MONOTONIC AND FATIGUE BEHAVIOUR OF RECTANGULAR THIN WALLED WELDED JOINTS USED IN TRANSPORT VEHICLES

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The static and fatigue strength of the main welded nodes, of mild steel used in public transport vehicles is presented. The loadings applied were bending,compression and tension in the main chord only.

S-N and crack propagation data was obtained in different tube thicknesses and node geometries. Fatigue life was computed as a function of defect size using a FM model based in FE computations. Comparison of theoretical and experimental results is presented.

A set of fatigue design curves was derived and compared with existing design curves for thicker sections.

INTRODUCTION

Transport vehicles are often subjected to dynamic loads leading to fatigue failures. These dynamic loads are usually transmited from the pavement to the structure causing fatigue in the welded joints. The fatigue cracks initiate at the toes of fillet welds of T type connections made with rectangular thin walled tubes.

The main structural element in public transport vehicles, such as bus structures, are welded rectangular thin walled sections with tube thicknesses ranging from 1.5 to 6 mm. These type of structures combine low weight with high values of the bending and torsion modulus.It is therefore possible to reduce the weight of the structure allowing an increasing load capacity in the vehicles and also reducing the fuel consumption. However, fatigue failures should be avoided and therefore an appropriate fatigue design is required.

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The need for fatigue studies was therefore recognized and three years ago a testing programme was initiated in order to assess the fatigue behaviour of welded rectangular hollow sections used in bus structures. Some results were published elsewhere(1-5) and reported on the influence of tube thickness and weld surface finish. The crack propagation phase was studied with fracture mechanics methods applying the similarity approach and two simple crack propagation models. Fractographic observations were carried out and as a result failure modes and crack initiation mechanisms were identified.

Research work in the field of the static and fatigue behaviour of welded rectangular tubes has been extensively done in Holland by Wardenier (6,7,8) and in the USA by Stephens (9). Wardenier tests were in several types of tubular connections such as K,T and Y joints loaded in tension and bending. However the size of the tubes was considerably greater than those used in bus structures and hence fatigue data may not be appropriate for design.

In Japan a detailed stress analysis study was published quoting structural stress concentration factor results obtained in several types of rectangular tubular connections(10). The finite element method was used but the geometry of the weld and defect size and shape were not considered in the investigation.

In the previous work monotonic and fatigue data were only obtained in plain rectangular tubes and specimens with simple gusset plates simulating the weld detail. These tests do not represent entirely the fatigue behaviour of the welded joints and their results may lead to significant errors in the prediction of fatigue life. On the other hand existing design curves for hollow rectangular sections such as those defined in the Eurocode (11) may not be applicable to thin sections since data was obtained in thicker and wider sections.

For the reasons mentioned above an investigation was carried out to study the monotonic and fatigue behaviour of full scale welded nodes made of rectangular thin walled sections used in public transport vehicles. Only the more critical welded nodes were tested and their fatigue and tensile data will be reported in this paper together with the results of a flaw acceptance analysis obtained using stress intensity solutions derived with the FEM. A set of fatigue design curves was obtained and compared with the existing design curves for thicker sections.

EXPERIMENTAL

The critical detail of the bus structure where fatigue cracks usually start(12)is represented in Fig.1. The rectangular tubes of the longitudinal seam type are mild steel grade St 44-2 DIN 17100. The T type welded node gave higher values of strain as measured by strain gauge readings in service and confirmed by a FEM analysis in the structure(12). In this joint the chord is usually made of tube 80x40x4 or 80x40x2 and the brace is either the same nominal size, 40x40x2 or 40x40x4.

Previously (4,5) three different grades of mild steel were fatigue tested and grade St 44-2 gave the higher values of static and fatigue strength. After the welding with the MIG process (electrode SAF NIC 70S) the tubes were subjected to a stress relieving treatment of 650°C during 1 hour followed by cooling in the furnace .

The welded node specimens are shown in Fig.2. Fig.2 a)is the specimen used in the monotonic three point bend tests where the vertical load was applied in the attachment. The detail in Fig. 2b) was used in the monotonic tension and compression tests where the load was applied in the vertical tube. Finally Fig. 2c) is the joint tested both in the monotonic and fatigue tests in cantilever bending. The testing load was applied vertically at the free end of the chord(horizontal tube) whereas the vertical brace was subjected to a constant compressive load, giving a nominal stress range of 100 MPa in the brace.

Monotonic tests were carried out in a 400 kN capacity hydraulic universal testing machine. Load,deflection and strain were monitored during the tests using appropriate transducers. The specimens were tested up to fracture or up to the onset of plastic instability. Load vs. nominal strain and load vs. deflection curves were obtained. From these plots the yield loads and yield stresses and also the ultimate strength or stress of the nodes were obtained.

Fatigue tests were performed in cantilever bending in a specially made fatigue test rig (12).All the tests were done in air at R=0.05 and in constant amplitude loading at a loading frequency of 1410 cycles/min. In each specimen the nominal stresses were monitored with strain gauges bonded in the weldment area. The vertical load in the specimen free end was monitored with the load cell of the machine.

The fatigue craks initiated usually at the weld toe in the chord (Fig.2) and propagated initially through the horizontal and afterwards through the vertical walls In some tests after the crack has crossed the horizontal wall, initiation of other cracks occured at the weld toe in the brace and in the horizontal direction (Fig.2).In order to obtain fatigue crack propagation data for the fracture mechanics prediction the crack length was monitored with a travelling microscope.

FATIGUE LIFE COMPUTATION

S-N fatigue crack propagation curves were obtained applying the simplified model described in detail elsewhere (4,5). The method uses the integration of a Paris type law where the stress intensity factor formulation in the upper chord wall was obtained with the weight function method (13), based on stress computation with the FEM. Fig.3 a) shows the 2D finite element mesh in the weld toe zone for calculation of stresses along the crack propagation line in the thickness direction of the upper chord wall (Fig.3b). The stress intensity values in the upper wall were obtained as a function of LG (Fig.3a) and thickness of tube, B,keeping Θ= constant = 45° and ρ = 0.05 to 0.07 mm depending on the thickness. As in the fatigue tests LG was varied between 6 and 7 mm,fatigue life was only calculated for these range of values. Work is now in progress to assess the influence of ρ on the computed fatigue life results.

Basically the crack propagation model in the nodes assumes that the total fatigue life is given by the sum of three endurance values

i) number of cycles of crack propagation in the upper chord wall and in the stress gradient at the weld toe(Fig.3 c).
ii) number of cycles of crack propagation also in the upper chord wall but outside the stress gradient at the weld toe
iii) number of cycles of crack propagation in the lateral sides of the chord.

It was found that phase i) occupied 75 to 85% of the total fatigue crack propagation life thus emphasizing the importance of the stress gradient at the weld toe. For the vertical walls no FEM results were used and in alternative a stress intensity factor solution available in the literature,for a bar subjected to cantilever bending and with a lateral crack,was found more appropriate (14).

Fatigue life was obtained as a function of initial flaw size at the weld toe. The values of m and C were experimentally obtained from the results of crack propagation tests carried out in tubular specimens with a similar geometry and where an initial flaw was started. Thus fatigue crack initiation was made absent and the slope of the resulting S-N curve could be taken as the exponent m of the Paris Law.

Due to the predominant crack propagation phase in the horizontal wall no meaningfull difference was obtained between the S-N crack propagation curves of the welded nodes with 80 or 40 mm nominal size. The resulting crack propagation curves for the thicknesses of B=2 and 4mm and 0.2 mm flaw size are plotted in Fig.4. This is a typical flaw size value in welded joints(15) and gives also an average value of flaw size in these type of weld nodes as confirmed by measurements taken in an extensive number of joints.

The results in Fig. 4 show that crack propagation life is higher for the thickness of 2 mm in comparison with the tubes of 4 mm wall thickness. The difference is due to the higher values of the geometrical factor Y, in the stress intensity formulation, which were obtained in the nodes with 2 mm wall thickness. Provided crack initiation is not taken into account in the analysis, which is approximately true for endurance levels less than 10^6 cycles, the curves in Fig.4 could be used as basis for the design of thin walled welded nodes. Comparison of these curves against the experimental S-N curves will be presented in the next section.

RESULTS AND DISCUSSION

Monotonic tests

The mean values of the results obtained in the monotonic tests carried out in the tubular joints represented in Fig.2 are given in Table 1. In this table the proportional load (elastic limit) was taken as the value of load at the first deviation from linearity in the load-deflection or load-nominal strain curve of the test. The proportional stress was the stress at the proportional load and was calculated in the elastic region. The ultimate stress is the stress at the maximum load attained in the tests(Table 1) and was calculated, in the bending cases, using fully plastic limit equations available in the literature.

Table 1 - Mean results of the monotonic tests in welded rectangular tubular joints. St. 44-2 steel

Specimen type and Test(Fig.2)	Proportional limit load (kN)	Proportional limit stress (MPa)	Maximum load(kN)	Ultimate stress(MPa)
Tension 80x40x4	323.5	340	373.5	393.0
Tension 80x40x2	169.3	348	189.2	389.0
Compression 80x40x4	265.5	279.3	336.4	354.8
Compression 80x40x2	142.8	291.2	183.2	373.4
3PB 80x40x4	74.27	239.1	210	363.6
3PB 80x40x2	40.68	244.2	63.46	371.4
Cantilever bending (80x40x2)	9.69	234.2	14.08	313.12
Cantilever bending (80x40x4)	17.01	229.8	24.63	314.66
Cantilever bending (40x40x4)	6.10	236.2	9.27	315.24

Fig.5 is a typical plot load vs. vertical deflection of the attachment in a 3PB test (Fig.2a). Both proportional and maximum load points are identified in the plot.The curve shows an extensive amount of plasticity and the point of fracture gave a very low load and past maximum load.Similar behaviour was obtained in the other tests.

The fracture modes observed in the tests were: i) buckling of the chord walls in the weldment area in the bending and compression tests, and: ii) necking in the base metal in the tension tests. Hence in all these tests failure was preceedeed by extensive plastic instability.

Data such as given in Table 1 is usefull in the design of the structure. For example it shows that in bending the static strength of the joints is lower than in compression or tension. Also a thickness effect was observed in the results and both proportional limit stress and ultimate stress have increased when the thickness varied from 4 to 2 mm. Since bending is predominant in these type of structures (12) the static design stresses should be based in the results obtained in bending and given in Table 1.

Fatigue tests

Four series of fatigue tests were carried out in specimens with the following nominal dimensions:

a) Chord and brace 80x40x4
b) Chord and brace 40x40x4
c) Chord and brace 80x40x2
d) Chord and brace 40x40x2

The S-N curves are plotted in Fig.6. In this curve the stress range is the nominal stress value resulting from the extrapolation to the weld toe line of the strains measured in a location close to the weld toe. These results show that there is no influence of the height of the tube since about 80-85% of fatigue life is spent while the crack is propagating in the upper(horizontal) wall of the tube. Hence this difference in height may not be enough to change the fatigue life of the specimens.

A thickness effect was observed in the results. The fatigue strength in the joints with 2 mm wall thickness is higher than in the 4 mm wall thickness. This is in agreement with the fracture mechanics predictions(Fig.4) where a higher crack growth rate was obtained for the 2 mm specimens due to considerably higher values of K near the weld toe.

A thickness effect was observed in the results. The fatigue strengths in the tubular joints with 2 mm wall thickness are 20% higher than those obtained for the similar joints with 4 mm wall thickness (Fig.4).Comparison of the experimental S-N curves with the computed S-N crack propagation curves for the initial crack size of 0.2 mm show a good agreement bearing in mind the crack initiation phase. It is seen that the theoretical and experimental curves are paralell which indicates an increasing crack initiation period with the number of cycles as expected. Therefore the derived crack propagation model gives a good prediction of fatigue life in these tubular joints.

The equations of the S-N curves in Fig.4 refer to the mean curves and the curves for 97.5% survival probability are plotted in Fig.6. The value of slope(exponent m)is very close to 5.0 thus confirming the results recently obtained by Mang (16) in similar tubular joints with greater nominal sizes.

A comparison of the experimental S-N curves with the proposed curves in Eurocode (11) can also be done in Fig. 6. These curves are the class 90 and 72 both for m=3.0 and 5.0.The curves for m=3.0 are unsafe in the region 1.0 to $5.0x10^5$ cycles.It is clear that both Class 90 and 72 curves are too conservative and the appropriate design curve is the Class 114 for m=5.0. Hence the exponent m= 5.0 gives better correlation with the experimental results in welded rectangular tubular joints confirming the results obtained elsewhere (8,16).

Therefore it may be concluded that welded rectangular joints with wall thicknesses below 4 mm and nominal dimensions below 80 mm have a higher fatigue strength than the tubular joints with thicker sections and greater dimensions. This should lead to an upgrading of classification of the thin walled sections in the slope of the S-N curve instead of the value m=3.0 presently recommended in the code.

CONCLUSIONS

1- Fatigue strength of welded rectangular thin walled tubular joints was found to be dependent on the tube thickness increasing with decreasing thickness.
2- The results of a fatigue crack propagation model based on LEFM and derived for a T type welded rectangular type thin walled tubular joint gave a good correlation against the S-N experimental results.
3- Local buckling in the chord walls preceeded by extensive plastic deformation and instability, was the main fracture mode observed in the monotonic tests carried out in the main types of welded rectangular thin walled tubular joints used in transport vehicles.
4- Class 114 design curve of Eurocode 3 with m=5.0 can be used with adequate safety as a design curve in welded rectangular thin walled tubular joints used in transport vehicles and loaded mainly in bending. This curve can replace with advantage the Class 90 and 72 curves proposed in the code for similar type of joints but with greater dimensions.

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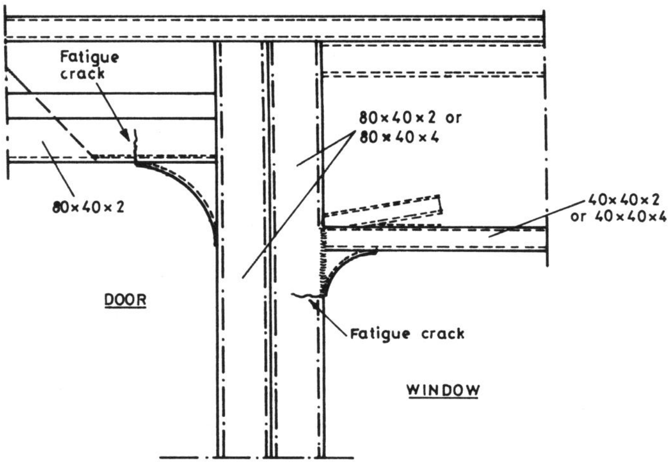

Fig.1-Critical detail(tubular joint)leading to fatigue failure

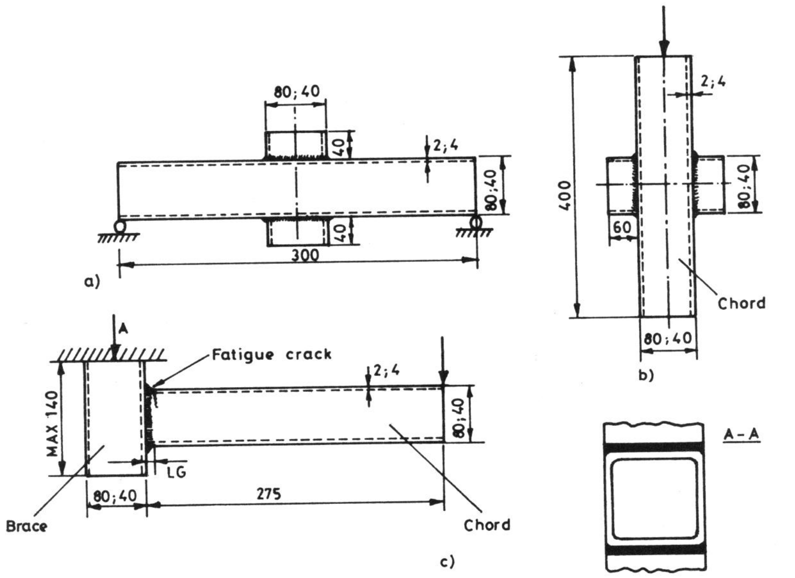

Fig.2-a) Monotonic 3PB specimen;b) Monotonic tension and compression specimen c) Specimen for cantilever bending

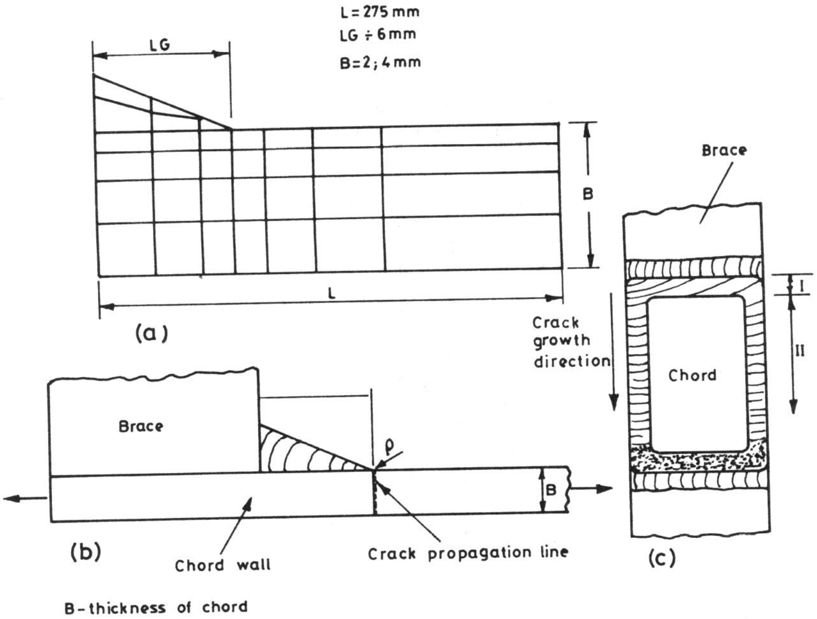

Fig.3-Finite element mesh and fatigue crack propagation model in the tubular joints

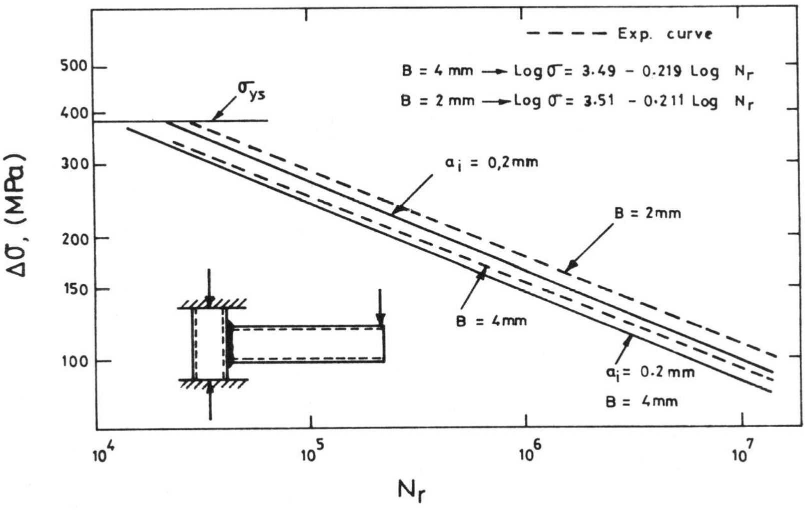

Fig.4-Theoretical and experimental S.N curves.Tubular joints 80x40 and 40x40.St 44-2 steel.Cantilever bending.R=0

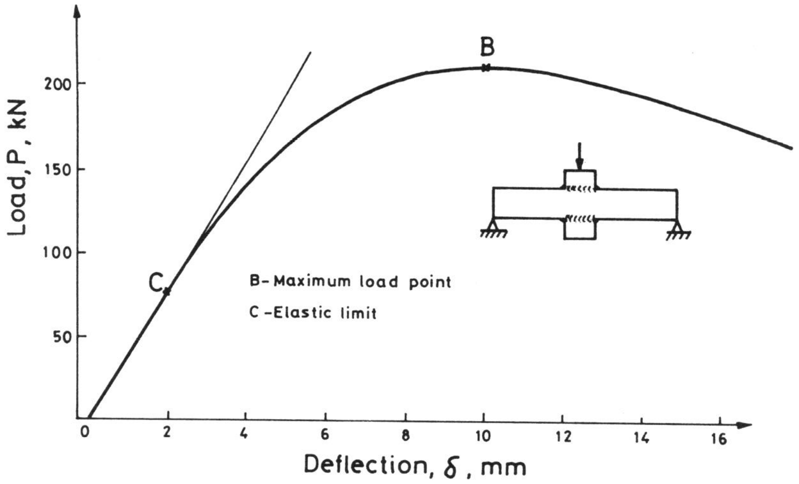

Fig.5-Typical load-deflection curve in a monotonic 3PB test. St 44-2 Steel.Tubular joint 80x40x4

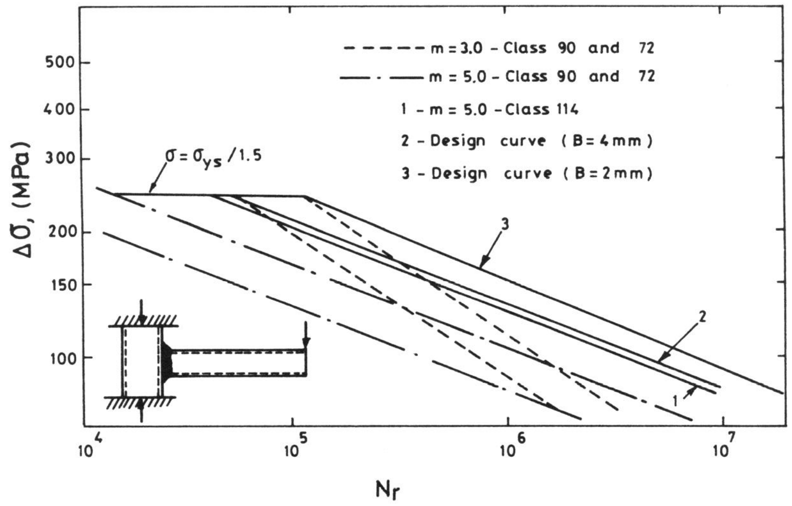

Fig.6-Design S-N curves for welded thin walled rectangular tubular joints.Comparison with Eurocode design curves