SENSOR USING A LABORATORY MODEL OF CRACKS IN STEEL GIRDERS

F.Raeisi[1], A. Mufti[2], D.J.Thomson[3] and G.Mustapha[4]

[1]Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
raeisif@myumanitoba.ca
[2]Department of Civil Engineering, University of Manitoba, Winnipeg, Canada
Muftia@cc.umanitoba.ca
[3]Department of Electrical Engineering, University of Manitoba, Winnipeg, Canada
Douglas.Thomson@umanitoba.ca
[4]Program Management, Structure Monitoring Technology, Vancouver, Canada
Gamal@smtresearch.ca

ABSTRACT

Steel girders of bridges exposed to cyclic truck traffic loads experience fatigue stress, resulting in potential cracks and damages that can lead to catastrophic failures. Bridges across North America are aging and lack the necessary monitoring to ensure proper health and safety. Current inspection regimes are expensive, limited and infrequent. The application of structural health monitoring systems could be used to augment inspection criteria to detect cracks and defects early. Available sensor systems such as fiber optic sensors and their Data Acquisition systems (DAQs) are expensive and difficult to install, making them impractical for use on most bridges.
The requirement to design a low cost sensor to detect the presence of cracks in steel girders led to the design of an electronic based, smart binary sensor. The sensing element designed, is comprised of a composite material capable of detecting the presence of a developing crack once it exceeds a crack width of 0.15mm. The following paper examines the methodology and testing criteria for selecting an appropriate sensing material to be used for steel girder crack detection.

Keywords*:* Sensor, Materials, Structures.

INTRODUCTION

North American bridges constructed more than 50 years ago are reaching the end of their intended service life. In Canada, more than 40% of bridges were built over 50 years ago and need repair and rehabilitation[1]. Steel girder bridges are one of the common types of bridge construction where plate girders are constructed from web and flange steel plates, welded together to form I-shape or Box girders. Over time, cyclic truck traffic over steel superstructures causes stress concentration in locations such as flaws in welded parts of steel girders (web to flange connection or stiffener connections to the web or flange) and exacerbates pre-existing flaws into small cracks and eventually propagates into the web or flange of the steel girder [2], [3]. Since crack formation and propagation may cause the loss of critical structural members, methods for the detection of cracks has become a major maintenance and safety concern.

The most common method of inspecting the condition of a bridge is to perform visual inspections. Thin fatigue cracks are difficult to detect and are often missed during visual inspections[4]. Several non-destructive evaluation (NDE) methods have been developed to inspect bridge girders. NDE inspection methods are performed periodically with the known risk that a crack may form between scheduled inspection intervals. For example in 2003, just a few months after the last full inspection of I-95 Highway Bridge over the Brandywine River, a fracture occurred in one of its girders [3].

Structural health monitoring (SHM) systems have been used to help engineers perform continuous real-time monitoring. Current SHM systems are comprised of different types of sensors such as vibrating wire and fiber optic sensors [5]. Fiber optic sensor hardware and installation can be very costly and may exceed $300,000 per girder, making this technology only justified in very limited instances. The high cost of available sensors prohibits project managers and maintenance personnel from using them frequently.

Since there are a large number of structures that require crack monitoring and available sensors are not economical, there is an urgent need for a cost-effective method for detecting bridge girder cracks that is reliable and easily installed.

In this paper, a new smart binary sensor will be introduced. The binary sensor can detect cracks with less than 0.15mm width in steel girders.

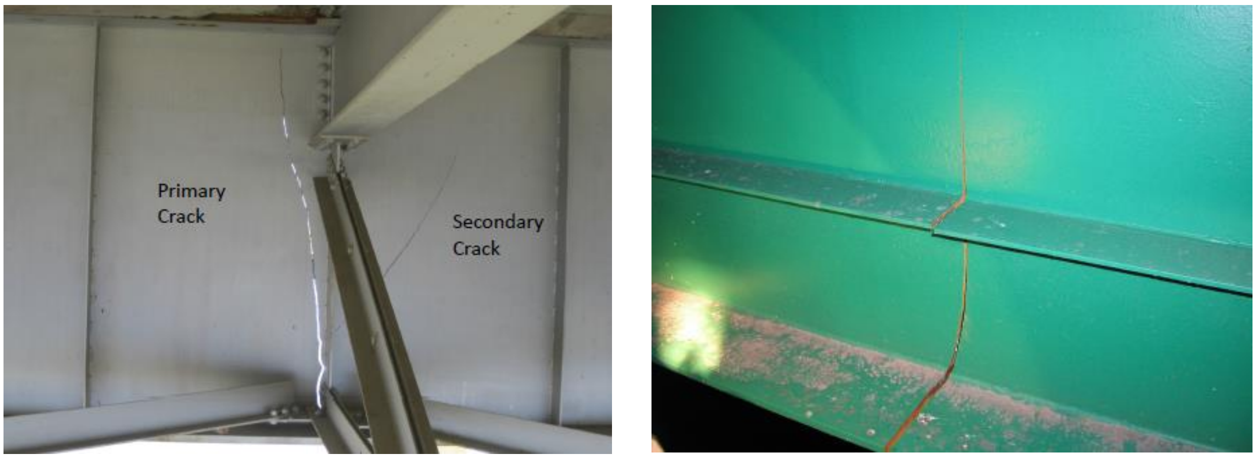
CRACK WIDTH IN STEEL GIRDERS

Crack formation in steel girders are due to fatigue, flaws in welding and/or other deficiencies in materials [6]. The crack can propagate over time causing a failure of the girder and in non-redundant bridges it may result in a serious failure or collapse.

In the experimental results section the sensor is shown to be capable of detecting cracks of less than 0.15 mm. As it will be discussed in following sections, the sensor is a composite material, which is composed of wire and adhesive. The mechanical properties of wire and adhesive will define the crack width which binary sensor can detect.

Ideally, the binary sensor can be used to detect cracks in a girder before they become severely structurally compromised. There are examples of stable bridges even with severe cracks on their girders. For example the crack width on the girder of I-95 Highway Bridge over the Brandywine River was about 13mm [3] and on Diefenbaker Bridge over North Saskatchewan River in Prince Alberta in Canada, a crack was detected with width of about 25mm [7]. However, it would be ideal to detect cracks before they reach such extremes.

If such cracks could have been detected in early stages -when the crack width was less than 0.15mm- these would have been repaired and would not propagate through the web and flange of girders.



(a) (b)

Fig. 1: Crack on (a) Diefenbaker Bridge [7], (b) Brandywine river Bridge [3]

Fig. 2 shows different crack widths versus crack lengths of a typical 30 meter plate girder under service loads, the cross section is shown in **Fig. 3**. The girder with different crack lengths at its mid-span has been simulated using finite element software, ABAQUS, by applying the service load to the girder and observing the simulated crack width. The crack opening can be measured in ABAQUS at every point of the crack. The binary sensor is able to detect cracks of 0.15mm width, which will occur in crack lengths of greater than 200mm, which is about 13% of the height of the girder. This simulation demonstrates that at service loads, a crack of 200 mm crack would be detected before the crack propagates through the web, as long as the sensor is located in the appropriate plane.

Visual inspections are presently the primary method to evaluate the overall condition of a bridge, however thin cracks may go undetected using visual inspection techniques. Using the Binary sensor will detect the presence of cracks of 0.15mm width and will allow appropriate actions and maintenance to be performed.

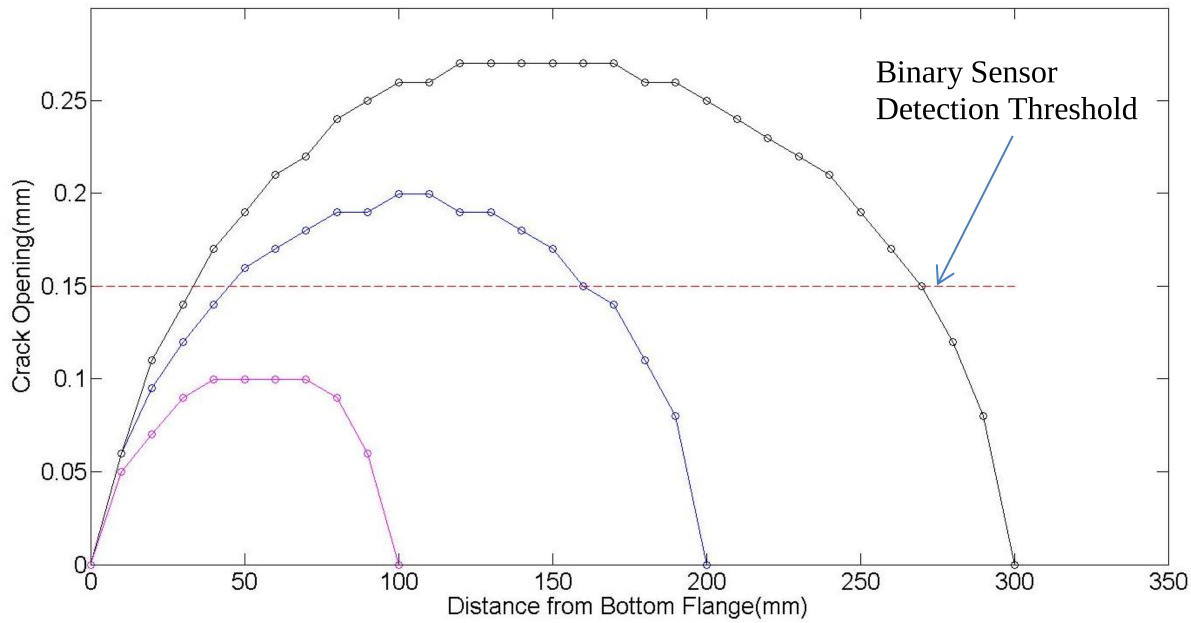


Fig. 2: Crack Opening versus Crack distance from bottom flange of typical girder (1617mm height and 30m span) under service loads. Smart wire sensor detects cracks of 0.15mm width

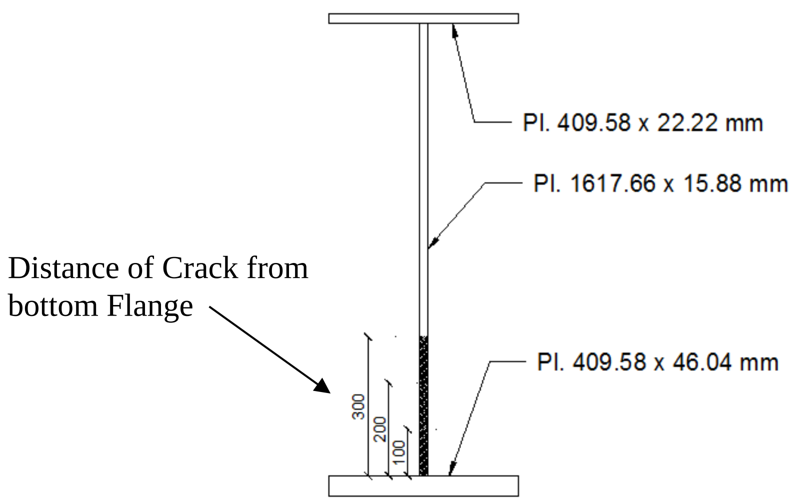


Fig. 3: Cross Section of the simulated cracked girder

SMART WIRE SENSOR: METHODOLOGY AND APPLICATION

The smart wire sensor is a composite material, composed of a copper wire bonded to the structure with a carefully designed adhesive. The wire will be adhered to the entire length of the girder using the adhesive and will connect to a return wire, which is then connected to a Data Acquisition (DAQ) and monitoring system. When a crack of about 0.15 mm width forms in the structure, it will propagate through the sensor and will cause the wire to break. It can be detected easily by measuring the electrical continuity of the wire, the procedure is shown in **Fig. 4**.

The first challenge in developing the smart wire sensor is to find the proper adhesive and wire system; the wire should be thin enough to break at the desired crack width of 0.15mm and the adhesive should be a material that transfers the strain to the wire so that the wire reaches its breaking strain at less than the required crack width.

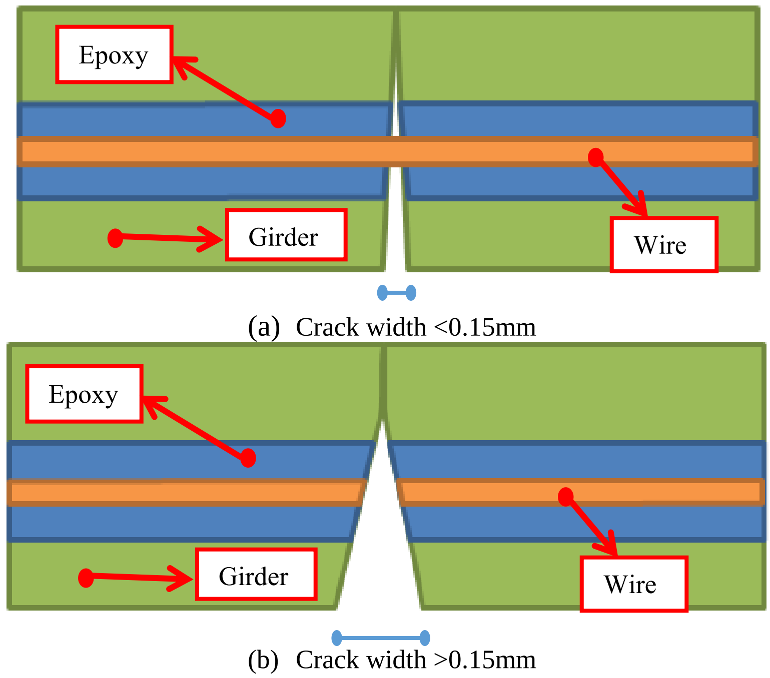


Fig. 4: Girder, Crack, Wire&Epoxy (a) before crack opens to 0.15mm, (b) after crack opens more than 0.15 mm[8]

After finding the proper material for the adhesive and wire, the next challenge will be simulating the new sensor in a Finite Element Program to reconcile the experimental results with theory. Certain data such as mechanical property of materials and bonding behaviour are required for the simulation.

In next part, the experimental program for developing the sensor and gathering required data will be discussed.

EXPERIMENT

TEST SETUP

As mentioned above, the first step to develop the sensor is to define a proper combination of wire and adhesive. In order to test the material the first step is to design a test apparatus which can simulate the crack of 0.15mm width. The test setup is made of two steel plates, which are connected to each other with a hinge at one end and can be separated along the edge of the plates. This simulates the crack opening on the web of a steel girder. The test setup also includes a micrometer and a pi-gauge (**Fig. 5**). By turning the micrometer, it will apply force to the steel plate and will cause plate B split from plate A. The pi-gauge records the gap width while the micrometer is being turned. Turning the micrometer will force the two plates apart and the gap between two plates will widen until the sensor breaks as shown in **Fig. 6**. To measure the gap between two plates a pi-gauge was used. The pi-gauge is connected to a Data Acquisition system (DAQ), which records distances in time intervals (100-1000 samples/s).

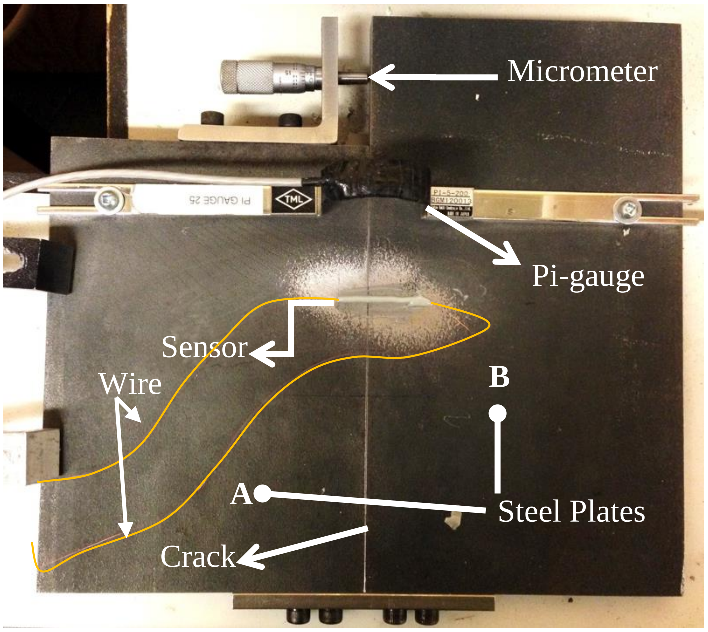


Fig. 5: Test setup, Sensor, Pi-gauge and Micrometer on steel plates

As mentioned earlier, to observe the exact opening of the wire fracture, electrical resistance of the sensor will be measured. The continuity of the resistance of the wire will change from a short (Ω=0) to an open ($\Omega=\infty$) circuit as soon as the sensor breaks.

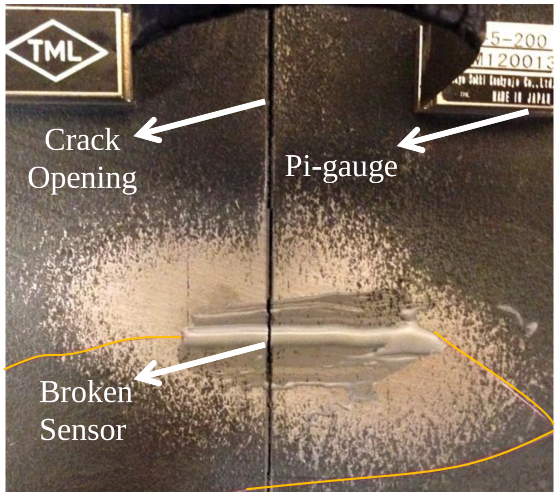


Fig. 6: The sensor breaks by opening the crack width

The test will be continued for different combinations of material until a combination breaks at 0.15 mm.

TEST RESULTS

In a previous study with a similar test setup made of aluminum plates, copper wire of 39 AWG (D=0.09mm) was tested in composition with different adhesives. The first adhesive was "Loctite Quicktite". It made a good bonding with copper wire but since cracks formed on the surface of the adhesive after curing, the test results were not repeatable. [8]

In this new study, 39 AWG copper wire was tested using steel plates to simulate a steel girder. The adhesive used is "Epoxy Steel" from the Lepage Company. It is a two-part epoxy consisting of an epoxy resin and a hardener. The wire was tacked to the steel plates with tapes at both ends and the epoxy was painted over ~5 cm length of the wire. Dimension of epoxy is 2x2mm.

The results with copper wire and epoxy adhesive used in this work are promising. With this combination of wire and epoxy, the crack width at which the breaking strain in the wire is reached is less than 0.15mm (**Fig. 7**).

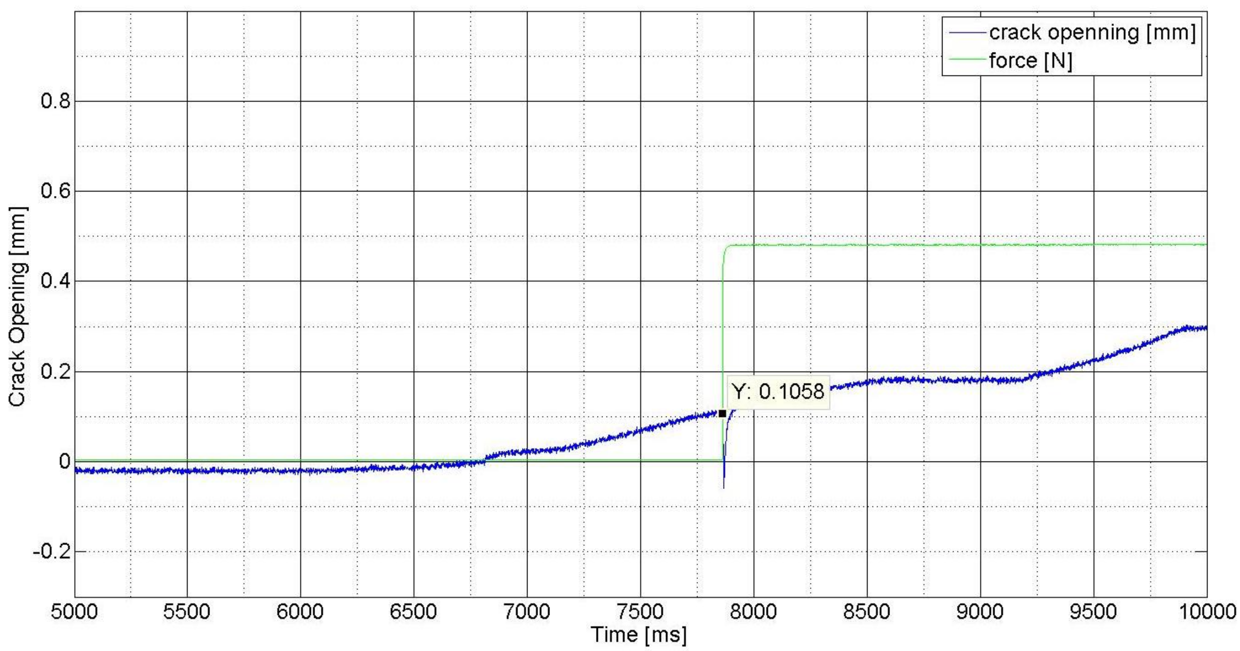


Fig. 7: Test results of Epoxy Steel and Copper wire, Wire breaks at 0.11 mm

CONCLUSION AND FUTURE WORKS

- A smart binary crack sensor using a broken wire princple with copper wire and epoxy demonstrated promising results.
- A Finite Element Model (FEM) of a steel girder concluded that for a 1.6 m deep steel girder a crack sensor can detect cracks of 20 cm or less if the crack sensor can detect cracks of 0.15 mm or less.
- The bonding properties and interfacial stress between wire and epoxy need to be measured in order for comprehensive FEM simulations of the complete sensor system.
- After completeing the tests mentioned above, the sensor will be simulated in FEM.
- In the future the sensor will be tested on cracks in steel girders in the lab.
- The sensor will also be tested over a range of temperatures.

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