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AN EVALUATION OF A METHOD OF RECONSTITUTING FATIGUE LOADING FROM RAINFLOW COUNTING

by

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SUMMARY

On-line Rainflow analyses of load histories in structures may be used to reconstitute fatigue load sequences either for cycle-by-cycle damage analysis or for fatigue testing. This Report describes work which used Rainflow counting and reversed Rainflow reconstitution to create 'extreme' sequences which have the same Rainflow count as the original sequence but which were intended to maximise and to minimise the rate at which fatigue damage accumulated. Fatigue life and crack propagation tests have been used to compare 'extreme' sequences derived from the two load sequence standards FALSTAFF and MINITWIST. In addition a method has been used which allows the direction of the Rainflow cycles to be reproduced in the reconstituted sequence in order to recreate the highly structured features of the randomized 'extreme' sequences.

Increases in fatigue lives by factors of up to five have been measured for the 'extreme' highly structured reconstituted sequences while all of the randomized reconstituted sequences have been shown to produce fatigue lives which are statistically the same as those under the original sequences FALSTAFF and MINITWIST.

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1 INTRODUCTION

In order to achieve efficient management and adequate safety in the operation of large fleets of aircraft it is important to have accurate records of load histories for individual aircraft to aid the detection and control of fatigue damage.

To make the recorded data manageable it is convenient to compress the data by applying some form of intelligent counting method to identify damaging load cycles and store them in a loads matrix. The contents of this matrix may then be used to calculate the fatigue life consumed by individual aircraft during the period of measurement. This could be calculated on a flight-by-flight basis or for the total service life of the aircraft.

The loads matrix can also be used to reconstitute a sequence of loads which, although not having the same sequence as the original, is required to have the same fatigue damage content. The new sequence may be used to carry out full scale or component fatigue testing. Furthermore, recent crack growth modelling methods require a reconstituted sequence to allow crack growth to be calculated on a cycle-by-cycle basis.

Of the various counting techniques currently available the Rainflow method is the most favoured for in-service loads monitoring. This method produces a comprehensive description of loads data in that it can recognise large discontinuous load transitions by remembering the locations at which such cycles begin.

Various techniques exist which provide a means of reconstituting load sequences from the recorded Rainflow matrix. This Report describes a study where the reversed range-mean-pairs reconstitution technique was used to produce sequences having the same Rainflow count as the original Rainflow counted loads data. Although this reconstitution method reproduces the same damage as the original sequence in terms of a linear summation such as Miner's Rule, under normal circumstances it will not reproduce the same sequence of loads. This means that the load interaction effects which give rise to the acceleration and retardation of damage growth will be different in the new sequence. The significance of such interaction effects with respect to fatigue damage and crack growth is examined in this Report by reconstituting loads to produce extreme sequences from a Rainflow count of the sequences FALSTAFF[1] and MINITWIST[2]. The extreme sequences all produce the same linear cumulative damage as the original but re-associate loads so as to produce highly structured directional patterns which appear most likely to maximise or to minimise fatigue damage.

This Report describes a method of recording the direction of loads in a way that allows the direction to be reproduced during the process of reconstitution while maintaining the original Rainflow count.

Reconstituted sequences produced from directional counts of the extreme sequences are compared with the original sequences. Fatigue lives and crack growth rates observed for the extreme sequences are compared with those measured under the original sequences in order to evaluate the significance of load interactions with respect to the reconstitution process.

2 RAINFLOW COUNTING AND RECONSTITUTION ALGORITHM

2.1 The Rainflow counting algorithm

The Rainflow counting technique is illustrated in Fig 1 for a load sequence experienced by material in the vicinity of a structural discontinuity such as a fastener hole or a fatigue crack. In this example the technique records not only the continuous cycles, such as that between turning points 2 and 3, but also the discontinuous cycles, such as that between turning points 4 and 7, which form the hysteresis loops. Indeed it is possible to differentiate between continuous and discontinuous cycles within the Rainflow algorithm.

The original Rainflow counting algorithm, as described in Ref 3, is a moderately complicated procedure that uses computer processing time inefficiently. It has been shown in Ref 4 that the range-mean-pairs algorithm recognises the same load cycles as the Rainflow algorithm but uses a simpler set of rules. The popular implementation of the range-mean-pairs method uses a four-point algorithm to extract complete cycles from the sequence for storage in a peak-trough matrix.

The fundamental rule describing the four-point algorithm allows the extraction of a full Rainflow cycle if the peak and trough of that cycle are enveloped by the turning points on either side of them. Fig 2 describes the three different circumstances under which the transition 2-3 may be recognised as a Rainflow cycle. The counting technique is further illustrated in Fig 3 where a sequence consisting of seven turning points is counted. Turning points 1 and 4 do not envelope the cycle 2-3 which cannot therefore be counted into the loads matrix. Next the four points 5, 4, 3, 2 are considered, but here also cycle 3-4 cannot be removed. However, turning points 6 and 3 enclose the cycle 4-5 which therefore qualifies as a 'Rainflow' cycle. This is removed from the sequence and one count is added to the peak-trough matrix element (13,6) as defined by the load levels of 13 and 6 for turning points 4 and 5.

The algorithm then moves to the four points 6, 3, 2, 1 which fail to satisfy the extraction rule. The algorithm advances to the next four points and leaves the waveform 1, 2, 3, 6, 7 which cannot further satisfy the extraction rule. In service the sequence would be much longer and the remaining cycles would have the opportunity to pair up with following cycles and be counted out using the extraction rule or, as in this case, produce a left-over or residual waveform. As this residual sequence exists because the Rainflow algorithm can no longer remove cycles, it has a common form of increasing and then decreasing amplitudes. This is illustrated in Fig 4a which shows a typical residual sequence which contains no embedded Rainflow cycles.

Although the Rainflow algorithm can no longer remove cycles it is not sensible to ignore the remaining sequence as it contains the largest cycle that has occurred and represents damage that might be 'counted out' in a continuing sequence. In addition, if the whole of the load history were applied again, as it would be in a fatigue test, then this sequence would automatically be removed on encountering the same transitions for a second time. Indeed, one method of completing the Rainflow count is by passing through the sequence a second time. However, Ref 5 describes a method where the left-over waveform is discontinued at the largest peak and the two halves are then reversed and joined to be Rainflow-counted into the loads matrix. This effectively simulates a second pass of the sequence and is illustrated in Fig 4b.

2.2 The reversed method for reconstitution

Ref 6 describes how the counting process may be reversed in order to use the Rainflow loads matrix to produce a new sequence that has the same Rainflow count as the original. Fig 5a&b illustrate the technique which withdraws loads from the matrix in a strict order and makes a random selection of insertion site based on a choice of sites that obey the four-point counting rule. The sequence may be initiated by starting with the maximum load range recorded in the loads matrix. Allowed insertion sites are then defined as transitions which fully envelope the cycle to be inserted. In Fig 5a either site 3 or 4 may receive the next cycle; the site is then chosen at random. The process is continued by choosing loads from the matrix in the strict order of descending range and descending mean for each range, which in a peak-trough matrix requires a scan down the constant range diagonals starting at the high peaks and low troughs.

This is illustrated in Fig 5b which shows the progression through the first six elements of the loads matrix. The current matrix element is reduced by one count and the reconstituting sequence is scanned to locate sites which will accept the next load to be inserted. A site is chosen at random from the list of those allowed and so the reconstituting sequence increases by one cycle. This process is continued until the matrix is emptied producing a sequence which has the same number of cycles and the same Rainflow count as the original.

3 DIRECTIONAL RAINFLOW COUNTING AND RECONSTITUTION

3.1 Directional counting

Directional counting methods have been used for some time and have been applied to the Rainflow algorithm by Kilburn and Williams[7]. The directional information described below refers primarily to the direction of the load transition that defines a particular cycle which is either to be counted by the Rainflow algorithm or inserted by the reconstitution algorithm.

The four-point counting algorithm requires that the embedded cycle should have the opposite sense to the enveloping transition. Directional information is therefore already available within the algorithm. Fig 6 shows negative-going and positive-going Rainflow cycles '2-3' embedded in a positive-going and a negative-going transition respectively. The directional relationship between the embedded and the containing cycles is easy to understand. However, the case of adjacent constant amplitude cycles can lead to ambiguity. The four point algorithm in its traditional form cannot be used consistently to define the directional relationship within a large block of constant amplitude cycles. Turning points adjacent to the Rainflow cycle being counted have the same amplitude as the counted cycle. Consequently the direction of the containing cycle is not clear. However, under variable amplitude loading the relationship becomes more clear. Fig 7 illustrates four possible combinations of constant amplitude cycles and enveloping transitions. It can be seen that the algorithm will remove the constant amplitude cycles as successive negative cycles for case 'a' and positive cycles for case 'b'. For cases 'c' and 'd' it is not possible to define the enclosing cycle as either negative-going or positive-going. However the algorithm treats such cases consistently with respect to the transition leading in to the group of constant amplitude cycles. Hence case 'c' is defined as a group of negative-going Rainflow cycles in a positive transition and case 'd' as a group of positive Rainflow cycles in a negative transition.

Having thus defined the directional properties of the algorithm it only remains to implement storage of the Rainflow cycles. Several methods are possible but in order to be consistent with other directional counting techniques the 'From-To' or Markov matrix has been used. Here negative-going Rainflow cycles are stored in the lower triangle of the Rainflow matrix while positive-going Rainflow cycles are stored in the upper triangle. This is illustrated in Fig 8.

3.2 Directional reconstitution

A directional reconstitution is produced by creating a sequence whose Rainflow cycles obey the counting algorithm described above. This can be achieved with a small alteration of the reconstitution algorithm described in section 2.2. Directional properties can be retained by allowing insertions only in transitions which have the opposite sense to the cycle being inserted. However, the standard algorithm again may behave ambiguously in the case of groups of constant amplitude cycles. The algorithm allows insertion if a receiving transition has a peak equal to or greater than that of the cycle to be inserted and a trough equal to or less than the cycle to be inserted. Fig 9a illustrates how a directional insertion may be made ambiguously when the random generator chooses a site such as d-e from those marked between 'a' and 'm'. The transition d-e has the same amplitude as the cycle to be inserted and although it appears to fulfil the directional requirement it is actually part of a group of constant amplitude cycles inserted in a negative-going transition from 'a'. As explained earlier the counting algorithm retains the large excursion from 'a' to 'b' as the first two points of the four point algorithm until all the enclosed Rainflow cycles are counted. All of these enclosed cycles would be counted as positive-going cycles.

It is therefore necessary to exclude such sites as transitions bc, de, fg, hi, jk and lm in Fig 9a as possible recipients for negative Rainflow cycles. This can be achieved with a minor alteration to the rule that identifies insertion sites. This is described in Fig 9b where the peak at 'b' can be equal to or greater than the peak of the cycle to be inserted, but the trough of the containing transition must be less than the trough of the cycle to be inserted. This means that in the short sequence shown in Fig 9b the only allowed site is the transition a-b. This will also exclude all sites within the previously allowed insertion sequence shown in Fig 9a and ensures that the directional properties of the original sequence may be unambiguously reproduced.

In order to proceed with a directional reconstitution, when a new loads matrix element is addressed, it is necessary to withdraw loads from the matrix by alternating between the relevant transposed peak-trough elements. This is illustrated in Fig 8 where loads would be withdrawn alternately from the elements A and A' with A releasing negative cycles and A' releasing positive cycles. On releasing a load the appropriate element is reduced by one count and the reconstituting sequence increased in length by one cycle by inserting a cycle of the appropriate size in a transition of the opposite sense. This continues until one element reaches zero. Any loads remaining in the other element are then withdrawn and placed at sites having the opposite sense. By randomly selecting appropriate insertion sites the procedure reconstitutes a sequence having a random distribution of loads with the same Rainflow count and the same directional relationship between load transitions as the original.

4 LOAD SEQUENCES DERIVED FROM FALSTAFF AND MINITWIST

4.1 Introduction

The ordering of loads in fatigue load sequences may be important because the rate at which fatigue damage accumulates has been shown to be sensitive to interactions between loads of varying amplitude. Material local to structural discontinuities such as fastener holes and fatigue cracks has been shown to behave differently if small loads follow large loads rather than precede them. This has led to the development of complex cycle-by-cycle fatigue damage rules, particularly in the field of fracture mechanics, to estimate the magnitude of sequence effects in terms of their effect on plastic zone size, crack opening loads, surface displacements and residual stresses.

The aim of the work presented here is to compare the fatigue damage resulting from a number of sequences derived both from FALSTAFF and from MINITWIST. The sequences which are described below, all have the same Rainflow count as the sequence from which they originate and therefore have the same linear damage. However, they are heavily structured in order to associate load cycles in patterns which might produce interactions that cause fatigue damage to accumulate at rates either faster or slower than predicted by linear cumulative damage theory. In addition a sequence referred to as DIRECTFAL has been produced using a directional reconstitution from a directional Rainflow count of FALSTAFF using the algorithm described in section 3.2.

4.2 Reconstitution of the extreme sequences

Fig 10 shows part of the sequence FALSTAFF, from which most of the extreme sequences were derived, and part of the sequence DIRECTFAL produced from a Rainflow count of FALSTAFF using the directional method described in section 3.2. As explained earlier, the directional reconstitution method controls the distribution of positive and negative-going inserted cycles to match that of the directional Rainflow count. It is possible to override the insertion rule and alter the relative proportions of positive and negative insertions in order to form sequences which have a structured rather than a random pattern whilst retaining the Rainflow count of the original sequence. This technique was used to produce four sequences each containing patterns having pronounced characteristics. The first two sequences, DECAY and DIVERGE, comprise descending and ascending block sequences respectively, reconstituted from a Rainflow count of FALSTAFF obeying the four-point insertion rule. The sequence DECAY was achieved by forcing insertions to be made only on the falling side of an enveloping transition and always at the most recently inserted allowed insertion site. This resulted in a sequence of blocks of decaying peaks each containing various decaying ranges all having the same peak value, the whole sequence having the same Rainflow count as FALSTAFF. The complete sequence can be seen in Fig 11a. The sequence DIVERGE, shown in Fig 11b, was achieved by forcing insertions to be made only on the rising side of an enveloping transition and always at the most recently inserted allowed insertion site. The two sequences DECAY and DIVERGE have the same Rainflow count as FALSTAFF.

In addition two random sequences were created by restricting each random choice of insertion site either to only those transitions that are positive-going, or to those that are negative-going. By restricting the choice to positive-going enveloping transitions, a sequence can be produced containing load patterns as shown in Fig 12a. Similarly, by restricting the choice to negative-going enveloping transitions, patterns similar to that shown in Fig 12b are produced. These two approaches have been used to produce the sequences FALSUP and FALSDOWN, samples of which are shown in Fig 13a&b. Although a random generator was used to choose the insertion site, it is evident that the two routines associate loads in structured groupings and it is possible that these may influence the accumulation of fatigue damage.

In addition to the extreme sequences derived from FALSTAFF, the algorithms used to produce the decaying and the diverging sequences were also applied to the MINITWIST Rainflow peak-trough matrix to produce the two sequences referred to as MINIdecay and MINIdiverge. Fig 14 shows two parts of the sequence MINITWIST while Fig 15 shows the two complete sequences MINIdecay and MINIdiverge. It can be seen that similar characteristics are produced as in the sequences DIVERGE and DECAY, except that for the sequence MINITWIST a greater proportion of cycles have the same amplitude which results in larger blocks of constant amplitude loading in the two extreme sequences. In addition a wholly random reconstitution of MINITWIST was used to create the sequence MINIRAND.

4.3 Directional counting and reconstitution applied to the extreme sequences derived from FALSTAFF

The directional reconstitution algorithm was used to produce sequences from a directional Rainflow count of the extreme sequences FALSUP, FALSDOWN, DECAY and DIVERGE. The new sequences have the same directional Rainflow counts as the originating sequences but associate loads in a different order. Figs 16 and 17 show arbitrary sections from the four sequences. However, these directional reconstituted sequences have not been used to produce fatigue data.

In Fig 16 it can be seen that for the two sequences FALSUP and FALSDOWN, the directional reconstitution reproduces the same trend in the way that loads are associated. However, in Fig 17 it can be seen that for the two non-random sequences DIVERGE and DECAY, the directional method is not capable of reproducing the highly structured patterns contained within these sequences. This is a consequence of the non-random structure of the two original sequences, which, although appearing to be constructed in very different ways, are from the point of view of directional Rainflow counting very similar. Fig 18 describes the general structure of both sequences with respect to the directional properties of their load patterns. In both cases it can be seen that the cycle patterns are achieved by inserting the smaller cycles in the rising side of the containing cycles. Thus, in both cases when randomising the reconstitution process, sequences are produced which predominantly contain the characteristics of the sequence FALSUP (see Fig 16). Although not all cycles are inserted in positive-going excursions, as they are in the sequence FALSUP, a large majority of cycles are assembled in this way.

5 FATIGUE AND CRACK PROPAGATION TESTS USING EXTREME SEQUENCES

5.1 Fatigue tests and results

In order to gauge the sensitivity of the fatigue process to variations in load sequence and load interaction the sequences described above were applied to several types of specimen in both simple fatigue tests and also crack propagation tests.

The majority of fatigue tests reported below were carried out at the British Aerospace Materials and Structures Testing Laboratories at Woodford[8]. However crack propagation tests under FALSTAFF (see section 5.2) and all of the tests under MINITWIST and its derivatives were carried out at RAE Farnborough.

Two types of specimen were used to generate fatigue performance data. The open-hole specimen shown in Fig 19 represents a moderate structural discontinuity having a stress concentration factor of 2.3 based on the net section. The Q-joint shown in Fig 20 represents a high load transfer fastener connection such as might be found at a chord-wise wing joint. The single-shear test section indicated in Fig 20 transfers 45% of the load in the joint and experiences a level of secondary bending that varies between 0.3 and 0.5 over the range of loads most frequently encountered during FALSTAFF loading. This joint was chosen for its non-linear characteristics which result in significant hysteresis both in load transferred by the joint and in the secondary bending experienced at the single-shear test section. It was felt that such behaviour would tend to highlight any load interaction effects which influence the rate at which fatigue damage accumulates.

To generate the FALSTAFF-based data these two types of specimen were tested using Dartec electro-hydraulic fatigue machines having load ranges up to 100 KN. Two stress levels were chosen such that lives achieved would be between 5000 and 10000 FALSTAFF flights at the high stress and 20000 to 40000 flights at the low stress. Computer-based monitoring was used to ensure that each load level was achieved within 1% of the applied level. Tests containing transitions outside these limits were abandoned.

Fatigue tests under sequences derived from MINITWIST were applied (only) to open hole specimens. These were tested on a Dowty 200KN fatigue machine using adaptive control to keep all load levels within 1% of the values demanded.

Fatigue test data for the open-hole coupon specimens tested under FALSTAFF at two stress levels are shown in Fig 21 which plots life to failure in FALSTAFF-sized flights. Table 1 lists individual lives for the various combinations of sequence and stress level. Although for reconstituted sequences individual flight lengths were not the same as in FALSTAFF, the total number of cycles in each reconstituted sequence was the same as in FALSTAFF and the number of characteristic air-ground-air cycles was the same.

Failure in the open-hole specimens always occurred in the net section and as can be seen in Fig 21 little effect due to sequence type was found; the only sequences which produced behaviour which deviated from that of the main group were DECAY and to a lesser extent DIVERGE. In the sequence DECAY large ranges and peaks prior to the smaller cycles are considered to induce beneficial residual stresses which delay the growth of fatigue damage. Even so this effect is only small and the lives for DECAY are only a factor of two greater than the main body of data at both stress levels. The sequence DIVERGE also produces a predominantly beneficial interaction with lives 40% longer than the main body of the data. This may be a consequence of the conditions applying at the end of one sequence when the large transition is applied and followed by the smallest cycles which then increase through the sequence.

Fig 22 and Table 2 show fatigue test data for the sequences derived from MINITWIST and for MINITWIST itself. The sequence MINIRAND was generated using a random reconstitution of MINITWIST and produced lives within the scatter band of MINITWIST. The extreme sequences produced using the decaying and diverging algorithms were also investigated. The fatigue lives for MINIdec are approximately five times longer than for MINITWIST and the lives for MINIdiv are about three times longer. The trends are the same as those found for FALSTAFF but the magnitudes are greater; for the FALSTAFF-based sequences DECAY and DIVERGE, the increases over FALSTAFF were 200% and 40% respectively.

Fatigue test data for the Q-joints are shown in Table 1 and Fig 23 which plots peak stress against life to complete failure in FALSTAFF-sized flights. The average flight length in cycles is the same for FALSTAFF and the reconstituted sequences. The failure characteristics of this joint are particularly important when considering the significance of the fatigue data. The nominal test section in this joint is by design the single-shear section containing clearance fit fasteners (see Fig 20). The double-shear connection which transfers the remainder of the load has been strengthened by cold working the fastener holes which introduces beneficial compressive residual stresses. As a consequence, in the majority of cases it is the single shear connection which proves the weaker in fatigue. However, in a number of specimens the bolts in the double-shear section have failed in shear and these data are highlighted in Fig 23.

Although only a limited number of specimens were tested for each sequence it can be seen that in general the fatigue life was not significantly affected by the type of loading sequence. However, the two sequences DIVERGE and DECAY, applied only at 280 MPa, produced lives which deviated from those of FALSUP and FALSDOWN. With only one exception the sequence DIVERGE produced lives having log-mean values one and a half times greater than the log-mean values for FALSUP and FALSDOWN. The sequence DECAY produced lives that without exception were shorter than FALSUP and FALSDOWN, the log-mean life being only three quarters of the log-mean life for FALSUP and FALSDOWN. In the case of DECAY however, failure in four out of the five specimens was initiated by shear of the fasteners, which occurred only infrequently for the other sequences. Initial failure occurred in the fasteners at the double-shear connection (Fig 20). When these fasteners failed, greater load was transferred at the single-shear site and as a consequence final failure occurred early at this section of the joint. The mechanisms of load transfer at the double-shear connection are complicated and a specific investigation would be required in order to describe precisely how the sequence DECAY influences shear load transfer during testing. However, the most likely explanation is associated with the period at the start of the fatigue life when 'settling' of the joint causes changes in displacements local to the fastener which affect the load transferred in shear by the fastener. During the early stages of the life, frictional forces between the clamping surfaces will increase as the surfaces become 'roughened'. As fatigue life increases so the load transferred due to clamping will increase and the load transferred in shear will decrease. Although all the extreme sequences contain continuous large Rainflow cycles, the sequence DECAY applies these cycles at the start of the fatigue life when the frictional forces are at their lowest and the shear loads are at their greatest. This may account for the large number of fastener failures in Q-joints tested under the sequence DECAY.

The sequence DIVERGE applies large numbers of small cycles at the beginning of the test. The delay in applying the larger Rainflow cycles which occur later in the sequence may enhance the strength of the single shear connection as the smaller cycles will roughen the clamped surfaces surrounding the fastener connection. As the surfaces become more irregular so the frictional forces between the clamped surfaces will increase and protect the fastener from the increasing shear loads caused by the larger Rainflow cycles. The ring of fretting damage between the clamped surfaces transfers load around the fastener rather than through the fastener shank, due to bearing between the shank and hole surfaces. This may explain the observations that at 280 MPa the sequence DIVERGE produced fatigue lives in excess of the main body of data by approximately 75% (see Fig 23). No tests were carried out under MINITWIST based sequences for the fastener joint specimen.

5.2 Crack propagation tests and results

Using only those sequences derived from FALSTAFF, crack propagation tests were carried out to establish the effect of reconstitution on the periods of initiation, short crack growth through the thickness (across the notch) and long crack growth to failure across the specimen width. The specimen shown in Fig 24 was used to study all these phases. The specimens were machined down to a thickness of 6mm from 8mm-thick 2024-T351 aluminium alloy plate material. Fatigue cracks initiated in the root of the side notch and were monitored using an acetate replica technique as they propagated both across the notch and across the width to failure.

The specimens were tested under adaptive control using a Dowty electro-hydraulic fatigue machine having a load range of 200 KN. The adaptive control technique monitors each transition, measures any error associated with the latest transition applied and adds a proportion of this error to the next demand of the same transition. This process continues for the duration of the test. The method also differentiates between positive and negative-going transitions of the same range.

Tests were paused at the load level corresponding to FALSTAFF level 20 while replicas were applied to the surface of the notch. The replicas were moulded to the radius of the notch by applying pressure around the circumference of a hot metal rod. Cracks were then measured using an optical microscope viewing the surface of the replica. With this technique it was possible to resolve cracks down to a length of 0.02 mm.

Multiple fatigue cracks formed within a short period of one another and growth across the notch occurred in the early stages of life by the propagation of individual cracks until two or more major cracks combined to complete growth through the thickness. Fig 25 shows a typical example of crack growth rate varying with crack length for the many cracks formed in one specimen during the period between first detection and growth to one millimetre. As the behaviour of the cracks during this phase is difficult to analyse due to interaction between the cracks, no attempt has been made to evaluate sequence effects with respect to individual cracks.

Crack growth measurements were taken for the sequences FALSTAFF, FALSUP, FALSDOWN, DECAY, DIVERGE and DIRECTFAL. Table 2 lists fatigue lives for these specimens. The measurements are presented in Fig 26 in the form of a bar chart showing the period of life to the first detected crack (0.02 to 0.06 mm long), the period of growth from first detection to a crack through the thickness and finally the period of growth across the width of the specimen to final failure. In Fig 26 the numbers shown at the end of the initial crack growth phase are the lengths in mm of the first crack that was detected by replica for each specimen.

It can be seen in Fig 26 that there is very little difference in crack growth behaviour for most of the sequences. However for DECAY the period of growth through the thickness was greater than for the other sequences. If it is assumed that all the data apart from that under DECAY can be treated as if from one population, then the log-mean life of the specimens tested under DECAY is approximately twice that of the value for the main population. The same is true for the period of growth from first detected crack to growth through the thickness.

5.3 Discussion

5.3.1 FALSTAFF data

Considering the results of both fatigue life tests and crack propagation tests a number of general observations can be made. Despite the use of some extreme reconstitutions of the FALSTAFF sequence, most of the sequences appeared to be able to produce a good representation of the load interactions created by the FALSTAFF sequence. However, the highly structured sequences DECAY and DIVERGE produced significant improvements in fatigue performance, the most marked improvements being observed for DECAY, particularly in the case of open-hole specimens (Fig 21) and side notch specimens (Fig 26).

In all of the extreme sequences (DECAY, DIVERGE, FALSUP and FALSDOWN) the large Rainflow cycles occurred as continuous unbroken ranges. In the case of FALSUP these occur as negative-going transitions; in the case of FALSDOWN as positive-going transitions and for DIVERGE and DECAY as both positive and negative-going transitions. However, the test data (Figs 21, 23, 26) suggest that the large Rainflow cycles produce similar amounts of damage whether applied as a continuous positive-going range as in the sequence FALSDOWN or whether broken up by smaller cycles contained within the large rising transitions as in the sequence FALSUP. However, this may not be the case for sequences which have only few major cycles whose peaks and troughs may be widely separated in time. Here local damage conditions (*eg* length of a fatigue crack) may change significantly between the peak and the trough and it would make less sense to apply this transition as an unbroken range.

Genuine sequence effects have been observed in the present work; different load sequences either changed the mode of failure in a complex mechanical joint or changed the crack tip load interactions affecting the rate at which the fatigue cracks propagated. The behaviour observed in this work is consistent with that found by Schijve, Jacobs and Tromp[9] who used sequences very similar to DECAY and DIVERGE and observed reductions in crack growth rates of up to approximately 250% for 2024 T3 clad aluminium sheet specimens. Finney and Denton[10] also investigated sequences similar to DECAY and DIVERGE and in crack propagation tests observed increases of approximately 60% in crack growth lives when compared with those for randomized sequences having the same Rainflow count.

In the present work for all cases where the reconstitution process was randomized, the resulting sequence reproduced the damage of the FALSTAFF sequence very accurately (see Figs 21, 22, 23, 26). DIRECTFAL, the directional reconstitution of the FALSTAFF sequence, produced lives particularly close to those of FALSTAFF in both the crack propagation and open-hole coupon specimens. However, as the directionally biased sequences FALSUP and FALSDOWN showed no significant difference in fatigue performance it would appear that directional relationships in large, well mixed randomized sequences are not sufficiently powerful to influence fatigue damage.

5.3.2 MINITWIST data

The small number of fatigue tests under sequences derived from MINITWIST behaved in a similar way to those derived from FALSTAFF but showed a greater sensitivity to beneficial load interactions. Both the decaying and the diverging versions of MINITWIST (Fig 15) produced lives significantly longer than those produced by MINITWIST itself with factors on life of approximately five times and three times respectively. (Fig 22).

The sequence MINITWIST differs from FALSTAFF in the way that its loads are distributed and contains a greater number of constant amplitude cycles spread over fewer levels (22 as compared to 31 for FALSTAFF). The sequence is also approximately three and a half times longer than FALSTAFF and it is not surprising that the sensitivity to load interactions - particularly those that delay crack growth - should be different.

6 FUTURE WORK

The work in this Report concentrates on crack initiation and short crack growth under FALSTAFF and load sequences based on FALSTAFF which are relevant to military combat aircraft structures. However, additional data gathered using the sequence MINITWIST showed a greater sensitivity to sequence effects than did FALSTAFF. Further work studying long crack growth behaviour would provide the opportunity to measure immediate fluctuations in growth rate by using either surface crack monitoring methods or a striation counting procedure. This would produce more detailed information concerning the effect of load sequence on crack growth. Using sequences of the kind described in this Report in conjunction with more straightforward overload tests may help to more fully understand load interaction effects.

7 CONCLUSIONS

(1) The process of Rainflow counting and randomized reversed range-mean-pairs reconstitution creates sequences that produce fatigue lives that are statistically the same as those produced by the sequences which have been Rainflow counted. For the three types of specimen described in this Report the randomly reconstituted load sequences resulted in fatigue lives which were essentially the same as those obtained with the original sequences.

(2) Although a wide range of reconstituted sequences, having the same Rainflow count, have been studied, significant effects have only been observed with highly structured reconstitutions. The sequences formed using a series of decaying ranges descending from a peak value produced beneficial effects in terms of retarded crack growth. However, this pattern of loads was found to accelerate damage when applied to joints where fretting forces significantly influenced the failure mechanism. For the heavily structured decaying sequences it has been found that fatigue life could be increased by up to five times for open-hole and side notch specimens due to retardation effects and could be reduced by approximately 25% in joints where fretting has a significant influence.

(3) The degree of influence of reconstituted load sequences on fatigue life and crack growth has been found to depend on the nature of the load sequence being considered. Highly structured sequences based on MINITWIST resulted in greater increases in life and slower crack growth than occurred under similar sequences derived from FALSTAFF.

(4) It has been shown that minor modifications to the Rainflow counting and reversed range-mean-pairs algorithms can be used to reproduce directional load patterns occurring in randomly mixed waveforms. However, the work in this Report suggests that in a well mixed sequence directional relationships are not likely to significantly influence the rate at which fatigue damage accumulates.

TABLE I

FATIGUE PERFORMANCE DATA FOR THE OPEN HOLE AND Q-JOINT SPECIMENS UNDER SEQUENCES HAVING THE SAME RAINFLOW COUNT AS FALSTAFF

FATIGUE PERFORMANCE DATA						
SEQUENCE	Fatigue lives for open hole specimens		Fatigue lives for Q-joint specimens			
	Peak=260 MPa	Peak=210 MPa	Peak=305 MPa	Peak=280 MPa	Peak=290 MPa	Peak=270 MPa
FALSTAFF	8575 9027 9740 9830 12157	23957 28334			7370 10530 14570 22970+	16430 48970
FALSDOWN	8850 9000 9340 9400 9450 9540 10130	21920 22800 25040 26340	5340 6940+ 7040 9440 11540	18140 20040 20440 24340 30740	9340 14340 16000 19000 22850	23340 37180 49700
FALSUP	7850 8400 8720 8940 8970 9850 10120 10230	17110 18890 19940 23850 24170 27970 28720	5120 6170 6650 12320	16450 17650 26850 27570	8850 9600 11400 13200 13800 20250	17450+ 23000 24850
DIRECTFAL	8535 8955 11275	20092 27202				
DIVERGE	12610 14050 14754	33598 34720 37750 41439		13600+ 32800 34200 36000 37200		
DECAY	18720 19440 20520	42880 49760 62718		15200+ 16200+ 16800+ 20200+ 32200		

TABLE 2

FATIGUE PERFORMANCE DATA FOR THE SIDE NOTCH SPECIMEN UNDER FALSTAFF BASED SEQUENCES AND THE OPEN HOLE SPECIMEN UNDER SEQUENCES BASED ON MINITWIST

Fatigue lives for side notch specimens		Fatigue lives for open hole specimens	
SEQUENCE	Peak=157 MPa	SEQUENCE	Peak=282 MPa Mean=108.5 MPa
FALSTAFF	23422 24840	MINITWIST	32353 37452 42240
DIRECTFAL	22288 23422	MINIRAND	32261 33377 33978
FALSDOWN	21904 27870 34371	MINIDIV	74096 97096 139241
FALSUP	22210 24401 27676	MINIDEC	109453 112621 178712 226294
DIVERGE	31335 32792		
DECAY	42624 57777		

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No	Author	Title, etc
1	Several authors	"Description of a fighter aircraft loading standard for fatigue evaluation - FALSTAFF" Joint Report NLR, IABG, LBF, F&W (1976)
2	Lowak H. Schutz D. DeJonge J.B.	"MINITWIST - A shortenend version of TWIST (Transport wing standard)." ICAF conference Darmstadt (1977)
3	Matsuishi M. Endo T.	"Fatigue of metals subjected to varying stress" Paper presented to Japan Society of Mechanical Engineers (Fukuoka) (1968)
4	Perrett B.	"The effect on fatigue performance and life estimation of load sequence reconstitution methods applied to aircraft load histories" RAE Technical Memorandum MAT/Str 1058 (1985)
5	Ellis Susan D.	"A combined range-mean-pairs Rainflow count of load time histories for use in the formulation of structurally relevant cost functions and fatigue analysis" RAE Technical Report 81122 (1981)
6	Holford Dorothy M.	"Synthesis of loading sequences from a range-mean-pairs count or fatigue load meter data. RAE Technical Report 82080 (1982)
7	Kilburn Ian Williams D.P.	"An improved Rainflow counting method" NAE, LTR-ST-1290 (1982)
8	Neary I.	"The effect on fatigue performance of variations in range-mean-pairs counting and reconstitution techniques. BAe Report No BAe-MSM-R-GEN-0576 (1987)
9	Schijve J. Jacobs F.A. Tromp P.J.	"The effect of load sequence on fatigue crack propagation under random loading and programme loading" NLR TR 71014U (1971)

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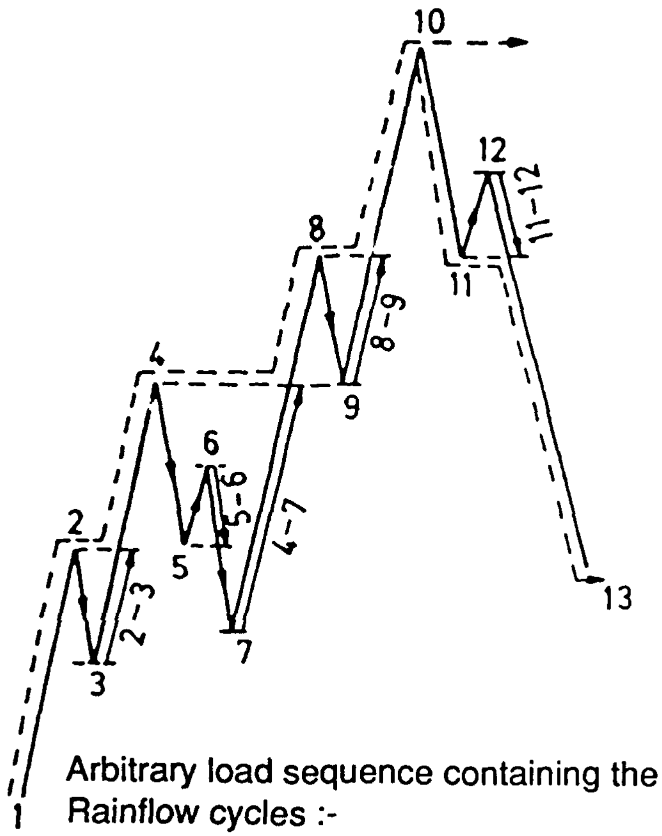
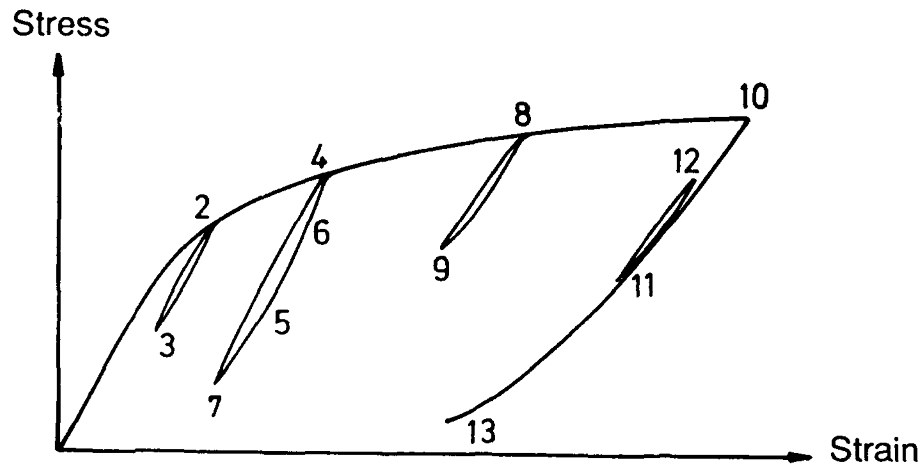
No.	Author	Title, etc
10	Finney J.M. Denton A.D.	"Cycle counting and reconstitution with application to the aircraft fatigue data analysis system" I Mech E Conference on Fatigue of Engineering Materials and Structures" Sheffield (1986)



Arbitrary load sequence containing the Rainflow cycles :-

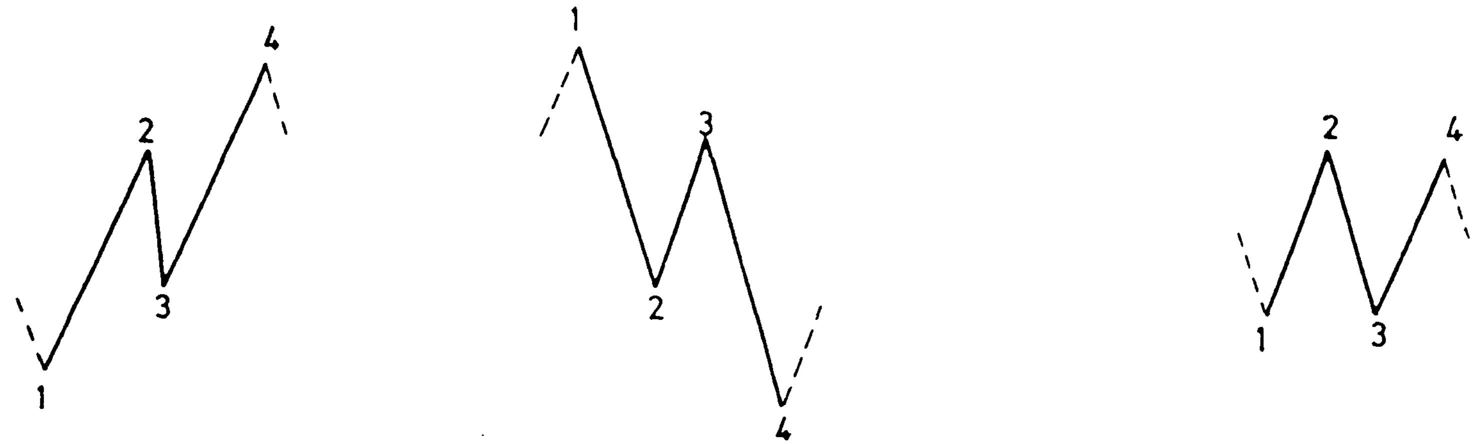
2 - 3
5 - 6
4 - 7
8 - 9
11 - 12

leaving the large containing cycle 1-10-13



Arbitrary local stress/strain relationships for a notch – root/crack tip showing how the Rainflow cycles are enclosed by the large hysteresis loop 1-10-13

Fig 1 Identification of Rainflow cycles and their enclosing ranges

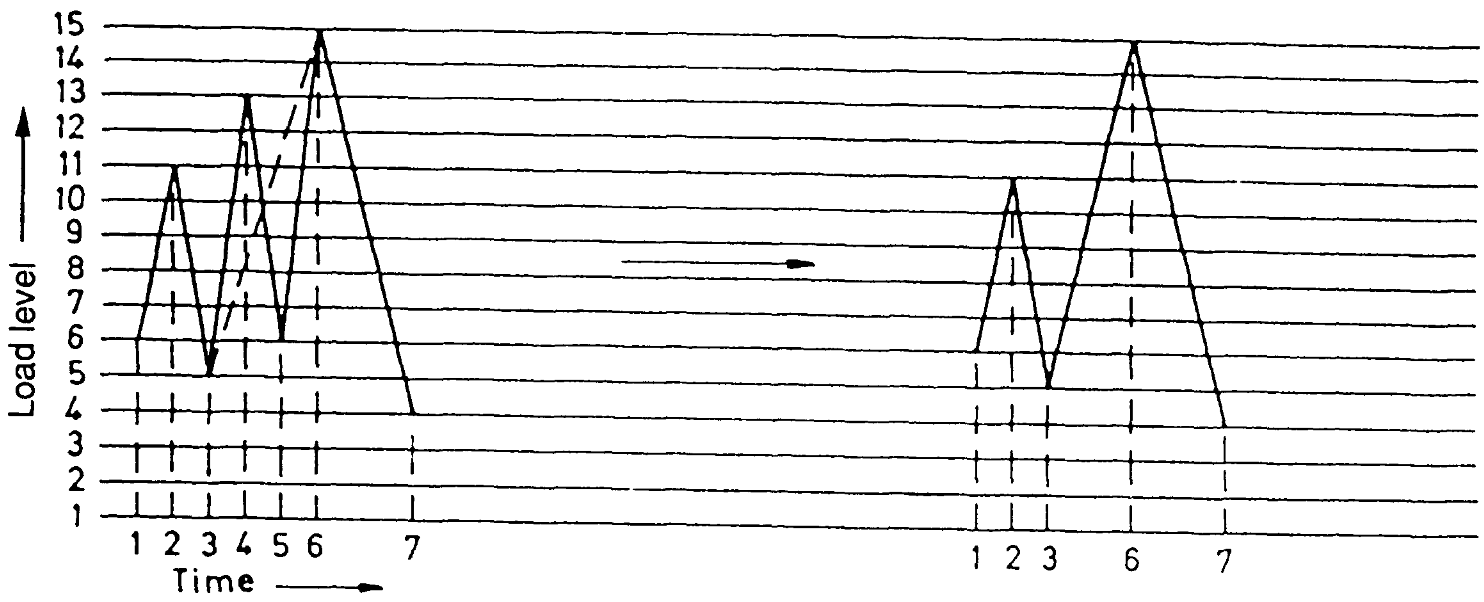


$1 < 3$
$\& \ 4 > 2$

$1 > 3$
$\& \ 4 < 2$

$1 = 3$
$\& \ 4 = 2$

Fig 2 Simple logic for recognising the Rainflow cycle '2-3'



a) The 4 points 4,3,2,1 do not hold an embedded cycle
b) The 4 points 5,4,3,2 do not hold an embedded cycle
c) The 4 points 6,5,4,3 envelope the cycle 4-5
d) This cycle is removed and the peak-trough load level matrix element 13,6 is incremented
e) The 4 points 6,3,2,1 are scanned for an embedded cycle
f) The above sequence 1,2,3,6,7 forms either a 'residual waveform' or the beginning of a continuing sequence where the cycles may be subsequently Rainflow counted

Fig 3 The four point counting algorithm

Fig 4a&b

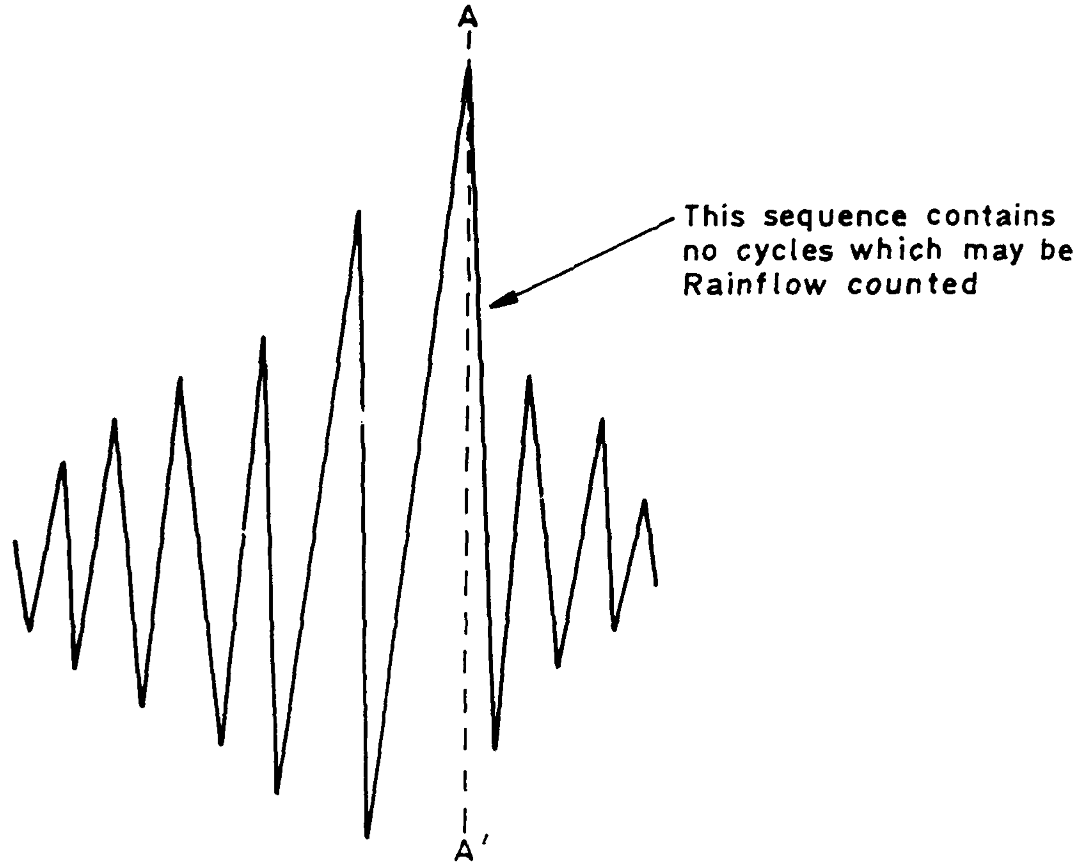


Fig 4a Typical structure for a residual waveform after one Rainflow pass

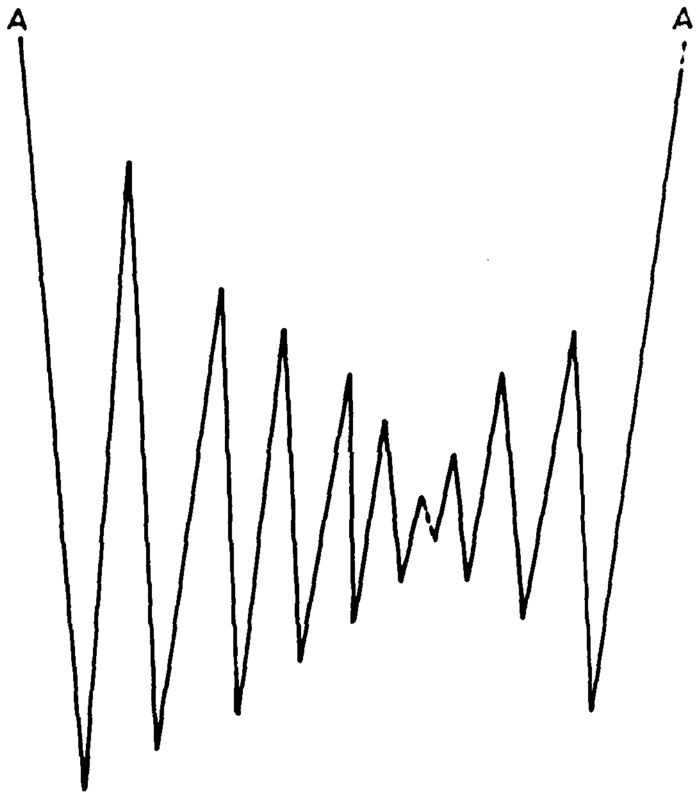
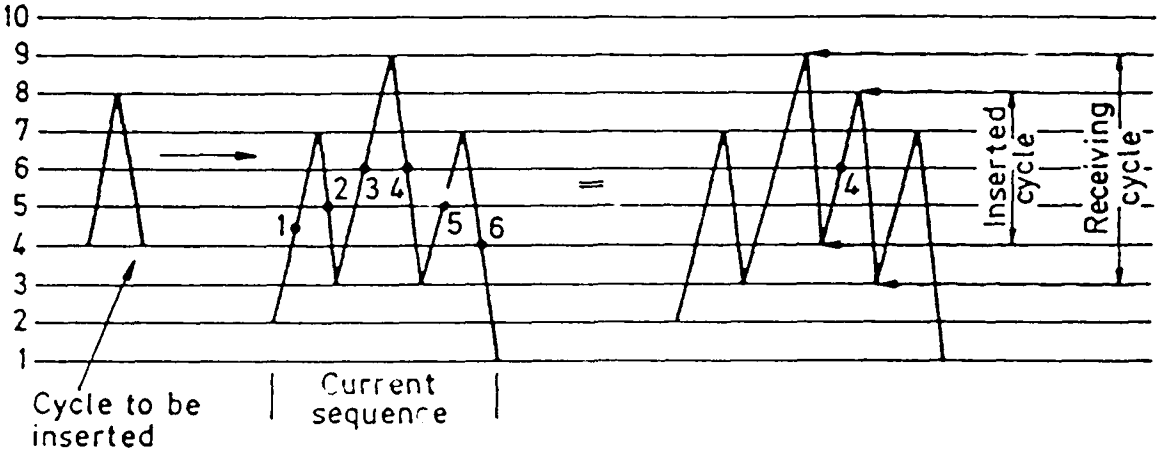


Fig 4b Residual waveform from 4a re-ordered as in Ref 5 for further Rainflow counting



a) Current sequence is scanned to find an allowed insertion site

b) Inserted cycle can only be embedded at site 3 or 4

c) A random generator choses between these sites

d) Site 4 is chosen and the transition between levels 4 and 8 is inserted to form the new sequence

Fig 5a Reconstitution algorithm

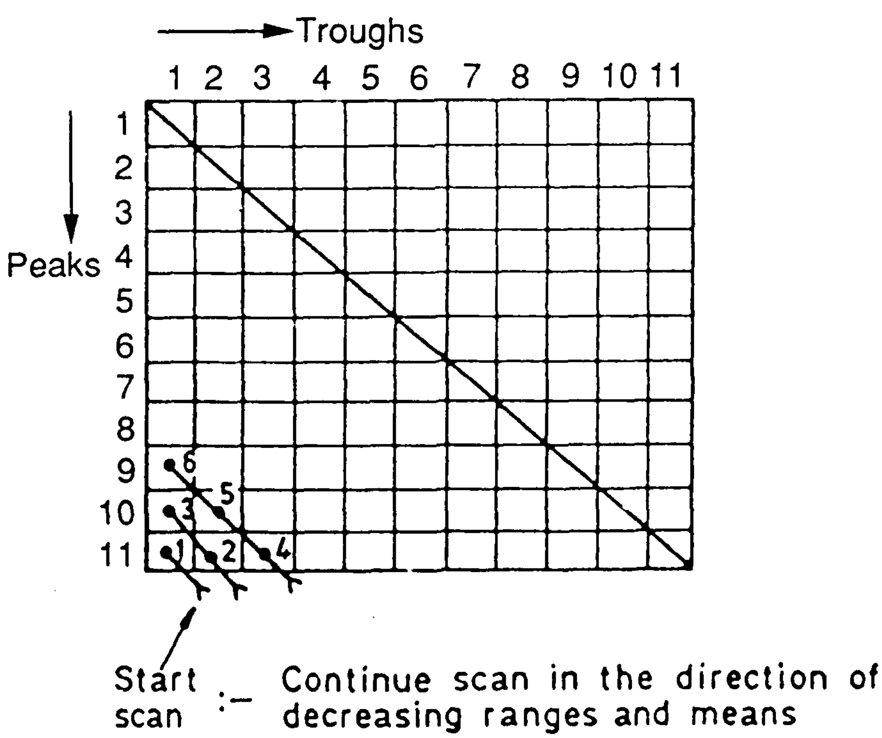
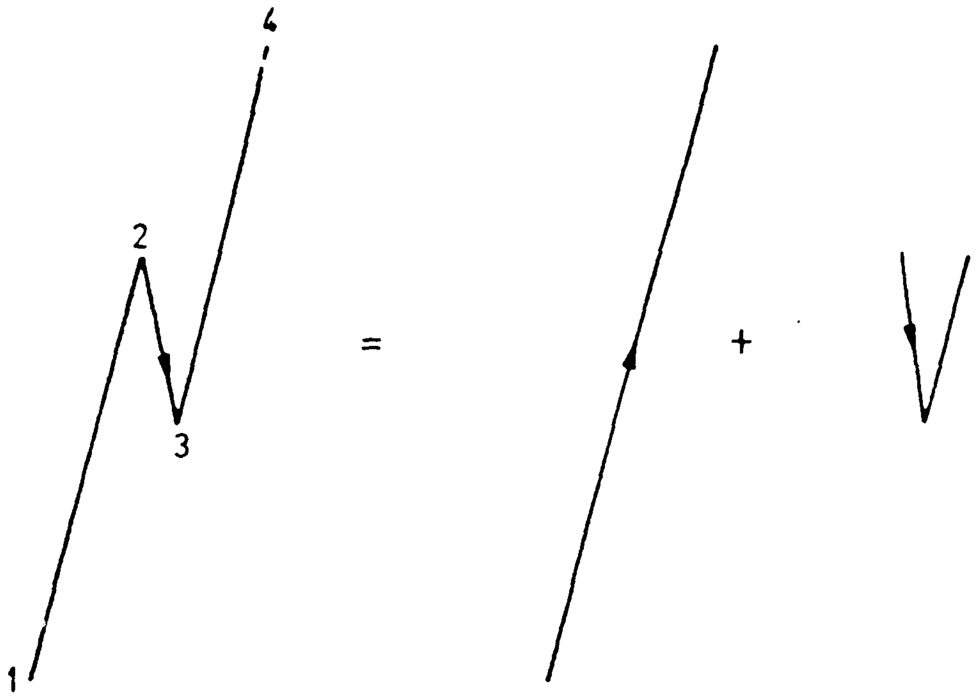
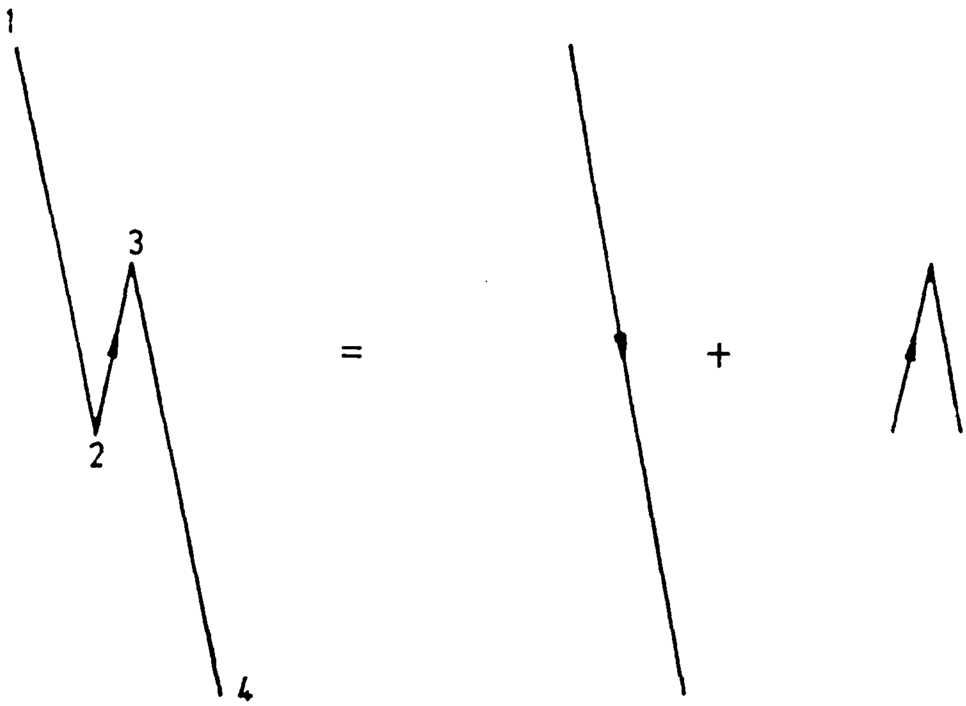


Fig 5b Matrix scan for the next group of cycles to be inserted

Fig 6



Negative - going Rainflow cycle in positive going enveloping transition



Positive - going Rainflow cycle in negative going enveloping transition

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Fig 6 Directional Rainflow cycles

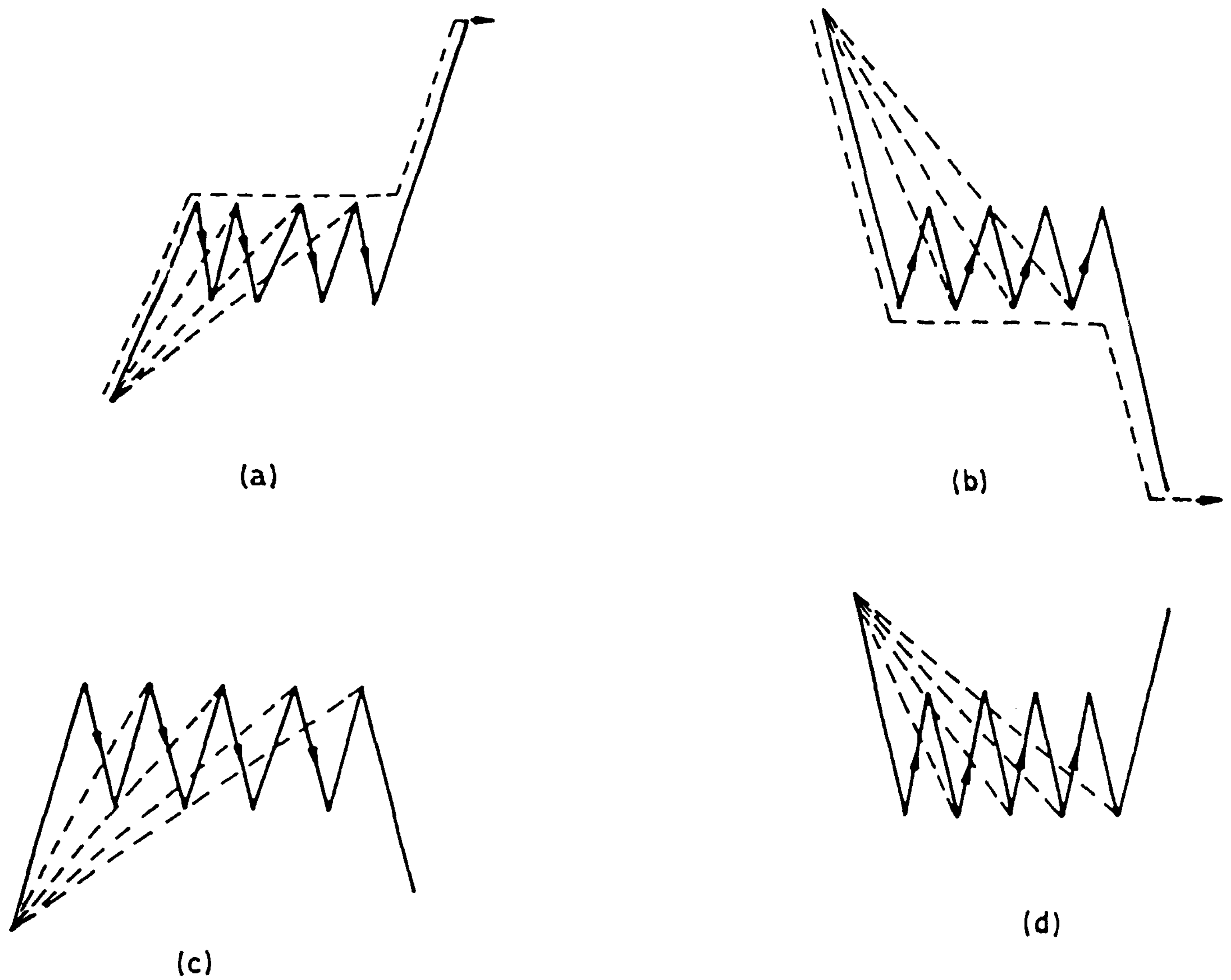
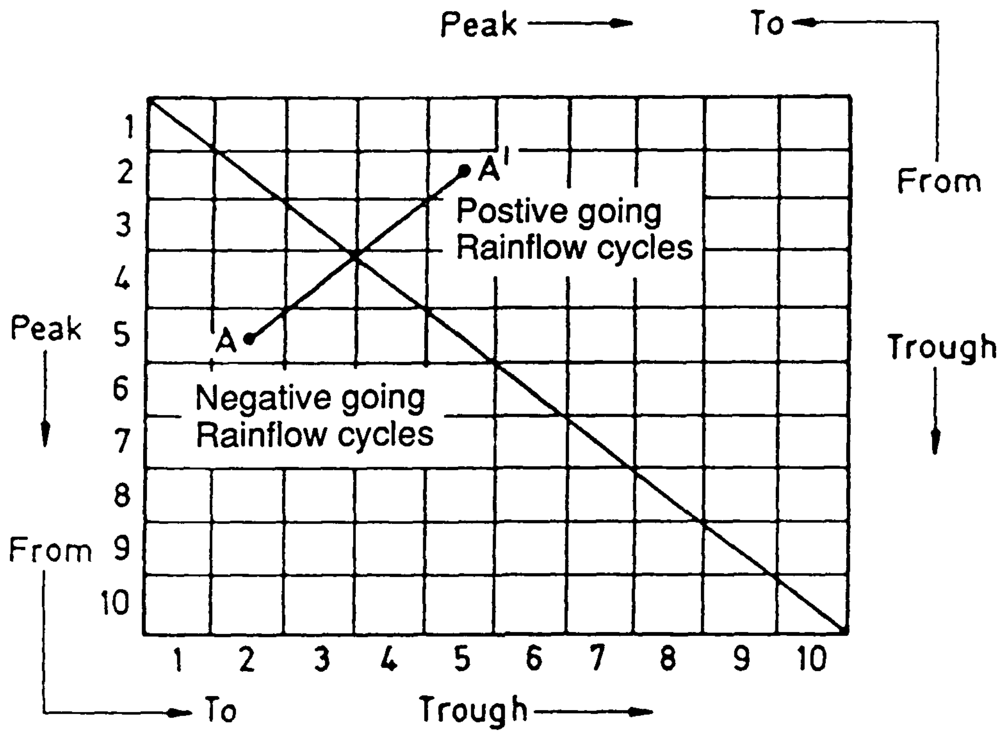


Fig 7 Directional properties of embedded constant amplitude blocks

Fig 8



Element A = peak of 5 to a trough of 2

Transpose element A' = trough of 2 to a peak of 5

Fig 8 Peak-trough matrix for storing directional Rainflow cycles

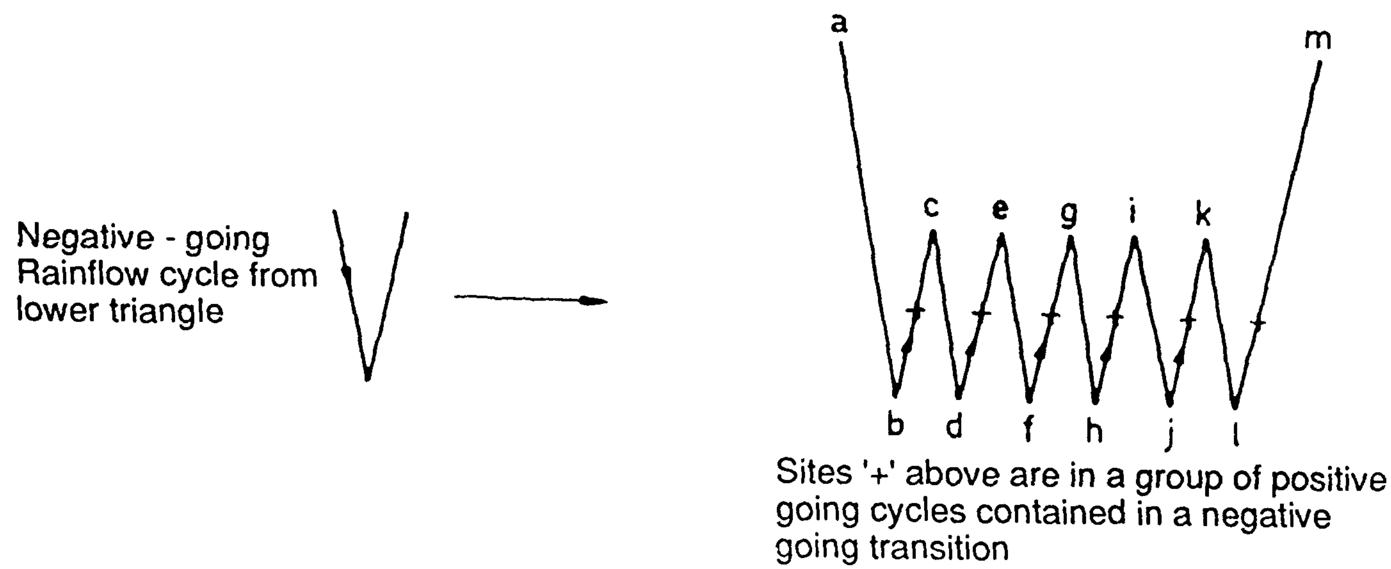


Fig 9a **Ambiguous directional insertion**

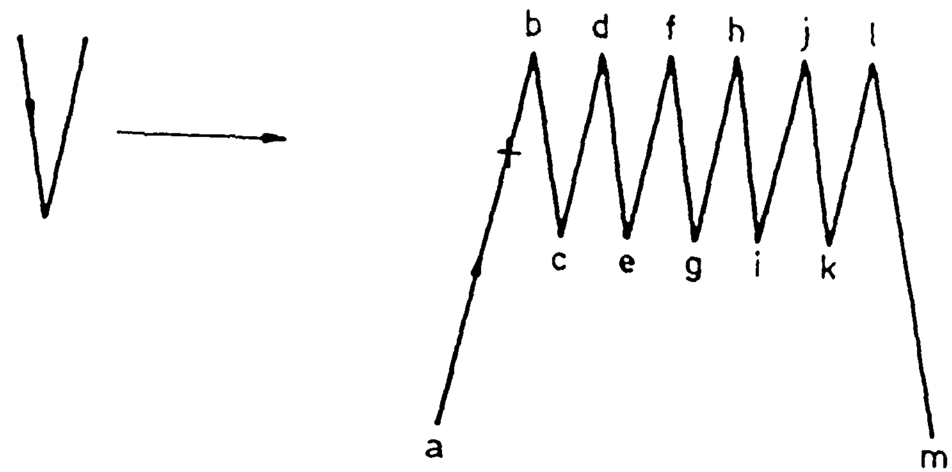
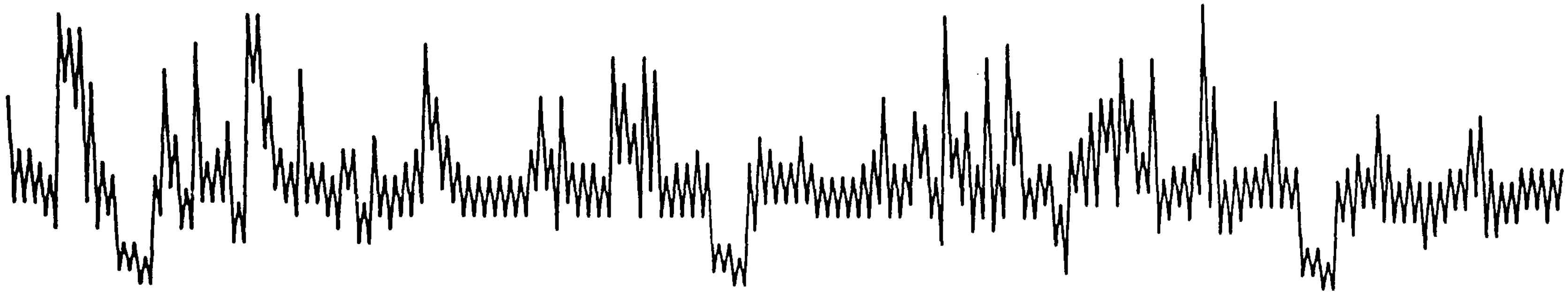
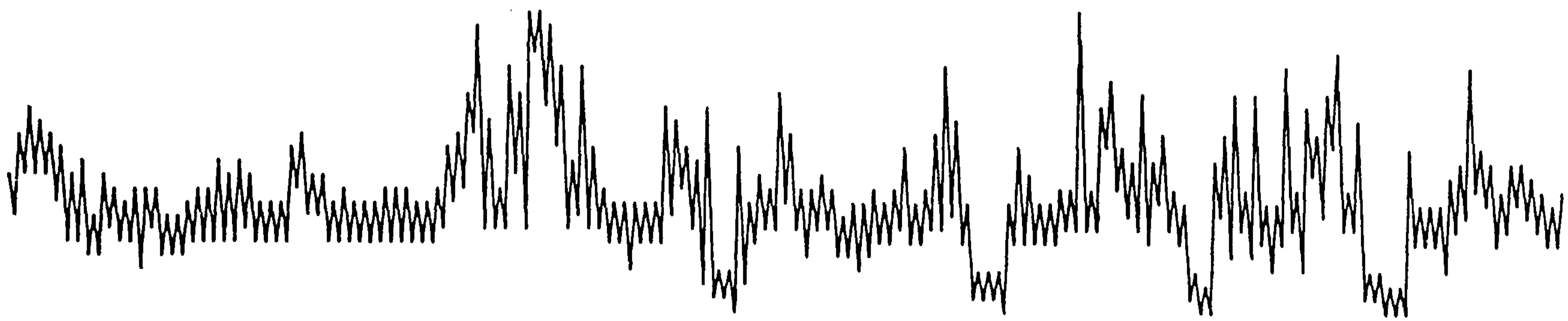


Fig 9b **Unambiguous directional insertion**

Fig 9a&b



Part of the sequence FALSTAFF



Part of the sequence DIRECTFALS

Fig 10 Samples from the two random sequences FALSTAFF and DIRECTFALS

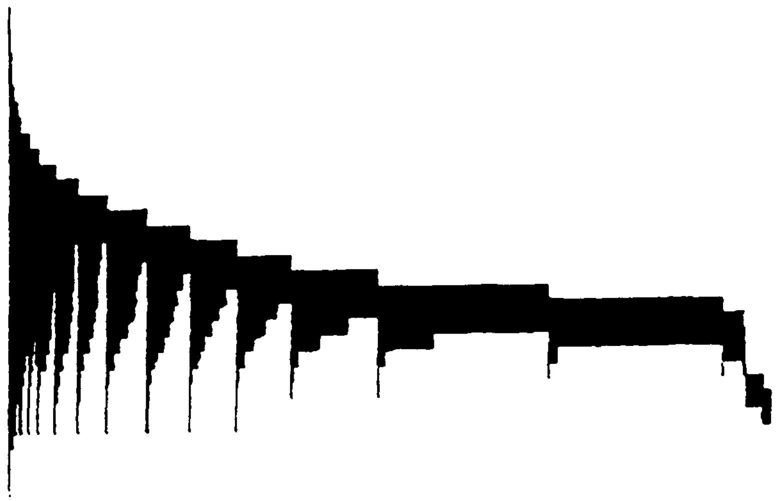


Fig 11a The complete sequence DECAY

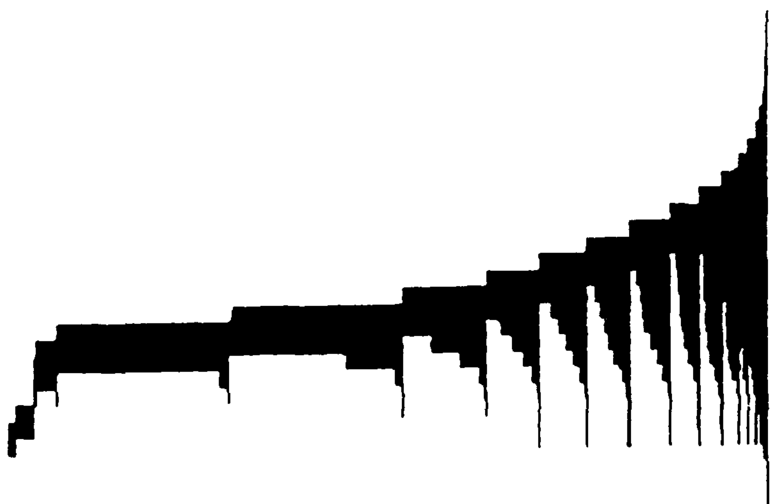


Fig 11b The complete sequence DIVERGE

Fig 12a&b

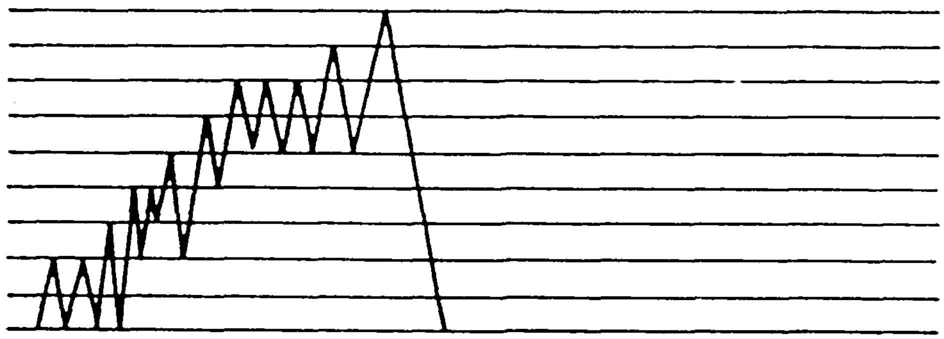


Fig 12a A typical waveform derived from insertions in the positive going side of a containing cycle

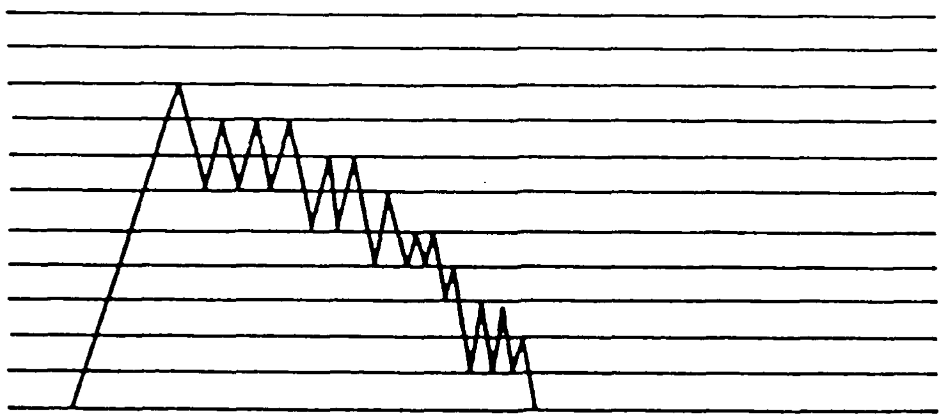


Fig 12b A typical waveform derived from insertions in the negative going side of a containing cycle

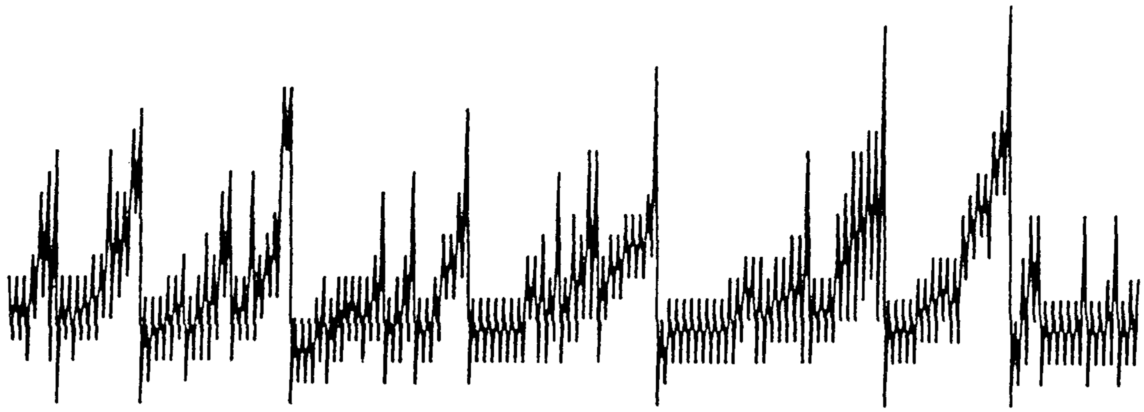


Fig 13a Part of the extreme sequence FALSUP

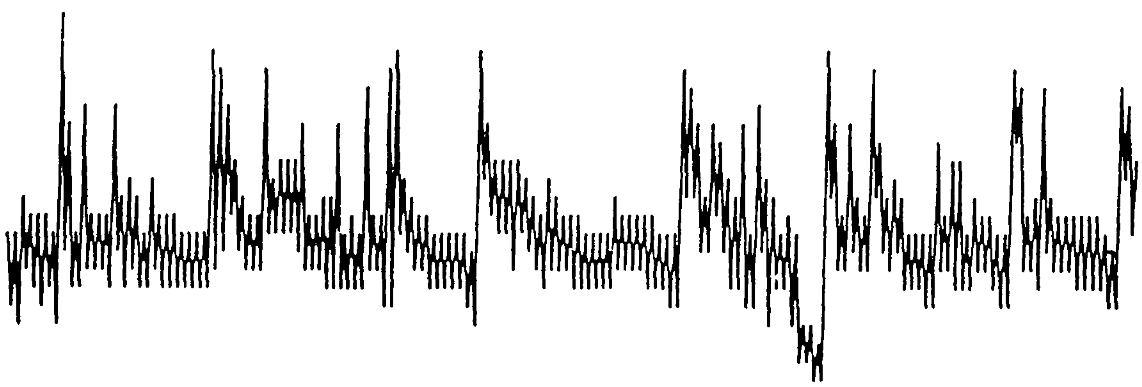
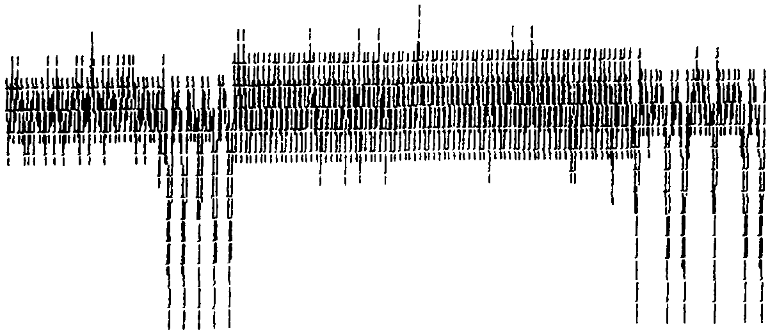
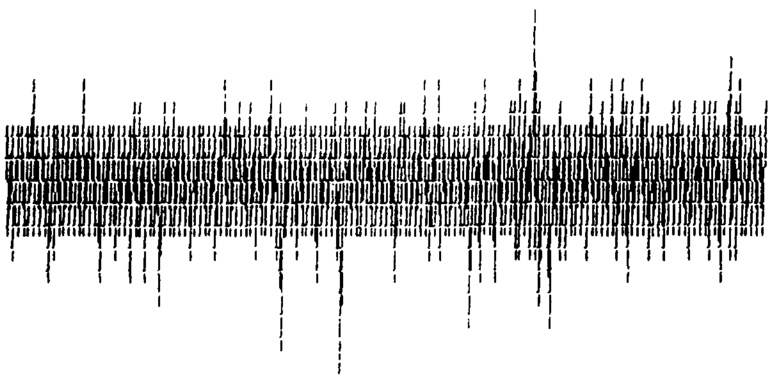


Fig 13b Part of the extreme sequence FALSDOWN

Fig 14



Part of the sequence MINITWIST



Part of the sequence MINITWIST

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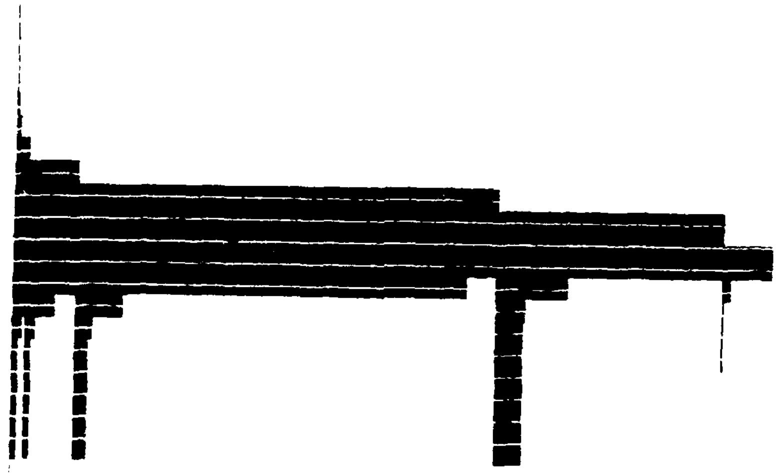
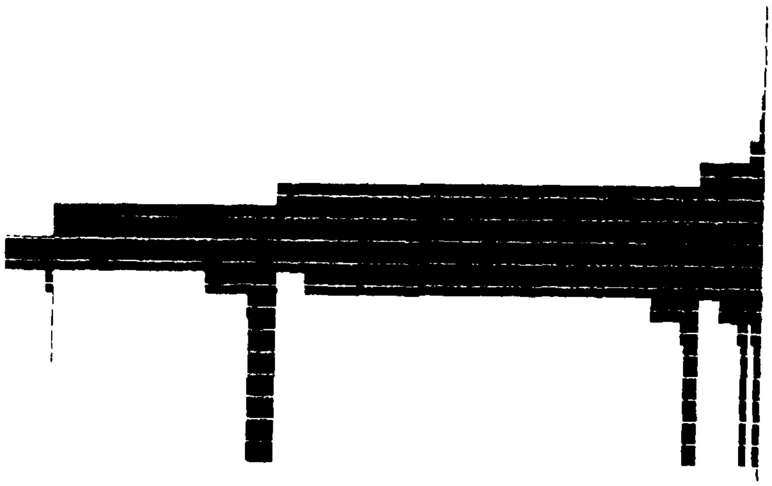
Fig 14 Two samples from the sequence MINITWIST



a) The complete sequence MINI decay



b) The complete sequence MINI diverge

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Fig 15 The two highly structured reconstitutions of the MINITWIST sequence

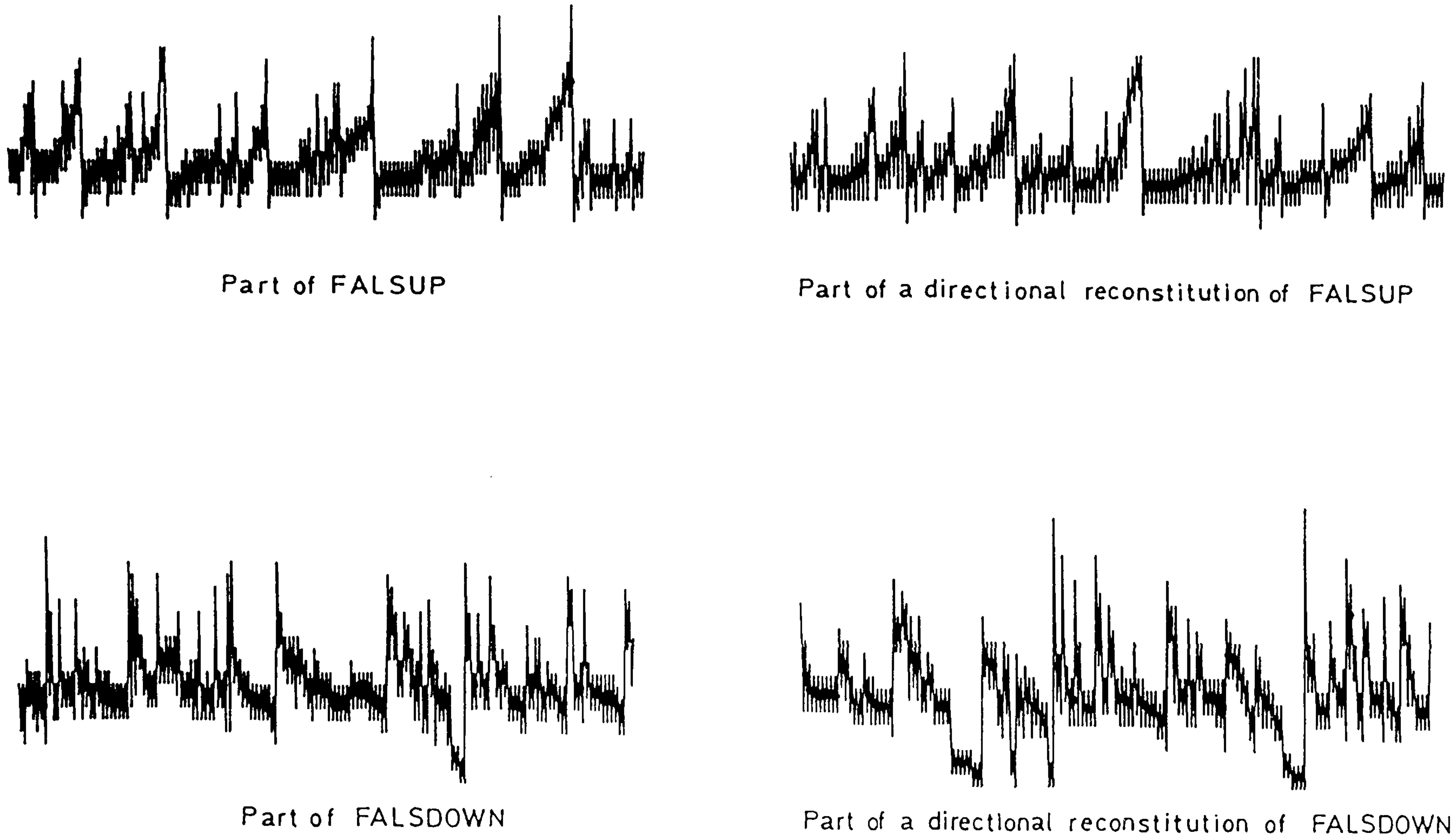
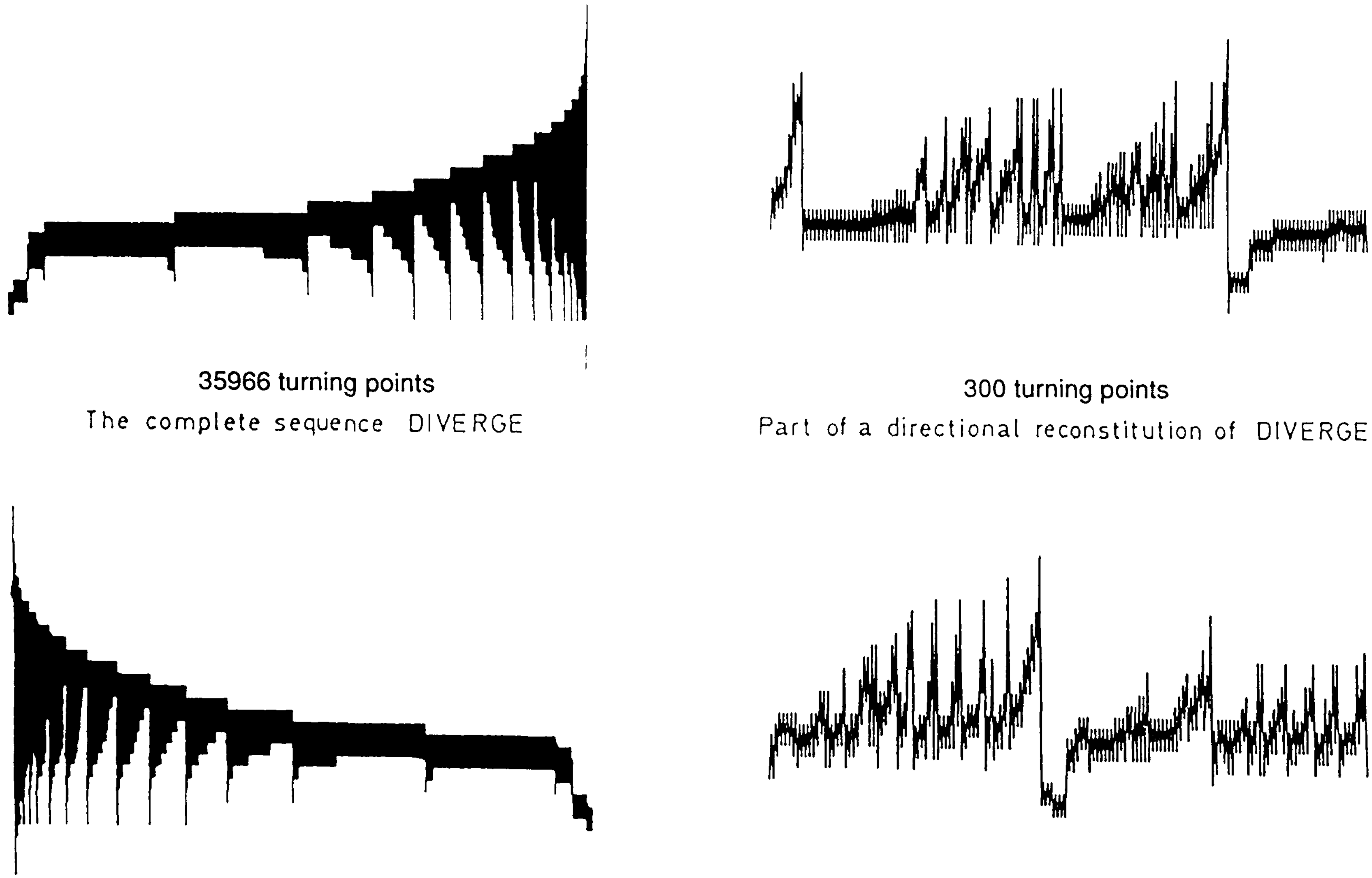


Fig 16 Samples from the extreme sequences FALSUP and FALSDOWN and their directional reconstitutions



35966 turning points

The complete sequence DIVERGE

300 turning points

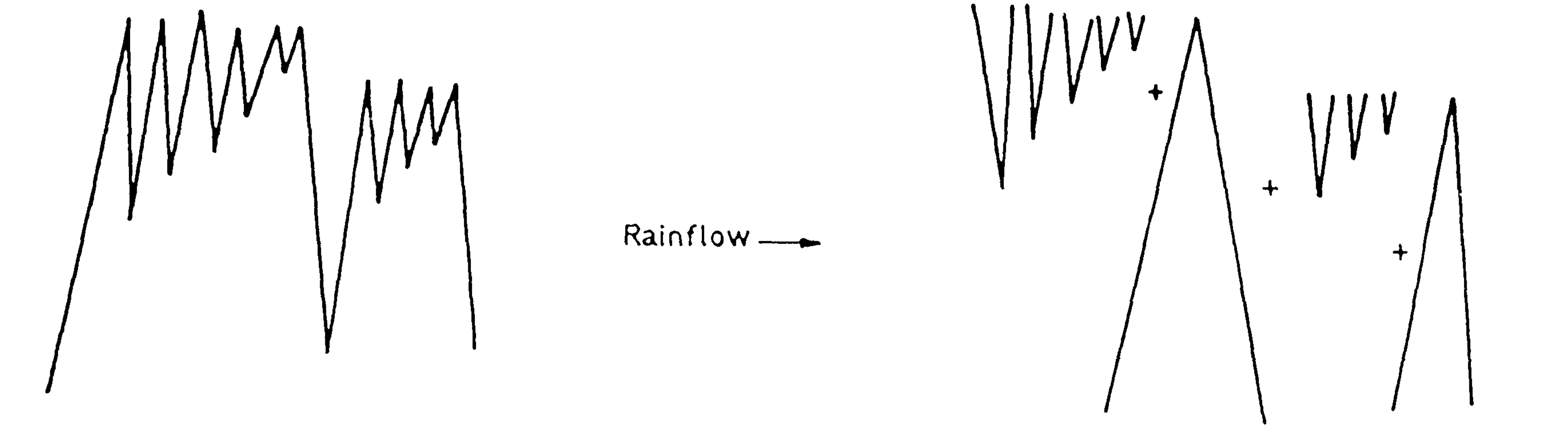
Part of a directional reconstitution of DIVERGE

The complete sequence DECAY

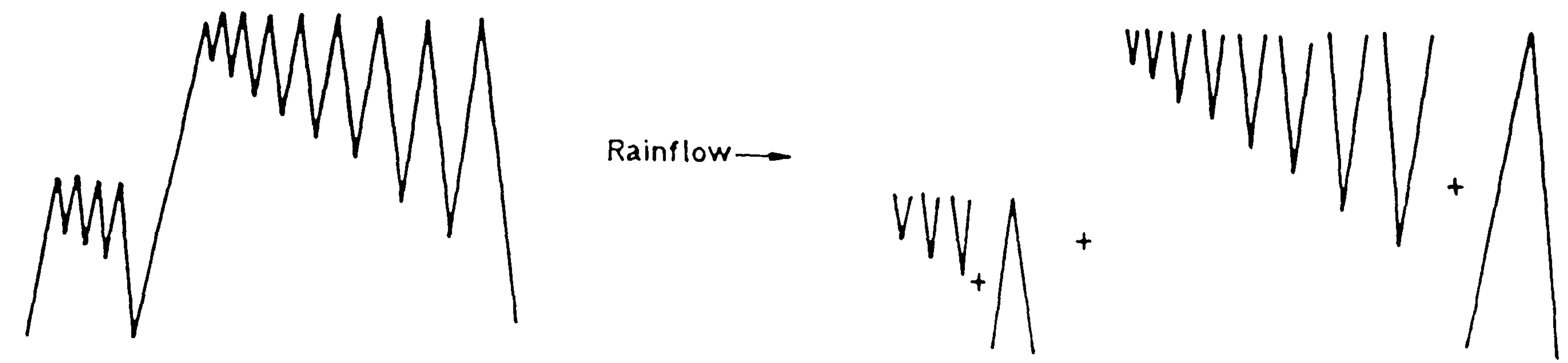
Part of a directional reconstitution of DECAY

Fig 17 Directional reconstitutions from DECAY and DIVERGE

Fig 18



Characteristic feature of DECAY



Characteristic feature of DIVERGE

Fig 18 The general structure of the sequences DIVERGE and DECAY

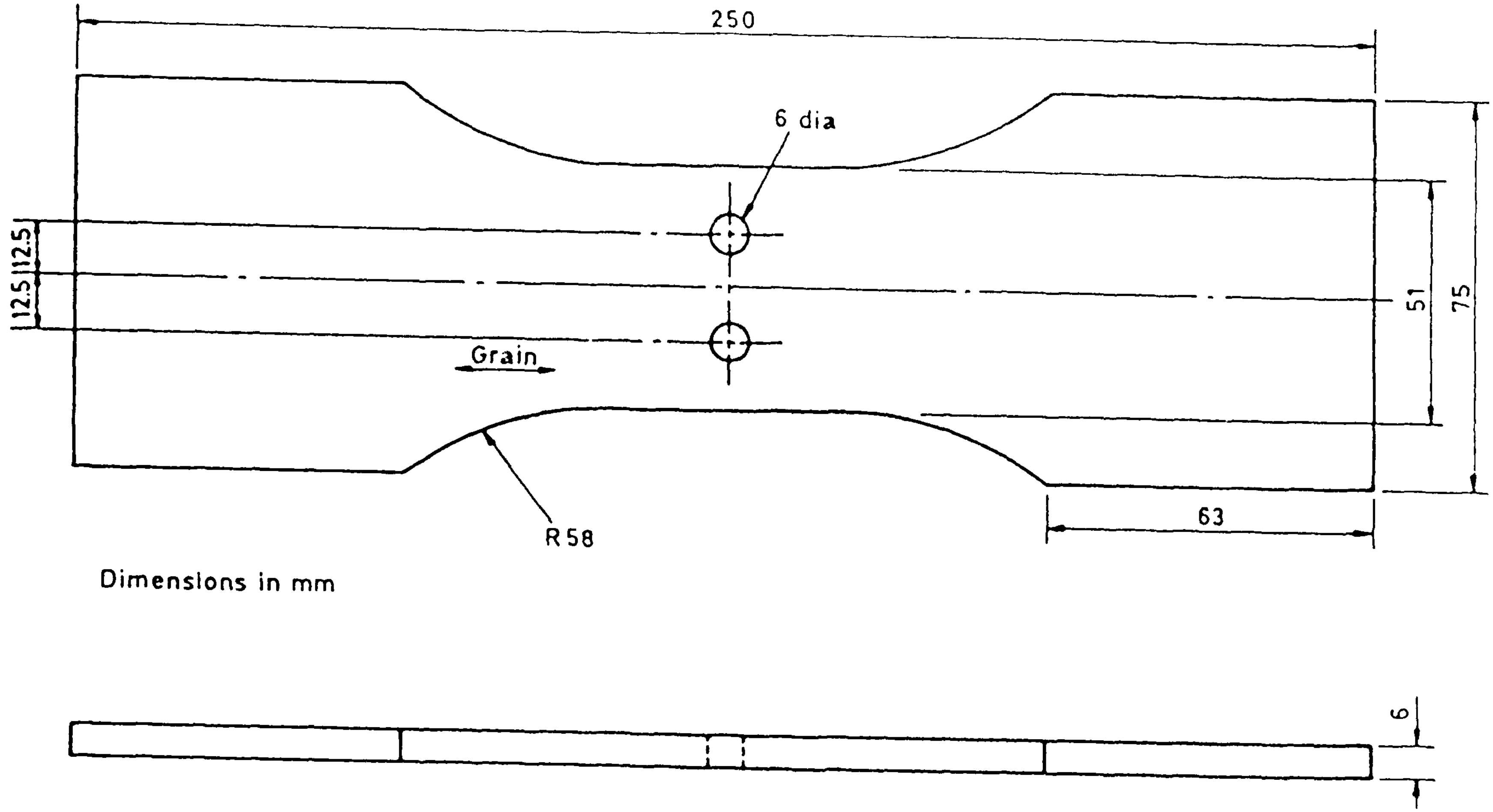


Fig 19 The open hole coupon specimen

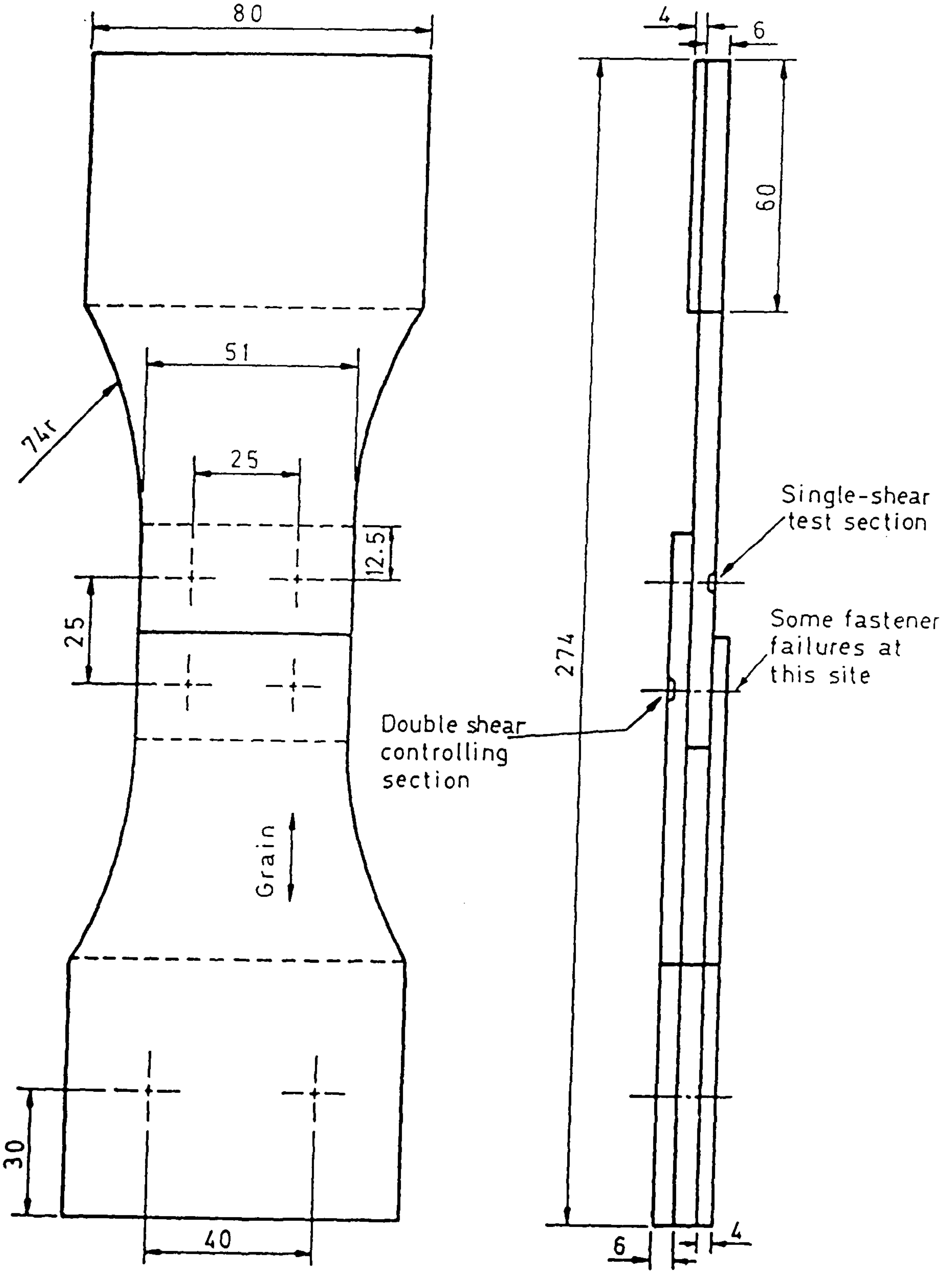


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Fig 20 Q-joint specimen

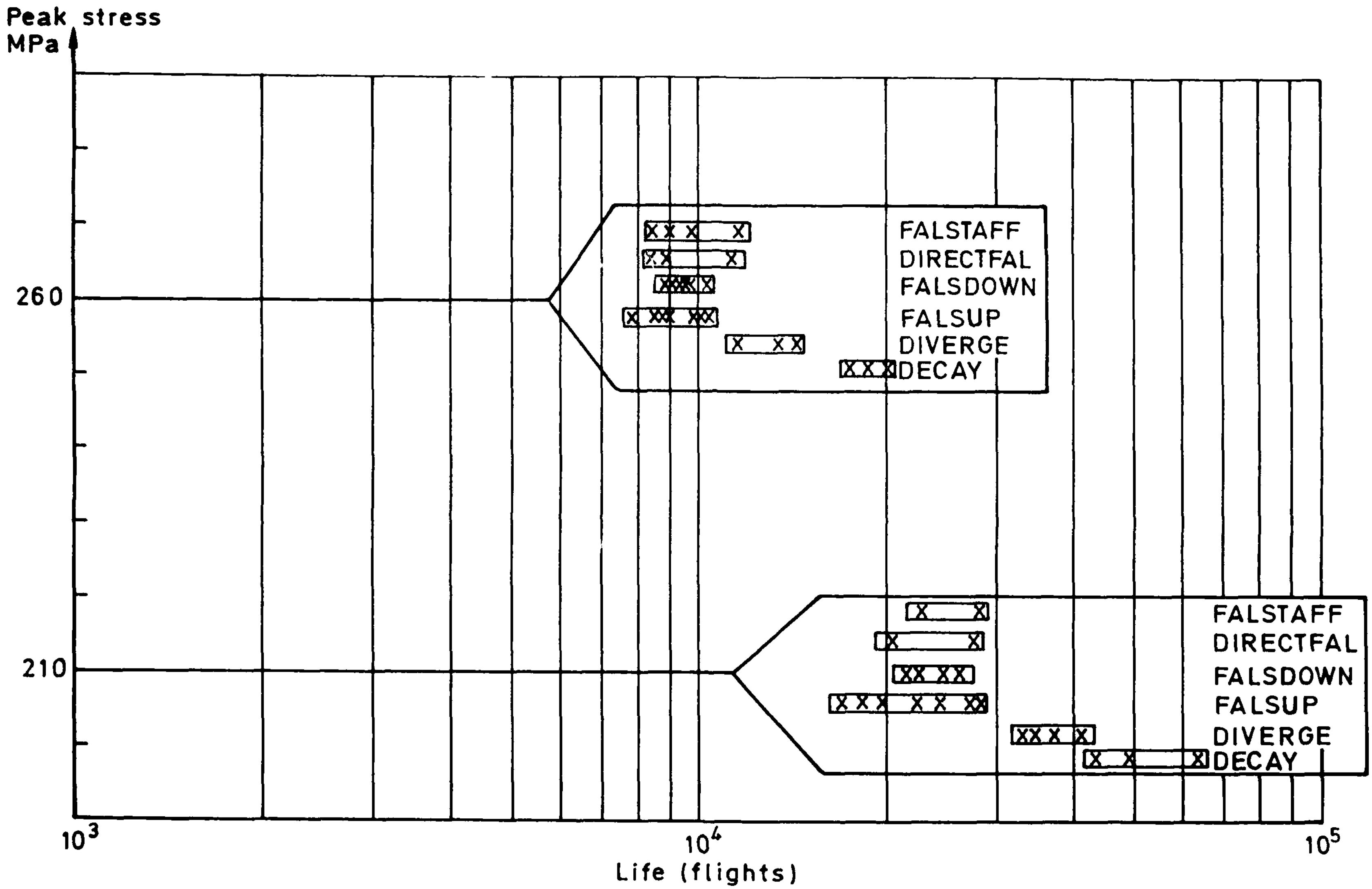

Fig 21 Fatigue test data for the open hole coupon specimen under various sequences having the same Rainflow count as FALSTAFF

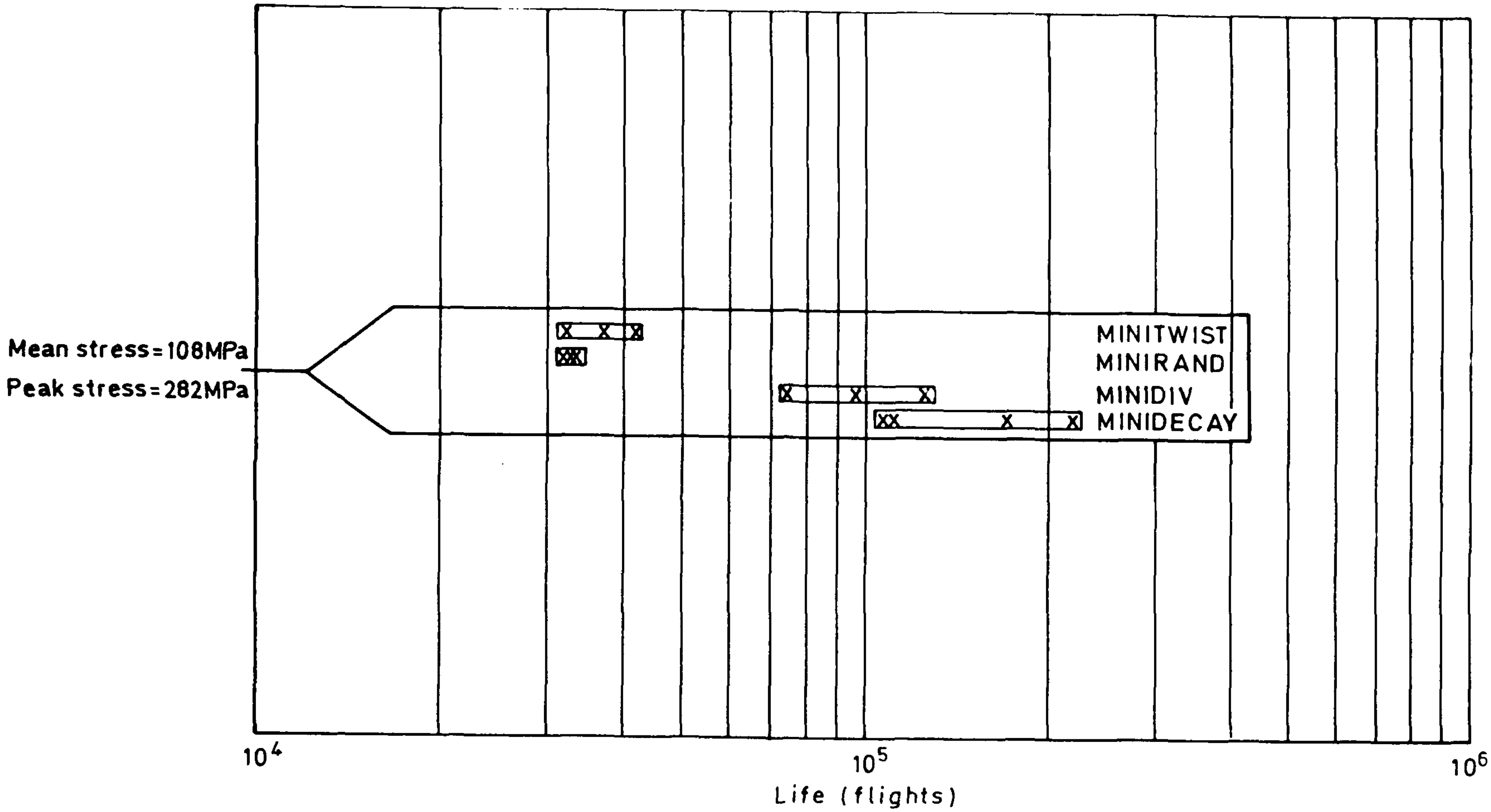

Fig 22 Fatigue test data for the open hole coupon specimens under various sequences having the same Rainflow count as MINITWIST

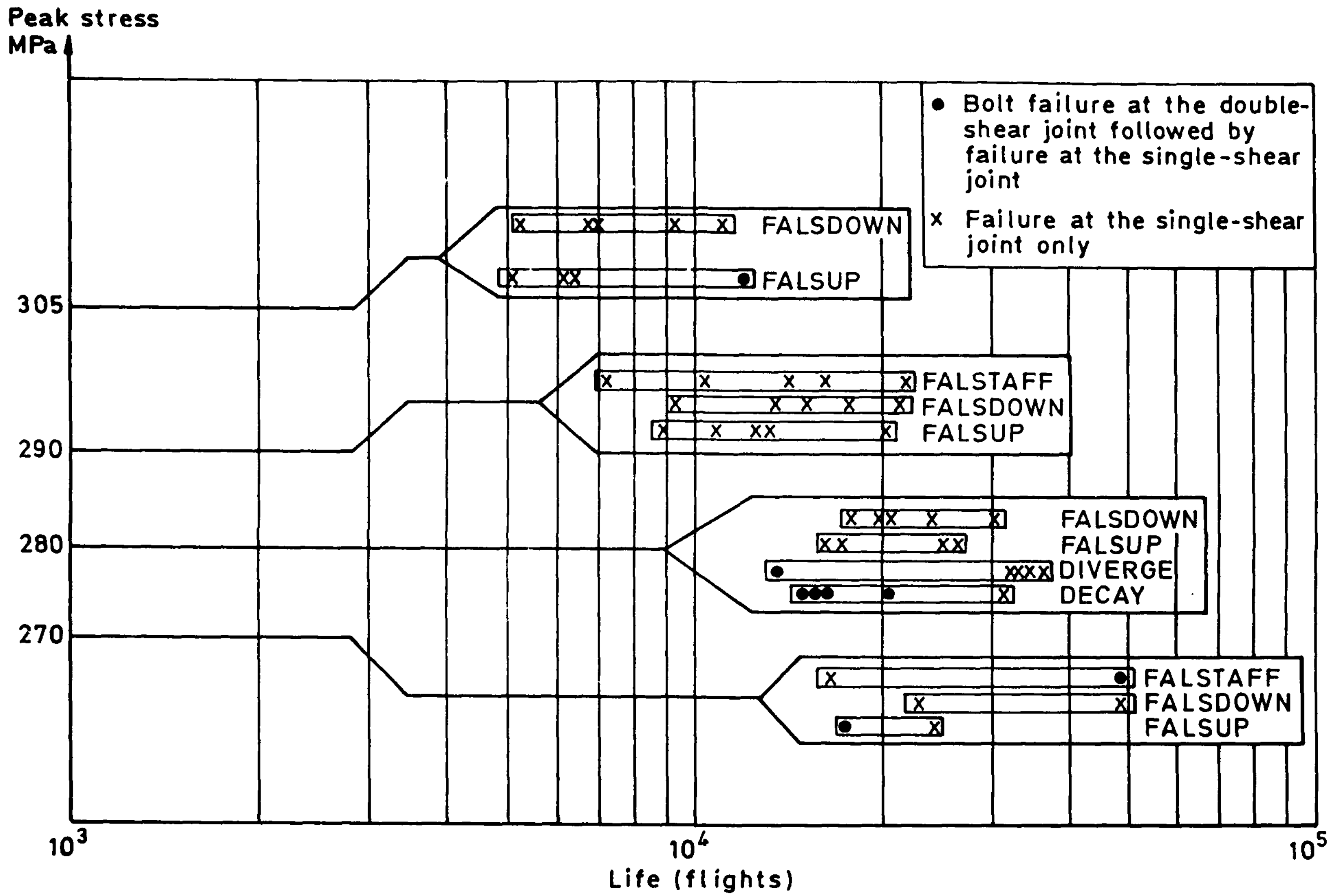

Fig 23 Fatigue test data for the Q-joint under various sequences having the same Rainflow count as FALSTAFF

Fig 24

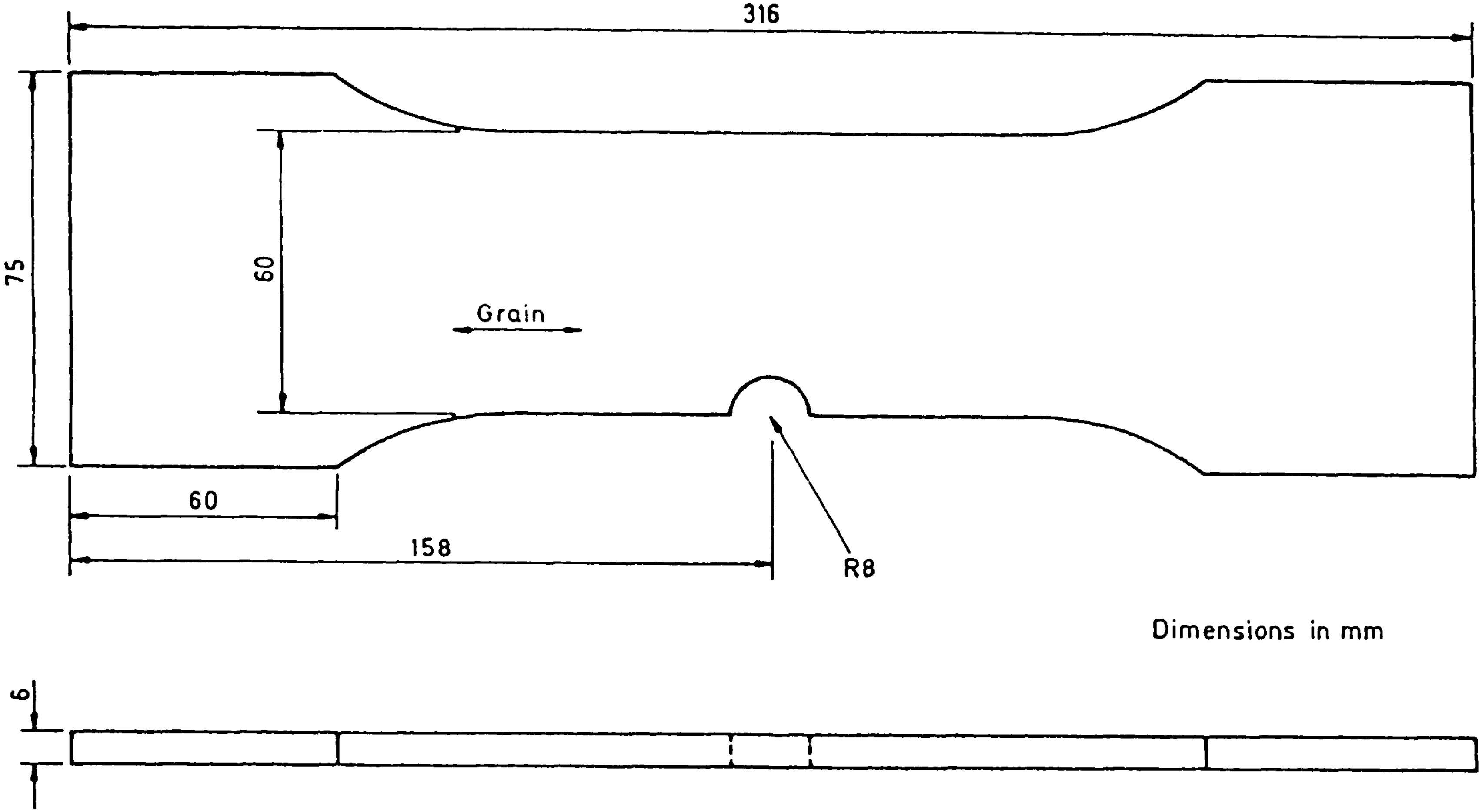

Fig 24 The side-notch specimen used for crack propagation tests

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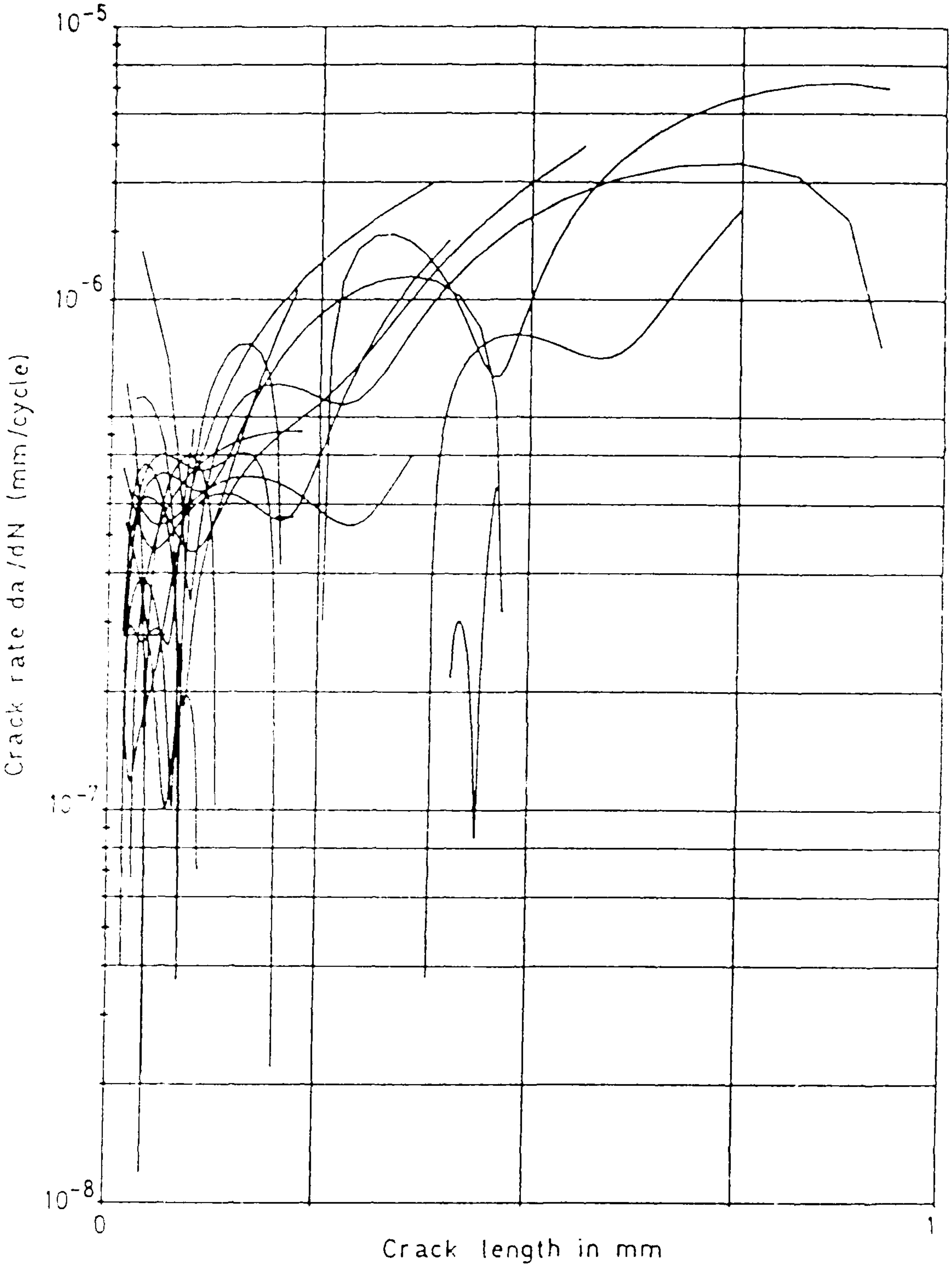

ML3 (cracks 0-1mm)

Fig 25 Typical early crack growth behaviour for multiple cracks in the side-notch specimen

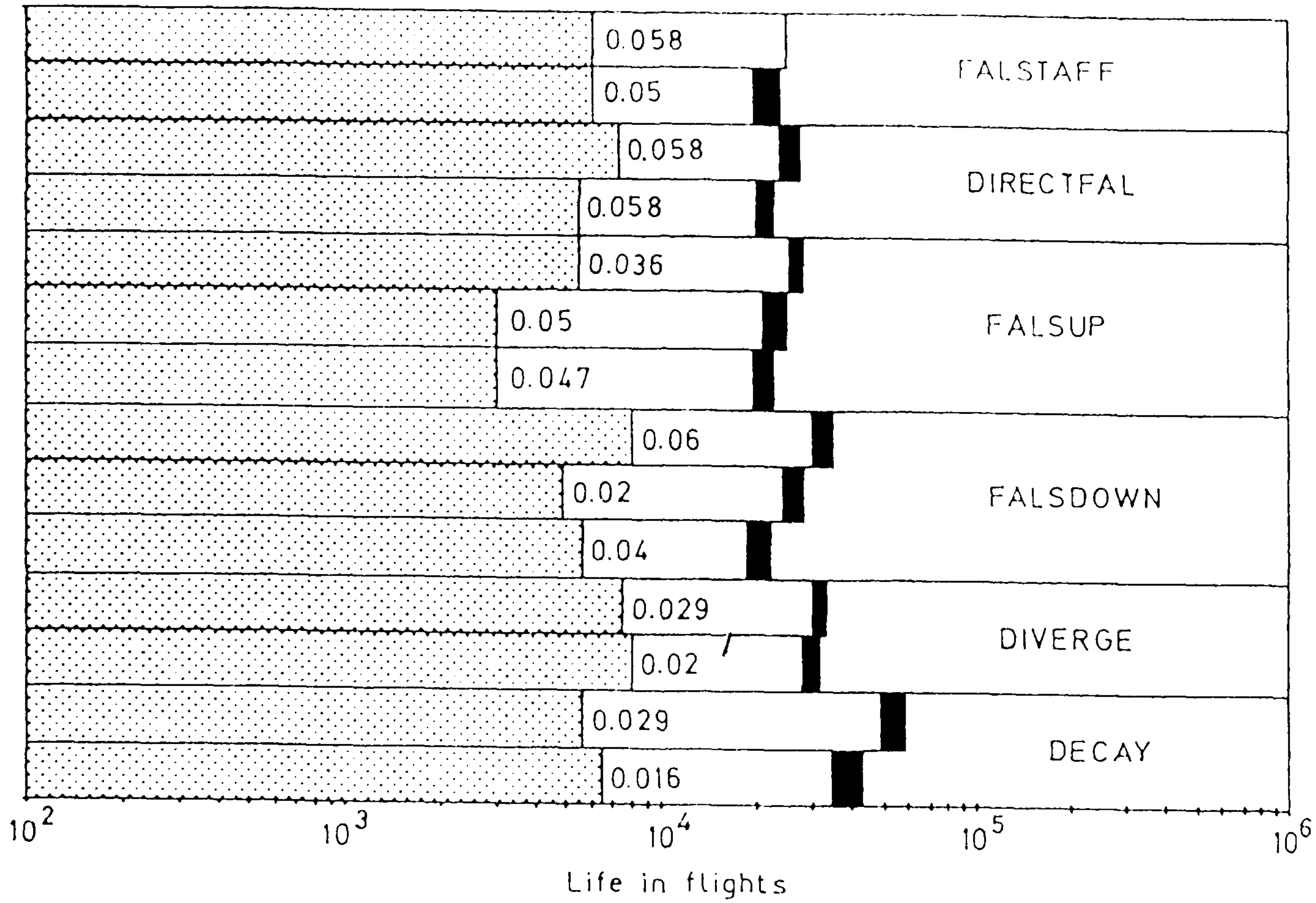

Fig 26 Crack formation and growth behaviour for the 2024-T351 side-notch specimen under various sequences having the same Rainflow count as FALSTAFF