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Assessment of Fatigue Life of Orthotropic Steel Decks

Evaluation de la durée de vie des dalles orthotropes en acier

Berechnung der Lebensdauer orthotroper Platten aus Stahl

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SUMMARY

Using traffic measurements, a finite band computer program calculates stress range histograms at the joints where cracks occur. Further, as the fatigue strength has been obtained by tests, the fatigue life is calculated. Finally general information is given that allows an orthotropic steel deck design to account for traffic flow.

RÉSUMÉ

En considérant des mesures du trafic, un programme d'ordinateur utilisant les bandes finies calcule les histogrammes des amplitudes de contraintes aux points d'apparition des fissures. Par ailleurs, comme la résistance à la fatigue a été obtenue sur la base d'essais, la durée de vie est calculée. Finalement, des informations générales sont données pour la conception des dalles orthotropes en acier en fonction du volume de trafic.

ZUSAMMENFASSUNG

Mit Hilfe eines Finite-Elemente-Programmes werden unter Berücksichtigung von Verkehrs-messungen für Punkte, von denen Risse ausgehen, Histogramme der Spannungsamplituden berechnet. Da die Ermüdungsfestigkeit aus Versuchen bekannt ist, kann die Lebensdauer berechnet werden. Es folgen einige allgemeine Angaben zum Entwurf orthotroper Stahlfahrbahn-platten in Abhängigkeit des Verkehrsvolumens.

1. INTRODUCTION

The main parts of the connection stiffener-deck are the deck plate, the stiffener and the weld between them.
Usually the deck plate is minimum 10 or 12 mm thick and the surfacing thickness is, following the case +/- 10 mm or +/- 60 mm.

The stiffener studied have a closed trapezöidal shape (Fig. 1). Stiffener dimensions are about 300 mm wide, 250 mm high and 6 mm thick. They are placed 300 mm apart. Because of the closed sections of stiffeners, welding is realized on only one side of the stiffener web. The aim of this work is to know the fatigue life of this weld. Therefore, we use wheel load measurements of traffics, a finite band computer program and fatigue tests. This paper summarizes a work realized in Belgium with the help of the European Community [1].
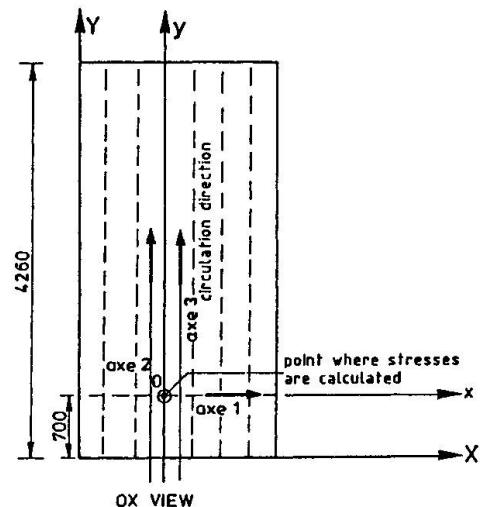
Fig.1 : Structure used for the calculation
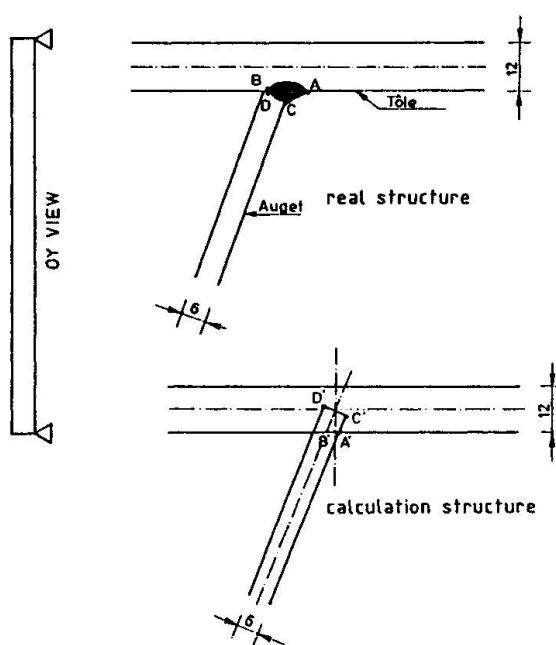
Fig.2 : Detail

2. STRESS DETERMINATION

2.1 Traffic measurments

During previous works [2][3], the stresses near the weld are measured under traffic loads and under vehicles of calibrated load. These measurements are influenced by the distribution of wheel load, in intensity, in transverse position, and by temperature. The temperature influences the behaviour of the surfacing and its collaboration with the steel plate. On the other side, it is not possible to measure a stress at crack initiation point.
As simultaneously with the stress measurements, the axle loads of the vehicles are recorded, load histograms may be established for three types of wheels : normal wheel, extra large wheel, twin-wheels.

In this paper we consider only the traffic recorded in Rheden in 1978, because it is very well known and very aggressive [4].

2.2. Calculation

In view to have a general approach of the behaviour of the weld connection under wheel load, it is necessary to develop a stress calculation method. Stresses have been calculated by a finite band program. The frame used for the calculation has the geometry of orthotropic decks met in Belgium bridges (Fig. 1). The points where stresses are calculated are located in the neighbourhood of the weld (Fig. 2). Points A', B' : in the deck plate ; points C', D' : in the weld.

Axial and bending stresses are calculated in the cross-section in which they are the highest (section 0 - axis 1 - Fig. 1).
With the finite band program it is possible to study influences of the following parameters :

- dimensions of wheel contact area depending of the type of wheel (Fig. 3) and the surfacing :

  - deck without surfacing :load does not diffuse ;
  - deck with a 60 mm surfacing thickness : load diffuses through the tickness with an angle of 45° ; no composite effect is considered.
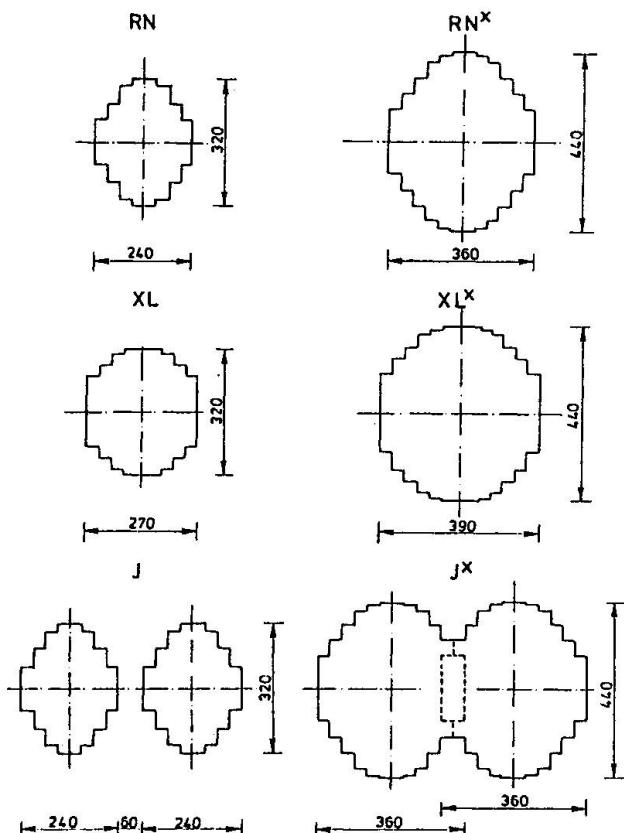

Fig 3 Wheel contact area
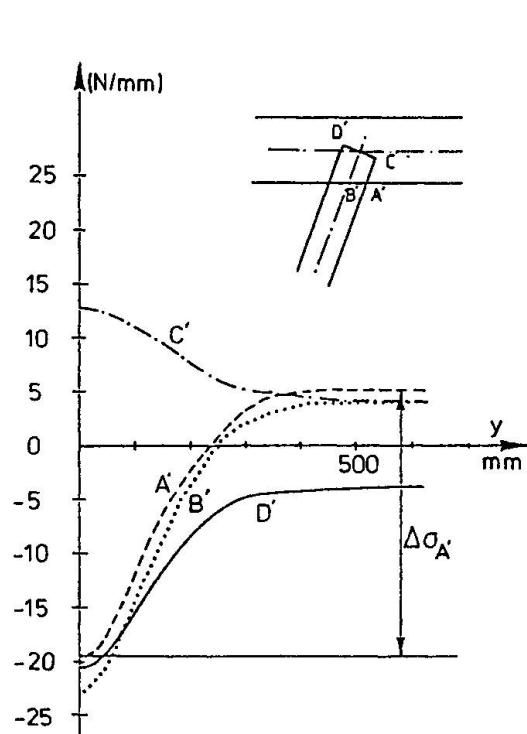
Fig. 4 σ influence line in 0 for a 10kN circulating on axis 2

- wheel longitudinal location : longitudinal influence lines are drawn in
  Fig. 4. It appears that at points A' and B' (deck plate) stress values
  change sign at a certain distance from 0 section. Thus stress amplitude at
  point A' and B' is higher than the maximum stress obtained when the wheel is
  on axis 1 ;

- wheel transverse location : results are presented in forms of transverse
  infuence lines (Fig. 5 and 6).

2.3. Stress histograms.

The calculation of the stress spectra is made by means of the simulation
program [5][6]. For each axle of the traffic the program chooses at random a
transverse position on the deck plate to which corresponds a value of the
transverse influence line (Fig. 5 and 6). This value, multiplied by the load
of the axle, gives the stress induced.

The data introduced in the simulation program are :

1. Traffic : the vehicle axles of the Rheden traffic have been divided in four
   groups according to their wheel type [4].

2. Transverse distribution : the axle transverse distribution is obtained from
   measurements [2][3].

3. Transverse influence lines : calculated following the above mentioned
computer program.

The histogram obtained at point D' and given in the table 1 is used for
fatigue tests under variable amplitude and for the fatigue life calculation.

Stresses σ_i (N/mm^2)	Number	Stress-ranges $\Delta\sigma_i$ (N/mm^2)	Number
70 - 80	13	10 - 20	6767
60 - 70	19	20 - 30	4163
50 - 60	61	30 - 40	2489
40 - 50	222	40 - 50	1690
30 - 40	635	50 - 60	1090
20 - 30	1175	60 - 70	872
10 - 20	2751	70 - 80	601
0 - 10	5176	80 - 90	441
0	} 12627	90 - 100	314
-10 / -0		100 - 110	253
-20 / -10	6629	110 - 120	142
-30 / -20	4348	120 - 130	134
-40 / -30	2348	130 - 140	81
-50 / -40	1668	140 - 150	48
-60 / -50	1068	150 - 160	17
-70 / -60	570	160 - 170	21
-80 / -70	365	170 - 180	11
-90 / -80	189	180 - 190	7
-100 / -90	83	190 - 200	5
-110 / -100	36	200 - 210	2
-120 / -110	9	210 - 220	2
-130 / -120	7		
-140 / -130	2		
TOTAL	40000	-	19150

Table   1

Stress and stress-range histograms

at point D' (variable amplitude tests)

Fig 5 : σ_A Influence lines for a wheel (axis1 ; y=0) transverse repartition
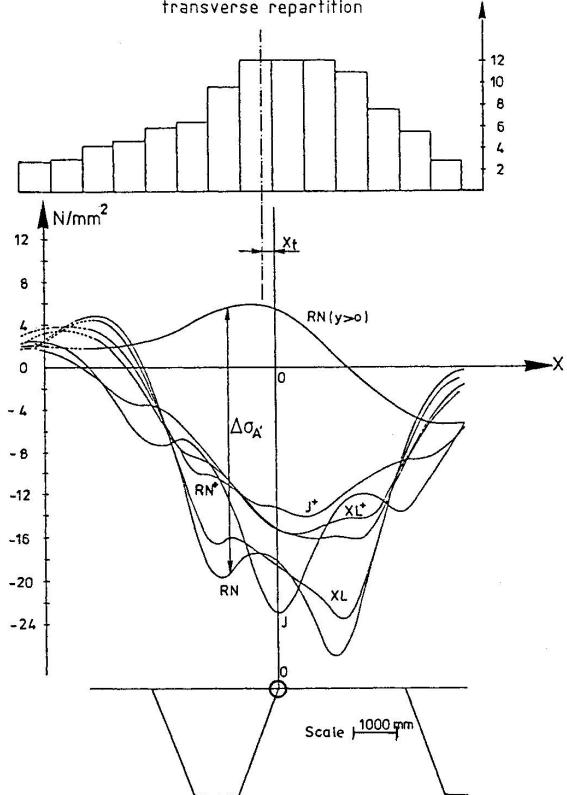
Fig 6 : σ_D Influence lines for a wheel (axis1 ; y=0) transverse repartition
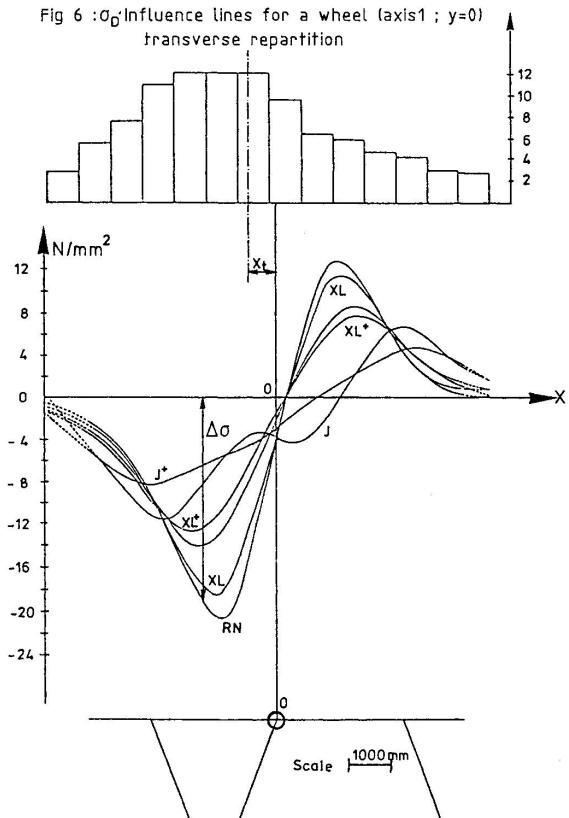
3. FATIGUE STRENGTH

3.1 Test specimens

The loading mode and the geometrical characteristics of the specimens are given in figure 7.
The material used is of the type E 36-4.
General welding procedure characteristics are :

- no edge stiffener preparation ;

- horizontal position ;

- one run ;

- no preheating ;

- no postheating ;

- automatic welding (submerged arc).
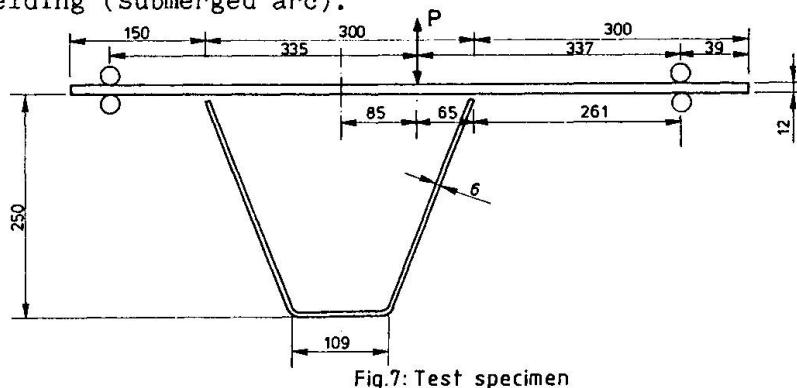
Fig.7: Test specimen

Welding procedure has evolved : firstly the procedure was manual (CRIF [7]), now it is automatic submerged arc welding and it is still evolving to obtain a smaller lack of penetration.

The geometrical characteristics of the welds tested are given in table 2.

Specimen	Lack of penetration	Fillet weld
CRIF [7]	3,0 to 4,5 mm	3,5 to 4,5 mm
Ulg [1]	1,5 to 2,5 mm	4,7 to 6 mm
IRSID [8]	+/- 1 mm	5,5 to 6,5 mm

Table 2

The tests realized under constant amplitude determine the S-N curve. Some tests realized under variable amplitude gives information about the possibilities of a damage calculation applicating the Miner Rule.

3.2. Test result

3.2.1. Presentation

Depending on the stress distribution in the deck plate and in the trough, as well as the weld quality (penetration, throat, underents, ...,) fatigue cracking may occur either :

a) from the weld toe on the deck plate, point A Fig. 2, and develops in the decks plate that corresponds to $\Delta\sigma_d$;

b) from the weld root in the stiffener, point D Fig. 2, and develops in the throat of the weld ; that corresponds to $\Delta\sigma_s$.

From these tests are derived the nominal stresses definition to be used in the fatigue S-N diagrams, by extrapolating the measured stresses.
The results obtained earlier by CRIF [7] and recently by ULg [1] and IRSID [8] are presented on Fig. 8 and Fig.9.

3.2.2. Failure in the deck plate $\Delta\sigma_d$.

Tests under constant amplitude determine the fatigue strength of the deck plate at the weld toe. Results are plotted on Fig. 8.

Main conclusions are :

- There is no significative differences between specimen with 2 mm gap between the top of the stiffener web and the deck plate and specimen with no gap provided the lack of penetration is less the 2 mm.
The mean Wöhler curve is determined with $R_s = 1$ in the weld root for the specimen tested at IRSID :

$$\Delta\sigma_d = 26777 \ N^{1/3} \quad (m = 3 \text{ imposed})$$

and the characteristic value for 97,5 % is

$$\Delta\sigma_{dc} = 163 \ N/mm^2 \text{ for } N_c = 2.10^6 \text{ cycles.}$$

- The two tests conducted at IRSID show a lower fatigue resistance at R = 0,1 than R = -1. Nevertheless, two similar tests performed at Liège do not indicate such a detrimental effect.
In only two U.Lg. specimens did failure occur in the deck plate that corresponding to $R_s = 0$ (only tensile at point A).

The loading histogram used for tests under variable amplitude is the stress spectra calculated (table 1). This histogram simulates traffic effects. Loads are applied at random on the test specimen, taking in account the sign of the stresses. The results of tests are plotted in Fig. 8 by their equivalent values $\Delta\sigma_e$, n_e calculated from the histogram with an SN curve with a slope of -1/3, corresponds to the centre of gravity of the damage distribution [9][10] :

$$\Delta\sigma_e = \frac{\sum_{\Delta\sigma_i}^{\infty} n_i \cdot \Delta\sigma_i^4}{\sum_{\Delta\sigma_i = 0}^{\infty} n_i \cdot \Delta\sigma_i^3} \qquad n_e = \frac{\sum_{\sigma_i=0}^{\infty} n_i \cdot \Delta\sigma_i^3}{\Delta\sigma_e^3}$$

Results are similar to those obtained with constant amplitude loading.

3.3.3. Failure in the weld $\Delta\sigma_s$.

Tests results under constant amplitude are plotted on Fig. 9.
Main conclusions are :

- the fatigue strength increases significantly when using automatic welding, this technique allows larger penetration and throat thickness at the weld.
- the mean S-N curve is determined for automatic welding :

$$\Delta\sigma = 17258 \ N^{1/3}$$

and the characteristic value for 97,5 % is

$$\Delta\sigma_{sc} = 114 \ N/mm^2 \text{ for } N_c = 2.10^6 \text{ cycles.}$$

- The tests show the importance of R_s ratio. To obtained the failure in the weld it was necessary to have more tension than compression at the root of the weld (point D) :

$$1 < R_s < 0 \text{ in the Ulg specimens}$$

$$R_s = 0,1 \text{ in the IRSID specimen.}$$

The loading histogram used for tests under variable amplitude is the calculated stress spectra (table 1).
The loads are applied random, but to obtain failure in the weld (point D), it has been necessary to change the sign of the stress calculated, so that there is more tension than compression : $R_s = -0,5$ instead of $- 2,0$ at the root for the highest stress range.
The results are plotted in Fig. 9 by their equivalent values assessed as in Fig. 8.
Results are similar to those obtained with constant amplitude loading.

4. FATIGUE LIFE CALCULATION

We consider as characteristic stress range the values deduced from the fatigue tests. For $N_c = 10^6$ cycles :

$$\Delta\sigma_{sc} = 114 \ N/mm^2 \text{ , if the crack occurs in the weld (point D) ;}$$

$$\Delta\sigma_{dc} = 163 \ N/mm^2 \text{ if the crack occurs in the plate (pointe A).}$$

Following Eurocode 3, the SN curves have two slopes : $m = 3$ for $N < 5.10^6$ and $m = 5$ for $5.10^6 < N < 10^8$.
If the traffic composition measured in Rheden is considered [4], the allowed number of lorries during the life time may be calculated. The results are given on table 3.
Putting there data in perspective the traffic flows recorded on highways generally comprise between 1000 and 4000 lorries during a working day [2][3]. Such flows produce after 100 years between 20 and 80.10^6 lorries.
The examination of table 3 calls the following comments :

1. The fatigue life calculated in the deck ($\Delta\sigma_d$) is always a little longer than in the weld ($\Delta\sigma_s$) : the higher strength is partially offset by higher stress ranges produced in this point by the traffic loads ;
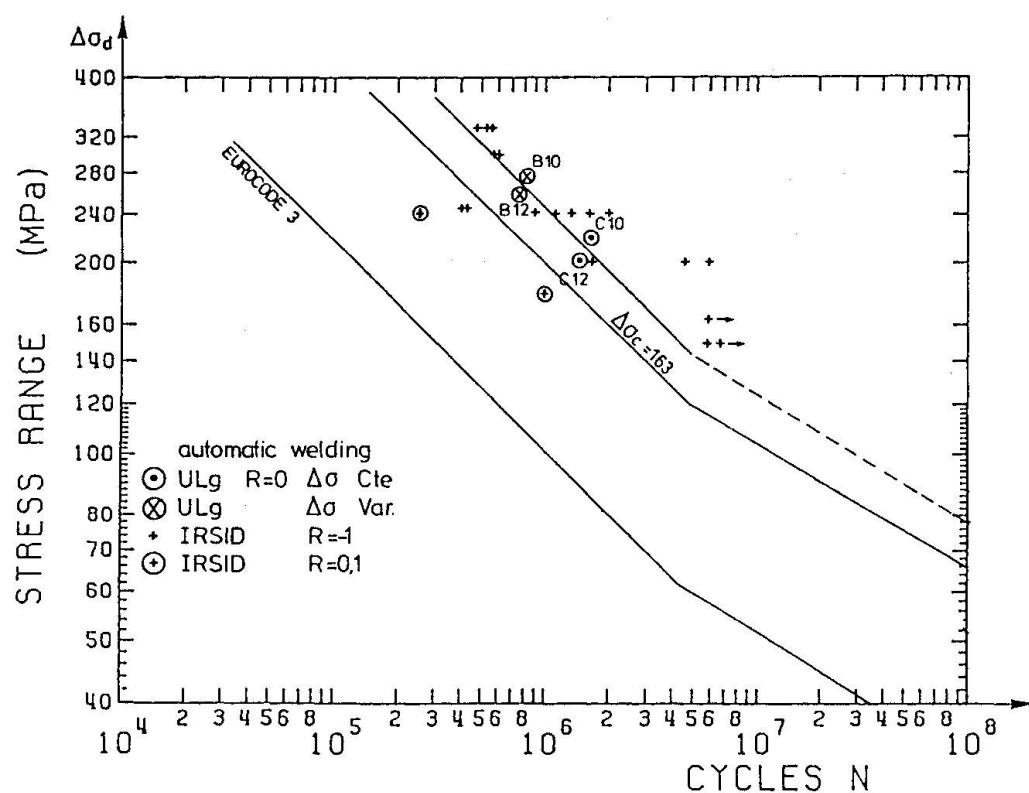
Fig.8: Crack initiation at the weld toe : $\Delta\sigma_d$
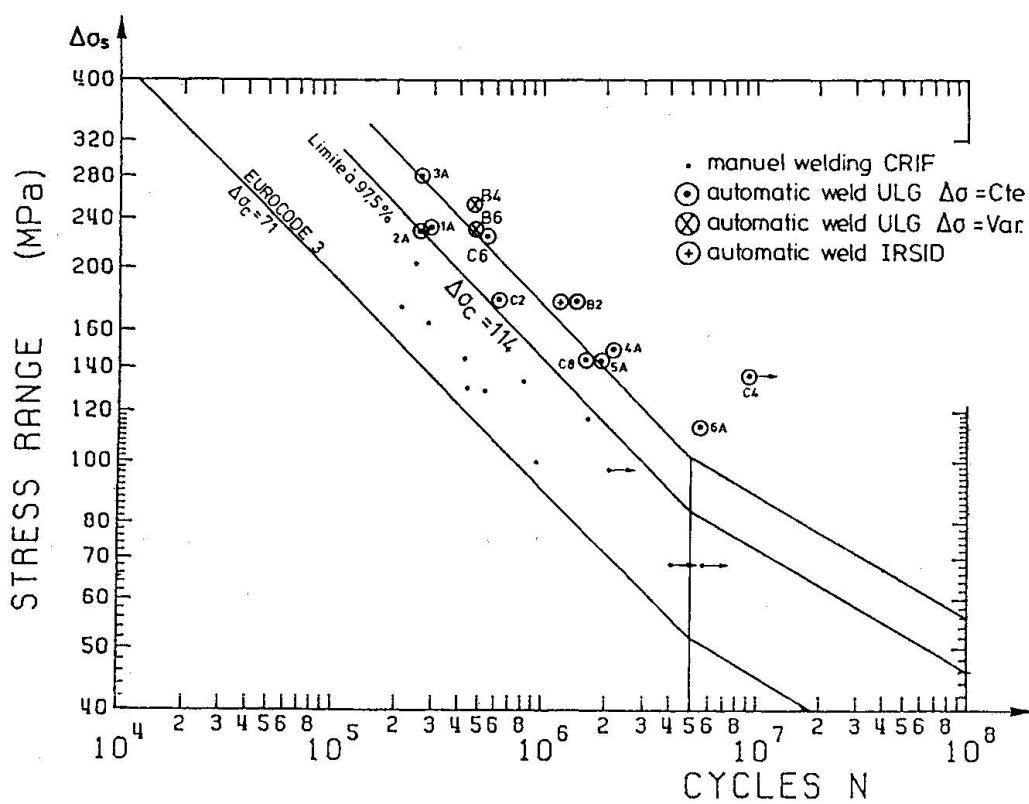
Fig.9: Crack initiation at the weld root: $\Delta\sigma_s$

Fatigue life

Connection Stiffener - Deck plate

Thickness (mm)				Number of lorries (10^6)	
Plate	Stiffener	surfacing		$\Delta\sigma_s$	$\Delta\sigma_d$
12	6	0		20	20
12	6	60		71	75
13	6	0		44	45
13	6	60		199	219
14	6	0		89	103
14	6	60		494	647
14	7	0		62	73
14	7	60		297	393

Table 3

2. A surfacing of 60 mm gives a fatigue life 3 to 5 times longer, than the unsurfaced deck ;

3. An increase in the plate thickness of 1 mm gives a fatigue life +/-2 times longer.

4. An increase in the thickness of the stiffener reduces the fatigue life a little.

5. The given fatigue lives are pessimistic, because the transverse position of the traffic flow considered in the calculation is the most unfavourable and in surfaced deks, now composite effect is considered.

We may conclude :

1° For the weld tested, the failure may not occur in the weld but in the plate, if the thickness of the plate is at least twice as thick as that of the stiffener ;

2° the required thickness of the deckplate depends on the expected number of lorries and the thickness of the surfacing.

5. CONCLUSIONS

The specimens used in the experiments were welded with automatic submerged arc welding in an industrial situation. It has been shown that full penetration, (lack of penetration lower than 1 mm.) can nearly be achieved without edge preparation.

In these conditions, there is no significant difference in fatigue behaviour for specimens with a 2 mm gap by welding or without gap.

For alternate bending, that is a little more severe than the loading in bridges, with a lack of penetration not greater than 1 mm, the cracks initiate at the weld toe in the deck plate.

Using a computer band program it is possible to calculate the fatigue life of the connection taking in account :

- thickness of the surfacing that increases the wheel contact area ;

- geometry of the orthotropic deck ;

- traffic defined by a number of lorries and by load histograms for each type of wheel.

To increase the fatigue life, the designer has the possibility to choose between increasing the thickness of the surfacing or that of the steel plate. Table 3 gives fatigue lives for common sizes of orthotropic plate (Fig. 1).

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