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# BEHAVIOR OF 40 YEAR-OLD PRESTRESSED CONCRETE BRIDGE GIRDERS STRENGTHENED WITH CFRP SUBJECTED TO CYCLIC LOADING

O.A. Rosenboom and S. Rizkalla
Department of Civil, Construction and Environmental Engineering, North Carolina State University
Constructed Facilities Laboratory, Campus Box 7533, Raleigh, NC, USA
oarosenb@ncsu.edu sami_rizkalla@ncsu.edu

**ABSTRACT:** One of the challenges facing bridge maintenance engineers today is the upgrading of bridges whose service life has been exceeded but due to evolving demands must stay in service. Of particular concern are rural short span prestressed concrete bridges that may be required to carry loads above the original design value. Carbon Fiber Reinforced Polymer (CFRP) systems have the potential to increase the ultimate capacity of such bridge girders. This research project investigates the fatigue performance of CFRP strengthening systems used to increase the flexural capacity of 40 year-old prestressed concrete bridge girders. Five 9.14 m prestressed concrete bridge girders were tested under fatigue loading conditions: one as a control and four strengthened with various CFRP systems. Results show that CFRP strengthened prestressed concrete bridge girders can withstand over two million cycles of fatigue loading equivalent to a 20 to 60 percent increase in live load with little degradation.

## 1. INTRODUCTION

### 1.1 Research Objectives

Through examination of various parameters, including structural behavior as well as a thorough value engineering analysis, the main objective of the research is to provide the prestressed/precast concrete industry as well as transportation agencies with a feasibility estimate of strengthening of prestressed concrete with CFRP. The feasibility of using carbon fiber reinforced polymers (CFRP) strengthening systems to upgrade the load carrying capacity of 40 year old prestressed concrete bridges is investigated. Although there is an ever-expanding research database of reinforced concrete structures strengthened with different CFRP systems, information on various strengthening techniques for prestressed concrete structures is very limited. The first phase of the research investigated the static behavior of prestressed concrete bridge girders strengthened with CFRP and reported in reference [1].

### 1.2 Background

Recent surveys have indicated that between 30 percent and 40 percent of all bridges in North America are either structurally or functionally deficient [2]. Many of these bridges are structurally deficient because they do not conform to current design standards. If they are not strengthened, they may need to be replaced to accommodate the increase in axle-load carrying capacity. One of the biggest concerns to departments of transportation is short-span prestressed concrete bridges in rural areas which have exceeded their design life but due to evolving industry demands may be required to carry loads above the initial design value. CFRP systems have the potential for cost-effective retrofitting of prestressed concrete bridges by increasing the load-carrying capacity thus extending their service life.

The use of externally bonded and near surface mounted (NSM) CFRP systems to repair or strengthen reinforced concrete beams in flexure has been well researched [3-5]. Takacs and Kanstad [6] showed that prestressed concrete girders could be strengthened with externally bonded CFRP plates to increase their ultimate flexural capacity. Reed and Peterman [7] showed that both flexural and shear capacities of 30 year-old damaged prestressed concrete girders could be substantially increased with externally bonded CFRP sheets. The investigated strengthening schemes were limited to one type of externally bonded CFRP sheets. Reed and Peterman also encouraged the use of CFRP U-wraps as shear reinforcing along the length of the girder in externally bonded systems to delay debonding failure. The use of NSM CFRP in prestressed concrete bridge decks was explored by Hassan and Rizkalla [5] and found to be a viable alternative to externally bonded systems.

Debonding of externally bonded FRP systems has been noted by many researchers often at the termination point of the FRP plate/sheet for members with a short span, and at the midspan section for long span members. Many models have been proposed to predict the failure loads of FRP strengthened reinforced concrete members due to plate-end debonding [8, 9], yet the midspan debonding mechanism has not been as extensively researched [10, 11]. U-wrap CFRP reinforcement has been recommended for use at the termination point of the main CFRP strengthening system, but the benefits of providing this extra reinforcement throughout the length of the girder is not known [10]. One of the benefits of NSM FRP strengthening is to reduce the propensity for debonding failure. Models to predict this debonding load have been characterized from earlier plate-based work [3].

The fatigue behavior of reinforced concrete beams strengthened with externally bonded CFRP systems has been investigated [12, 13], yet no work has been done on prestressed concrete members strengthened with CFRP and tested in fatigue. The fatigue behavior of prestressed concrete was extensively examined in the 1960’s and 1970’s [14, 15] with results showing that very little fatigue degradation occurs if the girder remains uncracked. If the fatigue load is above the cracking load the failure will be due to fatigue rupture of prestressing strands.

In the first phase of this research [1], it was shown that prestressed concrete girders strengthened with various CFRP systems tested under static loading conditions could achieve an increase in ultimate strength of up to 60 percent.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Test Girders

As part of a research program sponsored by the North Carolina Department of Transportation, ten 9.14m long prestressed concrete bridge girders were tested at the Constructed Facilities Laboratory at North Carolina State University. Five of the girders were tested under fatigue loading conditions: one as a control specimen (F0), two strengthened with near surface mounted CFRP bars (F1) and strips (F2) and two strengthened with externally bonded CFRP strips (F3) and sheets (F4). Five identical girders were tested under static loading conditions and details of the results of these experiments can be found elsewhere [1]. All girders were C-Channel type prestressed concrete bridge girders (see Fig. 1). The girders were taken from a decommissioned bridge in Carteret County, NC, USA, which was erected in 1961. Each girder was prestressed with ten 1725 MPa seven-wire stress relieved, 11 mm prestressing strands (five in each web) and had a 125 mm deck with minimal reinforcing. The measured camber of the girders at midspan, due to prestressing, ranged from 32 to 38 mm. Details of the various strengthening systems are provided in Figure 1.

### 2.2 Design of Strengthened Girders

The design of the strengthened girders proceeded after testing the control girder under static loading conditions. The objective of the strengthening was to achieve a 20 percent increase in the ultimate load carrying capacity with respect to the control girder, except for F4 which was designed for a 60 percent increase in the ultimate load carrying capacity for further comparison. Each strengthened girder was designed using a cracked section analysis program, Response 2000 [16].

For the design, the manufacturer’s properties were used to model the FRP materials. The prestressing steel and concrete material properties were taken from the provided specifications.

Flexural failure, defined as rupture of the FRP or crushing of the concrete in compression, was the desired mode of failure. To delay FRP delamination-type failures along the length of the girder, 150 mm wide U-wraps were installed at 900 mm spacing for all externally bonded strengthened girders. This arrangement was selected to simulate typical anchorage details commonly used by the construction industry for reinforced concrete members strengthened with FRP.

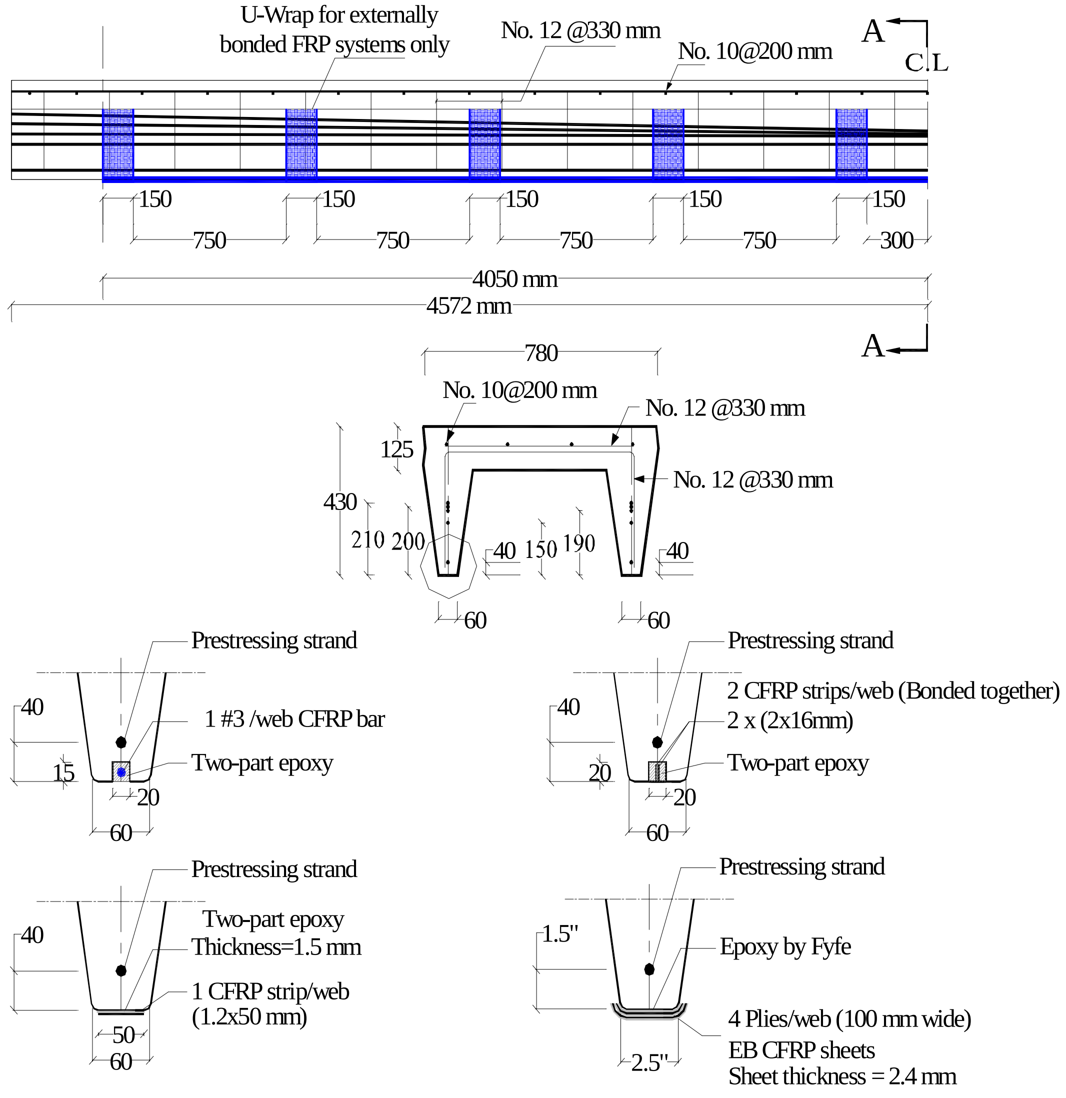

**Figure 1 – Reinforcement and strengthening details of the test specimens**

## 2.3 Test Setup and Instrumentation

All girders were tested using a 490 kN MTS hydraulic actuator. The actuator was mounted to a steel frame placed at the midspan of the girder. The loading sequence for the tested girders started by increasing the applied load to a load level slightly higher than the cracking load, unloading, and then reloading again at a rate of 2.5 mm/min up to the load at which the crack at midspan reopens. This loading sequence was selected to determine the prestress force loss by observing the re-opening of the flexural cracks [17]. Based on an initial prestress force in each strand of 84.1 kN, the losses for the girders tested in fatigue varied between 14.3 to 18.3 percent.

The girders were then cycled between two load values at a frequency of 2 Hz. The dead load for all the girders was the same, 8.9 kN. The live load used for the control specimen was 40 kN. This was based on the service load the original girder was designed for (HS15 type loading) and includes the appropriate distribution and impact factors. For three of the strengthened girders tested in fatigue (F1, F2, F3), the live load was increased 20 percent to 49 kN and for F4 it was increased 20 percent for one million cycles and 60 percent for the next one million cycles. This increase in live load corresponded to the increase in ultimate static load that was achieved during each static test of the respective girders. Basing the fatigue test loading on a specific stress range in the prestressing strands, or a nominal tensile stress in the bottom fiber would have lead to wide variations due to the variation in prestressing force observed for each girder.

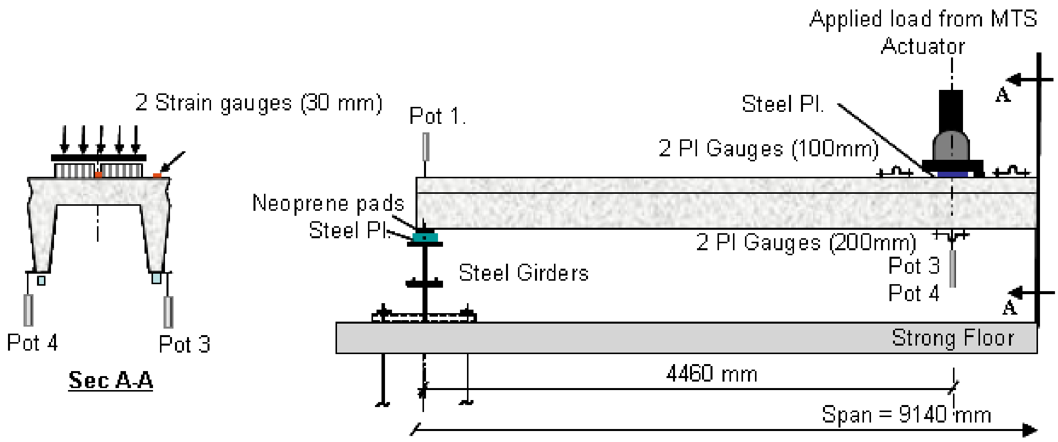

**Figure 2 – Test setup for prestressed concrete C-Channels under fatigue loading**

## 3. FATIGUE TEST RESULTS AND DISCUSSION

### 3.1 Control Girder

Cracking of the control specimen occurred at a load of 55.6 kN. After unloading and reloading, the flexural crack at midspan reopened at a load of 45.4 kN, which shows an approximate loss of prestress of 6.7 percent. After the initial loading cycles, the girder was cycled between 9 kN and 49 kN as described above. The load deflection behavior of the control girder is shown in Fig. 3. The strain profile of the girder at any stage of loading was determined from a combination of strain gauges applied to the concrete compressive surface and on the CFRP. From this profile, the strain in the lower prestressing strand can be found at the upper and lower limits of loading and can be converted to a stress using the Ramberg-Osgood equation with constants determined from material testing [16]. The stress range in the lower prestressing strand, which can be defined as

$$SR = \frac{f_{ps2} - f_{ps1}}{f_{pu}} \qquad (1)$$

where

| | |
|---|---|
| $f_{ps2}$, $f_{ps1}$ | upper and lower stress range in prestressing subjected to cyclic loading conditions |
| $f_{pu}$ | ultimate strength of the prestressing |

is shown in Fig. 4 versus the number of cycles. The control girder survived 2 million cycles with very little noticeable degradation. The girder was then loaded to failure, which occurred at a load of 142 kN, a 3.64 percent decrease from the ultimate strength achieved in the static test of the control girder.

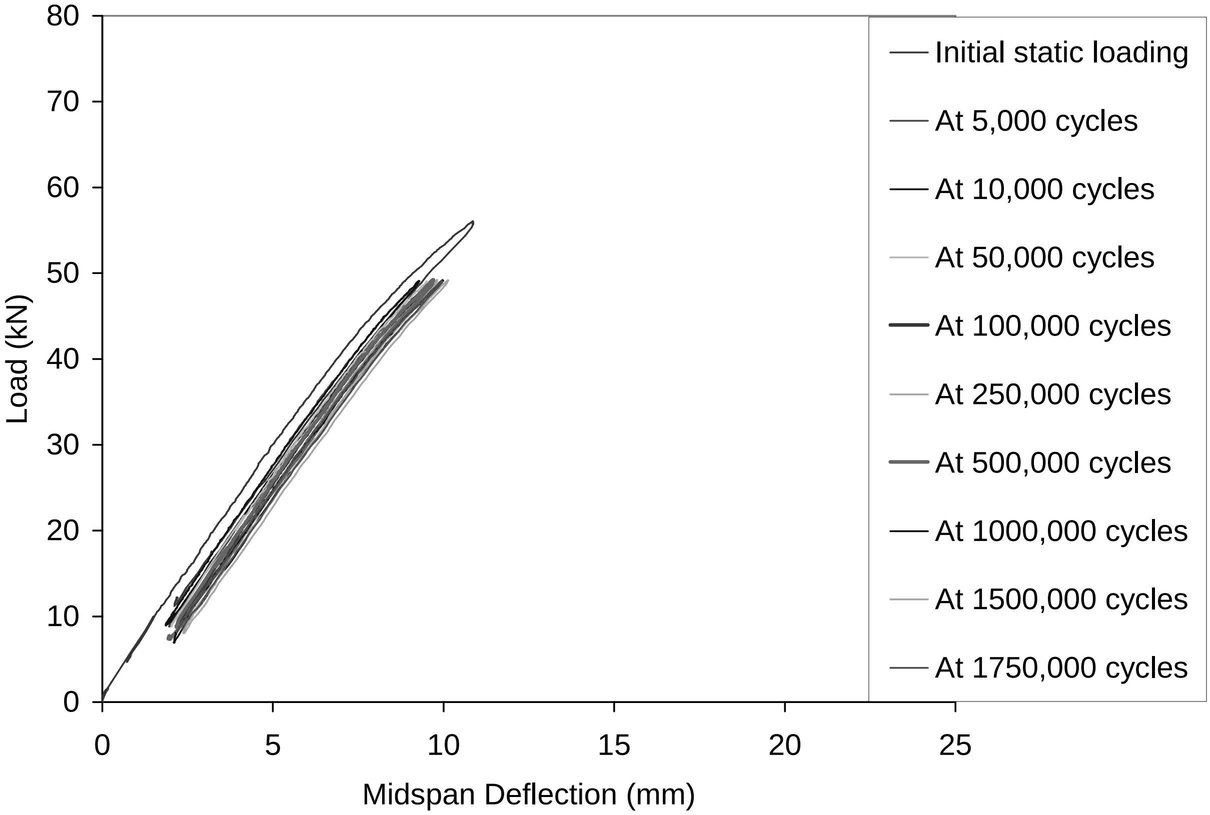

**Figure 3 – Load versus deflection behavior of the control girder, F0**

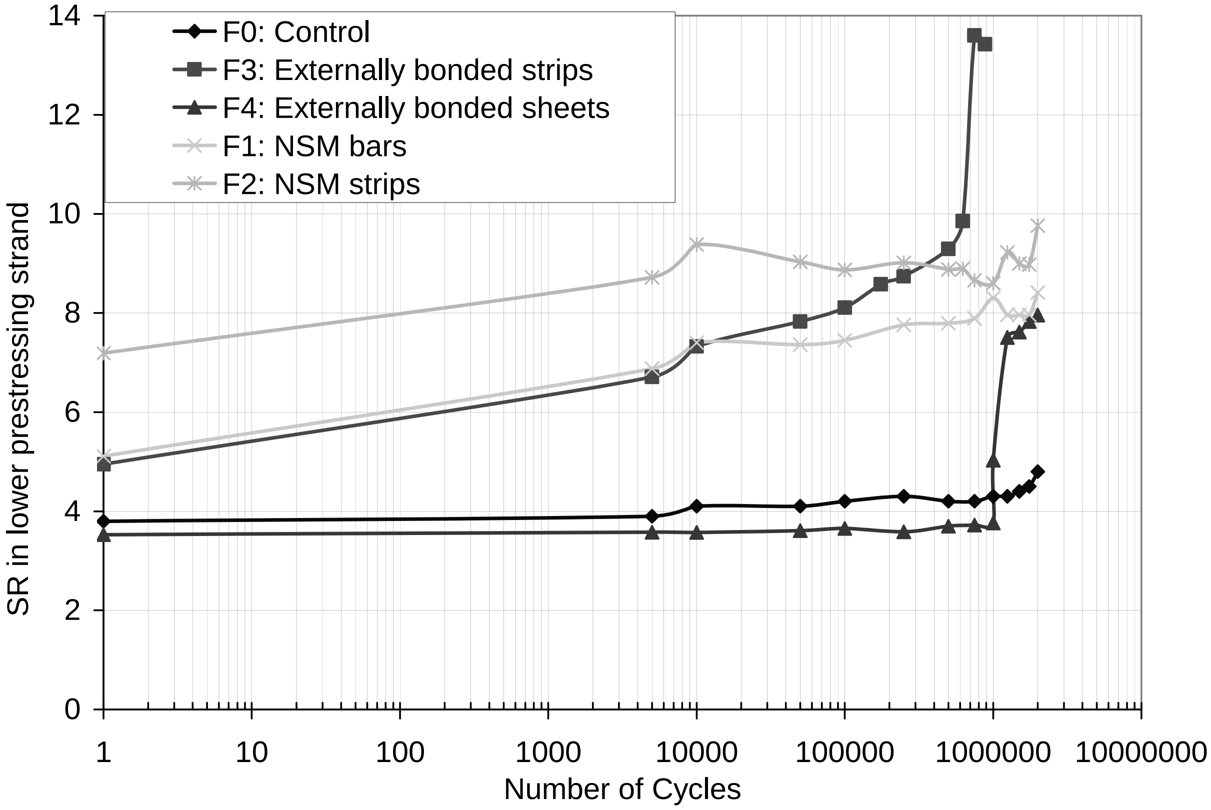

**Figure 4 – SR versus number of cycles for all girders tested in fatigue**

### 3.2 Near Surface Mounted CFRP Strengthened Girders

One girder strengthened with NSM bars and another strengthened with NSM strips (identical to two girders tested under static loading conditions) were tested in fatigue, F1 and F2 respectively. After the initial loading the strengthened girders were tested at a frequency of 2 Hz between 9 kN and 57.6 kN. The cracking load of the NSM bars and strips strengthened girders occurred at loads of 54 kN and 51 kN respectively. For both girders, the largest degradation in stiffness occurred between the secondary loading sequence (used to determine the prestress losses) and 10,000 cycles.

After 2 million cycles the girders were tested up to failure and showed little difference between the girders tested under static loading conditions. For the NSM bars strengthened girder tested in fatigue, failure was due to crushing of the concrete at a load of 178 kN, compared to the statically tested girder which failed at a load of 181 kN. The NSM strip strengthened girder tested in fatigue also failed due to crushing of concrete at a load of 163 kN, compared to the statically tested girder which failed at a load of 180 kN (40.6 k).

### 3.3 Externally Bonded CFRP Strengthened Girders

Two girders strengthened with externally bonded CFRP systems were tested in fatigue: one girder strengthened with externally bonded strips (F3) and another strengthened with externally bonded sheets designed for a 60% increase in capacity compared to the control (F4). These were identical to two girders tested under static loading conditions.

The girder strengthened with externally bonded strips had a cracking load of 54 kN. After 10,000 cycles, the behavior of the strengthened girder changed markedly from that of the NSM strengthened girders. Whereas the stress range and the maximum deflections of the other girders stabilized, F3 showed a steady increase in both these quantities. At 625,000 cycles a large crack was noticed near midspan which led to localized delamination of the CFRP sheets from the concrete substrate. This crack was due to rupture of a prestressing strand. The test was continued and catastrophic failure occurred at 908,000 cycles due to progressive rupture of the prestressing strands followed by debonding of the CFRP strips. The rupture of the first prestressing strand constitutes failure of the girder, since the deflection under service loading exceeded the limits specified for this type of girder.

A girder strengthened with externally bonded CFRP sheets designed to achieve a 60% increase in the ultimate load carrying capacity of the control girder was tested in fatigue (F4). The cracking load of this girder was measured to be 70 kN, much greater than any of the previously tested girders due to a higher effective prestressing force. Due to the uncertainty in calculating the stress range in the lower prestressing strand for the girder, it was decided to test this girder identically to the other strengthened girders. Very little degradation was noticed between the initial loading sequences up until 1 million cycles. At this stage it was decided to cycle between the load range of 8.9 kN to 72.7 kN, representing a 60 percent increase in live load. A static test performed at one million cycles showed very little change in stiffness up to 72.7 kN. Another 250,000 cycles degraded the girder so that a secondary stiffness can be seen after reopening of the crack as can be seen in the load versus deflection plot in Fig. 5.

The stress range in the prestressing strands, as shown in Fig. 4, was lower than that of the control girder up to one million cycles (due to the higher prestressing force), but increased dramatically after the 60 percent increase in live load was applied. Between 1.25 million cycles and 2 million cycles very little change was observed in the cracking pattern or the load-deflection behavior. After 2 million cycles the girder was tested to failure. Like the girder tested under static loading conditions, failure was due to rupture of the CFRP sheets. Due to the higher prestressing force observed in this girder, the girder tested in fatigue failed at a load of 245 kN, greater than the ultimate load observed for girder S6.

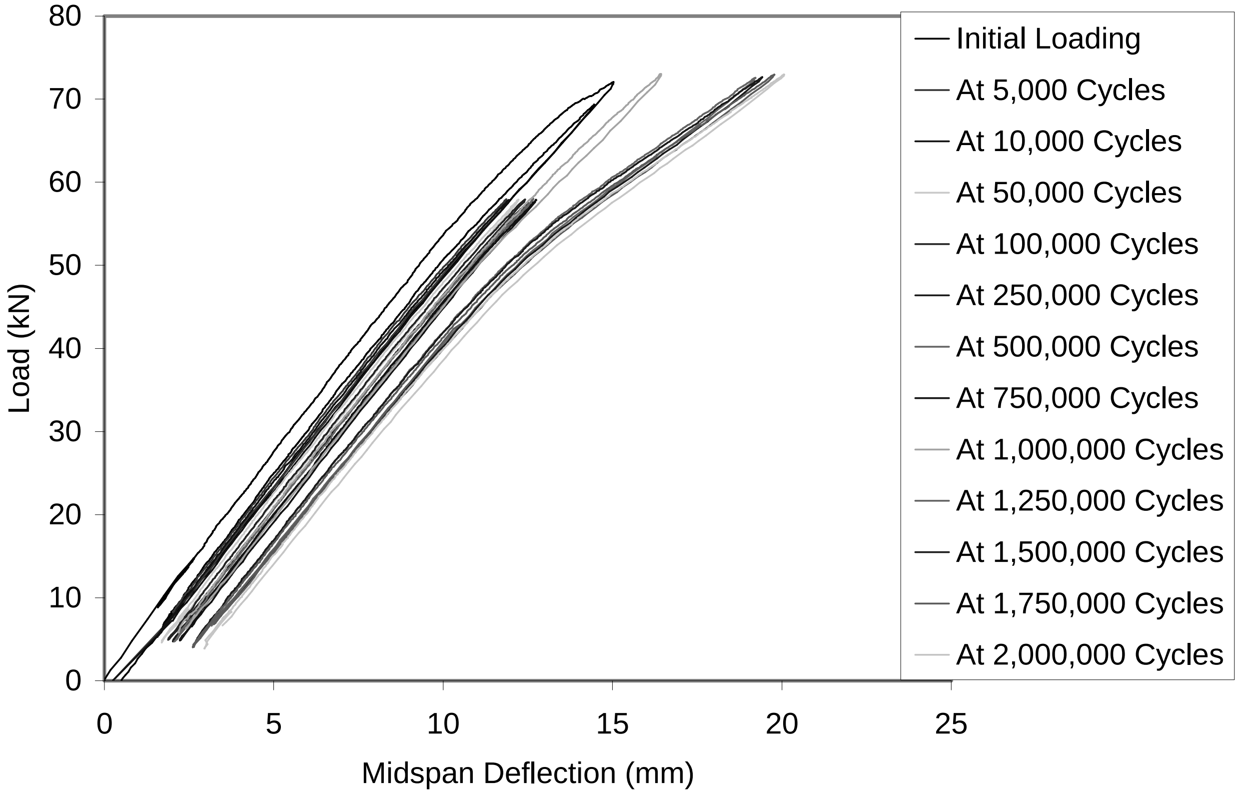

**Figure 5 – Load versus deflection behavior of the girder strengthened with externally bonded CFRP sheets, F4.**

## 4. CONCLUSIONS

Five 40-year-old 9.14m long prestressed concrete girders have been tested under fatigue loading conditions. One was tested as a control specimen and four were strengthened with various CFRP systems. The cyclic loading was designed to simulate loads on an actual bridge girder, from the dead load to the dead load plus live load. Based on the results, the following conclusions can be drawn:

1. Prestressed concrete girders strengthened with NSM CFRP systems to achieve a 20 percent increase in ultimate load carrying capacity can withstand over two million cycles of a loading equivalent to a 20 percent increase in live load.
2. Girders strengthened with externally bonded CFRP sheets to achieve a 60 percent increase in ultimate load carrying capacity can withstand over one million cycles of loading equivalent to a 60 percent increase in live load.
3. The girder strengthened with externally bonded CFRP strips performed worse under fatigue loading conditions than either the NSM systems or the externally bonded sheet strengthened systems, although this performance could be due to other circumstances such as corrosion of the prestressing strands.
4. The influence of the CFRP U-wraps placed along the length of the girder for preventing fatigue initiated debonding is not known.

Future fatigue testing of similar prestressed concrete girders will involve the testing of an externally bonded CFRP sheets girder strengthened to achieve a 40 percent increase strength, as well as a girder strengthened to achieve a 20 percent increase in strength using externally bonded high modulus sheets.

## 5. ACKNOWLEDGEMENTS

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