LIFE EXTENSION OF FATIGUE DAMAGED COMPONENTS

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ABSTRACT

The complete procedure for the repair of fatigue damaged metal components is suggested and explained in this paper. All necessary steps are described and the most important one - the choice of the adequate fatigue crack retarding method - is supported with the fatigue test results of several fatigue crack repair methods. One group of fatigue tests deals with welding repairs as the most frequent repair procedure. The measures for fatigue strength improvements of repair weldments are described as well. Another group of specimens was tested with different fatigue crack retarding methods: metal reinforcement, CFRP patches, different crack arrest holes and tensile overloads. Structural stress factor was introduced as a crucial for the behavior of the repaired component.

KEYWORDS

Fatigue crack, repair welding, crack arrest holes, CFRP patches, structural stress factor.

INTRODUCTION

Fatigue failures, as the most frequent metal construction failures, cause high expenses and danger for human lives. A fortunate circumstance with many fatigue failures is a relatively long crack propagation period from its origin to the final failure and the crack can be discovered easily. What to do with discovered fatigue crack is a well known question in such situations. The usual answer is one of the following actions (Domazet, 1993):

a) instantaneous unloading of the entire system and replacing the cracked component or the whole structure ("with one blow of an ax" solution),
b) reducing the external loads and continuing careful crack growth control ("release excess steam" solution) and
c) retarding, stopping or even eliminating the crack in a very short time ("defeat the devil" solution).

As the conventional repairs with complete replacement can be time consuming and expensive, and reduction of service loads with existing fatigue crack is very dangerous and mostly unacceptable, the quick and cheap crack retardation methods seem to be the best solution. Because of numerous methods and lots of their parameters, the real question is which fatigue life extension method should be applied at any particular case. The aim of this paper is suggestion of the whole fatigue crack repair procedure with explanation of all steps, especially a choice of the most efficient crack retarding method.

FATIGUE CRACK REPAIR PROCEDURE

The necessary steps for a successful repair of fatigue cracked component are summarized in fig.1 (Domazet, 1993a). Each step of the suggested procedure is briefly explained.

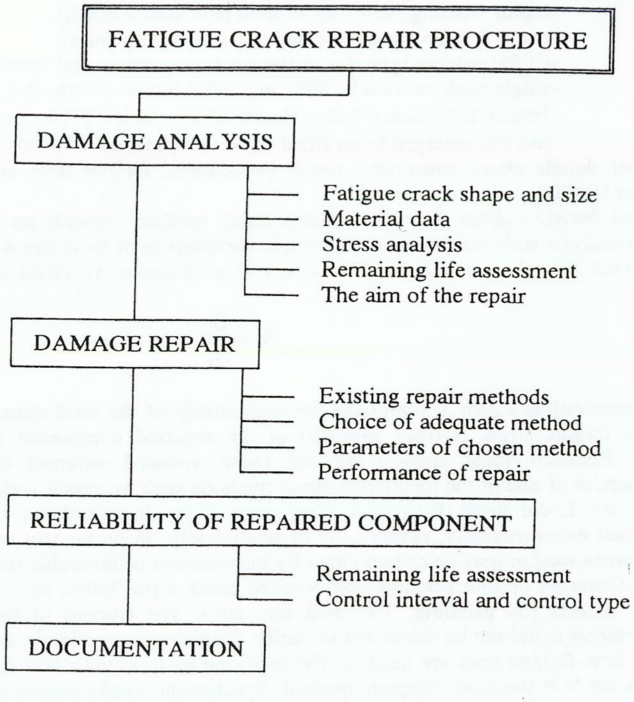

Figure 1 The suggested fatigue crack repair procedure

DAMAGE ANALYSIS

The first step with any damage and its possible repair should be damage analysis. It should give answers to some important questions, such as: what is the reason for the fatigue crack (design errors, overloads, heavy environmental conditions, end of predicted life, etc.), how dangerous is the existing fatigue crack (what are the consequences of further crack growth), how long is the remaining component life (approximate number of cycles to final failure), etc. Gathering of material data and load history studies are important due to stress distribution and remaining life calculation. Global and local stresses can be estimated by analytical, numerical (FEM) or experimental (strain gauges) methods. In the estimation of remaining life the linear fracture mechanics (LFM) may be used with some degree of success. If the LFM constants are not known, short and careful crack growth propagation should be undertaken and these parameters estimated. The role of experience and case studies from literature should not be avoided either.

DAMAGE REPAIR

Several existing fatigue crack retarding/stopping methods are shortly described and compared in this chapter. The choice of adequate method and its parameters is explained, too.

Existing repair methods

Repair welding. The repair welding is the most frequent repair method with all kinds of weldeable metal damages. Fatigue crack, as a sharp stress raiser, has been removed entirely by this welding, but lots of small welding errors are introduced in the critical area in the same time. Because of weld shape (stress concentration) and welding errors, the fatigue strength of welded metal is significantly lower than the fatigue strength of virgin metal. Hence, only the best welding methods and welding parameters are permitted in repair welding jobs (Domazet, 1993a, 1993b; Grubišić, 1993). If the fatigue strength of the repaired component is not satisfactory, significant improvements may be achieved in one of the following ways (Harrison, 1969):
-removing the small welding errors (slag intrusions, pores, lack of penetration) at weld toes by grinding or TIG - dressing , and
-introducing the compressive residual stress in the critical area by hammer peening, thermal treatments, etc.
The comparison of obtained fatigue lives by simple repair welding, quality insured repair welding, and quality insured repair welding followed by weld toe grinding or hammering is shown in fig.2.

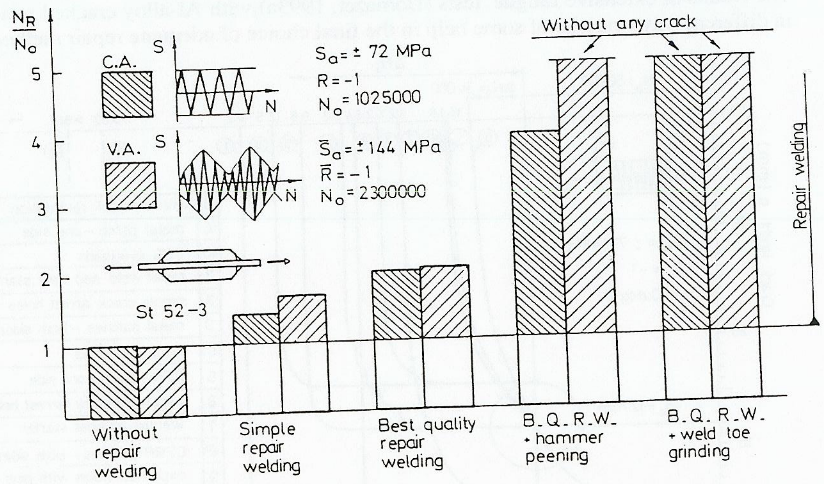

Fig.2 Comparison of remaining fatigue lives by different repair welding procedures

The used specimens were steel plates (12 mm thick) with longitudinally non-load carrying attachments welded at both sides. In both load cases, constant and variable load amplitudes, fatigue crack originated in the fillet weld toe and after its propagation to the opposite side of plate, specimens were repaired in different ways. Then they were loaded again, under the same load conditions, and the respectively reached fatigue lives are compared.

Metal reinforcement. As a possible solution in a fatigue crack retardation, strengthening panels are bolted or welded. Well known is "Metalock" method for repair of cracked cast iron and mild steel. High strength keys are inserted in prepared holes ("Metalock", 1972). The essence of these methods is reduction of stresses in the critical area, but new stress raisers are unavoidable.

CFRP patches. The repair of fatigue cracked component with adhesively bonded carbon fiber reinforcement plastic (CFRP) offers several advantages: speed of repair, absence of new holes or welds which might act as crack initiators, sealing the area around the crack, curved and double curved surface application, etc.

Single tensile overloads. The single tensile overloads normally cause a slight increase in the crack growth rate followed by a significant decrease in the growth rate and than a gradual increase back to the steady state growth. During this reduced growth rate period, a significant delay may occur.

Fatigue crack arrest holes. Simple holes are bored very often in the crack tips to reduce local stresses and stop or postpone further fatigue crack propagation. Additional improvement of fatigue behavior can be achieved when these holes are mechanically treated (cold-worked) or filled with pins, or both in the same time.

Choice of adequate method

The results of extensive fatigue tests (Domazet, 1993a) with Al-alloy cracked panels repaired in different ways may be of some help in the final choice of adequate repair method, fig.3.

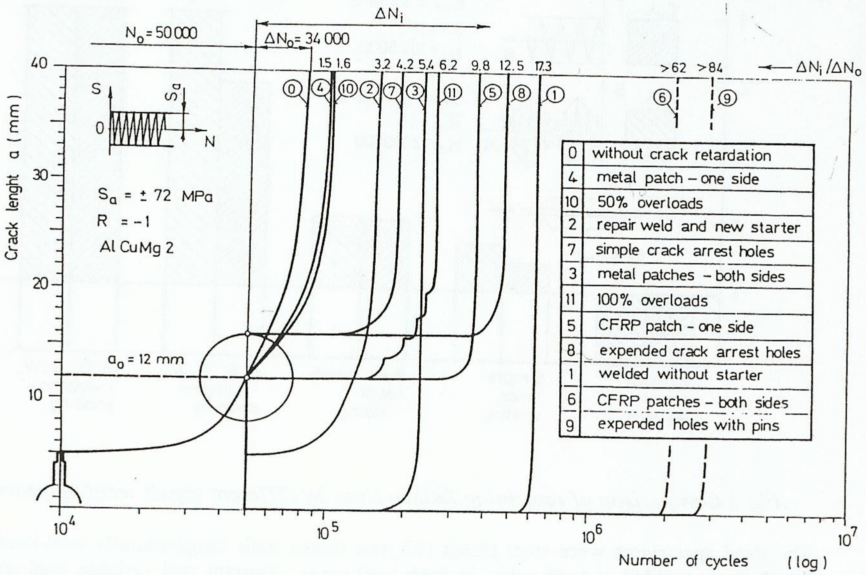

Fig.3 Comparison of remaining fatigue lives by different crack repair procedures

AlCuMg2 (according DIN 1725 or 2024-T3 according AA) panels, size 250x80x10 mm, with central fatigue crack, double length a = 24 mm, were repaired in different ways, and than loaded again under the same load conditions. The best repair method can be determined by comparing the fatigue lives (number of cycles) of specimens with the crack retardation treatment and those without it.

Following crack retarding/stopping methods were compared:

- -repair welding (with and without new starter notch),
- -metal reinforcement (welded at one and both sides),
- -CFRP patches (glued over the crack area at one and both sides),
- -single peak overloads (50% and 100% tensile overloads),
- -fatigue crack arrest holes (simple ϕ8 mm holes; 5% enlarged holes, ϕ8.4 mm; and 5% enlarged holes filled with steel pins, ϕ8.45 mm).

All other details about specimens, repair procedures, fatigue tests etc. are presented by Domazet (1993a).

The final decision about the most suitable repair method depends on all data obtained by damage analysis and could be made by simple comparison of local stress and bearable fatigue stress in the critical cross section, (Domazet, 1993a; Domazet, Grubišić, Jecić, 1995), eq.1.

$$V = \frac{S_l}{S_b} \qquad (1)$$

The dimensionless factor V represents the relationship of the local stress with respect to the bearable fatigue stress (fatigue strength) of the repaired component in the critical cross section. Reduced local stresses do not mean reduced external (service) loads, but consequences of one of the mentioned repair methods such as: repair welding, metal or CFRP patches, etc. Local stress distribution after some of repair procedures was applied could be determined experimentally, numerically or analytically. Improvement of fatigue strength in critical cross section may be caused either by introduction of favorable (compression) residual stresses (hammer or shot peening, cold-worked crack arrest holes, etc.) or removing surface welding defects (by grinding, TIG melt run, etc.). The amount of these fatigue strength improvements could not be calculated so easily. Significant experience, results from literature or even new fatigue tests are needed. The analyzed method with best (minimum) structural stress factor V is the most adequate method. Spectacular results should not be expected with combination of two or more methods at the same time because the fatigue strength reserves are limited.

Parameters of chosen repair method and its performance

The parameters of the chosen method should be determined very carefully, because the final result of repair, fatigue behavior, strongly depends on their values. Welding is the most frequent assembling procedure for steel constructions and repair jobs. Hence, its parameters are well known and summarized in standards (DIN 8563, 1978). Repair weld toes should be ground to a depth below the deepest undercut found in any length of weld to improve the fatigue strength significantly. In the case of hammer or shot peening, the compression yield point should be reached for maximal improvement. When the crack arrest holes are cold-worked, the correct degree of enlargement should be found having material properties, length and shape of crack, hole diameter, etc., in mind. Vulić (1995) determined degrees of hole enlargement by numerous combinations of materials, dimensions, crack forms, etc. With CFRP application in fatigue crack retardation, the research of appropriate number of layers, their orientation, patch size and other parameters is still in progress. It is important to find out the optimal repair parameters, because excessive welding, grinding, peening, cold-working, etc. would cause a reduction of fatigue strength, including results worse than without any repair in some cases.

After complete damage analysis and the choice of the best repair method and its optimal parameters, the repair itself should be performed. In spite of repair simplicity, the state of the art, related standards and quality assurance must be taken into account (Grubišić, 1993).

RELIABILITY OF REPAIRED COMPONENT

Remaining life assessment

Remaining life of repaired component should be estimated once again. With the new stress distribution and possible improvements of fatigue strength, remaining component life (number of cycles) can be estimated, but the S - N curve of base component should be known, fig.4.

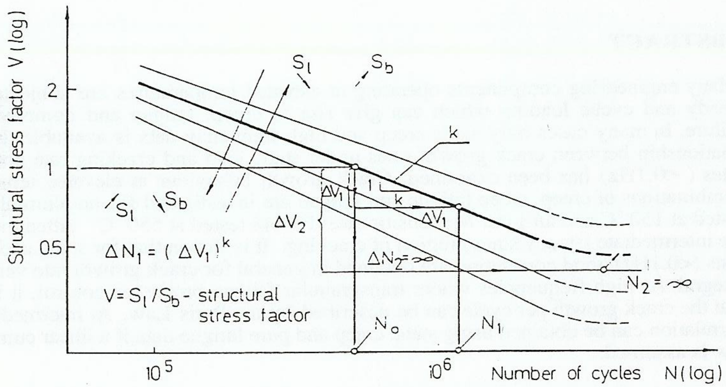

Fig.4 Structural stress factor and extended fatigue lives

The value V = 1 means failure of component. When the structural stress factor V is reduced only by 20% (reduced local stress S_l or improved bearable fatigue stress S_b, or both), and slope of S - N curve is $k \cong 4$, the remaining fatigue life is doubled or even becomes infinite.

Control interval and control type

Depending on the component size and shape, base material, approachability and other influences, the type of nondestructive control (NDT) must be defined as well as the control interval. With the lack of other methods, Griese and Müller-Wiesner (1985) suggested the use of fracture mechanics for the control interval estimation. He starts with the biggest expected (undiscovered) welding error (pore, slug intrusions, undercuts, etc.) as a fatigue crack initiator and than calculates the number of cycles for its growth up to four error diameters. This crack length makes crack discovery quite possible and its removal (by grinding) is simple and harmless.

DOCUMENTATION

In spite of numerous literature on fatigue, fracture mechanics and fatigue damages, there are very few papers dealing with fatigue behavior of repaired components or constructions. This lack of literature represents an additional reason for new fatigue damages and new doubts about their repairs, because the majority of fatigue damages are unique items. Correct and complete documentation of all undertaken activities, as well as quality ensurance, represents evidence of good work and valuable source for future repair jobs. Collections of fatigue damages in steelworks, oil industry, air traffic, etc. are encouraging, as well as few publications ("Der Maschinenschaden", "Engineering Failure Analysis", etc.) dealing with failures and its repairs.

CONCLUSIONS

From the results of this investigation the following conclusions are made:

- Simple, low cost and efficient fatigue crack retardation or even crack stopping is possible at all load conditions.
- The best fatigue crack retardation methods are quality repair welding followed by weld toe hammering or grinding (for weldeable materials), the CFRP patches applied at both sides and cold-worked crack arrest holes filled with steel pins.
- Best quality repair welding means a minimal number and minimum size of unavoidable welding errors and their further reduction by post-welding treatments. Weld toe grinding reduces the stress concentration factor and hammer peening introduces favorable residual stresses, what has lead to significant improvement of fatigue strength.
- As expected, a large stress reduction and absence of any new concentrations or out-of plane bending are main reasons for the results obtained with adhesive bonded composite patches.
- Favorable residual stresses, low stress concentration and the load transfer role of oversized pins in cold-worked crack arrest holes lead to best results in crack retardation.
- The newly introduced structural stress factor V is crucial for the behavior of the repaired component. The repair method and its parameters with minimum structural stress factor would be the best solution for any fatigue damage situation in practice.

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