BONDED PRESTRESSED METHOD FOR FATIGUE CRACK REPAIR

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Abstract: Fatigue strengthening is an efficient and economical way to combat fatigue cracking of metallic structures. This research work aims at developing a bonded and prestressed crack repair solution using the iron-based shape memory alloy (Fe-SMA). The shape memory effect of the Fe-SMA is exploited to generate compressive stresses around the crack tip in metallic structures to be repaired. An experimental campaign has been therefore implemented to study factors that can impact the repair efficiency. A series of metal plates containing the same initial notch were repaired by bonding prestrained Fe-SMA. Different activation methods were employed to activate the prestrained Fe-SMA to form desirable compressive stresses. Different Fe-SMA patch sizes have also been tested to study its influence on the repair efficiency. The specimens with bonded and prestressed Fe-SMA were subjected to tension-to-tension fatigue loading with beach marking technique. The fatigue crack growth behaviour after repair shows that the prestressed solution is highly effective in retarding fatigue crack growth thanks to the bridging mechanism and most importantly the prestressing effect. Increasing the patch size further increases the patch stiffness and the prestressing forces, resulting in a complete fatigue crack arrest in the end. The experimental results substantiate that this bonded and prestressed fatigue crack repair method has great potential for repairing.

Keywords: Fatigue crack retardation; Prestressed repair; Bridging mechanism; Crack arrest;

INTRODUCTION

Fatigue life extension methods and fatigue crack repair methods have always been a vibrant research topic, seeking effective methodologies to significantly prolong the service life of aircraft [1]. Bonding fibre reinforced epoxy composite patches have delivered superior fatigue crack growth life extension in comparison with mechanically joined metal patches. The longer fatigue life extension of bonding composite patches results from the bridging mechanism and the circumvention of new fatigue hot spots. However, tensile residual stresses in the parent metal structure due to mismatch of thermal expansion coefficients of composites and metal structures have adverse effects.

A state-of-art fatigue crack life extension methodology is to bond prestressed patches. There are three fatigue crack retardation mechanisms in this system, namely added load path, bridging mechanism and compressive stresses due to prestressing [2]. The emergence of an iron-based shape memory alloy (Fe-SMA) that exhibits excellent shape memory effect and generates notably high recovering stresses makes the bonded prestressed method for fatigue crack repair feasible to achieve [3].

An experimental campaign has been carried out to study the feasibility of developing such a bonded prestressed fatigue strengthening method and to demonstrate its repair efficiency. The specimen configuration consists of a metal plate with a central crack repaired with Fe-SMA patches on both sides. Different activation methods to generate compressive stresses around the crack area in the metal plate using the shape memory effect of Fe-SMA were investigated. Different patch sizes were also studied. The repaired specimens were then subjected to tensile-tensile fatigue loading with beach marking technique. The a-N data were analysed and the role of bridging mechanism and prestressing were discussed.

EXPERIMENTAL PROCEDURES

Specimen preparation and test matrix

The specimen configuration is shown in Figure 1. A steel plate of 850 mm × 140 mm × 10 mm containing a central notch is repaired by bonding Fe-SMA patches on both sides. As shown in Figure 1, the length and width of the Fe-SMA are L and W respectively, which are provided in Table 1 for each specimen.

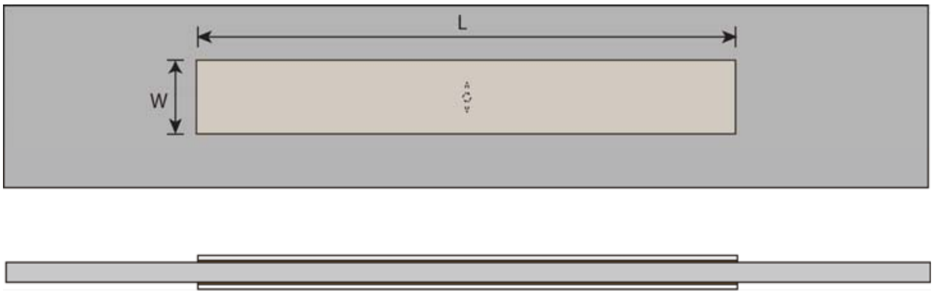

Figure 1. Specimen configuration.

The notch contains a circular hole of 2.5 mm in radius, the total length is 15 mm. Electrical discharge machining (EDM) technique was used to make the notch according to ASTM E647-00 [4]. Precracking was performed to form a sharpened crack ahead of the notch tip. The stress range and stress ratio for precracking are $\Delta\sigma_{pre} = 75\ MPa$ and $R_{pre} = 0.2$ respectively. The loading frequency was $f = 10\ Hz$ and $N_{pre} = 20{,}000$ cycles were applied to the bare steel plate to form a precrack around 1.5 mm.

After precracking, the steel plate was strengthened by bonding Fe-SMA patches on both sides. The steel plate and Fe-SMA surfaces were cleaned with Acetone, grid blasted and cleaned again prior to bonding. Sika1277 [5] was used as the adhesive to join Fe-SMA patches and the steel plate. It has been validated in a previous work that this surface pre-treatment can render cohesive failure in Sika 1277 bondline [6]. The specimens were cured at room temperature for 15 days according to the data sheet [5].

Table 1 summarizes the material properties used in this study. It is of particular interest to have a basic understanding of the Fe-SMA. Figure 2 depicts the thermomechanical behaviour of the Fe-SMA. The pristine Fe-SMA needs to be prestrained at room temperature to cause a forward austenite-to-martensite (γ-ε) phase transformation. The prestrain, ε_{pre}, of 2% was adopted in this study. Plastic deformation and phase transformation form a permanent strain ε_r in the Fe-SMA. The prestrained Fe-SMA may be bonded to the cracked steel plate. The Fe-SMA can then be heated to a target activation temperature T_h. The deformation of the Fe-SMA is inhibited by bonding and tensile stresses build up in the Fe-SMA during activation. In the beginning of the activation process, thermal expansion dominates and leads to compression in the Fe-SMA. As the temperature increases, the reverse ε-γ phase transformation prevails and tensile stresses in the Fe-SMA increases. During the cooling process, the tensile stresses keep increasing. The nonlinearities in Figure 2 are mainly attributed to the phase transformation in the Fe-SMA, more details can be found in references [2, 7]. Available research has shown that a recovery stress of 350 MPa can be reached in the Fe-SMA when the activation temperature is 160 ℃ [2, 7]. The development of tensile stresses in the Fe-SMA implies that compressive stresses are formed in the repaired steel plate. The SME of the Fe-SMA is therefore exploited to develop a bonded and prestressed repair solution.

Table 1: Mechanical properties of materials [2].

	Steel	Fe-SMA	Sika1277 [5]
Tensile Young's modulus, E [GPa]	205	187	2
Yield strength, σ_y [MPa]	355	345	-
Tensile strength [MPa]	526	1000	30
Thickness, t [mm]	10	1.5	-
Glass transition temperature, T_g [°C]	-	-	67

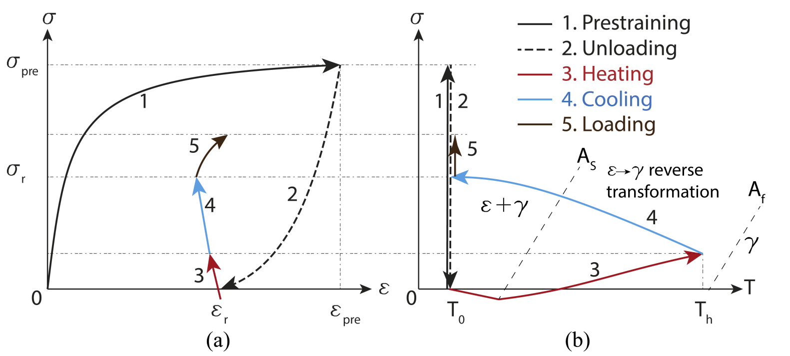

Figure 2. Schematics of the behavior of the Fe-SMA [2].

Table 2 provides the test matrix. A reference specimen, Sp-1, were tested to obtain the fatigue crack growth behaviour of the steel plate itself. A series of specimens with the same patch size were activated using different activation methods. The target activation temperature, T_h, was around 160 ℃. The patch size for the last specimen was enlarged to increase the prestressing forces and patch stiffness with the aim of achieving fatigue crack arrest.

Table 2: Test matrix.

Specimen	*L [mm]*	*W [mm]*	*Activation*	*T_h [℃]*
Sp-1	-	-	-	-
Sp-2	500	50	-	-
Sp-3	500	50	Hot bonder	160
Sp-4	500	50	Heat gun	~160
Sp-5	500	50	Gas torch	>160
Sp-6	250	120	Gas torch	>160

Activation methods

The activation methods used in this study is described in this section. As can be seen from Table 2, in total 3 activation methods were adopted to study the impact of activation on the fatigue life extension. Figure 3 illustrates the three activation methods, namely hot bonder (HB) activation method, heat gun (HG) activation method and gas torch (GT) activation method.

The activation length of the Fe-SMA was 150 mm, i.e., the 150 mm Fe-SMA over the crack was subjected to heating. In order to eliminate the effect of asymmetry on the fatigue crack growth behaviour, the Fe-SMA strips on both sides of the specimens were activated and the activated Fe-SMA length was symmetric with respect to the crack plane.

(a) Hot bonder activation (b) Heat gun activation (c) Gas torch activation

Figure 3. Activation methods.

As shown in Figure 3(a), a Briskheat ACR®3 hot bonder was used to activate the middle portion of the Fe-SMA of the Sp-3 specimen. The heating blanket was placed on one side of the specimen first. The target temperature, T_h, was set to be 160 °C. A vacuum bag was made to press the heating blanket against the specimen surface during the activation process. Thermal couples were placed between the Fe-SMA and the heating blanket. The temperature distribution of the Fe-SMA was monitored by the hot bonder during the heating process. The maximum heating capacity of the hot bonded was used to heat up the Fe-SMA, however, the heating rate became very low when the temperature was beyond about 130 °C. The heating process was stopped when the temperature was about 160 °C.

A heat gun (Steinel HG2320E) was employed to activate the Fe-SMA of Sp-4. As shown in Figure 3(b), the surface of the Fe-SMA was painted white in order to accurately measure the temperature using an infrared camera (Testo 885) [2]. The heat gun was turned on for some time until the hot air reached 600 °C. Then the hot airflow was directed at the surface of the Fe-SMA. The Fe-SMA to be activated was heated area by area. One area was heated until the temperature monitored by the infrared camera was at least beyond 160 °C. Then the area next was heated and this procedure was repeated until the whole activation area was completed.

In the last activation method, a camp gas torch was utilized to activate the Fe-SMA, as can be seen in Figure 3(c). The strategy of gas torch activation was similar to the heat gun activation method. The Fe-SMA was heated area by area. However, the temperature on the Fe-SMA surface was measured immediately after heating using a thermocouple. The measured temperature should be at least 160 °C to make sure that the Fe-SMA was activated with a temperature higher than 160 °C during activation. What's more, the flame temperature was much higher than the airflow of the gas torch. The Fe-SMA was therefore activated instantaneously.

After the Fe-SMA was activated, the specimen was kept at room temperature until the temperature of the Fe-SMA reached the environment temperature. After the activation of the specimens, a fatigue testing campaign was carried out.

Fatigue tests

Figure 4 shows the fatigue test setup. The specimen was mounted to a test frame. The test frame is a computer-controlled servo hydraulic fatigue machine (walter + bai, Type LFV 500- HH) with a 500 kN load cell (GTM DR-F 500kN). Two sets of wedge grips were equipped to clamp the specimen to apply fatigue loading. All the specimens were tested at room temperature.

Figure 4. Fatigue test setup.

Figure 5 schematically depicts the loading spectrum involving the beach marking technique for the fatigue test campaign. As can be seen, the loading spectrum consists of two alternating types of constant amplitude fatigue loading. The cyclic loading with a maximum load of 140.7 kN and a minimum load of 7 kN was to advance the fatigue crack. The stress ratio is 0.05. Each block of this type of fatigue loading is 5,000 cycles. The other type of loading is to leave a mark on the fatigue crack surface. The maximum load was 140.7 kN as well. The stress ratio is 0.6 and each block of this type of loading is 2,500 cycles. Only the cyclic loading for fatigue crack growth was counted as the fatigue crack growth life of the tested specimens.

The fatigue test stopped until the steel plate was completely cracked. Then the Fe-SMA strips on both sides were removed to expose the crack surfaces with thin marks. It was then able to map the relationship between the crack lengths and fatigue life, making the study of the impact of prestressed and bonded repair on the fatigue crack growth behaviour possible.

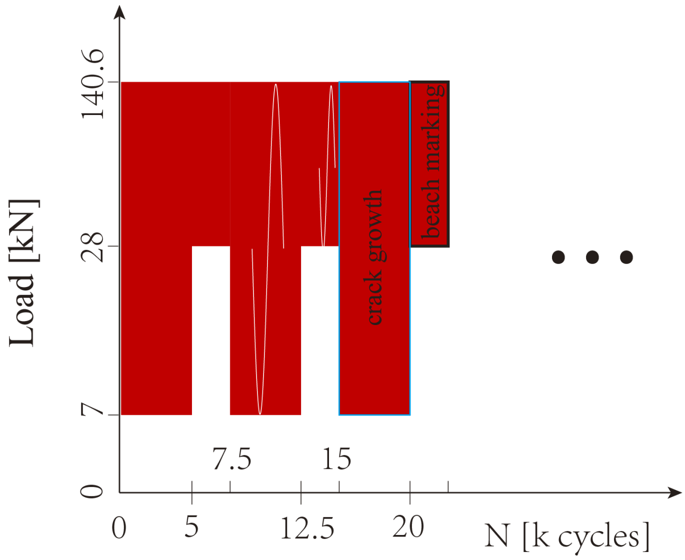

Figure 5. Schematics of the fatigue loading spectrum.

RESULTS AND DISCUSSION

Figure 6 shows the photo of crack surfaces of one tested specimen. As can be seen, visible marks were formed by the beach marking technique. The software ImageJ was used to postprocess the crack growth behaviour data. The ruler scale was used to calibrate the pixel size of the photo in ImageJ and then the crack length between the centre of the notch and the beach mark could be determined by counting the pixels between the two points.

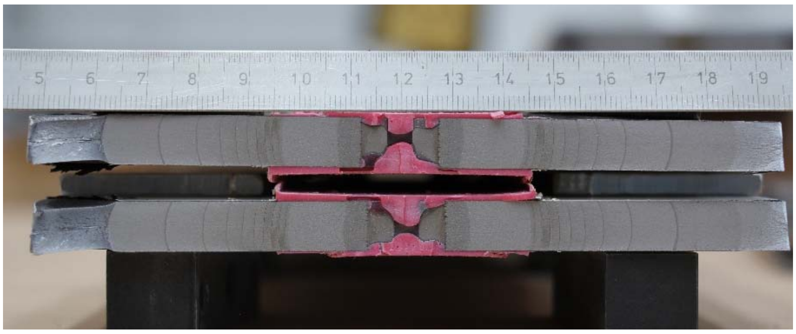

Figure 6. Crack surfaces with beach marks.

Table 3: Fatigue life extension results.

Specimen	*L [mm]*	*W [mm]*	*Activation*	*N [10^6 cycle]*	*Ratio*
Sp-1	-	-	-	0.48	-
Sp-2	500	50	-	1.47	3.1
Sp-3	500	50	Hot bonder	1.88	3.9
Sp-4	500	50	Heat gun	1.69	3.5
Sp-5	500	50	Gas torch	3.33	6.9
Sp-6	250	120	Gas torch	Inf	Inf

Table 3 summarizes the fatigue crack growth life extension results of tested specimens. The ratio in Table 3 is defined as the ratio between the fatigue life of a strengthened specimen to the life of Sp-1. It is evident that bonding non-activated Fe-SMA strips already significantly increases the fatigue crack growth life. This significant extension could be attributed to the bridging mechanism provided by the adhesive joining technique. When the Fe-SMA was activated, the fatigue crack growth life extension ratio was further increased. The heat gun activation method and the hot bonder activation method do not have significant difference in terms of fatigue life extension.

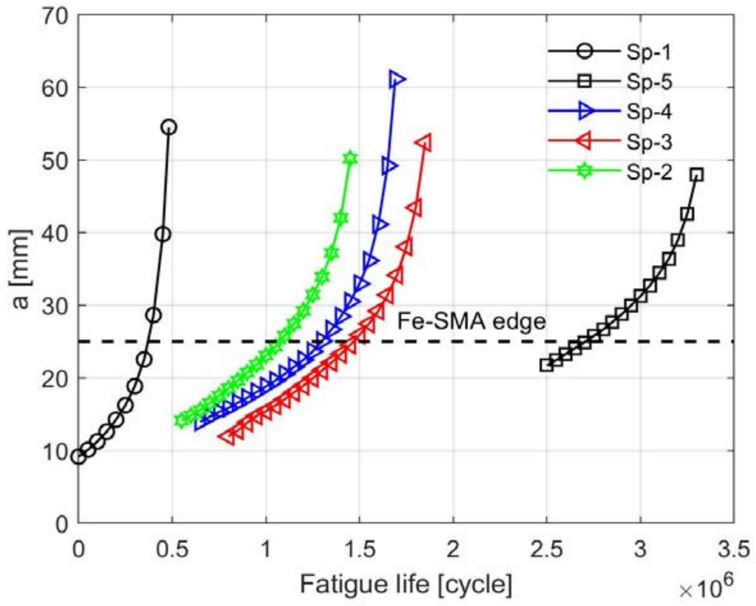

Figure 7. Crack length vs fatigue life results.

It is noted that the gas torch activation method increases the fatigue crack growth life by 6.9 times. This activation method results in the best repair efficiency. When this activation method was combined with a wider Fe-SMA, complete crack arrest was achieved.

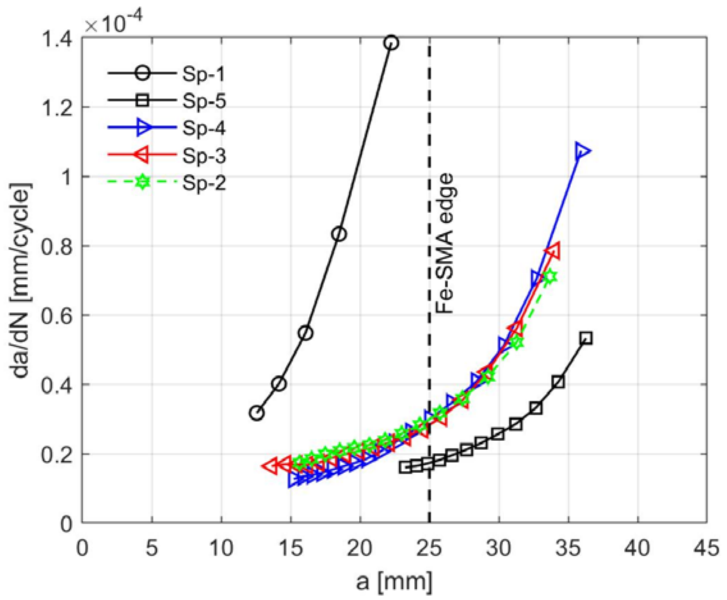

Figure 8. Fatigue crack growth behaviour.

Figure 7 and Figure 8 show the a-N and da/dN-a data of the tested specimens respectively. More insightful understanding of the crack growth behaviour could be developed. As can be observed, the bonded Fe-SMA without prestressing could retard the fatigue crack growth. The activated Fe-SMA could further retard the fatigue crack growth.

The generated compressive stresses in the steel plate are very desirable. Especially, when the crack was underneath the Fe-SMA patch, the prestressing effect retards the crack growth and leads to significant fatigue life extension. For Sp-2, Sp-3 and Sp-4, it seems that the crack growth rates for the crack beyond the Fe-SMA edge are the same.

On the other hand, Sp-5 shows that even for the crack beyond the Fe-SMA edge, the prestressing effect could significantly retards the crack growth.

CONCLUSIONS

The experimental results demonstrate the superior repair efficiency of the newly developed repair solution. The repair solution takes advantage of the bridging mechanism and prestressing effect of the Fe-SMA. The prestrained Fe-SMA patches need to be bonded and activated. The fatigue life can be extended several times and even complete crack arrest can be achieved. Based on this study, the gas torch activation method leads to the best crack retardation effect. The great potential of bonded prestressed fatigue strengthening method to significantly prolong the service life of fatigue damaged aircraft structures is substantiated in this paper.

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