Fatigue behaviour of CFRP strengthened steel plates with different degrees of damage

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\textbf{A B S T R A C T}

An experimental and analytical study was conducted to further investigate the effectiveness of the carbon fibre reinforced polymer (CFRP) plates in extending fatigue life of steel structures. Different lengths of artificial cracks were introduced to represent different degrees of fatigue damage. The experimental results demonstrated that the CFRP patches could effectively slow down the crack growth and prolong the fatigue life. A theoretical model was developed to predict the fatigue life of tested specimens. Thereafter, a parametric study was carried out to investigate the fatigue behaviour of steel plates with a wider range of damage degrees. This study extends the understanding of CFRP repair at different stages of crack propagation and provides some useful suggestions for the strengthening method.

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1. Introduction

Fatigue damage is a major concern for many infrastructures such as steel bridges, offshore structures. Repairing and retrofitting fatigue cracks are more economical and environmentally friendly than replacing the aged steel structures, and are attracting much research attention. Much research has focused on the way of keeping the integrity of steel structures and extending the fatigue life of cracked members. Traditional reinforcement techniques such as the use of stop hole, steel plate attachment and crack welding are either time consuming and costly or complex to apply. Composite fiber patching techniques have been considered as alternatives to these methods of fatigue crack repair in steel structures [1,2]. CFRP bonding repair has its own advantage over traditional methods in strengthening work for the outstanding physical and mechanical properties as their high strength, long durability, light weight and ease of installation. The “bonded patch” method was early researched by the Aeronautical and Maritime Research Laboratory in the 1970s [3], and till now, adhesively bonded composite patch repairs have been successfully applied in the aeronautical industry [4–7]. However, research on using CFRP materials to strengthen steel structures in civil engineering is still in the early stage [8]. CFRP materials applied to damaged members can bridge the crack area and transfer the load, thereby decreasing the stress intensity factor (SIF) at the fatigue crack tip and extending the fatigue lives of steel structures. Being different from standard reinforcement, bonding repair neither lessens the cross section due to stop hole nor introduces new stress concentration because of welding. The ease of installation and light weight makes the repair faster to complete without adding much weight. Tavakkolizadeh and Saadatmanesh [9] tested 21 steel beams repaired by CFRP patching. Specimens notched in the tension flange, were reinforced with CFRP plate and loaded in fatigue at different stress levels using a four point bending rig. The fatigue life of retrofitted specimen was greatly extended by 2.6–3.4 times which was equivalent to improve the detail from AASHTO category D to C. Jones and Civjan [10] proposed a series of fatigue experiments on CFRP repaired steel plates. The specimens were either notched from the edge or from a center hole. Variables such as CFRP system, bond length, bond area, one or two sided applications, and applications prior or subsequent to crack propagation were studied. The test results showed that two sided applications extended the fatigue life by as much as 115%. Liu et al. [11,12] presented experimental and numerical studies on center notched steel plates strengthened with CFRP sheets. For double-sided repairs, the repair scheme extended the fatigue life by 2.2–7.9 times compared to the non-strengthened ones. A theoretical model was proposed to predict the crack propagation and fatigue life of the steel plates. High modulus CFRP was adopted in the repair system and it was demonstrated that the strengthening was more effective using CFRP materials with higher modulus [13–15].

The high tensile strength of CFRP allows the application of a pretension to composite strips in order to increase the reinforcement effectiveness. Colombi et al. [16,17], Täljsten et al. [18]...
2. Experiment programme

2.1. Description of test specimens

The configuration and dimensions of the notched steel plates are presented in Fig. 1(a). Specimens were 500 mm long, 100 mm wide and 8 mm thick with a 10 mm hole and two initial cracks of 0.2 mm wide in the center. There were three different crack lengths in order to simulate the different degrees of damage. Here we use the ratio of half initial crack length ‘a0’ to half of the plate width to define the degree of damage, i.e. the degrees of damage ‘β’ are 2%, 10% and 20% corresponding to initial crack length of 1 mm, 5 mm and 10 mm, respectively. In Fig. 1(a), ‘b’ is the width of the tested specimen. 200 mm-long CFRP plates, having a cross section of nominally 1.4 mm by 40 mm, were positioned and applied on each side of the specimens with the two-component viscous epoxy for bonding. The center notch was also filled with 4 layers of CFRP plate.

and Ye et al. [19] investigated the fatigue behavior of steel plate strengthened with the pre-stressed composite materials. The introduction of a compressive stress by pretension of the CFRP strips prior to bonding produced a significant increase in the remaining fatigue life. Other than research into the retrofitting of damaged steel plates, research on strengthening other steel structures such as welded web gusset joints, tubular structures and aluminum connections with CFRP materials has also been conducted [20–26].

Previous studies revealed that bonded patches can decrease the stress level and enhance the fatigue lives of steel structures subjected to cyclic loading. However, there have been few studies on specimens with different degrees of damage strengthened with CFRP materials. Most previous studies focused on the fatigue behaviour of steel plates notched with a very short initial crack. A study on strengthened specimens with different degrees of damage is necessary to investigate the effectiveness of CFRP application at different stages of service life. This paper presents the fatigue test results of steel plates with different degrees of damage strengthened by CFRP plates. The failure modes and corresponding fatigue lives were recorded. Crack propagation was monitored by the “beach marking” technique. A theoretical model was also established to predict the fatigue life of tested specimens based on the fracture mechanics theory. The predicted fatigue lives had a good agreement with the experimental results. Thereafter, a parametric study was carried out using this model to investigate the fatigue behaviour of steel plates with a wider range of damage degree. This study extends the understanding of CFRP application repair at different stages of crack propagation and provides some useful suggestions for the strengthening method.

2.2. Material properties

The mechanical properties of the steel plate, CFRP plate and epoxy resin adhesive are shown in Table 1. The chemical composition of the steel is listed in Table 2. Mild carbon steel (Q345) conforming to Chinese Standard GB 50017–2003 in the form of hot rolled plates was used. The mechanical properties of the steel plates were determined through tensile coupon tests and those of CFRP plate and epoxy were based on the technical data provided by the manufacturers.

![Fig. 1. Specimen geometry (Unit: mm, not to scale). (a) Unreinforced specimen geometry, and (b) reinforced specimen geometry.](image-url)
2.3. Specimen preparation

The following processes were carried out for the preparation of the specimens. The steel plates were ground using a grinding disc and then cleaned with acetone to obtain a rough, clean and fresh chemically active surface to ensure better mechanical interlocking. The CFRP plates were cut to the proper size using a saw cut. The two components of the epoxy adhesive were dosed according to the manufacturer’s instructions and mixed evenly. Thereafter, the CFRP plates were glued using wet lay-up method to the steel surfaces and the specimens were cured for one week in room temperature before the testing (as shown in Fig. 2).

2.4. Test set-up

The fatigue tests were carried out on an Instron 1434 servo hydraulic testing machine with a dynamic capacity of 200 kN (Fig. 3). All the specimens were tested under constant amplitude tensile loading with the frequency of 10 Hz and stress ratio of 0.1. The stress range was kept unchanged for all the specimens as 110 MPa in the nominal section of the un-reinforced specimen. The test was set to stop when the displacement of loading end reached 30 mm.

2.5. Measurement of crack propagation

The technique of “beach marking” was adopted to trace the crack propagation. A small number of cycles of low stress range were added at different stages of the loading, as shown in Fig. 4. Since the SIF value at the crack front was changed during the low stress range cycles, the rate of crack development was changed which left visible marks on the fracture surface and enabled the observation of crack size and shape by naked eye after fatigue failure of the test specimens.

3. Fatigue test results

All the six specimens failed at the middle of the steel plates when the fatigue crack reached a certain length which was accompanied by CFRP plates debonding. Fracture of CFRP plates was not observed during all tests but delamination was in some. During the test of the three strengthened specimens, the CFRP plates debonded early on one side of the specimen of 10% initial fatigue damage while debonding was not observed until the final failure stage in the other two.

The number of fatigue life cycles at failure for each specimen is listed in Table 3. The number of load cycles corresponding to the low stress range for “beach marking” tests has been changed to an

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Number of fatigue cycles</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-strengthened specimen with a damage degree of 2%</td>
<td>234533</td>
<td>–</td>
</tr>
<tr>
<td>Strengthened specimen with a damage degree of 2%</td>
<td>462679</td>
<td>97%</td>
</tr>
<tr>
<td>Un-strengthened specimen with a damage degree of 10%</td>
<td>123738</td>
<td>–</td>
</tr>
<tr>
<td>Strengthened specimen with a damage degree of 10%</td>
<td>234710</td>
<td>90%</td>
</tr>
<tr>
<td>Un-strengthened specimen with a damage degree of 20%</td>
<td>65625</td>
<td>–</td>
</tr>
<tr>
<td>Strengthened specimen with a damage degree of 20%</td>
<td>187856</td>
<td>186%</td>
</tr>
</tbody>
</table>

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Steel plate</th>
<th>CFRP plate</th>
<th>Epoxy resin adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield point (MPa)</td>
<td>279</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>406</td>
<td>3089</td>
<td>41.6</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>32.33</td>
<td>1.7</td>
<td>1.53</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>1.82 × 10^3</td>
<td>1.91 × 10^3</td>
<td>3.32</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Mn</th>
<th>C</th>
<th>S</th>
<th>Si</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q345</td>
<td>1.52</td>
<td>0.16</td>
<td>0.004</td>
<td>0.22</td>
<td>0.017</td>
</tr>
</tbody>
</table>
equivalent number of cycles corresponding to the high stress range by assuming that the conventional $S$–$N$ relationship is valid for all cases as shown in Eq. (1) [27]. The equivalent number of cycles is included in the fatigue lives listed in Table 3.

$$N = \frac{C}{\Delta S_m^{m}}$$

(1)

where $N$ is defined as number of stress cycles to failure and $m$ is the slope of $S$–$N$ curve. The value of $m$ here is set to be 3 [27]. The fatigue life ratio between the high stress range ($N_h$) and low stress range ($N_l$) can be expressed as Eq. (2). $\Delta S_h$ is the high stress range and $\Delta S_l$ is the low stress range used for the “beach marking” test.

$$\frac{N_h}{N_l} = \left(\frac{\Delta S_h}{\Delta S_l}\right)^{m}$$

(2)

“Beach marks” were clearly left on the fracture surface for all low stress range cycles, and therefore the “beach marking” technique was proven to be effective in recording the crack development during the fatigue test. “Beach marking” tests were done at equal intervals during the fatigue test, so the spacing of beach marks which increased from inside to outside on the fracture surfaces indicated that the crack grew faster during the propagation. Generally, there were two kinds of crack shapes, i.e. symmetric and unsymmetric about the mid-thickness axis as shown in Fig. 5. In the bare steel plate specimens (control specimens) and the strengthened specimens without debonding during the test, the through-thickness fatigue crack grew almost at the same rate on both sides of the steel plates, so the crack shape tended to be symmetric about the mid-thickness of the plate. On the other hand, in the strengthened specimens with debonding at the beginning of test, crack grew faster on the debonding side, which led to an unsymmetric crack shapes. Therefore, bonding behavior is considerably important. Early debonding may affect the strengthening effectiveness since the CFRP plate on the debonding side does not work.

From crack surface measurements and testing recordings, crack length versus number of cycles ($a$–$N$) curves are plotted in Fig. 6 for all the specimens. The dimension “$a$” is half of the crack length measured at the mid-thickness of plate. It is seen that the longer the initial cracks were, the faster the cracks propagated. Comparisons between bare steel specimens and corresponding strengthened specimens show that CFRP repairs retard crack development dramatically in all cases of fatigue damage.

To the crack propagation lives as shown in Fig. 6, we would like to add the initial fatigue life $N_i$ to see the relationship between the crack length and the total fatigue life. For the 2% damage cases, $N_i$ is set to be 0 since it is thought to be small. The $N_i$ for specimens with 10% and 20% damage can be estimated from the $a$–$N$ curve of the 2% damage specimen when $a_0$ reaches 5 mm and 10 mm, respectively. It is seen from Fig. 7 that with the addition of $N_i$, the curves of the un-strengthened specimens are very close to each other in the overlapping region as they should be, because theoretically, specimens of the same crack length should have the same crack propagation rate. However, we can see more difference between the curves of CFRP strengthened specimens, especially on the slope change. If denoting the curve of strengthened specimen with damage degree of 2%, 10% and 20% as $C_2$, $C_{10}$ and $C_{20}$, respectively, it can be seen that the slope of $C_{10}$ is greater than that of $C_2$ while the slope of $C_{20}$ is less than those of $C_2$ and $C_{10}$. The big slope of $C_{10}$ is resulted from the early debonding of CFRP plate during the fatigue test. The turning point of $C_{20}$ is due to the debonding in the later stage of fatigue test which is indicated by the asymmetric crack shapes shown on the crack surface. It is shown with the limited test results that the application of CFRP at late stages results in smaller slope of $a$–$N$ curve (crack propagation rate).

Three crack lengths were adopted to simulate the degrees of damage or different phases of crack propagation. Fig. 8 describes the relationship between damage degree and fatigue life improvement. Here, $N_{p-CFRP}$ is the fatigue crack propagation life of a specimen strengthened with CFRP, whereas $N_{p-plate}$ is the fatigue crack propagation life of a bare steel specimen. It seems that the longer the initial crack is, the more effective the application is. The improvement of specimen with 2% and 10% degree of damage is

![Fig. 5. Fracture surfaces with beach marks. (a) Fractured specimen, (b) symmetrical beach marks, and (c) non-symmetrical beach marks.](image-url)
almost the same which may be due to the early debonding of CFRP plate of specimen with 10% degree of damage.

Similar to Fig. 7, we would like to include the crack initiation time \(N_i\) into the comparison. Fig. 9 shows the ratio of \((N_{p-CFRP})/(N_{p-plate})\) against damage degree, which indicates that it is better to adopt early repair.

We also normalize \(N_{p-CFRP}\) at different damage levels by \(N_{p-CFRP}\) at a damage degree of 2%, as shown in Fig. 10. It is shown that, at the later stage of crack propagation, crack propagates faster and the improvement becomes insignificant.

4. Fatigue life prediction

Based on the fracture mechanics theories, a theoretical model is proposed to predict the fatigue life of centrally cracked specimen repaired with CFRP plate. Perfect bond is assumed which means that the strains of the steel plate, CFRP plate and adhesive are the same. For the specimen with damage degree of 10%, as mentioned before, early debonding was found during the test, so both double-sided model and single-sided model are adopted for the prediction.

4.1. Stress analysis of cross section

For the un-strengthened specimen, the bare steel plate is loaded with a far field fatigue stress of \(\sigma_0\) and the axial tensile force can be expressed by Eq. (3). For the strengthened specimen, the composite patch helps to share the load by taking the part transferred by the adhesive. The equilibrium is shown by Eqs. (4) to (7) for double-sided repair. The equilibrium of the forces is illustrated in Fig. 11.

\[
F = \sigma_0 b t_s \quad (3)
\]

\[
F = F_s + 2(F_f + F_a) \quad (4)
\]

\[
F_s = E_s \varepsilon_s b t_s \quad (5)
\]

\[
F_f = E_f \varepsilon_f b_f t_f \quad (6)
\]

\[
F_a = E_a \varepsilon_a b_f t_a \quad (7)
\]

\[
b_s = b - 2a_0 \quad (8)
\]

\[
a_0 = \beta b / 2 \quad (9)
\]

In the equations above, \(F\) is the external force and \(\sigma_0\) is the nominal stress in the steel plate for un-strengthened specimen; \(b\) is the width of specimen. \(F_s, F_f\) and \(F_a\) are the forces carried by the steel plate, CFRP plate and adhesive, respectively; \(E, \varepsilon, b\) and \(t\) represent the Young’s modulus, strain, width and thickness of the plate; the subscripts, \(s, f\) and \(a\) denote steel, CFRP plate and adhesive, respectively, as shown in Fig. 11.

Substitution of Eqs. (5) to (7) into Eq. (4) results in Eq. (10). The strains of steel plate, composite and adhesive are assumed to be the same according to the perfect bond premise as expressed in Eq. (11). Finally, the strain is calculated by Eq. (12).

\[
\frac{N_{p-CFRP}}{N_{p-plate}} = \frac{E_s \varepsilon_s b t_s}{E_s \varepsilon_s b t_s + 2(E_f \varepsilon_f b_f t_f + E_a \varepsilon_a b_f t_a)} \quad (10)
\]

\[
\varepsilon_s = \varepsilon_f = \varepsilon_a \quad (11)
\]

\[
\varepsilon_s = \frac{\sigma_0 b t_s}{E_s b t_s + 2(b_f \varepsilon_f (E_f t_f + E_a t_a))} \quad (12)
\]

In the crack growth analysis, the average stress over the whole steel section is adopted. So the average stress of steel plate is expressed as Eqs. (13) and (14).

\[
\sigma_s = E_s \varepsilon_s b / b \quad (13)
\]

\[
\sigma_s = E_s t_s / E_s t_s + 2(b_f \varepsilon_f (E_f t_f + E_a t_a)) \quad (14)
\]

Substituting Eqs. (8) and (9) into Eq. (14) results in

\[
\sigma_s = \frac{E_s t_s}{E_s t_s + 2(b_f ((1 - \beta) b)) \times (E_f t_f + E_a t_a)} \quad (15)
\]

For single-sided repair, the stress of steel plate can be derived by Eq. (16) using the same process.

\[
\sigma_s = \frac{E_s t_s}{E_s t_s + b_f ((1 - \beta) b) \times (E_f t_f + E_a t_a)} \quad (16)
\]
4.2. Fatigue life prediction

The linear elastic fracture mechanics (LEFM) method is adopted here for the prediction. The fatigue crack propagation rate is expressed by Paris Law as in Eq. (17) \[ da/dN = C(\Delta K)^m \] [28], thereby we can obtain the fatigue life with integration.

\[ N = \int_{a}^{\infty} \frac{1}{C \Delta K^m} da \] (18)

where \( a \) is the half of crack length, \( N \) is the number of fatigue cycles, \( C \) and \( m \) are material constants that are determined experimentally, \( \Delta K \) is the range of stress intensity factor during crack growth, \( a_i \) and \( a_f \) are the initial crack size and final crack size, respectively. For the constants \( C \) and \( m \), mean curve is selected of which \( C \) is equal to 1.5 \times 10^{-13} \text{ and } m \text{ is equal to } 2.75 \text{ where the units are } da/dN \text{ in m/cycle and } \Delta K \text{ in MPa}\sqrt{m} \text{ [28]. The solution of stress intensity factor } K \text{ is presented in Eq. (19) [29].}

\[ K = F(\pi a)\sqrt{\pi a} \] (19)

where \( F = F_F F_S F_{FW} F_G \text{ and } F_F, F_S, F_{FW} \text{ and } F_G \) denote the effect of elliptical crack fronts, free surface, finite width and non-uniform opening stresses, respectively. Here, the value of \( F_F, F_S, F_{FW} \text{ and } F_G \) is equal to 1.0 for the through-thickness crack without non-uniform opening stresses. The correct factor \( F_{FW} \) for finite width is expressed by Eq. (20).

\[ F_{FW} = \sqrt{\sec \left( \frac{a_i}{b} \right)} \] (20)

4.3. Fatigue life comparison

The crack length and fatigue life corresponding to the last crack front recorded by the “beach marking” test are used in the calculation below. This is acceptable since the part of total fatigue life after this point is negligibly small. The comparison between the recorded fatigue lives and the calculated results is shown in Fig. 12.

Fig. 12 shows that the calculated fatigue lives compare well with the experimental results. All the differences are less than 20% excepted the strengthened specimen with a damage of 10%. The predicted result of the strengthened specimen with a damage of 10% should be between the predictions of double-sided and single-sided models. It demonstrates that bond behaviour is critical to the repair method. Once debonding occurs, the patch does not work. The estimated results show that the LEFM method is applicable for estimating fatigue life for both un-reinforced and reinforced steel plates.

From Eq. (15) above, we can see that when the degree of damage \( \beta \) grows, the stress of steel plate \( \sigma_i \) decreases. Hence the CFRP plate will be carrying more loading since the remote loading is kept the same. The stress range at the crack tip is therefore reduced leading to the reduction of SIF. It is consistent with the slope trend shown in Fig. 7.

5. Parametric studies

Since the fatigue lives of un-strengthened and strengthened steel plates were estimated well by the theoretical model, it is used in the parametric study below to further investigate the relationship between fatigue life improvement and degree of damage. A wider range of damage degrees is studied, i.e. 2%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%.

In the fatigue life prediction presented before, we used the actual crack size of last crack front left on the fracture surface. A unified crack length is needed in the parametric study, and therefore fatigue failure is assumed to occur when the crack propagates to 60% of the plate width based on the experimental records. Under this assumption, fatigue lives of specimens with damage degree equal to 2%, 10% and 20% are recalculated and the difference from the experimental results are less than 20%. For the strengthened specimen, a uniform thickness of adhesive layer is supposed to be 2.5 mm according to the experimental data. Perfect bond of double sides is assumed in the fatigue analysis.

Similar to Figs. 8–10, Figs. 13–15 illustrate the relationship between damage degree and fatigue life. Comparing the residual fatigue lives between strengthened and un-strengthened specimens, Fig. 13 shows that the larger the damage degree \( \beta \) is, the more the fatigue life is extended. It is consistent with Fig. 7 that the application of CFRP at later stage brings about drastic retardation of crack propagation. Adding the crack propagation life from
2% to the preset degree of damage for more than 2% initial damage. Fig. 14 gives a clearer picture about CFRP application at different stages of crack propagation. The fatigue life will be extended by up to 100% if the strengthening is applied at the damage degree of 2%, while the extension decreases to about 12% for application at a damage degree of 40%. The downturn becomes gentle at the late stages, which demonstrates that it is better to adopt an early repair. Furthermore, in Fig. 15, it is seen that the ratio of $N_p$-CFRP at different damage levels to $N_p$-CFRP at a damage degree of 2% decrease quickly as the damage degree increases. It is recommendable to adopt early strengthening at low degree of damage levels.

6. Conclusions

The experimental and theoretical study of the fatigue behaviour of CFRP strengthened steel plates with different degrees of damage has been carried out. Significant fatigue life extension was obtained for CFRP strengthened cracked steel plates. The application of CFRP plates is a promising technique for strengthening fatigue damaged steel plates. The strengthened specimens had their fatigue lives prolonged by 97% to 186%. The application of composite patches was confirmed to be effective for retarding the propagation of existing cracks and therefore extending the fatigue life.

The technique of “beach marking” was adopted to record crack propagation and it was proven to be a reliable method of recording crack shapes during fatigue testing for later measurement. Tests results clearly showed that the CFRP repair restrained the crack propagation. Symmetric and asymmetric crack fronts were left on the fracture surfaces owing to the different bonding behavior of tested specimens which indicates the significance of bonding.

Based on the LEFM theory, a theoretical model was proposed to calculate the fatigue lives of tested specimens. The predicted fatigue lives of different specimens agreed well with the experimental results which indicates that it is applicable to use this model to estimate the SIF value and fatigue life for both un-strengthened and strengthened specimens.

Different crack lengths were introduced to simulate the different initial damage degrees. The test results showed that the strengthening method was useful for different stages of crack propagation. A parametric study was carried out to investigate the relationship between the fatigue behaviour and a wider range of damage degrees. The comparison between the residual fatigue lives of un-strengthened and strengthened specimens of the same damage level showed that a late strengthening at a larger damage level tend to result in a more significant extension in the remaining fatigue life. However, the late stage life accounts for little in the total fatigue life, and with the inclusion of the fatigue propagation life from a low damage lever (2%), both the test results and LEFM calculations showed that an early repair is more effective in extending the total fatigue life. Early repair is therefore recommended.

Acknowledgements

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References


[27] IIW. Recommendations for fatigue design of welded joints and components, IIW document IIW-1823-07 (IIW Annual Assembly, Graz, Australia; 2008).
