# Fatigue tests of stiffener to cross beam connections

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## Essais de fatigue de liaisons entre raidisseur et entretoise

## Versuche zur Ermüdung des Anschlusses einer Steife an einen Querträger

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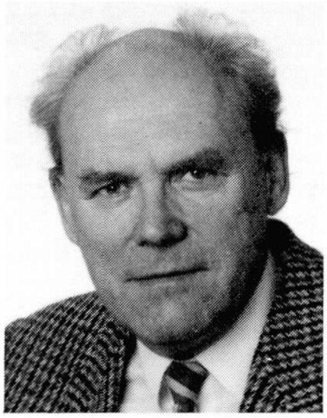

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**SUMMARY**

Traffic loads produce high stress concentrations leading to fatigue cracking at the edges of cut-outs in webs of cross beams. High local stresses can be reduced by improved shaping of cut-outs. Fatigue tests were performed using two types of specimens; one with a commonly used shape of cut-out and the other with a new shape. The results showed a considerable increase of fatigue life for the new shape. However residual stresses of unknown distribution and high intensities were observed in all specimens and these may have influenced the increase in fatigue strength.

**RÉSUMÉ**

Les charges du trafic produisent des concentrations de contraintes élevées aux bord des découpes dans les âmes des entretoises pouvant conduire à un dommage en fatigue. Ces pointes de contraintes peuvent être réduites par des géométries de découpes plus favorables. Des essais de fatigue ont été réalisés sur des entretoises comprenant l'ancienne et la nouvelle géométrie. Bien que les résultats montrent un accroissement considérable de la durée de vie pour la nouvelle découpe, ceux-ci demandent encore à être confirmés du fait de la présence dans les éprouvettes de contraintes résiduelles inconnues et élevées qui peuvent avoir influencé cette amélioration.

**ZUSAMMENFASSUNG**

Verkehrslasten rufen an den Rändern der Ausnehmungen in den Stegblechen von Brückenquerträgern hohe Spannungsspitzen und möglicherweise Ermüdungsschäden hervor. Diese Kerbspannungen können durch eine günstigere Ausnehmungsform reduziert werden. Ausgeführt wurden Ermüdungsfestigkeitsversuche an Querträgern mit einer derzeit gebräuchlichen und einer neuen Ausnehmungsform. Die bisher erzielten Ergebnisse ergaben eine deutliche Lebensdauersteigerung für die neue Form, können aber nicht als abgesichert gelten, weil unbekannte Eigenspannungen hoher Intensität in sämtlichen Versuchsträgern beobachtet wurden.

## 1. INTRODUCTION

During the last years institutes from six European countries have performed a joint research program on steel bridges supported by the EC with the following main topics

- measurement and description of traffic loads
- operational stresses in steel bridge components and
- fatigue of orthotropic steel bridge decks.

The longitudinal stiffener to cross beam connection is one design detail of orthotropic decks susceptible to fatigue failure.

In orthotropic steel decks the traffic loads are transferred from the deckplate via the longitudinal stiffeners to the cross beams and from there to the main structure of the bridge. Depending on the number of traffic lanes, one cross beam may gather the loads of several wheels and axles belonging to more than one vehicle. Cross beams have the dimensions of beams. They are stressed by bending moments, shear forces and torsional moments. Besides the globally distributed beam stresses, additional stress fields are distributed more locally e.g. due to the load introduction and due to local stress concentrations.

Orthotropic decks in modern design contain cut-outs in the web of the cross beams to let the longitudinal stiffeners pass through. The cut-outs interrupt the stress fields and evoke stress concentration at their free edges. Besides the highly stressed edges, the welds connecting the stiffeners to the webs of the cross beams must also be regarded to be potentially critical to fatigue failure.

Approaching the real stress state in a bridge, two main load cases may be defined stressing the longitudinal stiffener to cross beam connection at the two critical points just mentioned:

- the load introduction into the cross beam which is passing the welds connecting the stiffeners to the web and
- the load transfer in the cross beam from the points of load introduction to the main structure of the bridge.

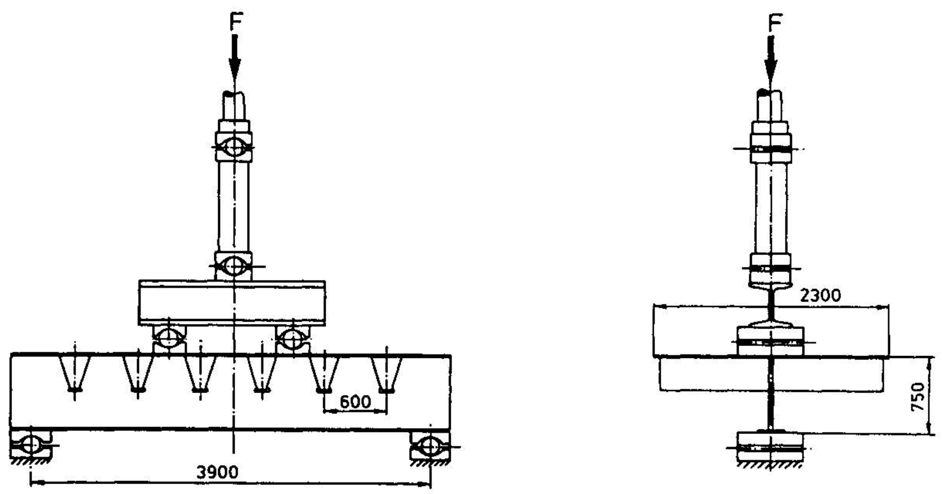


Fig. 1 Testing performed

Each load case may produce fatigue at both critical points. While the firstly mentioned load case is investigated by other groups in the joint research project, the objective of this paper is limited to the second load case. Thus, the function of cross beams to carry the loads of several wheels introduced at different points, as in large bridges with several traffic lanes, is emphasized.

## 2. STRESS ANALYSIS

A simply supported cross beam loaded by a shear force and a bending moment may be used as a model to simulate the load case of interest.

As a first approach to calculate the stress distribution in the critical regions, the web was modelled by two-dimensional in-plane finite elements, and the deck plate together with the stiffeners by in-plane beam elements of equivalent stiffness.

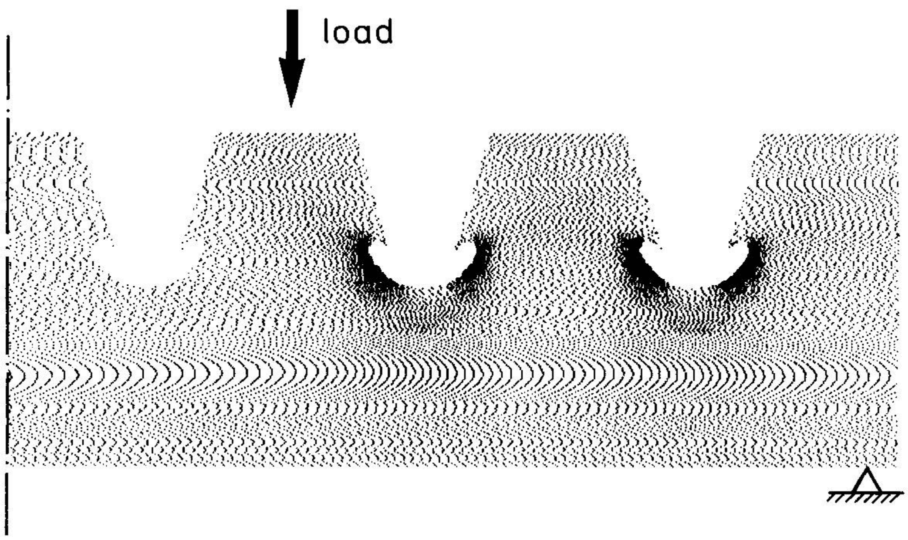


Fig. 2 Global stress distribution in one half of the web loaded as in Fig. 1

Fig. 2 gives an impression of the global stress distribution in the web of one half of the symmetrically loaded cross beam. High stress concentrations occur at the edges of the cut-outs but only in the beam segment loaded by a shear force. The level of high spot stresses depends on the shear force and nearly not on the bending moment. These high stresses at the edges of the cut-outs can be explained by bending the so-called teeth of the web located between each two cut-outs. The bending is produced by a shear force acting between each tooth and the deck plate because the deck plate is the upper flange of the cross beams.

Fig. 3 shows the distribution of the bending stresses in the narrowest section of one tooth between two cut-outs calculated by finite elements and verified by strain measurements. When comparing the highest spot stress with the nominal bending stress at the edge of the cut-outs, the stress concentration factor can be estimated. It yields $K_t \approx 2.8$ in this example.

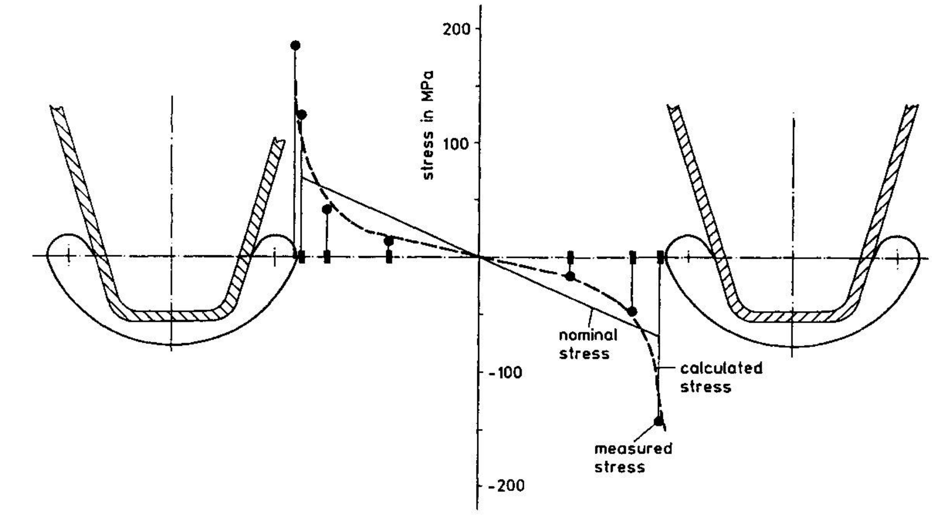


Fig. 3 Stress distribution in the narrowest section between two cut-outs

Generally, the stress level at the edges of the cut-outs exceeds the stresses in all other parts of the web by a factor larger than 5. Therefore, one design objective must be to have a better exploitation of material i.e. to reduce the stress concentration. Basically, this can be achieved by an extension of the distance between the stiffeners. This, however, requires a change of the whole orthotropic deck design. Therefore, the only reliable solution seems to be to change the cut-outs' shape. But this may influence fatigue at the second critical point where the welds connecting the stiffeners to the web meet the cut-outs.

After investigating cross beams of railway bridges, Haibach and Plasil proposed a new shape of cut-outs [ 1 ]. They found it superior with respect to fatigue to the commonly used shape when performing fatigue tests on cross beams simulating the particular load case of a railway bridge with one rail. But they did not quantify the gain with respect to strength and fatigue life. This question and the question whether the new shape can also be recommended for large highway bridges under the load case just defined are of interest.

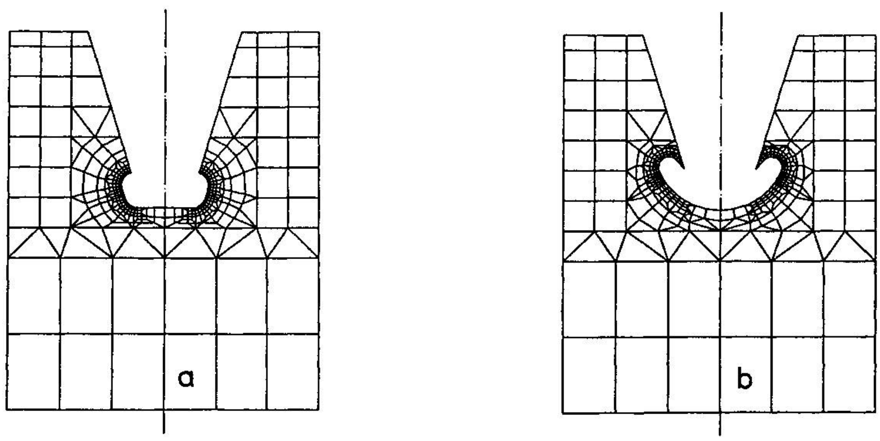


Fig. 4 Cut-outs of the commonly used (a) and of the new (b) shape modelled by finite elements

Fig. 4 shows the commonly used and the new shape of cut-outs modelled by finite elements. The stress distributions along the edges of both types of cut-outs differ significantly (Fig. 5) when the cross beam is loaded as shown in Fig. 1. But the levels of the maximum stresses are nearly the same. Only the volume of highly stressed material and the highly stressed surface at the edges of the cut-outs, respectively, are considerably larger for the commonly used shape. Besides this small advantage of the new shape at one of the critical points, the stresses are reduced at the second point where the welds meet the cut-outs. This result was verified by measurements because the accuracy of the used finite element model is questionable in the vicinity of the welds.

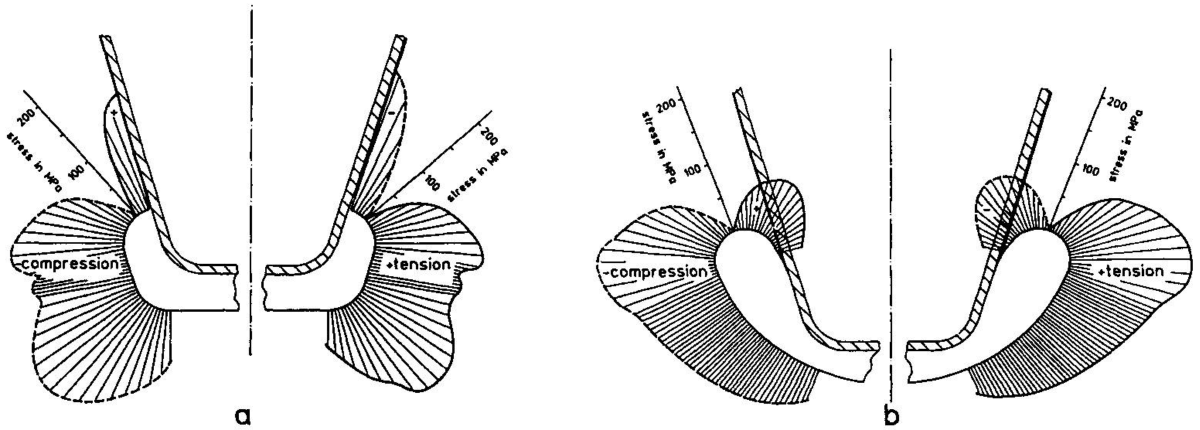


Fig. 5 Stress distribution along the edges of the cut-outs of the commonly used (a) and the new (b) shape

## 3. TEST DESCRIPTION

Three test specimens of nearly original size were fabricated as orthotropic decks of real bridges, each consisting of a cross beam, six stiffeners, and a deck plate made of structural steel St.53 (Fig. 1). The dimensions of all three specimens were identical except that one had cut-outs of the commonly used shape and the other two the proposedly improved shape. When a specimen is loaded as shown in Fig. 1, four of the six cut-outs are stressed nearly at the same level. This is due to the equal shear force at four of the cut-outs. Therefore, from each fatigue test up to four results could be expected, provided that cracks are detected early and repaired. Three fatigue tests were performed, one with constant amplitude loads applied to a specimen with cut-outs of the new shape and two using identical variable amplitude load sequences applied to the other two specimens with differently shaped cut-outs.

At the beginning of each test, the strains were measured at symmetrically located points on each specimen to guarantee the symmetry of loading. In particular, the torsional moment in the specimens was observed and reduced by changing the points of load introduction until its contribution to the maximum stresses was less than 5 %. Thus, reproducible test results could be expected.

The traffic induces mainly fluctuating compressive loads on the cross beams of bridges. The test rig with the simply supported cross beam allows to simulate this loading.

## 3.1 Constant amplitude test

The load range of the constant amplitude test was determined taking into account the test results of Haibach and Plasil [ 1 ] at

$$\Delta P = 485 \text{ kN}$$

with an upper load of $P_u = 500$ kN
and a lower load of $P_l = 15$ kN.

This load results in a stress range of $\Delta \sigma = 480$ Mpa

at the edges of the cut-outs with
an upper stress of $\sigma_u = 495$ Mpa
and a lower stress of $\sigma_l = 15$ Mpa.

The results of the constant amplitude test are given in Fig. 6.

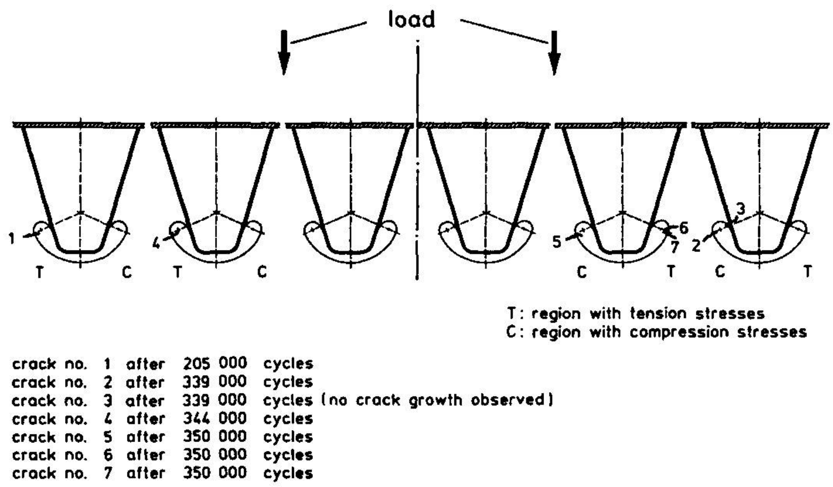


Fig. 6 Results of the constant amplitude test on one of the specimens with cut-outs of the new shape

## 3.2 Variable amplitude tests

Time histories of traffic loads acting on bridge components may be found by measurements or may be derived by a computer program developed as a part of the joint research project [ 2 ]. The program requires input data to describe the traffic on the bridge and the load transfer in the bridge from the wheel contact points to the points of interest. Fig. 9 shows a frequency distribution of range pair cycles counted from a load time history of a cross beam, which was calculated by the program due to 10000 vehicles passing the bridge on one lane.

From this range pair frequency distribution a first load sequence to be applied to the tests was developed by randomly deriving compressive load cycles. Although the initially calculated load time history contains small traction forces besides high compressive forces due to the applied influence line of load transfer, the load sequence used only compressive load cycles to maintain the simple test rig of Fig. 1.

As a result of damage calculation by Miner's Rule and in order to achieve acceptable test times an omission level was chosen that reduced the applied frequency distribution of Fig. 7 to 3084 from originally 15243 cycles which produce 98.5 % of the calculated damage. The load level was fixed to

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| the maximum load | $P_{max}$ | = | 500 kN |
| the minimum load | $P_{min}$ | = | 15 kN and |
| the maximum load range | $\Delta P_{max}$ | = | 485 kN |

which means the same nominal loads as in the constant amplitude test.

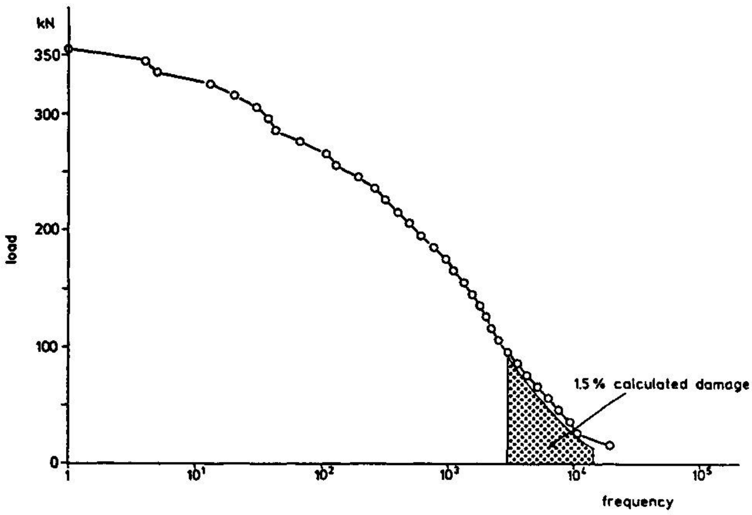



Fig. 7 Frequency distribution of the load sequence used in the variable amplitude tests

The results of both variable amplitude tests with the specimens of both cut-out types are given in Fig. 8 and 9.

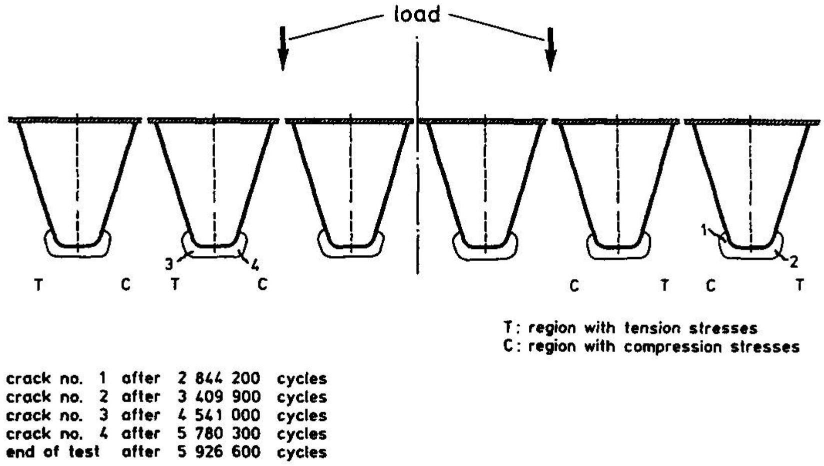



Fig. 8 Results of the variable amplitude test on the specimen with the commonly used shape of cut-outs

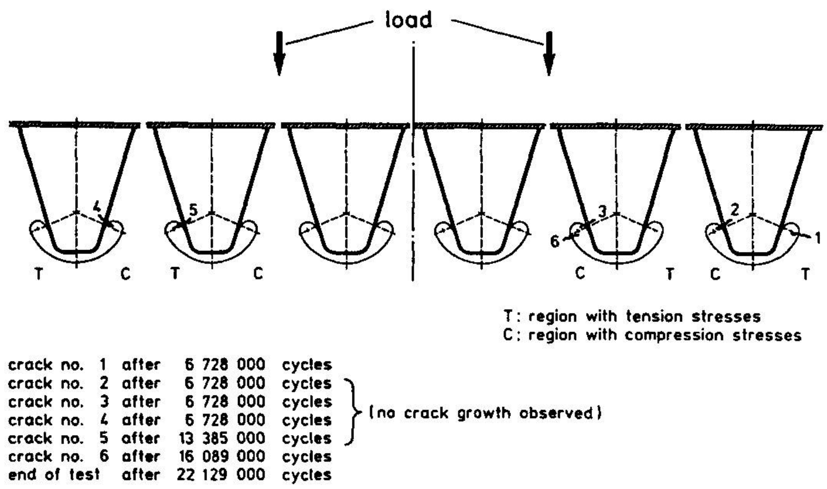



Fig. 9 Results of the variable amplitude test on one of the specimens with cut-outs of the new shape

## 4. DISCUSSION OF TEST RESULTS

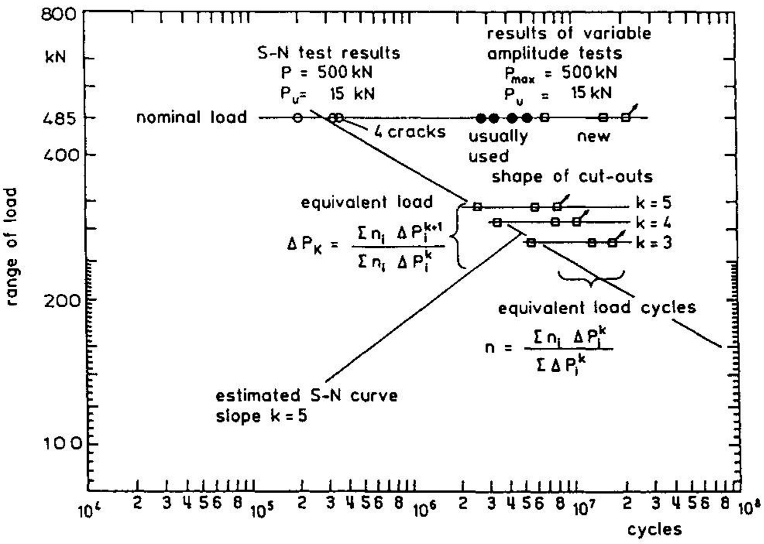
Cracks were observed at both critical points of the stiffener to cross beam connection. Cracks at the ends of the welds occured only in the specimens with the new shape of cut-outs, although this shape was developed to reduce the stresses in this region. In fact, the stresses due to the external loads are really low, as proved by measurements. Therefore and since the cracks did not grow after their detection, residual stresses must have contributed to crack initiation.The new shape of the cut-outs seems to favour residual stresses to appear locally at the ends of the welds because the heat-flux into the web is during the welding restricted by the small area of material.

In contrast, the cracks initiated at the free edges of the cut-outs grew and would have destroyed the specimens if they had not been repaired. These cracks occurred at the cut-outs of the new shape after a 3 - 5 times higher number of load cycles than at the commonly used shape during the identical variable amplitude tests This is a considerable improvement of fatigue life.

However, cracks occurred at edges stressed in compression under external loads while other edges stressed in tension at the same level remained crack-free. The cracks under tension grew faster than those under compression. Moreover, the cracks in the compression regions remained open when the load was removed. These observations can only be explained by residual stresses globally distributed in all three specimens.

Residual stress fields are known to exist in large welded structures. Thus it is not clear, whether the observed increase of fatigue life can be attributed to the new shape of the cut-outs or is at least partially due to a more favourable residual stress distribution. These doubts are supported by the results of stress analysis which show no significant differences between the maximum stresses at both types of cut-outs (Fig. 5).

All test results are summarized in Fig. 10, those of the variable amplitude test on the specimen with cut-outs of the new shape in two representations one using nominal loads and really endured load cycles and the second using equivalent loads and equivalent load cycles as defined in Fig. 10. This was done to compare all results from the specimens with the new shape of cut-outs and to estimate their S-N-curve.




$$\Delta P_K = \frac{\Sigma n_i \Delta P_i^{k+1}}{\Sigma n_i \Delta P_i^k} \qquad n = \frac{\Sigma n_i \Delta P_i^k}{\Sigma \Delta P_i^k}$$

Fig. 10 All results of three tests

## 5 CONCLUSIONS

As a consequence of the above-mentioned shortcomings a recommendation for the new shape is not yet possible, though it showed an improved fatigue behaviour in the test performed. The following measures during design and fabrication can improve the fatigue strength at both mentioned critical points of the stiffener to cross beam connection

- a reduction of the stress concentration at the edges of the cut-outs by increasing the notch radius
- a reduction of the residual stresses at the ends of the welds between the stiffeners and the web by a shape which improves the heat-flux during welding
- the control of residual stresses introduced into the structure during fabrication to avoid unfavourable residual stresses.

## REFERENCES

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