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SURVEY OF FRENCH ACTIVITIES

CONCERNING STRUCTURAL AIRWORTHINESS

AND AGING AIRCRAFT

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SUMMARY

French activities concerning Structural Airworthiness and Aging Aircraft are presented. A first part is derived to Basic and Applied Research actions while a second one deals with Full-Scale Testing, Tear-down inspections and continuing Airworthiness approaches.

INTRODUCTION

We present here a survey of actions conducted in France in order to improve the methods and means of accomplishment of the demonstration of Aircraft Structural Airworthiness, with particular emphasis on Aging aspects.

These actions range from basic research up to full-scale testing and tear-down inspections of aged aircraft.

The works cited here are performed by Govermment Agencies :

- C.E.A.T. : Centre d'Essais Aéronautiques de Toulouse
- O.N.E.R.A. : Office National d'Etudes et de Recherches Aérospatiales.

and Manufacturers :

- Aérospatiale
- Dassault-Aviation
- Messier-Bugatti (Landing gears).

we shall distinguish here :

o Basic and Applied Research studies
o Full-scale testing (including Tear-down).

BASIC AND APPLIED RESEARCH STUDIES

Part 1 : Metallic Structures.

o Crack initiation

In this area it is worth mentioning the development of a methodology for crack initiation computation by Dassault-Aviation. Among the numerous difficulties to be dealt with, special attention was paid to the definition of a parameter able to give a unified presentation of basic test result and consequently leading to master curves like the one presented in figure 1 for the 7010 T73651 aluminum alloy.

Two studies were conducted at CEAT and ONERA concerning the influence of load history on crack initiation. The first one (C.E.A.T.) aimed at the derivation of a method to predict fatigue damage allowing for small cycles (i.e below the endurance limit) which would lead to no-fatigue damage according to the Palmgren-Miner's rule whereas this is not in accordance with certain experimental results. Through two modifications of the Wöhler's curve indicated on figure 2, very good predictions are achieved, compared to experimental results where specimens undergo TWIST, MINI-TWIST and modified MINI-TWIST standard sequences.

Concerning the second one (O.N.E.R.A.) the influence of apparition of an overload was predicted using a damage model developed at O.N.E.R.A which proved worthwhile when compared to experimental results as shown on figure 3.

Material's characterization was conducted at Aérospatiale in particular for Al-Li alloys. Figure 4 shows the main observed tendencies. The lower endurance limit of the Al-Li alloy is attributed to the higher brittleness of its precipitates.

Concerning landing gear structures, the following studies were conducted at Messier-Bugatti :

- Fatigue life prediction under complex load histories
- Investigation of several damage criteria in the case of multiaxial loading
- Evaluation of the influence of factors like design, loading history, processing and assembly modes, etc... on fatigue life of landing gear components.
- Figures 5 and 6 show the influence of surface treatment on fatigue life of an aluminum alloy and a steel.

o Résidual Strength (R curves)

Careful examination of results from the open literature indicates that Linear Elastic Fracture Mechanics (L.E.F.M.) cannot be an accurate prediction method, particularly in presence of thickness effects. Taking plasticity and energy balance into account results in subtantial improvement as demonstrated by the results obtained by Dassault-Aviation and Aérospatiale (see figures 7 and 8).

o Fretting Fatigue

The assessment of fretting-fatigue susceptibility should be taken into account in the early part of an alloy development. The experimental device described on figure 9 is used at C.E.A.T to compare the intrinsic behavior of various alloys under fretting-fatigue conditions and to value surface protections which are intended to delay fretting occurrence. Figure 10 shows the observed behavior for several aluminum alloys and figure 11 points out that 2000 alloys have a better behavior under fretting fatigue than the 7075 one. With the same goals, a study was conducted at Aérospatiale on the 30 NCD 16 steel and aluminum alloys and confirms the conclusions of C.E.A.T. (see figures 12 and 13).

Fatigue Crack Growth

In this field, various studies allowed checking capabilities of several models for predicting crack growth under aeronautical type spectrum loadings. It is worth mentioning here that a comprehensive survey has been achieved through a fruitful GARTEUR cooperation associating N.L.R. (Netherlands), R.A.E (Now D.R.A.) (U.K.), D.L.R (Germany) and O.N.E.R.A (France).

In particular, two databases were created :

- extended F27 spectrum variations (associated with 2024 alloy and thickness effects) were studied.
- FALSTAFF database, with the same investigations as for the F27 one and associated with several materials : 2024, 7075, 7475 and 2214 aluminum alloys, a titanium alloy and a steel.

Figure 14 shows the prediction obtained with the ONERA 's model.

In another cooperation between Boeing Commercial Airplane Division and ONERA, ONERA's model was also tested versus a "wing upper surface" type of spectrum, and results are illustrated in figure 15.

Developments were also conducted at Aerospatiale in order to improve the description of the influence of compressive cycles during spectrum loadings. Special attention was focused, at CEAT, on Al-Li alloys for A330/A340 applications ; it has been noted a good consistency between data on simple specimens and those on specimens representative of a structural feature. A good behavior regarding crack growth and some weakness regarding throughness are confirmed for 2091 sheets (see figures 16 and 17).

Non Destructive Inspection (N.D.I)

For metallic materials, works in this domain concern essentially the eddy current technique and significant efforts were undertaken to improve both the methods and the associated hardware. Let us mention the SIAM (System of Inspection-Assisted by Microprocessor) developed by Aerospatiale, for which practical runs on 65,000 rivet samples have demonstrated a capability of up to 1,400 rivets inspected per hour, without any false alarm. AIDA system was developed by DASSAULT AVIATION with the help of TECRAD Society in view of

For failure, special attention was paid at Aérospatiale to the problem of fastener holes in view of prediction of bolted area failure, taking into account parameters like :

- type of loads (tensile, compressive, shear, bending ...)
- geometry (lay-up, diameter, spacing ...)
- environment (temperature and relative humidity).

FULL SCALE TESTING AND TEAR DOWN

Part 1 : Fatigue and Damage Tolerance Testing

o Falcon 900 : (Dassault Aviation and C.E.A.T.)

Within the type certification framework for this aircraft, a general fatigue and damage tolerance test on its structure has been conducted. 2 lives (40,000 flights) were simulated in a safe-life approach followed by 1 life (20,000 flights) in a damage tolerance approach. It should be noted here that the fatigue load spectrum applied was deduced from in-service load monitoring which improves the significance of such a test.

o A 320 : (Aerospatiale and C.E.A.T.)

1.25 economic life (60,000 flights) was simulated in a safe-life approach, followed by again 1.25 economic life in a damage tolerance philosophy. On the front fuselage part 24 artificial cuts were tested ; the pylon and centre wing box achieved 120,000 flights with 11 and 13 artificial cuts respectively.

o ATR 42/72 :(Aerospatiale and C.E.A.T)

The design life goal is 70,000 flights and the simulated flight goal is 140,000. For ATR 42 flights 134,000 were achieved on the wing box (15 artificial cuts) and 100,000 on the fuselage and empennage (34 artificial cuts). For ATR72 centre wing box achieved 30,000.

o A330/340 : (Aerospatiale and C.E.A.T)

The design life goals are respectively 40,000 flights for A330 and 20,000 for A340.

For the forward fuselage, the simulated flight goal is 120,000 and the corresponding test starts at end 91. The wing/centre fuselage will be submitted to mixed typical mission (A330 + A340) a simulated goal of 80,000, test being started at mid-92. The figures for the A340 pylon are 50,000 (flight goal) with test starting at end 91.

investigating cracks in holes ; here again, this system microprocessor-automated which allows, for example, differential and absolute measurement, 400° rotation of probe with reciprocating motion, variable frequency output ... etc and further developments will lead to automatic crack detection and automatic signal compensation to account for edge effect. Finally, CEAT has also conducted in-depth evaluation of the possibilities of eddy current techniques particularly with respect to reliability and statistical signification of this technique.

Part 2 : Composite Structures.

o Damage Tolerance

In this domain, the problem of low-energy impact on composite structures has received substantial attention since the damage created in these conditions is often barely visible and can subsequently develop under normal service loadings before being detected.

Several actions were conducted at Aerospatiale and Dassault Aviation:

- identification of main stress effects governing damage
- experimental study of morphology of degradations induced on composites by low speed impact
- study of impact behavior of prestressed panels (simulation of hail for example) either from the prediction side (development of theoretical models) or the experimental one.

It appears clearly, from this analysis, that peeling resistance and shear resistance of the interply play a very important role in the process and should deserve particular attention in future works.

Concerning residual strength, Aerospatiale has carried on instrumented compression tests in order to determine the successive steps leading to the ruin of a pre-impacted plate. Figure 18 illustrates the tests conditions and those of the associated numerical analysis. It was remarked a good agreement between measured and predicted strains and a failure criterion is now under study for complete prediction of residual strength.

Finally, we wish to mention here the probabilistic approach developed by Aerospatiale combining three types of probabilities, namely :

- prob. of encountering an impact of given energy
- prob. of encountering loads between Limit and Ultimate load
- prob. of detecting damage.

In view of defining the residual load a structure must sustain with a risk factor less than 10^{-9} per flight hour.

o Failure and fatigue behavior.

Concerning fatigue, the main problem to be tackled is the accurate representation of the fatigue spectrum which is required to gain further knowledge in the following areas :

- scatter and standard variation on life
- variation coefficient on fatigue stress
- endurance curve with load-effect, R factor...

Part 2 : Tear down inspections.

They include the following operations :

- detailed inspection of the structure as it is, implementation of procedures described in the maintenance manual.
- experimentation and development of new NDT procedures
- cutting out of known cracks plus microfratographic examinations
- disassembly of components difficult to inspect and search for hidden damage.

In cooperation between Aerospatiale and C.E.A.T, the following aircraft structures undergo a tear-down inspection after a full scale fatigue test :

o Airbus A310 :

58 critical sites were inspected and about 60 cut-outs were performed (see figures 19 and 20). This structure was subjected to 100,000 simulated flights for a design life goal of 40,000 flights. The zone inspected are :

- the wing centre section
- the centre fuselage

o Concorde SST :

21 sites were inspected and cut-out :

- 9 zones on the fuselage (50 holes cracked in 3 new sites)
- 12 zones on the wing (50 holes cracked in 6 new sites)

The Concorde structure was subjected at about 34,000 simulated flights in the course of fatigue testing, which have so far enabled 6,700 supersonic flights at heavy weight to be authorized in service. Figure 21 gives indications on the location of the inspected sites.

Part 3 : In service loads

o General :

During entry into service of an aircraft, maintenance activities are essentially based on analysis. The very first years of operation are also protected with respect to fatigue by the credit opened by the progress of fatigue testing. It is no less true that all the data used for this purpose is based on assumptions as to how airlines operate their aircraft. It is therefore necessary to be able, in one way or another to identify the reality of aircraft operation as accurately as possible, in order to correct the maintenance instructions given to the operators, as necessary.

o A300 B2 - B4 campaign

Among the possibilities that exist in this fields it is interesting to mention the campaign performed by Aerospatiale at Airbus Industries request, on the A 300 B2 - B4 fleet.

The purpose of this campaign was above all to check that the assumptions chosen for establishing typical fatigue missions (which constitute the basis for fatigue and damage tolerance calculations and test)

- take off weight,
- landing weight,
- range,
- payload,

are not found to be at fault.

About 45,000 flights were analysed, involving five airlines in Europe and the USA, and both A300 B2 and A300 B4 aircraft. The results of this analysis highlighted significant variations with respect to predictions. This

made it necessary to make a comprehensive parametic study of the general loads, based on :

- payload,
- range,
- fuel at landing.

After fatigue calculations on sensitive structural components, this study provided correction laws affecting the inspection intervals given in the maintenance manuals.

o A310 campaign

For the A310, a similar activity was initiated with two European airlines. In addition to checking the typical fatigue mission, the purpose of this campaign was to assess other data such as equivalent gust speeds, moving surface deflection, etc.

The same phenomena as those observed on the A300 exists on the operating weights ; it has already been decided to take corrective actions on thresholds and intervals on the basis of A300 investigations.

Part 4 : Continuing Airworthiness

o General :

Within the framework of continuing aircraft airworthiness, the development of supplementary structural inspection programmes for the Caravelle SE 210 and the A 300 B2-B4 should be noted.

The aircraft, in particular the Caravelle, were not certificated according to far 25 amendment 45 and must thus, in compliance with amendment 45, form the subject of suitable monitoring whose conditions must be defined while respecting the spirit of damage tolerance.

o Caravelle SE 210 :

Certification in 1957, entry into service in 1959, the Caravelle in its different versions, has accumulated a total of about 6,300,000 flights. To date there are still 70 aircraft in service in the seven versions sold. The aircraft which have accumulated the greatest number of flights have reached 43,000 flights. The structure in its basic definition was subjected to a fatigue test (104,000 simulated flights) to substantiate a target service life which was 32,000 flights at that time. The experience gained year after year allowed 43,000 flights to be achieved. The supplementary inspection programme was developed and issued, at least in preliminary form, at the end of 1989.

The stages which have been defined are as follows :

- reorganization of maintenance instructions in the form of a maintenance manual,
- analysis of the structure in the spirit of damage tolerance : identification of the Principal Structural Elements,
- analysis of the PSE : identification of the sites forming the subject of special monitoring, and the sites which are not monitored at the present time and are thus candidates for additional inspection tasks.

To date 60 new sites have been selected which requires at least 200 damage tolerance analyses. These analyses are performed on the basis of 4 typical missions defined further to a study of actual fleet operation.

o A300 B2/B4 :

Certified and put into service in 1974, the A 300 in its different versions, (A 300 B2-B4) has accumulated a total of about 3,600,000 flights.

Although this aircraft had not been certificated to amendment 45, Aerospatiale and its partners decided at that time to develop calculation and test activities with a view to determining propagation duration and the residual strength of the structure tolerance in the presence of damage. Implementation of the damage tolerance concept to set up a supplementary inspection programme has not thus raised any particular difficulties.

The development of the SSIP covers the following operations :

a) analysis of the fatigue test results and the tear-down operation leading to the fatigue sensitive sites.
b) analysis of in-service problems which had revealed sensitive sites not identified during tests or damage initiation earlier than the date on which it occurred on the fatigue test.
c) recording of the sites for which it is necessary to re-evaluate the inspection thresholds and intervals.
d) taking the analysis of in-service operation statistics into account for correcting the intervals according to mission durations.

For the parts under AS responsibility, 14 service bulletins and 25 new zones to be inspected were thus provided.

When this supplementary programme was implemented, a method for calculating the inspection intervals was developed by Aerospatiale based on :

- the probability of fatigue crack initiation,
- the probability of propagation of this crack,
- and the probability of its being detected during inspection,

This method consists in determining the inspection threshold on interval causing a value of the risk of failure which is not to be exceeded at the end of the aircraft operation.

o A 310 :

Contrary to the A 300 models, the A 310 models were certificated in compliance with the requirements of amendment 45 and do not thus need to be subjected to an additional inspection programme. Fatigue tests were carried out, up to 100,000 simulated flights with a view to substantiating a target life of 40,000 flights and the tear down operation already mentioned is naturally extended by a revision to the basic programme.

The general outlines of the method adopted are using those developed for the A 300 SSIP and led to some adjustment of the basic inspection program.

CONCLUSIONS

The results presented here demonstrate that a very important effort is still maintained for Structural Airworthiness Assessment. Yet, although the safety level with respect to Structural Resistance has dramatically improved over the past, this effort should be maintained and even increased for many reasons :

- Fundamental knowledge, and moreover modelling, of the various types of damage appearing in an aircraft structure is still not sufficiently accurate and this justifies the on-going associated basic research.

- Actual loads are still difficult to predict even for "classical" aircraft and in-service experience still continues to reveal non-predicted sites of damage and poorly predicted initiation and damage growth rates.

- This should continue with the coming in service of modern technology aircraft were the fly-by-wire/Computer assisted commands will generate, at least partly, new loading spectra.

- The emergence of new materials and fabrication processes will induce new types of behavior with specific manifestations of damage.

Finally we wish to stress that, even if national resources should be activated at their maximum, we are convinced that international cooperation is a major key on our way towards progress.

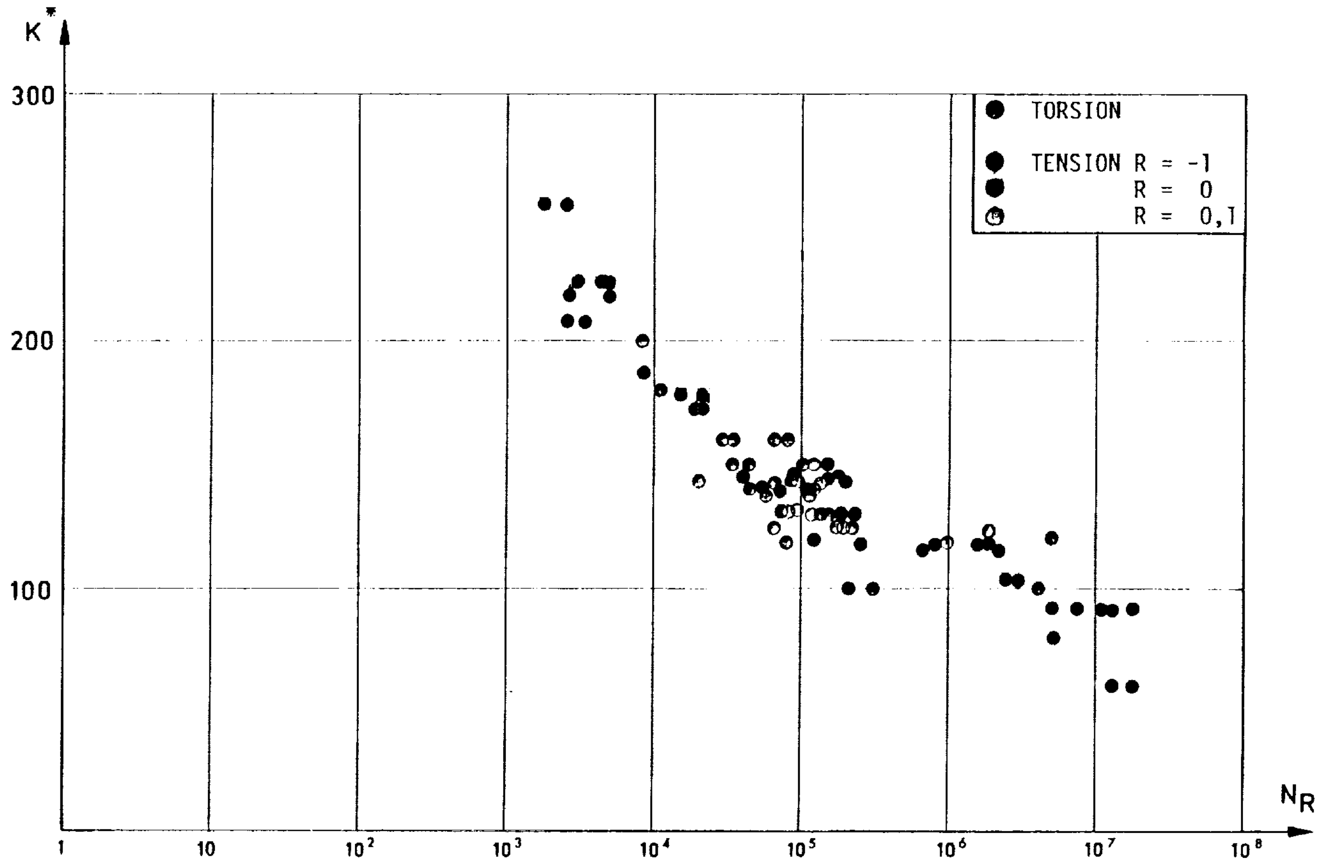


Fig 1 - Master fatigue curve for 7010 T3651 alloy

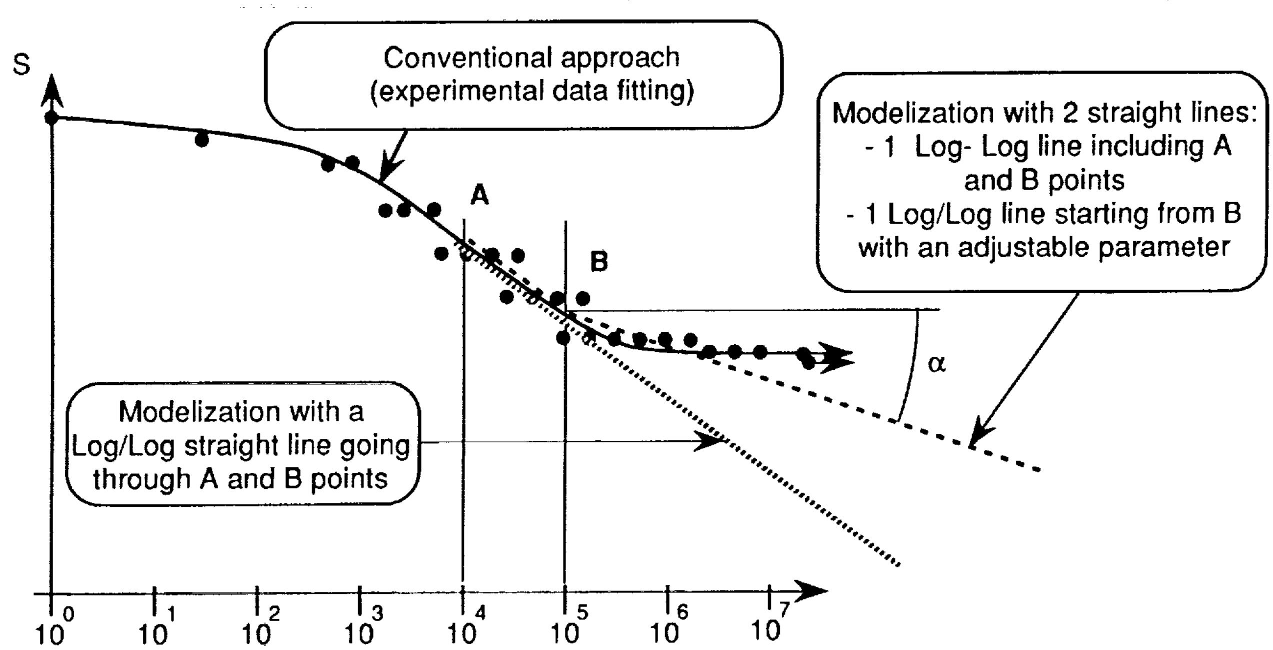


Fig 2 - Definition of the lowest part of the Wöhler's curve

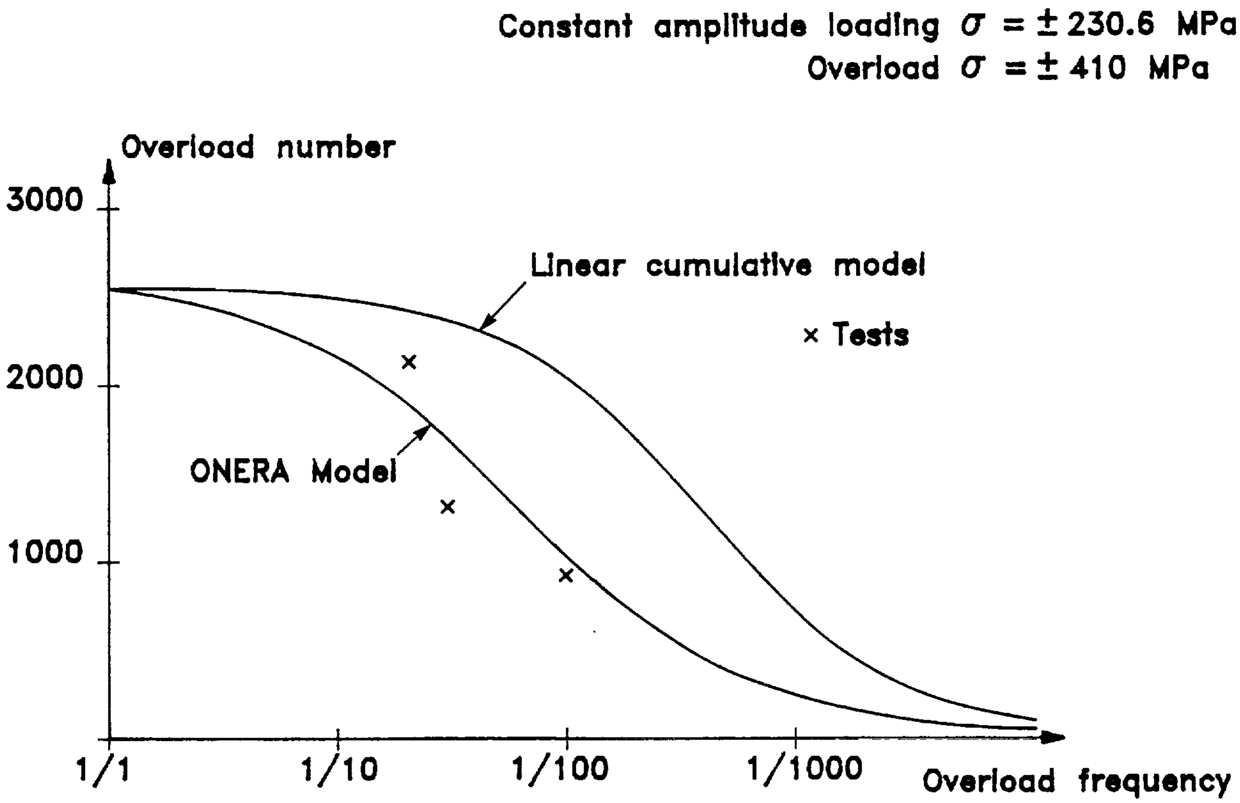


Fig 3 - Influence of overload

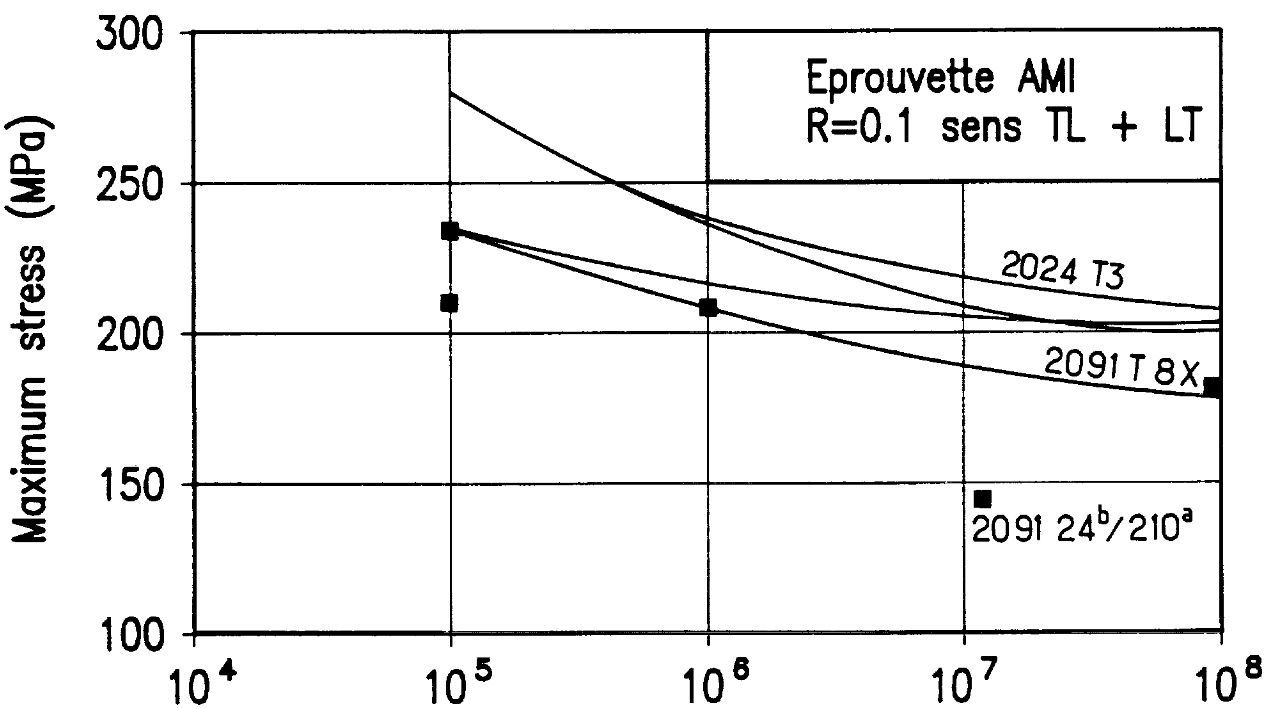


Fig 4 - Fatigue crack initiation in 2024 and 2091 aluminium alloys

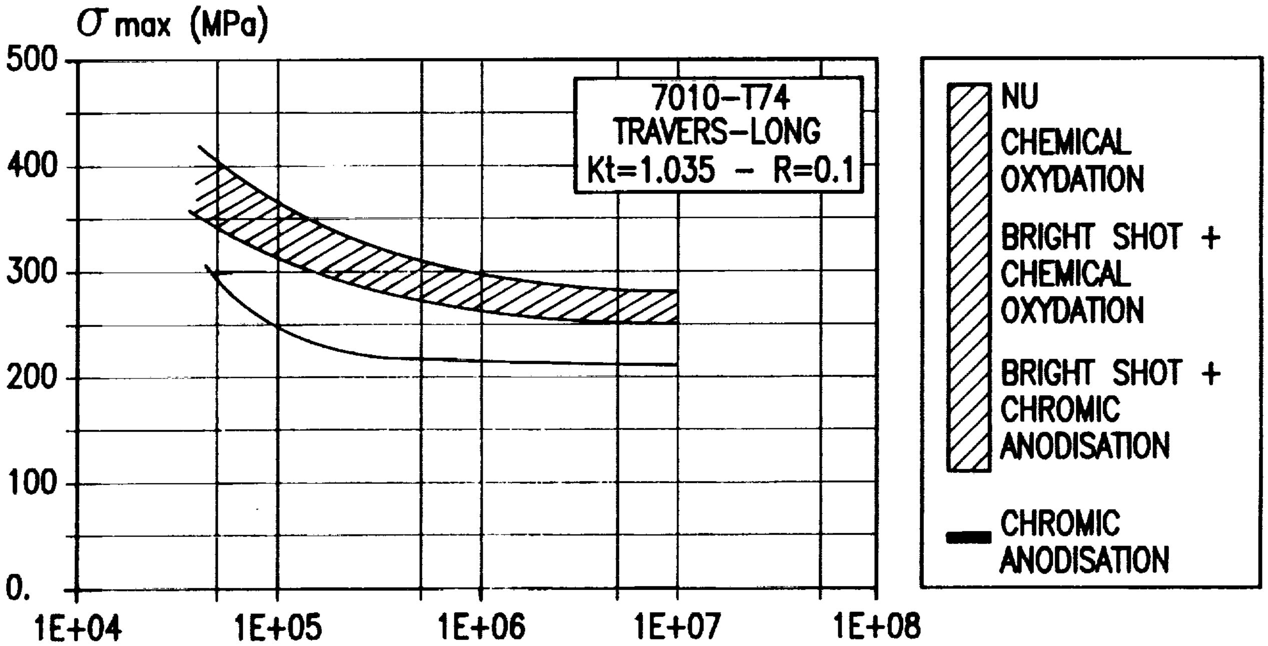


Fig 5 - Fatigue behavior with various surface treatments (aluminium alloys)

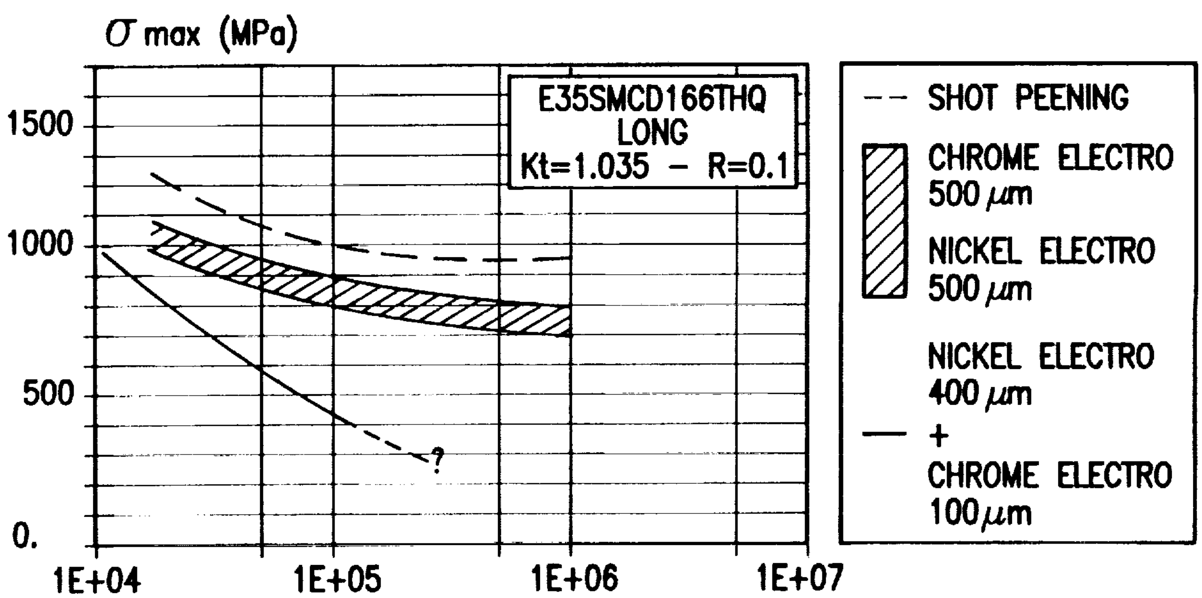


Fig 6 - Fatigue behavior with various surface treatments (high strength steel)

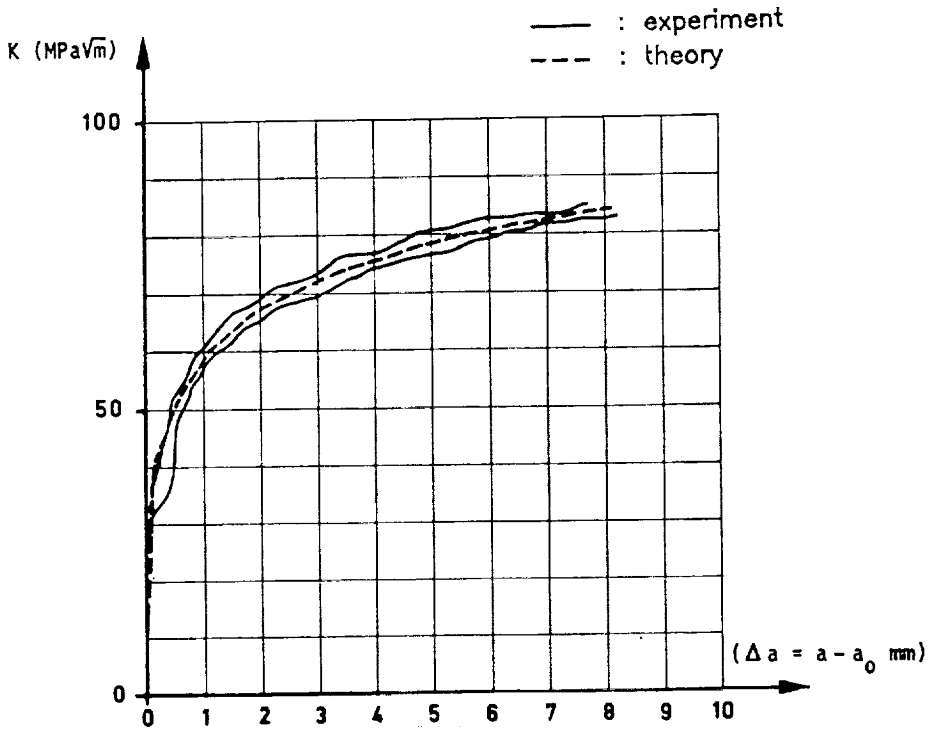


Fig 7 - Fracture toughness : comparison between theory and experiments.

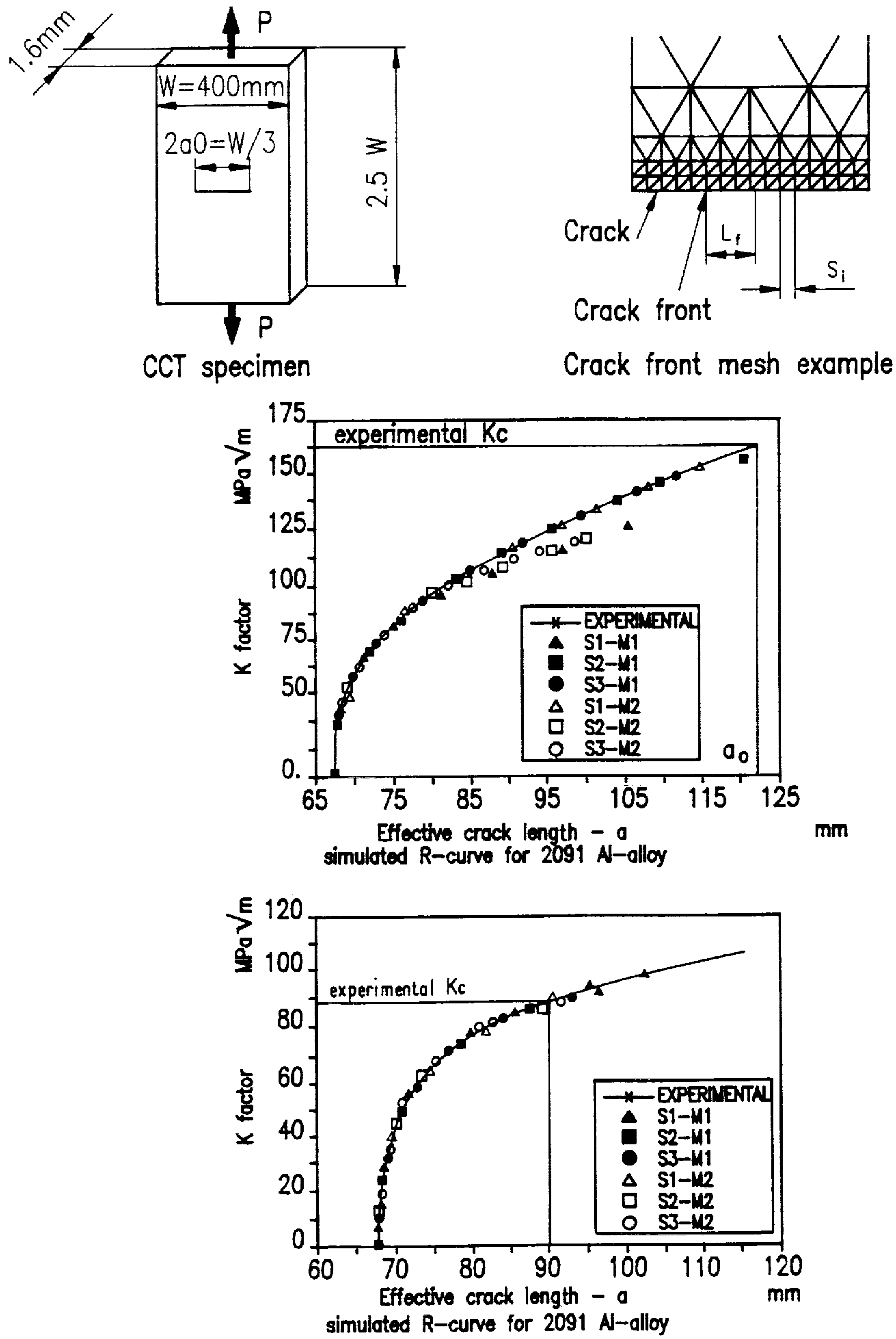


Fig 8 - R curves simulations for 2024 and 2091 aluminium alloys.

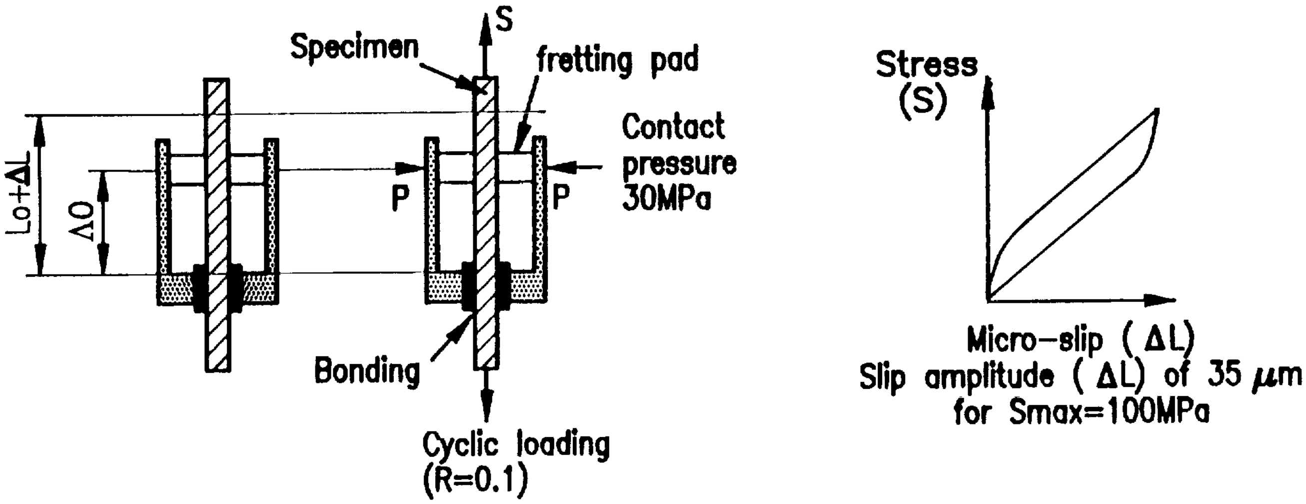


Fig 9 - Fretting experimental device

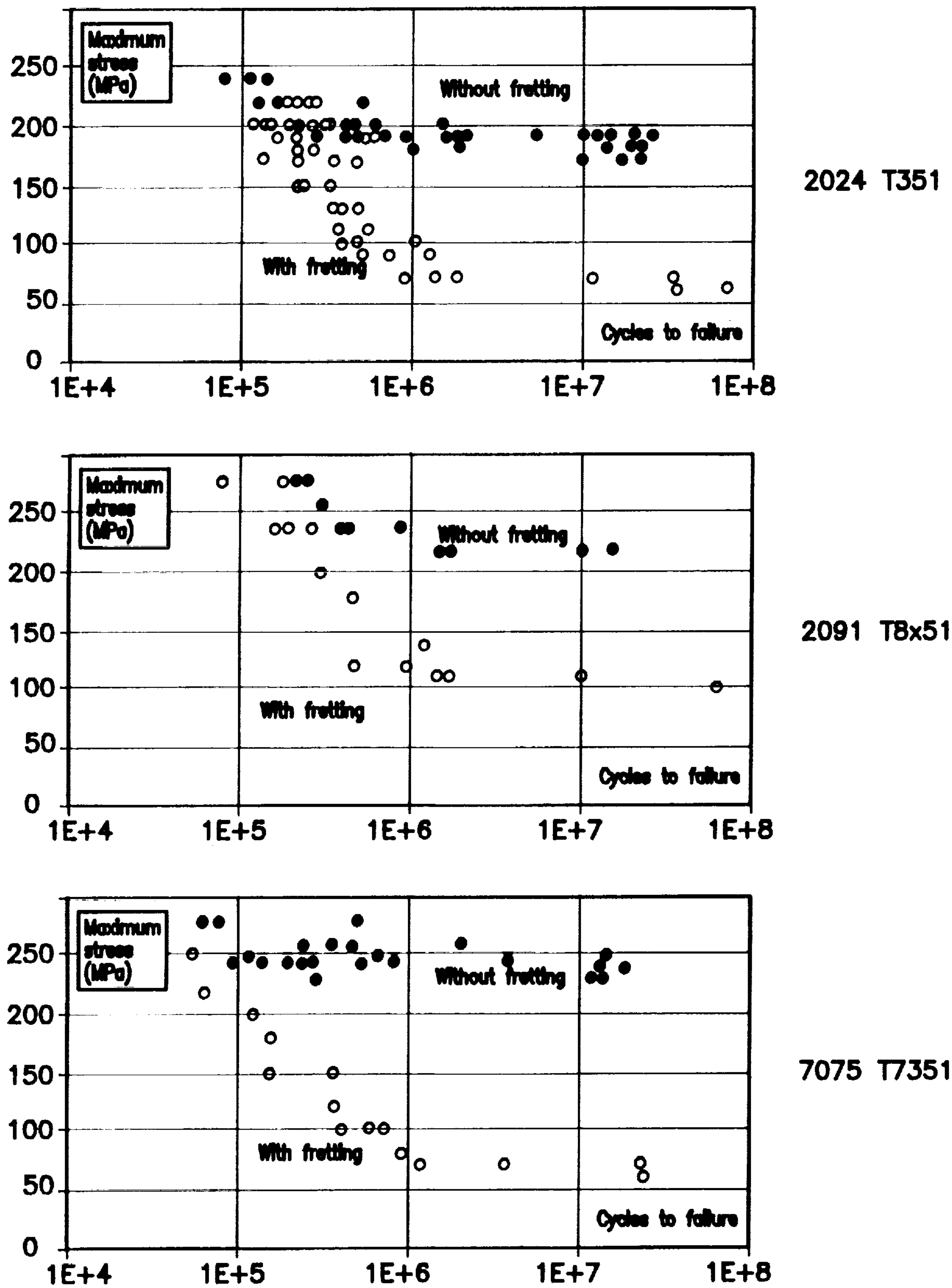


Fig 10 - Behaviour of various aluminium alloys under fretting fatigue

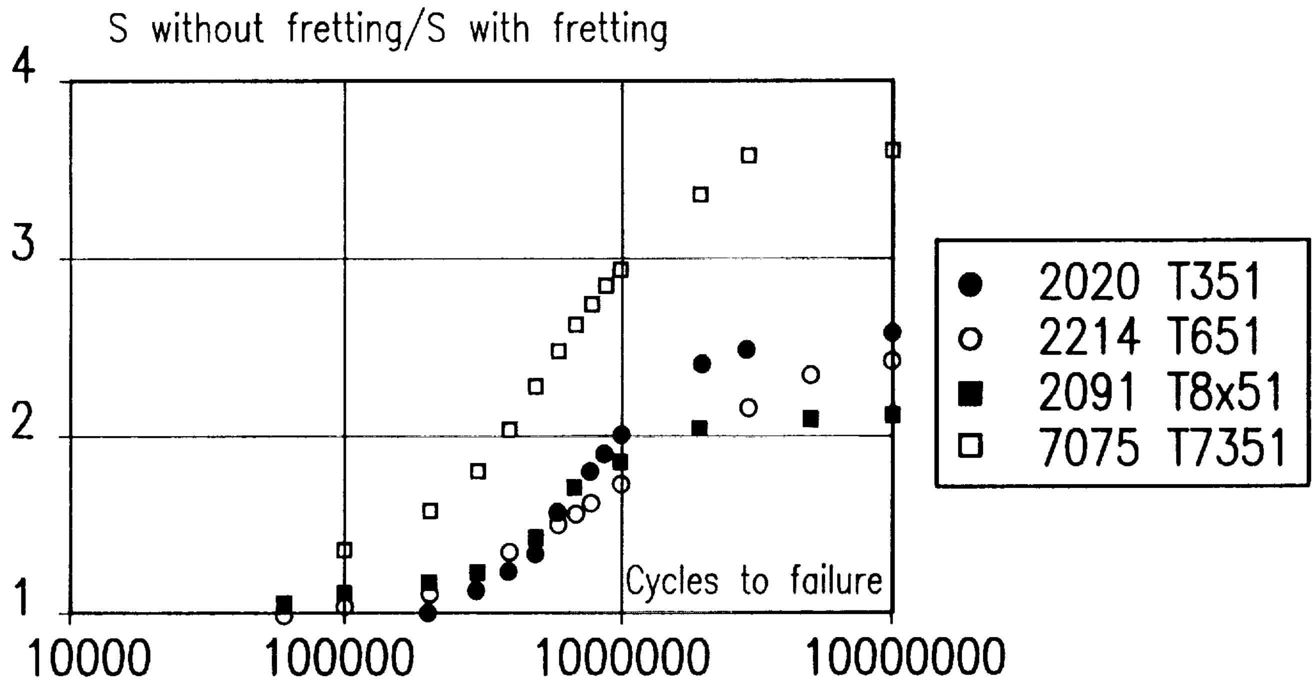


Fig 11 - Influence of fretting on fatigue resistance

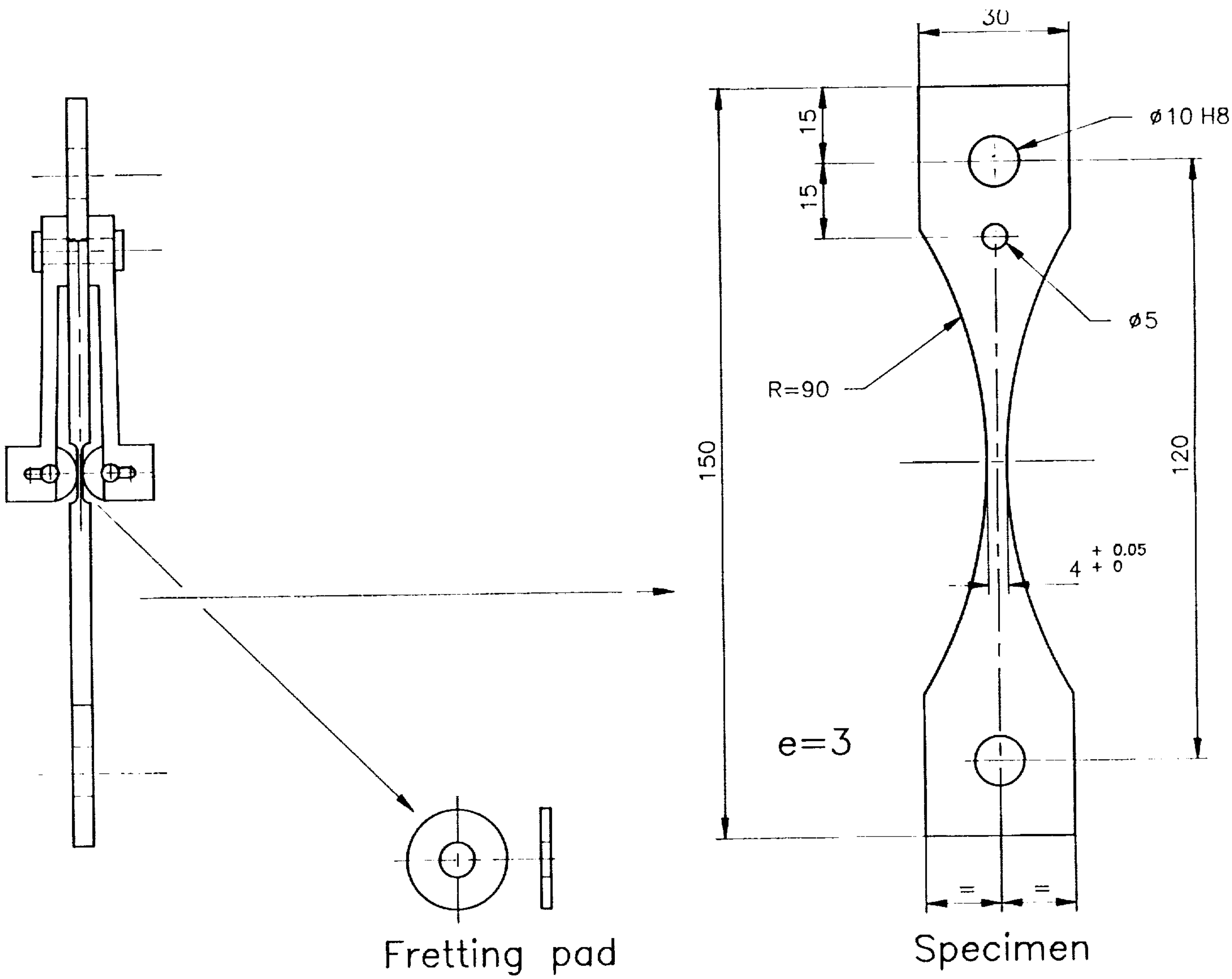


Fig 12 - Uni-axial Fretting-Fatigue test

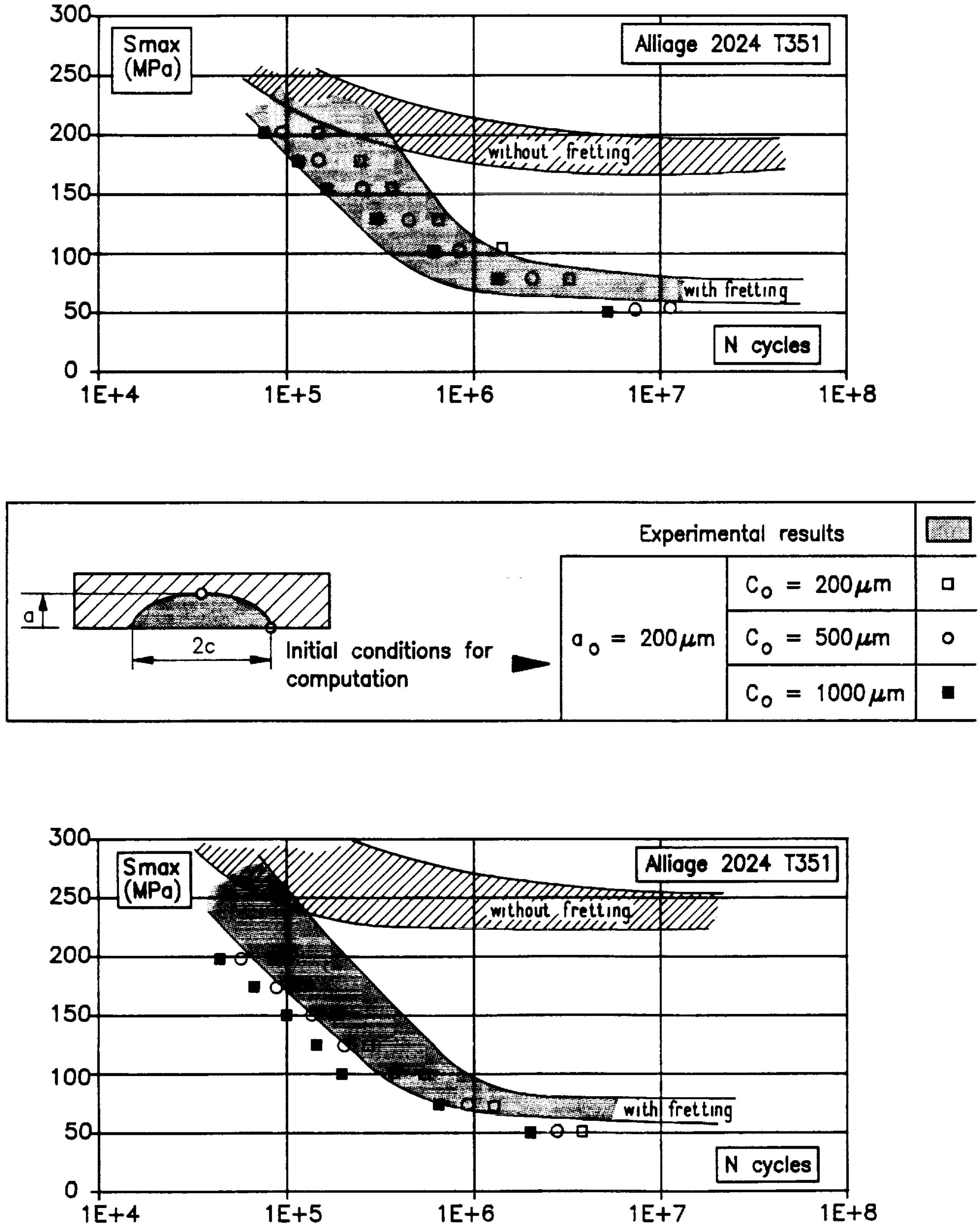
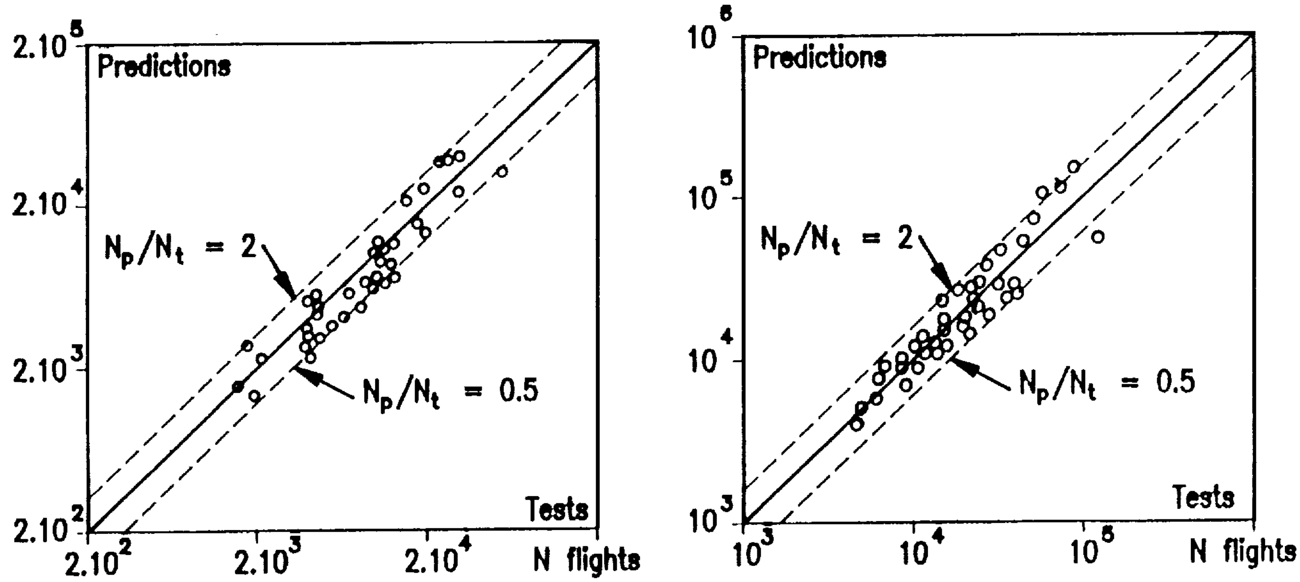


Fig 13 - Crack growth predictions in presence of fretting fatigue



a b

Fig 14 - Crack growth predictions vs tests for :
a) - FALSTAFF spectrum
b) - F27 spectrum

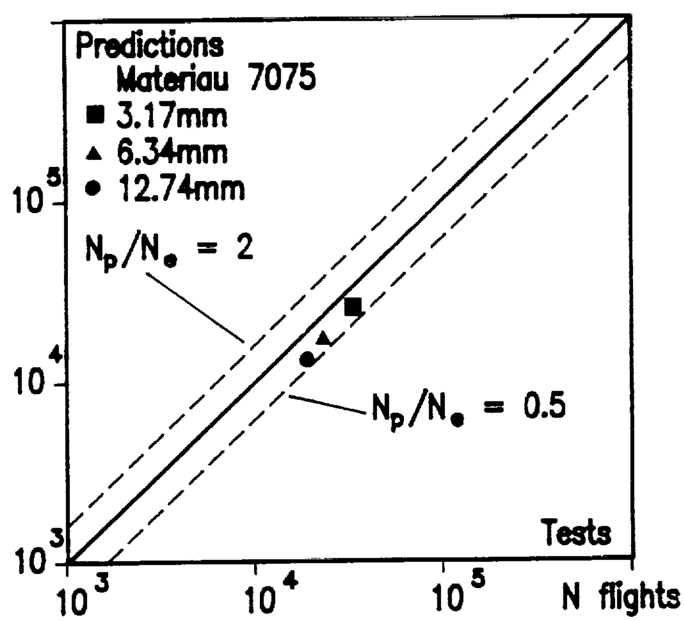


Fig 15 - Crack growth predictions vs tests for wing-upper-surface type of spectrum

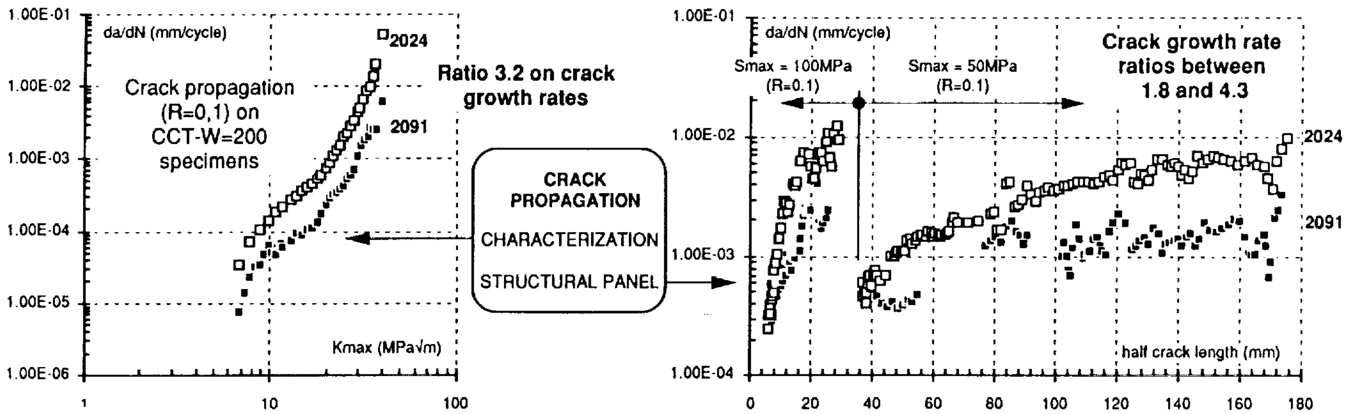


Fig 16 - Al-Li exploratory development, damage tolerance tests on typical fuselage segments : Crack growth aspects

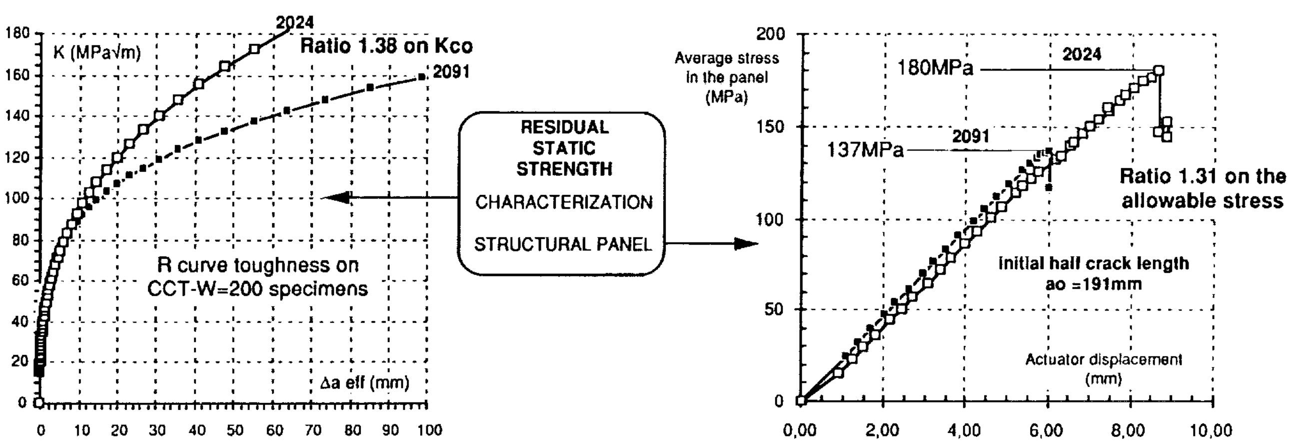


Fig 17 - Al-Li exploratory development, damage tolerance tests on typical fuselage segments : Residual strength aspects

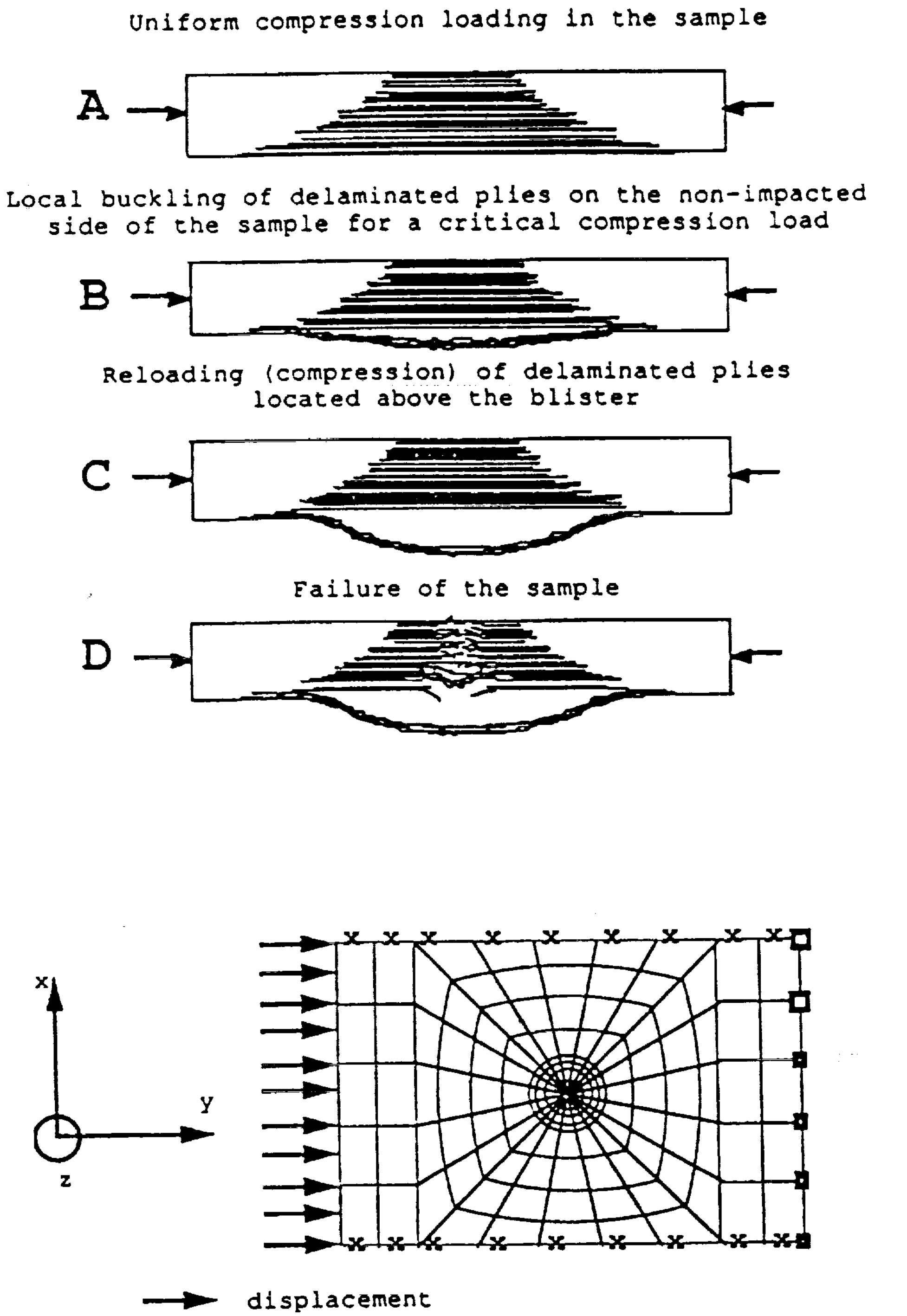


Fig 18 - Ruin mechanism and F.E mesh of an impacted composite specimen

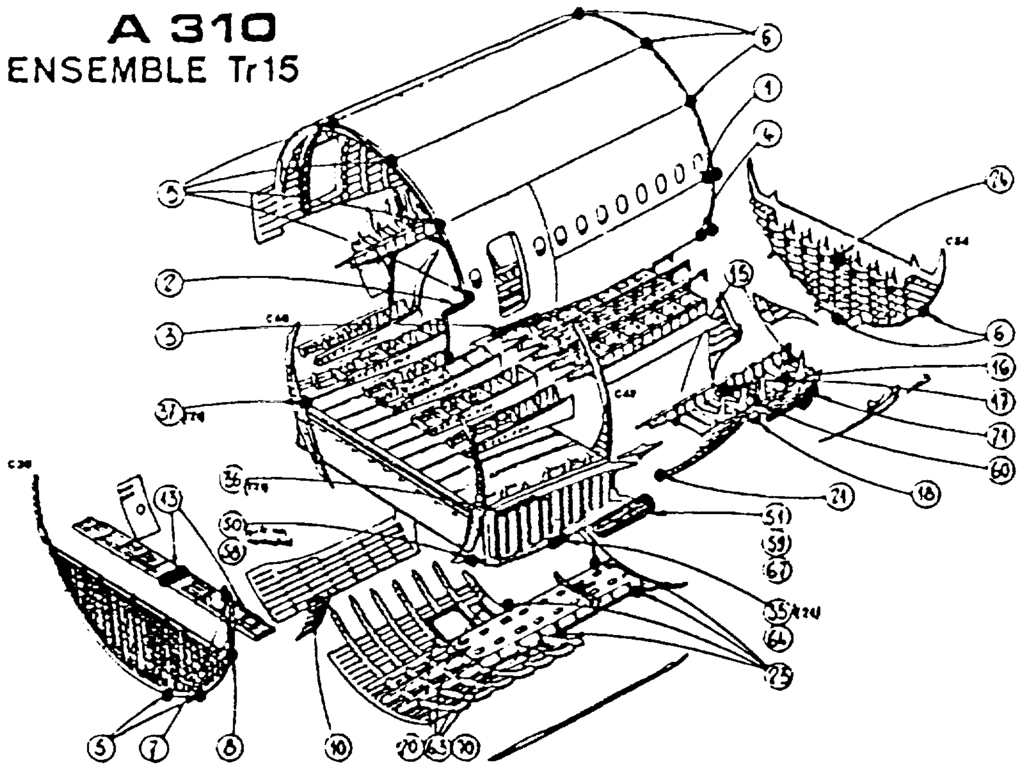


Fig 19 - Tear down - A310 center fuselage

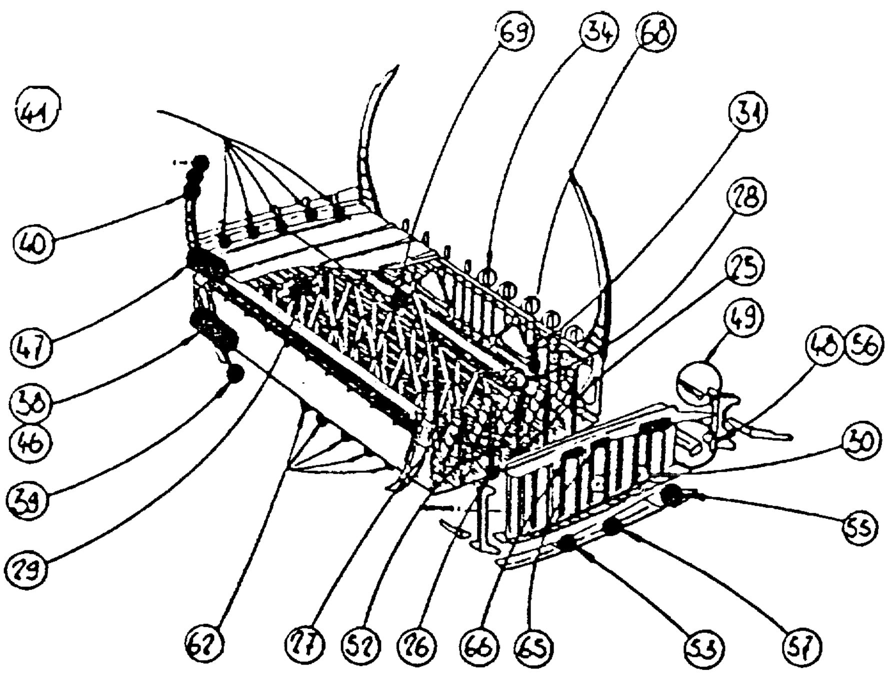


Fig 20 - Tear down - A310 center wing box

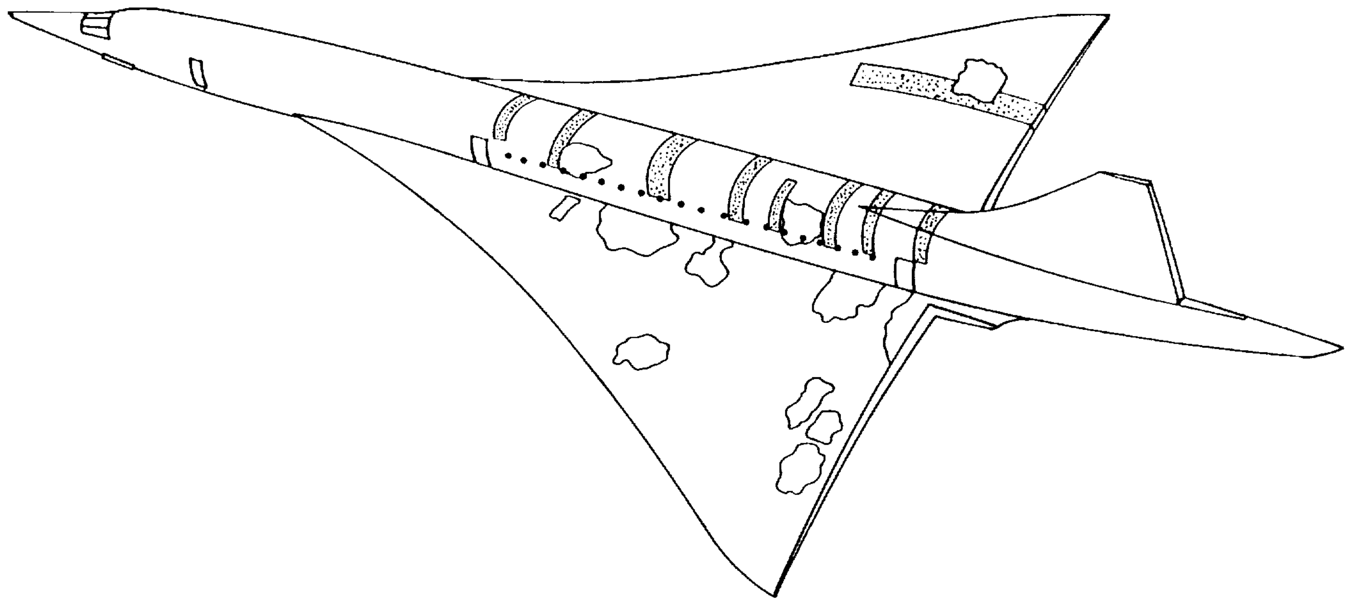


Fig 21 - Tear down - Concorde (locations of investigated areas).