Effect of initial damage level and patch configuration on the fatigue behaviour of reinforced steel plates

P. COLOMBI, G. FAVA and L. SONZOGNI

Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano P.zza L. da Vinci, 32 20133 Milan, Italy

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NOMENCLATURE

a_i = initial crack length
A_p = patch section
A_s = steel section
E_p = patch Young's modulus
E_s = steel Young's modulus
$N_{f,reinf}$ = number of cycles to failure of the reinforced specimen
$N_{f,unrein}$ = number of cycles to failure of the unreinforced specimen
R_G = reinforcement ratio
R_N = fatigue life increase ratio
t_a = adhesive thickness
t_p = CFRP patch thickness
W = plate width
α = a_i/W (a dimensional crack size)

SUBSCRIPTS

a = adhesive
p = reinforcement patch
s = steel

ACRONYMS

CCT = Central Cracked Tension
CFRP = Carbon Fibre Reinforced Polymer
EDM = Electric Discharging Machining
FRP = Fibre Reinforced Plastic
SENT = Single Edge Notched Tension

Correspondence: P. Colombi. E-mail: pierluigi.colombi@polimi.it

INTRODUCTION

Fibre reinforced plastic materials are regarded as a good alternative to standard techniques for the reinforcement of civil engineering structures such as bridges, buildings and infrastructures with particular reference to concrete and masonry structures. In particular, carbon fibre reinforced polymer (CFRP) wraps and strips were recently suggested for the reinforcement of steel structures.[1,2] Guidelines are also available[3,4] in order to help in the design of CFRP repaired steel structures.

With respect to the fatigue failure of steel members under cyclic loadings, several repair techniques may be considered to reduce the crack growth rate and stop the fatigue crack propagation, as blunt the crack tip with a hole, bridging the cracked section by means of welding, bolting or steel plate bonding.[5] Such techniques may lead to several disadvantages mainly because of the increase of the self-weight or to the fatigue sensitivity of welding and bolting. High installation and maintenance charges and costs connected to the substructure unavailability also have to be mentioned. On the other hand, the application of CFRP reinforcements bonded to the damaged steel structural element by using epoxy adhesives may present several benefits.[1,2] Despite the higher material cost, because of the unique properties of composite materials (low self-weight, high strength and stiffness and good durability), the strengthening operation can be quickly realized reducing the global rehabilitation costs.

It is relevant to consider that CFRP does not produce any significant improvement of the elastic structural response from the global point of view. This is due to the marginal increment of the cross-sectional area and moment of inertia of the reinforced steel section. Conversely, CFRP significantly improves the local structural response through a significant increment of the local stiffness and strength. This is particularly appealing for flexural strengthening at the ultimate limit state, strengthening against local buckling and confinement of hollow steel tubes and in particular fatigue reinforcement as showed by several research programmes in the literature from the experimental, analytical and numerical points of view.[6]

Problem statement

Reinforcement with CFRP materials was proposed in the literature as an efficient technique for the reinforcement of fatigue sensitive steel elements.[6] In general, the use of CFRP strips to decrease fatigue crack propagation acts in three different ways:

- by reducing the stress range around the crack tip;
- by reducing the crack opening displacement; that is, CFRP materials bonded to the crack bridge the crack lips and moderate the crack opening displacement; and
- by promoting crack closure; as the reduction of the crack opening displacement produced by crack patching promotes crack closure.

From the aforementioned list, it is clear that the patch stiffness plays a very important role. High stiffness reinforcing materials result in a significant decrease of the stress range around the crack tip, in a noticeable reduction of the crack opening displacement and promote crack closure. Crack closure is also emphasized by the prestressing of the CFRP strips because the compressive stresses reduce the stress ratio promoting crack closure. Finally, the patch location also plays a role in the fatigue life increment. On the other hand, high patch stiffness produces high interface shear stresses promoting then patch debonding or delamination, reducing then effectiveness of the reinforcement.

Most of the previous studies focussed on the fatigue behaviour of central cracked tension (CCT) specimens with double side[7] (symmetric) or single side[8] (un-symmetric) CFRP reinforcements. The notch is usually realized by a central hole and two symmetric cracks emanating from the hole. Such a damage configuration is representative of a fatigue crack emanating from the rivet of a riveted steel element. Anyway, other damage configurations are worth of investigation such as the single edge notched tension (SENT) specimen with single side (non-symmetric) reinforcement. Such a damage configuration is representative of a fatigue crack emanating from the border of a tensile flange of a steel beam under bending loading where the reinforcement is often bonded to one side, that is, in a non-symmetric way.

Finally, former studies investigated mainly the reinforcement of short initial crack neglecting the influence of the initial crack length on the effectiveness of the repair technique.

Scope of the research

The present experimental research aimed to investigate the fatigue behaviour of SENT specimens reinforced by using pultruded CFRP strips bonded by epoxy adhesive to a single side of the cracked specimens. SENT configuration was selected, and tensile tests were performed in order to represent an edge defect in the tension flange of a steel beam under bending fatigue loading. Besides, in practical situations, the reinforcement cannot be applied on both the flange surfaces resulting in an asymmetric strengthening configuration.

Experimental tests were performed under tensile cyclic loads to explore the efficacy of the bonded CFRP repair. The effect of different initial damage level and different strengthening configurations (reinforcement amount and patch location) is investigated by comparing the achieved fatigue lifetime extension and the effectiveness of the reinforcing system quantified and discussed.

The experimental results are also used to provide useful information on the more efficient strengthening configuration.

Previous studies

Fundamental researches were focused on the effectiveness of the fatigue reinforcement of steel plates strengthened by using CFRP wraps and strips. Jones and Civjan[9] analysed the fatigue behaviour of steel plates notched either from a central hole or from the edges (double edge notched tension) with respect to the CFRP system and bond geometry. The effects of one or two side reinforcements and of an application prior or subsequent to crack propagation were also taken into account. The application of CFRP strips, and eventually, the pretension of the strips prior to bonding remarkably increased the remaining fatigue life. Liu *et al.*[10,11] investigated the effects of patch system, thickness, length, width and patch configurations on single-sided and double-sided repaired steel plates. Tsouvalis *et al.*[12] considered CCT specimens reinforced by CFRP patch on a single side. Results showed that such patches, despite their relatively low stiffness ratio, can effectively extend the fatigue life by a factor of 2.

In several studies, the fatigue behaviour of notched steel members reinforced by using prestressed CFRP laminates is considered: prestressed reinforcements were observed to be more effective in extending the crack growth life.[13–15] Crack patching by prestressed CFRP strips also produces benefits because the compressive stress introduced by the prestressing in the steel elements gives rise to an additional reduction of the crack opening displacement and emphasizes the crack closure phenomenon.

Fatigue tests by Wu *et al.*[16] revealed that ultra-high modulus CFRP plates are very effective for the fatigue strengthening of cracked steel plates. Yu *et al.*[17] considered three different lengths of artificial cracks to simulate the effect of increasing degrees of fatigue damage on notched steel plates with a hole and two initial cracks in the centre. More recently, Yu *et al.*[18] presented the results of fatigue tests on notched steel plates with a hole and two initial cracks in the centre, taking into account degrees of damage from 2% to 40% corresponding to increasing slot lengths in the steel section. The experimental results showed that the CFRP patches could effectively slow down the crack growth and prolong the fatigue life. The effect of initial damage and reinforcement configurations was also investigated by Wang *et al.*[19] Results showed that the repair efficacy was highly dependent from CFRP thickness, initial crack length, reinforcement arrangement and local debonding size.

A peculiar aspect of the CFRP reinforcement of steel structures is that the adhesive layer is the weakest point of the system because of the very high strength of the steel substrate. Reinforcing debonding is then the dominant failure mode of CFRP reinforced steel elements. In particular for fatigue strengthening crack, mouth debonding plays an important role as clearly demonstrated in Colombi *et al.*[20] and Aggelopoulos *et al.*[21] The presence of a debonded area in the crack tip region significantly reduces the effectiveness of the reinforcement technique and should be taken into account in the evaluation of the fatigue lifetime. The present paper addresses the need for further and well-documented experiments in such a field, as also mentioned in Colombi *et al.*[22]

THE EXPERIMENTAL PROGRAMME

The experimental campaign was performed at the Testing Material Laboratory of the Politecnico di Milano. The dimensions of the SENT specimens are presented in Fig. 1. Specimens were 450 mm long, 50 mm wide and 8 mm thick.

A total of nine SENT specimens were reinforced on one side and subject to cyclic loading by using an axial testing machine with a total capacity of 250 kN. One unreinforced specimen (specimen U-D12) was also tested as control case. The total number of tested specimens was then equal to 10. Different parameters were investigated

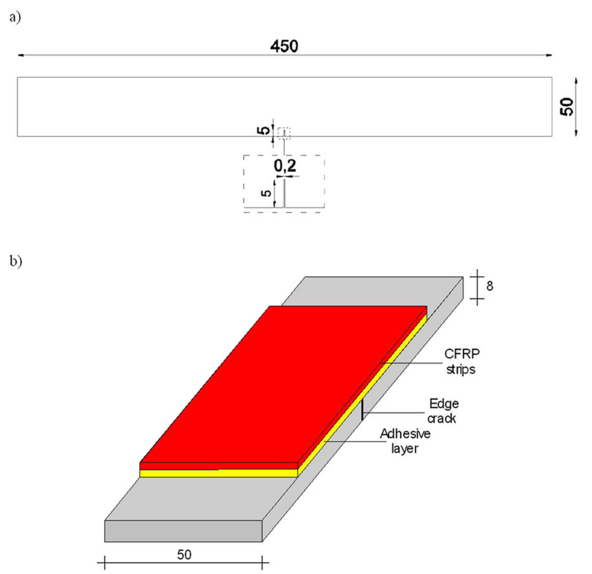

Fig. 1 Single edge notched tension specimen geometry: (a) steel plate and (b) specimen reinforcement.

such as the initial crack length when the steel plate is reinforced and the patch configuration (reinforcement amount and location). To simulate different degrees of damage, two values were considered for the initial crack length, that is, 6 and 15 mm. The initial damage is characterized in the following by the ratio, α, of the listed initial crack length and the plate width W ($W = 50$ mm). The selected initial crack lengths correspond to an initial percentage of cracked cross section of 12% and 30%, respectively. Concerning the patch configuration, different amounts of the reinforcement are considered. These correspond to different patch thicknesses, that is, a thickness of 1.4 mm consistent to the application of one CFRP layer and a patch thickness of 2.8 mm consistent to specimens reinforced with two CFRP layers. Different patch locations were finally considered as the fully or partially covered steel plates. Details of the experimental programme are presented in Table 1 where a_i is the initial crack size of the reinforced specimen and t_p is the patch thickness. R_G is the reinforcement ratio, and α is the initial damage level.

Specimen labels are as follows. The first letter indicates the specimen configuration (A, B or U for the unreinforced specimen). Then the number (1 or 2) refers to the number of CFRP layers, while D12 or D30 defines the damage level.

The reinforcement ratio in Table 1 is defined as the ratio between the patch and the steel plate section:

$$R_G = \frac{E_p \cdot A_p}{E_s \cdot A_s} \tag{1}$$

where E_s and E_p are the steel and the patch Young's modulus, respectively, while A_p and A_s are the patch and steel sections, respectively. This ratio is used in the following to characterize the amount of reinforcement applied to the steel plates and the axial stiffness of the reinforced steel plates.

In the following additional details on the materials, patch location and specimen preparation are provided.

Table 1 Details of the experimental programme

Specimen	Patch configuration	a_i [mm]	t_p [mm]	R_G [/]	α [%]
U-D12	/	6.0	/	/	12
A2-D12-1	a	6.1	2.8	0.353	12
A2-D12-2	a	6.4	2.8	0.353	12
A2-D12-3	a	6.0	2.8	0.353	12
A1-D12-1	a	6.0	1.4	0.175	12
A2-D30-1	a	14.8	2.8	0.353	30
A2-D30-2	a	14.9	2.8	0.353	30
B2-D30-1	b	15.0	2.8	0.175	30
A1-D30-1	a	14.7	1.4	0.175	30
B1-D30-1	b	14.8	1.4	0.087	30

Materials

Specimens were realized with a steel type S275J0 according to European standard. The specimens were machined with a side notch consisting of a slot 5 mm long and 0.20 mm wide (Fig. 1). The slots were realized by electric discharging machining. The mechanical properties of the steel plates were determined through tensile coupon tests. The mean yielding stress and tensile strength were 330 and 444 MPa, respectively. The steel Young's modulus was assumed equal to 208 GPa.

The pultruded reinforcements were realized using CFRP strips (Sika CarboDur® M514, SIKA ITALIA SpA, Como, Italy) with a thickness of 1.4 mm. The nominal values of the Young's modulus and tensile strength were greater than 200 GPa and 2800 MPa, respectively. In this paper, the reinforcement Young's modulus was assumed equal to 210 GPa. The pultruded CFRP strips were bonded to the steel plates using a thixotropic epoxy resin (Sikadur® 30, SIKA ITALIA SpA, Como, Italy). The mixing ratio of the epoxy was three parts of component A (resin) to one part of component B (hardener) by volume/weight. The epoxy had a pot life of 70 min and was cured at room temperature. The adhesive Young's modulus and tensile strength were greater than 4500 and 28.4 MPa, respectively.

For specimens reinforced with two layers of pultruded CFRP strips, a less viscous epoxy (Sikadur® 330, SIKA ITALIA SpA, Como, Italy) was used to bond the outer CFRP strip to the inner one. The mixing ratio in this case was four parts of component A (resin) to one part of component B (hardener) by weight. The epoxy had a pot life of 30 min and was cured at room temperature. The nominal values of the Young's modulus and tensile strength were greater than 3800 and 30 MPa, respectively.

Patch location

Apart from specimen U-D12, consisting of a bare steel plate without any patch and tested as a control specimen, two types of patch configuration were designed. Case (a) is the steel plate fully covered by the patch, and it is considered as the reference reinforcing configuration. Case (b) is the steel plate partially bonded by the patch on the lateral side. In this case, the crack is covered by the patch for a crack length up to 25 mm, that is, half of the steel plate width. The reinforcement configurations are presented in Fig. 2.

Specimen preparation

Specimens were initially subjected to fatigue loading in order to produce an initial precrack with length of approximately 6 mm. Few specimens were immediately reinforced, while other specimens were reinforced after being additionally subjected to fatigue loading

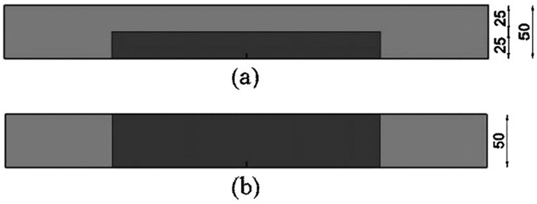

Fig. 2 Patch configurations of type (a) and (b).

up to a crack length of approximately 15 mm. The precrack represented an initial damage condition and was performed in order to investigate the effect of initial crack length on the effectiveness of the reinforcement technique.

The surfaces of the steel plates were first accurately grid blasted by using an abrasive disc in order to remove the rust and to create a rough surface. Then a xylene-based solvent was used to remove dust and obtain a clean and chemically active surface in order to ensure mechanical interlocking. For the CFRP reinforcement, very fine sandpaper (grit P240) was used to increase the surface roughness and hence improve the bond strength.

Specimens were reinforced according to the following procedure. The CFRP strips were cut to a proper length using a saw cut and were bonded immediately after the surface preparation in order to avoid any possible contamination. No adhesive promoter (e.g. primer) and spacers to control the adhesive thickness were used. The two components of the epoxy adhesive were dosed according to the manufacturer's instructions and mixed until a homogeneous light grey paste was obtained. The adhesive (Sikadur® 30, SIKA ITALIA SpA, Como, Italy) was then distributed evenly on the composite surface. The CFRP strips were pressed on the steel substrate in order to avoid air bubbles, and the adhesive in excess was removed. In the case of specimens reinforced with two layers of pultruded CFRP strips, the adhesive (Sikadur® 330, SIKA ITALIA SpA, Como, Italy) was distributed on the composite material, and strips were pressed on the steel plate. Finally, the specimens were cleaned and subjected to uniform pressure by applying dead weights on the CFRP surface. After 2 days, the dead weights were removed, and the bond line visually inspected. The adhesive thickness was found equal to approximately 1.1 mm. Reinforced specimens are shown in Fig. 3.

A similar adhesive thickness was in steel plates reinforced by using CFRP strips and in tensile steel/CFRP joints specimens previously tested under fatigue loading at the Politecnico di Milano.[23,24] With respect to debonding failure, the results showed in both cases that the fatigue resistance of the bond between the steel plate and the CFRP reinforcement is remarkably superior to that of welded cover plates and joints, respectively.

TEST PROCEDURE

The test procedure is summarized in the following. In particular, the fatigue loading is described together with the experimental setup. Finally, the adopted crack growth measurement techniques (travelling digital microscope and beach marking) are presented.

Fatigue loading

The fatigue tests on SENT specimens were carried out with a servo-hydraulic closed-loop testing machine (MTS Systems Corporation, Eden Prairie, MN USA) under sinusoidal loading control until bond failure occurred. Tests were performed at room temperature, and the interaction between cyclic loading and environmental conditions was not taken into account.

Uniaxial sinusoidal loading cycles were applied at a loading frequency of 18 Hz. All the specimens were tested under constant amplitude tensile loading with maximum and minimum loads of 60 and 24 kN, respectively. The applied loads correspond to a maximum stress level in the bare steel plates equal to 150 MPa, which is about 33% of the ultimate strength of the steel and 45% of its yield strength. The adopted loading ratio $R = 0.4$ was selected in order to reproduce a severe fatigue crack propagation scenario. At this loading ratio, the retardation effects are minimized, and the fatigue crack propagation is then faster. The experimental setup is shown in Fig. 4.

Measurement of crack propagation

During the execution of fatigue tests, it was essential to capture the crack growth developing with the fatigue cycles. After positioning a piece of graph paper close to the ligament on the unreinforced side of the specimen (Fig. 5a), the crack growth was recorded at intervals approximately equal to 5.000 or 10.000 cycles, depending on the crack-front velocity, by using a travelling microscope with a 5× magnification and a resolution in the order of 0.01 mm (Fig. 5b).

Fig. 3 Specimens reinforced with CFRP strips.

Fig. 4 Experimental setup in the fatigue tests.

The 'beach marking' technique was also adopted to characterize the crack propagation. At different crack lengths, few cycles at low stress range (33–51 kN) were added, as shown in Fig. 6. The reduction in the applied stress range for a short number of cycles causes changes in the stress intensity factor at the crack tip, modifying the rate of crack propagation and leading to the generation of visible marks on the crack surfaces. The crack shape and size is then observed by the naked eye after the specimen collapse.

EXPERIMENTAL RESULTS

The achieved experimental results are presented in the following in terms of fatigue life, failure modes,

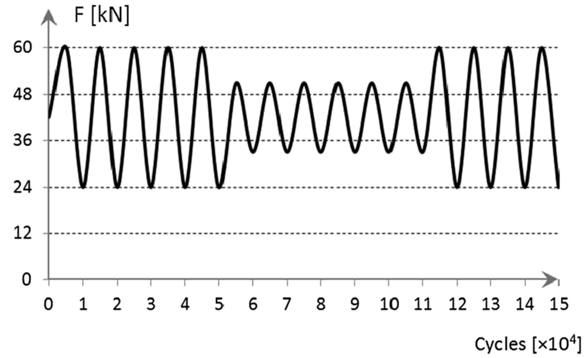

Fig. 6 Stress range of cyclic loading.

crack-front shape and fatigue crack propagation curves. In particular, the fatigue life extension of the reinforced specimens compared with the bare specimen is evaluated in order to quantify the repair efficacy. Failure modes and the crack-front shape are also discussed.

Fatigue life

The fatigue life extension of SENT specimens reinforced by using pultruded CFRP strips are analysed and compared. Specimens' details and the experimental results are collected in Table 2, including the following parameters: patch configuration, initial crack length, reinforcement thickness, reinforcement ratio R_G and initial damage level α. In Table 2, the fatigue life is reported together with the fatigue life increase ratio.

The fatigue life increase ratio, R_N, is defined as follows:

$$R_N = \frac{N_{f,re\inf}}{N_{f,unre\inf}} \tag{2}$$

where $N_{f,reinf}$ is the number of cycles to failure of the reinforced specimen and $N_{f,unrein}$ is the number of cycles to failure of the control specimen (specimen U-D12). In Table 2, the fatigue life was counted from the initial crack (~6 or ~15 mm) until complete failure of the specimens.

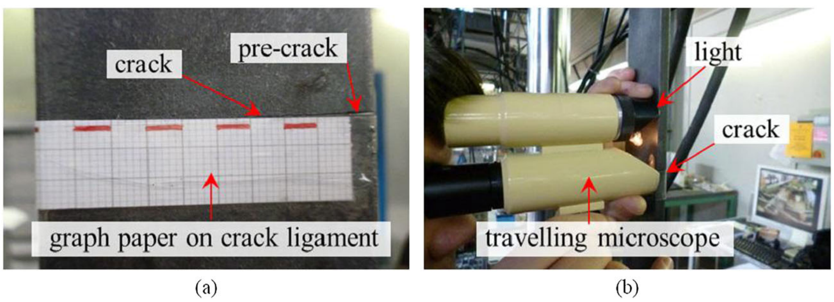

Fig. 5 Crack growth recording: (a) graph paper on the crack ligament and (b) travelling microscope.

Table 2 Detail of the experimental results

Specimen	Patch configuration	a_i [mm]	R_G [/]	α [%]	Cycles to failure	R_N [/]
U-D12	/	6	/	12	196 714	/
		15		30	29 264	
A2-D12-1	a	6.1	0.353	12	584 000	2.97
A2-D12-2	a	6.4	0.353	12	565 000	2.87
A2-D12-3	a	6	0.353	12	605 000	3.08
A1-D12-1	a	6	0.176	12	512 500	2.61
A2-D30-1	a	14.8	0.353	30	172 000	5.88
A2-D30-2	a	14.9	0.353	30	133 000	4.54
B2-D30-1	b	15.0	0.176	30	100 000	3.42
A1-D30-1	a	14.7	0.176	30	77 000	2.63
B1-D30-1	b	14.8	0.088	30	66 800	2.28

For short initial cracks, case (a) reinforcement type and two reinforcement layers (specimen type A2-D12), a mean fatigue life increase ratio equal to 2.97 was achieved. Single layer reinforcement (specimen type A1-D12) is less efficient because a fatigue life increase ratio was equal to 2.61.

For long initial cracks, case (a) reinforcement type and two reinforcement layers (specimen type A2-D30), a mean fatigue life increase ratio equal to 5.21 was achieved. Single layer reinforcement (specimen A1-D30-1) is much less efficient with a fatigue life increase ratio equal to 2.63.

Case (b) reinforcement type and two reinforcement layers (specimen B2-D30-1) produced a fatigue life increase ratio equal to 3.42. A single layer (specimen B1-D30-1) reinforcement configuration and the same reinforcement type produced a much smaller fatigue life increase ratio of 2.28. The achieved fatigue life increase ratios for case (b) reinforcement location are then significantly smaller than the ones attained for case (a).

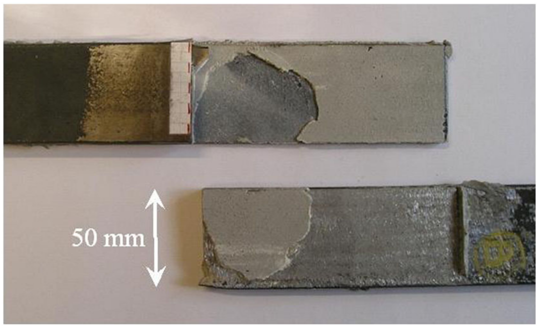

Fig. 7 Typical observed specimen failures (specimen A2-D30-2).

Failure modes

In reinforced specimens, failure consisted of debonding occurring at the composite/adhesive interface in the crack region and of debonding at the steel/adhesive interface close to the reinforcement ends (Fig. 7). Debonding promoted the final unstable crack propagation in the steel plate.

The relationship between the crack growth and debonding phenomena (crack mouth debonding) around the crack tip region is worth of investigation and should be conducted in the future.

Crack-front shape

In Fig. 8a and b, the typical fracture surfaces for the unreinforced steel plate (specimen U-D12) and for the reinforced steel plate (specimen A2-D12-1) are illustrated and compared. The crack-front shape was recorded by means of the 'beach marking' technique. For the bare steel plate (specimen U-D12), the crack-front shape is curvilinear and symmetric, corresponding to uniform crack propagation on both sides (Fig. 8a). For the reinforced specimens, the crack-front shape was not uniform through the steel plate thickness. The crack length on the side of the bonded CFRP reinforcement is shorter than that at

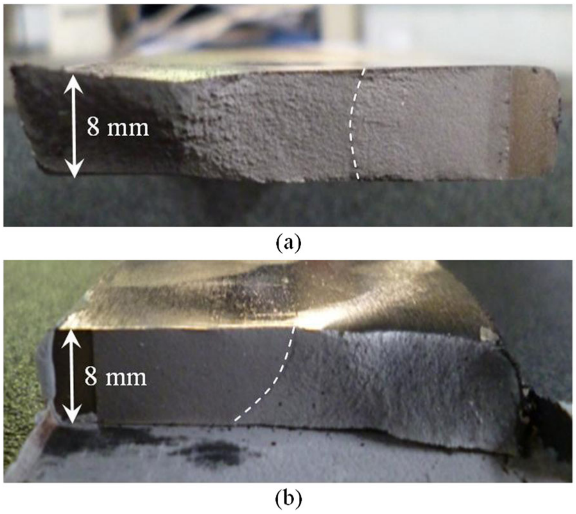

Fig. 8 Typical fracture surfaces observed by means of the 'beach marking' technique: (a) bare steel plate (U-D12) and (b) reinforced specimen (A2-D12-1).

the unreinforced surface (Fig. 8b). This is because the CFRP application delays the fatigue crack propagation in the steel plate. A non-uniform crack front may be also caused by secondary bending effects, leading to stress variations over the thickness of the cracked steel section.

Crack propagation curves

In Fig. 9, the relationship between the crack length and the number of cycles is plotted for each specimen. The unreinforced specimen U-D12 is considered as a control specimen. The curves clearly show that the crack growth rate is significantly slowed by the presence of the composite even if it is located on one side of the steel plate. Composite reinforcement bridges the stress in the cracked section, reduces the crack opening displacement and promotes crack closure, leading to a reduction of the stress intensity factor and then a fatigue life extension.

As it may be noticed from Fig. 9, the best fatigue performance for short initial crack size is achieved for specimen type A2-D12. The steel plate is, in fact, fully covered by two layers of composite patch, and then the greatest stress bridging effect is reached. Besides, a significant reduction of the crack opening displacement is attained because of the high reinforcement stiffness. As a result, a noticeable decrease of the stress intensity factor is accomplished. Finally, the reduced crack opening displacement promotes crack closure too. For short initial crack size and specimen type A1-D12, the reduced reinforcement stiffness (a single layer was used) produces a less pronounced stress intensity factor decrement and crack closure effect. This finally results in a reduced efficacy for specimen type A1-D12. The observed trends are also investigated by evaluating the experimental fatigue crack growth rate according to ASTM E647[25]:

$$\left(\frac{da}{dN}\right)_{\overline{a}} = \frac{(a_{i+1} - a_i)}{(N_{i+1} - N_i)} \tag{3}$$

Equation 3 makes use of the 'secant method' to evaluate an average crack growth rate in the interval $[a_i – a_{i+1}]$. The computed experimental crack growth rate corresponds then to the average crack length in the relevant interval, that is, $\overline{a} = \frac{1}{2}(a_{i+1} - a_i)$. The experimental crack growth rate for specimen type A2-D12 and A1-D12 is reported in Fig. 10.

In Fig. 10, it is evident that two-layer reinforcement configuration is the more efficient for short initial crack size.

From Fig. 9, it is also apparent that two-layer configuration type is again the most efficient for long initial crack size. In this case, the reinforcement stiffness plays a very important role in the strengthening efficacy. Two-layer configuration is, in fact, much more efficient than the single layer one, and this holds for both reinforcement Cases a) and b). As an example, specimen types A1-D30 and B1-D30 have the same fatigue lifetime, which is smaller than the one of specimen types B2-D30 and A2-D30. Single reinforcement layer is, in fact, unable to efficiently produce stress bridging, reduce the crack opening displacement and promote crack closure. This is also confirmed by the experimental fatigue crack growth rate plot in Fig. 11.

In the first part of the fatigue crack propagation of Fig. 11, the specimens were unreinforced because the CFRP patch was applied at a crack size equal to 15 mm. The effect of the reinforcement is then evident, and it results in a significant decrement of the fatigue crack growth rate. In Fig. 11, it is again manifested that two-layer reinforcement configuration is the most efficient for log initial crack size.

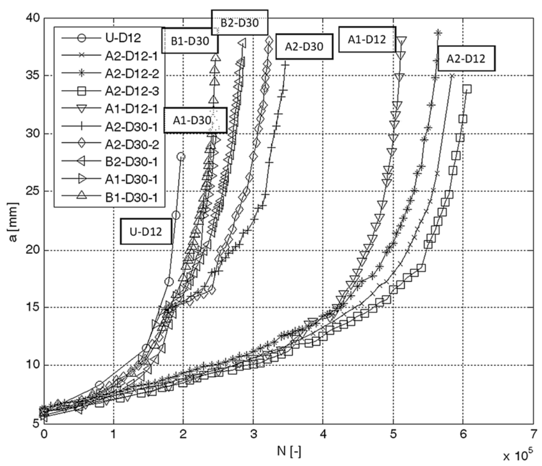

Fig. 9 Crack propagation curves.

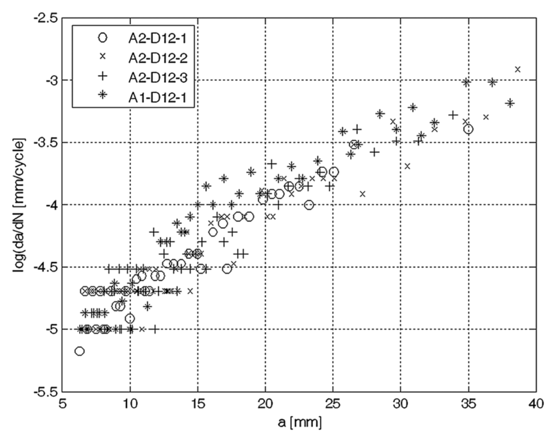

Fig. 10 Crack growth rate for short initial crack size (specimen type A2-D12 and A1-D12).

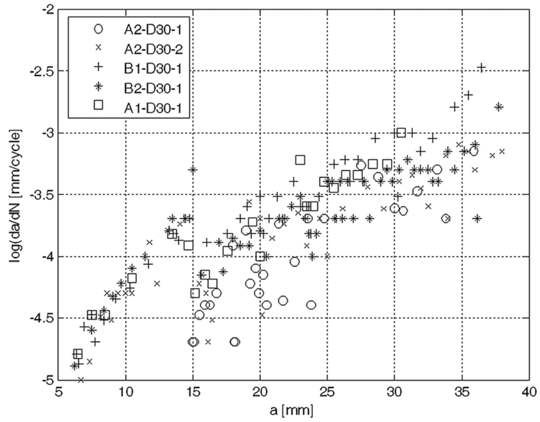

Fig. 11 Crack growth rate for long initial crack size (specimen type A2-D30, A1-D30, B1-D30 and B2-D30).

EFFECT OF COMPOSITE PATCH ON FATIGUE CRACK GROWTH

In the following, the effect of initial crack length, reinforcement ratio and patch position on the fatigue life increase ratio is investigated. The fatigue life of each repaired specimen was compared in Table 2 with the one of the unreinforced specimen U-D12, which was tested as a control specimen. In detail, for specimen U-D12, the values of cycles to failure are reported both for an initial crack length of about 6 mm and for a crack length of about 15 mm. For a certain initial crack length value, the ratio between the fatigue life of each reinforced specimen and the unreinforced one is referred to as the fatigue life increase ratio R_N (Eq. 2).

Effect of the initial crack length

In order to enucleate the effect of initial crack length, specimens' results with equal reinforcement ratio and patch position are compared.

For small initial crack (specimen type A2-D12), on the basis of the R_N value, the fatigue life is observed to increase by a factor ranging from 2.87 (specimen A2-D12-2) to 3.08 (specimen A2-D12-3) over the unreinforced control specimen U-D12. For long initial cracks (specimen type A2-D30), the fatigue life is observed to increase by a factor ranging from 4.54 (specimen A2-D30-2) and 5.88 (specimen A2-D30-1) over the unreinforced control specimen. Two-layer reinforcement configuration is clearly efficient to produce stress bridging, to reduce the crack opening displacement and to promote crack closure.

Effect of reinforcement ratio

In order to emphasize the effect of reinforcement amount (as defined in Eq. (1)), specimens' results with equal initial crack length and patch position are compared.

The effect of reinforcement amount on fatigue life is firstly analysed with reference to case (a) patch configuration. The results obtained with two reinforcement layers are compared to the ones with one reinforcement layer. For short initial cracks, the effect of reinforcement amount on fatigue life is studied by comparing the results of specimen type A2-D12 with the ones of specimen A1-D12-1. In the first case, the average fatigue life increase ratio is equal to 2.97, while in the second case, the fatigue life increase ratio is equal to 2.61. These results indicate then a moderate influence of the reinforcement amount for short initial crack and case (a) reinforcement location. For long initial cracks, results of specimen type A2-D30 are compared with the ones of specimen A1-D30-1. In the first case, the average fatigue life increase ratio is equal to 5.21, while in the second case, the fatigue life increase ratio is equal to 2.63. These results clearly indicate a significant influence of the reinforcement amount on the repair efficacy for long initial crack and case (a) reinforcement location. A single reinforcement layer is, in fact, unable to produce a significant stress bridging, reduce the crack opening displacement and to promote crack closure.

This trend is confirmed by the fatigue results of specimens with case (b) reinforcement location and long initial cracks. The effect of the reinforcing ratio is analysed by comparing the results of specimen B2-D30-1 with two reinforcement layers with the ones of specimen B1-D30-1 with one reinforcement layer. In the first case, the fatigue life increase ratio is equal to 3.42, while in the second case, the fatigue life increase ratio is equal to 2.28. These results again clearly indicate, for the same reasons discussed earlier, a significant influence of the reinforcement ratio on the repair efficacy for long initial crack and case (b) reinforcement location.

Effect of patch position

In order to highlight the effect of patch position, specimens' results with equal initial crack length and reinforcement ratio are compared.

The effect of patch position on fatigue life was analysed by comparing results for cases (a) and (b) reinforcing position with the same initial crack length and reinforcement ratio. The results of specimens A1-D30-1 and B2-D30-1 are then considered. The corresponding fatigue life increase ratios were of 2.63 and 3.42, respectively. These results indicate then a significant effect of patch position on the fatigue life increase ratio. The repair is in fact much efficient if the same amount of reinforcement is located on the crack region as in case (b). On the contrary, if the same amount of reinforcement is distributed on the whole steel plate as in case (a), the reinforcement efficacy is significantly reduced.

CONCLUSIONS

This paper presented the results of an experimental study on the fatigue behaviour of side-cracked steel plates reinforced by single side composite patch. The main conclusions are the following:

- The reinforced specimens failed mainly by debonding at the steel/adhesive interface and sudden static failure of the steel plate. The crack size in the steel plate at debonding was about 35–40 mm, that is, equal to 70–80% of the specimen width (50 mm).
- Significant fatigue life increments were recovered by using the reinforcing techniques investigated in this work. The most efficient reinforcement configuration was configuration (a) with the steel plate fully covered by the reinforcing patch. For short initial crack, the achieved fatigue life increment was 2.97, while for long initial crack, it was 5.21.
- There was also a clear influence of the reinforcement ratio on the efficiency of the fatigue repair. This effect is in particular evident for long initial crack size and reinforcement configuration (b) where higher reinforcement amount produced a significant increment of the fatigue life increase ratio.
- There was finally a clear influence of the patch position on the efficacy of the fatigue repair. In particular, patch configuration (b) with an adequate reinforcement ratio is really efficient in the repair of fatigue-damaged steel elements. Anyway, for long initial crack size, if a certain reinforcement amount is not provided, the patch position does not play a role for the fatigue life increment. Specimen types A1-D30 and B1-D30 have, in fact, a very similar fatigue life increment ratio. A single reinforcement layer is evidently insufficient to produce an adequate stress bridging, reduce the crack opening displacement and promote crack closure.
- Patch location (a) is clearly the most efficient one for both investigated initial damage levels. Anyway, patch location (b) is efficient too if a sufficient amount of reinforcement is used. The reinforcement amount and then the reinforcement stiffness are in fact the dominant parameter on the fatigue repair efficacy of steel plate by using CFRP reinforcement.

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