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Fatigue Testing With Periodic Heating - An Investigation of Some Methods of Acceleration

by

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FATIGUE TESTING WITH PERIODIC HEATING - AN INVESTIGATION OF SOME METHODS OF ACCELERATION

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SUMMARY

Tests were conducted on aluminium alloy notched and riveted joint specimens under flight-by-flight loading sequences to examine the effects of varying the number of applications of heat and the maximum temperature. The effect of these parameters on fatigue life, and the underlying mechanisms are discussed. It is shown that changes in the number of applications of heat and in the maximum temperature cause appreciable changes in performance. An observation of general significance was that fatigue lives were affected by the inclusion of periods of load dwell in tests at a constant temperature of 40°C.

A description is given of the multi-channel testing facility used for this work.

The substance of this paper was presented at the SEE International Conference "Fatigue Testing and Design" held at the City University, London in April 1976.

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** Hawker Siddeley Aviation Ltd., Woodford.

CONTENTS

1 INTRODUCTION

In aircraft service operation, periods of fatigue loading are interspersed with periods during which the loading is sensibly steady or is changing very slowly, eg a jet transport aircraft will experience fatigue loading at the beginning and end of a flight but very little when cruising or standing on the ground. During these periods of steady load, the level of stress in different parts of the structure will range from compressive to tensile values. In order to avoid protracted fatigue tests it is customary to eliminate dwell periods at steady load from the loading sequence. However, when fatigue testing a supersonic aircraft, abbreviation of the time scale is more difficult because of the need to heat and cool the structure periodically in order to induce thermal stresses, and because of the importance of representing that phase of each flight during which the structure is hot and time-dependent effects such as overageing and creep may influence the fatigue performance. The need to include periodic heating and cooling is time consuming and it is necessary to develop methods of test acceleration to achieve an acceptable rate of testing. The philosophical aspect of the acceleration of testing by adjustment of the thermal stress levels has been covered by Ripley[1] and an experimental investigation has been carried out by Kiddle *et al*[2]. This paper considers the separate issue of accelerating those phases of the test that represent the dwell of the structure at elevated temperature.

A supersonic transport aircraft may be subjected to a heating cycle of some 90 minutes duration in each supersonic flight and the service life may include some 20000 hours at maximum temperature. Two test acceleration techniques have been explored in laboratory tests which could be used to compress this long service experience, namely:

(a) reducing the frequency of heat interspersions by omitting heating cycles from some flight cycles;

(b) shortening the cruise period but maintaining representative overall creep and overageing by increasing the maximum temperature of the heating cycle.

This paper describes a programme of tests on an Al 2% Cu alloy (RR58) to examine the effects of varying the frequency of applications of heat and the maximum temperature. The material in the form of notched specimens and riveted joints was tested under flight by flight loading sequences representing typical supersonic transport operations. Following discussion of the effect of heating on fatigue life and the underlying mechanisms, it is shown that increases in the number of applications of heat and in the maximum temperature each caused decreases in performance. An observation of general significance was that in the tests at a constant 40°C, the inclusion of dwells in the load sequence had a significant effect on fatigue life; the effect was detrimental or beneficial depending on whether the majority of the life was spent in initiating or propagating a crack.

The work described is part of an extensive programme of work[3,4,5] investigating heat-fatigue interaction effects which has been carried out for fifteen years or so and is still continuing.

2 SCOPE OF THE INVESTIGATION

Specimens were extracted from an Al 2% Cu material, which is a development of RR58 alloy, in the forms of plate (CM003) and 6% stretched clad sheet (CM001). Nominal compositions and tensile properties are given in Table 1. The stretched form of the material was included in the investigation to represent clad sheet heavily deformed by shaping for aircraft production. Two types of specimens were used, a notched specimen (see Fig.1) with a theoretical net stress concentration factor of 2.7 and a riveted joint with either Monel or titanium rivets (see Fig.2).

The principle of the tests was to establish the fatigue performance of these specimens under a flight by flight sequence at a constant temperature of 40°C, a convenient temperature somewhat above room temperature, and then to study the effect of heating the specimens, during each period representing the cruise phase, to temperatures of 100°C and 125°C, corresponding to possible values of temperature[1] in service and in full scale test respectively. Two levels of stress were applied during the heating cycle, either zero or tension, to represent the cruise condition at difference locations in the aircraft.

Different frequencies of heat interspersion were applied as described by the term Cycle Ratio, which is the ratio of the number of flight cycles to the number of temperature cycles, eg for a Cyle Ratio of 10 a heating cycle is included in one of every ten flight cycles. In general, values of Cycle Ratio of 1, 3 and 10 were studied.

3 TESTING FACILITY

The 'Avro Rig' testing facility[6] is a multi-channel rig with loading by either a mechanical system or by electro-hydraulic jacks, heating by infra-red elements and cooling by air blown over the specimen surfaces. Fig.3 illustrates the arrangement of hydraulic jack, load cell, oven and specimen.

The overall programme of testing in the rigs involves more than 500 specimens with a total running time for the 74 testing channels of 13 years. The lengthy duration of this programme is inevitable as some tests must approach real-time conditions - in the practice the longest test was of 28500 hours duration. Such a test represents heavy investment both in money and in time, and probably cannot be repeated if spoilt by malfunction of the equipment. Therefore the rigs must be highly reliable over a long period of continuous running, but at the same time a balance must be struck between reliability and the utilisation rate which would suffer from too many safeguards. A fuller description of these rigs, and the way in which the difficulties associated with heat-fatigue interaction testing were handled, is given in the Appendix.

4 FATIGUE TESTS

The basic loading sequence used is shown in Fig. 4a and represents possible conditions on fuselage structure, composed of pressurisation cycles and superimposed gust load cycles of constant amplitude with the additional application of two high gust loads once every ten flight cycles on average; the sequence shown was applied at a constant temperature of 40°C and repeated until specimen failure. The same sequence was also used with periods of dwell at tensile or zero load inserted as shown in Figs. 4b and c respectively. These tests were conducted at a constant 40°C and also with the temperature elevated to 100°C or 125°C during the dwell periods. Tests with heating cycles are termed Intermittent Creep or Intermittent Heating tests depending on whether the dwell is at tensile or zero load. In Fig. 4 stress levels are defined in terms of P, the peak stress of the pressurisation cycle, which was 90 MN/m^2 for riveted joint tests and 103 MN/m^2 for notched specimen tests.

As described earlier, the term Cycle Ratio defines the frequency of heat interspersions in the fatigue loading. Examples of Intermittent Creep load and temperature sequences for Cycle Ratios of 3 and 10 are illustrated in Figs. 5a and b. The waveform and frequency of the gust cycles differed with the type of rig used for testing (see Appendix), but was kept constant for particular combinations of specimen and material. The type of waveform and frequency used in each test is noted in the tables.

5 REVIEW OF HEAT-FATIGUE INTERACTIONS

The present understanding of the effects of kinetic heating on fatigue in aluminium alloy aircraft structure has been reviewed[5] recently and it is relevant to the following discussion to outline the conclusions.

Considering first the effect of the application of heat to an unloaded specimen on subsequent fatigue performance at ambient temperature, it has been shown that strain-hardened material at machined surfaces is appreciably softened by heating exposures of a few hours duration. This softening makes the material more vulnerable to subsequent fatigue at ambient temperature. The effect of surface softening was studied over a range of heating times and temperatures and Fig.6 shows some results of pre-heating on the endurance of notched specimens. It should be noted that mean endurance was reduced to a constant value over the range 110°C to 150°C, but below 110°C the effect was less pronounced. A similar phenomenon is thought to affect material at the tip of a crack and, under some conditions, to result in higher crack propagation rates.

The second consideration is that of the more general situation where the material is under steady stress during heating. During periods of heating of a few hours duration, local stress at geometrical stress concentrations and at crack tips is redistributed by creep and the subsequent fatigue performance at ambient temperature was shown to be improved or reduced depending on the local stress being less or more tensile than before. This influence of creep is dependent on the rate at which redistribution occurs; it was shown that at temperatures down to 100°C, initial redistribution was comparatively rapid.

A typical clamped joint in aircraft structure contains a complexity of features which are likely to be sensitive to heat. The two heat-fatigue interactions described above occur but in addition heating can affect the clamping stress in the joint, the state of the interfay material which is used to separate metal surfaces and prevent fretting, and the interference fit stresses induced by fasteners to reduce alternating stress and fretting amplitude at the holes. Heating was shown to reduce clamping with an adverse effect on performance but on similar specimens containing an interfay of fluorocarbon polymer material heating improved the performance considerably by increasing both the rigidity of the interfay and its adherence to the joint faces (see Fig.7). In joints with interference fit fasteners, heating was shown to have both beneficial and detrimental effects: there was a tendency for joints to have improved strength, possibly from such factors as interfay curing and reduction of loading irregularity between fasteners by creep relaxation, but there was additionally a loss of performance due to the relaxation of interference which was most pronounced for fasteners with high interference. It is probable that all these effects of heat in clamped joints are dependent on the temperature and duration of the heating.

6 INFLUENCE OF FREQUENCY OF HEAT APPLICATION

The effect of frequency of heat application was investigated by tests with Cycle Ratios of 1, 3 and 10. These values of Cycle Ratio indicate that heating was applied during every flight cycle, every third flight cycle and every tenth flight cycle respectively. Results of these tests are given in Tables 2 and 3 for notched and Monel riveted joint specimens in CM003 material respectively. These results have also been presented as Life Ratios, ie mean life divided by the mean life from tests without dwell and heating cycles.

It is seen that for every elevated temperature condition the minimum Life Ratio is associated with tests in which heat was applied during every flight cycle and that there is a general trend of increase in Life Ratio with decrease in the frequency of heat application. This result indicates that each heating cycle contributes to the overall effect on life. Fig.8 demonstrates graphically the trend of increasing life with decreasing frequency of heat applications, common to both notched and riveted joint specimens of CM003 material.

An effect of frequency of heat application is also observed in the Intermittent Creep results given in Table 4 for 6% stretched CM001 material but it is seen that although a change in Cycle Ratio from 1 to 3 increased the Life Ratio for 125°C it had little effect for 100°C. The reason for this possibly lies in the influence of prestrain on the creep properties of the material. Wilson[7] from work on two Al-Cu-Mg alloys suggested that prestrain affects the degree of mechanical recovery of alloys during creep and hence significantly reduces creep strength. Dyson and Rodgers[8] investigated the effect of different degress of prestrain on the creep strength of Nimonic 80A and demonstrated that prestrains ranging from 1% to 15% were progressively more damaging to creep strength. From the results in Table 4 it is deduced that for 6% stretched CM001 material, the total duration of the 100°C heating cycles was insufficient to cause significant creep to occur, whereas at 125°C, creep damage did take place and the life was particularly sensitive therefore to the frequency of heat application.

7 INFLUENCE OF TEMPERATURE OF HEATING CYCLE

The effects of the two maximum temperatures studied, 100°C and 125°C, can be compared in Tables 2, 3 and 5 which give results for CM003 material in the form of notched specimens and riveted joints with two different solid rivets. It is seen that the Life Ratio for 100°C tests is nearly always larger in magnitude than the Life Ratio for 125°C at each test condition. This effect of temperature is illustrated graphically in Fig.9 for the notched and riveted joint specimens in CM003 material under all Cycle Ratios. The average reduction in life from increasing temperature from 100°C to 125°C was 17% in Intermittent Heating tests and 34% in Intermittent Creep tests. Effects of similar magnitude have been noted in crack propagation tests[5] on thin sheet specimens and are attributed to the temperature dependence of the softening mechanism affecting the strain hardened material at the tip of a crack.

The Intermittent Creep behaviour of notched specimens of 6% stretched CM001 material given in Table 4 differs somewhat from the above results. Whereas at a Cycle Ratio of 3 the effect of increasing temperature from 100°C to 125°C is to reduce life by 28%, a figure similar to that for CM003 material, the corresponding reduction at a Cycle Ratio of 1 is 50%. As discussed in section 6, this difference in behaviour is attributed to the influence of pre-strain on the creep properties of the material; the magnitude of the creep damaging effect at 125°C is very dependent on the frequency of heat applications.

8 INFLUENCE OF LOAD DWELLS IN TESTS AT A CONSTANT 40°C

In a number of tests, dwells in the fatigue loading were included without an associated heating cycle in order to establish their effect on fatigue life. Tests were confined to a Cycle Ratio of 3 and dwells were included either at steady load or at zero load. The results of these tests are presented in Table 6 as Life Ratios, ie mean life divided by the mean life from tests without dwell and heating cycles. It is seen that these ratios are greater than unity for riveted joints tests and less than unity for notched specimen tests. This limited information suggests that in specimens where the life is predominantly spent in initiating a crack (ie notched specimens), endurance is reduced by the inclusion of dwells in the loading sequence whereas in specimens where cracks appear early in the life (ie riveted joint specimens) endurance is increased. In an attempt to substantiate the latter effect, a research programme was undertaken to investigate the effect of dwells in fatigue loading on crack propagation and it was shown[9] that dwells both with and without steady load appreciably reduced crack propagation rate.

Turning to the significance of the load applied during the dwell, it is seen from Table 6 that the effect of dwells at load was more beneficial or less detrimental than dwells at zero load. This result is also in line with the crack propagation work[9] although in the latter less difference was noted.

No evidence has been obtained on the mechanisms of dwell effects but it is worthwhile speculating on phenomena which could induce these effects. The metallurgical state of the material at an initiation site or at the tip of a crack undergoes change during fatigue cycling. Some of these metallurgical changes are time dependent, eg diffusion, generation of dislocations, dislocation movement, etc and thus it is probable that changes in the state of the material will differ in fatigue loading with and without dwell periods. Another time dependent phenomenon which occurs is corrosion. It is possible that when dwells are included in the load sequence, sufficient corrosion takes place to affect subsequent crack growth.

To evaluate the effect of heating it is strictly necessary to compare endurances with those from tests without heating cycles but including dwells. The table below shows the difference obtained in Life Ratio according to whether or not dwells are included in the tests without heating cycles.

Type of specimen	Type of test without heating cycles	Intermittent Heating (dwell at zero load)		Intermittent Creep (dwell at steady load)	
		Max. temp. 100°C	Max. temp. 125°C	Max. temp. 100°C	Max. temp. 125°C
Monel riveted joint	No dwell	0.61	0.51	1.12	0.94
	Dwell	0.53	0.44	0.73	0.61
CM003 notched	No dwell	0.66	0.45	1.91	1.11
	Dwell	0.87	0.59	1.99	1.16

It is seen that the inclusion of dwells in the tests without heating cycles has an appreciable effect on the relative sensitivity of riveted joint and notched specimens to heat. If dwells are omitted, notched specimens on average have a Life Ratio 20% greater than for riveted joints, whereas with dwells included the Life Ratios now differ on average by 100%.

9 CONCLUSIONS

It has been demonstrated that in fatigue tests involving periodic heating, increases in the number of applications of heat and in the maximum temperature each caused decreases in performance. An observation of general significance was that in the tests at a constant $40^{\circ}C$, the inclusion of dwells in the load sequence had an appreciable effect on fatigue life; the effect was detrimental or beneficial depending on whether the majority of the life was spent in initiating or propagating a crack.

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Appendix
THE 'AVRO RIG' TESTING FACILITY

A.1 Introduction

This appendix describes machines developed to meet the requirements of the heat-fatigue interaction testing. Some of the continuing problems associated with operating such machines over the past 15 years are also discussed.

Basically the requirement is that the machines should be capable of the automatic testing of a quantity of specimens separately and should impose fatigue loadings and temperatures to the basic flight cycle shown in Fig.10; this programmed sequence is to be repeated continuously until specimen failure. The functions required in each flight cycle are typically as follows:

(i) Ground-to-air load change followed by one or two gust loads at datum temperature.

(ii) Heating to and holding at elevated temperature with constant load for one hour.

(iii) Cooling to datum temperature.

(iv) Nine or ten gust loads followed by an air-to-ground load change.

A.2 Testing machines

A.2.1 The prototype

The prototype machine shown in Fig.11 was built in 1961/62 and houses twenty specimens in tandem pairs in ten loading frames. Each pair of specimens are in series, vertically, in the loading frame as shown in Fig.12 and loads are applied by means of a weighted trolley on a lever arm. Fatigue cycling (ie gusting) is achieved by movement of the trolley along the lever arm. The result is a rather slow gusting rate of five gusts per minute and the maximum load available is 4.5kN, sufficient only for testing notched coupon specimens. To avoid the possibility of the failure of a specimen affecting the other tandem specimen, the pair is split at approximately 80% of the anticipated endurance and tested singly to failure.

A.2.2 The extension

The extension machine shown in Fig.13 was built as a development of the prototype in 1964/65. The specimens are housed singly in the loading frames, of which 48 were built initially and a further 6 in 1972. The main departure from the prototype is the use of servo-controlled hydraulic jacks to apply loads to the specimens. By this means loads up to 45kN are available, suitable for testing riveted joint specimens, and the frequency of the gust loading is increased by a factor of about 10. The loading frames are linked in pairs controlled by a common programming console, as shown in Fig.14.

On both the prototype and extension each specimen is housed in its own furnace capable of achieving test temperatures up to 220°C by means of two strip infra-red radiant heating elements. An air blower is provided for each furnace to facilitate cooling.

A.3 The test cycle

The basic flight cycle is represented on the machines by a test cycle divided into twenty five programme positions as shown in Fig.15. Functions are allocated to these programme positions as follows:

1 to 5	gusting at datum temperature (40°C for all tests)
6	heating to elevated temperature at static load (on or off load as required)
7	temperature stabilisation
8	scan (record if required) and alarm if error
9, 10	static dwell
11	gusting at elevated temperature if required
12, 13	static dwell
14	scan, record and alarm if error.
15	cooling to datum temperature.
16	temperature stabilisation, programme hold position if test requires to be halted
17	scan (record if required) and alarm if error
18 to 22	gusting at datum temperature
23, 24	static dwell at datum temperature if required.
25	test cycle and pre-select skip count.

Any of the positions may be used, or skipped, as required.

One basic problem was that of acceleration of the tests. Acceleration of thermal cycle was achieved simply by testing at higher maximum test temperatures but mechanical acceleration, involving increasing the numbers of gusts associated with each temperature cycle was a greater problem. Initially mechanical acceleration was achieved by increasing the numbers of gusts in each programme position and, on the extension, capacity was provided for up to 990 gusts in each programme gusting position. This was acceleration by what might be termed 'gust multiplication' and is shown in Fig.16. Nowadays however the flight-by-flight testing sequence is adhered to. For this style of testing the sequence of gusts representing one flight cycle is regarded as a discrete event, and acceleration involves increasing the recurrence of this event in relation to the recurrence of the thermal cycle, but with the correct sequence of gusts within each event as shown in Fig.17. The requirement led to the addition of the pre-select static skip facility whereby all the static positions, 6 to 17 inclusive, can be skipped for a given number of test cycles and then inserted for one cycle. A similar facility is available for the gusting positions.

A.4 Test conditions - measurement and recording

A.4.1 Test temperatures

Specimen temperatures are measured, controlled and recorded from stick-on 'patch' thermocouples of the nickel-chromium/nickel-aluminium type (Type K) bonded to the specimen surface. Temperatures are referred to $0^{\circ}C$ by means of cold junctions in 'FRIGISTOR' units and are initially set and regularly checked by a certified digital voltmeter. During the course of testing, temperatures are measured and recorded by the digitiser (described later) and are normally maintained to within $\pm 1^{\circ}C$ of the required test temperature.

A.4.2 Loads

Loads on the specimens are sensed by load cells in the linkage in series with the specimens and are set initially and checked regularly using certified elastic proving rings. No measurements or recordings of loads are made during testing, but the facility exists for taking short-term visual records of the loading sequence, eg during gusting, using a U-V recorder to monitor the output of strain gauge load links. The accuracy of loading during the gusting sequence on each specimen is regularly checked using this facility.

A.4.3 Creep extensions

Creep extensions are measured over the gauge length of each specimen by means of LVDTs mounted on straight extensometer arms secured to the specimen, as shown in Fig.18. These extensions are measured and recorded by the digitiser.

A.4.4 The digitiser

The digitiser is the data-logging facility for both the prototype and extension machines and is shown in Fig.19. In addition the temperature and extension error alarms originate at the digitiser. Recordings of test data are made for each specimen during each programme cycle at position 14, though positions 8 and 17 are available also, if required. The recording comprises the following data:

Master clock hours (giving a time reference)
Test cycle count
Temperature error
Creep extension
Frame number.

A calibration signal for both temperature and extension measurement is recorded once per hour on demand from the Master Clock.

In addition to the above, if an error is detected, ie if the temperature is outside the limits of $\pm 3^{\circ}C$ or the extension reading exceeds 0.004 inches, the alarm scan activates the digitiser which records the error. (Note: the extension error limit is to protect the specimen in the event of sustained overload). In the event of an error being detected the affected channel is shut down as described later.

A.5 Specimen protection and alarm systems

The requirement to achieve the highest possible degree of specimen protection is obvious when the accumulated value of a specimen that has been on test for two or three years is considered. The monetary value invested in such a specimen together with the loss in programme time if the test had to be repeated make as high a degree of specimen protection as possible imperative. The following aspects of machine malfunction are used to illustrate some of the problems involved.

A.5.1 Temperature drift

When the machines were originally built the obvious possibility of temperature run-away was foreseen and therefore in all programme positions except the heating position the furnace is prevented from giving full output. In addition, to meet the problem of gradual temperature drift the temperature alarm scan was incorporated to halt the test and reduce the temperature and load to the datum settings if any digitiser scan showed a temperature deviation greater than $\pm 3^{o}C$. Although for each channel a temperature alarm is a relatively infrequent occurrence, with an average of 65 specimens on test at any given time temperature alarms occur, typically at the rate of 2 per 24 hour period.

Such temperature drift problems, whilst not likely to affect tests in a catastrophic manner, are undesirable since protracted testing outside specified limits will obviously invalidate the result obtained.

A.5.2 Load errors

Maintaining accurate loads requires regular attention to load settings and to the electro-mechanical-hydraulic servo system controlling the loads. Since loads are not measured continuously minor load drifts are not detected until the regular load check and hence a rather generous tolerance of ±5% is allowed on overall load accuracy.

One relatively infrequent occurrence is the catastrophic application of full load due, usually, to an electronic failure. On an elevated temperature test such an event can very quickly give completely unrepresentative amounts of creep or even premature specimen failure. This condition is detected by an alarm on the extension measurement function of the digitiser which shuts down the channel if the extension suddenly increases. The elastic extension of the specimen on being subjected to full load is ample to trigger this alarm.

A.5.3 Counter problems

A major part of the function of the programme unit is that of counting events, gusts, static dwell minutes, test cycles etc. All counting is done by electromechanical counters, the correct operation of which depends upon finely balanced setting of the various parts, particularly regarding proper resetting to zero. Due to the ease with which this fine balance deteriorates errors in counting and resetting are relatively frequent. Since the test depends upon the counters for its correct sequencing through the programme positions, a fault which holds the programme in, say, a gusting position can quickly invalidate the test.

The latest, though not complete, solution to problems with counters has been the introduction of a time limit on each programme position. A separate timer has been built into each channel which measures the length of time the channel stays in each programme position. On reaching a pre-set time (at present around 11 minutes) which indicates that some malfunction is holding the programme in one position the channel is shut down. This device covers, in addition to the counters, many other aspects of the programme sequencing system.

Table 1

NOMINAL CHEMICAL COMPOSITION AND TENSILE STRENGTHS OF MATERIALS

Nominal Chemical Composition

CM003 plate and
Core material of 6% stretched CM001

Element	% by weight	
	Min	Max
Cu	1.8	2.7
Mg	1.2	1.8
Si	0.15	0.25
Fe	0.9	1.4
Mn	-	0.2
Ni	0.8	1.4
Ti	-	0.2
Zn	-	0.1
Pb	-	0.05
Sn	-	0.05
Al	-	Remainder

Cladding

Element	% by weight	
	Min	Max
Zinc	0.8	1.2
Aluminium	-	Remainder

Tensile Properties

CM003

0.2% Proof stress = 438 MN/m^2
UTS = 457 MN/m^2
Elongation = 10%
(on 40mm gauge length)

6% Stretched CM001

0.2% Proof stress = 441 MN/m^2
UTS = 456 MN/m^2
Elongation = 7.7%
(on 50mm gauge length)

Table 2

FATIGUE PERFORMANCE OF NOTCHED SPECIMENS IN CM003 MATERIAL

Intermittent Heating

Max. temperature of heating cycle T	Cycle ratio	Endurance (N_T) flight cycles	Life ratio = $\frac{N_T}{N40^*}$
100°C	1	6226 6812	0.44
	3	10113 14583 7850 7859	0.66
	10	7510 10180	0.59
125°C	1	7738 5579 6588 6639	0.44
	3	7856 5678	0.45
	10	8010 8840	0.57

Intermittent Creep

100°C	1	13552 16189	1.00
	3	28041 28531	1.91
	10	16080 16200	1.09
125°C	1	12941 11666 7898	0.72
	3	14784 18367	1.11
	10	14290 23520	1.24

*Log mean fatigue life for tests without dwell (N_{40}) = 14825 flight cycles (16240, 12821, 12320, and 18830 flight cycles).

Loading frequency = 0.8Hz, waveform approximately square.

Table 3

FATIGUE PERFORMANCE OF MONEL RIVETED JOINTS IN CM003 MATERIAL

Intermittent Heating

Max. temperature of heating cycle T	Cycle ratio	Endurance (N_T) flight cycles	Life ratio = $\frac{N_T}{N40*}$
100°C	1	3902 3860 4310	0.43
	3	5488 5455 6216	0.61
	10	6170 6330 4510	0.60
125°C	1	4660 2589 3469	0.37
	3	4980 4439 4998	0.51
	10	4570 6350 5690	0.58

Intermittent Creep

100°C	1	7588 12605	1.04
	3	7770 9732 15387	1.12
	10	9990 11520 12350	1.19
125°C	1	7059 5820 8331	0.74
	3	6208 8371 13317	0.94
	10	7550 6380 9360	0.81

*Log mean fatigue life for tests without dwell (N40) = 9419 flight cycles (9450, 9190, 8150 and 11120 flight cycles)

Loading frequency = 0.8Hz, waveform approximately square.

Table 4

FATIGUE PERFORMANCE OF NOTCHED SPECIMENS IN 6% STRETCHED CM001 MATERIAL

Intermittent Creep

Max. temperature of heating cycle T	Cycle ratio	Endurance (N_T) flight cycles	Life ratio = $\frac{N_T}{N40*}$
100°C	1	12975 17754	1.15
	3	19257	1.20
125°C	1	7548 × 7809	0.58
	3	10740 12267	0.87

*Log mean fatigue life for tests without dwell (N40) = 13159 flight cycles (14772, 13887, 17970, 8400 and 12741 flight cycles)

Loading frequency = 0.08Hz, waveform sinusoidal

Table 5

FATIGUE PERFORMANCE OF TITANIUM RIVETED JOINTS IN CM003 MATERIAL

Intermittent Heating

Max. temperature of heating cycle T	Cycle ratio	Endurance (N_T) flight cycles	Life ratio = $\frac{N_T}{N40*}$
100°C	1	4860 3950 4773	0.47
125°C	1	3447 2994 3103	0.33

Intermittent Creep

100°C	1	11010 12261 9218	1.12
125°C	1	5719 7527 7285	0.71

*Log mean fatigue life without dwells (N40) = 9576 flight cycles (9531, 7231, 13510 and 9030 flight cycles)

Loading frequency = 0.8Hz, waveform approximately square.

Table 6

TESTS WITH DWELL IN THE LOADING

Specimen	Tests with dwell at zero load			Tests with dwell at steady load		
	Endurance flight cycles	Log mean endurance flight cycles	Life* ratio	Endurance flight cycles	Log mean endurance flight cycles	Life* ratio
Monel riveted joint	10380 11984 8976 12630	10897	1.16	11217 16380 12777 19056	14543	1.54
CM003 notched	9075 11925 13308	11293	0.76	10875 15623 15354 15594	14202	0.96

*Life ratio = Endurance for tests with dwell/Endurance for tests without dwell.
Monel riveted joints - log mean fatigue for tests without dwell = 9419 flight cycles. (9450, 9190, 8150 and 11120 flight cycles.)

CM003 notched specimens - log mean fatigue life for tests without dwell - 14825 flight cycles (16240, 12821, 12320 and 18830 flight cycles).

Loading frequency = 0.8Hz, waveform approximately square.

All tests at cycle ratio = 3.

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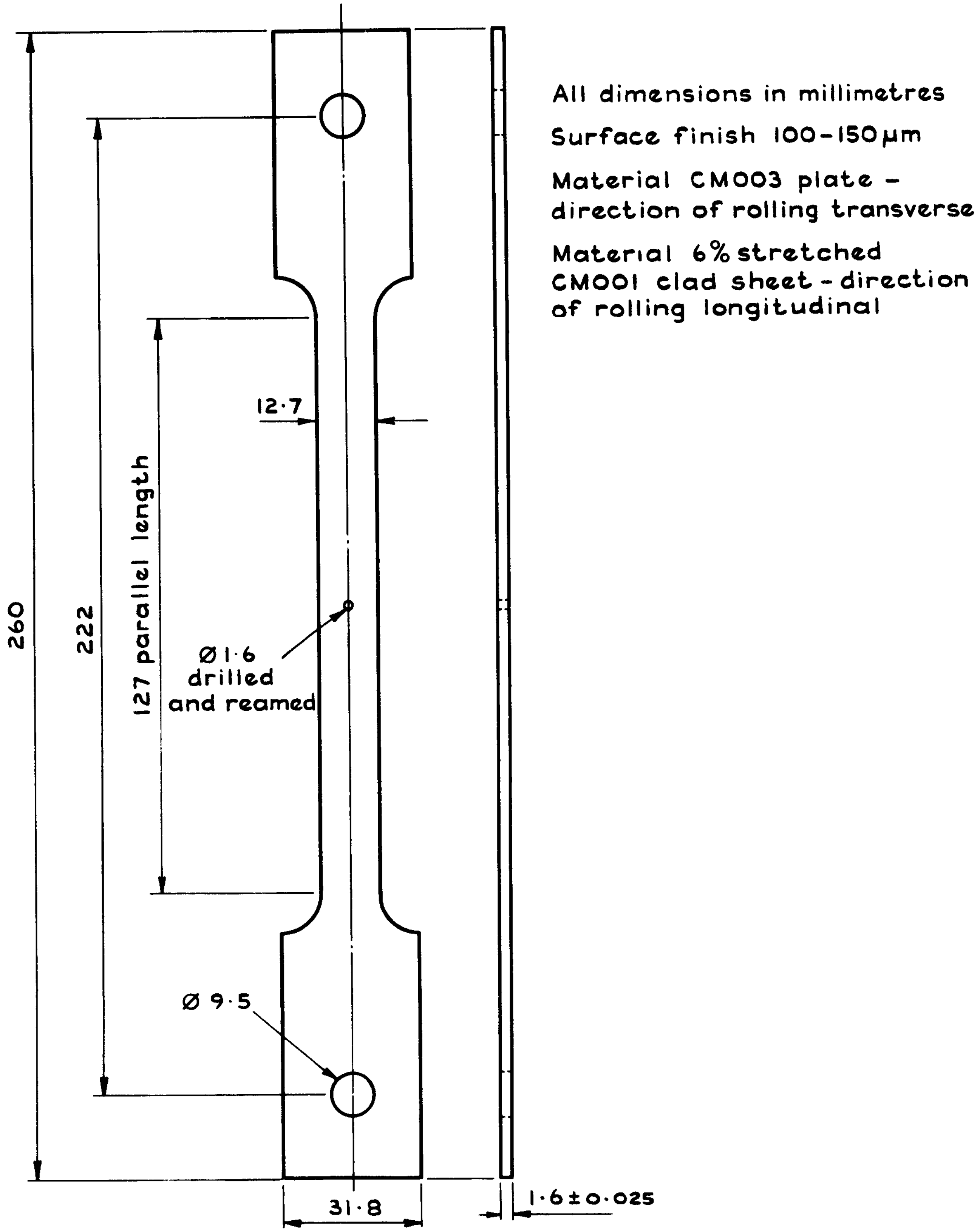
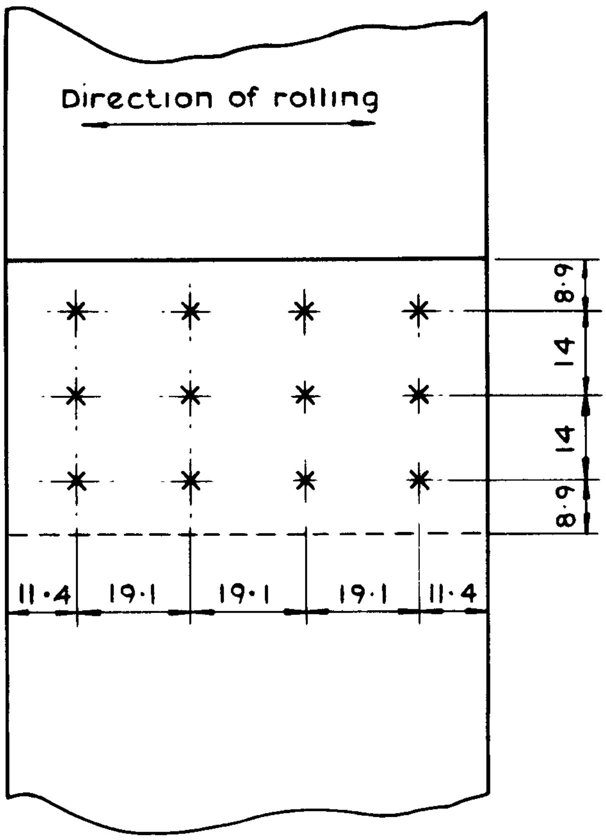
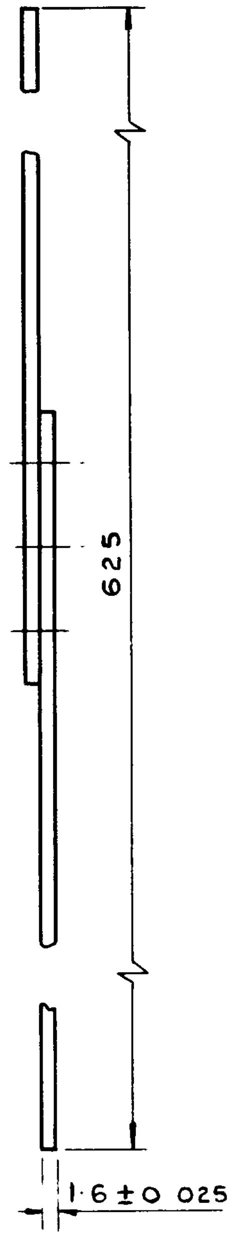


Fig. 1 Notched specimen – $K_t = 2 \cdot 7$





All dimensions in millimetres
Surface finish 100 - 150 μm

Sheet CM003 machined plate to 1·6mm thickness
Rivets (*)
(a) 3 175 dia 100° c'sk Monel
(b) 3 175 dia 100° c'sk Titanium (T40, taper shank, anodically treated)

Sealant in joint : a fluoro-carbon polymer

Fig.2 Riveted joint specimens

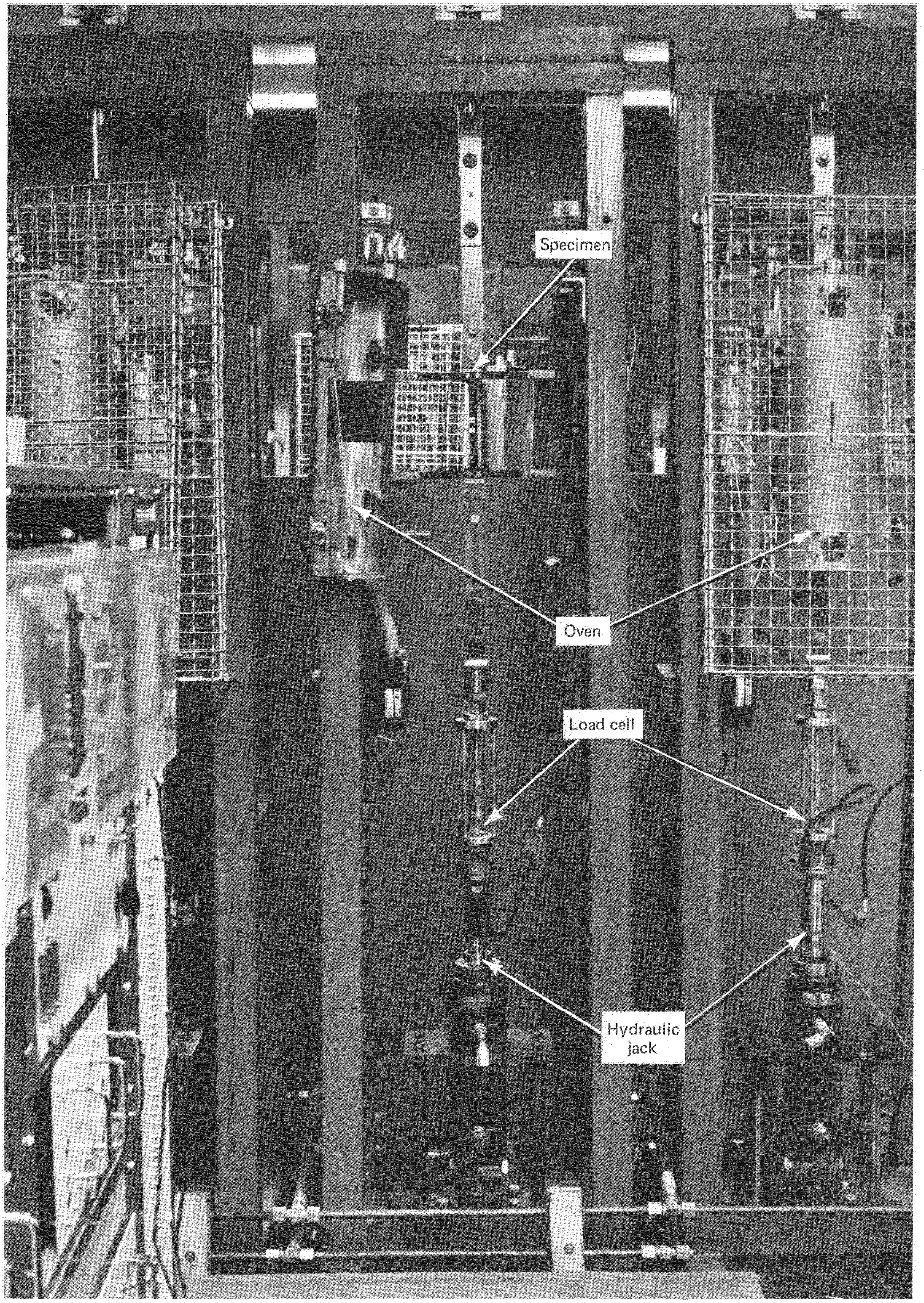


Fig.3 General arrangement of rig and specimen

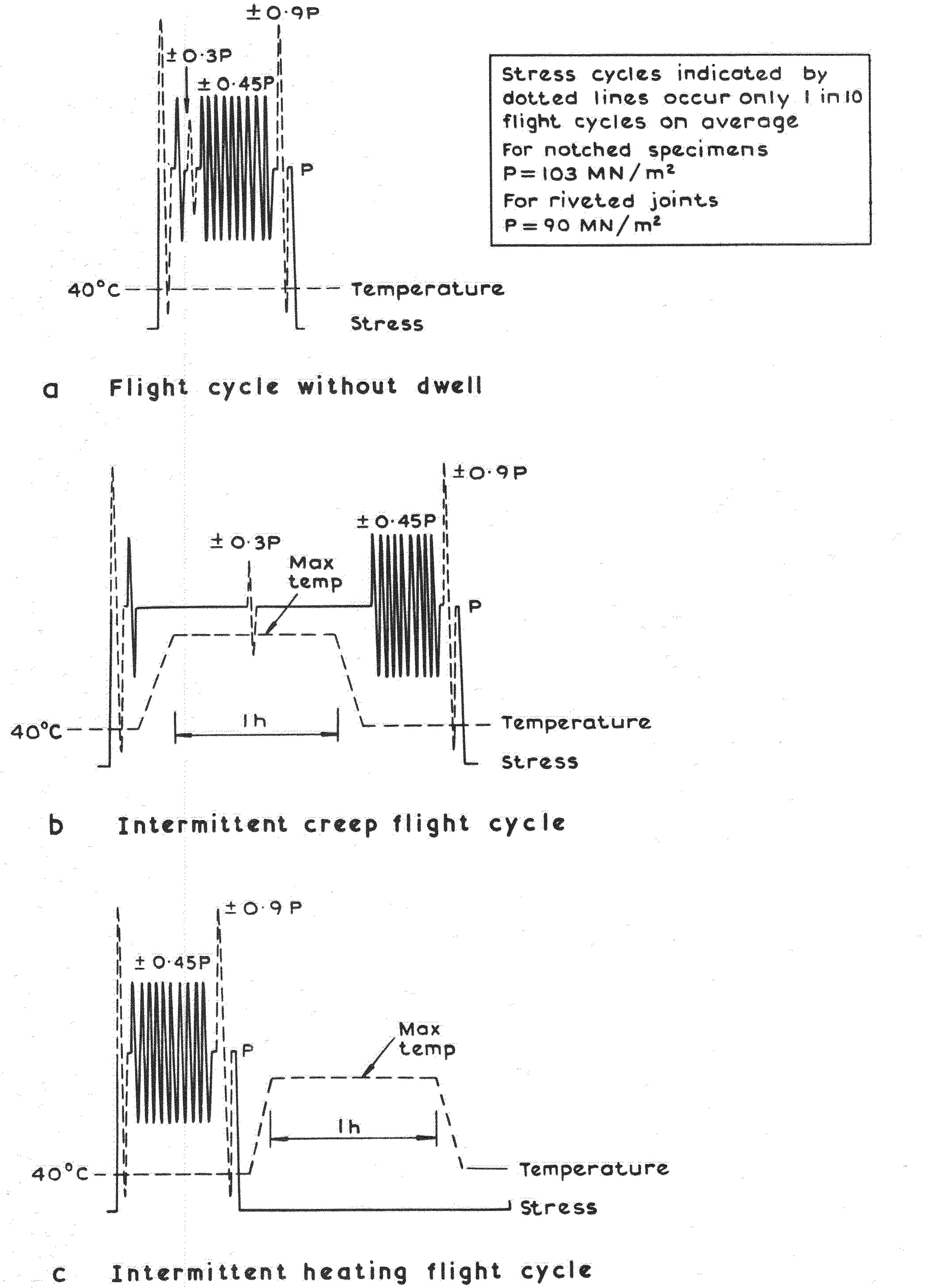
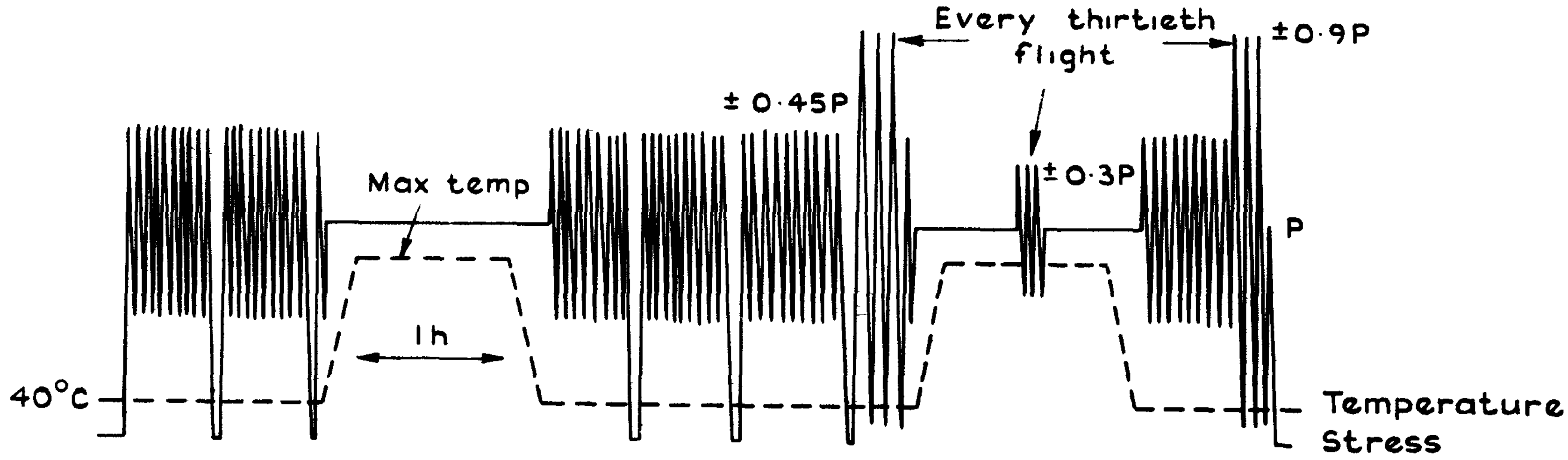
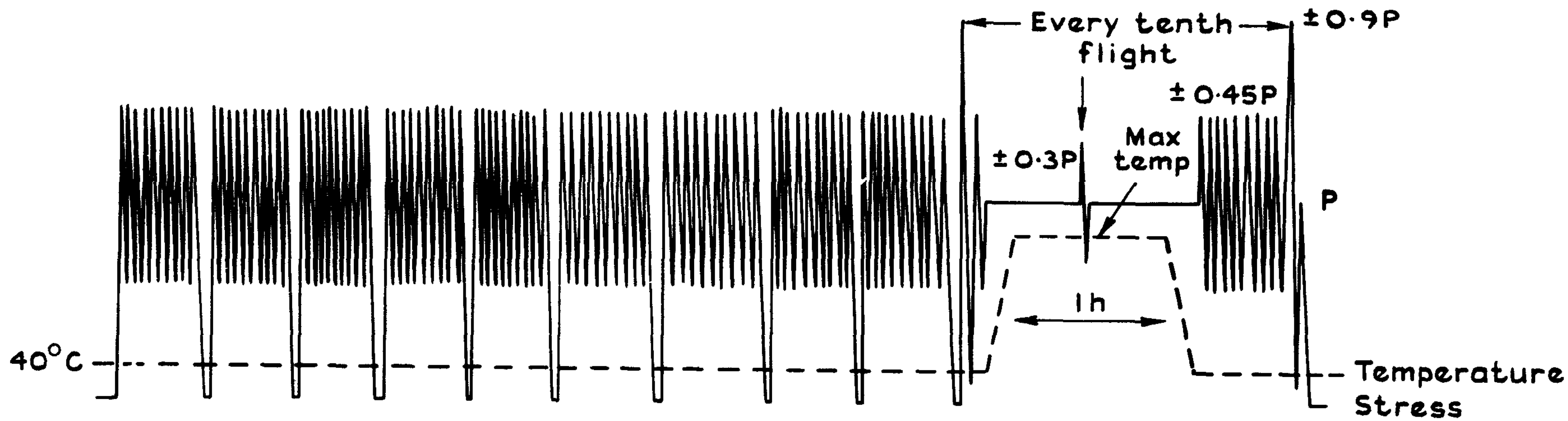


Fig. 4 a–c Flight-by-flight load and temperature sequences



a Load and temperature sequence for cycle ratio = 3



b Load and temperature sequence for cycle ratio = 10

Fig. 5a & b Intermittent creep load and temperature sequences for cycle ratio 3 and 10 tests

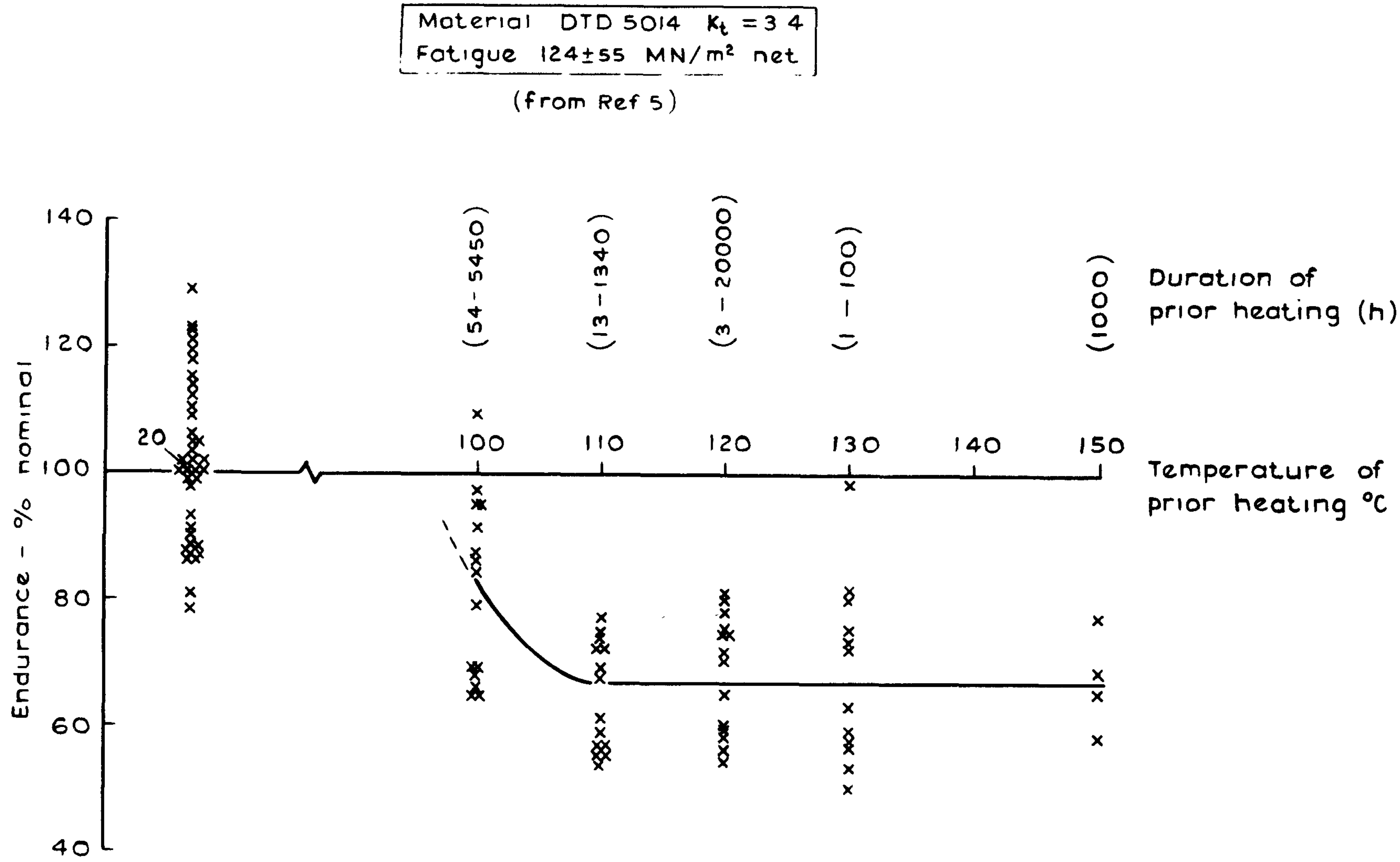


Fig. 6 Effect of prior heating for various times and temperatures on endurance of a notched specimen

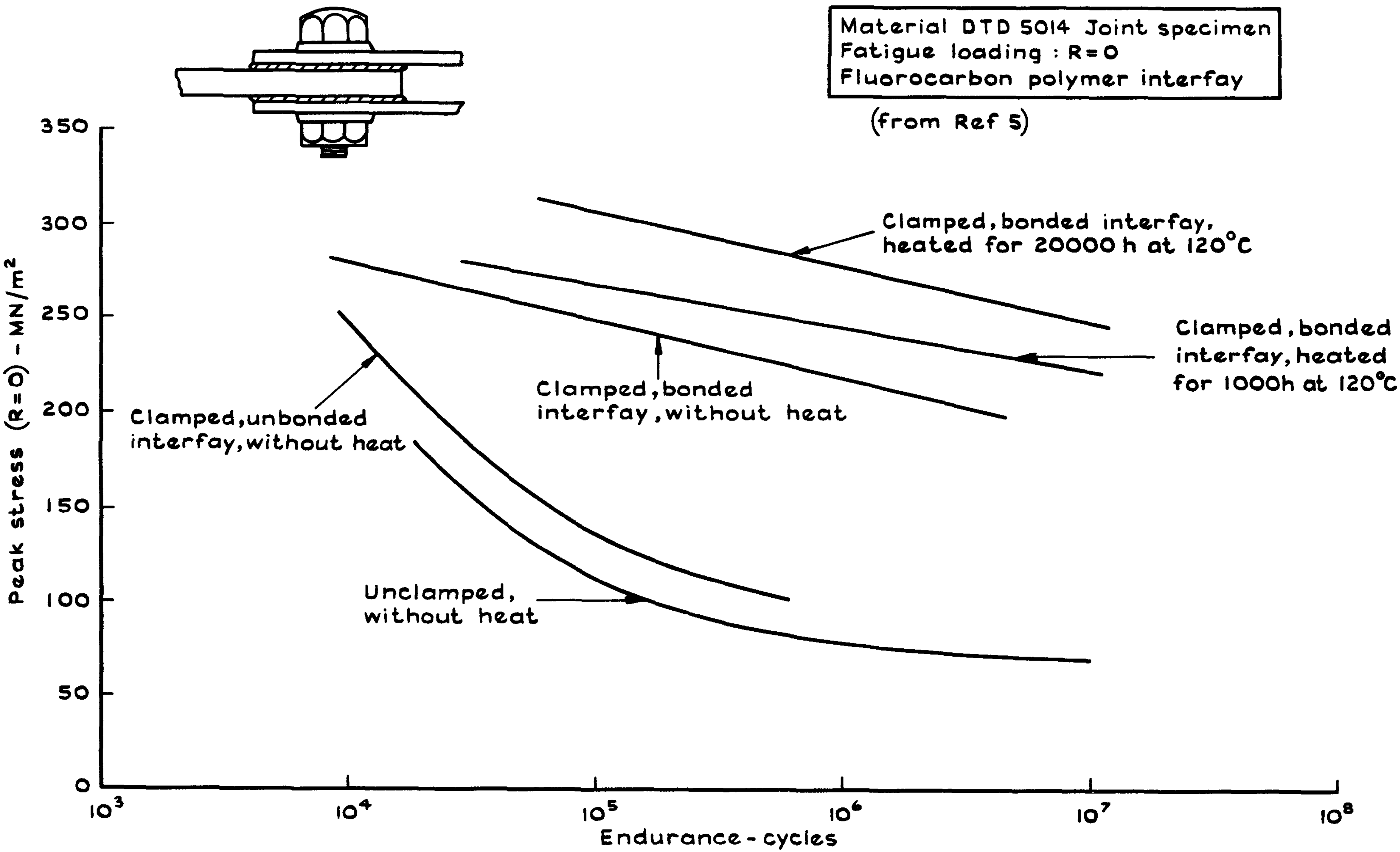


Fig. 7 Effect of heating on clamped joint with bonded interfay

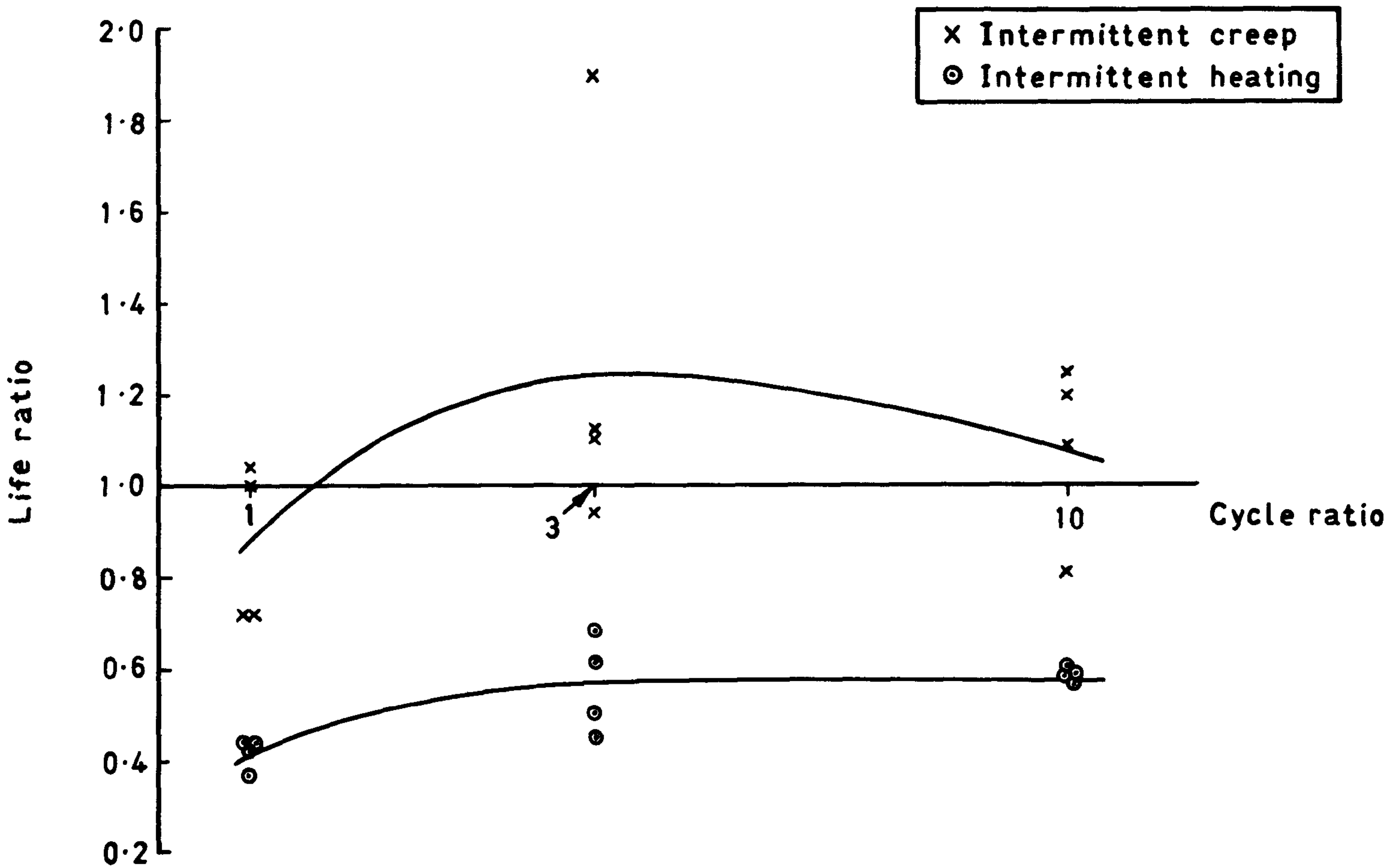


Fig.8 Influence of frequency of heat application

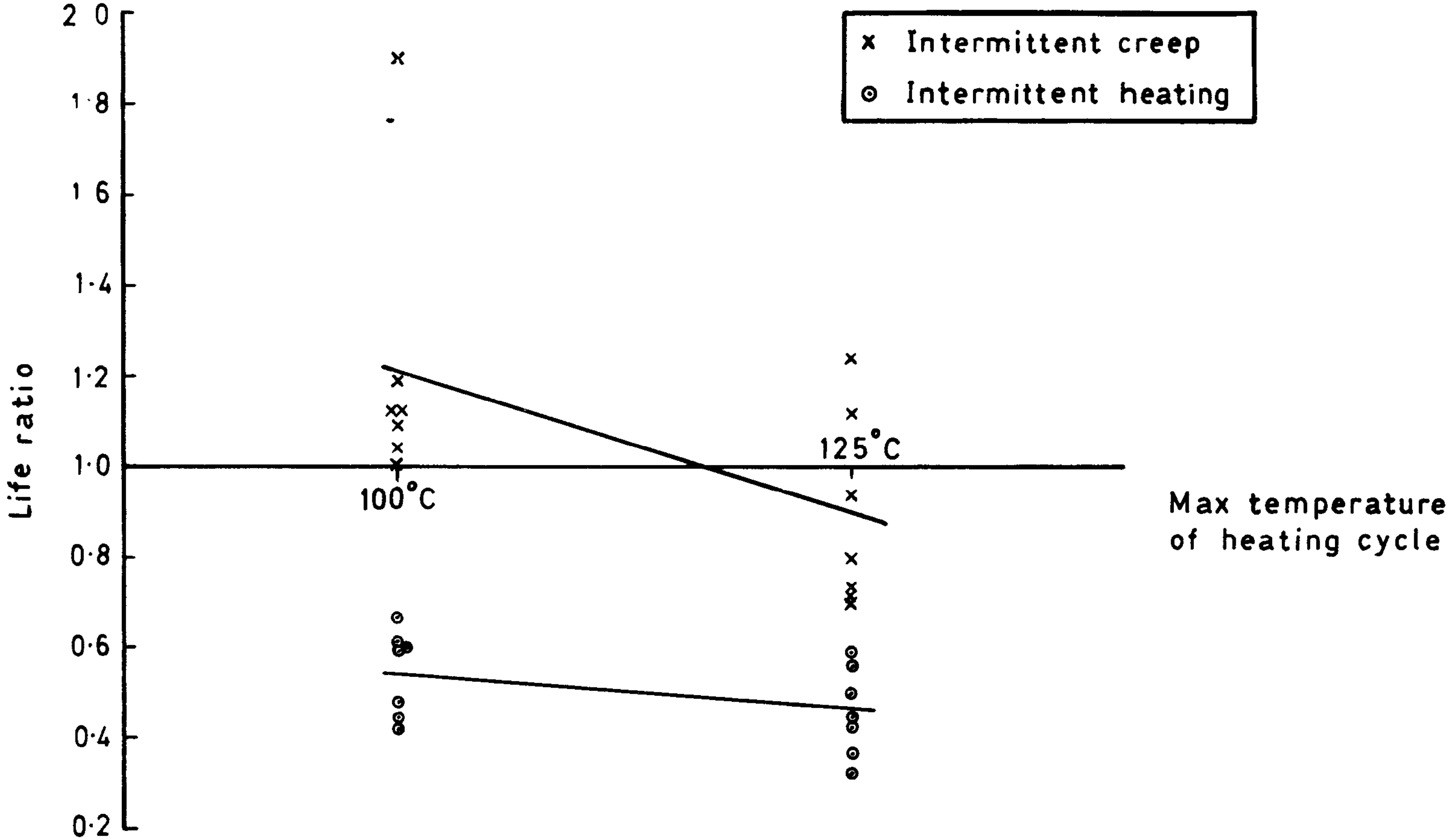


Fig. 9 Influence of temperature of heating cycle

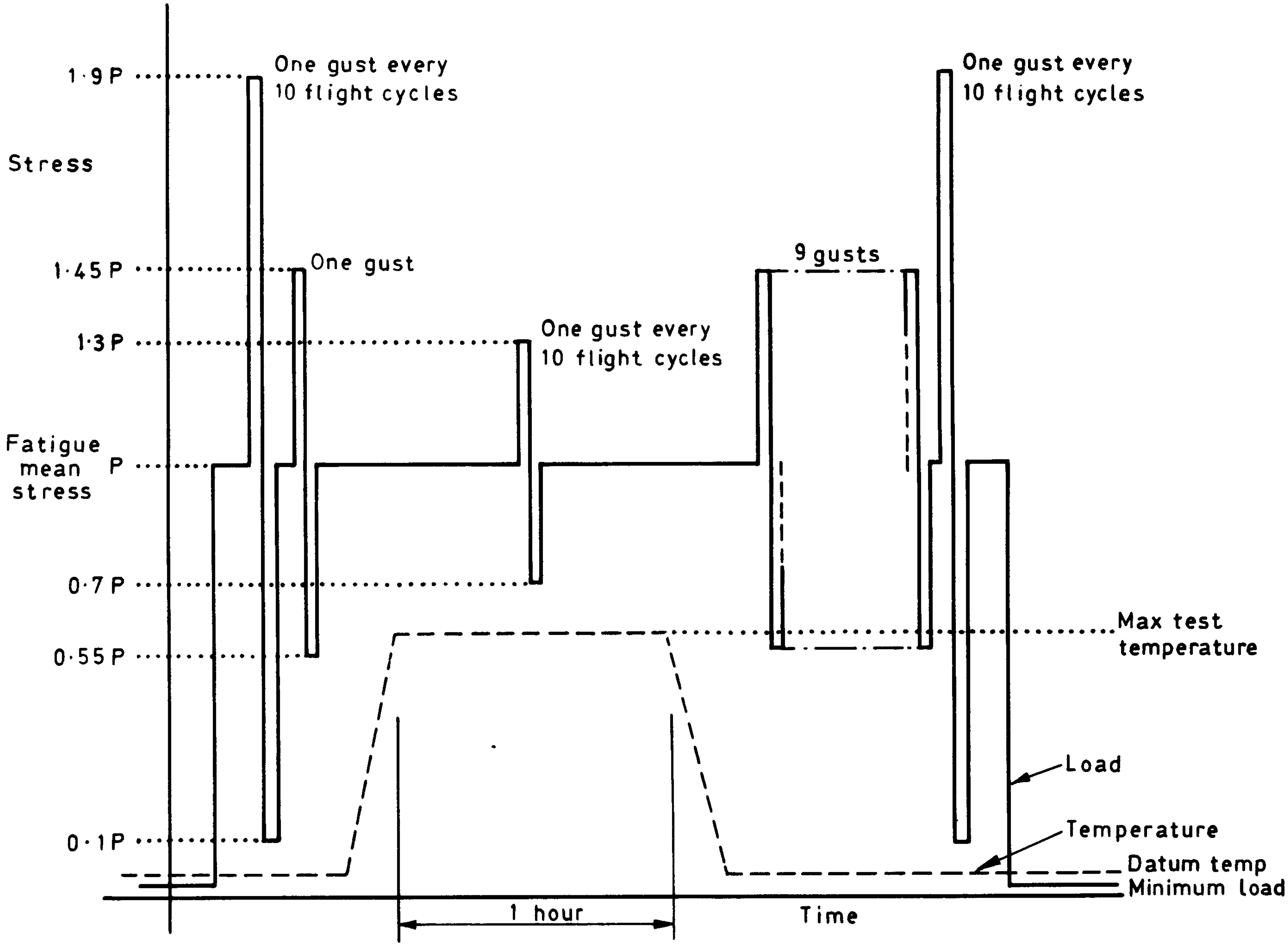


Fig.10 Intermittent creep flight cycle. Cycle ratio 1

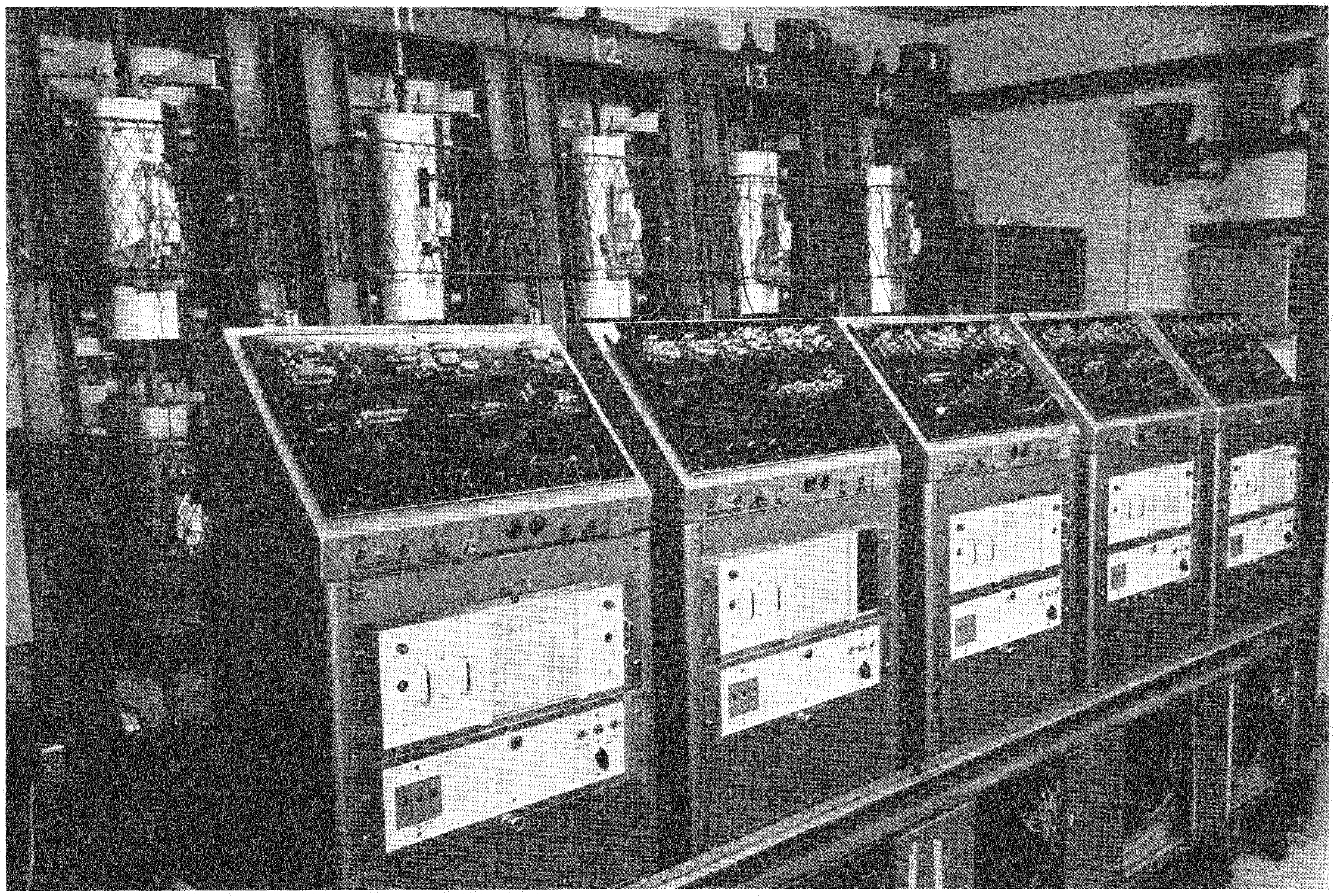


Fig.11 The prototype machine

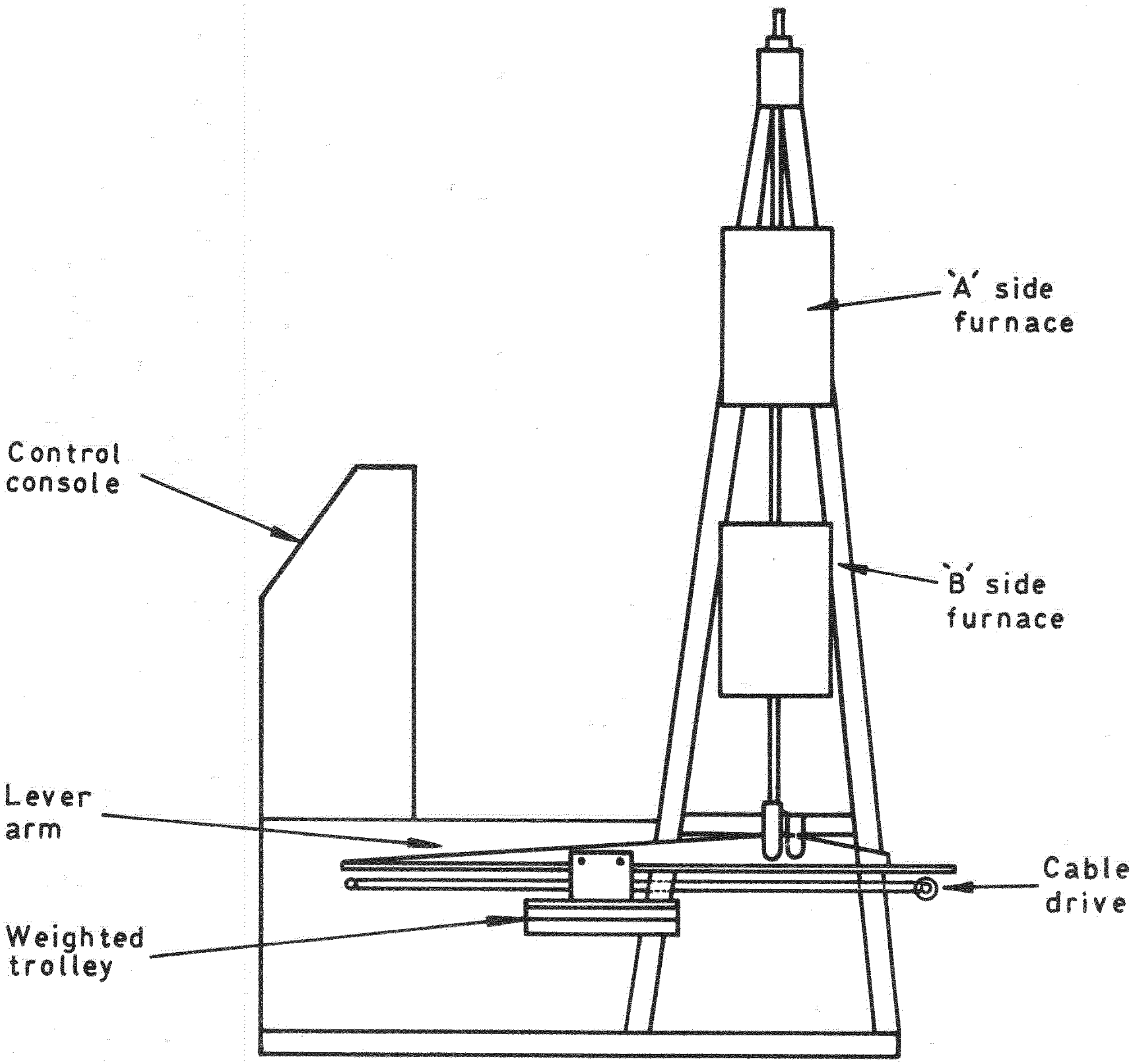


Fig.12 Diagram of prototype machine channel

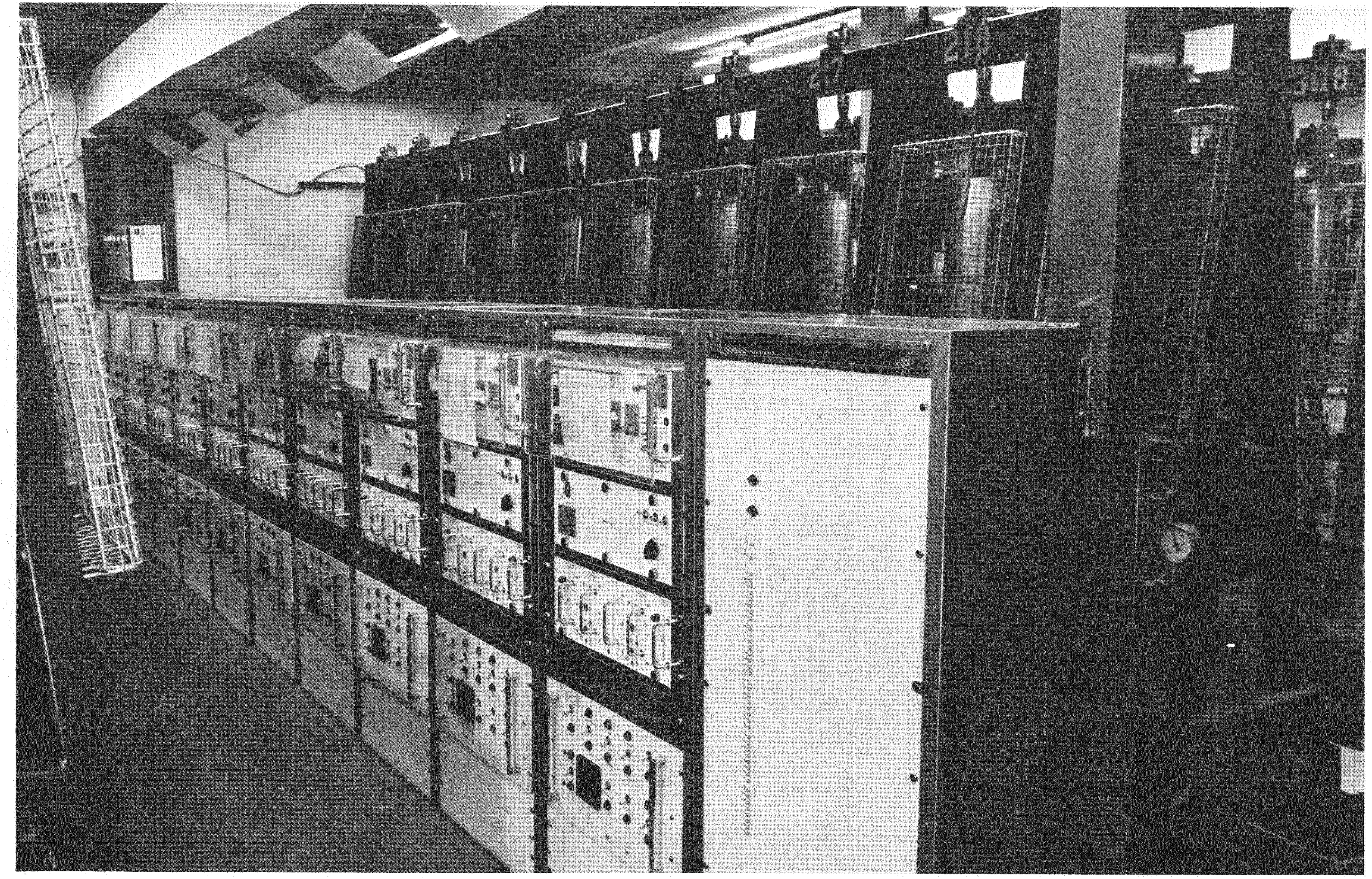


Fig.13 The extension machine

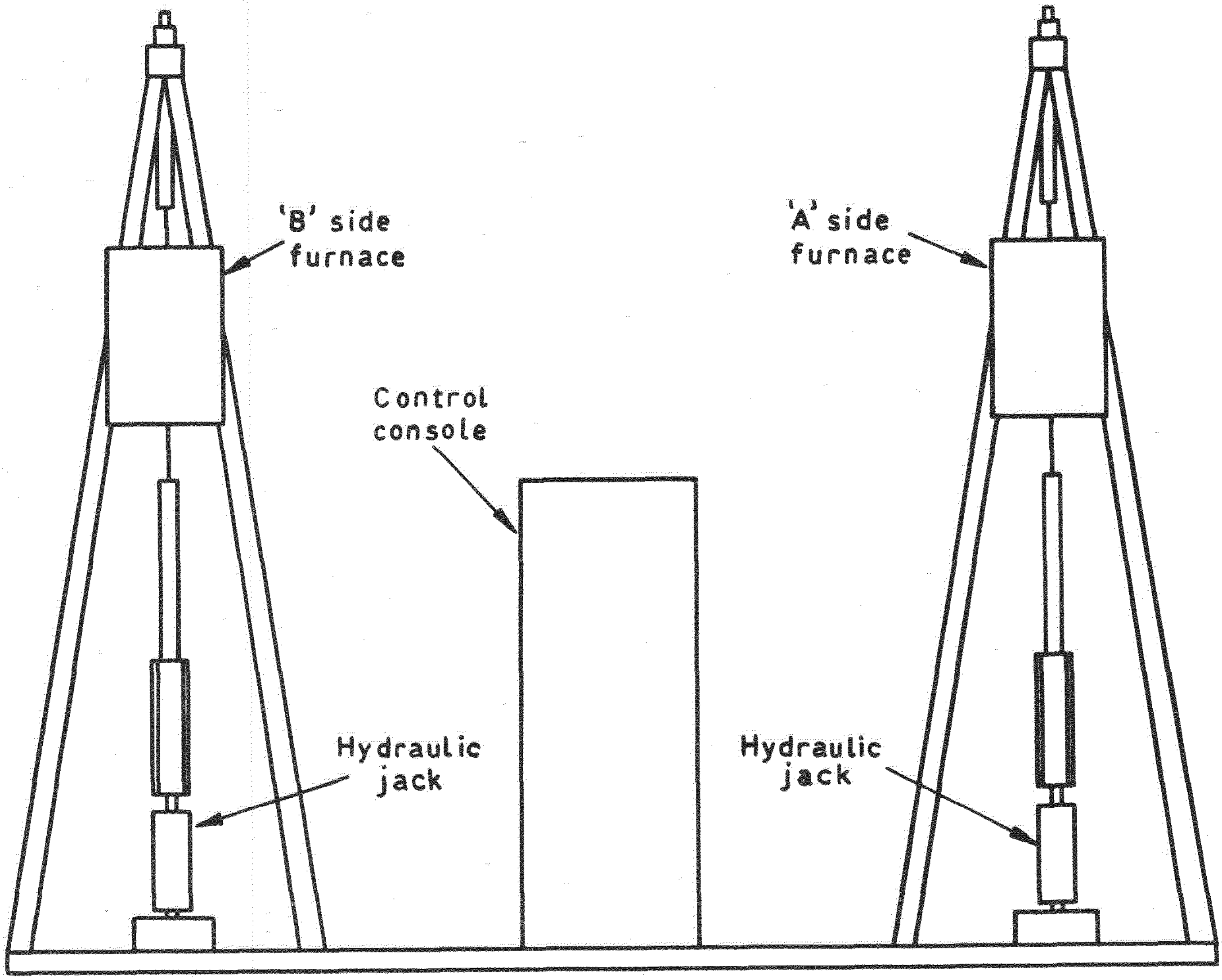


Fig.14 Diagram of extension machine channel

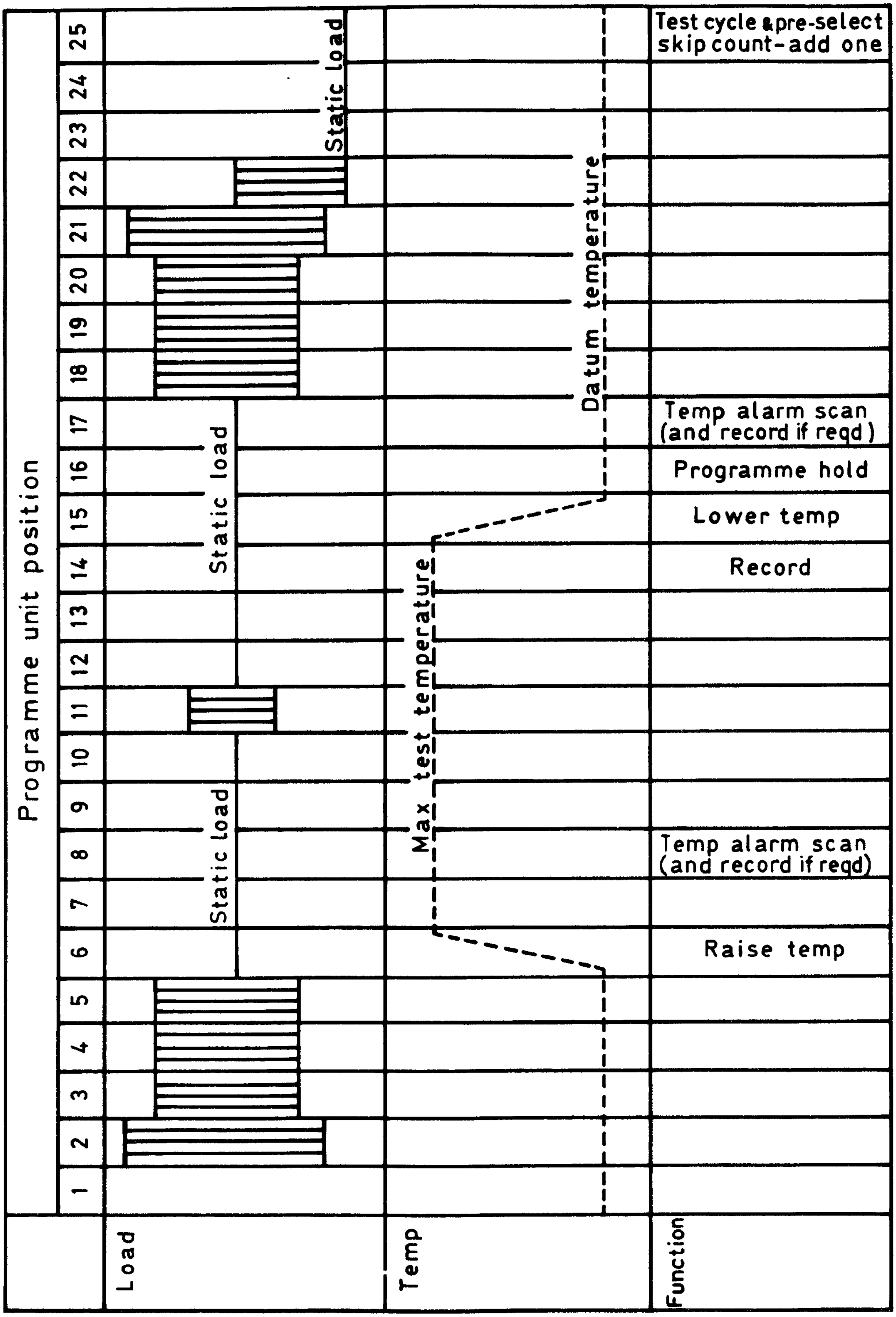


Fig.15 Diagram of programme unit position functions

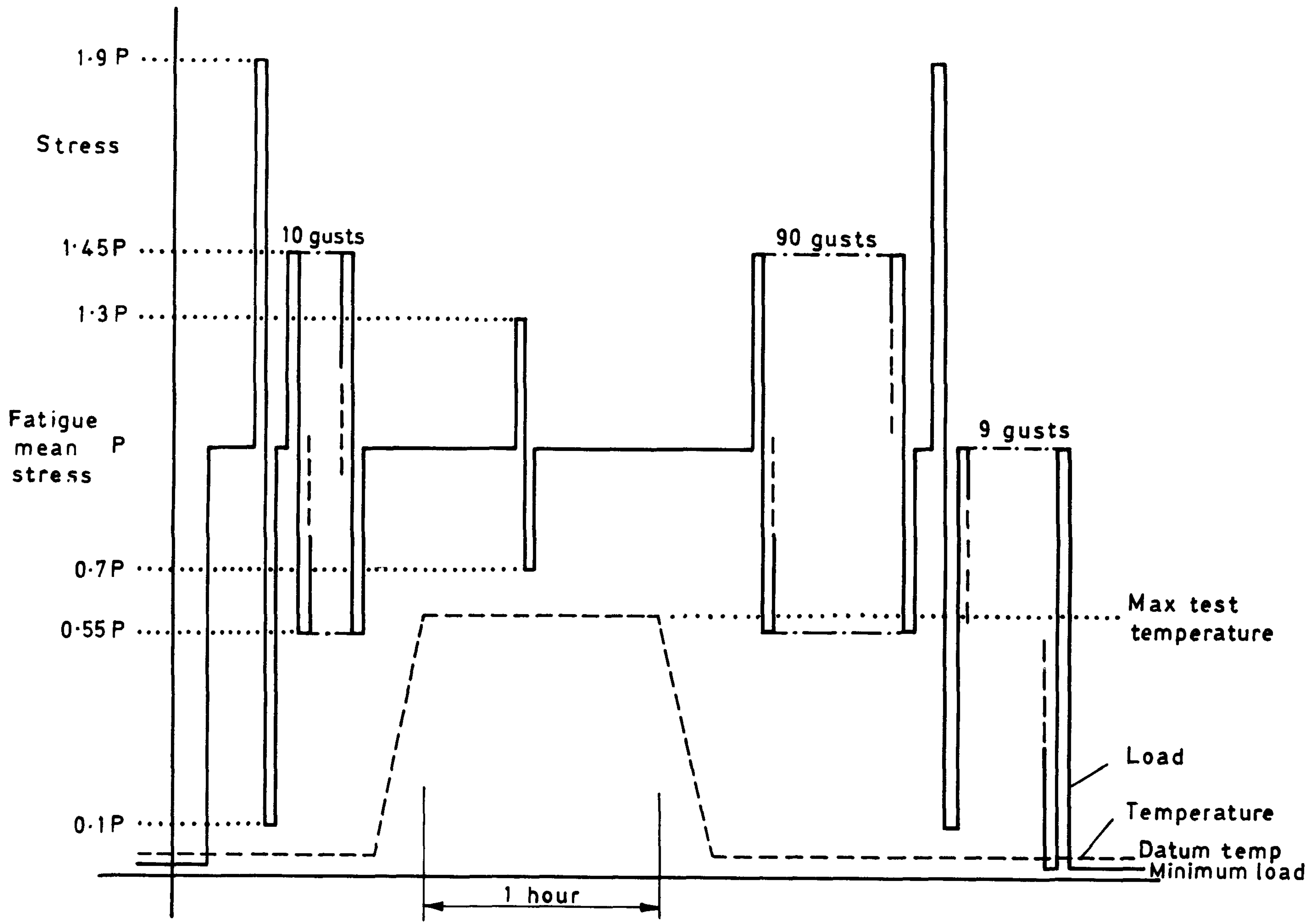


Fig.16 Intermittent creep test cycle ratio ·10 accelerated by gust multiplication

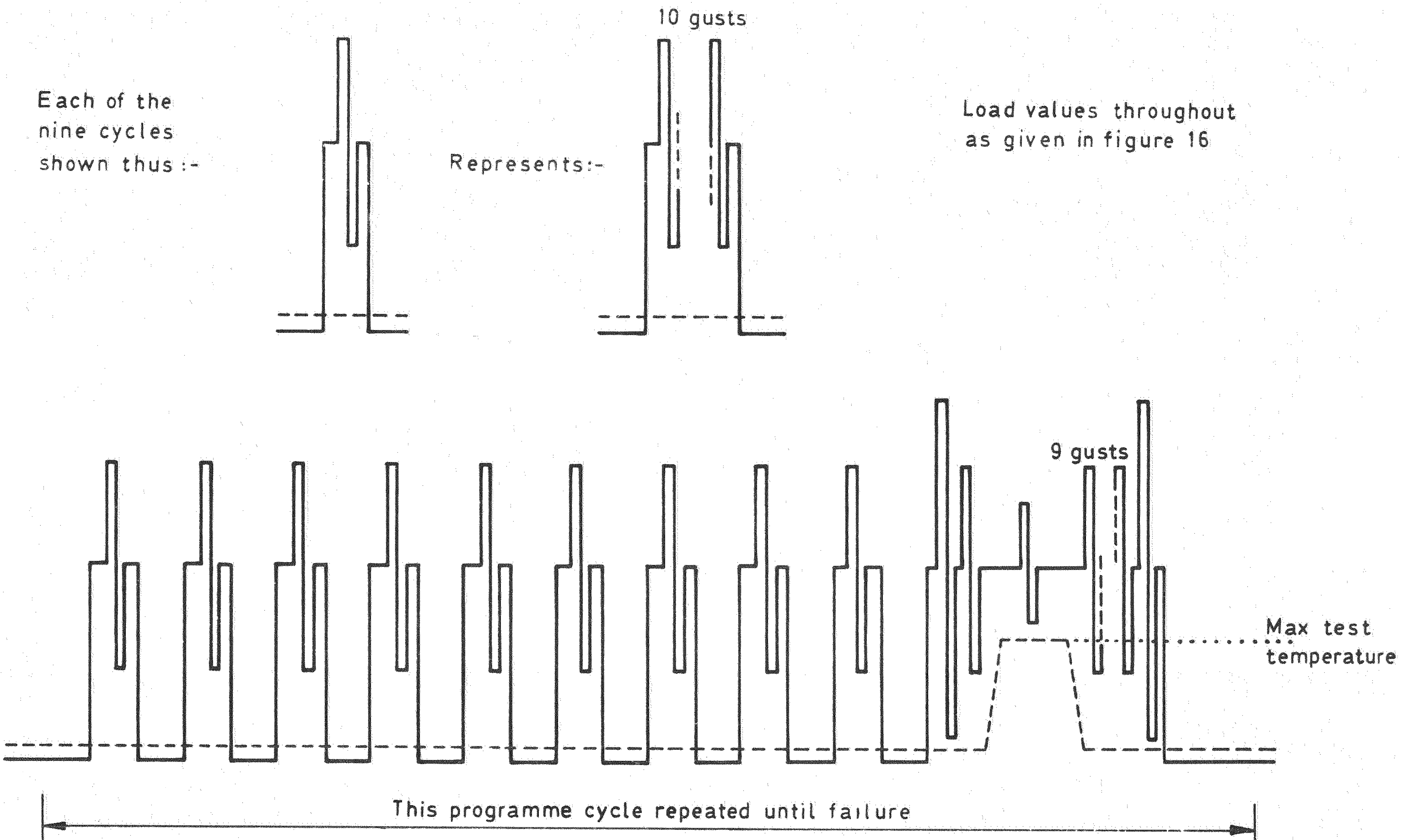


Fig.17 Intermittent creep test cycle ratio 10, accelerated flight by flight

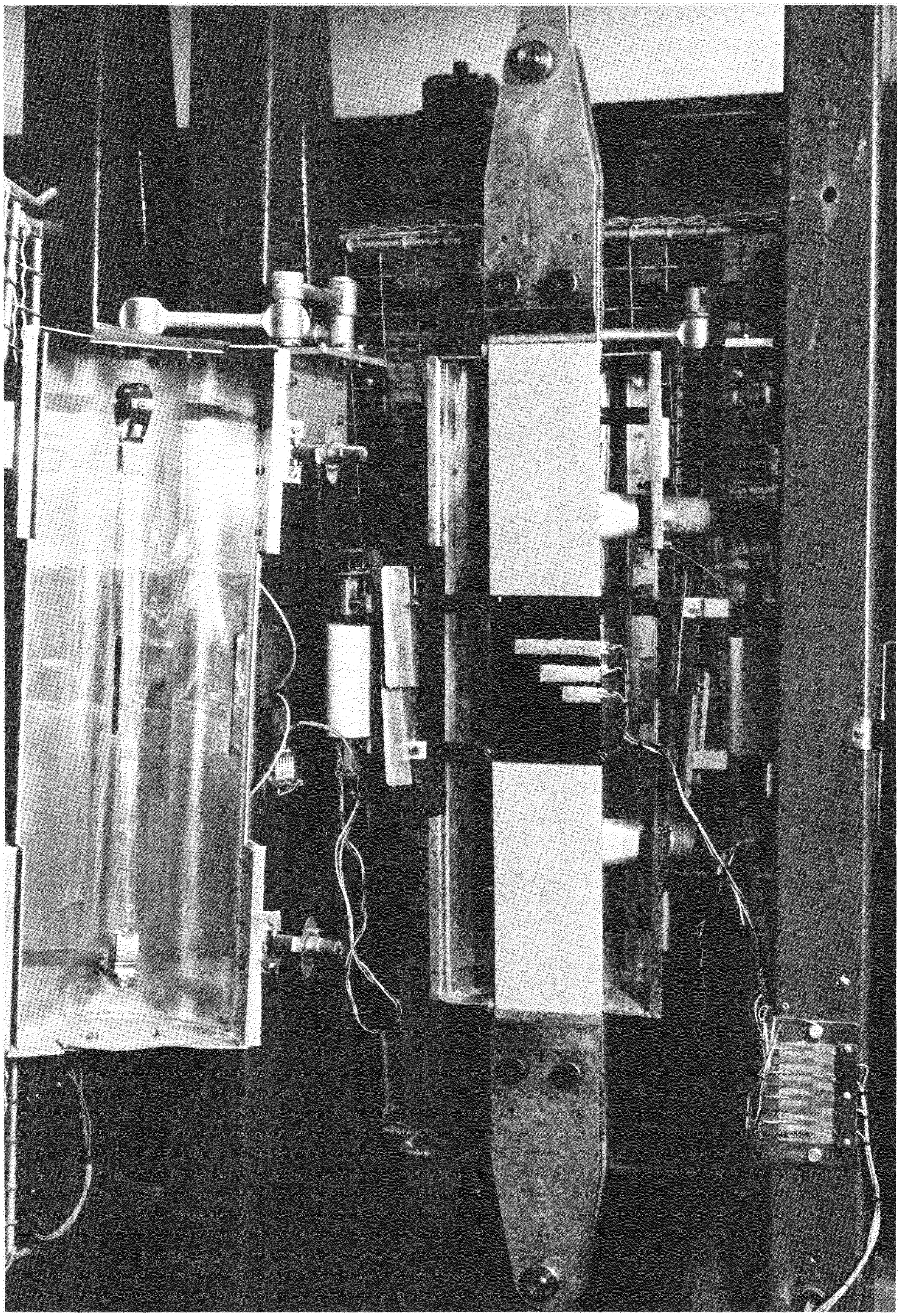


Fig.18   Riveted joint specimen in extension machine

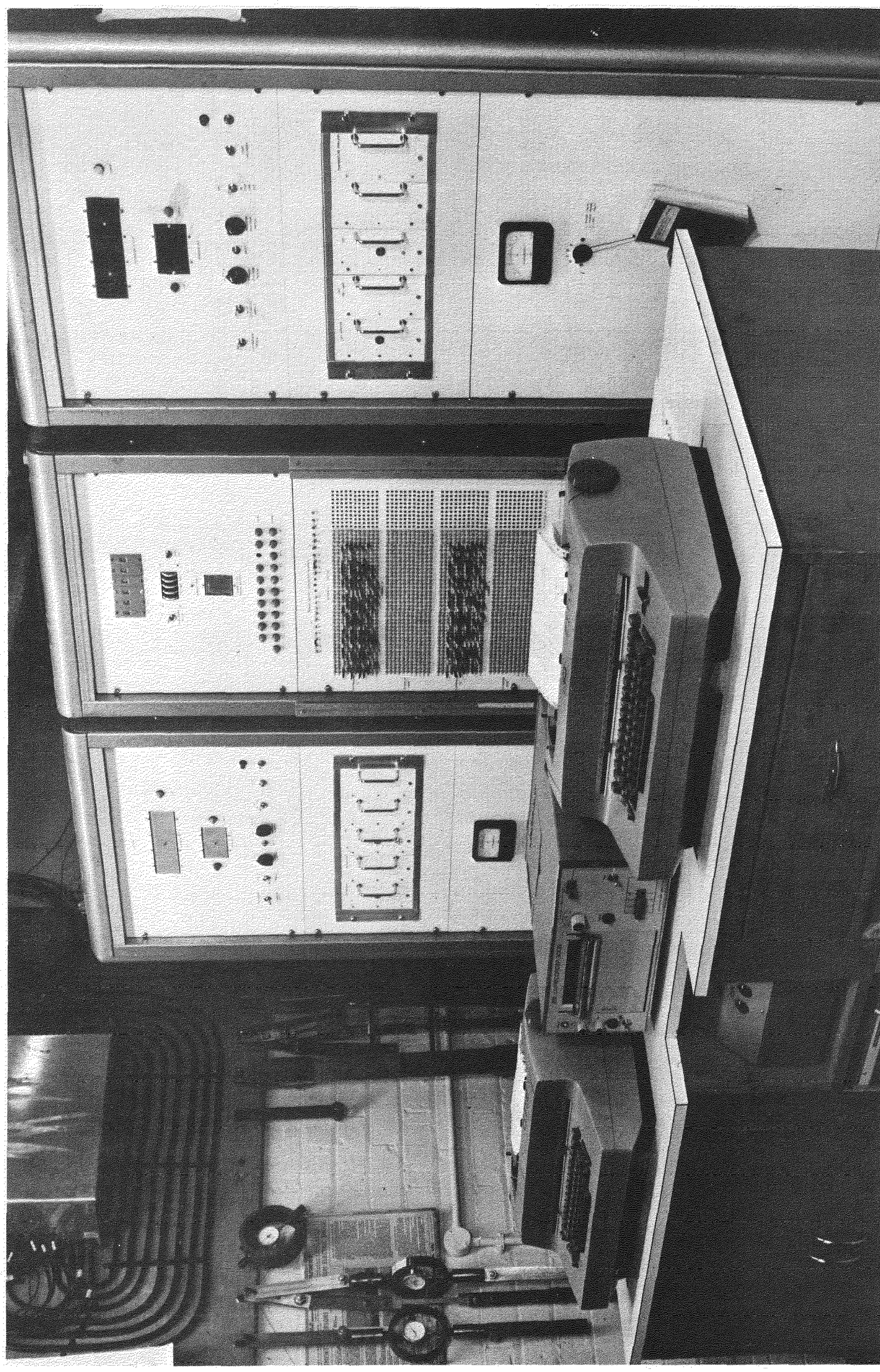


Fig.19 The digitiser

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June 1976

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620.178.3 :
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669.715.3 :
620.115.842 :
621.884.05

Kiddle, F. E.
Redfern, A. K.

FATIGUE TESTING WITH PERIODIC HEATING – AN INVESTIGATION OF SOME METHODS OF ACCELERATION

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A description is given of the multi-channel testing facility used for this work.

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