FATIGUE TESTS ON DUPLEX STAINLESS STEEL TUBULAR T-JOINTS

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ABSTRACT

With the main aim of providing design guidance, fatigue endurance tests were performed on type S31803 duplex steel tubular T-joints. The test specimens were fabricated from two sizes of tube, 170 mm outside diameter (OD) × 7.5 mm wall thickness and 50 mm OD × 5 mm wall thickness. In line with normal industrial practice for duplex steel, the specimens were welded by the TIG process. The tests were carried out under in-plane bending at R = 0.1. In most joints, the brace was set onto the chord, but two specimens were made with the brace penetrating the chord to simulated pipework. The chord SCF was lower in the pipework joint than the tubular joint. However, all the results correlated on the basis of the hot spot stress range. The results were in reasonable agreement with those for similar joints in C-Mn steels, and hence the recently proposed CIDECT design curve.

IIW-Thesaurus keywords: *Fatigue tests; Fatigue strength; Lifetime; K1c; Stress distribution; Stress; Strain gauges; Strain; Fatigue cracks; Crack initiation; Diagrams; Tubes and pipes; Pipework; Duplex stainless steels; Carbon manganese steels; Comparisons; GTA welding; Welded joints; Weld toes; Design; Recommendations; Practical investigations.*

1 INTRODUCTION

Following several years of review and analysis of fatigue data obtained from welded joints between tubes, new fatigue design recommendations have been developed [1, 2]. They are directed specifically at the application of rectangular and circular hollow sections (RHS and CHS) for structures in general, as compared with the use of large steel tubes in offshore structures. Thus, special attention has been paid to relatively thin tubes, which offer an advantage over thick ones from the fatigue viewpoint.

A recent investigation [3] of the fatigue performance of welded stainless steels involved a few tests on joints in duplex stainless steel tubes. This paper presents the results in comparison with the new fatigue design recommendations and the background data upon which they are based [4].

2 EXPERIMENTAL DETAILS

2.1 Material

The test specimens were fabricated from two sizes of type S31803 duplex stainless steel tube, 170 mm outside diameter (OD) × 7.5 mm wall thickness and 50 mm OD × 5 mm wall thickness. The chemical compositions and tensile properties are given in Table 1.

2.2 Specimen design

The test specimens consisted of tubular T-joints, as shown in Fig. 1. Most of these were intended to represent structural joints, such that the smaller pipe (brace) was welded onto the larger (chord). However, stainless steel tube is widely used as pipework and this often experiences fatigue loading. Indeed, a recent spate of fatigue failures occurred in duplex pipework used in oil processing equipment in North Sea platforms. The cost of these failures, including lost revenue while repairs were made, ran into millions of dollars. Therefore, the opportunity was taken in this study to explore the effect of the brace penetrating the chord, as in pipework.

2.3 Manufacture

In line with normal industrial practice for duplex steel, the specimens were welded by the TIG process. AWS type ER 2205 filler wire was used. The ends of the brace tubes were bevelled to allow full penetration welding. However, the "pipework" joints were fillet welded after first inserting them through drilled holes in the side of the chord.

Based on the usual fatigue behaviour of tubular joints, potential fatigue cracking from the weld toe in the chord was of primary interest. However, as will be seen later, the stress in the brace was higher. Therefore, to avoid

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Table 1. Material properties of S31803 duplex tubes.

a) Chemical analysis

Tube size, mm	Element, % by weight								
	C	Si	Mn	P	S	Cr	Mo	Ni	N
170 OD × 7.5 wall	0.018	0.58	1.14	0.030	0.001	22.45	3.18	5.29	0.193
50 OD × 5 wall	0.013	0.47	0.77	0.021	0.0001	22.13	3.17	5.50	0.165

b) Tensile properties

Tube size, mm	Proof strength, N/mm²	UTS, N/mm²	Elongation, %
	0.2%		
170 OD × 7.5 wall	470	814	38
50 OD × 5 wall	450	620	25

the risk of cracking in the brace, the weld toes were burr ground.

2.4 Fatigue testing

The specimens were fatigue tested in a servo-hydraulic fatigue testing machine, as shown in Fig. 2. The small diameter brace tubes were rigidly clamped and the load was applied through the chord to give in-plane bending (IPB) at the joint. The tests were performed under constant amplitude sinusoidal loading at a frequency of between 0.5 and 5 Hz. The specimens were tested until fatigue cracking was so extensive that their deflections under load exceeded the limits of the actuator. The fatigue crack was also through the tube wall thickness at this stage.

The intention was to represent the fatigue test results obtained from these specimens in terms of the hot spot stress range, as is normally used for presenting fatigue data obtained from tubular connections. A method for establishing the hot spot stress by extrapolation from the stress distribution approaching the weld was established during the extensive research programme carried out in Europe on fatigue of offshore tubular structures [5]. Although the present tube sizes are considerably less than those tubulars used for offshore structures, the same approach was adopted, and electrical resistance strain gauges were attached to the braces and

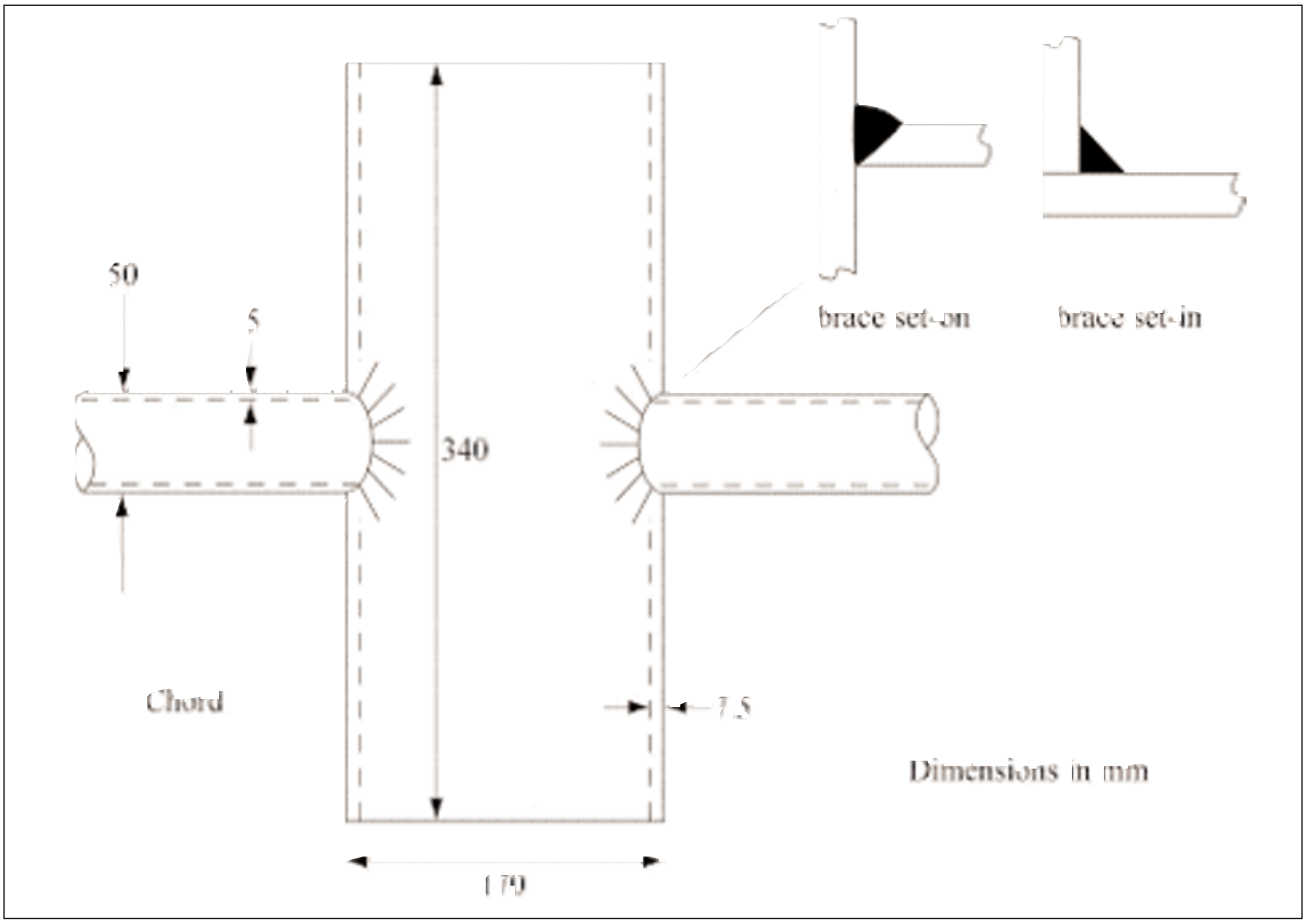

Fig. 1. Tubular T-joint test specimens.

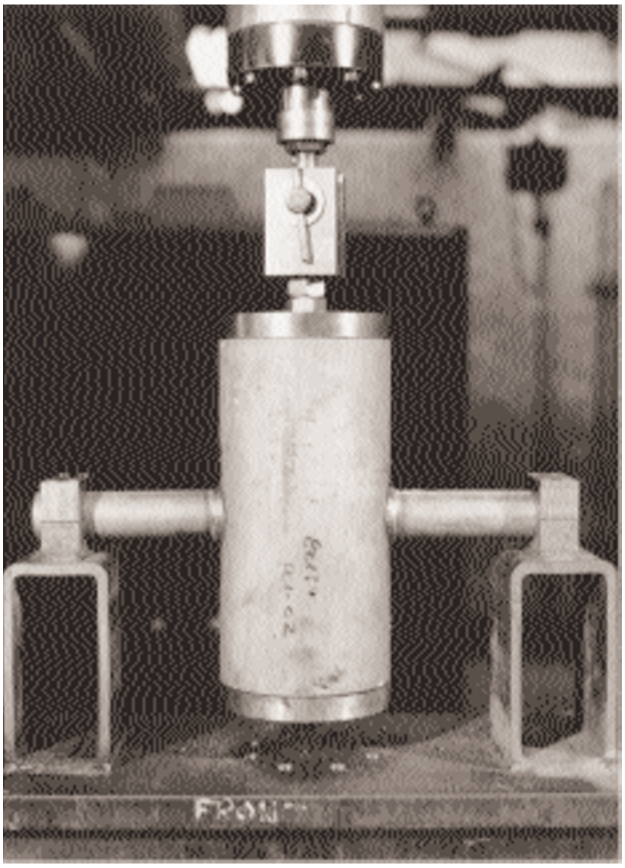

Fig. 2. Servo-hydraulic fatigue testing machine.

chord in order to establish the relevant stress distributions, as shown in Fig. 2(a). In practice, strain gauges were attached to the braces and chord in order to establish the relevant stress distributions. 5-element strip gauges were used, with elements at 2 mm spacing and the first element fixed 4mm from the weld toe. Gauges were attached to the chord in all cases, since this was usually the location of failure, but only to the brace in selected specimens of both types. In addition, strain gauge rosettes were attached close to the weld in the chord and brace in one specimen. The objective was to determine the ratio of strains normal and parallel to the weld for use in the conversion of hot spot strains to stresses.

3 PRESENTATION AND DISCUSSION OF TEST RESULTS

The fatigue test results obtained from the tubular joints are presented in Table 2. In both types of joint, as intended, fatigue cracking usually initiated at the weld toe in the chord and propagated through the chord wall thickness. However, one of the pipework joints failed in the brace from the weld toe. This was particularly surprising because the weld toe had been burr ground to prevent fatigue cracking.

The strain gauge measurements made on each specimen allowed the stress distribution approaching the weld toe to be established and the corresponding hot spot stress range at the weld toe to be deduced. This information and its analysis are presented in the Appendix, and the resulting hot spot stresses are included in Table 2. In the case of the pipework joint that failed in the brace, the hot spot stress in the brace is given, as well as that in the chord for comparison.

The test results are presented in Fig. 3 in terms of the nominal bending stress range at the weld toe in the brace pipe. As noted in the Appendix, this was estimated from the measured strains to be 7.4 N/mm^2 per kN applied force. It will be seen that while there is good correlation between the tubular joint results, much longer lives have been obtained from the pipework joints. However, this is consistent with the fact that the stress concentration factor, relating the nominal stress in the

Table 2. Fatigue test results.

Specimen No.	Joint Type	Applied force range, kN	Nominal stress in brace,* N/mm	Estimated hot spot stress range, N/mm²	Endurance cycles	
P01-02	Tubular	14.4	107	249	655,706	Failed by through-thickness cracking at weld toe on chord side
P01-03		16.2	120	268	743,270	Failed by through-thickness cracking at weld toe on chord side
P01-04		18	133	302	363,920	Failed by through-thickness cracking at weld toe on chord side
P01-05		23.6	175	430	70,125	Failed by through-thickness cracking at weld toe on chord side
P01-06		27	200	432	85,229	Failed by through-thickness cracking at weld toe on chord side
P01-07		27	200	427	80,952	Failed by through-thickness cracking at weld toe on chord side
P01-08	Pipe	23.6	175	259	458,540	Failed by through-thickness cracking at weld toe on chord side
P01-09		18	133	190 (209 in brace)	3 028,776	Failed by thought-thickness cracking in brace at position of ground weld toe

* 7.4 × force range (see Appendix).

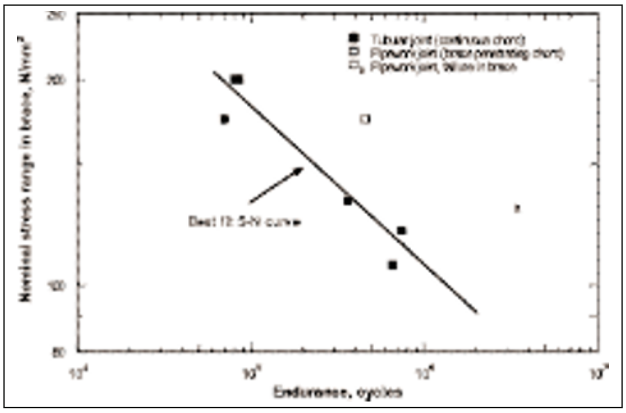

Fig. 3. Tests results in terms of nominal bending stress range.

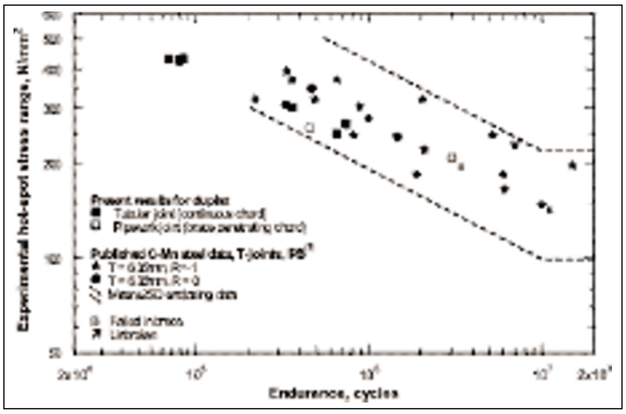

Fig. 4. Tests results in terms of hot spot stress range.

brace to the hot spot stress at the weld toe in the chord, was lower in this type of joint. The results are re-plotted in Fig. 4 in terms of the hot spot stress range. In the case of the pipework joint, which failed in the brace, the hot spot stress in the brace has been plotted. The results for the two joint types are now in reasonable agreement, particularly bearing in mind that the brace failure result refers to a burr ground weld toe, which would be expected to exhibit a longer fatigue life than an as-welded toe.

Fig. 4 includes published test results for C-Mn steel, obtained from various types of tubular T-joints tested under in-plane bending [6], also expressed in terms of the hot spot stress range. Ideally, C-Mn steel data obtained from the same tube sizes and tested under IPB with R ~ 0 are of interest. However, the available data are very limited and those shown in Fig. 4, for thinner chords and mainly tested with R = -1, are the most relevant. They are rather scattered and not ideally suited for regression analysis. However, the best fit S-N curve was calculated and lines two standard deviations of logN either side of the mean are included in Fig. 4, to facilitate comparison with the present results. As will be seen, the present results lie towards the lower bound of the C-Mn steel data, but within the scatterband. This is reasonable in view of the more severe applied stress ratio. It is also consistent with the fact that fatigue lives obtained from weld details in stainless steel plate agree with corresponding data for C-Mn steels [7] and that fatigue crack growth rates are similar in C-Mn and stainless steels [3, 8].

4 DESIGN RECOMMENDATIONS

With regard to current design curves, the main focus of attention had been on structural connections, especially in relation to offshore structures. Thus, they refer specifically to much larger tube sizes than those used in the present test specimens. On this basis, it can be expected that the present joints will give much better fatigue performance than that indicated by the design curve. As discussed in the Appendix, this has prompted alternative design curves, which reflect the expected increase in fatigue life with decrease in tube wall thickness. The basic design curve, intended primarily for C-Mn steel offshore structures, is the UK Health and Safety Executive's T' curve [9], while an alternative curve for a chord wall thickness of 7.5 mm, as in the present specimens, has been proposed by CIDECT [2]. The two curves are shown with the present test results in Fig. 5(a). As will be seen, the results are well above the T' curve, but consistent with the CIDECT curve.

In design, the likelihood is that the hot spot stress would be estimated using an SCF based on an appropriate parametric formula; suitable equations for the present tubular joints are included in the Appendix. Considering

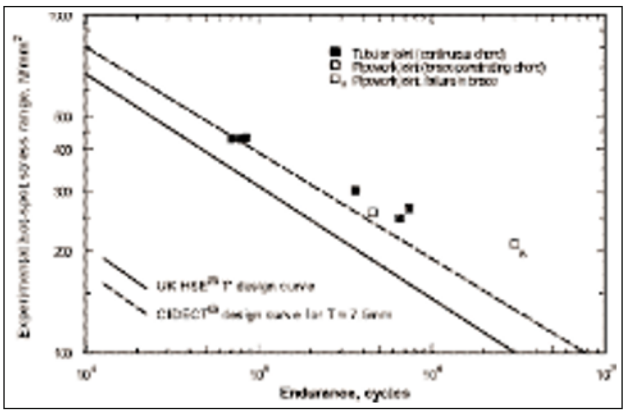

Fig. 5(a). Test results – experimental hot spot stress range.

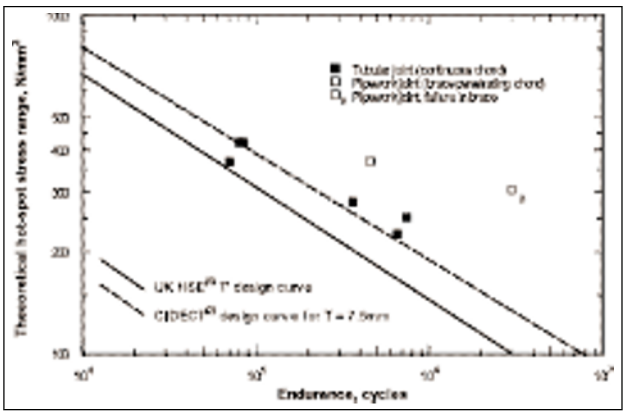

Fig. 5(b). Test results – theoretical hot spot stress range.

the present results in terms of this theoretical hot spot stress range, as shown in Fig. 5 (b), brings the tubular joint results closer to the CIDECT curve, with one below it. Thus, on this basis the CIDECT curve could be considered to be marginally unconservative. However, it is still safe for pipework joints.

With regard to the distinction between structural tubular and pipework joints, the present limited results, which are confined to one mode of loading, show that their fatigue behaviour is similar or the pipework is better when considered in terms of the experimental or theoretical hot spot stress range respectively. Thus, the same design curves can be used. Furthermore, for the case considered here, the SCF in the brace of a pipework joint is essentially the same as that in the structural joint, as given by the parametric equation in the Appendix. However the SCF is the chord is some 35% lower in the pipework. Clearly, it would be useful to develop parametric equations for pipework joints, similar to those available for structural connections, to take advantage of this in design.

5 CONCLUSIONS

Based on fatigue tests of tubular T-joints in type S31803 duplex stainless steel tested under in-plane bending, the following conclusions may be drawn:

a) The fatigue performance was similar to that expected from the database for C-Mn steels and hence consistent with the corresponding new CIDECT design curve.

b) The CIDECT curve was less conservative if the hot spot stress was calculated using the CIDECT parametric equations.

c) Limited tests on pipework joints, in which the brace penetrated the chord, showed that the chord SCF was some 35% lower than that in a similar tubular connection. However, based on the hot spot stress, the fatigue lives were similar.

ACKNOWLEDGEMENTS

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REFERENCES

1. van Winderde A. M., Packer J. A. and Wardenier J.: “IIW fatigue rules for tubular joints”, Proceedings IIW Conference on Performance of Dynamically Loaded Welded Structures, Welding Research Council, New York, 1997, 78.

2. Zhao X. L. et al.: “Design guide for circular and rectangular hollow section joints under fatigue loading”, CIDECT Research Project, 7M, IIW Doc. XV-E-98-236.

3. Branco C. M., Maddox S. J. and Sonsino C. M.: “Fatigue design of welded stainless steels”, European Commission Report No. EUR 199972, ECSC Steel Publications, Brussels, 2001.

4. van Delft D. R. V., van Wingerde A. M., Wardenier H., and Packer J. A.: “Scale effects on the fatigue behaviour of tubular structures”, Proceedings IIW Conference on “Performance of Dynamically Loaded Welded Structures”, Welding Research Council, New York, 1997, 123.

5. Anon: “Background to new fatigue guidance for steel welded joints in offshore structures”, HMSO, London, 1984.

6. Pozzolini P. F.: “Tests on tubular joints”, Proceedings International Conference on “Steel in Marine Structures” Plenary Session 2, EUR 7347, Commission of the European Communities, Luxembourg, 1981, 97-146.

7. Maddox S. J., Branco C. M., Sonsino C. M., Manteghi S., Kueppers M. and Infante V.: “Fatigue design data for welded stainless steels”, IIW Document XIII-1768-99, 1999.

8. Razmjoo G. R.: “Design guidance on fatigue of welded stainless steel joints”, Proc. OMAE, Vol. III Materials Engineering, ASME, 1995, 163.

9. Offshore Installations: “Guidance on design, construction and certification”, 4th Edition, 1990 (including February 1999 amendments), Health and Safety Executive, HMSO, London.

APPENDIX
ANALYSIS OF TUBULAR JOINTS

A1 FATIGUE DESIGN OF TUBULAR JOINTS

The fatigue behaviour of tubular joints is normally considered in terms of the hot spot stress range at the weld toe where fatigue cracking takes place. The hot spot stress differs from the nominal stress in that it incorporates the influences of all sources of stress concentration at the welded joint except the local effect of the weld profile itself. Thus, it has been possible to correlate the fatigue performance of a wide range of geometries and types of tubular joint to give a single hot spot stress S-N curve for tubular joints in steel [5]. In fact, the tube wall thickness needs to be considered as a separate influencing factor and therefore a hot spot stress S-N curve applies only to a particular thickness range. For C-Mn steel tubular joints in wall thicknesses up to 16 mm, the UK Health and Safety Executive T’ curve is widely used for the design of offshore structures. Expressed in terms of the hot spot stress range $\Delta\sigma_{HS}$ in N/mm², this has the equation:

$$\Delta\sigma_{HS}^{3}\ N = 3 \times 10^{12} \qquad (1)$$

A recent proposal from CIDECT [2] introduces a correction to the T’ curve to allow for wall thickness. This results in the following S-N curve:

$$\Delta\sigma_{HS}^{3}\ N^{[1-0.18\log(16/T)]} = 3 \times 10^{12} \qquad (2)$$

where T is the thickness of interest in millimetres.

A.2 DETERMINATION OF HOT SPOT STRESS FROM STRESS DISTRIBUTION

The hot spot stress is determined from the stress distribution approaching the weld toe by linear extrapolation. What is now regarded as the conventional way to do this for joints between circular section tubes was developed during the European Offshore Programme [5]. In the present case, the stress distributions in the chord and brace at the crown of the joint are relevant. The resulting extrapolation points are essentially the same in both, 7.6 and 4 mm in the brace and 7 and 4 mm in the chord.

A.3 THEORETICAL ESTIMATE OF HOT SPOT STRESS

In the absence of the detailed stress distribution approaching the weld, stress concentration factors are widely used to determine the hot spot stress. Extensive stress analysis of a wide range of tubular joints has resulted in parametric equations for stress concentration factors, related to the nominal stress in the brace. For T-joints between circular tubes loaded under in-plane bending, as in the present case, the equations for the stress concentration factors at the crown position are [2]:

$$SCF_{chord} = 1.45\beta\tau^{0.85}\gamma^{(1-0.68\beta)} \quad (3)$$

$$SCF_{brace} = 1 + 0.65\beta\tau^{0.4}\gamma^{(1.09-0.77\beta)} \quad (4)$$

where $\beta = r/R$,

$\tau = t/T$

and $\gamma = R/T$.

The validity ranges for these equations are $0.2 \leq \beta \leq 1$; $0.2 \leq \tau \leq 1$; $8 \leq \gamma \leq 32$. In the present joints, for which $\beta = 0.2941$, $\tau = 0.67$ and $\gamma = 11.33$, these validity ranges are satisfied. Hence,

$SCF_{chord} = 2.11$

$SCB_{brace} = 2.29$

Thus, on the basis of these theoretical stress concentration factors, the hot spot stresses are very similar in the chord and brace. Since in most practical tubular joints the stress concentration factor in the chord dominates, the welds in the braces of the present specimens were toe ground to prevent fatigue cracking there.

The above analysis refers to joints between tubes and cannot be assumed to be applicable to pipe joints where the brace tube penetrates the chord tube, as in the present pipework specimens. There are no known parametric stress concentration factor equations for such cases. It is to be expected that the chord stress concentration factor will be higher, but the brace stress concentration factor should be lower due to the lower restraint offered by the chord wall when it has a hole in it.

A.4 ANALYSIS OF STRESS DISTRIBUTIONS IN PRESENT TEST SPECIMENS

All but one of the present tubular test specimens failed in the chord, as intended. Therefore, the strain distributions approaching the weld toe in the chord were used to determine the hot spot stresses. These are plotted in Fig. A1 to A8. In addition, examples of the corresponding strain distribution in the brace are given for one of each type of specimen. In fact, one of the pipework type specimens (P01-09) failed in the brace and for that case the stress distribution in the brace was used to determine the hot spot stress. This had to be estimated from the measurements made in specimen P01-08 because brace strains were not measured in specimen P01-09. As will be seen, the stress distributions were close to linear in all cases. However, linear extrapolation from the conventional positions was carried out, as shown. In order to allow for biaxiality of the stress system in the hot spot region, strains acting both normal (ε_n) and parallel (ε_p) to the weld toe were measured in one specimen. These gave the ratios $\frac{\varepsilon_p}{\varepsilon_n}$ = 0.82 in the chord and 0.14 in the brace. The hot spot stress σ_{HS} was then calculated from the extrapolated hot spot strain ε_{HS} from the equation:

$$\sigma_{HS} = \frac{E\varepsilon_{HS}}{(1-\nu^2)}\left(1 + \nu\frac{\varepsilon_p}{\varepsilon_n}\right) \quad (5)$$

where E = elastic modulus and n = Poisson's ratio (assumed to be 2×10^5N/mm² and 0.3 respectively for duplex stainless steel). The resulting hot spot stresses are given in Table A1.

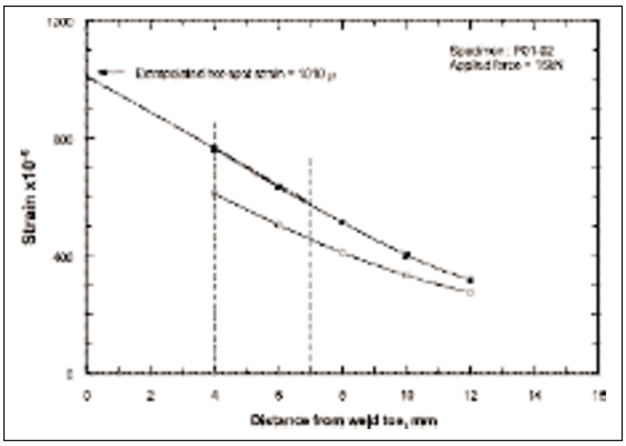

Fig. A1(a). Strain distributions in chord of specimen P01-02.

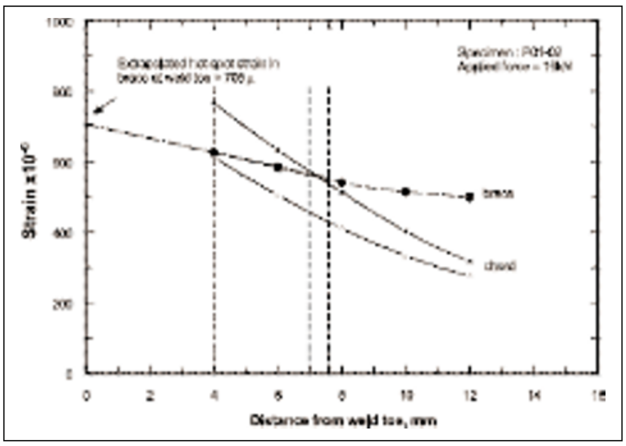

Fig. A1(b). Strain distributions in chord and brace of specimen P01-02.

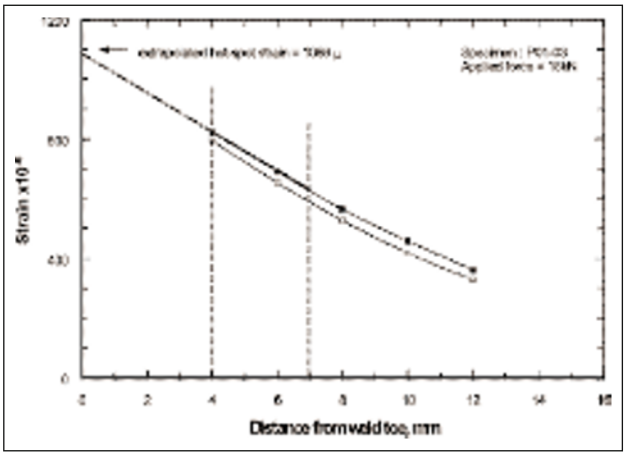

Fig. A2(a). Strain distributions in chord of specimen P01-03.

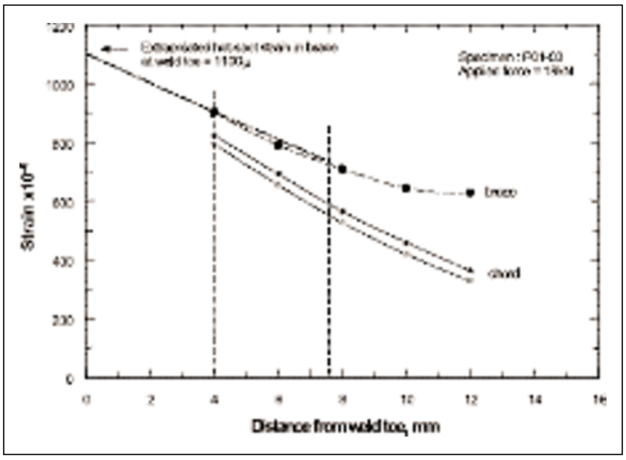

Fig. A2(b). Strain distributions in chord and brace of tubular specimen P01-03.

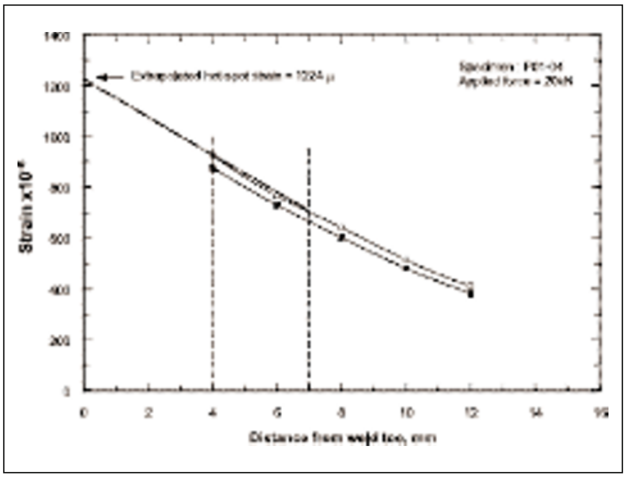

Fig. A3. Strain distributions in chord of tubular specimen P01-04.

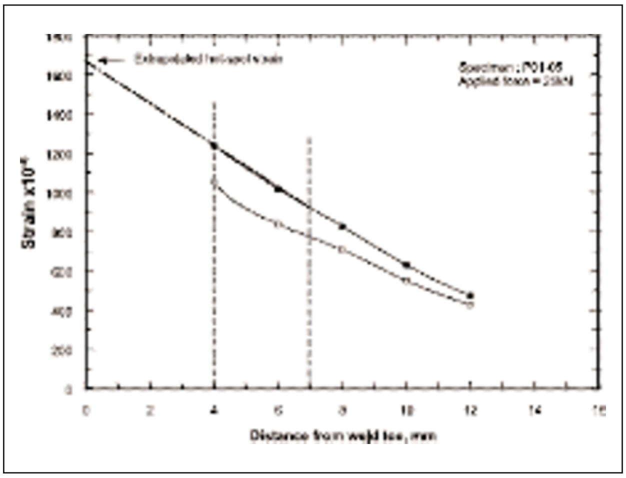

Fig. A4. Strain distributions in chord of tubular specimen P01-05.

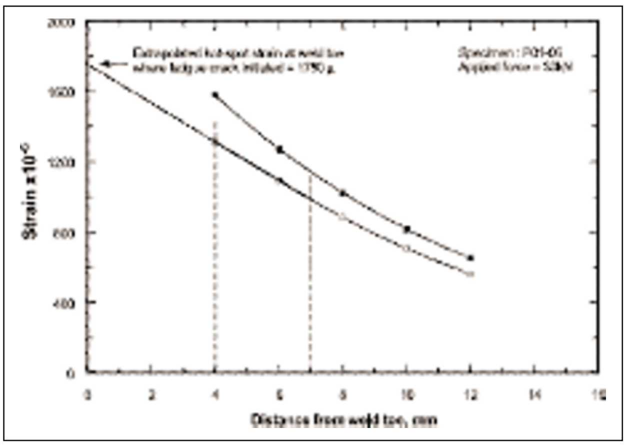

Fig. A5. Strain distribution in chord of tubular specimen P01-06.

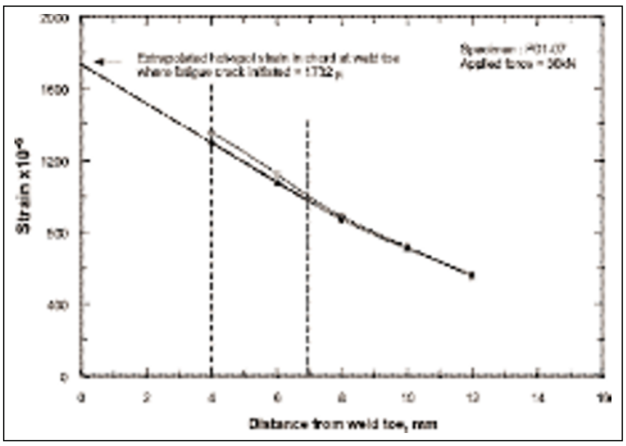

Fig. A6. Strain distribution in chord of tubular specimen P01-07.

A.5 COMPARISON OF MEASURED AND CALCULATED STRESS CONCENTRATION FACTORS

In order to compare the experimental and theoretical estimates of stress concentration factor, it is necessary to determine the nominal stress in the brace. This was estimated assuming that the bending moment distribution in the brace was linear, so that the nominal bending stress at the weld toe could be deduced from that remote from the toe. It was further assumed that the strain gauge farthest from the chord was not affected by the joint and hence read the nominal strain at that location. Based on the average measured strain per unit

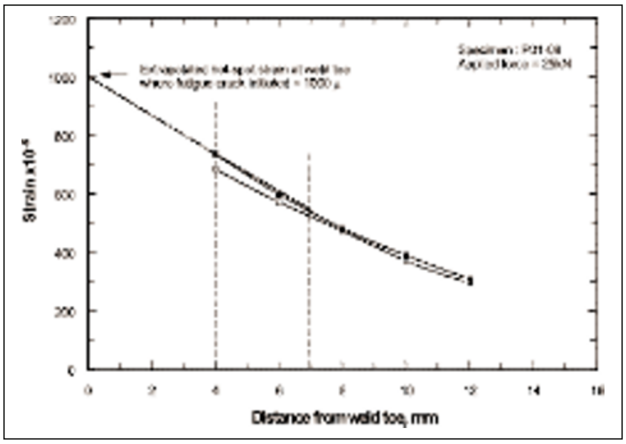

Fig. A7(a). Strain distribution in chord of pipework specimen P01-08.

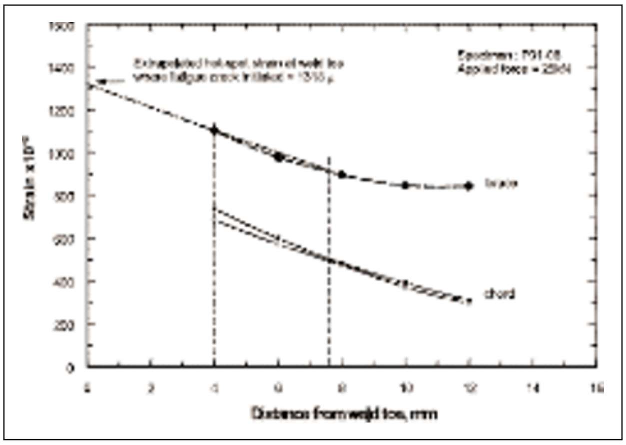

Fig. A7(b). Strain distribution in brace and chord of pipework specimen P01-08.

applied force at that strain gauge, the resulting nominal stress at the weld toe was estimated to be 7.4 N/mm^2 per kN applied force. The same value was obtained for both specimen types. The resulting nominal stresses are included in Table A1. Comparison of these with the hot spot stresses gives the experimental stress concentration factors. As will be seen, the experimental stress concentration factors in the chord for tubular joints were very similar but slightly higher than the theoretical value. In contrast, the two values obtained for the brace SCF are lower than the theoretical value. They are also lower than the chord SCFs, which contradicts the theoretical values. However, on the basis of these tests the parametric equations are clearly safe.

With regard to the pipe type joints, having the brace penetrate the chord wall has certainly influenced the local stress, although only in the chord. The brace SCF is seen to be essentially the same as that in the tubular joint, indicating that the stiffness of the joint is unchanged with respect to brace wall bending. However, the chord SCF is around 35% lower than that in the tubular joint, reflecting the much lower hot spot stress

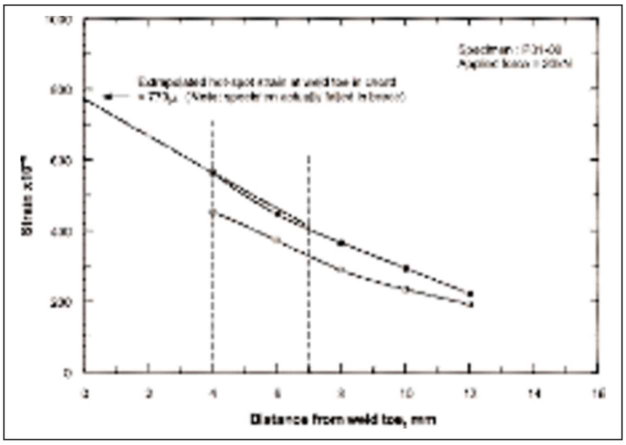

Fig. A8. Strain distribution in chord of pipework specimen P01-09, which failed in brace.

per unit applied force. A possible explanation for this is that there is better distribution of the load on the chord due to the greater flexibility of the joint. From the practical viewpoint, the weld toe in the brace is now definitely more critical than that in the chord.

Table A.1. Stress analysis of tubular specimens.

Joint Type	Specimen no.	Applied force range, kN	Nominal stress in brace, N/mm^2	Hot spot stress range, N/mm^2		Stress concentration factor*	
				chord	brace	chord	brace
Tubular	P01-02	14.4	107	249	145	2.33	1.36
	P01-03	16.2	120	268	227	2.23	1.89
	P01-04	18	133	302	–	2.27	–
	P01-05	23.6	175	430	–	2.46	–
	P01-06	27	200	432	–	2.16	–
	P01-07	27	200	427	–	2.14	–
Pipe	P01-08	23.6	175	259	285	1.48	1.63
	P01-09	18	133	190	209+	1.43	–

* Theoretical values for tubular joints: chord, 2.11.
brace, 2.29

+ estimated on the basis of specimen P01-08.