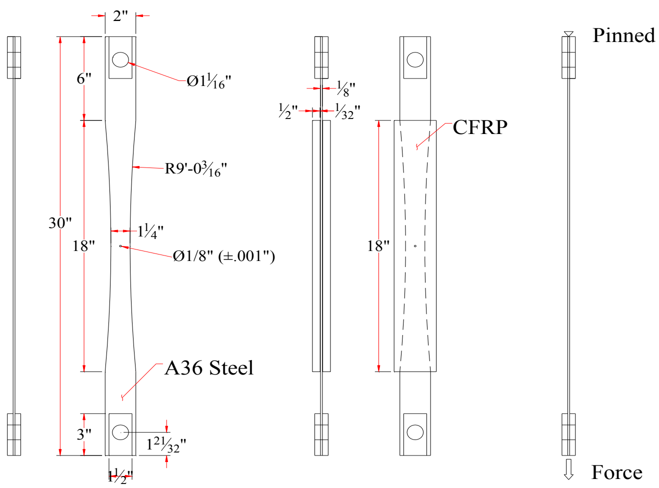
Evaluating the Performance of Composite Overlays to Repair of Fatigue Damage in Steel Plates Under Tensile Cyclic Loading:
Specimen Preparation and Testing

Regan Gangel
Fatih Alemdar

Tensile Specimen Dimensions and Testing Machine

The steel coupons used in the test specimens were fabricated using grade A36 steel and had a thickness of either 3.20 mm ($^{1}/_{8}$ in.) or 6.4 mm ($^{1}/_{4}$ in.). A hole with a diameter of 3.20 mm ($^{1}/_{8}$ in.) was drilled and reamed at the center of each coupon (Fig. 1). All specimen dimensions are shown in Fig. 1. Specimens were loaded in tension through circular-shaped bars acting in direct bearing on 27 mm (1-$^{1}/_{16}$ in.) diameter holes at both ends of the specimens, where the cross section was augmented as shown in Fig. 1 to prevent fatigue damage.



a) b) c)

Fig. 1 : Tension specimen a) bare steel b) specimen with CFRP overlay attached c) boundary and loading conditions imposed on the model

Specimen Preparation

Fatigue cracks initiating at both edges of the center hole were induced by imposing a sinusoidal cyclic load on the bare steel coupon. All loading of the coupons and test specimens was performed under load control. The tensile load was applied at the ends of the specimen using an MTS closed-loop servo-controlled loading system with a loading rate of 5 Hz in order to expedite the preparation of the coupons.

Tensile Specimen Loading

The magnitude of the applied load was determined on the basis of the nominal stress demand at the un-cracked net section of the steel coupon, calculated using the actual (measured) net cross sectional area without any adjustments for stress concentration in the area surrounding the hole. The minimum load was computed so that the minimum stress applied to the specimen would be 2 ksi. The maximum load was calculated on the basis of the cross sectional area and the intended stress range.

It is recognized that the stress on the net section of the steel coupon increases as the cross-sectional area of the specimen is reduced due to propagation of the fatigue crack. However, no adjustment of the load was made to account for this reduction in area. All computations of load were based on the uncracked net cross-sectional area of the steel coupon.

Before a specimen was tested under cyclic loading, the testing machine was loaded slowly to ensure that the specimen was seated properly and did not experience any impact loading. This was accomplished in a series of five steps listed below:

1. Load the specimen with 0.1 kip (100 lbs) over a period of 30 seconds
2. Hold the 0.1 kip (100 lbs) load for a period of 30 seconds
3. Ramp the load to half the desired maximum load over a period of 30 seconds

4. Hold the load at half the desired maximum load for a period of 30 seconds
5. Begin cyclic loading ranging between the desired minimum and maximum load

Fatigue Crack Initiation

The stress range used to initiate the two fatigue cracks was varied depending on the thickness of the steel coupon. It is recommended that fatigue cracks in ¼ in. thick coupons be initiated using a stress range of 38 ksi and that fatigue cracks in $^{1}/_{8}$ in. thick coupons be initiated using a stress range of 32 ksi in order to keep the preparation time reasonable.

The stress ranges mentioned above are recommended for two reasons. First, the stress range should be high enough that a fatigue crack will initiate in a reasonable number of cycles. Using a higher stress range will cut down on the lab testing time of each specimen. However, the stress range should not be so high that after a fatigue crack initiates, it propagates in an unstable manner. This may cause yielding of the steel plate specimen and render it unusable.

Fatigue Crack Propagation

Each fatigue crack was propagated to a maximum length of 0.3 in. on either side of the hole before the specimen was repaired using composite overlays. This was done for three reasons. First, in early tests of steel coupons with smaller cracks repaired with composite overlays the fatigue crack propagation rate was so small that each specimen took weeks for the fatigue crack to propagate through the entire steel cross-section. By using a longer initial crack length, fatigue crack propagation can still be tracked and analyzed but the lab testing time of each specimen was greatly reduced. Second, by giving each specimen the same initial crack size the different composite overlay repairs can be compared more consistently and the benefits of one repair over another can be more easily determined. Third, an initial crack length of 0.3 in. is long enough to decrease lab testing time as mentioned above, yet the not large enough to cause yielding of the steel coupon during the specimen preparation phase.

When propagating a fatigue crack, the stress range used was decreased as the crack length increased. The stress range was usually lowered to approximately 24 ksi after a crack length of 0.15-0.20 in. had been observed. This reduction in the stress range ensured that crack propagation would remain stable and that a crack length very close to 0.3 in. could be achieved.

It must be mentioned that although a crack length of 0.3 in. on each side of the hole was the desired goal, it is not possible to achieve that through the preparation process employed. In all cases a fatigue crack would reach a length of 0.3 in. on one side before the other did. After one of the two fatigue cracks reached a length of 0.3 in. the specimen was considered ready for CFRP repair. However, most specimens had fatigue cracks on either side of the hole that grew at about the same rate. Reducing the lateral bending of the specimen by either choosing a specimen with inherent low bending or restraining the specimen in the lateral direction helped ensure similar crack growth on both sides of the hole.

Displacement Limits

It is very important to put into place precautionary measures for preventing unstable crack growth during the preparation phase. In this study, this was done by establishing shutdown triggers based on the maximum displacement measured by the testing machine. As a crack increased in length the measured maximum displacement increased as well due to the reduction in the net cross section of the steel coupon. The testing machine was programmed to stop the cyclic load and return to zero load if the maximum displacement increased by more than 0.0005 in. After this limit was exceeded, if the crack required further propagation the limit was re-set to

0.0005 in. above the current displacement measurement. The displacement limit would then continue to be reset throughout testing as the crack propagated.

Attachment of Composite Overlays

After a fatigue crack of 0.3 in. had been achieved, the surface of the specimen was prepared for bonding the composite material using a process of abrading and cleaning. This was done to ensure an adequate bond between the composite and the steel coupon. Abrading consisted of roughening the surface with a hand grinder to achieve a surface roughness of approximately 0.80 mm (0.031 in.). After abrading, cleaning of the surface was performed using acetone and methanol. A composite overlay was then attached to each side of the steel coupon over a length of 18 in., as shown in Fig. 1.

Determination of Fatigue Crack Propagation Life

After the composite overlays were attached to the steel specimen it was placed in the testing machine where it was tested under load control at a constant stress range and a loading rate of 2 Hz. During testing the percent change in stiffness was monitored. The percent change in stiffness was calculated using the following equation:

$$\%\text{ change in } K = (\delta L/\delta P)/K_{max} \quad (1)$$

where K is the stiffness of the combined steel and composite overlays, δL is the load range imposed on the specimen, δP is the displacement range recorded by the testing machine, and K_{max} is the maximum stiffness recorded during testing.

In all but two of the specimens tested there was a significant increase in compliance at some point during the testing, as shown in Fig. 2. The maximum stiffness referred to in Eq. 1 is a constant for each specimen, and because testing was performed under load control, the change in load remained relatively constant. Therefore, according to Eq. 1, any decrease in the stiffness (increase in compliance) would be a direct result of an increase in the extension of the specimen measured by the testing machine.

Increases in compliance under a constant load range are caused by softening of the specimens, which is indicative of damage. An increase in compliance could be caused by loss of bond, damage in the composite overlays, or a reduction in the net cross sectional area of the steel coupon. In most specimens, after testing was stopped, the composite overlays showed almost no visible signs of damage. A single exception was observed in which the composite overlay suffered total failure following the propagation of the fatigue crack through the entire cross section of the steel. Because the composite overlays showed no signs of damage or distress it is hypothesized that gradual increases in compliance were caused primarily by the reduction of the net cross sectional area of the steel coupon. Propagation of the fatigue crack through the entire cross section of the coupon led to 100% of the load being transferred through the composite overlays. Having the load transmitted entirely through the composite overlays caused a rapid increase in the damage to the overlays and local loss of bond near the fatigue crack in the steel coupon, leading to a much greater increase in compliance (or reduction in the stiffness) than that observed during propagation of the crack through the steel. The number of cycles at which a significant change in compliance was observed was adopted as the fatigue propagation life for that specimen.

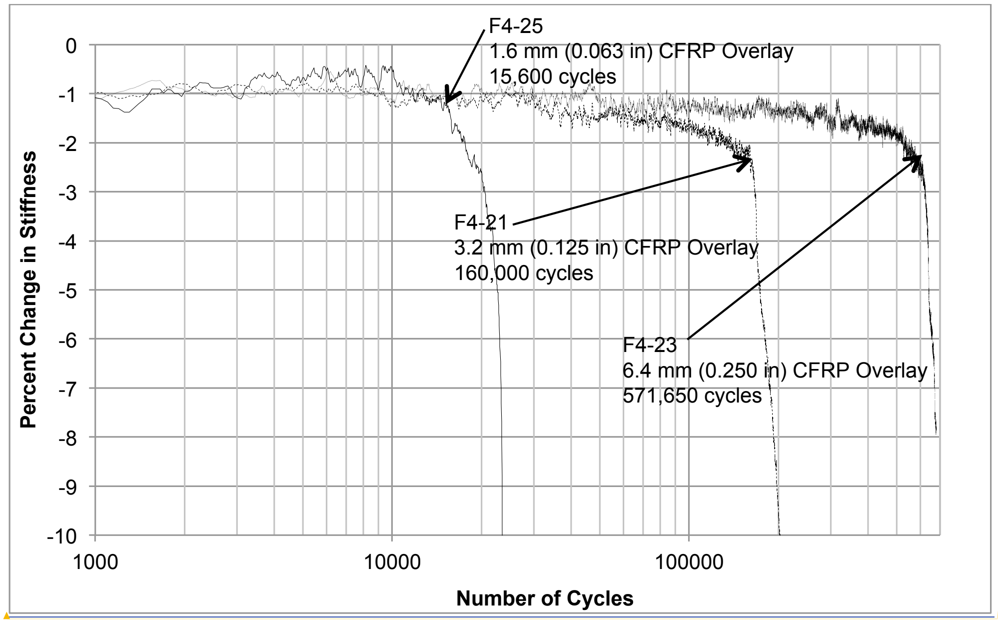


Figure 2 : Percent change in stiffness during testing of 6.4 mm (0.250 in) thick specimens tested at 221 MPa (32 ksi)

After a large change in the compliance was observed the test was stopped and the composite overlays were removed from the steel coupon to verify that the fatigue crack had propagated through the entire net section of the steel.

In the case of two specimens a significant change in compliance was never observed after the number cycles exceeded the infinite fatigue threshold for the corresponding nominal stress range established in the AASHTO bridge specifications. After the number of cycles associated with infinite fatigue life in the AASHTO bridge specification was surpassed in these two specimens, the composite overlays were removed to reveal negligible fatigue crack propagation.

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