# FATIGUE BEHAVIOUR OF CRACKED STEEL PLATES REPAIRED WITH HIGH AND LOW MODULUS CARBON FIBRE REINFORCED POLYMERS

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**Abstract:** Fatigue behavior of edged cracked steel plates repaired with carbon fiber reinforced polymers (CFRP) was studied experimentally under tension- tension fatigue loading, with stress range of 180 MPa and the stress ratio of 0.1. Main parameters were the CFRP type, adhesive strength and adhesive thickness ($t_A$). Two different moduli of CFRP, 165 GPa and 65 GPa, were used. It was found that lesser adhesive thickness resulted in 9% reduced fatigue life of higher modulus CFRP repairs because of induced higher shear stresses and corresponding more adhesive failure in it, that resulted in more patch delamination and reduced fatigue life. Lower modulus CFRP repairs achieved 5% to 22% higher fatigue lives because of higher adhesive shear and bond strengths, although the induced shear stresses in their adhesive were expected to be higher because of smaller thicknesses but on the other hand these had higher shear and bond strengths that prevented their shear failure or the patch delamination. Higher fatigue life of lower modulus CFRP repairs also indicated that the stress intensity factor (SIF) must have reduced initially because of lower adhesive thicknesses or their corresponding higher shear stiffness ($G/t_A$). Later on SIF could not rise up quickly because of higher adhesive bond strengths that prevent early patch delamination near the crack and kept the SIF and the crack opening to a lower value, thus, resulting in higher fatigue life.

## 1. INTRODUCTION AND BACKGROUND

Use of bonded 'Fiber Reinforced Polymers' (FRP) has emerged as an efficient and effective technique for strengthening, re-strengthening and fatigue life enhancement of metal and concrete structures because of its several leading advantages over the other traditional techniques. It has been successfully used in this regard since last two to three decades, with aircraft industry as the most beneficial that has been using FRPs in fatigue repairs of cracked and corroded parts of aircrafts (Baker 2003). Use of FRP in civil industry is less frequent and mostly found in strengthening of reinforced concrete beams and pre-stressed concrete girders, which are mostly used in bridges (ElSafty 2012 and Klaiber et al. 2003). Strengthening and repair of steel structures using FRPs is not much common but still found to be successful in several research works (Bocciarelli et al. 2009, Kennedy and Cheng 1998, Lui et al. 2009, Holden 2012, Mobeen et al. 2012, Papanikos et al. 2007, Colombi et al. 2003a,b, Lam and Cheng 2008, Tavakkolizdeh et al. 2003, Stanford 2009).

Use of CFRP in steel structures to improve its fatigue behavior is also growing as a need of the day, especially in steel bridges because of existence of several details that are more susceptible to stress concentration and fatigue cracks, and, these are very difficult to be avoided in the design. Need of fatigue repairs in steel bridges is gaining importance also because of growing number of aging bridges in North America and Canada that requires a recurring financial budgeting.

Most of the traditional fatigue crack repair techniques in steel structures have already shown to be effective to some extent but their main drawback is their secondary effects, which, in most of the cases, become additional sources of stress concentration or the crack initiation, like cutting holes to remove crack tip, or re-welding steel cover plates. Drilling holes is good in reducing the SIF but it reduces the net section capacity and increase the net section stress. Welding of cover plates found to be resulting in martensitic formation within the heat affected zone (Bayraktar et al. 2004) and in some cases resulted in even lesser fatigue life than the un-welded plate (Alam 2005).

Fatigue crack repair using bonded fiber reinforced polymers (FRP) has several advantages over the other traditional methods. It reduces stresses in the cracked plate without creating a minimal damage to the already weakened and cracked element. It also minimizes the stress concentration in load transfer regions because of providing a fairly larger bond area. In addition to reducing stresses in cracked element it also provides restriction to the crack opening because of its high stiffness. FRP strength to weight ratio is much higher than steel, so, it merely adds weight to the repaired structure which also provides ease in its on-site installation.

Although the use of FRP in improving the fatigue life of steel structures has found to be successful in to-date research work but still it requires more detailed analysis of the failure modes of bonded repairs to discretize quantitatively the failure initiating parameters and to develop relevant strategies to minimize these and to achieve more effective and reliable repairs. As already shown in majority of the previous research works the most common failure mode of bonded FRP repairs under fatigue loading is the progressive delamination of the FRP patch (Kennedy and Cheng 1998, Liu et al. 2009, Holden 2012, Mobeen et al. 2012, Bocciarelli et al. 2009, Papanikos et al. 2007, Colombi et al. 2003a). It has also been shown in previous research works that the patch delamination increases SIF, which in turn increases the fatigue crack growth rate (Papanikos et al. 2007, Colombi et al. 2003a, b, Mobeen and Cheng 2013). Attempts have also been made to quantify the delamination initiating parameters (Mobeen and Cheng 2014) which may help in selecting suitable FRP and adhesive properties to minimize the sources of delamination. In current research work an attempt is made to add further experimental work to the research on fatigue behavior of cracked steel plates laminated with FRP patches, with emphasis on the impact of adhesive properties on the fatigue life of edge cracked steel plates repaired with double sided CFRP patches.

## 2. OBJECTIVE AND SCOPE

The main objective of current research work was to experimentally study the impact of repair patch properties on the fatigue behavior of cracked steel plates. Main parameters of the study included adhesive thickness ($t_A$), adhesive shear and bond strengths, modulus of elasticity of adhesive ($E_A$) and CFRP ($E_{CFRP}$). The scope of study was limited to edge cracked steel plates repaired with bonded double sided CFRP patches with identical axial stiffness or the effective thickness ratio (ETR). ETR is defined as the ratio of axial stiffness of CFRP patch to the axial stiffness of the steel plate:

$$[1] \qquad \text{ETR} = \frac{E_{CFRP} t_{CFRP}}{E_S t_S}$$

Where $E_{CFRP}$ and $E_S$ are the elastic tensile moduli of CFRP and steel respectively and $t_{CFRP}$ and $t_S$ are respectively the thicknesses of CFRP and steel respectively. The ETR selected for the current work was 0.2, or in other words the relative patch stiffness was 20% of the steel plate in the current study. One more aspect of the current research work presented here is to verify experimentally the impact of adhesive properties on the fatigue life of the double sided repairs as predicted by the author in one the previous research work (Mobeen and Cheng 2014).

## 3. MATERIAL PROPERTIES

Two types of CFRP were used; SikaWrap HEX 103C having lower $E_{CFRP}$ and; Sika Carbodur having higher $E_{CFRP}$. SikaWrap HEX 103C physically resembled a thick fabric sheet while the Sika Carbodur was like a stiff plastic plate. Material properties of both CFRPs, together with their recommended adhesives are shown in Table 1, as provided in their supplier's data sheets (Sika Canada Inc. 2007).

Table 1: Material Properties

| Material | Elastic Modulus (GPa) | Thickness (mm) | Yield / Tensile Strength (MPa) |
|---|---|---|---|
| Steel | 200 | 9.5 | 360 (Yield Str.) |
| Sika CarboDur | 165 | 1.2 | 1300 |
| Sika Wrap HEX 103C | 65 | 1.016 | 717 |
| Sikadur 30 (Adhesive) | 4.5 | 3 | 25 |
| Sikadur 300 (Adhesive) | 1.714 | - | 55 |
| Sikadur 330 (Adhesive) | 2.0 | - | 30 |

## 4. TEST MATRIX

To achieve the desired research objectives the test parameters were selected to be the modulus of elasticity of CFRP ($E_{CFRP}$), the adhesive type and the adhesive thickness ($t_A$). It is obvious that using different types of adhesives is equivalent to using different adhesive modulus ($E_A$) and different adhesive bond and shear strengths. Practically the $t_A$ is difficult to maintain uniform throughout, especially in liquid forms of epoxy resins but it can be better controlled in thick paste-type adhesives. So, keeping in view the test parameters as well as the practical limitations of material's availability the test matrix selected is shown in Table 2. The specimen names had three parts separated by hyphens; the first part was a number that showed the number of CFRP layers applied on each face of the steel plate, the second part was the CFRP name (in short form) and the third part was the adhesive name (in short form). It is indicated in the supplier's information that the thickness of lower $E_{CFRP}$ CFRP (also provided in Table 1) is the thickness of its one layer, impregnated and cured in its epoxy resin and that is why its epoxy thickness is not mentioned separately in Tables 1 and 2. The specimen 1-CBDR-Sk-30/2 had half the adhesive thickness than the specimen 1-CBDR-Sk-30. In order to maintain ETR identical in all specimens it can be shown that 2 layers of higher $E_{CFRP}$ CFRP type (1 on each face) is equivalent to 6 layers (3 on each face) of lower $E_{CFRP}$ CFRP type. It is also important to mention that the adhesives selected for each CFRP type were those recommended by the supplier.

## 5. METHODOLOGY

The edge cracked steel specimen was 500mm long, 100mm wide and 9.5mm thick, such that it satisfied the criteria of having its half-length greater than twice its width, to have a sufficient length available for the stress flow to become uniform between the crack and outer boundary of the specimen. A 5mm long notch was created at mid-length of one of its longer side using electric discharge method (EDM) and the specimen was then fatigue loaded under tension-tension fatigue load cycles to develop a sharp crack from the notch using MTS 1000 testing machine. This phase was referred in this research as the pre-crack phase. A typical patched specimen is shown in Figure 1, both schematically as well as during the test in MTS 1000 kN hydraulic testing system.

Table 2: Test matrix

| Repair ID | CFRP Modulus of Elasticity (GPa) | CFRP Thickness (mm) | CFRP Layers (Each Face) | ETR | Adhesive Thickness (mm) | Adhesive Modulus (GPa) |
|---|---|---|---|---|---|---|
| Controll Specimen | NA | NA | NA | NA | NA | NA |
| 3-SKWRP-Sk-300 | 65 | 1.016 | 3 | 0.2 | NA | 1.714 |
| 3-SKWRP-Sk-330 | 65 | 1.016 | 3 | 0.2 | NA | 2.0 |
| 1-CBDR-Sk-30 | 165 | 1.2 | 1 | 0.2 | 3 | 4.5 |
| 1-CBDR-Sk-30/2 | 165 | 1.2 | 1 | 0.2 | 1.5 | 4.5 |

The stress range ($\Delta\sigma$) used in the pre-crack phase as well as in the repaired phase was 180 MPa ($\sigma_{max}$ = 200 MPa and $\sigma_{min}$ = 20 MPa), with frequency of 4 Hz. Fatigue loading used in pre-crack phase in order to generate a 5mm long sharp crack from the notch. The crack was then further treated as the initial crack in this work with a total length of 10mm (5mm notch + 5mm fatigue crack). Figure 2 shows the fatigue stress range used to develop the pre-crack. It is to be noted that only the full load cycles mentioned in Figure 2 were applied in the pre-crack phase.

The specimens were then removed from the test frame, sandblasted and cleaned with acetone to have a shiny clean surface to receive CFRP repair patch. The CFRP layers were cut from their supplied rolls using scissors and saw and were cleaned with acetone to remove any loose fiber or matrix. Lower modulus CFRP was cut using scissors while the higher modulus CFRP was cut using sharp hand saw, mainly because of their physical nature. The CFRP patches were applied to the pre-cracked and cleaned steel plates following the supplier's instructions. Lower modulus CFRP layers were applied using wet on wet procedure, which was furnished by first soaking the CFRP layers into the epoxy resin and then applied on the steel surface, one layer over the other, following the supplier's instructions. Sponge roller was used after application of each layer on steel specimen to remove any air bubble in the resin beneath. The lengths of CFRP layers were cut in such a way to achieve a tapered patch-end with an approximate slope of 1:12 to minimize the patch end stresses. After application of all layers to one side of steel plate the specimen was left undisturbed for at least 24 hours and then the same patching procedure was repeated on the other side of the specimen. A complete double sided patched specimen was then left undisturbed for curing at room temperature for a minimum of 14 days before preparing it for the final test phase. High modulus CFRP was also applied on the pre-cracked, sandblasted and cleaned steel plates following the supplier's instructions and using its recommended adhesive, but, because of its pre-fabricated nature its one layer can be applied each day. Its layers were also cut in steps to achieve a 1:12 slope at the patch end. Additionally ends of each CFRP plate were also tapered using sand paper, to minimize the patch-end stresses.

The cured specimens were loaded again under tension-tension fatigue loading, similar to the pre-crack phase, till complete failure of the specimen. In addition to the full tension-tension fatigue cycles the specimens were also provided with the beach mark cycles (Refer to Figure 2) to achieve beach mark impressions on the failed surface and to trace the path of crack tip with number of fatigue load cycles. The number of fatigue load cycles in each beach mark was ranged between 5000 to 1000 cycles, depending upon the condition of the specimen. In the early stage of crack propagation larger number of beach-mark load cycles was provided while in the faster crack growth stage lesser number of beach-mark load cycles was provided. Large amplitude load cycles, in-between consecutive beach mark cycles, were varied from 50,000 to 5,000 and were also depending upon the condition of specimen or the rate of the crack growth.

Crack mouth opening displacement (CMOD) was additionally measured during the test through an extensometer as shown in Figure 1. Because of unavailability of a proper clip gauge the extensometer of the least available gauge (10 mm) was used to measure the CMOD, which was a close approximation in the current study. It is also important to mention here that the beach mark load cycles were introduced after getting an indication of start of the crack growth from an increase in the CMOD value.

The stress range ($\Delta\sigma$) of 180 MPa was used in full load cycles while a reduced stress range of 90 MPa was used in beach mark cycles, but in both stress ranges the $\sigma_{max}$ value was kept at 200 MPa. Apart from the patched specimens, control specimens were also tested under same stress range with the only difference that these were tested in a single and continuous loading phase. All tests were continuous until the specimen broke into two pieces. Extensometer was removed when the CMOD values reached close to the extensometer limit, to avoid its damage.

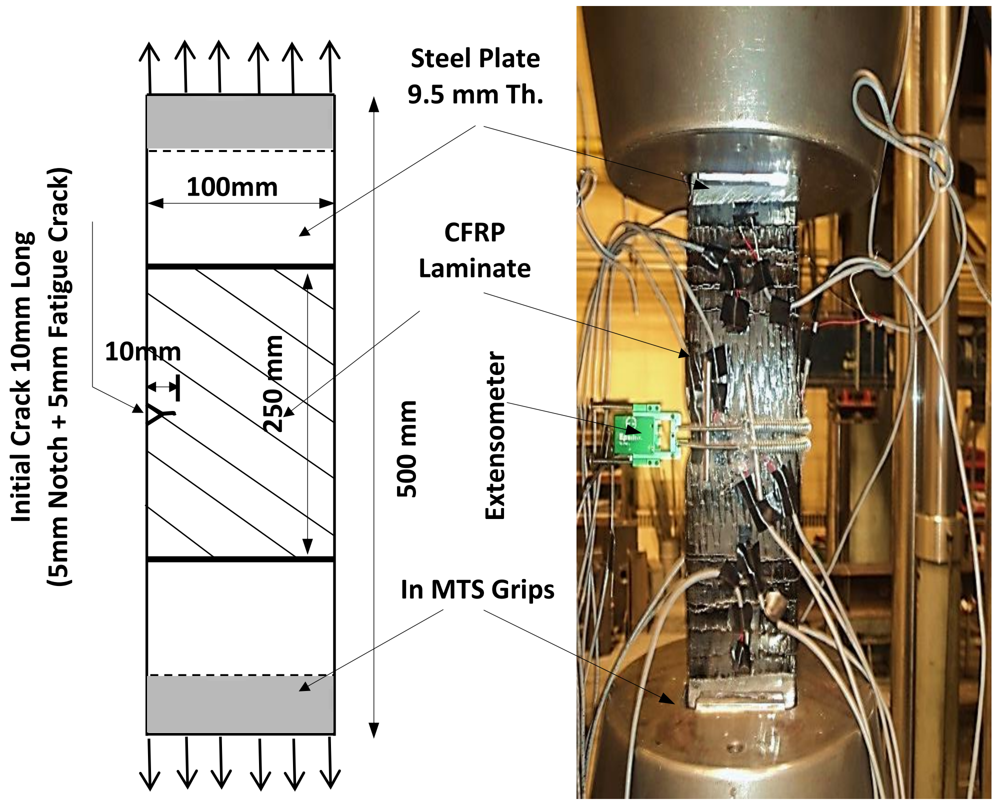


Figure 1: Test setup in MTS 1000 and the specimen's geometry

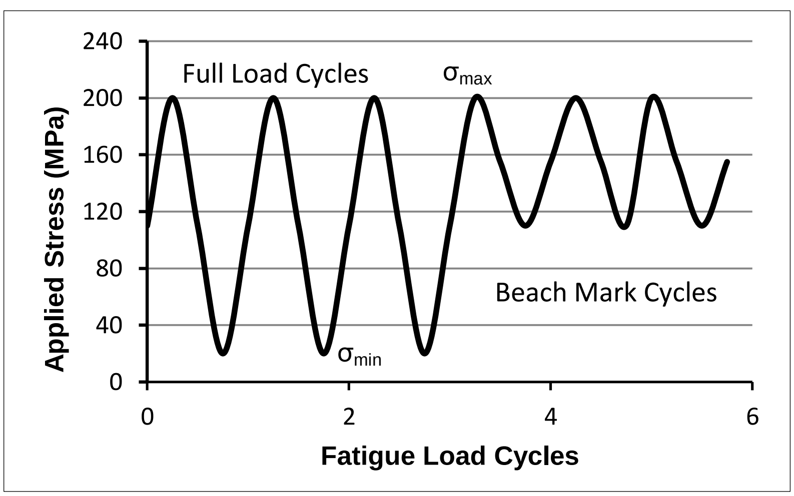


Figure 2: Fatigue loading

## 6. RESULTS AND DISCUSSION

Test results in the form of fatigue life or the number of fatigue load cycles are shown in Table 3. It shows the number of fatigue cycles recorded in the pre-crack phase as well as in the patched phase. The failed specimens are also shown in Figure 3. The beach mark cycles were converted into full load cycles using the Miner's damage rule as given by Equation 2 and are added to the full load cycles. For the control specimens the number of load cycles recorded from the start of test till the crack reached a total length of 10mm are treated as the number of pre-crack load cycles in Table 3. The efficiency of any repair shown in Table 3 is the ratio of total number of fatigue load cycles it achieved, after application of the repair patch, to the number of fatigue load cycles of the control specimen achieved after the crack length of 10mm. Table 3 values are also plotted in Figure 4 graphically.

$$[2] \qquad N_{S2} = N_{S1}\left\{\frac{S_1}{S_2}\right\}^4$$

Where,

$N_{S2}$ = Equivalent number of higher stress range load cycles
$N_{S1}$ = Number of fatigue cycle applied at lower stress range (Beach mark cycles)
$S_1$ = Value of lower or beach mark stress range (90 MPa)
$S_2$ = Value of higher or full stress range (180 MPa)

It is obvious from Table 3 that overall the repair patches enhanced the fatigue life of cracked steel plates by more than 10 times, compared to the unrepaired specimen. It shows that the bonded CFRP patches were greatly effective in enhancing the fatigue life of cracked steel plates. The test results are discussed in detail below with respect to the various patch parameters.

Failure mode in all the current tests was patch delamination, but, it was also noted that the delamination was not governing from the patch end, rather, the delamination mostly governed near the crack region. The patch end started delaminating after the specimen already reached 80% of their total fatigue lives and during that 80% life span the CMOD was kept on increasing, showing that the delamination was occurring near the crack only and not anywhere else. Final failure occurred when the patch from any two opposite faces of the specimen (out of four) suddenly delaminated and the specimen broke into two pieces.

Figure 3: Failed specimens

(Left to right: 1-CBDR-Sk-30, 1-CBDR-Sk-30/2, 3-SKWRP-Sk-330, 3-SKWRP-Sk-300)

Table 3: Test results (Number of fatigue load cycles)

| Repair ID | Pre-crack Phase (Fatigue Cycles) | Repaired Phase (Fatigue Cycles) | Repair Effectiveness |
|---|---|---|---|
| Control Specimen | 29005 | 14150 | 1 |
| 3-SKWRP-Sk-300 | 27800 | 180375 | 12.8 |
| 3-SKWRP-Sk-330 | 28050 | 220926 | 15.6 |
| 1-CBDR-Sk-30 | 29020 | 171992 | 12.2 |
| 1-CBDR-Sk-30/2 | 28501 | 158336 | 11.3 |

### 6.1 Impact of Adhesive Strength on Fatigue Life of Repairs

Comparing the resulting fatigue life of the repaired and unrepaired (control) specimens it is obvious that all the bonded CFRP patches were effective in enhancing the fatigue life of cracked steel plate and the resulting fatigue life enhancement was ranging between 11 to 16 times. The higher enhancement (16 times) was achieved in the repairs with lower modulus CFRP while the lower enhancement (11 times) was achieved in repairs with higher modulus CFRP. The most efficient repair was found to be 3-SKWRP-Sk-330, which was prepared with the lower modulus CFRP and Sikadur 330 epoxy resin. It is important to note that the repair 3-SKWRP-Sk-300 had the same CFRP type and exactly same number of CFRP layers (6 Nos.) as the 3-SKWRP-Sk-330 had but the difference in their fatigue life was 18 %, which appears to be mainly because of difference in their epoxy resins. The epoxy resin Sikadur 330 is also recognized by the supplier as the most efficient resin in developing good tack (bond) within the three types of adhesive/epoxy used in the current research work but it is only recommended for the lower modulus CFRP type. Fatigue lives of repairs with higher modulus CFRP were lesser than those with lower modulus CFRP by minimum 5% to maximum 29%. The higher difference achieved when fatigue life of higher modulus CFRP repair 1-CBDR-Sk-30/2 (i-e the one having half of its recommended adhesive thickness) is compared with the fatigue life of the lower modulus CFRP repair 3-SKWRP-Sk-330 (i-e the one having strong resin Sikadur 330), while the lower difference obtained when comparing the fatigue lives of higher modulus CFRP repair 1-CBDR-Sk30 (i-e the one having maximum recommended adhesive thickness) and the lower modulus CFRP repair SKWRP-Sk-300. It was so because there was already 18% difference of fatigue life existed within the lower modulus CFRP repairs just because of difference in their epoxy resins. Unfortunately the supplier’s data sheets for epoxy resins Sikadur 300 and Sikadur 330 did not provide any information about their bond or shear strengths but their application guide mentions the effectiveness of Sikadur 330 over the Sikadur 300. Although the bond and shear strengths of the adhesive Sikadur 30, which has been used with higher modulus CFRP, are provided in the supplier’s data sheet and are also shown in the Table 1. Stanford (2009) performed double lap tests of steel plates with bonded sheet-type CFRP under uniaxial tensile loading using several types of epoxies including Sikadur 300 and Sikadur 330 epoxy resins. Results of his double lap tests showed that the lap test with Sikadur 330 achieved 40% higher strength than the lap test with Sikadur 300 epoxy. Stanford (2009) also performed flexural tests of steel beams with bonded plate-type CFRP on their tension flanges using different types of adhesives. In that phase he also used the adhesive Sikadur 30 (which is also used in the current research work with higher modulus CFRP). Stanford (2009) reported that the adhesive Sikadur 30 was the least affective adhesive in developing good bond in shorter bond length within all the adhesives used in the flexural beam test phase. Re arranging the current test specimens in the order of their resulting fatigue lives shows that the results of current research work are in a similar strength order as Stanford (2009) achieved, although the percentage difference between the specimens in current test and those of Stanford (2009) is different which might be because of the difference in nature of test and loading, i-e uniaxial tensile (Stanford 2009) versus fatigue loading (current) and also the flexural (Stanford 2009 versus double lap (current; in case of Sikadur 30 adhesive).

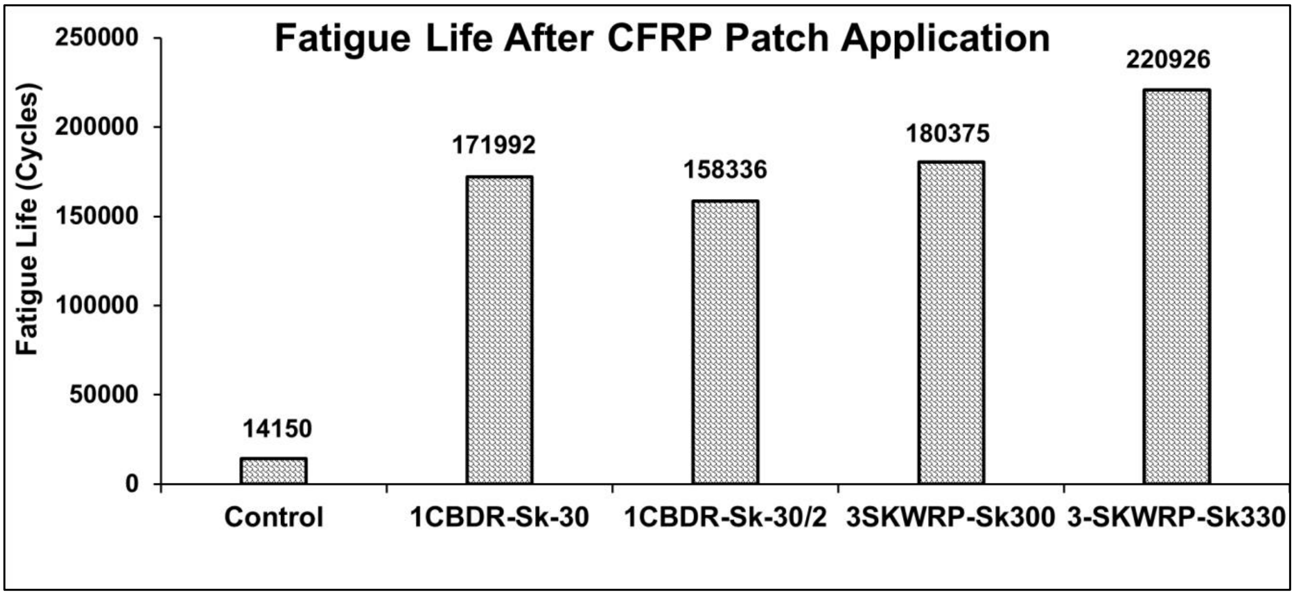


Figure 4: Fatigue life of test specimens after CFRP patch application

### 6.2 Impact of Adhesive Thickness ($t_A$) on Fatigue Life of Repairs

Comparison of specimen 1-CBDR-Sk-30 and 1-CBDR-Sk-30/2 highlighted the impact of adhesive layer thickness on the fatigue life because both the repairs had identical CFRP modulus and the adhesive type with the only difference of the adhesive layer thickness being 33% lesser in the later. The repair with lesser adhesive thickness (1-CBDR-Sk-30/2) achieved 9% lesser fatigue life than 1-CBDR-Sk-30. Although the planned difference in their adhesive layer thickness was 50% but the as-built difference was noted to be 33% because of less control on adhesive thickness during CFRP layering process. This comparison shows that for a thinner adhesive with weaker shear or bond strength the fatigue life may be lower and vice versa. This comparison is also in accordance with one of the conclusions already drawn by the author in another previous numerical study (Mobeen and Cheng 2014), which showed that thinner adhesive layer lowers the SIF by putting more shear stress demand on the adhesive. Therefore, if the adhesive's bond/shear strength is lesser than the imposed demand then its failure may results in patch delamination. It had also been shown in another previous numerical research work by the author (Mobeen and Cheng 2013) that the patch delamination near crack results in increased stress intensity factor (SIF). Conclusively, adhesive thickness may not be an independent parameter and it must be coupled with the adhesive bond and shear strengths as the upper or lower bound. In this scenario thinner adhesive layer appears to be best suited for adhesive having high bond or shear strengths.

The same reasoning can also be given for higher fatigue lives in repairs with lower modulus CFRP because their adhesives were not only thinner than the one used in repairs with higher modulus CFRP but also stronger at the same time, so, the interface shear stress in the adhesive would be higher (in lesser adhesive thickness) and the resulting SIF would have been lower. But being their shear and bond strengths greater than the imposed demand, the resulting fatigue lives were higher.

## 7. SUMMARY OF TEST RESULTS AND CONCLUSIONS

- All CFRP repairs were found effective in enhancing the fatigue life of cracked steel plate.
- Higher fatigue life achieved in repairs with lower modulus CFRP, which is expected to be because of stronger adhesives used in these.
- Fatigue life enhancement achieved in the test ranged from 11 to 16 times, the lower enhancement was achieved in higher modulus CFRP repairs while the higher enhancement was achieved in repairs with lower modulus CFRP, which was expected to be mainly because of adhesive properties.
- Role of adhesive found to be the most significant parameter in the current tests. Its strength and thickness both affect the fatigue life of repairs but strength was found to be more dominant.
- A difference of 18% was noted within the fatigue life of repairs with lower modulus CFRP because of the difference in the bond and shear strengths of their epoxy resins.
- Reduced adhesive thickness by 33% resulted in a 9% reduced fatigue life in repairs with high modulus CFRP. Its main reason might be the high shear stress around the crack being exceeded by the adhesive bond / shear strength. It is important to mention here that the high shear stress in adhesive around the crack must have developed as a consequence of reduced adhesive thickness.

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