*Científica* Vol. 10 Núm. 1 pp.9-14
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# Fatigue Crack Repair Profiles Based on Surface Defect Shapes

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Recibido el 4 de marzo de 2005; aceptado el 29 de octubre de 2005.

## 1. Abstract

A crack removal has the purpose to stop crack propagation and prevent future crack reinitiation, thus fatigue life of the component is extended. A profile design for the removal of fatigue cracks that grow under bending loading is presented. The design is based on the preferred shape development of surface defects under bending loading. Preferred shape development of surface defects was experimentally identified and validated with observations previously reported by other authors.

The design of a crack removal profile consists on determining a notch geometry and its dimensions to cut out a crack. The crack removal profile presented here induces crack reinitiation, if it would occur, on the surface plate at the notch ends rather than in the bottom of the notch, so original plate thickness is reinstalled for propagation and inspection is easier. This repair procedure is recommended for the removal of fatigue cracks in tubular joints of offshore jackets steel structures.

**Key words:** fatigue, crack, repair.

## 2. Resumen (Perfiles de reparación de grietas por fatiga basados en formas de defectos en superficie)

El propósito de remover una grieta es detener su propagación y prevenir una posible reinicialización de ésta y, por lo tanto, extender la vida por fatiga del componente estructural. En este artículo se presenta el diseño de perfiles para remover grietas por fatiga que crecen debidas a cargas de flexión, el cual se debe al desarrollo de formas preferenciales para defectos superficiales. Nuestros resultados se basan en estudios experimentales que son validados con respecto a resultados obtenidos por otros autores.

El diseño del perfil para remover la grietas consiste en determinar una geometría de marcas o ranurado superficial para remover una grieta. Tal perfil induce una reinicialización de la grieta, si ocurre sobre una superficie de la placa en los extremos del ranurado superficial en lugar del fondo de éste. Este procedimiento es recomendado para remover grietas por fatiga en juntas tubulares en estructuras marinas tipo *jacket*.

**Palabras clave:** fatiga, grieta, reparación.

## 3. Introduction

Fatigue cracking of welded connections subjected to cyclic loading is a frequent finding during inspection. Fatigue crack initiation in welded connections is usually located at the weld toes. Early crack detection allows removing the crack before it reaches the back wall disconnecting the component. This procedure extends the fatigue life of the component and reduces the cost of repair compared with other repair options applied in more advanced stages of damage. For example, cost of crack removal compared with joint clamping in offshore jackets.

It has been identified that growth of surface defects like fatigue cracks have a preferred shape. Based on the surface defect growth preferred shape concept it has been proposed a removal profile shape to remove the cracked region. Since the notch produced by the removal profile is a surface defect, it has been experimentally validated that if crack reinitiation would occur after crack removal, crack growth adjusts to the preferred shape growth. So, design of the removal profile consists on selecting the notch dimensions which under cyclic loading, induces crack initiation on a desired location of the notch. This location is where the notch has to increase its dimension (depth or length) to adjust to the preferred surface defect growth shape.

To reinstall the original plate thickness for crack propagation it is desired that crack reinitiation, if it would occur, takes place on the surface plate at the notch ends rather than in the bottom of the notch. Additionally, inspection on the surface plate is easier than in the bottom of the notch.

### Nomenclature

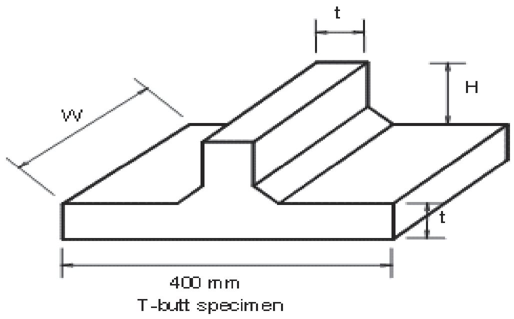
| | |
|---|---|
| *a* | crack depth |
| *t* | plate thickness |
| *c* | half surface length |
| *R* | machined groove transverse radius |
| *D* | machined groove depth |
| *L* | machined groove length |

## 4. Development

### 4.1 Experimental observations of crack shape development during fatigue

It has been found that growth of surface defects on structural components subjected to fatigue loading adopt specific preferred shapes. Defect shapes during growth mainly depend on the loading mode applied (tension or bending). Scott and Thorpe summarized empirical observations of crack shape development under tensile or pure bending fatigue loading [1]. They mentioned that fatigue cracks try to achieve an equilibrium shape. In tension, fatigue cracks in finite thickness plates grow preferentially in a nearly semi-circular shape while the depth is less than half of the plate thickness and then elongate as they grow towards the back wall. For the bending case, fatigue cracks tend to elongate; even for cracks whose surface length is longer than the preferred value, a relatively rapid adjustment to the equilibrium shape occurs.

To study the defect growth shape development in bending loading, which is less documented than the tension case, T-butt plates were fatigue tested under pure bending in a three point bending set-up. T-butt plates were manufactured by welding two plates or by machining a block of steel to the desired dimensions, see T-butt dimensions in Figure 1.



| Manufacture | T (mm) | W (mm) | H (mm) | Specimens |
|---|---|---|---|---|
| Automatic Welding | 20 | 300 | 20 | 2, 5, 6 |
| Machined | 20 | 200 | 10 | 3 |
| Machined | 30 | 200 | 55 | 4 |
| Manual Welding | 30 | 200 | 55 | 1 |

**Fig. 1.** T-butt welded and machined specimens dimensions.

Experimental crack shape development data was collected using the Alternating Current Power Drop technique (ACPD) incorporated in a U-10 micro gauge. Crack shape data obtained from defects growing at the weld toe in as welded condition showed an approximately similar growth rate in depth and in half length up to $a/t = 0.13$, see specimens 1 and 2 in Figure 2. To discard the effect of weld defects on a surface defect growth, two machined specimens with a centered shallow blade cut at the weld toe were tested; growth rate was similar as in the previous case, see specimens 3 and 4 in Figure 2. Specimens 2 and 4 show that for $0.13 < a/t < 1.0$, $a/c$ ratio would tend to assume an almost constant value which ranges from 0.1 up to 0.13.

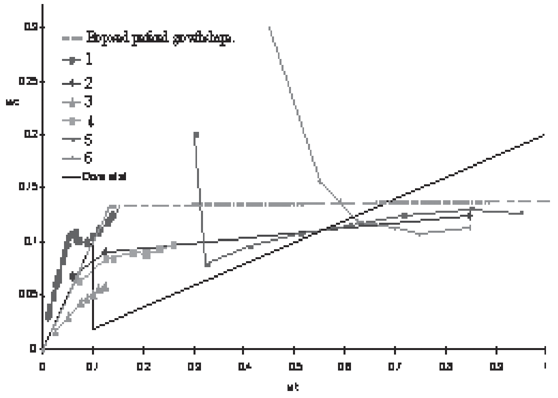


**Fig. 2.** Experimentally determined development of crack shape under pure bending fatigue loading.

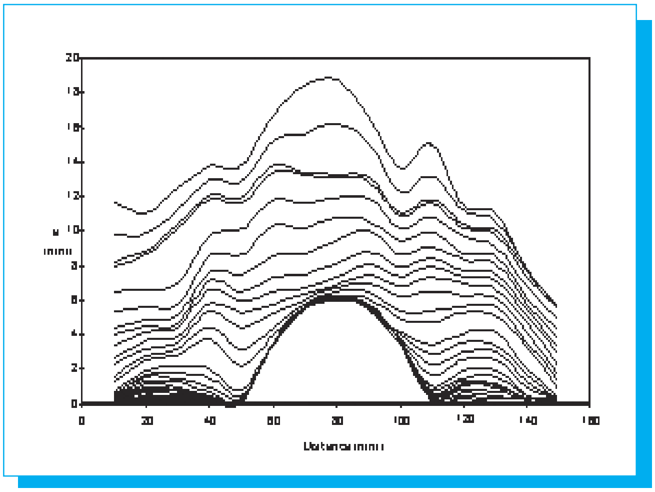


**Fig. 3.** Crack shape growth contours initiating at the ends of the groove of specimen 5 to adjust to the equilibrium shape.

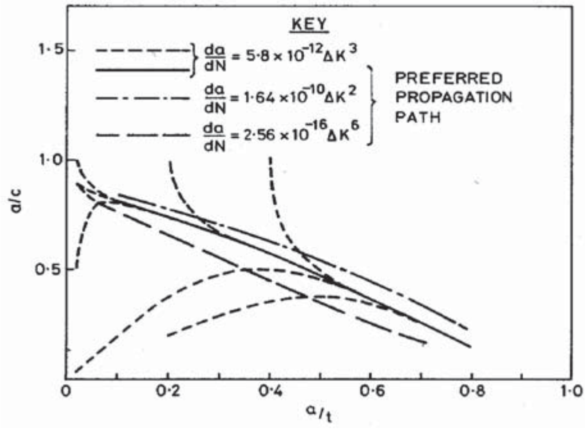


**Fig. 4.** Calculated crack shape under pure bending loading [1].

In addition to specimens 1 & 2 (tested in as welded condition) and 3 & 4 (tested in as machined condition), two welded specimens 5 & 6 with a machined groove were experimentally tested. The groove in each specimen is at the weld toe and is centered along the specimen; it was machined with a disc cutter. The groove dimensions are characterized by three parameters: transverse radius, depth and surface length. For specimens 5 and 6, groove dimensions in millimeters are: $R$=4, $D$ = 6, $L$ = 60 and $R$ = 4, $D$ = 9, $L$ = 60 respectively. The experiment had the purpose to demonstrate that a surface defect simulated by a groove, would tend to assume the equilibrium shape adjusting $a/c$ ratio. For specimen 5, $a/t$ = 6/20=0.3 and $a/c=a/0.5L$ = 6/30=0.2; and for specimen 6, $a/t$ = 9/20=0.45 and $a/c=a/0.5L$ = 9/30=0.3.

Since $a/c$ for specimens 5 & 6 was beyond 0.13, the crack shape development was expected to adjust to the equilibrium shape shown by specimens 2 & 4 beyond this point. Experimentally collected data during fatigue loading of specimens 5 and 6 demonstrated that the grooves were shorter than the preferred equilibrium shape for a surface defect growth, thus cracking initiated at the ends of the grooves to increase the surface length ($c$ value) and decreasing the $a/c$ ratios to the equilibrium shape, see Figure 2.

It is a curious consequence of the tendency to assume a preferred growth shape, that crack growth in the bottom of the groove in specimens 5 and 6 did not occur until $a/c$ reached a preferred growth shape, see Figure 3 where crack growth determined by ACPD in specimen 5 initiated at the ends of the groove increasing c value and decreasing the a/c ratio to adjust to the equilibrium shape in Figure 2.

## 4.2 Design of a removal profile for fatigue cracks

From the experimental data determined from pure bending fatigue loaded as-welded, machined and grooved T-butt specimens, it can be empirically deduced from Figure 2 that the equilibrium growth shape is in the range of $0.1 < a/c < 0.13$. This result is in accordance with calculated crack shape change during pure bending fatigue loading using stress intensity factors calibrations by Scott and Thorpe [1], see Figure 4.

However, it is worth pointing out that the data presented in Figure 2, shows an extended equilibrium growth shape region ($a/t > 0.8$) which is not shown in Figure 4.

From the experimental data, an estimated prediction of surface defect growth shape under pure bending can be expressed as in equations 1 and 2. This proposed preferred growth shape is shown in Figure 2.

$$a/c = a/t \quad \text{for} \quad 0 < a/t < 0.13 \qquad (1)$$

$$0.1 < a/c < 0.13 \quad \text{for} \quad 0.13 \leq a/t < 1.0 \qquad (2)$$

A lower bound crack aspect ratio for offshore jacket tubular joints was proposed by Dover *et al*. [2] and is described by the following equations:

$$a/c = a/t \quad \text{for} \quad 0 < a/t < 0.1 \qquad (3)$$

$$a/c = a/5t \quad \text{for} \quad 0.1 \leq a/t < 1.0 \qquad (4)$$

It can be observed a good agreement in equations (1) and (3) and a close approximation in equations (2) and (4); this is also shown in Figure 2. This similarity is due to the fact that for tubular joints, the stress field near the weld is predominantly bending, even under axial loading [3].

In practical terms it can be considered that fatigue crack removal profiles would be deeper than 0.13t thus, from equation (2) it is possible to identify *a/c* and *a/t* ratios for the design of a fatigue crack removal profile for bending loading. To select the most appropriate *a/c* and *a/t* ratios, it has to be considered that a crack removal profile with *a/c* ratios lower than 0.1 would develop cracks in the bottom of the groove to adjust to the equilibrium growth shape. On the contrary if a crack removal profile has *a/c* ratios higher than 0.13, it would develop cracks at the ends of the groove on the surface of the plate, see Figure 3.

From an engineering approach, it is preferable to design a crack removal profile where if crack reinitiates, it takes place on the surface plate rather than in the bottom of the groove closer to the back wall; repair profiles of this shape could be named short repairs. Crack initiation on the surface plate makes inspection of the groove easier thus, reliability of the component is increased.

Since growth shape depends on *a/c* and *a/t* ratios, the removal profile to comply with a desired *a/c* ratio is not unique. In the offshore industry crack removals are usually performed by burr grinding a profile with slanted walls ending on a flat bottom, however profile dimensions are not selected to force crack initiation in a desired place of the groove. Current practice to design crack removals is based on adding an allowance to the crack depth dimensions, to take in account inspection equipment inaccuracies, and a smooth transition from the surface plate to the repair bottom, see Figure 5. This type of repair has commonly an *a/c* ratio less than 0.1 thus, initiation if it would occur, is expected in the bottom of the repair.

## 4.3 Crack removal techniques for the offshore industry

Selection of a crack removal technique would depend on the environment, tools available and previous experience. Underwater crack removal by burr grinding is a common technique used in offshore jackets. It requires a great amount of force to be applied by the diver on the tool thus, high quality profiles are not regularly achieved since burr tool during grinding tends to skip sideways rather than biting into the metal.

A novel application of the Electrochemical Machining (ECM) Technique has been studied for this purpose. ECM is the controlled dissolution of a metal workpiece using electrolysis. Since offshore industry is moving into deep waters and diver intervention is increasingly risky in this environment, industry has been forced to consider the application of remotely operated vehicles (ROV) for underwater intervention. The ECM technique was considered appropriate for fatigue crack removal since it has been proved to be a more suitable technique than burr grinding to be deployed by an ROV arm [4].

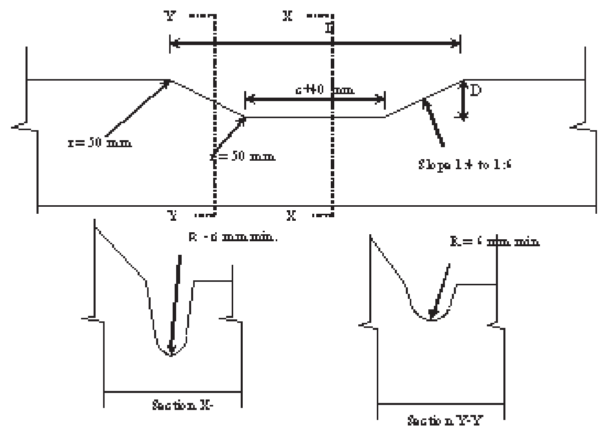


**Fig. 5.** Crack removal profiles used in the offshore oil industry for jacket platforms.

## 4.4 Experimental fatigue life extension of removed fatigue cracks

Experimental data of crack depth (measured by the ACPD technique) versus number of cycles, of specimens 3, 5 and 6 allowed to determine the fatigue life extension.

Specimen 3

Fatigue life for a crack growing in as welded condition up to $a$=3 mm was determined as $2.8\text{x}10^5$ cycles. A repair profile of dimensions $R$ =4, $D$ = 4 and $L$ = 60 was machined, and weld toes were smoothed at both sides of the repair with a profile $R$=8, $D$=3.

The specimen failed after $4.7\ \text{x}10^5$ cycles on the unrepaired side (other side of the vertical attachment plate) where weld toes were in as welded condition. Fatigue life increment with no sign of cracking would be 4.7/2.8 = 1.7 times the as-welded fatigue life. Repair depth to plate thickness ratio: 100(7/20) = 35%

**Table 1.** Fatigue life extension of crack repaired specimens.

| Specimen | Repair Profile | Weld Toes | Nom. Stress (MPa) | Repair Depth Thickness Ratio | Crack Depth after Repair (mm) | Fatigue Life Increment |
|---|---|---|---|---|---|---|
| 3 | R4D4L60 | R8D3 | 300 | 35% | 0 | 1.7 |
| 5 | R4D6L60 | As-welded | 200 | 30% | 6 | 2.1 |
| 6 | R4D9L60 | As-welded | 200 | 45% | 9 | 1.6 |

Specimen 5

Fatigue life for a crack growing in as welded condition up to $a$=6 mm was determined as 2.7x$10^5$ cycles. A repair profile of dimensions $R$=4, $D$=6 and $L$=60 was machined. The fatigue life after repair was 3.1 x$10^5$ cycles. Fatigue life extension obtained would be (2.7+3.1)/2.7=2.1 times the as-welded fatigue life. Repair depth to plate thickness ratio: 100(6/20) = 30%.

Specimen 6

Fatigue life for a crack growing in as welded condition up to $a$=9 mm was determined as 3.3x$10^5$ cycles. A repair profile of dimensions $R$=4, $D$=9 and $L$=60 was machined. The fatigue life after repair was 2.0 x$10^5$ cycles. Thus, after repair the fatigue life extension obtained would be (3.3+2)/3.3=1.6 times the as-welded fatigue life. Repair depth to plate thickness ratio: 100(9/20) = 45%.

Results presented above are summarized in Table 1, it is worth pointing out that these results are based on limited experimental data, thus an extensive validation is recommended for its application in the industry.

Fatigue life extension basically depends on the repair depth reached after the crack has been totally removed. Experimental research data from specimens 5 and 6 has demonstrated that the original fatigue life can be reinstalled when repair depths to remove cracks are up to 30% of the plate thickness. Beyond this repair depth, expected fatigue life extension is reduced. [5]. A recommended practice to extend even further the fatigue life after repair consists on smoothing the weld toes at both sides of the repair as was performed on specimen 3.

For short repair profiles, where shape ratio $2D/L > 0.13$, it is maybe possible to monitor crack initiation at the repair ends on the plate surface and make a second repair before the crack depth ($a$) reaches the repair depth ($D$) thus, fatigue life could be extended even more than the original fatigue life. Of course, the second repair could not be a short repair and crack initiation is expected to occur in the bottom of the repair. A second repair and its associated fatigue life extension has not been experimentally validated.

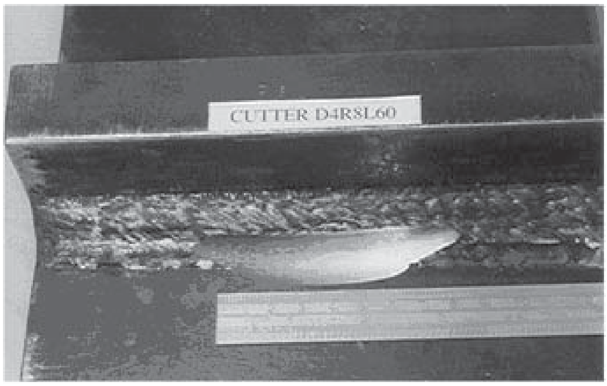


**Fig. 1.** A Short repair profile on a T-butt specimen.

A short repair groove profile machined on a T-butt specimen using a disc cutter is shown in Figure 6.

## 5. Conclusions

A surface crack shape growth prediction for fatigue bending loading has been experimentally determined. The prediction is based on limited experimental data, thus it was validated with calculated crack shape growth reported by other authors. Based on this prediction, it is possible to design groove geometries for the removal of fatigue cracks and extend the fatigue life of cracked components. An extensive experimental validation is recommended for the application of this finding in the industry.

Groove geometries for the removal of fatigue cracks have the purpose to stop crack propagation and prevent future crack reinitiation. However, if crack reinitiation would occur, the groove geometry is designed to induce crack reinitiation on the surface plate rather than in the bottom of the repair. Thus, the original plate thickness is reinstated for crack propagation. Inspection on the surface plate is easier and more reliable, this is especially useful for underwater applications like in repairs of cracked tubular joints of jacket platforms.

Groove geometries with this characteristics have to comply with a $2D/L$ ratio greater than 0.13 (short repairs). These geometries in terms of preferred crack shape growth are short in length compared with its depth, thus crack initiation occurs at the ends of the groove to increase its length. Once crack initiation begins, the groove behaves like a crack and its growth tends to merge the preferred crack shape growth described in this paper. Thus, long shallow groves (2*D*/*L* ratio less than 0.13) will always develop crack initiation in the bottom.

The limited experimental results obtained also showed that the application of short repairs in some cases can provide extensions of fatigue life larger than a factor of two. This is more likely to occur when the cracks are repaired in early stages of growth and the repair ends are machined to remove weld defects.

## Acknowledgements

Authors would like to express thanks for the support given by Instituto Mexicano del Petroleo and UCL Mechanical Engineering workshop personnel.

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