# PERFORMANCE OF GFRP STAY-IN-PLACE FORMWORK FOR BRIDGE DECKS AFTER REAL AND SIMULATED FIRE DAMAGE




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## ABSTRACT

This study addresses the fire performance of glass fiber reinforced polymer (GFRP) stay-in-place (SIP) structural formwork. Seven concrete slab strips constructed using a commercially available GFRP SIP structural form are tested. The GFRP formwork consists of a flat bottom plate with T-shaped ribs protruding upwards along its length that are designed to replace the bottom layer of tensile steel reinforcement in a concrete bridge deck. The specimens are subject to both real and simulated fire damage and are then tested under four-point loading to get an understanding of the structural performance of the GFRP SIP formwork relative to damage location and extent. Test results show that the severity of the simulated damage was a valid but over-conservative representation of the real fire damage. Under a real but moderate fire scenario, the GFRP formwork is shown to provide good performance in this scenario by maintaining structural integrity.

## 1 INTRODUCTION

In recent years, there has been a rise in the use of advanced composite materials such as glass fiber reinforced polymers (GFRP) in civil engineering applications. One innovative application of GFRP composites is in the use of stay-in-place (SIP) permanent formwork for reinforced concrete structural elements. The formwork is fabricated through a continuous molding process where the glass fibers are saturated with a polymeric resin and then formed into a structural shape by pulling the fibers through a heated die in a process known as pultrusion. The benefits of pultruded GFRP composite formwork include its high strength-to-weight ratio, resistance to corrosion, availability in a wide variety of shapes and sizes, and reduced construction time compared to traditional steel or wood formwork. Specifically, the corrosion resistance and ease of fabrication have made pultruded GFRP stay-in-place (SIP) formwork popular in bridge deck construction where harsh environmental conditions will accelerate the corrosion of steel reinforcement [1]. The GFRP SIP formwork in this application are built in the same manner as traditional formwork but after the concrete has been

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cast, the formwork remains in place as part of the structural member, generally replacing some or all of the steel flexural reinforcement.

The increasing use of composite materials in structural applications has outpaced the structural fire research community, resulting in minimal information available on their behaviour in fire. This lack of information is one of the major issues inhibiting the wide-spread use of GFRPs in structural applications [2]. At elevated temperatures, GFRPs could release toxic by-products as part of the polymer decomposition process that can harm a nearby users. In terms of mechanical performance, the material's glass fibers have been shown to retain strength at relatively high temperatures; the glass fibers in this project are E-glass, which have a softening temperature of approximately 850 °C [3]. However, the GFRP's polymer resin is more sensitive to high temperatures than the glass fibers due to the effect of glass transition, a parameter that influences the fire performance of GFRP composites. Glass transition temperature ($T_g$) is the temperature at which the polymer matrix transitions from a hard to a soft and rubbery consistency. After exceeding this temperature, composite action between the glass fibers and the epoxy resin is compromised, reducing the stiffness of the GFRP [3]. If temperatures increase further and reach the decomposition temperature, the GFRP's resin will begin to melt and may ignite once it has vaporized, potentially contributing to the growth of a fire under the specific conditions [4]. While some more chemically advanced composites can yield strong performance in fire, these hazards are especially prevalent in economic and chemically simple GFRPs.

In past research, a number of GFRP SIP cross sections have been studied for bridge deck applications including protruding box sections, hollow cavities, and corrugated sheets [1]. This paper focuses on a GFRP SIP form that features a GFRP base plate with four "T" shaped ribs protruding upwards, aptly named "T-Up" formwork. In a bridge deck, the T ribs in the T-Up formwork run transverse to the direction of traffic and transfer the traffic load to the bridge girders. In this configuration, the underside of the bridge deck is exposed to the environment. As a result, the bottom of a concrete bridge deck constructed with T-Up GFRP SIP formwork may be vulnerable to damage from fire or vandalism from below. This project aims to quantify the structural contribution of GFRP SIP T-Up formwork in a bridge deck that has been damaged from below under real and simulated (pre-damaged - albeit with specific limitations) fire.

## 2 BACKGROUND

The performance of GFRP SIP formwork used in concrete bridge decks has been studied in detail in the literature and researchers have successfully examined failure modes, behavioural mechanics, the effect of form splicing, and the impact of freeze-thaw cycles [1-6]. However, little-to-no large or small scale testing has been done to quantify the structural impact of fire damage on GFRP SIP plates, which continues to be a major research requirement for its widespread acceptance in the engineering community.

The limited research that has been conducted on the fire performance of GFRP SIP formwork include a series of material tests on small sections of similar GFRP composite formwork tested at the University of Waterloo. These samples were different from those used in this study though still informative [4]. Results of that study demonstrated the importance of material thickness in the fire performance of the GFRP composite. Specifically, it was shown that the behaviour of the GFRP composite in fire improves drastically once material thickness is large enough to be deemed "thermally thick", after which ignition time and other fire reaction characteristics are reduced significantly [4]. In the case of a thermally thick GFRP plate, the composite material is probable to melt and drip off a structure (with gravity) rather than igniting in place, and influencing fire spread. Because of this behaviour, it can be hypothesized that a fire from below a deck could only melt a portion of the resin in the bottom of the SIP formwork but potentially leave the embedded T-Up rib intact. In this study, those results [4], served as the basis for hypothesizing the extent and location of the simulated fire damage to the specimens. A more complete material study on the SIP formwork used for this study is still needed and planned by the authors. Essentially, it is assumed that the matrix of any exposed composite can potentially locally burn away with little to no flame spread – which will be confirmed in the experimental programme herein, but subjected to specific limitation(s). The study herein is meant as a pre-lude to inform a larger in –fire experimental and modelling endeavour by the authors.

## 3 EXPERIMENTAL METHODOLOGY

### 3.1 Test Specimens

A test programme was developed to approximate and inform the performance of GFRP SIP formwork subjected to fire damage. The test specimens are strips of a typical reinforced concrete bridge deck constructed using GFRP SIP formwork, separated longitudinally along the length of the T-Up ribs to form small beam specimens. The beam specimens are intended to represent the predominant one-way bending action in “strips” of a concrete bridge deck that span transversely to the direction of traffic between girders (note that any potential membrane actions will be beyond the scope of this study to investigate). Two 840 mm wide T-Up GFRP SIP formwork plates with a length of 1675 mm were cut length-wise into a total of seven strips. Six of the strips have a single T-Up rib along their length while the remaining specimen has two T-Up ribs along its length to verify the scaling process. A two-dimensional grid of sand-coated 10M GFRP VROD rebar was also placed as top reinforcement in each beam to better represent a “strip” of the bridge decks as used in past research [1]. The seven beam specimens include two controls, four specimens subjected to simulated fire damage, and a single specimen subjected to a real fire. The 28 day concrete compressive strength in this study was 45.7 +/- 1.2 MPa based on six concrete cylinder tests. Additional information on the type of GFRP SIP formwork used in this study is available in Nelson et al. [1].

The control specimens, referred to as C1 and C2, include two undamaged specimens with one and two T-Up ribs along their length, respectively. The variation in the width of the specimens is to examine if downscaling the deck width has a proportional effect on the strains developed in the member. The beam specimens with simulated fire damage are referred to as SD1, SD2, SD3 and SDF and have varying amounts of simulated damage. *Figure 1* shows the simulated damage to each specimen. To simulate fire damage, portions of the bottom GFRP plate were removed after casting, representing a worst case scenario damage to the GFRP base plate, leaving only the T-Up ribs embedded in the concrete. It should be noted that this application assumes that the concrete will not be damaged and only the GFRP base plate will be impacted from a fire which may not be true for every fire scenario but does allow the contribution of the base plate to be rationally studied in the absence of concrete damage. Simulated damage varied over different spans of the specimens to determine the effect of damage location has on ultimate load capacities. The final specimen, referred to as Specimen FD, was subject to a real pool fire to understand the behaviour of the material after elevated temperature exposure and inform interpretation of the simulated fire damage.

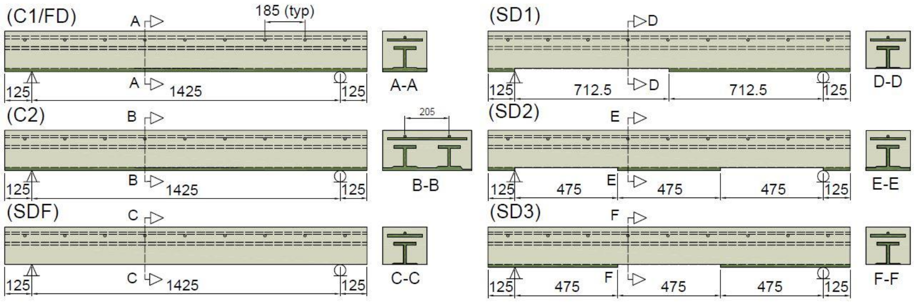
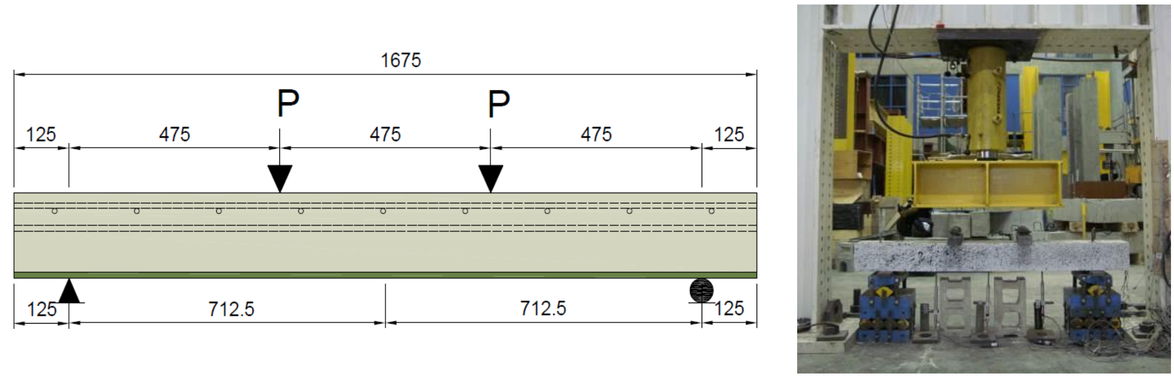



*Fig. 1.* Control and simulated damage specimens

### 3.2 Experimental Test Setup

Each specimen was tested under four-point monotonic loading up to failure. To compare the simulated damage to real fire damage, Specimen FD was exposed to a heptane pool fire for a total burn time of 14 minutes (a typical burn time approximated from other structural testing literature [7][8]). The pool fire had a pan diameter of 30 cm, burned 1.6 litres of heptane, had a continuous flame height of approximately half a meter. It should be noted that this pool fire is not strictly comparable to others as the test scale was small, and the fuel was adjusted to reach a sustained burn for a specific time. A pool fire was utilised as the application of this study is for bridges and this type of fire would be the more realistic exposure expected. The beam was supported 50 cm above the base of the pool fire pan. To precisely control the length of damage inflicted by the fire to the soffit, sections of the strip were covered in two layers of gypsum board. The fire was intended to damage only the moment span region, which would allow a comparison with Specimen SD3. Specimen FD was loaded after heating. Loading while heating was not considered but can have effect on any GFRP while it is being heated beyond glass transition [9]. *Figure 2* below shows a typical loading configuration used to test each strip specimen and the test set up for the pool fire.




*a)*

*b)*

*Fig 2.* (a) Typical test setup and load configuration (dim in mm); (b) Pool fire burn setup

### 3.3 Instrumentation

A variety of instrumentation techniques were employed in this study to monitor the response of the test specimens. In reference to this paper, three linear voltage displacement transducers (LVDTs) were used to measure the deflection profile along the length of the beam. GFRP strain gauges were installed at the quarter spans and midspan on the top surface of the T-Up ribs. Specimen FD was instrumented with two thermocouples placed on the interior side of the bottom GFRP plate at midspan to measure the heat transfer through the SIP during the real fire. Two additional thermocouples were used to monitor the ambient air temperature in the laboratory and the gas temperature near the surface of underside of the test specimen.

# 4 EXPERIMENTAL RESULTS

## 4.1 Load-Deflection Response

One of the goals of this project was to determine if the embedded T-Up ribs will carry additional load in the event of fire damage to the base of the GFRP plate. Specimens C1 and C2 established controls for the undamaged test strips and help quantified the effect down-scaling the width of the GFRP SIP had on strain in the T-Up ribs. Specimen C2 was twice the width of Specimen C1 and had two T-Up ribs. The load-deflection responses in *Figure 3* show that down scaling the width by a factor of two will also reduce the ultimate load by slightly more than the same factor while achieving similar levels of strains in the T-Up ribs. This slight load increase in addition to the factor of two may be a result of the confinement of the concrete between the two GFRP flanges. However, it is implied there is an approximately linear relationship between strip widths of these scales with flexural resistance in one way bending.

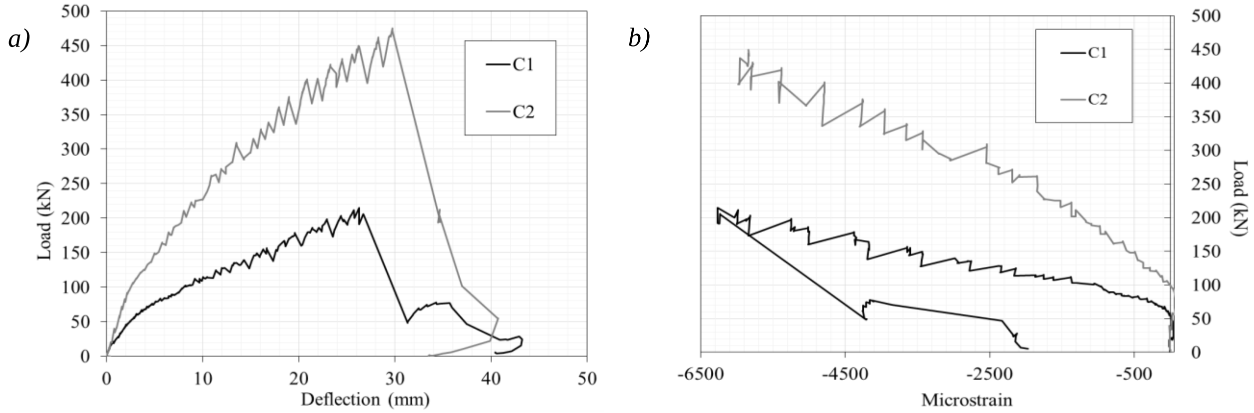



*Fig 3.* Control specimen strain responses: *a)* Load-midspan deflection; *b)* Midspan compressive strain

*Figure 4* shows the load versus mid-span deflection response for each of the damaged beams compared to Specimen C1, all of which shared the same dimensions. All simulated damaged strips showed an increase in mid-span strain for the same load when compared to the control. The strains developed in the T-Up ribs of the simulated damaged strips were approximately the same as that in Specimen C1 but occurred at half of the load. Specimen FD did not experience a noticeable increase in T-rib strain and matched very closely with the strains in Specimen C1 for a given load. The fire damaged beam experienced the largest deflection, likely due to a loss in cross-sectional area and a loss in GFRP mechanical properties from heating and cooling. Specimen FD also had a slightly higher ultimate load (approximately 10%) compared to Specimen C1. In Specimen C1, slip of the GFRP relative to the concrete caused eventual failure. A similar mechanism was observed in the fire damaged specimen, but exposure to elevated temperatures (in this experiment) actually increased the GFRP-concrete bond strength, which resulted in an increase in ultimate strength.

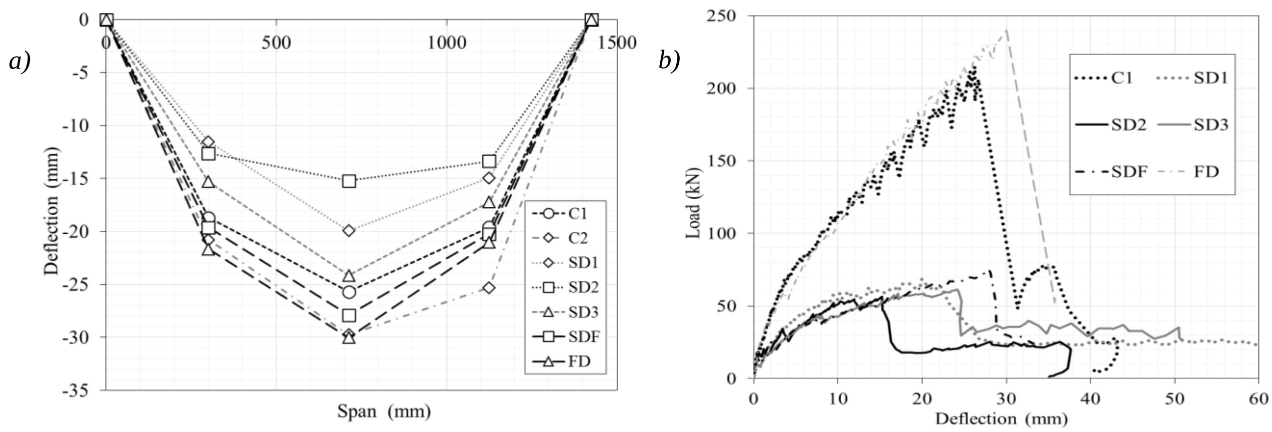



*Fig. 4. a)* Span-deflection at ultimate; *b)* Load-deflection responses of damaged strips

Compared to the control, the damaged beams have large deflections for similar load values. Surprisingly, the fully damaged specimen SDF out-performed the other damaged specimens and achieved the highest ultimate load among SD strips. This result indicates it may be more beneficial to have uniform damage across the section as opposed to localized damaged in specific areas.

### 4.2 Observed Failure Modes

The undamaged beams experienced significant flexural cracking but despite large crack widths, no concrete portions fell away from the GFRP. *Figure 5* shows the crack pattern and damage sustained by Specimen C2. The bottom GFRP plate was able to hold the fractured chunks of concrete in place as the load shifted to the formwork. This coupled with the additional bond surface area provided by the bottom plate held enough concrete intact to maintain partial composite action between the GFRP and concrete and eventually cause delamination of the GFRP formwork. This failure mechanism was observed in specimens C1 and C2.

*Fig. 5.* Specimen C2 crack distribution and GFRP delamination

The primary failure modes observed in the SD tests involved a combination of concrete crushing, GFRP debonding and eventual fracture of the GFRP formwork. *Figure 6* shows the flexural cracking and fracture of the GFRP near the damage boundary. In general, the damaged beams experienced significant flexural cracking in the moment span with the exception of SD3. Slipping between the formwork and the concrete was observed during all stages of each test but compatibility between the members was only severely reduced when flexural cracks were wide enough such that portions of concrete would fall away, exposing the GFRP T-Up rib. At this stage, most of the load was supported only by the formwork and eventually the GFRP section fractured. In tests where the bottom GFRP plate was removed, fracture of the formwork occurred at the boundary where the damaged and undamaged sections of the plate met. This behaviour is characteristic of each damaged strip test.

*Fig 6.* Sepcimen SD1 crack distribution and GFRP fracture

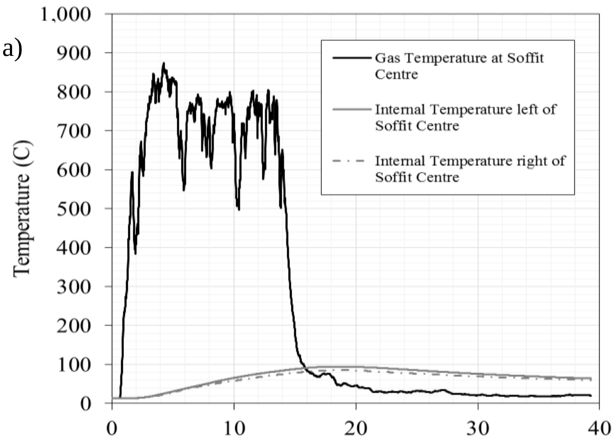
The location of GFRP reinforcement had a noticeable impact on the cracking patterns experienced in each strip. Specimen SD3 experienced no flexural cracking within the undamaged moment span, but significant flexural cracking was present outside and at the boundary of the damaged and undamaged sections. The GFRP rebar also limited the extent of cracking above the GFRP flange.

Specimen FD experienced similar flexural cracking patterns as Specimen C1/C2 shown in *Figure 5* and also experienced a similar failure mechanism involving loss of composite action and delamination where the bottom plate sheared off of the base of the GFRP rib on approximately one half of the span. Given these results it is believed the amount of fire damage sustained was insufficient to change the failure mode and behaviour of the strip when compared to Specimen C1 and SD3.

## 4.3 Assessment of Simulated Damage

Specimen FD performed very well during the real fire and demonstrated good resiliency. The melting and dripping of resin did not occur as substantially as predicted during past material testing [4]. A charred layer of the exposed GFRP surface formed which extended approximately 2 +/- 0.5 mm into the GFRP base plate (variation possibly due to flame dispersion effects). The exposed charred GFRP surface experienced delamination of its outer and exposed laminates. The GFRP experienced 'flame-out' once the pool fire fuel was exhausted no later than 30 seconds, suggesting that a higher incident heat may be required to ignite the GFRP surface or that the resin will melt (drip with gravity) off before ignition preventing a gaseous formation that can help enable flaming. It should be noted that the region directly beneath the char layer still contributes structurally to the member but may have undergone some level of change possibly including pyrolysis during heating. This layer will have altered post fire mechanical properties based on chemical change as well as partial melting and reforming of the GFRP during cooling. *Figure 7* shows the time versus temperature plot for the duration of the fire as well as the delamination and charring of the base plate. The effect of heating and cooling may have also had an impact on the bond between the formwork and the concrete. These factors will be examined further in the author's future work. Both thermocouples measuring temperature on the interior of the GFRP formwork base measured peak temperatures of less than 100°C on the interior concrete while the gas temperature at the exposed surface measured a peak of approximately 900°C. A numerical study would be useful to interrogate the heat transfer between the FRP to the concrete interface and beyond. This would be useful to assess the degree of damage the concrete can sustain beyond this layer. As the temperature sustained was below 100°C in the interior concrete, there exists minimal residual concrete strength capacity degradation. Test results seem to indicate that the interior concrete directly above the GFRP formwork sustained virtually no damage as a result of the fire. This is significant because it helps validate the authors' simulated damage assumption that only the exposed GFRP formwork would be damaged in the event of this fire. There was no simulated damage applied to any concrete above the GFRP formwork. It should be noted that this method of simulated damaged is only valid for pool fires of the extent of severity described. More severe fires may transfer more heat to the concrete and cause severe material degradation, expansion and/or spalling due to temperatures well beyond 100°C which was not accounted for in this study but is within the scope of the authors' future experimental and numerical research plans to investigate.

a)




b)

*Fig. 7. a)* Time-temperature history for Specimen FD; *b)* Delaminated pyrolysis/char layer on GFRP base plate

## 5 PRELIMINARY CONCLUSIONS

The main goal of this project was to understand the behaviour of GFRP stay-in-place formwork exposed to localized fire damage to the GFRP base plate. Based on the simulated damaged tests, it appears that a uniform distribution of damage resulted in better performance compared to localized damage at critical locations along the member length. The simulated damaged specimens experienced a large drop in ultimate load and larger deflections when compared to the control. The fire damage strip performed very well and closely resembled the behaviour of the control despite having a 2 mm layer of char and extended zone of pyrolysis on the base plate. The fire damage strip vastly outperformed the equivalent simulated damage specimens suggesting the extent of the simulated damage was an overly conservative assumption for the applied fire scenario. A second series of tests where only partial GFRP removal is performed and additional testing for variability would be enlightening. The lack of fire damage present in the interior concrete of the FD strip indicates for the severity of pool fire described in this project, only the exposed GFRP surface will experience damage and the assumption that the interior concrete is undamaged was valid in this case. Preliminary results suggest that GFRP SIP formwork hold great potential for civil engineering applications but the performance and behaviour of GFRP materials must be well understood.

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