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Multiaxial Fatigue of Notched Steel Plates and Investigation of CFRP Retrofits for Crack Initiation Prevention

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Multiaxial Fatigue of Notched Steel Plates and Investigation of CFRP Retrofits for Crack Initiation Prevention

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1. Introduction

Fatigue cracks are cracks that result from repeated loading over time, often following millions of loading cycles. Fatigue cracks occur even if the applied load is not large enough to cause material yield. Once a fatigue crack initiates, resulting stress concentrations at the crack tip often make it difficult to arrest the growth of the crack. In order to prevent growth and propagation of fatigue cracks within structural components, it is necessary to alter the stress condition at the crack tip. Fatigue cracks in steel structures resulting from multiaxial loading and or geometry conditions that result in complex states of stress [1] can be particularly challenging to address, as many existing crack mitigation approaches (which aim to alter the crack-tip stress) often target uniaxial stress conditions.

The objective of this research project is to observe how cracks initiate and develop in notched steel plates under different multi-axial stress states, and to assess the effectiveness of carbon fiber reinforced polymer (CFRP) orientations as a retrofit strategy to delay fatigue crack growth.

2. Experimental Procedure

Steel plates with yield stress of 250 MPa (36 ksi) were tested in a Walter+Bai biaxial fatigue testing machine under various combined loadings. Each plate had a notch of approximately 2.5 cm (1 in.) long at the edge to create a stress concentration to promote fatigue crack initiation and allow evaluation of retrofit effectiveness in preventing fatigue crack initiation. The research was divided into two parts, and each part consisted of three tests; 100 kN (22.5 kips) axial tension test, 1000 N-m (738 lb-ft) torsional test, and combined in-phase axial tensile-torsional loadings test. For the in-phase axial-torsional test, the maximum value of the axial stress waveform occurs simultaneously with the maximum value of the shear stress waveform [2]. Figure 1 shows the load time-history for the combined in-phase loading. Each of the three tests were run three times for a statistical purpose. The majority of tests were performed at a loading frequency of 3Hz; however, there were small variations in loading frequency between tests to accommodate the different phases of loading and machine performance requirements.

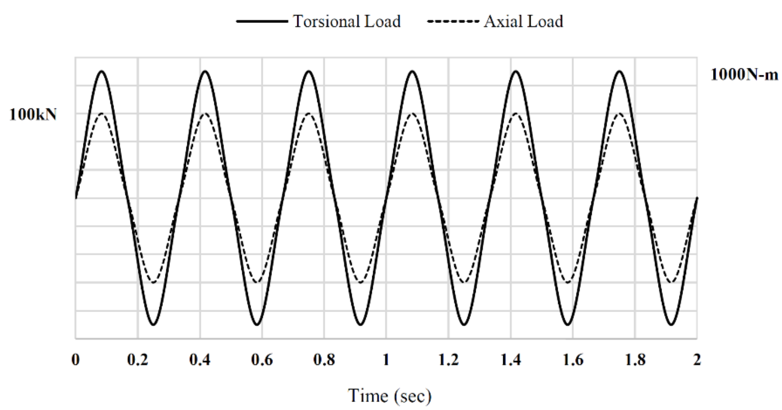

Figure 1. Load-Time Curve of In-phase Loading at 3Hz.

Figure 2 shows the simple representation of the experimental setup. Any notations regarding the plates (top, bottom, right, left, etc.) will be based on this figure throughout this thesis.

In order to know the nominal stress and strain, and the concentrated stress and strain at the crack edge, strain gauges were used on one of the plates for each loading combination. The strain gauges were located on at the center of the plates and at the edge of the notch of both sides of the plates (see Figure 3(a) below). Strain data of a total of six plates were recorded at 0.01 seconds intervals for the first 10 seconds of every hour to capture any changes due to crack growth.

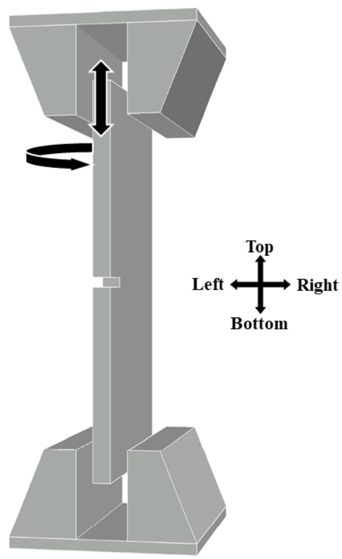

Figure 2. Schematic of experimental testing setup

The testing machine automatically stopped when each specimen failed. Failure in this project is defined as when a specimen reaches an additional 1mm stroke, which is another word for displacement, or a change in length, to the initial stroke or an additional 3° rotation to the initial rotation.

In the first part of the project, the three modes of stresses were applied on steel plates without CFRP to investigate how the plates behave under different stresses, when a crack occurs, how the crack develops, and to gather any other relevant information. Next, evaluation of the performance of CFRP retrofits was conducted. A CFRP retrofit plate was put on the right side of the plates so that it completely covers the notch (see Figure 3(b)). Then different modes of stresses were applied on each plate in the same way as with the non-retrofitted plates. By comparing the number of cycles it took for plates with no retrofit and plates with retrofit under the same stress to fail, the viability of CFRP crack mitigation could be obtained.

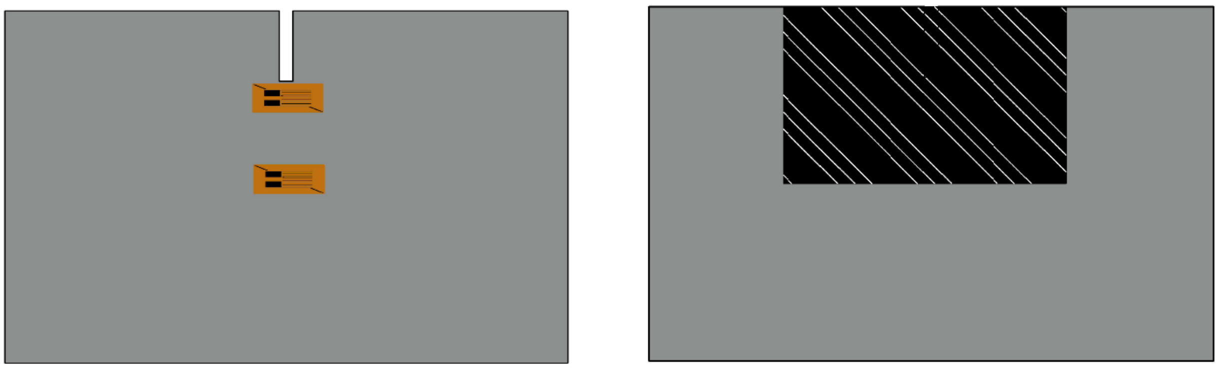

Figure 3. (a) Specimen with Strain Gauges (b) Specimen with CFRP Retrofit

3. Results and Discussion

3.1.1 Axial Only Test with no CFRP

Axial only stress test on plates without CFRP retrofit were run two times, one with strain gauges and one without strain gauges. The number of load cycles at which each specimen failed was 304,334 and 272,015 respectively. At the beginning of loading, the concentrated stress at the crack edge was 139 MPa (11.5 ksi), and the nominal stress at the middle of plate was 50 MPa (7.2 ksi), compared to the calculated applied stress of 87.5 MPa (12.7 ksi). The concentrated stress and the stress at the middle were found by averaging the values of the right side and the left side (canceling out any stresses induced by accidental bending of the plate). Applied stress was calculated by the applied load, 100 kN and the cross-sectional area, 127 mm × 9.0 mm as follows;

$$\sigma = \frac{F}{A} \tag{1}$$

where, σ = axial stress, F = axial force, and A = cross-sectional area.

It would have been possible to estimate at how many cycles the plate yielded from the strain at yield point calculated using the yield strength and the modulus of elasticity;

$$\varepsilon = \frac{\sigma_y}{E} \tag{2}$$

where, ε = strain (unitless), σ_y = yield strength (36 ksi for the plates used in this study), and E = modulus of elasticity (29,000 ksi); however, strain data became unavailable before the plate reached the yield point. From the available data, the maximum stress at the crack edge on the right side of the plate was 21.0 ksi and the maximum stress at the crack edge on the left side was 30.1 ksi.

Figure 4 below shows the crack geometry when the plate failed. As shown in Figure 4, the crack developed horizontally from the notch such that it split all the strain gauges and it penetrated the plate. It is considered that the crack abruptly developed around the point at which the plate reached a stroke of 1mm.

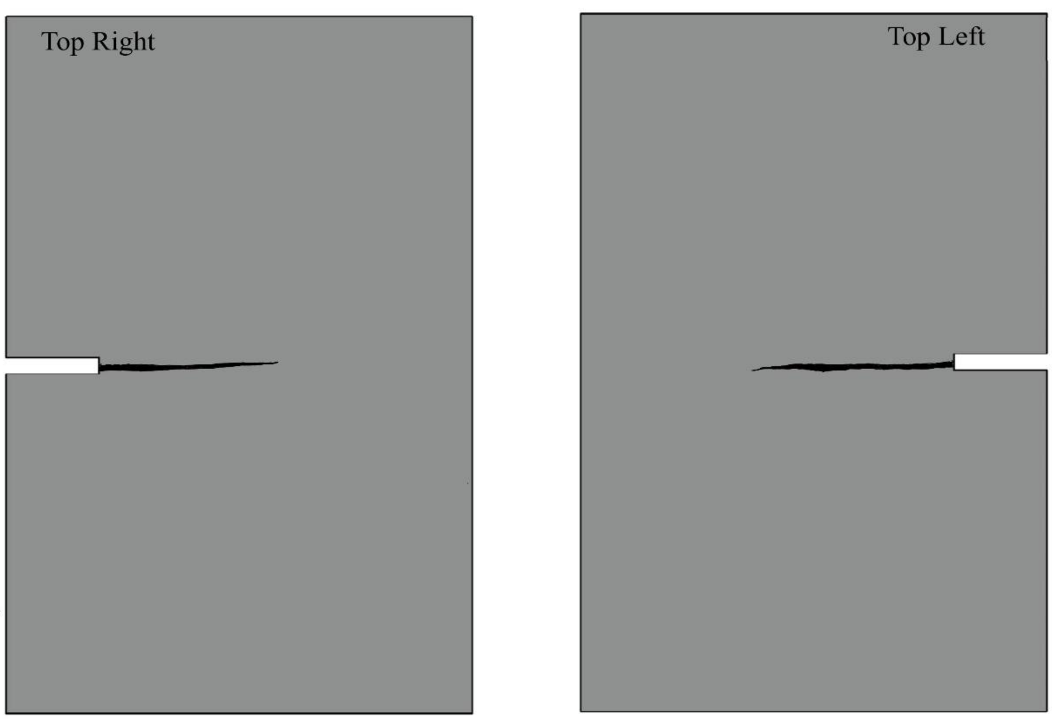

Figure 4. Crack Geometries of Plates after Axial Loading Test

In order to show the rate of the change in strain, a graph of strain to number of cycles was plotted. Figure 5 below shows the maximum strain at the crack edge on both sides of the plate at several points in time during the test.

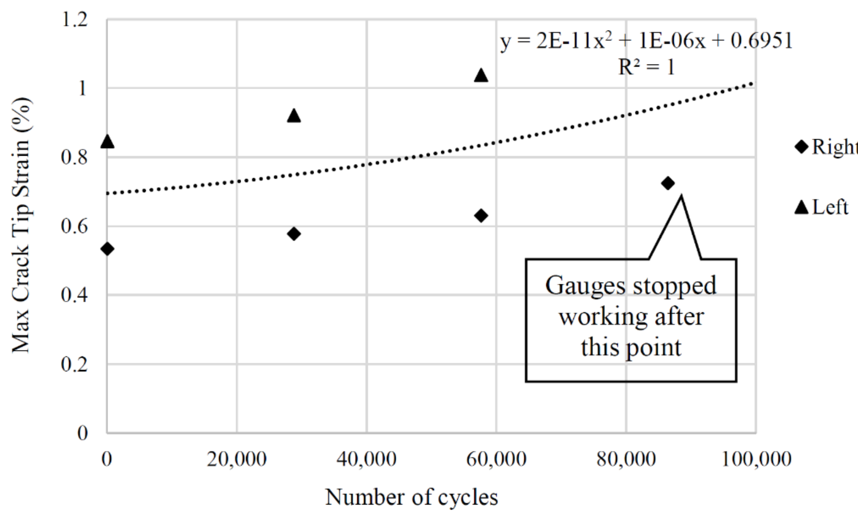

Figure 5. Change in Strain Over Time under Axial Loading

Recorded strain gauge data was not obtained after 86,450 cycles due to either the crack growing through the strain gauge or the gauge becoming unbonded. Also shown in the graph is the trendline of the average values of right and left strain to number of cycles. Even though only a few data points are shown, we can see that there is nearly a quadratic relationship between strain and duration at which load was applied.

3.1.2 Combined Axial and Torsional Test with no CFRP

Combined stress test on plates without CFRP retrofit were run three times, one with strain gauges and two without strain gauges. The number of cycles at which each specimen failed was 46,326, 79,240, and 95,424 respectively. According to the strain data and equation (2), the plate with strain gauges yielded before 9,210 cycles, where the second series of data were recorded. We can see that steel under in-phase combined stresses reaches a yielding point much sooner than steel under axial only stress. At the beginning of the loading, the strain at the crack edge was 3.50% and the strain at the center was 2.29%, compared to the crack edge strain of 60.2% and the middle strain of 6.97% from the last available data before failure. Since strain data of the left side became unavailable at an early stage of the test, all of these values are strain of the right side of the plate for consistency.

Figure 6 below shows the crack geometry when the plate failed. The cracks developed in different directions on the right and left side. The cracks did not penetrate the plate, rather, they occurred only on the surface from the visual observation. In addition, due to the twisting motion, there was a small deformation in the left-right direction.

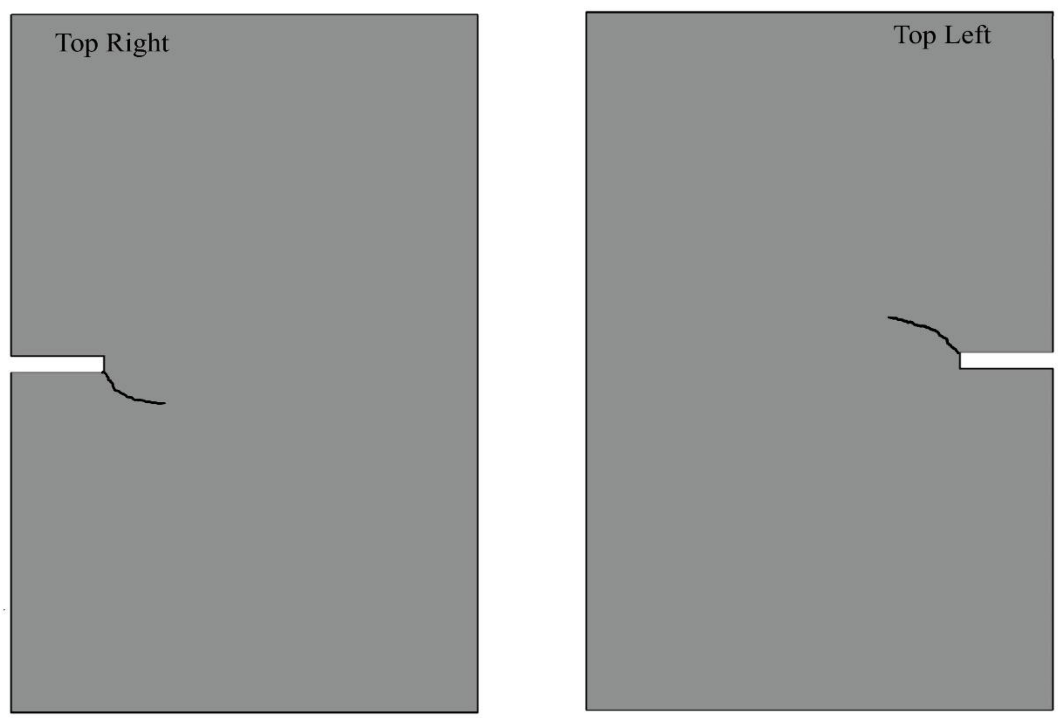

Figure 6. Crack Geometries of Plates after Combined Loading Test

Shown in the graph below is the relationship between strain and number of cycles stress was applied (Figure 7). Some of the data are missing due to troubles with electrical connectivity between gauges and the recording machine; however, it can be observed that the measured plate strain and number of cycles remain proportional, with increases in strain be connected to increases in the number of loading cycles as the crack grows.

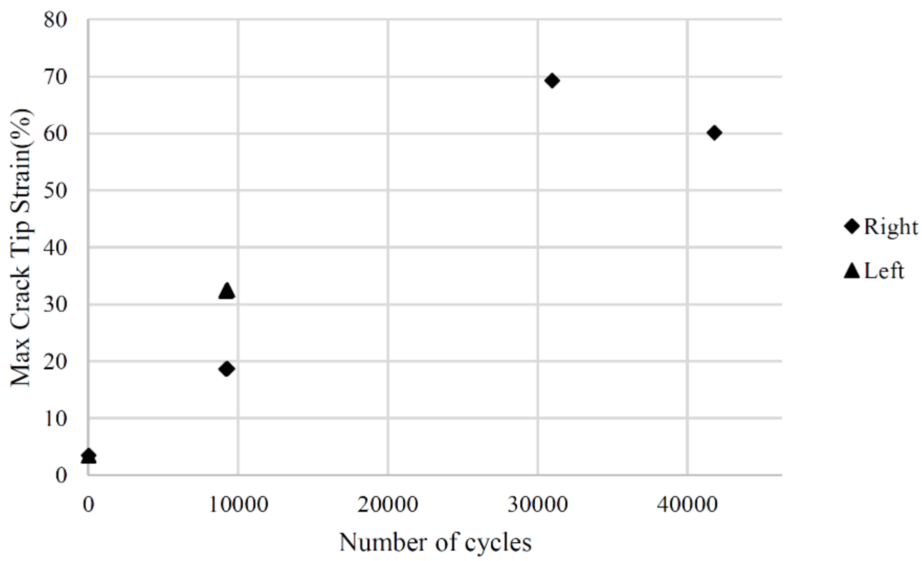

Figure 7. Change in Strain Over Time Under Combined Axial-Torsional Loading

3.1.3 Torsional Only Test with no CFRP

Torsional only stress test on plates without CFRP retrofit was run two times, one with strain gauges and one without strain gauges. The number of cycles at which each specimen failed was 115,970 and 202,148 respectively. In a torsion test, the single strain gauge at the crack edge does not tell us the true concentrated stress. The transition of strain-number of cycles curve with the passage of time is shown in Figure 8. It can be seen from the graph that in the early phase of the test, the series of the strain of the right side and the left side of the plate are out of phase. However, in the middle of the test, the strain of the right side goes through two cycles while the strain of the left side goes through one cycle, and in the final stage of the experiment before the failure, the waveform of strain of the right side and the left side are in phase.

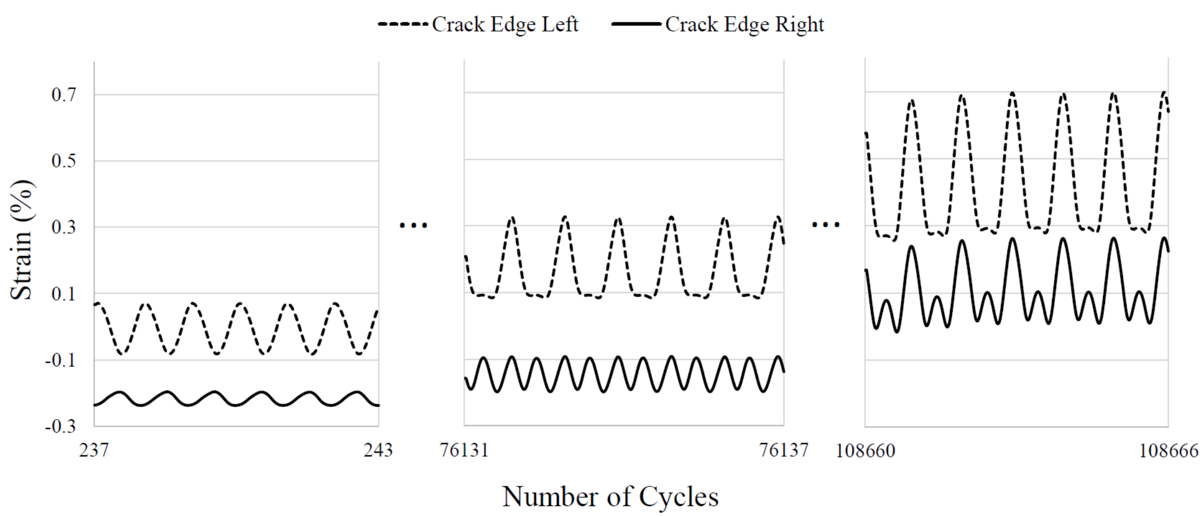

Figure 8. Strain Waveform Over Time under Torsion Loading

This irregularity is attributable to the fact that under shear stress, a strain gauge measures strain of compressive or tensile stress generated from the shear stress, rather than the strain due to the shear stress itself [3]. Therefore, it is difficult to accurately estimate at what cycles the plate yielded. In order to obtain more accurate and detailed strain and stress data, several methods could have been utilized. One of the ways is to perform finite element analysis (FEA). Although it will be only a simulation of load effects and still needs to be verified experimentally, it allows us to predict the stress states of the analyzed section in detail. Another way is to use more strain gauges. By combining strain data of multiple (usually three) gauges that are arranged so that two of them are oriented at +45° and -45° to the loading axis and the other one is oriented at 90° to the loading axis [4], it is possible to measure the true shear strain which takes twisting motion into account.

In Figure 9, the crack geometry when the plate failed is exhibited. The cracks developed in two different directions from the edge of the notch. Just like in the combined test, the cracks occurred only on the surface and did not penetrate the plate. In addition, due to the pure twisting motion, there was a larger deformation in the left-right direction.

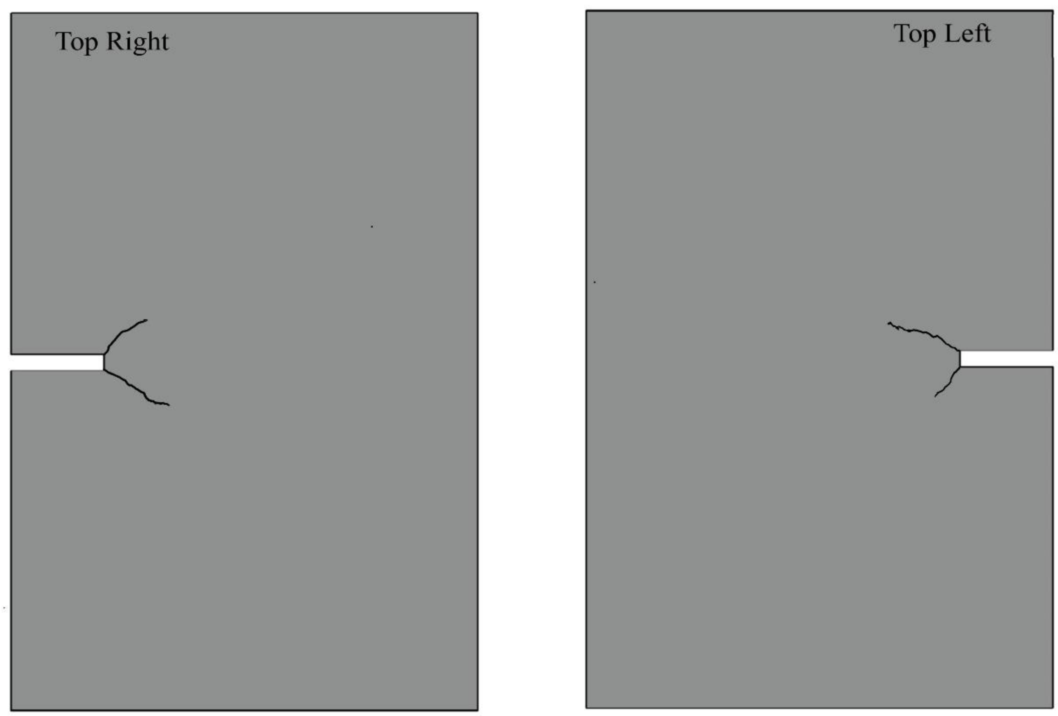

Figure 9. Crack Geometries of Plates after Torsional Loading Test

3.2.1 Axial Only Test with CFRP

Axial only stress test on plates with CFRP retrofit was run two times. The number of cycles at which each specimen failed was 829,532 and 1,464,362 respectively, compared to 304,334 and 272,015 cycles to failure with no retrofit. This means that in the axial only test, the CFRP retrofit succeeded in delaying failure of the plates by 173% to 438% in terms of number of cycles.

3.2.2 Combined Axial and Torsional Test with CFRP

Combined stresses test on plates with CFRP retrofit was run three times. The number of cycles at which each specimen failed was 49,259, 80,862, and 73,012 respectively, compared to 46,326, 79,240, and 95,424 cycles to failure with no retrofit. This implies CFRP did not have much effect in preventing crack development under combined axial torsional stresses. One of the reasons that can explain this result is that the retrofit partially peeled off from the steel plate. As the CFRP retrofit used in this project was a thin plate, part of it was separated from the steel plate due to the deformation generated by torsion (see Figure 10).

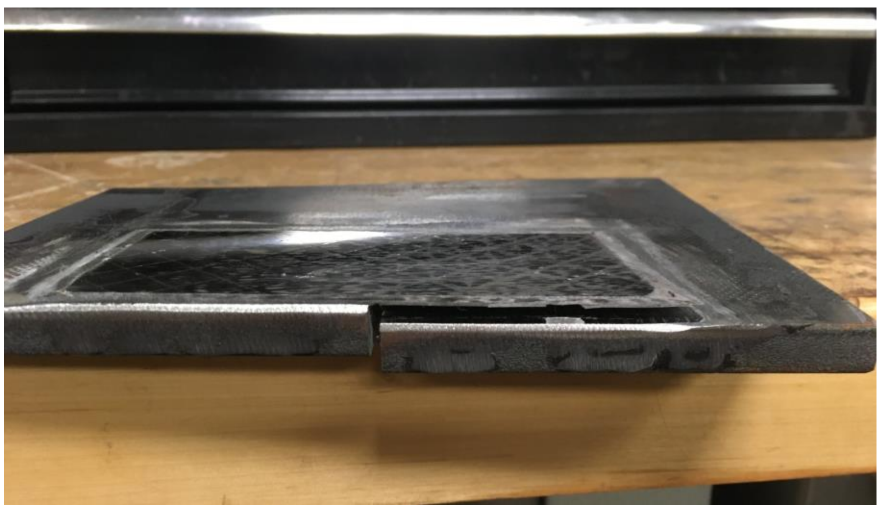

Figure 10. A Steel Plate with CFRP Retrofit After Combined Axial-Torsional Test

3.3 Summary of Results

Table 1 provides a summary of all the test results (Table 1). It can be seen that CFRP significantly delayed failure of the plates under axial only stress, but was ineffective for plates subjected to torsional (out-of-plane) stresses.

Table 1. Summary of Number of Cycles to Failure from all the Tests

	Non-Retrofitted			**Retrofitted**		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
100Kn-A	304,334	272,015		829,532	1,464,362	
100Kn-A+1000Nm-T	46,326	79,240	95,424	49,259	80,862	73,012
1000Nm-T	115,970	202,148				

4. Conclusion

This research experimentally investigated the fatigue behavior of notched steel plates subjected to multi-axial loading. A total of 11 fatigue tests (six bare-steel and five CFRP retrofitted) were conducted under various levels of multi-axial stresses. Following, an analysis of fatigue crack initiation and effectiveness of CFRP plate retrofit in crack prevention under cyclic multiaxial loadings was performed. Results from the multi-axial fatigue testing indicate that CFRP retrofit patches are capable of successfully delaying crack generation for plates under axial only loading; however, when out-of-plane torsional loadings were applied (both in-phase, and out-of-phase), the retrofit had little effect on improving fatigue life.

5. ***References***

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