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EUROPEAN RESEARCH ON FATIGUE OF ALUMINIUM STRUCTURES

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ABSTRACT

The paper is dealing with the results of a European research project within the framework of EUREKA on the fatigue behaviour of aluminium structures, focusing on welded, adhesive-bonded, and bolted joints.
Since five foreign partners are presenting their input into the project, this paper will overview the project and will go into detail as far as the TNO input is concerned.
At first the most important results of a literature study are reviewed covering design codes, S-N data and fracture mechanics data. On the basis of these results the parameters of the experimental and theoretical study were chosen. In addition to S-N tests numerical simulations have been carried out based on fracture mechanics.

KEYWORDS

Fatigue; aluminium structures; welded, adhesive-bonded, friction grip bolted joints; S-N data; fracture mechanics.

INTRODUCTION

In contrast with statically loaded aluminium structures the design of aluminium structures under fatigue loading is inadequate since the knowledge about the fatigue strength is limited and calculation methods as well as design rules are missing.
For those reasons in 1989 EUREKA project EU 269 "Design of Aluminium Structures under Fatigue Loading" was started with participation of:

- Spain : LABEIN (Bilbao) and INESPAL (Alicante);
- Portugal : TU-Porto, INEGI and UTAD (Vila Real);
- Italy : Alures, ISML (Novara);
- Denmark : Ramboll & Hannemann (Copenhagen) and TU-Aalborg;
- Great Britain : TWI (Cambridge), ABB, British Rail, DRA, London Underground and Metro Cammell;
- The Netherlands : TNO Building and Construction Research, Hoogovens Aluminium, Bayards, Schelde, Dutch Railways, 3M, Aluminium Centre, Alcan, and Pechiney.

The project was managed by TNO together with Hoogovens Aluminium.

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As fatigue failure of a structure usually occurs at joints the project focused on three types of joints i.e. welded, adhesive-bonded, and friction grip bolted joints. Aluminium alloys studied have been chosen out of the 5xxx, 6xxx, and 7xxx series, alloys applied for load bearing structures.
The research program was divided into three phases:

- State of the art studying existing data of the fatigue behaviour of aluminium structures; Phase I of the project, finished in 1990.
- Experimental and theoretical study of structural details; Phase II of the project, finished late 1993.
- Evaluation of all results and drafting of design rules; Phase III of the project which was finished at the end of 1994.

The most important results of the project will be summarized in the following chapters.

STATE OF THE ART

Since welded joints are applied very frequently, most attention has been given to this type of joints (Ref. 1, 2, 3, and 4). The most important conclusions were:

- Design curves in codes and recommendations can differ very much as is illustrated in fig. 1.
- Fatigue test data (S-N data) also show big scatter while relevant information to understand the differences mostly is missing.
- A large difference in fatigue life was observed between small scale and full scale specimens.
- For crack initiation suitable models are limited, but for crack propagation theoretical models exist. However, crack growth data for aluminium alloys are very scarce.

In Ref. 5 the state of the art as far as adhesive-bonded joints is concerned, is dealt with both S-N data as well as crack growth data.
The most important conclusions were:

- Nearly all information has to do with aerospace applications which means different alloys (mainly 2xxx series), other surface treatments, other adhesives, and last but not least other loadings, load spectra.
- The fatigue behaviour of properly designed adhesive joints is much better than that of comparable welded joints.
- Crack growth outside the joint can be modelled properly; crack growth in the adhesive layer is difficult to simulate.

The state of the art concerning the fatigue behaviour of friction grip bolted joints (Ref. 6) led to the following conclusions:

- The information available is limited but shows a very favourable fatigue behaviour of this type of joints.
- Cracks occur in the plate material, initiated by fretting and crack growth can be described by a suitable model.

The above summarized conclusions were basic for the experimental and theoretical study which is described now.

EXPERIMENTAL STUDY

Fatigue tests (S-N tests) have been carried out on **welded, adhesive-bonded, and friction grip bolted joints** applying:

- A limited number of joint details i.e.
  - 4 details in case of welded joints, see fig. 2;
  - 1 detail in case of adhesive-bonded joints, see fig. 3;
  - 1 detail in case of friction grip bolted joints, see fig. 4;
- Tests on small specimens (strips) as well as full scale specimens (beams) with equal details, see fig. 5;
- Three plate thicknesses i.e. 6, 12 and 24 mm;
- Constant amplitude loading (stress ratio R = 0.1) for the majority of tests and an additional number of tests with spectrum loading;
- The number of load cycles was varied between 10^4 and 10^7.

The fatigue tests on strips have been carried out on a standard fatigue test machine, while the fatigue tests on beams (four point bending tests) have been carried out in purpose-built test rigs, see fig. 6. In figs. 7, 8, and 9 some relevant results are given (see also Ref. 7, 8, and 9). For the welded joints one alloy has been applied i.e. 6061-T6 combined with filler metal 5356.
In case of the fatigue tests on **adhesive-bonded joints** is - in addition to the above mentioned parameters - the following applied:

- Two alloys i.e. 6061-T6 and 5754-H32;
- Two adhesives i.e. 3M 9323 and 3M 7823; the first one is a cold cured, modified epoxide and the second one is a heat cured, modified epoxide;
- Two surface pretreatments i.e. degreasing (D) as well as degreasing/etching/chromate based conversion (CC);
- Two test environments i.e. air and water; with the latter the adhesive layer was soaked with water.

In fig. 10 fatigue test results of adhesive joints in strips are given in case of alloy 6061-T6. For a complete survey of all results also for alloy 5754-H32 is referred to Ref. 10.

With the fatigue tests on **friction grip bolted joints** were used the alloy 6061-T6, plate thicknesses t = 6 and t = 12 mm, and joints with 2 bolts or with 4 bolts. In fig. 11 the test results for both strips and beams are shown (see also Ref. 11).

THEORETICAL STUDY

Within this part of the project crack growth data for the alloy 6061-T6 have been determined for parent metal but also for heat-affected zone as well as weld metal. Subsequently crack growth calculations have been carried out using a model based on linear elastic fracture mechanics. A relationship is assumed between the fatigue crack growth rate (da/dN) and the range of the stress intensity factor ΔK. The most well-known model is the Paris relationship: $da/dN = C\,(\Delta K)^m$ in which C and m are material constants.

With the calculation model the following steps have been carried out:

- The results of the calculations have been verified comparing them to the fatigue test results (see also fig. 12).

- Applying the model parameters like geometry of the joint and thickness of the material have been checked for their influence on fatigue strength.
- The model was used to calculate S-N data which are missing and to calculate fatigue life of other types of joints.

EVALUATION, (PRELIMINARY) CONCLUSIONS

Though the project was not finished yet at the moment of writing this paper, a few preliminary conclusions can be drawn (see Refs. 12 to 17):

- Fatigue tests on welded joints both small specimens as well as full scale specimens show a much better fatigue behaviour than sometimes stated in literature.
- Fatigue behaviour of adhesive joints appears to be more favourable compared to welded joints particularly in the high cycle range.
- Friction grip bolted joints show the most favourable fatigue behaviour of the three types of joints investigated; this type of joints almost equals parent metal fatigue behaviour.
- Crack growth models based on fracture mechanics may very well approach the fatigue life of structural details. The use of these models is an important tool to assist designers when analyzing structures for fatigue.

FINAL REMARKS

Within this project most attention was given to welded joints in aluminium structures under fatigue loading which is evident under the present circumstances. However, adhesive-bonded joints - particularly for thinner material - and also friction grip bolted joints do have a big potential for application in aluminium structures under fatigue loading as was demonstrated in this study. Design rules based on the results of this study will be forwarded to CEN/TC 250/SC 9 to take into account while drafting the chapter "Fatigue" of Eurocode 9 "Aluminium structures".

ACKNOWLEDGEMENTS

The research program described in this paper is a result of close cooperation between TNO Building and Construction Research and aluminium supplying or applying companies with a common interest in the use of aluminium for structural applications, see also the introduction. The contribution of all people concerned, is gratefully acknowledged.

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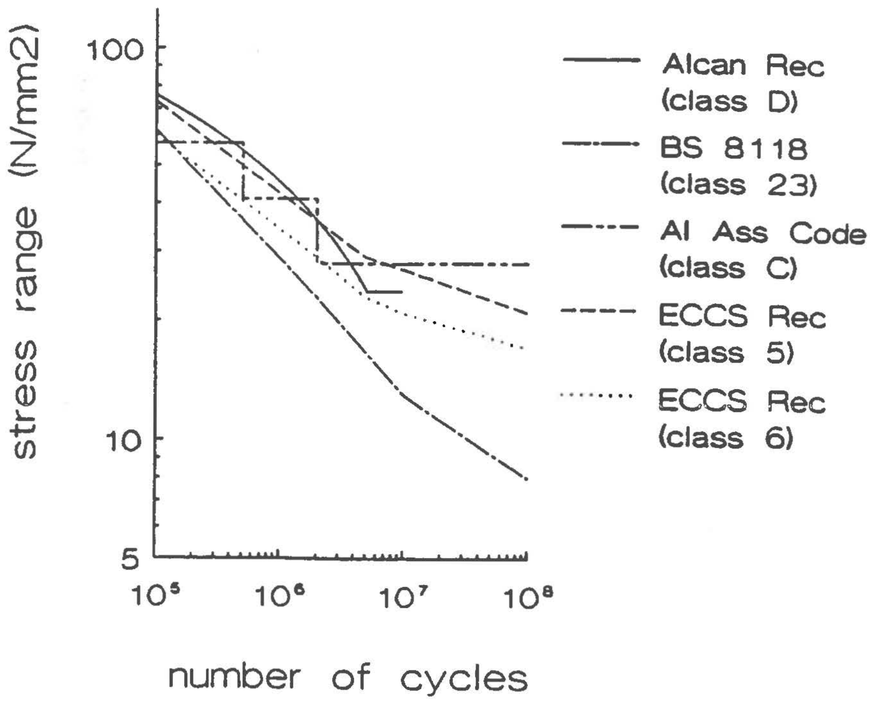

Fig. 1 Design curves butt welded joints (see also detail 1 of fig. 2)

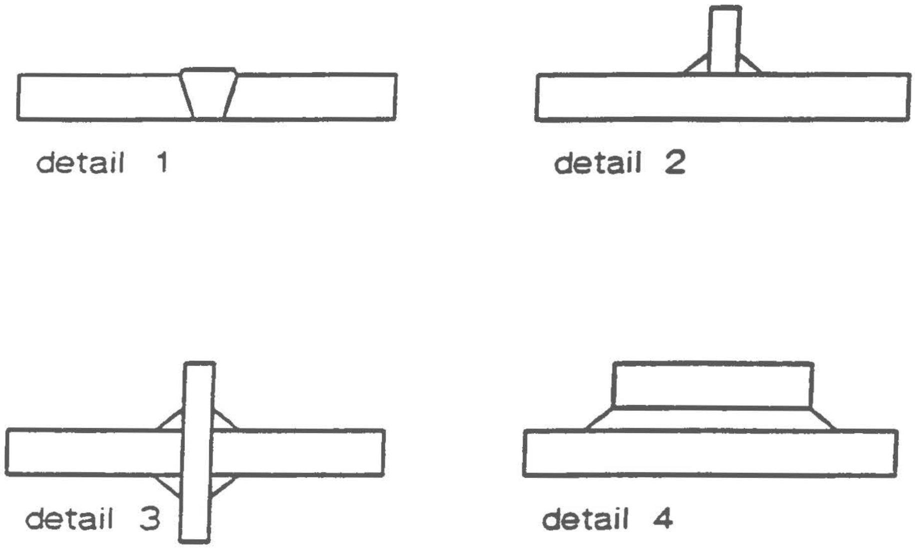

Fig. 2 Welded joint details investigated (S-N tests)

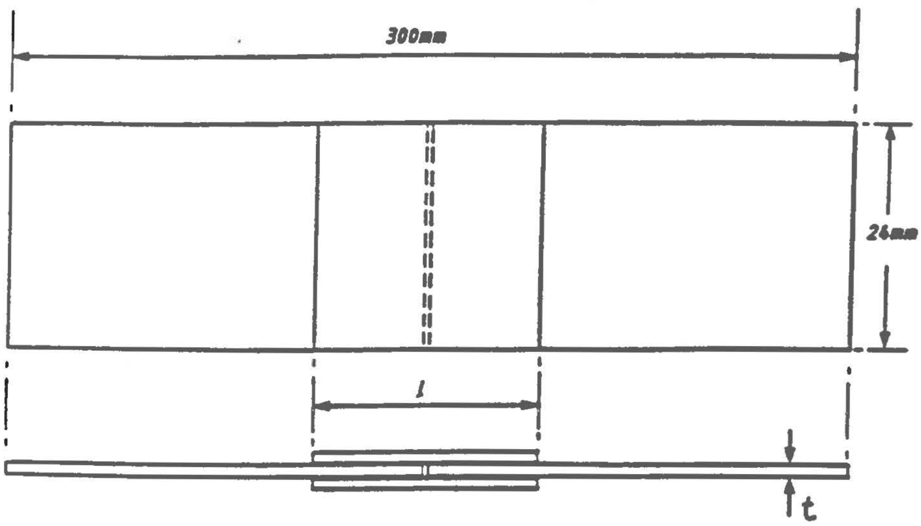

Fig. 3 Joint detail tested with adhesive-bonded joints (S-N tests)

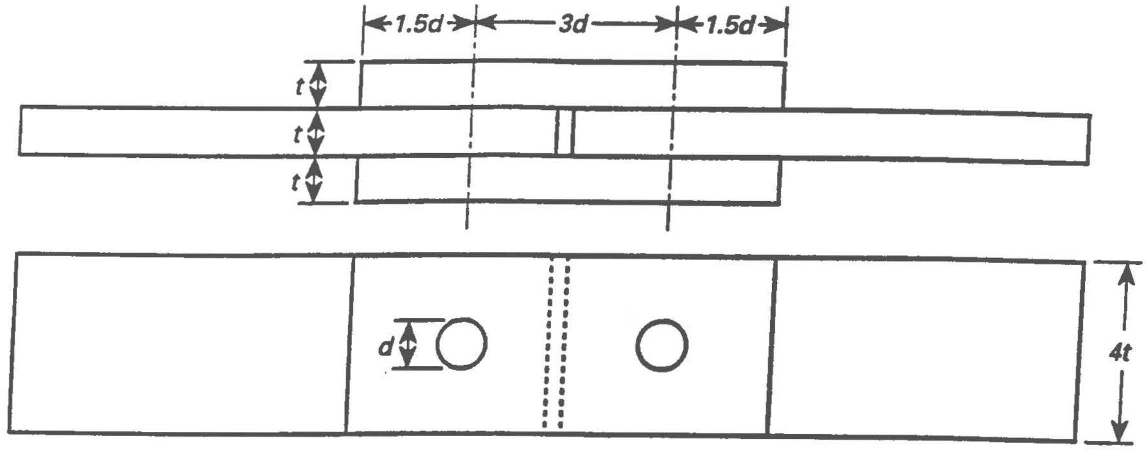

Fig. 4 Joint detail tested with friction grip bolted joints (S-N tests)

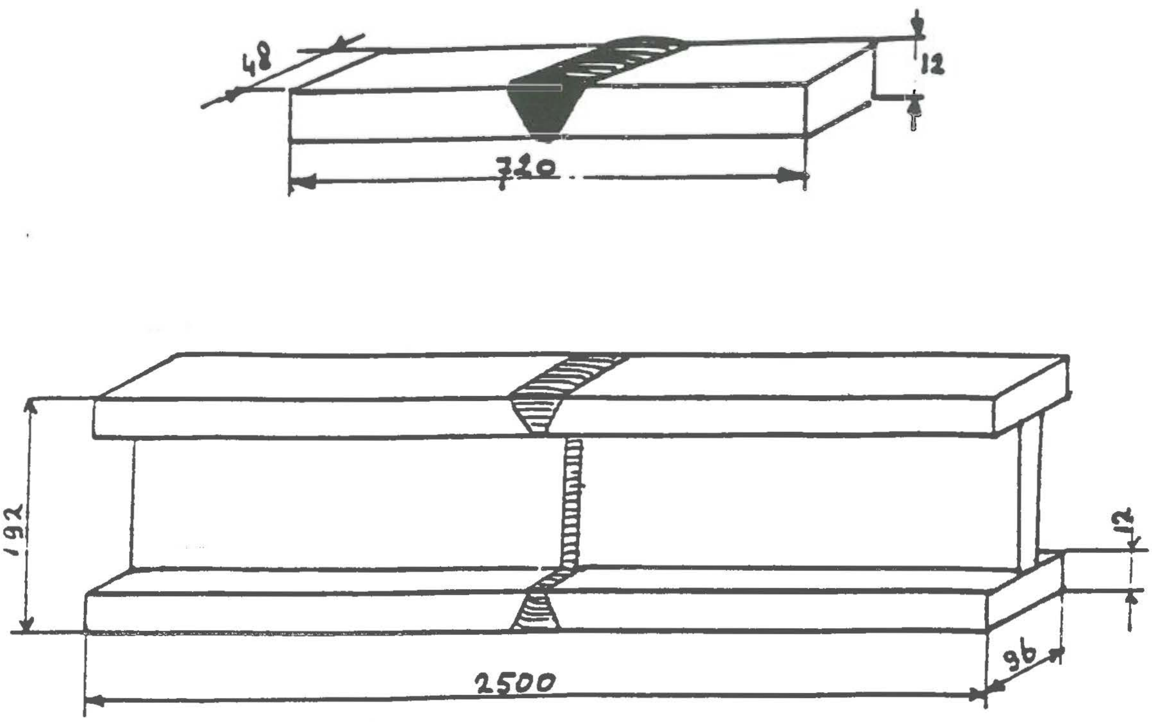

Fig. 5 Butt welded joint (detail 1) strip as well as beam specimen.
Material thickness t = 12 mm

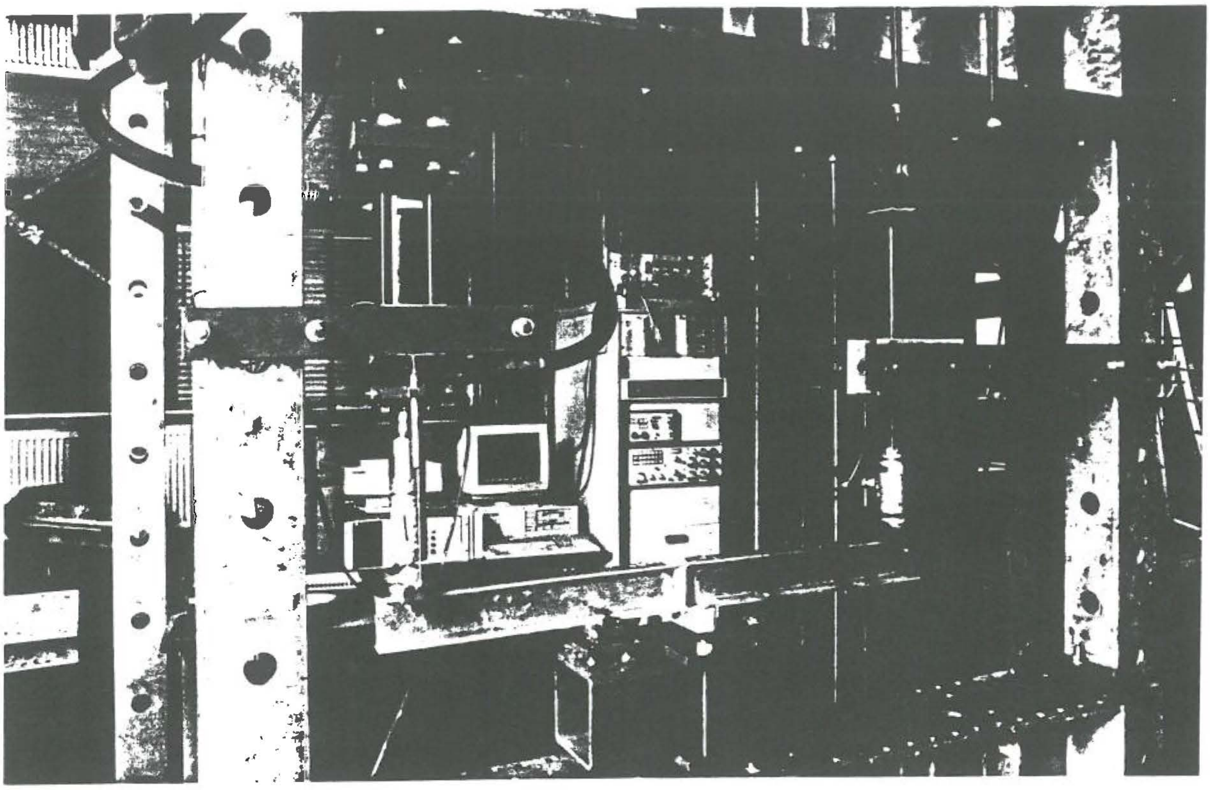

Fig. 6 Test rig fatigue tests beams, 4-point bending

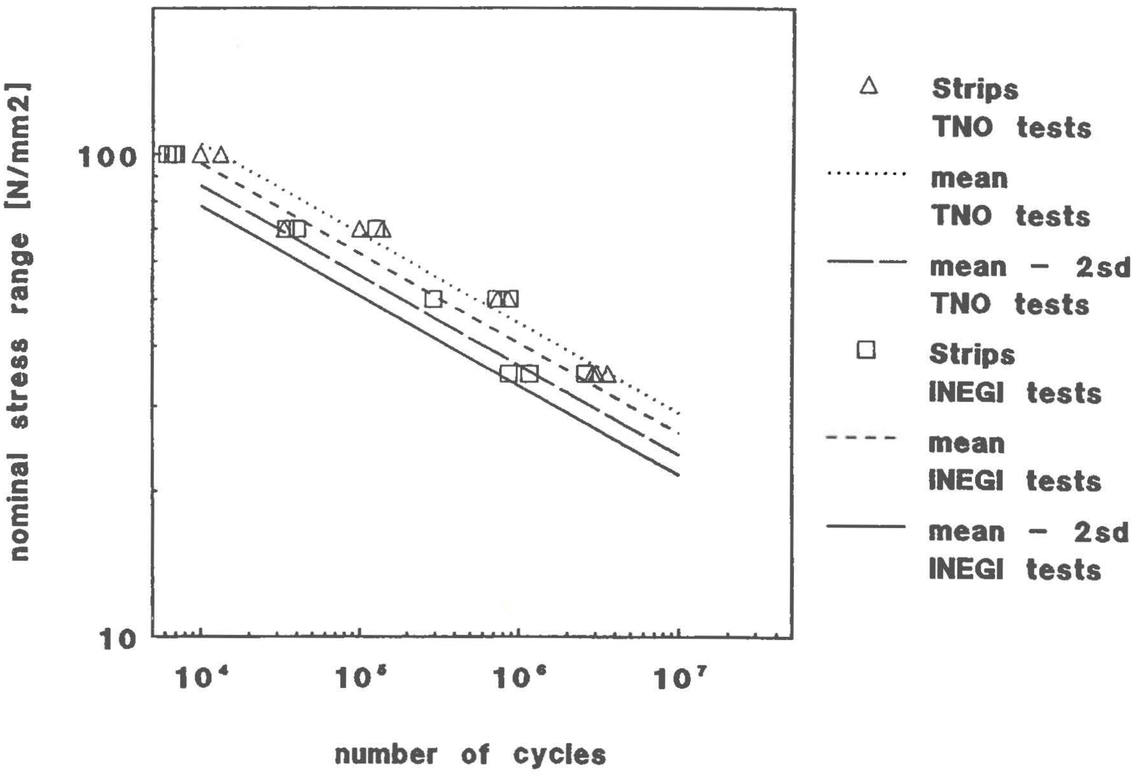

Fig. 7 S-N test results welded joints in strips; detail 3; t = 12 mm

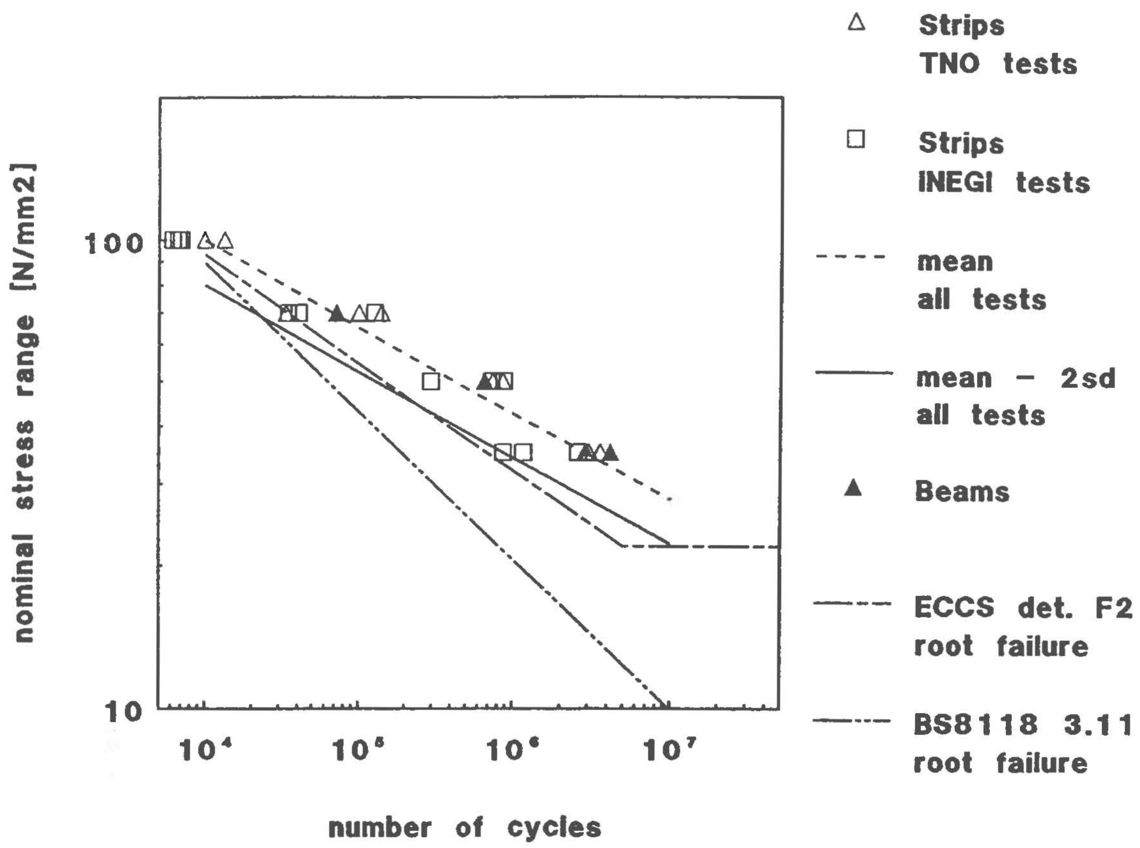

Fig. 8 S-N test results welded joints in strips and beams; detail 3; thickness t = 12 mm

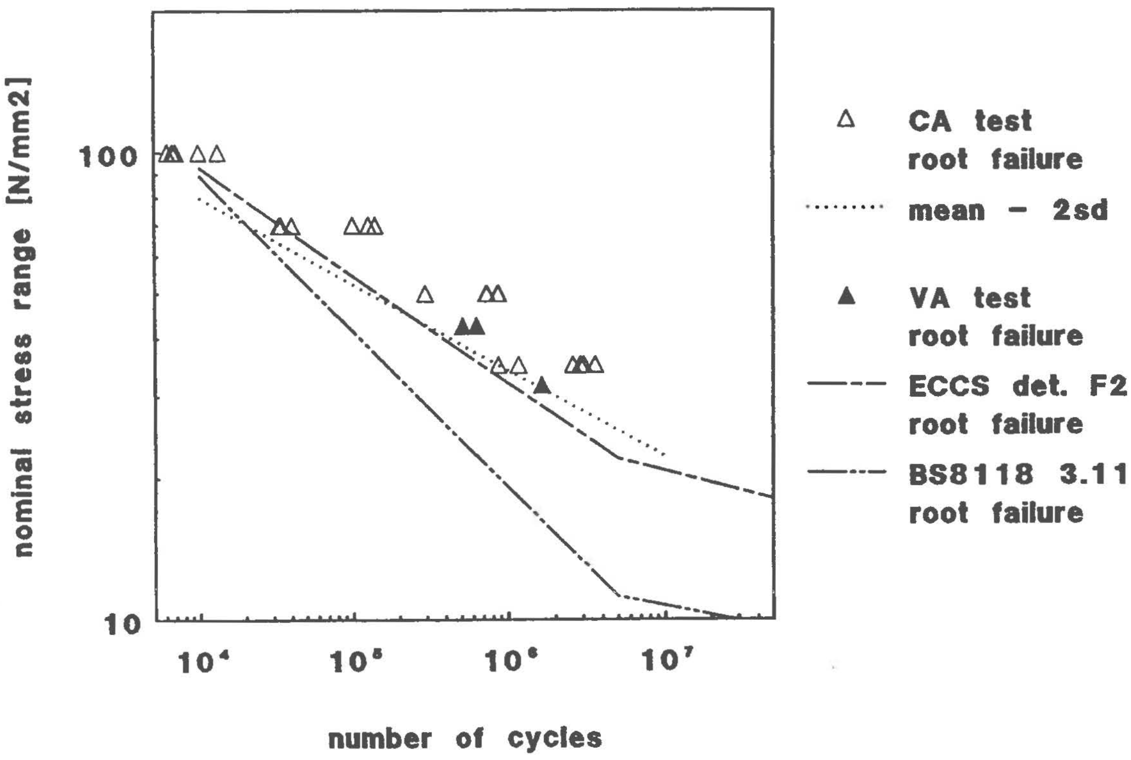

Fig. 9 S-N test results welded joints in strips; detail 3; t = 12 mm; constant and variable amplitude loading

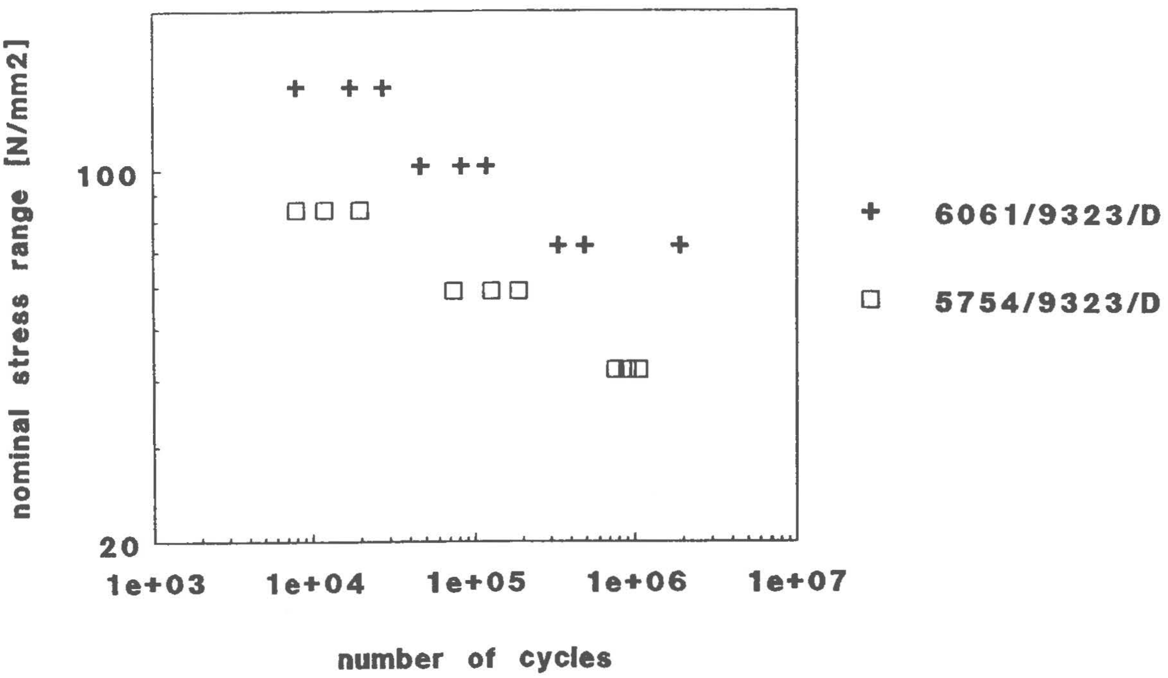

Fig. 10 S-N test results adhesive bonded joints in beams; t = 6 mm; air environment

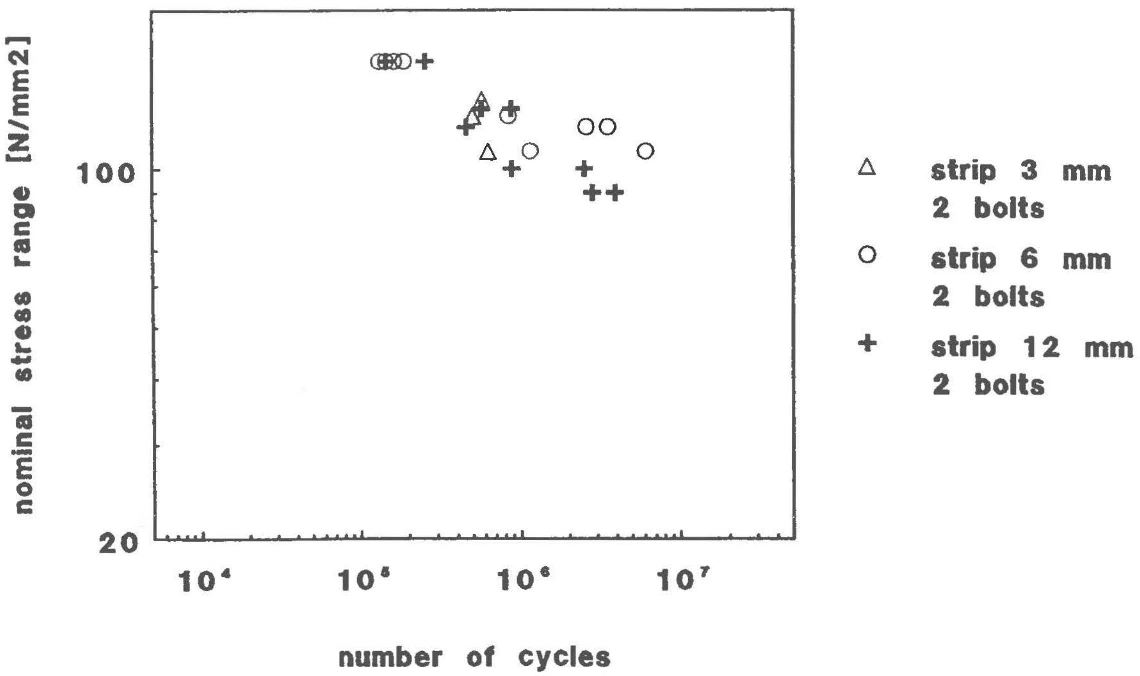

Fig. 11 S-N test results friction grip bolted joints; strips; t = 3, 6 and 12 mm

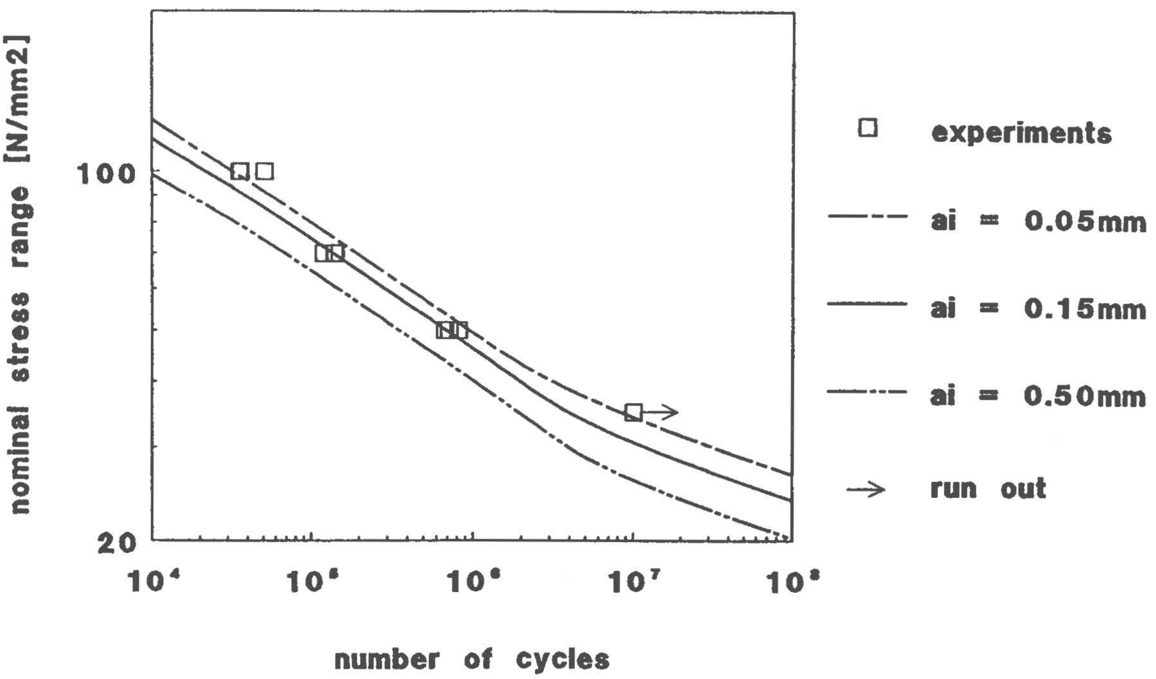

Fig. 12 S-N curve simulated by calculations based on a crack growth model