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## Fatigue strengthening of welds in light rail structures

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**London's Docklands Light Railway (DLR) has been in service for 20 years and has previously been strengthened when it was upgraded from one-car trains to two-car trains in 1990. It is now to be upgraded again to carry three-car trains to be run at higher frequencies and is required to have a fatigue life of 120 years from the year 2010, namely for the structures to remain serviceable until the year 2130. Some of the welds connecting stiffeners to main beams, which were found to be under strength in fatigue, were strengthened by ultrasonic impact treatment (UIT). A programme of fatigue tests has been carried out to evaluate the extent of the improvement and confirm that it is adequate. The tests were on tensile test pieces having non-load-carrying fillet welded attachments relevant to the (BS5400 class F2) under strength welds. Test pieces were pre-fatigued to simulate 20 years' service and treated by ultrasonic impact. The UIT improved the class F2 fillet welds to a performance between class D and class E. There is a 97.5% probability that performance is improved by a factor of 3 on life and the value of  $\sigma_0$  (the constant amplitude non-propagating design stress range) is raised from 35 to 50 N/mm<sup>2</sup>. The action of UIT is to halt crack propagation from the weld toe and propagation from the root is slowed as it passes through the treated zone. Furthermore, UIT is effective on existing fatigue cracks having an estimated surface length of up to 8 mm and depth of 1.5 mm. Experiences gained from the experimental programme enabled an improved specification for UIT quality control to be developed. These data were used in support of the design work to upgrade the DLR structures and the UIT was successfully applied to the under-strength welds under live loading.**

### 1. BACKGROUND

When the Docklands Light Railway (DLR) opened in August 1987 it was composed of 11 single-car trains operating on less than 10 miles of track. Since then it has been extended four times and now has 93 two-car trains running on 32 km of track.

When it was upgraded to two-car trains in 1990, it was identified that it would be necessary to increase the fatigue lives of some of the welded joints in the steel superstructure (Pilgrim and Pritchard, 1990).

In this earlier upgrade, it was calculated that a detail at the end of a fillet welded bearing support in a main girder had inadequate fatigue strength as it would experience stress ranges exceeding the constant amplitude non-propagating stress range ( $\sigma_0$ ) for a Class F2 weld in BS5400 (BSI, 1980), namely 35 N/mm<sup>2</sup>. It was therefore necessary to improve the fatigue performance of the weld. Hammer-peening the weld toes was selected as the appropriate treatment as work by (Knight, 1978) had shown that three-fold improvements could be achieved.

The Welding Institute (TWI) was commissioned to carry out work to confirm and evaluate the potential improvement by hammer-peening under conditions relevant to the bearing support. Fatigue tests were carried out on test pieces having non-load-carrying fillet welds with and without hammer-peening (Maddox, 1997). The tests confirmed that hammer-peening produced an adequate improvement as it doubled the value of  $\sigma_0$  and increased life by a factor of 8.

In the present upgrade, live loading has been raised to three-car trains to be run at an increased frequency. It has therefore been necessary to make a fresh assessment of the remaining fatigue lives of all the welded joints and carry out any strengthening that may be required.

The object of the work was to evaluate the improvement achieved by UIT and derive a safe design criterion. The structures requiring improved fatigue performance for this project were Docks Crossings South, Middle and North. Docks Crossing South is shown in Figure 1.

### 2. THE PRESENT UPGRADE

#### 2.1. Updated assessment

The present upgrade requires a fatigue life of 120 years from 2010. Depending on the location this is equivalent to as much as 20 million cycles of fatigue stress. An updated assessment of the structures based on DLR standards and conventional modelling techniques, indicated that many of the welded connections would have low fatigue lives when the more intensive loading is introduced (Jackson, 2010). However, strain gauge measurements showed that there are hidden reserves of strength as many of the measured stress ranges were lower than calculated. Nevertheless it was confirmed that there remained some 270 fillet welds connecting web-stiffeners to main beams which required improvement.



Figure 1. Docks Crossing South

## 2.2. Options to improve fatigue strength

Practical options to improve fatigue strength include techniques such as added plating, smoothing the weld profile by TIG (tungsten inert gas) dressing, grinding or peening. Although hammer-peening had been used successfully in the past it has drawbacks in that it involves relatively heavy equipment and generates a high level of noise that can be unacceptable to occupants of adjacent buildings. It was decided to use ultrasonic impact treatment (UIT), a variant of hammer peening. UIT was selected in preference to hammer-peening because it generates minimal noise and has a lower environmental impact. The equipment also produces near zero hand-arm vibration so that there are health and safety advantages as well as an easing of resource management because rotation of operatives is not required. Moreover the equipment is lightweight, portable and can be adjusted for use in difficult locations where hammer-peening would not be possible. The action of UIT is topeen the welds by way of 3 mm diameter pins vibrating at a frequency of around 27 kHz. Peening smooths the profile of the weld toe and imposes residual compressive stresses to achieve an improved fatigue performance. Measurements of residual stress by Gunter *et al.* (2005) showed that values of the compressive stresses imposed by UIT could be between 300 and 600 N/mm<sup>2</sup>.

Substantial improvements in fatigue performance by UIT have been confirmed by a considerable body of research, for example, Gunter *et al.* (2005) and Roy *et al.* (2001). Nevertheless it has not been used before in the UK and reported uses in other countries

have been on new build as opposed to structures that have already experienced some fatigue damage. It was therefore decided to carry out a programme of testing at TWI to confirm and evaluate the improvement that can be achieved to the welds in the DLR structures.

## 3. PROGRAMME OF TESTS

### 3.1. Technique

The testing programme was designed to be fully compatible with the earlier work. Uniaxial test pieces were fabricated from 30 mm thick steel plate complying with BS EN 10025:2004 grade 255J2 (BSI, 2004). Non-load-carrying stiffeners were attached with 8 mm leg fillet welds completed in three passes, as shown in Figure 2. This design of test piece has a Class F2 fatigue classification and was selected because it has well publicised properties and has been used in many investigations in the past. Moreover, it was used in support of the earlier upgrade of DLR structures (Maddox, 1997).

The fatigue tests were carried out in 1000 kN capacity hydraulic machines at cyclic frequencies in the range 5–8 Hz. The cycles were in repeated tension having minimum stresses of 120 N/mm<sup>2</sup>. The stress ranges were selected to produce lives in the range 10<sup>5</sup> to 2 × 10<sup>7</sup> cycles, the latter corresponding to the number of cycles for a required life of 120 years.

Reference tests were carried out on as-welded test pieces to establish the untreated fatigue strength and correlate with tests carried out in the earlier programme.

Tests on strengthened welds were carried out in three phases: pre-fatigue, UIT and cycling to failure. The pre-fatigue was essentially a fatigue test stopped at a fraction of the expected life and designed to simulate the damage caused by 20 years of service loading. Since there had been no reported cracking from the principal inspections of the DLR structures it was decided that the pre-fatigue phase should not extend beyond the first appearance of a crack. It was therefore set at the first appearance of a crack or 10% of the expected life of the as-welded test piece, whichever came first. Using magnetic particle inspection (MPI) it was possible to detect cracks as short as 2 mm but there was inevitably a degree of variability as inspections were carried out periodically. Eight of the pre-fatigue tests were halted with cracks of lengths from 2 to 8 mm and three without any cracks evident at 10% life.

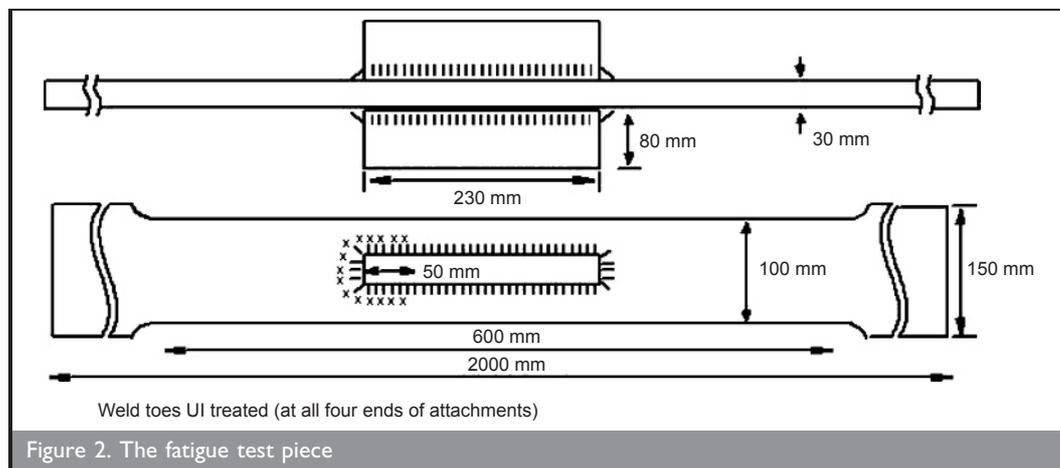


Figure 2. The fatigue test piece

After pre-fatigue, the toes of the welds were UI treated to compensate for the damage and extend their remaining fatigue lives. All the treatments were made with the test pieces staying in the fatigue machines. The grooves produced by the UIT were inspected to confirm that the required profile had been achieved.

On completion of the UIT, the tests were continued at the same ranges as the pre-fatigue. There was a problem with one of the hydraulic machines resulting in one of the tests being run at a lower limit of 105 N/mm<sup>2</sup> instead of 120 N/mm<sup>2</sup>. As the resulting life placed the failure at the lower end of the scatter band the test was included in the results but an extra test at the correct lower limit and the same range was added to the programme.

### 3.2. Fatigue data

The fatigue performances of the as-welded test pieces correlated closely with the earlier work and confirmed that the two programmes of testing were compatible, as shown in Figure 3. It was therefore possible to establish the reference *S-N* fatigue curve from a small number of tests. During the tests it was observed that cracking at the weld toe occurred within 10% of the eventual life to failure.

With one exception the pre-fatigued and UI-treated tests were run to failure, the exception was stopped unbroken after  $2 \times 10^7$  cycles. The *S-N* fatigue data are shown in Figure 4. In the analysis of fatigue data, unbroken tests can be ignored, assessed using the method of maximum likelihood, or treated as having failed. In the present analysis the latter approach was taken as it makes no allowance for the possibility of an extended life and is the most conservative interpretation. The data were analysed with the aim of providing estimates that correspond to the same 97.5% probability of survival as that embodied in BS5400 (BSI, 1980). The relationship between stress range and endurance was assumed to be a simple power law,  $\sigma^m N = \text{const.}$ , where  $\sigma$  is the stress range and  $N$  is number of cycles to failure. The sensitivity to the value of  $m$ , the stress exponent, was investigated and two values were considered: the best fit to the data giving  $m = 3.2$ , and the value used in BS5400 of  $m = 3.0$ . It was decided to adopt the value of

$m = 3.0$  as it produced the most conservative improvement factor on fatigue strength ( $\sigma_0$ ), namely 1.44, and the corresponding improvement in life of 3.0. This factor can be interpreted for design purposes as upgrading class F2 welds to a performance between class E and class D. A less conservative analysis simply based on the mean curves would give an improvement in fatigue strength of 1.62 and life by 4.2.

### 3.3. Modes of failure

The as-welded test pieces failed from cracks that initiated at the weld toes at one end of the stiffener and propagated through the parent plate, as shown in Figure 5. It was also found that cracking had initiated at the weld root and in two cases propagated through the throat but did not reach the stage when failure was threatened.

Examination of the fractures on the pre-fatigued and treated test pieces confirmed that the UIT was effective in halting propagation of cracks that had been initiated at the weld toes. The eventual mode of failure was the same in every case, consisting of crack growth from the weld root through the throat and finally through the parent plate, see Figure 6. This was the same as occurred in the earlier tests on hammer-peened welds. In the case of the long-running test that survived  $2 \times 10^7$  cycles without failure, it was subsequently found that cracking had initiated in the weld throat at one end of the stiffener to an extent that implied that it had reached an endurance estimated to be between 50 and 90% of life. This provides added support to the conservative decision to treat the run-out as a failure.

It was found that UIT had a second beneficial effect because the rate of propagation of the root cracks was slowed down when they passed through the region of compressive residual stress imposed by the treatment. It follows that the treatment should be continued around the ends of the stiffeners and some way along each side to ensure that the later stages of any cracking from the weld root are slowed down.

### 3.4. Implications of root cracking

In its early stages cracking initiated in the weld root is inaccessible and therefore difficult if not impossible to inspect

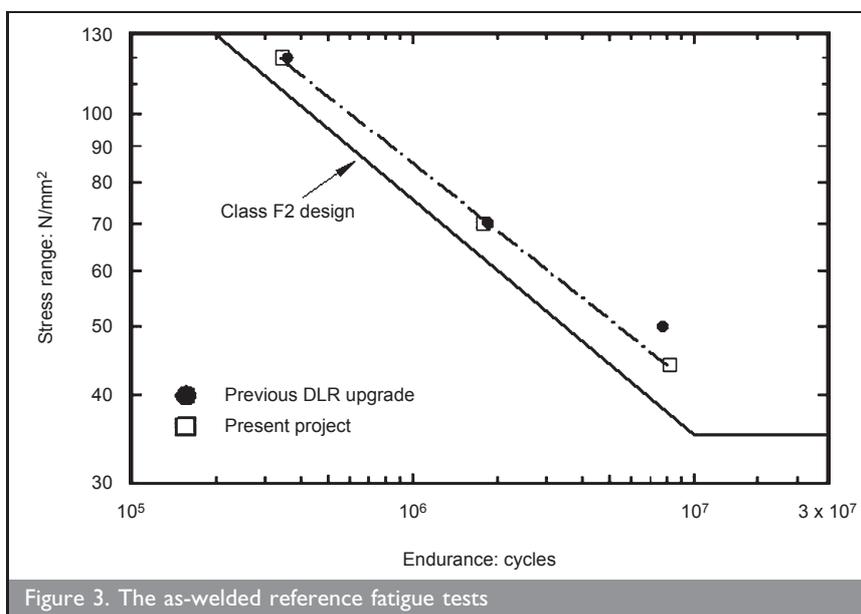
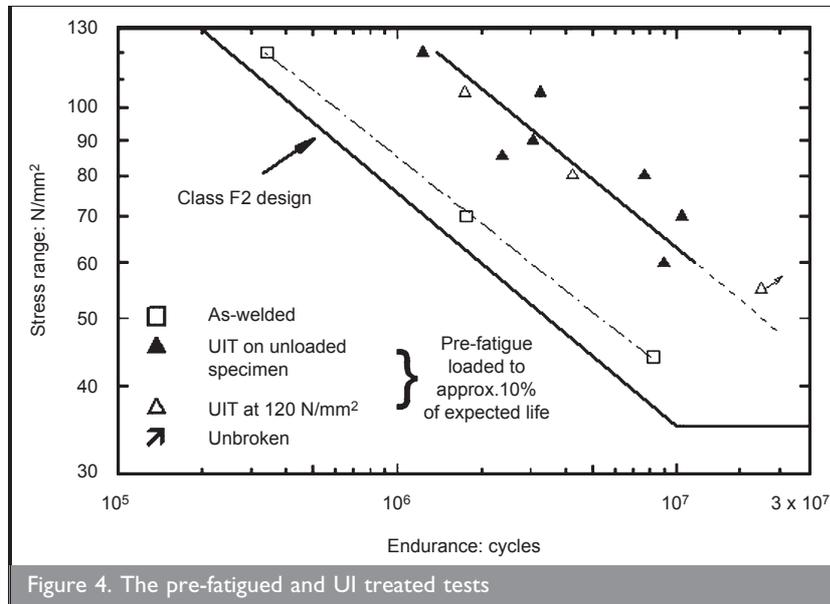


Figure 3. The as-welded reference fatigue tests



by available methods of non-destructive testing. However, subsequent observations of the cracking indicate that after about 30% of the available life it becomes visible on the weld face. This is followed by a stage when 30 to 40% of the life is available for inspection and monitoring.

#### 4. SITE WORK

##### 4.1. UIT procedure

The welds found to require treatment were inspected for the presence of cracking as it was considered that although the tests had demonstrated that UIT successfully strengthened welds having cracks of up to 8 mm in surface length, it would not be appropriate to treat longer cracks. In the event, no fatigue cracks were found even in locations where the assessment indicated a low remnant fatigue life. After inspection, paint was removed from the weld toes by use of a needle gun and wire brush grinders, taking great care to collect the detritus and prevent anything from dropping below the viaducts. The UI treatment was applied along the toe of the weld at the transition of the weld material and base material, as shown in Figure 7. The tool



Figure 5. Fatigue crack from weld toe and into main plate of an as-welded test piece

was continuously moved back and forth and progressively forward in a path parallel to the direction of the weld toe. The site work was carried out under live load conditions.

Some of the welds would have been impossible to access for hammer-peening and were difficult even with the more accommodating UIT equipment. In these cases a modified UIT tool was used that had an extended head to give it greater flexibility around the bases of the stiffeners. Where bolted connections were close to the web stiffener this would not have been sufficient and on confirmation of the remaining fatigue life, these areas were treated using a die-grinder as shown in Figure 8. An example of a stiffener weld requiring die-grinding is shown in Figure 9.

##### 4.2. Inspection of UIT

The treated welds were checked by an independent inspector to confirm that the UIT had been properly carried out. The following requirements were especially developed for the project.

- (a) The nature and appearance of a properly formed shiny groove at the weld toe was the main evidence that the UI



Figure 6. Fatigue crack from root and into main plate of a pre-fatigued and treated test piece.



Figure 7. Application of UIT on site

treatment had been correctly applied, as shown in Figure 10.

- (b) The groove should be clearly visible as a continuous shiny pathway.
- (c) The groove should be uniformly smooth after treatment, centred on the weld toe, and no less than 25% over the weld metal.
- (d) The groove should be homogeneous, uninterrupted and free of any remaining traces of the weld toe.
- (e) There should be no evidence of digging, undercut or other linear indications visible in the centre of the UI-treated area.
- (f) The dimensions of the groove should be in the range 3–5 mm wide and 0.3–0.6 mm deep. This was checked using plasticine moulds which were then measured with calibrated vernier callipers.

#### 4.3. Plating

Bolted doubler plates were installed in locations where it was calculated that the remaining fatigue lives of the Class D longitudinal welds between web and bottom flange in the main beams were very low and the enhancement produced by peening would not have been sufficient. On Docks Crossing Middle, both

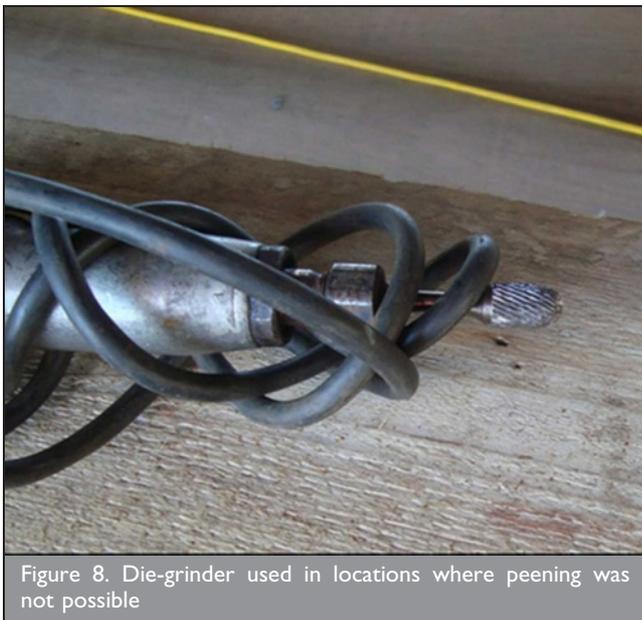


Figure 8. Die-grinder used in locations where peening was not possible



Figure 9. Stiffener requiring die-grinding at base (white area)

UIT and plating were applied. On Docks Crossing North the plating was heavier, and as access was more difficult, most of the plates were spliced to reduce their size.

#### 5. PROGRAMME AND COST

A total of three structures were treated on the Docks Crossings North, Middle and South. Each structure had around 90 stiffeners requiring treatment, with Docks Crossing North containing the greatest number of locations that were difficult to treat. On each structure (excluding scaffold construction and paint removal) the treatment was completed within four



Figure 10. Example of UIT groove

working days with the first day partly used for site familiarisation and set-up and the final half day recording all results and taking moulds of the UIT grooves.

Where bottom flange doubler plates were installed (again excluding scaffold construction and paint removal) a typical duration took two weeks drilling all holes, three days fitting plates and a further two nights of tightening bolts when no live load was being imposed.

A simple cost comparison exercise against the plating was completed for Docks Crossing Middle and Docks Crossing North. It was found that based on there being about 25 linear metres of doubler plates over the girders at Docks Crossing North and 133 m of UIT, that the UIT cost 15% of the doubler plates. At Docks Crossing Middle, there were about 43 m of doubler plates and 100 m of UIT and the UIT was 40% of the cost. The linear rate of the UIT was similar at each structure and variations were due to spacing of the stiffeners. Although the costs are not directly comparable as the doubler plates offer a higher fatigue life where UIT was not appropriate, it gives a good indication of the cost effectiveness of UIT. Principally this is because it is faster and although there are hire and licensing costs of the equipment there are no additional material costs.

## 6. CONCLUDING REMARKS

Many of the fillet welds connecting stiffeners to main beams of the DLR structures have been calculated to have inadequate fatigue lives under the higher loading imposed by increased traffic. Measurements of local stresses under live loading showed that some experienced lower than calculated stress ranges due to the action of hidden strength. Some 270 welds have been strengthened by UIT to provide a life of 120 years from 2010. Research carried out to support and evaluate the efficacy of the treatment has identified the following factors.

- (a) UIT improves the performance of class F2 fillet welds to a value between class D and class E. There is a 97.5% probability that fatigue life is improved by a factor of 3 on life and the value of  $\sigma_o$ , the non-propagating stress range, is raised from 35 to 50 N/mm<sup>2</sup>.
- (b) The action of UIT is described in the following two items.
  - (i) Crack propagation from the weld toe is halted and propagation from the root is slowed as it passes through the treated zone. This is similar to the action of hammer-peening investigated in earlier strengthening work on DLR structures.
  - (ii) UIT is effective on existing fatigue cracks having estimated surface lengths of up to 8 mm and depths of

1.5 mm. The presence or otherwise of dead load stress during UIT has no discernible effect on its efficacy.

- (c) Fatigue cracking initiated at the root of a UI-treated weld is initially difficult to detect but, after approximately 30% of the life, it propagates into the weld face and can be detected. Propagation continues for 30 to 40% of the life before the crack runs into the main plate. On a 120 year design life, this provides some 35 years when the crack is safe and detectable.
- (d) In cases where UIT provided an insufficient improvement in fatigue life and doubler plates were installed, costs were up to six times greater due to the increased time taken and additional material.

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