Re-evaluation of fatigue curves for flush-ground girth welds

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Re-evaluation of fatigue curves for flush-ground girth welds

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The fatigue performance of girth welded steel pipes with the weld cap and root flush-ground is designated as Class C in the BS 7608 code for fatigue design. However, this is not based on experimental data. Since fatigue results for flush-ground girth welds in steel pipes have now become available, it is necessary to re-evaluate the design S-N curve(s) for such welds on the basis of the relevant experimental data.

For flush-ground joints, internal defects become the weak link in the fatigue performance. The effect of embedded flaws on fatigue design must also therefore to be re-assessed since the current embedded flaw acceptance criteria were also based on joints in flat plate rather than girth welds.

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EXECUTIVE SUMMARY

Background

The fatigue performance of girth welded steel pipes with the weld cap and root flush-ground is designated as Class C in the BS 7608 code for fatigue design. However, this is not based on experimental data. Since fatigue results for flush-ground girth welds in steel pipes have now become available, it is necessary to re-evaluate the design S-N curve(s) for such welds on the basis of the relevant experimental data.

For flush-ground joints, internal defects become the weak link in the fatigue performance. The effect of embedded flaws on fatigue design must also therefore to be re-assessed since the current embedded flaw acceptance criteria were also based on joints in flat plate rather than girth welds.

Objectives

- To set up a database of S-N values for flush-ground girth welds and then to establish the best-fit mean and design S-N curves using the new data.
- To evaluate the BS 7608 C curve using these results.
- To compare the BS 7608 C curve with other pertinent fatigue design criteria in other codes and standards.
- To set up a database of S-N values for flush-ground girth welds with embedded flaws.
- To examine the critical embedded flaw size allowed in such welds for their designated design S-N curve.

Approach

A comprehensive examination of published works regarding fatigue performance of flush ground welds with and without reportable flaws was carried out. Discussion and communications were also held with research workers in this area.

Conclusions

- A database of fatigue test results for flush-ground girth welds has been set up and statistically analysed.
- There is a controversy in the fatigue performance of full-scale tube specimens. Although most of the results reviewed strongly support the BS 7608 C curve, limited data, not reported in full (lacking details of NDT records, failure locations and individual test results) suggest that Class C can be unsafe. These results may be misleading (e.g. if the welds contained severe defects) and it is apparent that there is a need for further information. This requires further effort to establish the missing details and / or more full-scale fatigue testing of flush-ground girth welds with full details of the welds.
- BS 7608 Class C is comfortably qualified on the basis of fatigue data obtained from strip specimens cut from girth welded joints. The margin between the test data and the pertinent curves in other codes, where the effects of seawater in CP and specimen thickness are considered, is even greater. Thus they are more conservative than BS 7608 Curve C.

- The optimistic fatigue performance of small specimens can be partly attributed to their reduced residual stresses compared to large–scale tube or pipe specimens. Fatigue testing of such specimens at high stress ratios is required in order to predict the behaviour of actual girth welds conservatively.

- All S-N curves designated for flush-ground girth welds have been collected and compared. Although many current fatigue design S-N curves for flush-ground butt-welds have a slope of $m = 3$, evidence from the present review indicates that better correlation of the data is achieved with a shallower slope, $m > 3$.

- Data from flush-ground plate specimens also support Class C classification. However, because of some deficiencies such as NDT records, weld quality and misalignment, the fatigue behaviour of butt-welded plate specimens is not truly representative of that in girth welds. Therefore they should be used with caution.

- A database of fatigue results for flush-ground girth butt welds containing reportable flaws has been set up

- The limited database on flush-ground girth welds containing reportable embedded flaws suggests that the flaw sizes present in the welds which achieved Class C can be detected using current NDT methods.

1 INTRODUCTION

1.1 BACKGROUND

Flush-grinding of a butt weld is an established method for improving its fatigue performance. This will eliminate the stress concentration created by the weld profile and remove the inherent weld toe flaws from which fatigue cracks typically initiate. Consequently a fatigue performance far superior to that typically assigned to conventional structural welds in the as-welded condition is expected. However, the current fatigue designs in various standards or codes for such welds are not based on fatigue test data from flush-ground girth welds, but on data for joints between flat plates, much of which was obtained many years ago. Furthermore, the welding procedures, types and consumables might not be representative of those currently used in offshore structures. However, since data from flush-ground girth welds in steel tubes have now become available, there is the opportunity to re-evaluate the design S-N curve(s) for such welds on the basis of relevant experimental data.

To qualify for BS 7608 Class C, the flush-ground welds must be free from significant defects. However, in the great majority of situations it is found that a fatigue strength higher than Class D cannot be justified. This is, based mainly on evidence from plate specimen tests, because of the possible presence of flaws which are too small for reliable detection using the current NDT methods, but which could be of sufficient size to reduce the fatigue strength of the joint. Therefore, it is necessary to examine the defect acceptance criteria for flush-ground welds using data from girth welds, particularly for embedded defects since they become the weak link in the fatigue performance. In the meantime, the minimum defect sizes need to be assessed against the detectability of the current NDT methods.

1.2 APPROACH

Although design should ideally be based on fatigue tests on full-scale flush-ground girth welded tubes or pipes, in order to include the proper effects of size and residual stresses, in reality such tests can be relatively expensive. Currently such data are very limited in the public domain (Wirsching et al, 1995, Salama, 1999). Traditionally small specimens have been used to assess the fatigue performance of large components after appropriate consideration of the differences between the two. Therefore, test data from strip specimens, extracted from flush-ground girth welds in steel tubes, which were not available until recently, were collected to re-evaluate the design S-N curve(s) for such welds. As the current fatigue design curves for girth welded tubes were traditionally based on plate specimen data, fatigue data from plates with flush-ground welds were also collected and compared with their counterparts from girth welds. The BS 7608 C curve was used throughout as the reference curve for comparison. An alternative would have been to have used the 1995 amendment to the HSE Guidance Notes (1990). However, these were withdrawn in 1998. It is worth noting that the C curve in the HSE Guidance notes in 1990 was the same as that in BS 7608.

To assess the effect of embedded flaws on fatigue performance, fatigue data from flush-ground welds with reportable defects were also investigated. The test data were compared with acceptance criteria that are currently used (BS 7910, 1999; ASME, 1993) to determine the actual maximum acceptable flaw size for a designated classification. The ability of relevant NDT methods to detect them reliably was also examined.

In this report, the BS 7608 C curve is used as a basis for comparison with the experimental data in all cases. BS 7608 does not require the application of a specimen thickness correction for flush ground welds. It also assumes that the fatigue crack growth rate for welds in seawater with CP is the same as that in air. However, some codes do recognise a specimen thickness effect on fatigue endurance in flush ground welds and an enhanced crack growth rate in seawater with CP when compared to air. To provide an insight of these effects on the pertinent curves in these codes, they have been considered for the strip specimens only where the thickness data are available and some of the experimental data were obtained in seawater with CP. In other cases, the recommended S-N curves for flush ground welds with the reference thickness are employed.

2 OBJECTIVES

- To set up a database of S-N values for flush-ground girth welds and then to establish the best-fit mean and design S-N curves using the new data.

- To evaluate the BS 7608 C curve using these results.

- To compare the BS 7608 C curve with other pertinent fatigue design criteria in other codes and standards.

- To set up a database of S-N values for flush-ground girth welds with embedded flaws.

- To examine the critical embedded flaw size allowed in such welds for their designated design S-N curve.

3 FLUSH-GROUND WELDS WITH NO REPORTABLE FLAWS

3.1 FLUSH-GROUND GIRTH WELDS

Published data from fatigue tests on full-scale tubes with flush-ground girth welds are very scarce and only three relevant test series were found (Wirsching et al, 1995; Salama, 1999; TWI, 2002). Fatigue test results for seven API-5L X60 steel tube specimens with outer diameter (OD) 610mm and wall thickness (WT) 20mm were reported by Wirsching et al (1995). Details of the test results, NDT examination records and failure locations were not reported and only the statistical analysis of fatigue endurances was published. The results reported by Salama (1999) were from four UOE X65 tube specimens with the same dimensions as those reported by Wirsching. Again no information on NDT examination or failure locations was reported.

TWI has been involved in fatigue testing of flush-ground welded tubes made of API 5L X60 steel with an OD of 609mm and WT of 21.4mm for tendons, and pipes made of API 5L X80 steel with an OD of 273mm and WT of 12.6mm for risers (TWI, 2002, confidential to the sponsors). Two tendon specimens containing three welds each were fabricated in the 1G position, using single sided SAW throughout. The weld root was made onto backing tape. Three riser specimens containing two welds each were fabricated in the 1G position, using a single sided GTAW root pass followed by SAW fill and cap. All weld root beads and caps were ground flush with the pipe surfaces after welding. Comprehensive NDT examinations including RT, UT and MPI did not reveal any defects. Six full-scale girth welds in the two tendon specimens and six full-scale girth welds in the three riser specimens were fatigue tested under tension-tension axial loading at a mean stress of ~ 175MPa and 125MPa, respectively. All the tests gave run-outs with no evidence of fatigue cracking in any of the welds.

These results are plotted in Fig.1 together with the BS 7608 C curve. Also shown is the American AWS Category C1 curve. Strictly speaking, this design curve is intended for as-welded, not for flush-ground, girth welds; the higher category B is provided for these. However, for critical applications, the C1 curve has been suggested to be more appropriate for fatigue design for flush-ground welds (Zettlemoyer 2002; Buitrago and Zettlemoyer, 1999), although details of the test results supporting this are not available.

As will be seen, the fatigue test results for full-scale specimens do not agree well. Although the mean curve from Wirsching et al (1995) was reported to be slightly above the BS 7608 C design curve, the design curve is significantly below the BS 7608 C curve and is even below the AWS C1 curve after $2x10^5$ cycles. This was because of the large standard deviation in the original data, due to the small number of the specimens tested. For the tests reported by Salama (1999), all the individual test results were above the AWS C1 curve, but the endurances of three of the four tests were below the BS 7608 design C curve. On the other hand, TWI's tests were all run-outs and all the data for the twelve welds fall above the C curve. It should be stressed that, because of the lack of details of the NDT examinations and the stringent requirement on the elimination of defects to qualify for the Class C curve, the test results from both Wirsching et al (1995) and Salama (1999) should be taken with caution.

In the early 90's, a large testing programme, led by TWI (TWI, 1998), was carried out in three laboratories to investigate the fatigue performance of strip specimens extracted from flush-ground girth welds in tubes, for applications in the Heidrun TLP. The tendons were made from 12m lengths of 1118mm OD by 38mm WT tubes in steel equivalent to API 5L Grade X70 specification. They were fabricated using a number of welding procedures (TWI, 1998). Waisted fatigue test specimens with a minimum cross-section width of around 100mm were extracted from the tubes. All welds were flush-ground both inside and outside before fatigue testing. The fatigue tests were conducted under constant amplitude axial loading with the stress ratio R being 0.1 in most cases. The tests were run until failure occurred or to target lives based on the BS 7608 C curve.

Among the total of 68 specimens, 18 flush-ground strip specimens were tested at 6°C in seawater with catholic protection (-1050mV). Others were tested at room temperature in air.

In general, establishing the fatigue strengths of the flush-ground butt welds was a challenge. In the absence of weld toes and any significant embedded flaws, fatigue cracking could initiate at various locations in the specimens other than the weld. In the event, a test was terminated for one of four reasons:

- Failure in the weld (11 specimens)
- Failure in the weld but from the edge of the specimen (11 specimens)
- Failure from the machine grips or in parent plate (22 specimens)
- Run-out (i.e. specimen did not fail) (24 specimens)

Thus, only 11 specimens failed in the weld, giving valid endurance data for statistical analysis. The results were analysed assuming the fatigue endurance, N, of flush-ground welds can be expressed by the power law equation:

$$N\Delta S^{m} = C \qquad [1]$$

where ΔS is the stress range and C and m are constants. The analysis gave m=4.26, and $C=2.55x10^{16}$ for the mean S-N curve with a standard deviation of log N, $\sigma = 0.3127$.

The resulting mean and mean-2SD S-N curves are plotted and compared with the C curve in Fig.2. It can be seen that all the test data and the mean-2SD curve (corresponding to 97.7% probability of survival) are above the C design curve. Table 1 summarises the S-N curves fitted to the results for both the strip and tube specimens, as well as the C curve.

Figure 2 also includes the test results of those specimens that did not fail from the weld. Those specimens, which failed from the specimen edge or away from the weld, were regarded as 'unfailed'. It can be seen that all these data were above the C curve and most of them had endurances far above the mean curve obtained from the failed specimens. Therefore, the statistical result from the failed specimens can be regarded as a conservative estimate for strip specimens. This conservatism was further highlighted by the results of those tests carried out under catholic protection (CP) environment (TWI, 1998). Although BS 7608 assumes that the fatigue performance of flush ground welds in seawater with CP is the same as that in air, under some codes the fatigue damage in such an environment is regarded as being more severe and a life reduction factor, for example 2.5 in HSE (1990) and DNV (2000), is applied when compared to the fatigue endurance in air. Furthermore, BS 7608 does not require a thickness correction for flush ground welds, as mentioned earlier, but other codes do. These effects were examined for the DNV and HSE codes. The thickness effect in the former is similar to Norsok (1998) and IIW (1996), while the latter represents a greater penalty on the fatigue endurance of flush ground welds. The reference thickness and thickness exponent are respectively 25.0mm and 0.15 for the DNV curve and 16.0mm and 0.3 for the HSE curve. The effects of both environment (seawater with CP) and specimen thickness on fatigue endurance in DNV and HSE codes are illustrated in Fig.3, where the fatigue results for the strip specimen, shown in Fig.2, are included for comparison. It can be seen that the results from the 18 tests in seawater with CP are far above the 0.76P and C1 curves and none of these specimens failed. By comparing to

Fig.2, it can be seen that consideration of thickness and seawater with CP brings the HSE 0.76P and DNV C1 curves further below the experimental data than the BS 7608 C curve, especially the HSE 0.76P curve, providing more safety margin. It can also be seen that the fatigue strength reduction due to specimen thickness up to 38.0mm was very small for the DNV code.

It should be noticed that the fatigue test results from both the full-scale tube and the small-scale strip specimens exhibited a flatter S-N curve than those obtained for as-welded joints, for which the slope (m) usually has a value of 3.0 (see for example BS 7608). This is to be expected since flush grinding introduces a significant crack initiation period, whereas the lives of as-welded joints consist almost entirely of crack propagation. This difference is reflected in some of the codes (BS 7608, 1993; ISO, 1999; AWS, 2002), whereas the now withdrawn 1995 amendments to the HSE Guidance assigned a slope of 3.0 to the curve for flush-ground joints (0.76P).

3.2 FLUSH-GROUND WELDS IN PLATES

As the S-N curve classification of welded plates is the same as that for girth welded tubes, a review of the fatigue performance of flush-ground butt welded steel plate specimens is useful. This was conducted recently by Maddox (1997), see Fig.4. Data in the low-cycle fatigue regime were expressed in terms of the pseudo-elastic stress range (i.e. strain range multiplied by elastic modulus) as suggested in PD 5500 (2000). As the tensile strength did not have any significant influence on the fatigue performance in these tests, no distinction was made between the materials with different tensile strengths.

As will be seen in Fig.4, the plate specimen data are more widely scattered than the girth weld strip specimen data. The majority of the results qualified for the C curve with only a few exceptions where the results were only slightly below the C curve. The larger data scatter is to be expected since the database is much larger than that for strip specimens. However, it might also be associated with inconsistent welding quality in the plate specimens obtained from many different sources, in contrast with the comparatively good welding control and stringent NDT acceptance criteria in girth welding. Consequently, some of the plate specimens might have contained defects larger than the acceptable limit for girth-welded pipes. Furthermore, the tests on these plate specimens were carried out at different stress ratios, some even with R<0. As stress ratio has a strong influence on fatigue endurance (Salama, 1999), tests performed at different stress ratios can be expected to be scattered. Overall, the results from plate specimens suggest the applicability of the C curve for flush-ground butt welds.

3.3 COMPARISON OF FATIGUE CODES REGARDING FLUSH-GROUND WELDS

Generally flush-ground butt welds have been recognised as having enhanced fatigue performance compared with as-welded joints. This is reflected in the different design Standards. Table 2 summarises the fatigue classification for flush-ground butt welds in the major international Codes or Standards. A graphic presentation of the corresponding design S-N curves is shown in Fig.5, where it can be seen that:

- Except for the difference in fatigue limits, the BS 7608 C curve is the same as the ISO C curve, the DNV C1 curve is the same as the Norsok C1 and the Eurocode3 category 112 curves.
- The Class C curves in BS 7608 and ISO/CD 13819-2 have a slope of 3.5, different from 3.0 adopted by other European codes and IIW. They are more conservative for endurances below $2x10^5$ cycles but less conservative above this endurance compared to some of the codes.

- As indicated above the 1995 amendments to the HSE Guidance, where the fatigue design curve for flush-ground welds was designated as the 0.76P curve with a slope of 3.0, was withdrawn in 1998.

The API designated curve was not included in Fig.5 since API recommends using the AWS's guidance (API, 1993). The AWS designation for flush-ground butt welds is Class B which has a shallow S-N curve slope (m=4.3). As noted earlier, a shallow slope with m>3 would be expected to be appropriate for flush-ground butt welds as a result of crack initiation occupying a significant proportion of the fatigue life. Compared to other Standards, AWS B curve is conservative at fatigue endurances below one million cycles, especially in the regime of high stress ranges. The AWS C1 curve is also included in Fig.5 for comparison since, as noted earlier, it has been proposed as a suitable design curve for flush-ground girth welds. (Zettlemoyer, 2002; Buitrago and Zettlemoyer, 1999).

It must be emphasised that the above comparison is based on the S-N curves at the reference thickness for each code. Since some codes do consider a thickness effect for flush ground welds and recommend some degree of penalty, care must be taken when such a comparison is made at a specimen thickness beyond the reference thickness for a certain code.

4 FLUSH-GROUND GIRTH WELDS WITH REPORTABLE FLAWS

4.1 FATIGUE DATABASE

To qualify for the fatigue design curves for flush-ground girth welds, the criteria of defect acceptance are very strict. Surface breaking and internal planar defects, such as lack of fusion or lack of penetration, are particularly important since they are much more deleterious to the fatigue performance of the weld than embedded volumetric defects such as pores or slag inclusions. In recognition of this, it has been proposed that any indication of their presence should not be allowed for flush-ground welds in TLP tendons designed to AWS C1 (Buitrago and Zettlemoyer, 1999).

Recently the effect of porosity and slag inclusions in flush-ground girth welds on fatigue performance has been investigated (Razmjoo et al 1996, Buitrago and Zettlemoyer, 1999). Razmjoo et al (1996) carried out fatigue tests on strip specimens containing embedded defects which were beyond the acceptance limit for production. Buitrago and Zettlemoyer (1999), however, deliberately introduced embedded defects into welds and investigated their fatigue performance. These results are summarised in Tables 3, 4 and 5. They are also compared with the plate specimen data studied by Harrison (1972) in Figs.5, 6 and 7.

4.2 EFFECT OF POROSITY

Fig.6 shows the fatigue test results from both strip and plate specimens containing porosity. Both porosity density and maximum pore size have been characterised by RT and UT in strip specimens (Buitrago and Zettlemoyer, 1999; TWI, 1998), but only porosity density was reported for plate specimens (Harrison, 1972). It will be seen that when porosity density was less than 4% and the maximum reported individual flaw size was up to 4.8mm, the fatigue performance could still be qualified as Class C, except in the high stress range/low endurance ($<10^5$ cycles) regime, Fig.6. The results suggest that, in the medium and long fatigue life regimes, a pore size of around 4mm can be tolerated, a size which can be detected reliably by RT or UT.

However, when porosity density was increased to 8% many plate specimen test data fell below the C curve, Fig.7 (Harrison, 1972). This suggests that when pore density is low (below 4%), the individual pore size plays an important role. When the pore density is high, however, the fatigue performance is significantly reduced regardless of the individual pore size.

4.3 EFFECT OF SLAG INCLUSIONS

Fatigue test results for flush-ground girth welds in the form of strip specimens (Buitrago and Zettlemoyer, 1999; TWI, 1998) and butt welds in plates (Harrison, 1972) with slag inclusions were collected and they are compared in Fig.8. The fatigue data from plates (Harrison, 1972) were selected with inclusions less than 10mm, but much larger defects were present in the specimens reported by Buitrago and Zettlemoyer (1999), see Table 4. It can be seen that the data from TWI (1998), which had defect lengths between those reported by Harrison (1972) and Buitrago and Zettlemoyer (1999), qualify for BS 7608 Class C. The data from other tests (Buitrago and Zettlemoyer, 1999; Harrison, 1972), however, show the effect of embedded inclusions and many test results fall below the C curve even from the plate specimens. This suggests that the fatigue life depends not only on the inclusion length as specified in BS 7910, but also on other factors such as the ligament and the inclusion height.

5 DISCUSSION

5.1 STRIP AND FULL-SCALE SPECIMENS

When considering fatigue design of tubular joints, results obtained from full-scale girth welded specimens are highly recommended in order to exclude uncertainties associated with other test specimens. However, the requirements for the special testing facility, time and cost make this difficult to achieve. In practice, small-scale specimens have often been used to simulate the behaviour of actual components. When the test results from these specimens are used for design purposes, however, care must be taken to ensure they represent the fatigue performance of large-scale components.

Available fatigue data from flush-ground welds in strip specimens cut from girth welded tubes confirm the qualification of the BS 7608 C curve. Even those specimens that were originally rejected due to the presence of unacceptable defects (TWI, 1998) still gave lives consistent with Class C. In fact, they showed little difference from those failed specimens containing no reportable defects, see Fig.9. This suggests that the fatigue performance of strip specimens free from defects can be comfortably classified as Class C. However, some of the results of the flush-ground girth welded tubes were lower than the corresponding strip specimen results and could not be qualified for the C curve (Wirsching et al, 1995; Salama, 1999). This can be readily seen in Fig.10 where a direct comparison of the fatigue performance of strip and full-scale specimens is shown. Although the data from the above full-scale specimens should be taken with caution since, as stressed before, no details of NDT, fatigue testing or failure locations were reported, the difference in fatigue performance between the strip and the full-scale specimens was not unexpected as the same has been observed in tests on as-welded girth welds (Maddox and Razmjoo, 1998). In this case, the difference was attributed to the possible effects of size and residual stress.

With regard to size, as a strip specimen contains only a small proportion of the length of a girth weld, it is unlikely to contain the most severe defect present and unlikely to introduce the same level of stress concentration as in some locations in the tube. Thus, it is probable that many of the strip specimens extracted from a girth weld will exhibit better fatigue performance than the full-scale girth welded tube.

With regard to residual stress effects, in general it is assumed that welded joints in real structures contain high tensile residual stresses acting in the most damaging directions, i.e. transverse to girth welds. It is normally assumed that the residual stress can reach the yield stress of the material. The effect of the residual stresses is to modify the mean stress of any applied cyclic stress, giving a relatively high mean stress and a tensile stress range. When a strip specimen is cut from a pipe, however, the residual stress will be significantly released. Although the strip and tube specimens were tested at the same nominal stress ratio, the actual stress ratio experienced might have been different due to a higher residual stress retained in the tube specimens. This effect can influence both crack initiation and growth, hence the fatigue performance.

The stress ratio effect on fatigue endurance can be directly seen from a comparison of fatigue data obtained at different R values, see Fig.11. All these results were obtained from flush-machined butt welded plate specimens (Oliver and Ritter, 1979). The results show that the fatigue performance did depend on the stress ratio used. It is also interesting to note that the results obtained at high stress ratios, R=0.4 and 0.5, were marginally above and below the Class C curve, respectively. By fatigue testing strip specimens at different stress ratios, Salama (1999) claimed that there was no difference in fatigue performance between the strip and the tube specimens if the former were tested at a higher mean stress with the maximum stress equal to the yield stress. It should be noted that residual stresses due to welding were often found to be widely scattered, from compressive to high tensile stresses even for a single weld (TWI, 2002). As a consequence, the fatigue performance of girth welds was sometimes sensitive to applied mean stress and exhibited a large scatter.

Thus, with strip specimens there is a risk of producing non-conservative S-N data. For a better and conservative correlation between small- and large-scale specimens, the former should be fatigue tested at a high tensile mean stress or high stress ratio.

With regard to the relative significance of specimen size on residual stress, it is worth noting that, although it has been generally accepted that the residual stress will be reduced once a strip specimen is extracted from a girth weld, no direct measurements of the stress release level using the same component have been reported. It would be very useful if a non-destructive method, such as neutron diffraction, which can measure residual stresses in thick plates, were used to measure the residual stresses at the same location both before and after cutting.

Another issue, which could affect the direct comparison of the fatigue results between strip and full-scale specimens, is the quality of flush-grinding at weld roots. For single sided welds in tubes, grinding the weld roots is not as easy as for strip specimens. Consequently cracking might preferentially initiate at the weld root, resulting in a lower fatigue endurance. Thus, to make the fatigue results of strip specimens representative of large-scale specimens, the same quality of grinding both inside and outside must be assured.

5.2 PLATE AND STRIP SPECIMENS

In addition to the factors encountered with strip specimens, the application of fatigue data from plate specimens to large-scale tube components was complicated by the differences from girth welds. First, no NDT records for these specimens (Maddox, 1997) were reported, which might explain the large data scatter displayed in Fig.4. As embedded defects can significantly affect the fatigue endurance of flush-ground welds, the results from these specimens cannot truly represent girth welds. Secondly, since the fatigue data from these plates were obtained some years ago, the welds cannot be assumed to be representative of those produced by modern fabrication processes, particularly for girth welds in pipelines. A special issue is the misalignment, which can significantly affect the local stress distribution around the weld and hence the fatigue endurance. In view of these factors, it would be prudent to use strip specimens, extracted from girth welded tubes, rather than from welds made between plates to simulate the fatigue performance of full-scale tubes, at least in terms of weld quality and geometry. However, it is interesting to note that, in spite of the differences between the two kinds of specimens mentioned above, the large database from plate specimens can still marginally qualify for the C curve.

5.3 RECOMMENDED S-N CURVE FOR FLUSH-GROUND GIRTH WELDS

To qualify for the Class C design curve, detailed NDT examination of welds must be conducted to ensure that the weld is free from significant defects. Thus, any test data for which the NDT results are lacking, e.g. the data reported by Wirsching et al (1995) and Salama (1999) on full-scale fatigue testing, should be taken with caution.

The work carried out by TWI (1998) provided full details of the NDT examination and testing conditions. All twelve welds qualified with respect to the C curve without failure. The results therefore strongly support the BS 7608 C curve. Furthermore, all the results from the strip specimens also support the adoption the C curve for flush-ground girth welds even for those tests undertaken in seawater with catholic protection (Razmjoo et al, 1996).

The statistical analysis of both full-scale and strip specimens reaching failure suggests that a shallower S-N curve than that recommended in many European guidance documents (DNV, 2000; Norsok, 1998; Eurocode 3, 1992) and IIW (1996) would be appropriate for these welds.

5.4 EFFECT OF EMBEDDED DEFECTS

The defect acceptance criteria in two codes, which might be used for flush-ground girth welds, are compared in Table 6. One is based on fitness-for-service (BS 7910, 1999) and the other on fabrication limits (ASME, 2001). It should be noted that the BS 7910 (1999) only provides defect limits up to quality category Q1 (equivalent to design Class D) on the basis that beyond this limit NDT cannot be relied upon to detect critical defects. The defect acceptance criteria in ASME, Section VIII, Division 1 (2001), are those currently used for some tendons (Buitrago and Zettlemoyer, 1999).

The results obtained from strip specimens cut from girth welded tendons reported by TWI (1998) provided a direct comparison between specimens containing reportable defects, some of which were measured, and no reportable defects under the same production procedures. A pore size up to 8mm and a slag inclusion up to 18mm long were reported. The comparable fatigue endurances of these specimens containing reportable defects with those containing no reportable defects suggest that these defects can be tolerated, which provides confidence in detecting the limiting defect sizes using current NDT methods. However, this finding was based on a comparatively small sample number. More such tests are required to determine the critical defect size. It was also noticed that when a defect was large (>20mm), the fatigue endurance began to be reduced below the C curve. Therefore, to be prudent and to determine accurate defect limits for acceptance (length, ligament, ratio of ligament to thickness etc), a comprehensive fracture mechanics assessment is required.

6 CONCLUSIONS

The following conclusions can be drawn on the fatigue performance of flush-ground girth welds on the basis of the database compiled from test results currently available in the public literature:

- A database of fatigue test results for flush-ground girth welds has been set up and statistically analysed.

- There is a controversy in the fatigue performance of full-scale tube specimens. Although most of the results reviewed strongly support the BS 7608 C curve, limited data, not reported in full (lacking details of NDT records, failure locations and individual test results) suggest that Class C can be unsafe. These results may be misleading (e.g. if the welds contained severe defects), and it is apparent that there is a need for further information. This requires further effort to establish the missing details and / or more full-scale fatigue testing of flush-ground girth welds with full details of the welds.

- BS 7608 Class C is comfortably qualified on the basis of fatigue data obtained from strip specimens cut from girth welded joints. The margin between the test data and the pertinent curves in other codes, where the effects of seawater in CP and specimen thickness are considered, is even greater. Thus they are more conservative than BS 7608 Curve C.

- The optimistic fatigue performance of small specimens can be partly attributed to their reduced residual stresses compared to large–scale tube or pipe specimens. Fatigue testing of such specimens at high stress ratios is required in order to predict the behaviour of actual girth welds conservatively.

- All S-N curves designated for flush-ground girth welds have been collected and compared. Although many current fatigue design S-N curves for flush-ground butt-welds have a slope of $m = 3$, evidence from the present review indicates that better correlation of the data is achieved with a shallower slope, $m > 3$.

- Data from flush-ground plate specimens also support Class C classification. However, because of some deficiencies such as NDT records, weld quality and misalignment, the fatigue behaviour of butt-welded plate specimens is not truly representative of that in girth welds. Therefore they should be used with caution.

- A database of fatigue results for flush-ground girth butt welds containing reportable flaws has been set up

- The limited database on flush-ground girth welds containing reportable embedded flaws suggests that the flaw sizes present in the welds which achieved Class C can be detected using current NDT methods.

7 RECOMMENDATIONS

- Fatigue tests on large-scale tubes with flush-ground girth welds with full details of NDT are required to check the apparently low results obtained from some of the reported large-scale tests.

- The degree of residual stress relaxation on removing strip specimen from girth welds should be determined using a non-destructive method such as neutron diffraction.

- If strip specimens are used and the above information is not available, they should be tested at high stress ratios ($R > 0.4$) to simulate the effect of high tensile residual stress and so eliminate the possible dissimilarity from the fatigue behaviour of full-scale components.

8 ACKNOWLEDGEMENTS

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TWI ENDORSEMENT

The report has been reviewed in accordance with TWI policy.

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(Signature)

TGM/Reviewer...
(Signature)

Print name..................................

Print name ....

Secretary/Administrator ....
(Signature)

Print name..................................

Table 1 Comparison of statistical analysis results of strip and pipe specimens

	Strip specimen (TWI, 1998)	*Tendon specimen (Wirsching et al, 1995)*	*BS 7608 C curve*
m	4.26	3.66	3.5
C, mean curve	2.55×10^{16}	1.33×10^{14}	1.08×10^{14}
C, design curve	6.04×10^{15}	2.84×10^{13}	4.23×10^{13}

Table 2 Details of the fatigue design curves designated for flush-ground girth welds in different standards. Note the API designation (1993) is the same as AWS (2002)

Standards	*Parameters*		*Fatigue limit*		*Reference thickness (mm)*
	C	*m*	*Stress range (MPa)*	*Endurance (cycles)*	
BS 7608- C (1993)	4.23×10^{13}	3.5	78	1.0×10^{7}	16
HSE-0.76P (1995)	3.46×10^{12}	3.0	70	1.0×10^{7}	16
DNV-C1 (2000)	2.81×10^{12}	3.0	65	1.0×10^{7}	25
Norsok-C1 (1998)	2.81×10^{12}	3.0	65	1.0×10^{7}	25
Eurocode3-Cat 112 (1992)	2.82×10^{12}	3.0	83	5.0×10^{6}	25
ISO-C (1999)	4.26×10^{12}	3.5	41	1.0×10^{8}	16
IIW: FAT 125 (1996)	3.91×10^{12}	3.0	92	5.0×10^{6}	25
AWS-B (2002)	1.88×10^{15}	4.37	91	5.0×10^{6}	not mentioned
AWS-C1 (2002)	9.12×10^{14}	4.33	69	1.0×10^{7}	not mentioned

Table 3 Fatigue test and post-mortem results for specimens containing embedded porosity, specimen thickness=20.6mm (Buitrago and Zettlemoyer, 1999)

Nominal stress range (MPa)	*Fatigue life (cycles)*	*Failure site*	*Apparent initiation pore size (mm)*	*Maximum reported pore size (mm)*	*NDE report remarks*
200	697,620	Edge	N/A	2.4 (<2%)	3 pores, largest: 2.4mm, smallest: 0.8mm
272	335,580	Edge	N/A	2.4 (<2%)	Cluster, largest: 2.4mm, smallest: 0.8mm
393	17,220	From flaw	3.9	4.8 (<2%)	Cluster, largest: 4.8mm, smallest: 2.4mm
212	4,621,260	Edge	N/A	1.6 (<2%)	Cluster, largest: 2.4mm, smallest: 1.6mm
181	6,454,540	From flaw	1.4	4.8 (<2%)	Cluster, largest: 4.8mm, smallest: 1.6mm
272	446,020	Edge	N/A	3.2 (<2%)	Cluster, largest: 3.2mm, smallest: 0.8mm
200	1,092,780	Edge	N/A	2.4 (<2%)	Cluster, largest: 2.4mm, smallest: 0.8mm
161	5,217,330	From flaw	3.2	3.2 (2<%)	Cluster, largest: 3.2mm, smallest: 1.6mm

Table 4 Fatigue test and post-mortem results for specimens containing embedded linear inclusions, specimen thickness=20.6mm (Buitrago and Zettlemoyer, 1999)

Nominal stress range (MPa)	*Fatigue life (cycles)*	*Failure site*	*Flaw length (mm)*	*Flaw height (mm)*	*Ligament (mm)*	*Maximum reported length (mm)*
154	2,413,070	From flaw	28.4	2.8	6.8	25.4
286	35,600	From flaw	24.4	1.6	10.6	22.2
132	12,298,720	From flaw	16.8	1.6	8.7	14.3
117	4,554,370	From flaw	34	1.8	11.7	31.8
198	280,920	From flaw	25.6	1.3	5.6	25.4
286	423,720	From flaw	23.9	1.1	9.5	27.0
198	222,970	From flaw	18.1	1.0	4.4	19.0
286	125,330	Edge	N/A	N/A	N/A	30.0

Table 5 Fatigue test results from specimens containing reportable defects, specimen thickness=38.0mm (TWI, 1998)

Welding procedure	*Nominal stress range (MPa)*	*Endurance, cycles*	*Details of flaws*	*Failure location*
Two-sided SAW	412	273,640	Slag inclusions. No dimensions reported	In the weld
Two-sided SAW	310	1,566,620	Probably slag inclusions. No dimensions reported	From specimen edge
Two-sided SAW	359	513,050	Slag inclusions. No dimensions reported	From specimen edge
Single-sided SWA with TIG root	343	316,280	Slag inclusions. No dimensions reported	From specimen edge
Single-sided SWA with TIG root	489	34,660	Slag inclusions. No dimensions reported	From specimen edge
Single-sided SWA with TIG root	405	364,000	Slag inclusions. No dimensions reported	From attachment
Single-sided SWA with TIG root	430	101,030	Slag inclusions 6mm long, 8mm ligament	From an inclusion
Single-sided SWA with TIG root	423	125,710	Slag inclusions. No dimensions reported	In the weld, from inner surface
Single-sided SWA with TIG root	424	143,960	Slag inclusions 4mm long, 5mm ligament	From inclusion
Two-sided TIG/MMA	200	3,165,610	Cluster porosity, 8mm long	From porosity
Two-sided TIG/MMA	235	498,590	Slag inclusions 16mm long, 8mm ligament	From inclusion
Two-sided TIG/MMA	290	333,240	Slag inclusions 18mm long, 6mm ligament	From inclusion
Two-sided TIG/MMA	290	577,250	Acceptable NDT indication	In the weld, from a tiny subsurface pore
Not reported	400	352,722	No details	

Table 6. Defect acceptance criteria for quality category Q1 (BS 7910, 1999) and flush-ground girth weld with thickness limited to 50mm (ASME, 2001)

	Flaw acceptance limit				
Standards	*Porosity, % area on radiograph*	*Individual pore size, mm*	*Slag inclusion length, mm*	*Undercut, (depth/wall thickness)*	*Planer defects*
BS7910-Q1	3.0	Thickness/4 or 6.0	2.5	0.025	Not allowed
ASME VIII Div.1	Not defined	6.3	6.0	No undercut	Not allowed

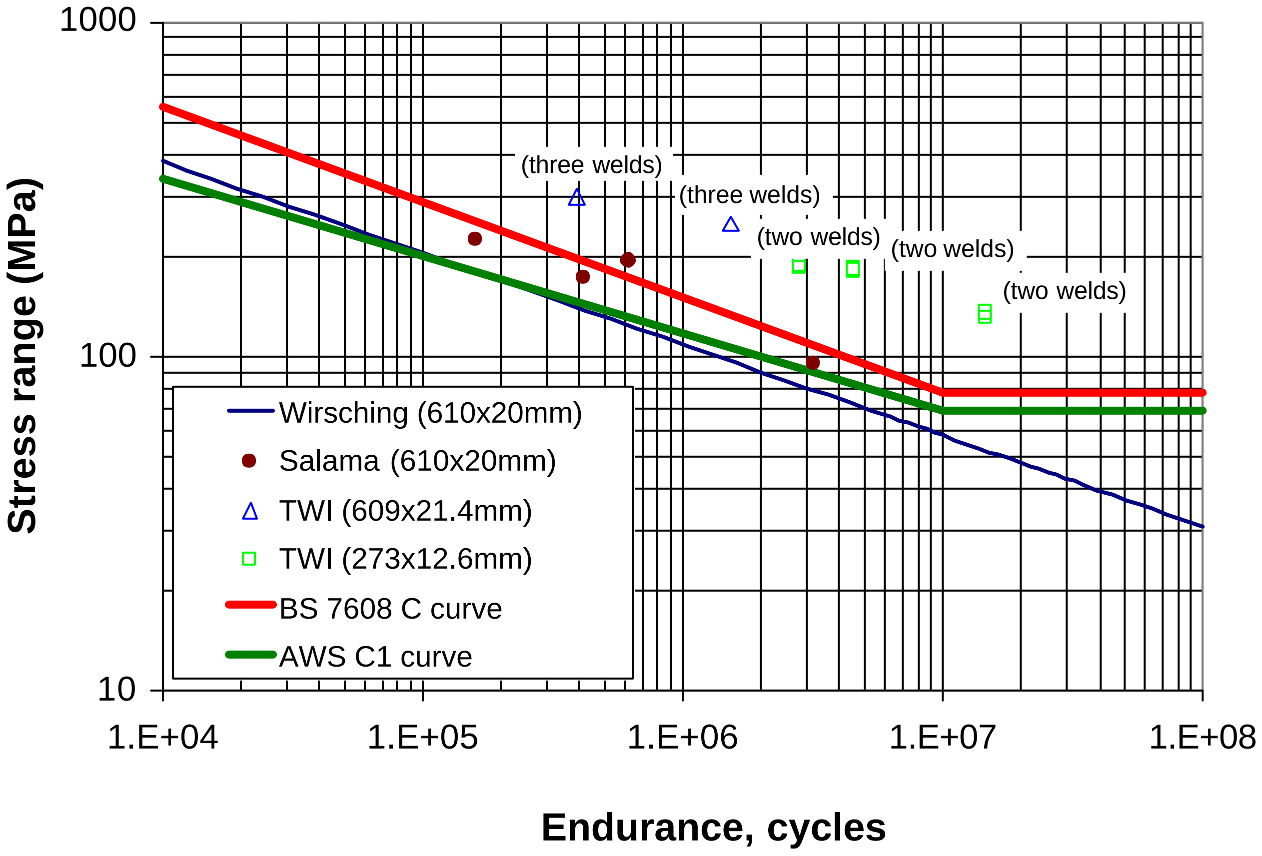

Fig.1 Comparison of fatigue endurance of full-scale specimens (Wirsching et al, 1995; Salama, 1999; TWI, 2002) with the BS 7608 C and AWS C1 curves. Solid symbols designate failed tests and open symbols designate run-outs. Note the curve from Wirsching is a design curve

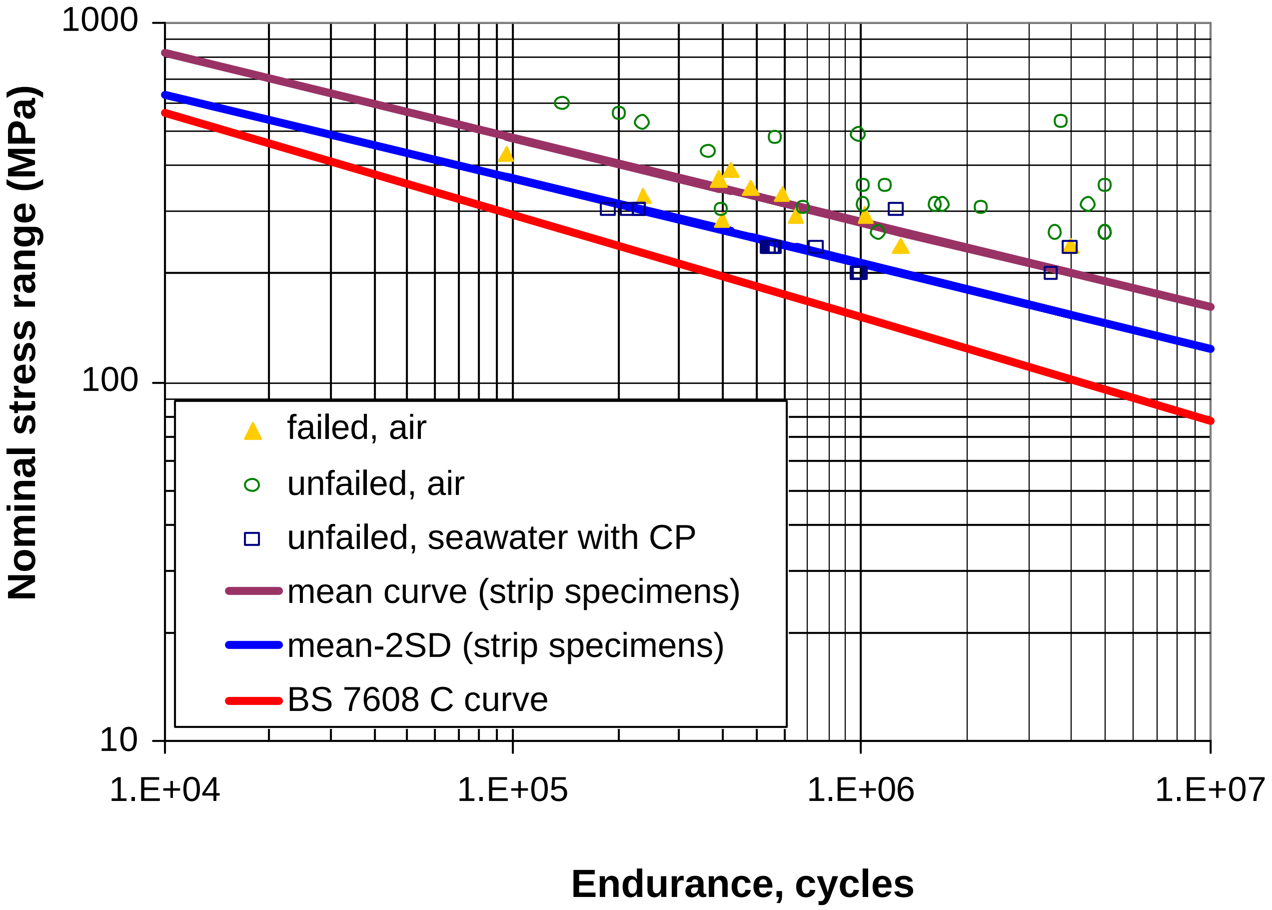

Fig.2 Comparison of the fatigue performance of flush-ground strip specimens cut from girth welds (TWI, 1998) with the BS 7608 C curve

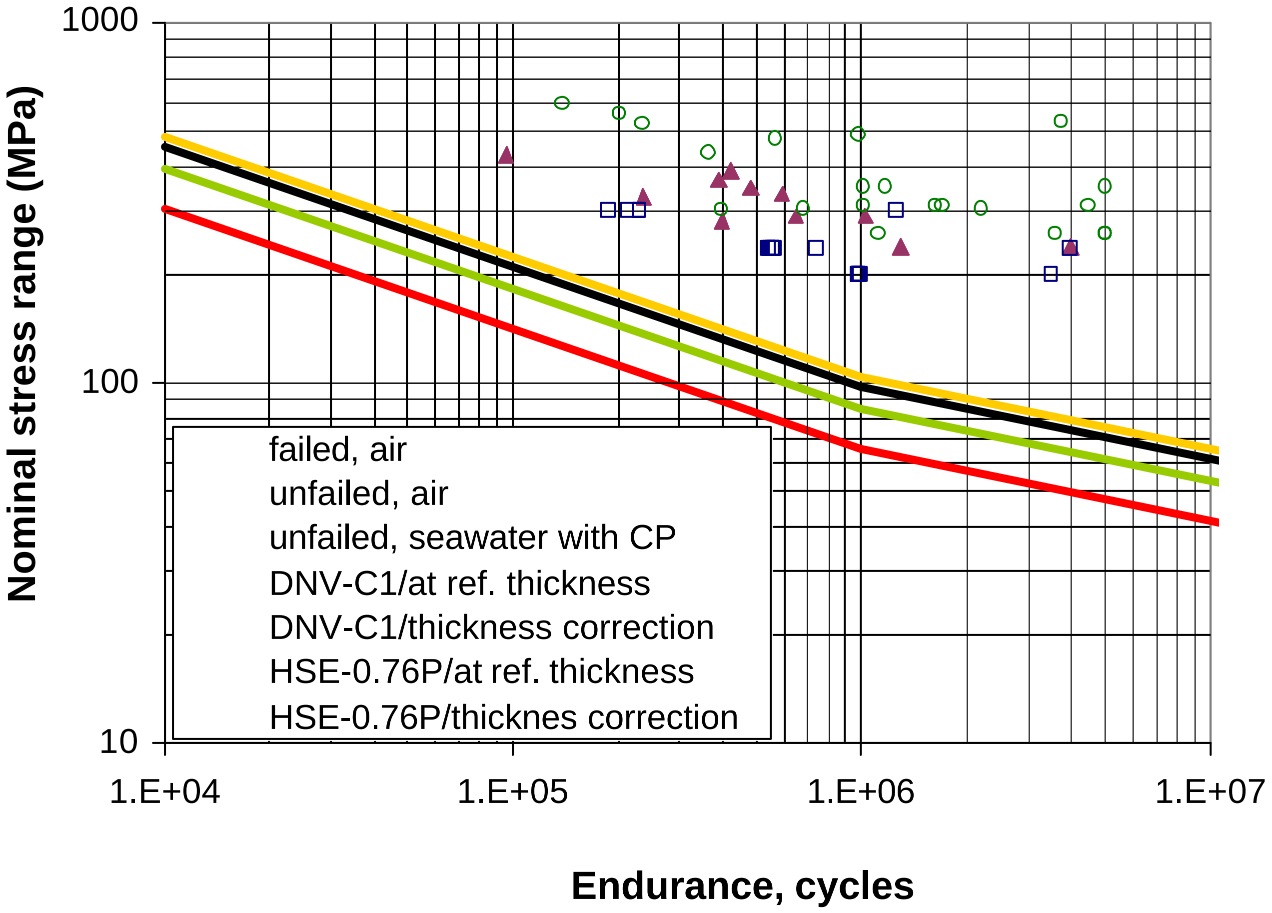

Fig.3 Comparison of the fatigue performance of flush-ground strip specimens cut from girth welds (TWI, 1998) with the DNV C1 curve and the HSE 0.76P curve in protected joints in seawater. Specimen thickness effect was also considered as recommended in these codes

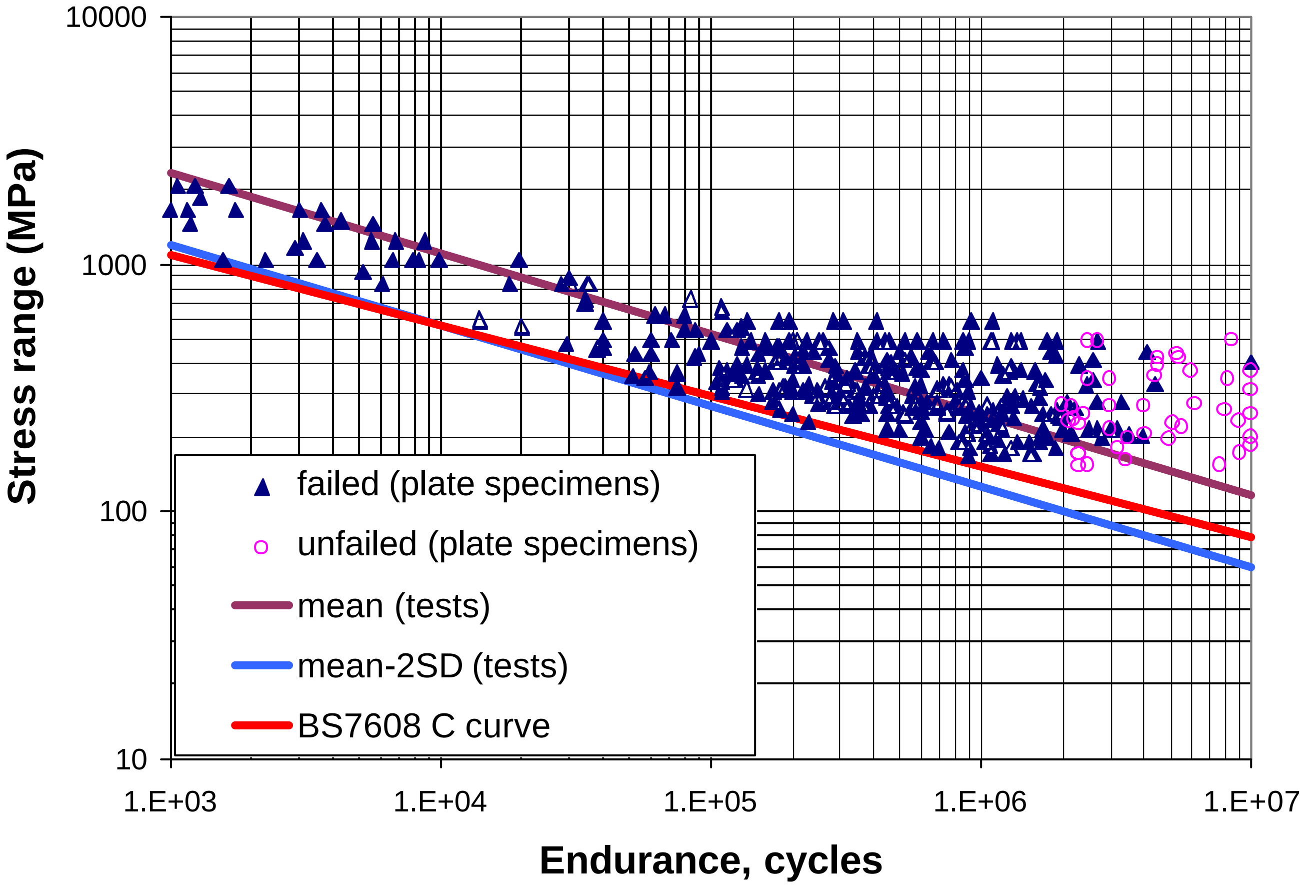

Fig.4 Fatigue endurance data for flush-ground butt-welded plate specimens (Maddox, 1997)

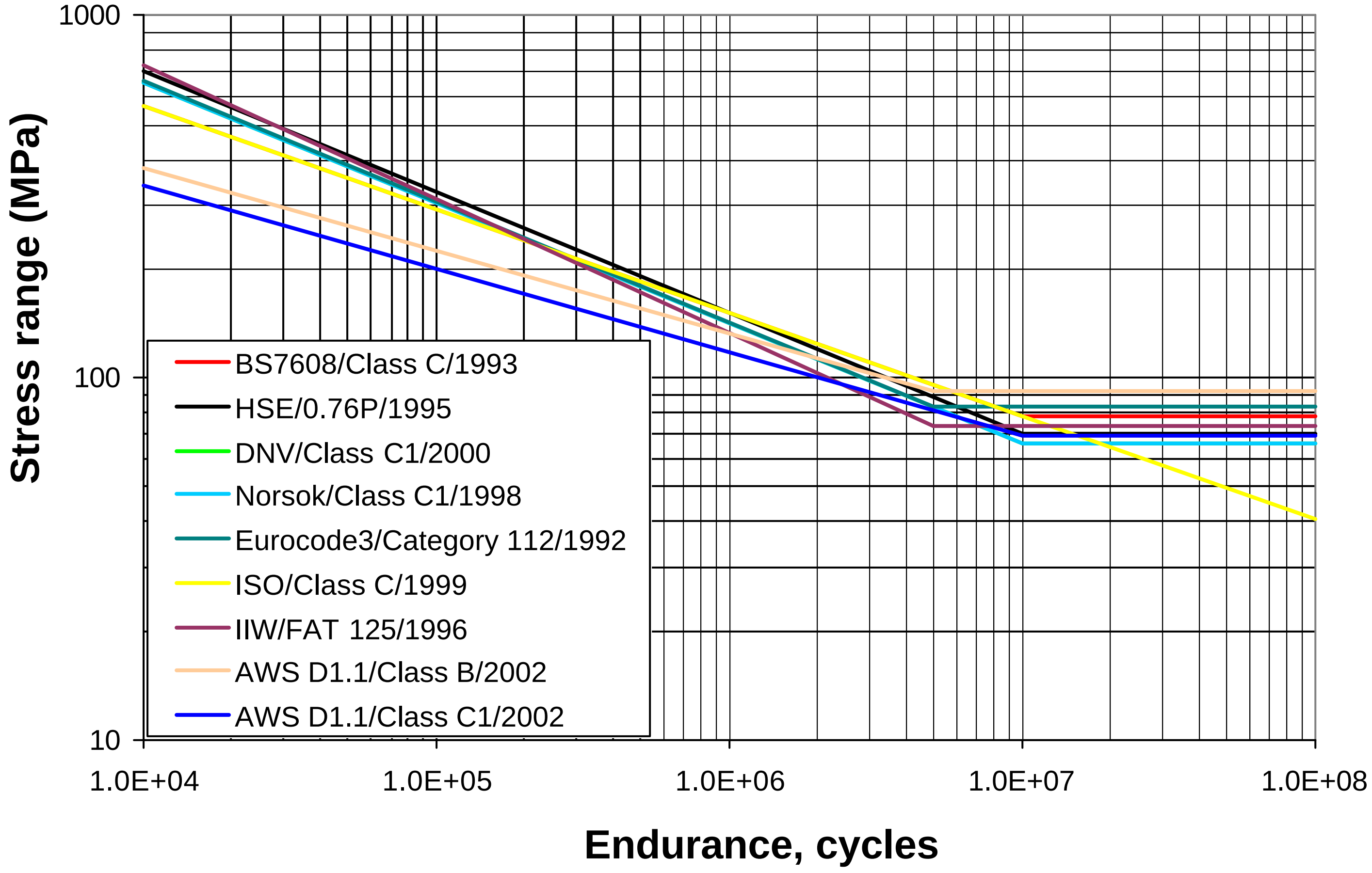

Fig.5 Comparison of fatigue design curves for flush-ground butt welds from different Standards. Note the API designation (1993) is the same as AWS (2002)

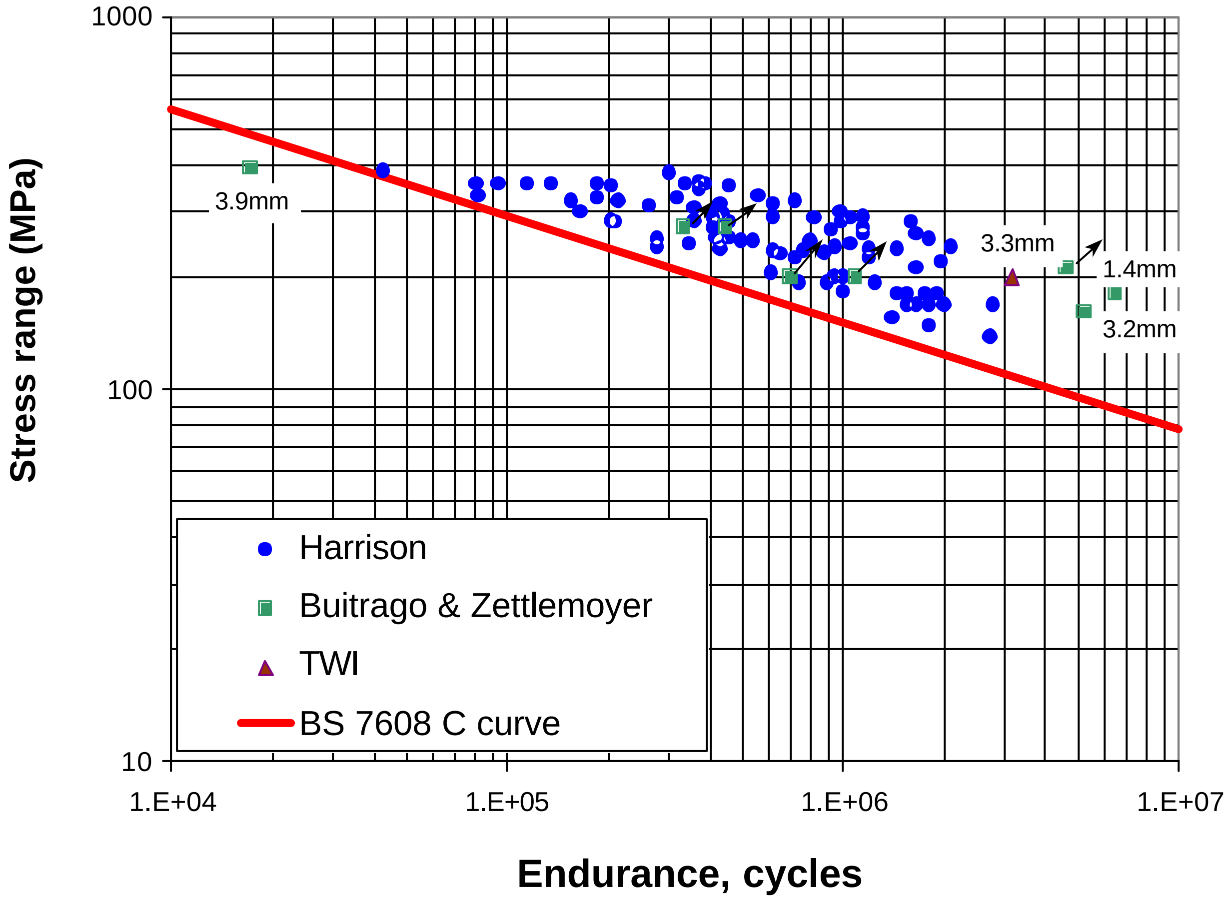

Fig.6 Fatigue endurance of plate and strip specimens with porosity less than 4%

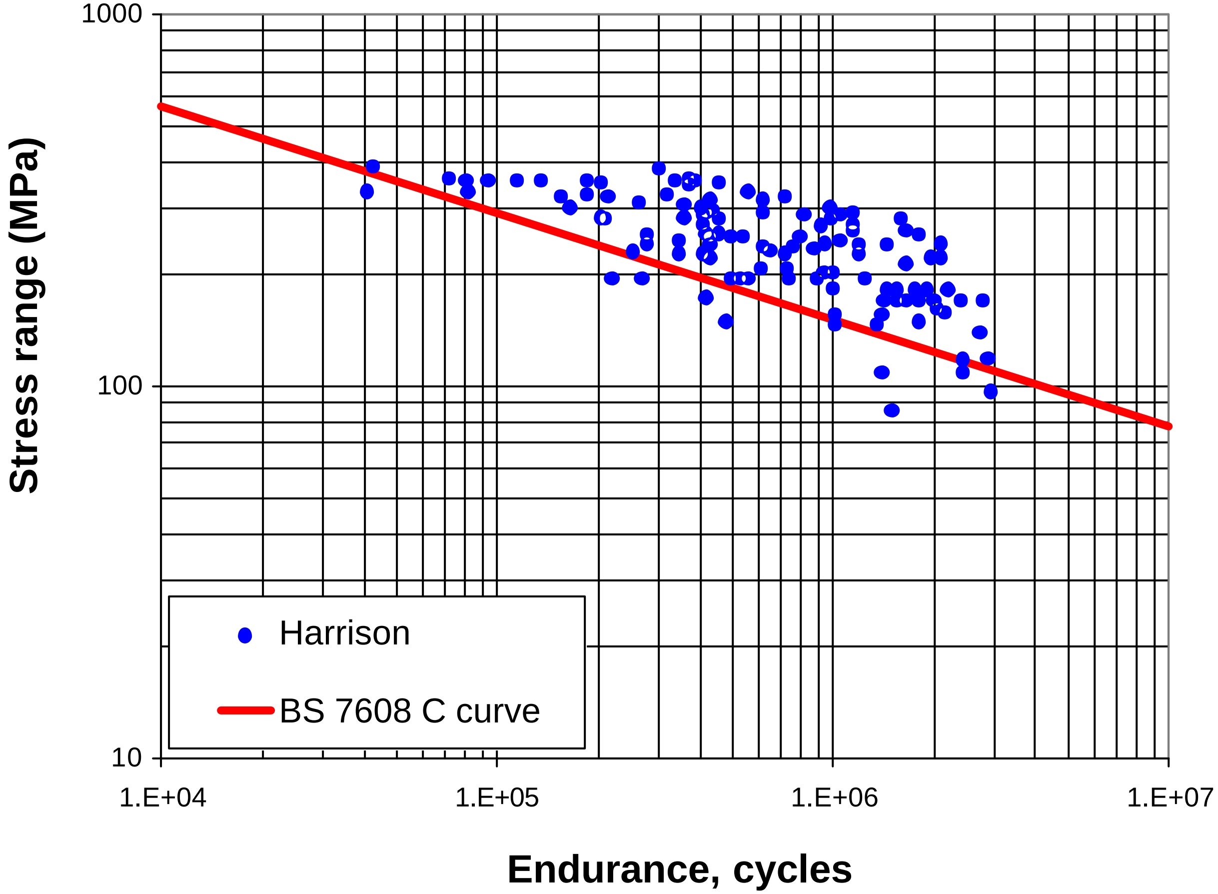

Fig.7 Fatigue endurance of plate specimens with porosity density up to 8% (Harrison, 1972)

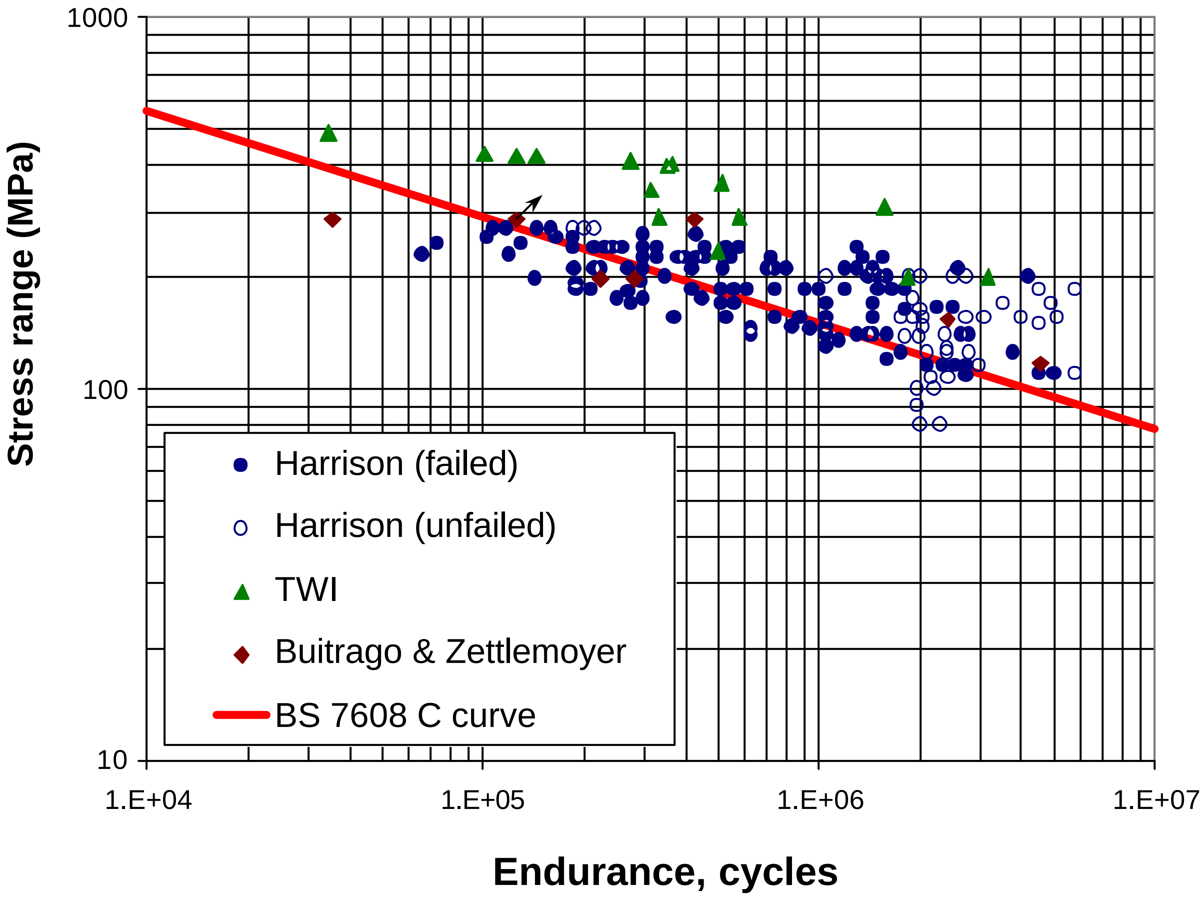

Fig.8 Fatigue performance of flush-ground welded specimens containing slag inclusions. Details of the inclusion sizes and the corresponding endurance of strip specimens can be found in Tables 3 and 4

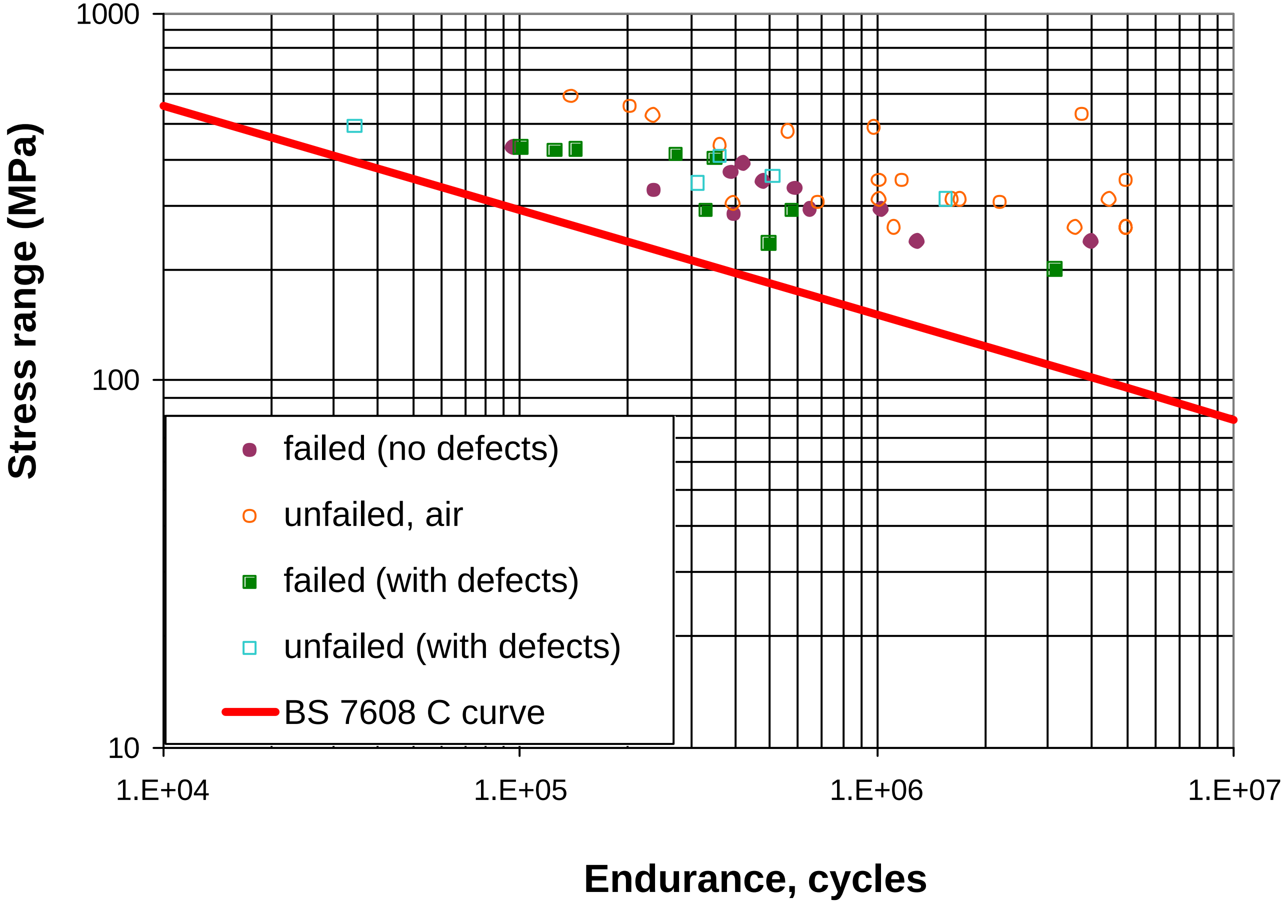

Fig.9 Comparison of fatigue performance of strip specimens with and without reportable defects (TWI, 1998)

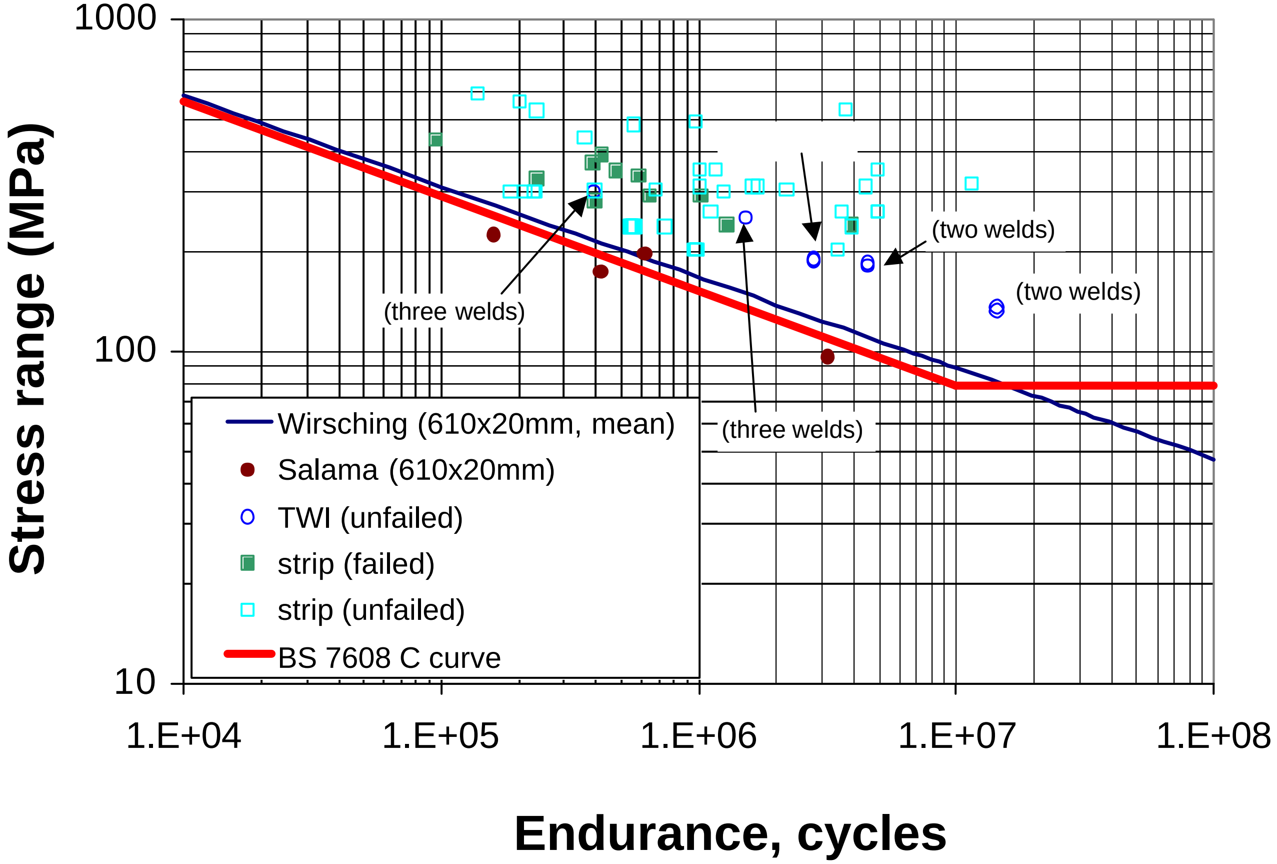

Fig.10 Comparison of the fatigue endurance of full-scale and strip specimens with flush-ground girth welds. Solid and circle symbols denote failed and full-scale specimens, respectively, while the open and square symbols denote run-outs and strip specimens, respectively

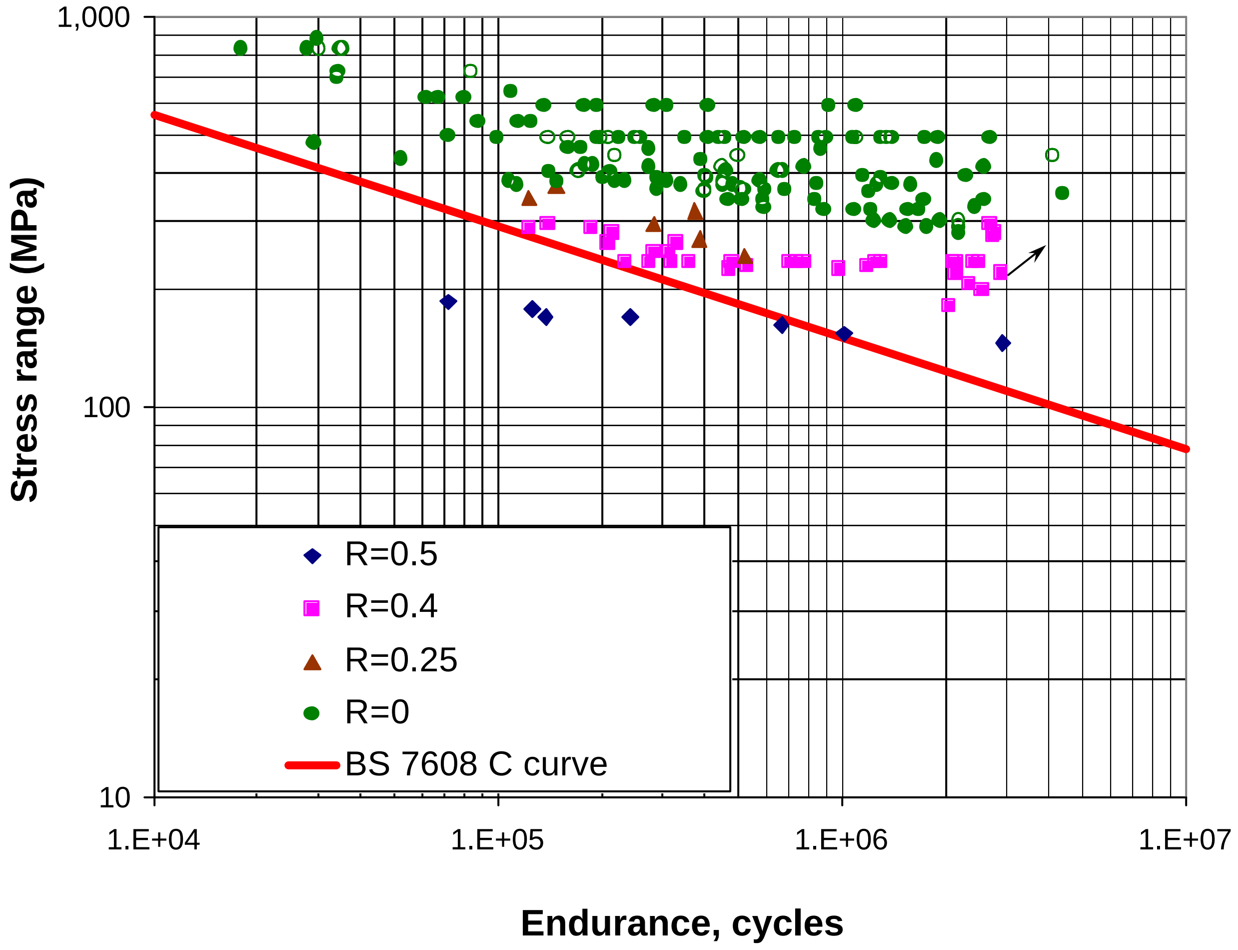

Fig.11 Comparison of fatigue performance of welded plates at different stress ratios (Oliver and Ritter, 1979). The BS 7910 C curve is also included for comparison

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