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AGARD REPORT No.731

Structures and Materials Panel Working Group 22 on Aircraft Operations on Repaired Runways

(L'Exploitation des Aéronefs sur les Pistes Refaites)

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.731

Report of Working Group 22 of the Structures and Materials Panel

Aircraft Operations on Repaired Runways

(L'Exploitation des Aéronefs sur les Pistes Refaites)

Edited by

Duncan J.Eckford

This Report was sponsored by the Structures and Materials Panel of AGARD.

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Preface

In recognition of the need to improve the procedures for the assessment of aircraft for repaired-runway operation the AGARD Structures and Materials Panel held meetings to review the methods used within the NATO nations and to promote the exchange of information between them. The outcome of those meetings is represented by the papers in AGARD-CP-326. However, it appeared that further progress was necessary towards the establishment of common approaches to designing aircraft for an environment which exhibited wide variability in runway repair methods and standards, to deriving data on aircraft capabilities and to presenting those data so that they could be related to particular runway characteristics and thus be used to determine the viability of desired operations. Accordingly, a Working Group was set up with the objective of developing design requirements and qualification methods the application of which across NATO would improve aircraft utilization and interoperability. This report presents the findings of that Working Group, which met between April 1983 and July 1986. The members of the Working Group are listed below.

Dr J.J.Olsen	– USA (Chairman)
B.W.Payne	– UK (Technical Chairman)
Y.Martin-Siegfried	– France
A.J.Krauss	– Germany
M.Hacklinger	– Germany
C.Altare	– Italy
Dr R.Freymann	– Luxembourg
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R.F.Buttles	– USA
B.M.Crenshaw	– USA
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M.W.Skinner	– USA
A.V.Petersons	– USA

Many thanks are extended to all who participated in the Working Group, especially to Mr D.Eckford (UK) who acted as editor of the report.

J.J.OLSEN
Chairman, Working Group 22

Préface

Pour répondre à la demande qui se fait sentir pour l'amélioration des procédures d'exploitation des aéronefs sur des pistes réparées, le Panel AGARD des Structures et Matériaux a organisé des réunions pour faire le point sur les méthodes employées par les pays membres de l'OTAN et pour promouvoir des échanges d'informations.

La publication AGARD-CP-326 résulte de ces réunions.

Néanmoins, du progrès restait à faire pour établir une approche commune sur les questions suivantes:

- la conception des aéronefs dans un environnement soumis à l'influence de la grande diversité de standards et des techniques de réflection des pistes
- en déduire les données sur les performances des aéronefs et
- la présentation de ces mêmes données de telle sorte qu'elles correspondent à des caractéristiques de pistes d'atterrissage spécifiques et qu'elles puissent être utilisées pour l'exploitation dans les opérations prévues.

Par conséquent, un groupe de travail a été constitué avec pour mandat d'élaborer des études de concept de spécifications et des procédures d'essai de qualification dont la mise en application par tous les pays membres de l'OTAN permettrait une meilleur interopérabilité et une plus grande utilisation des avoins en service.

Ce rapport présente les conclusions du groupe, qui s'est réuni plusieurs fois pendant la période avril 1983—juillet 1986. La liste des membres s'établit comme suit:

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1 INTRODUCTION

The dependence of most modern military aircraft upon specially provided surfaces for ground operation makes their destruction an attractive option for the restriction of effective sorties by an enemy. From the viewpoint of the force whose airfields have been attacked the need is to restore those surfaces to an adequate standard as quickly and economically as possible. The expediency of remedial measures depends both on the available repair techniques and on the capabilities of aircraft to operate from surfaces which exhibit deficiencies in smoothness and/or strength. Ideally, then, the design of aircraft which might be required to operate from damaged and repaired runways and the development of methods of runway repair should go hand in hand from an agreed common target of repaired-surface quality; in practice, however, such a requirement has not hitherto been considered in aircraft design, and repair techniques have been aimed at the goal of complete restoration but without explicit consideration of the benefits for aircraft capability of apparent improvements. The capabilities of individual aircraft types operated by a particular nation have been evaluated against the repair standards which they were fielding at the time. Clearly that is a far cry from the requirement within an alliance such as NATO to be able interchangeably to operate various aircraft from the airfields of various nations.

In seeking to define a unified approach to the problems of design, assessment and utilization of aircraft for repaired-runway operations the Working Group members offered experience in structural dynamics, in landing-gear design and in aircraft clearance and certification related to ground operations. Their aims were to distil that experience into an exposition of the important features of the operating environment, to relate them to the behaviour of aircraft and landing gears, as influenced by current design requirements, and to assess methods for establishing aircraft capabilities by calculation and test. The apposite presentation of those capabilities could then be discussed. Alleviation of the limitations found with typical current landing gears was to be considered. Finally, design requirements which accommodated operations from repaired runways were to be formulated.

This report develops and illustrates the subject of repaired-runway operation — its Sections reflect the various above aims while the Appendixes amplify particular aspects. Throughout, topics are discussed from fundamentals so that it may provide an introduction to the structural and dynamical implications of repaired-runway operation as well as a statement of the current level of development of techniques in design, assessment and operational clearance.

The production of the operational environment from damage by a variety of weapons and subsequent repair is described (Section 2 and Appendix 1) and its influences on aircraft operations outlined. The sources of the operational limitations imposed by critical responses and loads are then considered in Section 3: the use of mathematical modelling (see also Appendix 2) supported by component tests and aircraft trials (see also Appendixes 3 and 4, respectively) in determining those limitations is discussed. The relevance to repaired-runway operation of current design requirements is reviewed, with particular consideration of the ground profiles they define (Section 4). The basis of the design of landing gears typical for current military aircraft is discussed in Section 5 — data on their basic characteristics are given therein for a large number of aircraft, while Appendix 5 details two designs. The determination and utilization of the aircraft capabilities which result from current design requirements and practices are considered (Section 6), for which the concept of relating those capabilities to encounters with 'standard bumps' in the ground profile is introduced. (The development and definition of such standard bumps is fully described in Appendix 6.) The topic of Interoperability is considered in Section 7; the requirements for data presentation are discussed and an overall framework is developed, again referring aircraft capabilities to standard bumps. Two possible approaches within that framework are described in detail and compared for the extent to which they permit the exploitation of aircraft capabilities and for the demands which they make for their application. The data presentations which are yielded by those approaches are given in Appendix 7 for two aircraft types. Improvements in landing-gear design which would extend the capabilities of aircraft to cope with runway repairs are considered in Section 8. Section 9 defines a set of requirements which might be applied to the design of aircraft to operate from repaired runways — the rationale behind each case specified is given.

2 THE REPAIRED-RUNWAY OPERATIONAL ENVIRONMENT

The repaired-runway environment is one which has not been expressly considered in the design of any current aircraft. This Section briefly describes the runway damage and the repair techniques which lead to that environment. The general problem of establishing aircraft operations is discussed wih reference to the influence of the properties of the repaired runway and of operational techniques.

2.1 The repaired-runway environment

There are three classes of weapon which may cause damage to runways: those which impact on the surface, those which explode on the surface and those which explode in or below the surface layer. The first group is exemplified by some types of gun projectiles, weapons which fail to explode and fragments from larger weapons which explode nearby. The resulting craters are usually quite small and are often termed 'spalls' or 'scabs'. Such craters can also be caused by small weapons which explode on the surface. A general definition is that they do not penetrate the thickness of the runway surface layer and do not exceed about 1.5 m in length — because of the former condition there is no associated deformation of the surrounding pavement. The second group, those weapons which explode on the surface, are inefficient in producing runway damage and are normally intended to create other kinds of damage on the airfield. Typical kinds are cannon shells, cluster munitions, unguided rockets, nose-fused general-purpose bombs and area denial mines. Though the craters produced will vary in size depending on the yield of the weapon they are likely to be comparatively shallow and not accompanied by significant surrounding deformation. The final group of weapons comprises those specifically directed at damaging runways, which must penetrate the pavement surface before exploding. That is achieved by kinetic energy or by explosive penetration using a shaped charge. The former can be produced for a free-fall bomb by dropping from medium altitude — around 3000 m — or for a weapon deployed at a lower altitude by a rocket motor. A weapon of this type creates a deep crater which is usually associated with a considerable amount of upheaval of the surrounding runway surface. Fig 2.1 shows the likely form of such a crater together with the definitions of various features (following Ref 2.1, Paper 3).

In the aftermath of an attack using specialized weapons the airfield commander will be faced with widespread damage to the airfield and its services, which may be aggravated by the use of area-denial and delayed-action munitions, chemical weapons, ground attack by specialist forces and radio communications jamming. That is often called the 'post-attack environment'. The repair task in general is termed 'airfield damage repair' (ADR), which encompasses both the restoration of essential services and the repair of aircraft operating surfaces (RAOS). It is the latter aspect which is the subject of this discussion. Ideally the damage would be rapidly repaired and the airfield would resume its normal functions. The longer the repairs take the more potential aircraft sorties are lost and the greater is the likelihood of a follow-up attack before the airfield can be reopened. Speed of repair is therefore essential but first there must be a decision on which craters are to be repaired, access to the craters for repair plant must be established and the risk to plant and personnel must be reduced to an acceptable level by explosive ordnance disposal (EOD). The critical activity is the decision making since the others are dependent upon designation of the specific areas involved. That process must be based on accurate assessment both of the damage resulting from the last attack and of the preceding state due to previous damage. Assessment can be based on data from various sources ranging from sketch plans produced by a man on foot to computer processed output from special electro-optical reconnaissance systems, but the stages in the process remain the same. The RAOS command centre requires the following information: the positions and types of damage to the operating surfaces, the resources (personnel, plant and materials) available to effect repairs and their locations, the threats to those resources from unexploded ordnance, chemical warfare agents and ground forces, and the types, configurations, numbers and locations of aircraft for which the airfield is to be repaired and the dimensions of the minimum operating strip (MOS) which they require. Given that information a repair plan must be produced on the criterion of minimising a certain 'cost' — generally the time to reopen the airfield but possibly also accounting for the amount of material used and the risk to repair resources.

For many reasons each NATO nation has its own methods for RAOS although the basic principle is the same, giving a typical section of a repair as shown in Fig 2.2 (from Ref 2.1, Paper 3). The technique consists of removing excess debris and unacceptably upheaved pavement and filling the crater before covering with a cap which has sufficient structural strength to withstand both the overall wheel load and the tire contact pressure. The cap must also prevent the scattering of fill material since that would pose a hazard to the aircraft from foreign-object damage (FOD). For 'scab' craters a single agent usually provides both filling and capping, except in one method which uses steel plates to 'bridge' the crater. For large craters the cap can be metal (e g Class 60 trackway, AM-2 matting or steel matting), fibreglass matting, a plastic membrane, concrete slabs, high alumina or vacuum de-watered concrete, or other quick-setting, high-strength material. The fill material usually incorporates graded aggregates or crushed rock, possibly supplementing crushed debris from the crater. All the various repair methods have their own advantages and disadvantages and each yields a typical residual surface roughness characteristic. Appendix 1 gives a detailed discussion for each. Still further variations can be expected in the future as each nation strives to improve the efficiency of its repair techniques.

The development of better runway repair methods will be paralleled by improvements in the technology of runway cratering weapons so that in the foreseeable future the ability rapidly to reopen a runway after an attack will be determined by the capabilities of aircraft to cope with crossing repairs of a particular degree of roughness.

The capabilities of current aircraft vary widely; however most combat aircraft cannot tolerate adversely spaced multiple repairs to current standards when at normal operational mass. To ameliorate that situation requires one of four courses of action. First, the quality of the repairs could be improved but that carries penalties in time for making them initially and for maintaining their standard. Second, the mass of the aircraft could be reduced to make it more tolerant to roughness but the reductions in range and/or payload would lessen sortie effectiveness. Third, the MOS could be chosen to avoid critical repair spacings but the additional constraint on MOS selection could adversely affect the 'cost' of its establishment. Fourth, the manner in which the aircraft is piloted may be changed by specifying non-standard use of, for example, wheel brakes or reverse thrust but that would probably be of only limited effectiveness and might require special pilot training and the lengthening of the MOS.

The choice of which of the above courses is used to resolve the problem is dependent on a number of operational factors and will vary from one nation to another; however, to make it informed the effect on aircraft capability of aircraft configuration, repair location and surface roughness must be known for the operational procedures which that nation has chosen to adopt. Conceivably the airfield commander may decide to disregard the level of an aircraft's tolerance to roughness and so risk aircraft damage. That will have to be so if the required information is not available and will anyway become increasingly likely if the credibility or reliability of that information is seen as poor or the complexity of its application is too great. However, it must be realized that it is not just an individual aircraft which is at risk — the repairs made to establish the MOS may be damaged and the strip blocked. Removal of a burning aircraft with a full load of fuel and weapons will not be an easy task!

There are three aspects of runway roughness which affect operations from damaged and repaired runways: the inherent roughness of the runway itself, the roughness due to unrepaired damage and the roughness of repairs. These will be considered individually before looking at their combined effects and discussing restrictions which have been accepted in order to make tractable the analyses of which the results are presented herein. One which should be mentioned is the assumption that both the runway and the repairs are rigid; thus deformations of the surface during the passage of an aircraft have been ignored.

Both repaired and unrepaired damage create discrete obstacles but in contrast the height deviation of the inherent runway profile is of a mainly continuous nature, which gives rise to difficulties in considering in a general way their combined effects. That in practice they cannot be totally divorced has been shown by studies such as that reported in Paper 7 of Ref 2.1, from which Fig 2.3 is taken: the effect of the underlying runway profile on the critical spacing between two repair mats is shown. Some allowance has in the past been made for the errors due to the separation of the two types of roughness by reducing the permissible incremental load by its average excursion due to inherent roughness, on the assumption that there is a low probability of the maximum value of the latter coinciding with the peak load due to a discrete repair. There is no fundamental reason why the effect of a particular runway profile cannot be allowed for in the determination of the acceptability of a particular repair pattern; however, the results would then be specific to that runway and repair location. The level of the inherent runway roughness may be increased in time for two reasons: first, many NATO airbases have taxiways designated for use as emergency runways which are not maintained to the same standards as the main runways and, second, it is possible that a number of adjacent explosions may distort the profile of a runway with a flexible pavement and thus increase its roughness.

2.2 Operational considerations

The way in which an aircraft is operated can have a considerable influence on its ability to cross runway repairs, particularly during the landing roll-out wherein significant effects can be introduced by pilot actions. Fig 2.4 shows an example of the effects of elevator and wheel-brake inputs on the loads over repairs. The use of reverse thrust, wing flaps and brake parachutes and encounters with arrestor gears can also produce significant effects both from changes to the steady balance of the aircraft and from transient conditions. Careful consideration of the training requirements would be necessary before recommending any piloting technique specific to repaired-runway operations: if the efficacy of training could not be relied upon the use of a potentially advantageous technique might be precluded.

The capability to cross repairs is generally reduced as the level of braking is increased; hence during the landing roll-out there is a conflict between those two requirements. When the length of the MOS is determined by take-off requirements that conflict might be resolvable by specifying the braking level as that needed to stop the aircraft within the take-off distance; however, that is an imprecise approach since the pilot's subjective appreciation of deceleration is poor and he finds descriptions such as 'light' or 'medium' braking difficult to interpret. Therefore, for determining the braking distances required it is the lowest interpretation of the description which must be assumed whereas for determining the ability to cross repairs it is the highest.

Another factor which affects the determination of the acceptability of repairs is the accuracy with which the aircraft's ground speed can be predicted. For take-off runs, which can be started at a defined point, the speed at any point on the runway can be fairly accurately predicted if the mass is known and adjustments are made for air density, runway slope and environmental conditions. On landing, however, predictions are much more difficult since there are considerable variations in touchdown speed, touchdown position and level of deceleration. Fig 2.5 gives data for C-130 aircraft landing on a short, narrow runway in good visibility but without approach aids – conditions which are thought to be fairly representative of landing on a MOS. It is seen that at some points on the runway almost the whole range of speeds may apply; thus it is difficult precisely to delimit acceptable repair locations for a landing strip.

REFERENCES

2.1 Aircraft response to damaged and repaired runways, AGARD-CP-326, August 1982

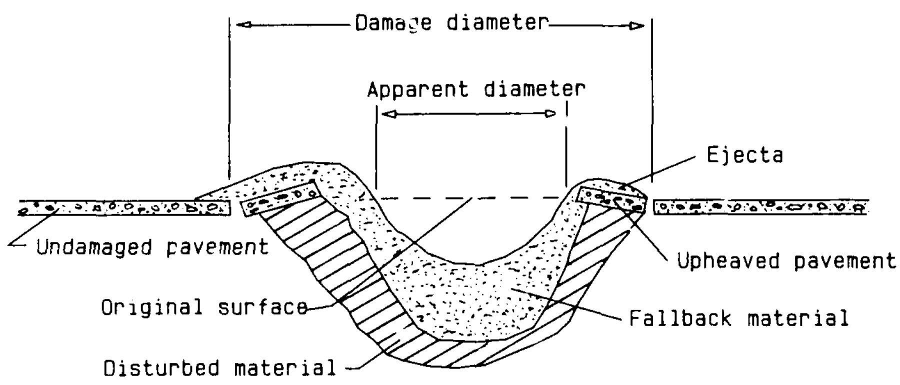


Fig.2.1 Crater features and nomenclature

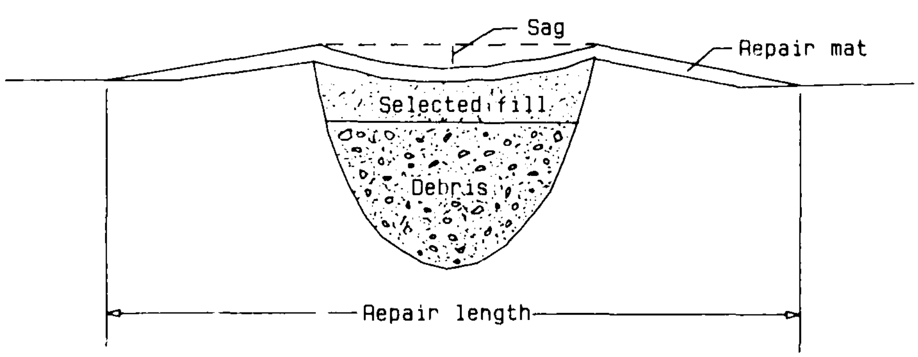


Fig.2.2 Crater repair using mat

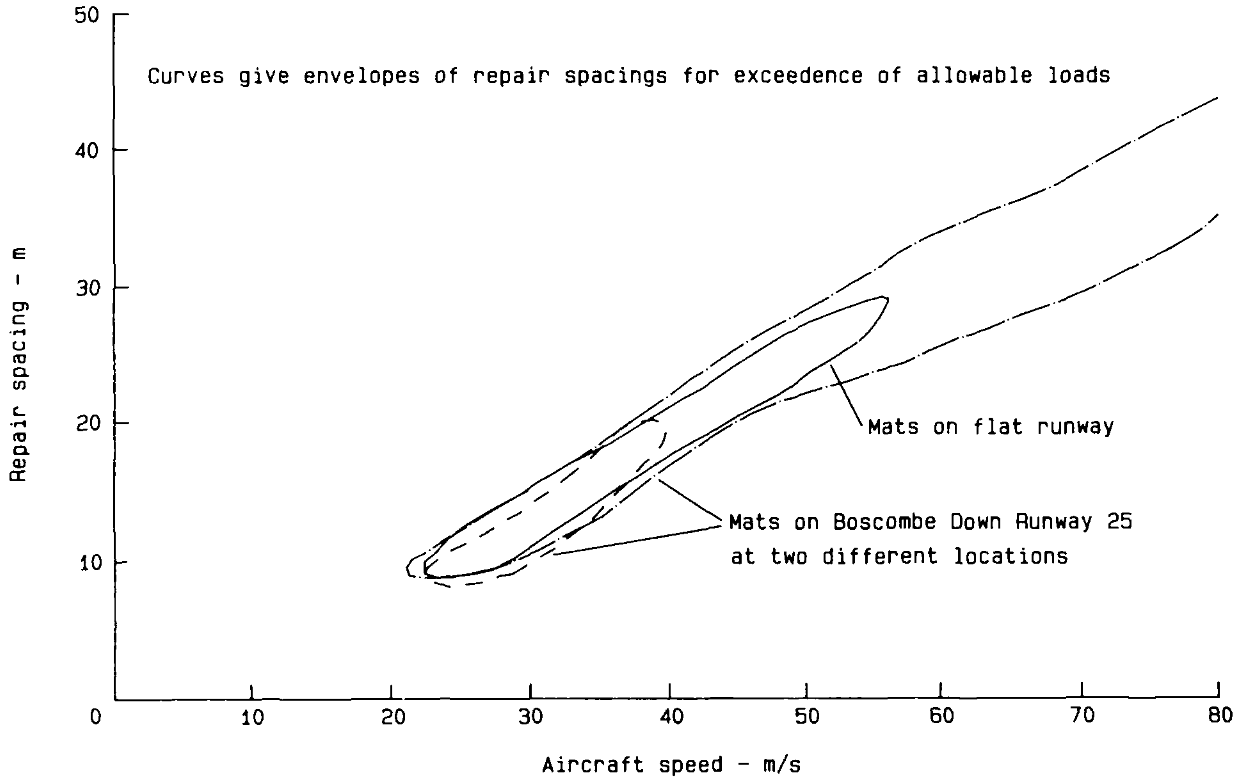


Fig.2.3 Calculated effects of underlying runway profile on critical repair spacings

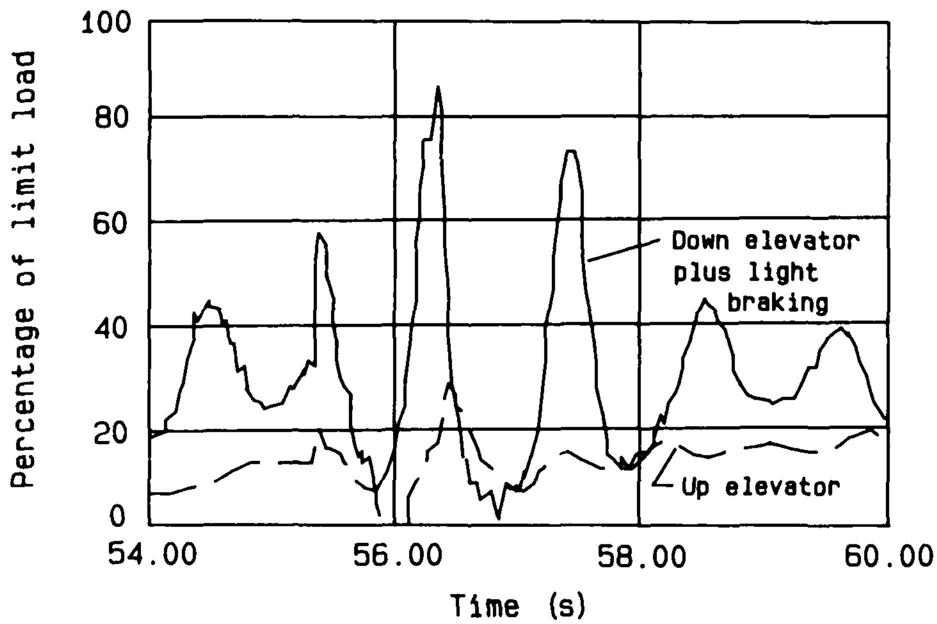


Fig.2.4 Effect of pilot action on loads due to crossing repairs

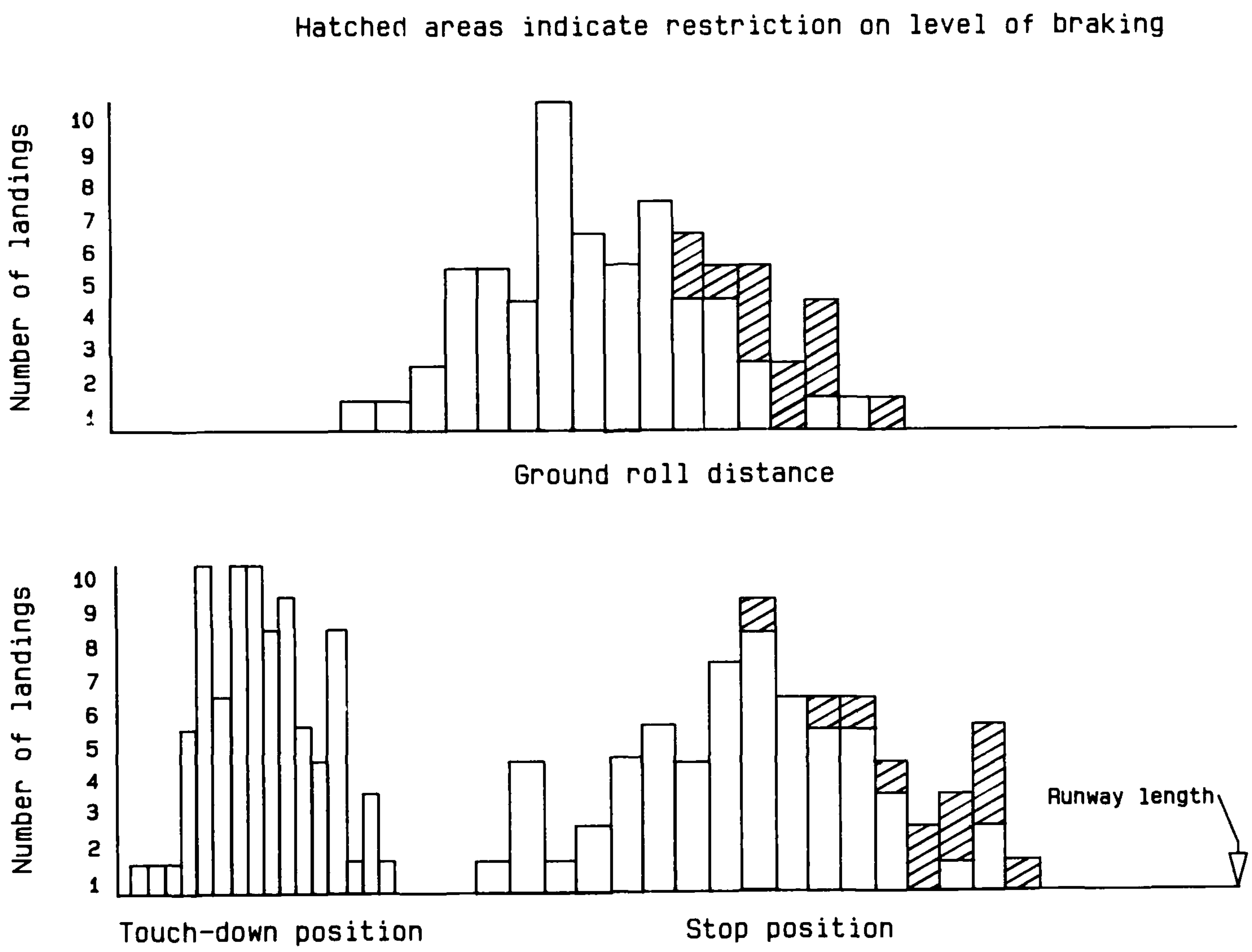


Fig.2.5 Achieved landing performance on a short narrow runway

3 ESTABLISHMENT OF AIRCRAFT CAPABILITIES

Operations from damaged and repaired runways are dictated by the exigencies of wartime situations and therefore inherently allow the full utilization of an aircraft's capabilities up to a point where the risks involve outweigh the operational gains. The determination of those capabilities in such circumstances must be largely based on calculation. This chapter discusses the requirements for analytical modelling in relation to the conditions which occur during the crossing of repairs and approaches to solution are described in general terms. Additional information on the details of modelling aircraft and their components is given in Appendix 2. The use of rig tests to support analytical modelling is discussed herein, while Appendix 3 provides information on current test methods and the capabilities of existing facilities. The role of aircraft tests in providing further such support and in exploring limitations which are not amenable to analytical determination is also considered – Appendix 4 expands on that topic.

The discussions of this Section and investigations to be reported later – in Sections 6 and 7 and Appendix 7 – reflect some restrictions in scope which were imposed to reduce the complexity of the problems studied. It has already been mentioned that the effects of inherent runway roughness cannot be completely separated from those of discrete obstacles. Nevertheless, the former have been ignored for the purpose of calculation; their influence is subsequently reconsidered in deriving aircraft capabilities. Experience has shown that most problems in the operation of combat aircraft from rough surfaces are associated with symmetric motion, therefore asymmetric motion has been ignored in the following discussions and in all the analytical studies reported herein. Aircraft trials have, however, revealed that, particularly for larger aircraft, problems associated with asymmetric motion can arise both in structural loading and in handling.

3.1 Basic considerations

It is generally assumed from the outset that the capability of an aircraft to operate from a repaired runway will mainly be defined by those conditions for which the limit of its assured structural integrity is reached. Many components may be subject to critical conditions; however, because most of them are consequent upon the loads developed by the landing gears it is the latter to which reference will be made in the following discussion.

The loads for which an aircraft structure is designed are established either directly by specification or from analyses of the loading conditions in specified operating environments. Those basic loads are referred to as 'design limit loads'. A safety factor, commonly 1.5, is applied to the design limit loads to give the 'ultimate loads'. At a particular structural location the difference between the ratio of the stress corresponding to ultimate load to the allowable stress and unity is the 'margin of safety': any structure with a positive margin of safety is considered satisfactory for use up to the design limit load.

Complex built-up structures seldom have a uniform margin of safety. Any portions of the structure which have a zero margin of safety for a defined loading condition are called 'critical areas' with respect to that condition: even then it is likely that much of the structure will have a positive margin of safety and be capable of carrying higher loads. During the life of an aircraft new missions or operating techniques which produce formerly unconsidered loading conditions may be introduced. Additional stress analyses may show that the structure, perhaps with modification to new critical areas, has a positive margin of safety for those conditions. Such conditions which lead to an extension of the defined structural capability are referred to as 'design limit strength' conditions. The analyses reported herein to define the capability of an aircraft to operate from a repaired runway have based that definition on limit load or on a higher load corresponding to design limit strength where that was established.

3.2 The anatomy of a repair encounter

As a basis for defining the required features of analytical models in order to determine the limiting loading conditions the behaviour of an aircraft when crossing a runway repair will be described. For simplicity it will be assumed that the profile of the repair is of the simple form defined in Appendix 6 – a flat plateau with leading and trailing ramps.

When the tires of the nose landing gear encounter the leading ramp they will be further compressed, so increasing the force they apply to the axle. Under the influence of that force the shock strut will be compressed and upward motion and nose-up pitching of the whole aircraft will occur; those actions all tend to decrease the incremental load due to tire compression. Thus at some instant during the time when the nose tires are on the leading ramp there will be a peak in the load on the nose landing gear. Some time later the main tires will reach the leading ramp and a similar action will take place as regards the main landing gears, but with a nose-down pitching influence. At that instant the aircraft will probably already be pitching nose down – indeed, if the repair length is shorter than its wheelbase the nose tires will have crossed the trailing ramp. There will follow a second peak in the nose-gear load either while it is still on the repair plateau or after it has reached the subsequent undamaged runway surface. Which of those circumstances produces the greater load depends on the characteristics of the aircraft and of its landing gears. A particularly severe case will occur in the latter if a second repair is encountered at the time of the peak load. The above description has concentrated on the loading conditions of the nose undercarriage – similar conditions apply to the main gears, for which also the following discussion is generally applicable.

From the above it can be seen that there are three phases in which peak landing-gear loads are usually generated:

(a) The encounter with the leading ramp of a repair

(b) The subsequent downward motion of the aircraft while the main landing gear is still on the repaired surface

(c) As 'b' when both gears are on the following unrepaired surface, particularly when compounded with 'a'.

3.3 Application of mathematical modelling

For analysis the aircraft may be regarded as a system having multiple degrees of freedom which are 'driven' by the variations in ground elevation at the landing gears. It is necessary, therefore, for dynamical models realistically to determine the input forces which excite them and the resulting responses therein. Because each of the degrees of freedom – landing-gear movements, overall bodily motions and responses in structural modes – has associated with it a fundamental frequency one may expect to be able to focus on likely occurrence of peak responses by correlating various sources of excitation with the times at which they occur.

In phase 'a' the time taken by the force generated by the tires to reach its peak is short; therefore the input forces for the 'rigid-body' aircraft modes and the lower-frequency structural modes will be little affected by the corresponding responses. The vital parts of the system for modelling are the tires, to define the rate at which the applied force builds up, and the shock strut, to determine the relief of the loading due to upward axle movement. For the former, since the length of the ramp will often be comparable to the tire footprint length, the use of a 'distributed-contact' rather than a 'point-contact' tire representation is indicated while for the latter it is necessary realistically to represent the increases in shock-strut spring and damping forces under the condition of rapid compression. The severity of this case will, as is shown in Appendix 6, usually be greater the shorter the time to traverse the ramp; i.e. the smaller the ratio R/V, where R is the ramp length and V the aircraft speed.

For a single repair of length L the value of the ratio L/V in relation to the period of one of the modes of response will be an approximate measure of the degree of forcing of that mode. Therefore the maxima of a particular output quantity, say a structural load, are likely to occur at approximately the same value of L/V. If, then, to reduce the number of cases which have to be considered a number of fixed values of L are chosen, interpolation and extrapolation of results to estimate maxima for other values will be most reliable if carried out for that value of L/V.

The ensuing response in any mode will exhibit the fundamental period of that mode. Hence the characteristics of that response, in particular the maxima, can be related to the ratio X/V, where X is the distance travelled from the repair. (The exact definitions of X and V are problematical, especially since the cases of practical interest are for accelerating or decelerating motion — specific recommendations are given in Section 7, but for our present general discussion we need not be concerned.) The maximum values of output quantities resulting from encountering a following repair are therefore associated with particular values of S/V, where S is the spacing between that repair and the first. Again, that gives a basis for reliable interpolation of maxima for various chosen values of S.

For calculation of the loading and motion of the aircraft the system model must allow for the simulation of responses in the rigid-body modes of heave and pitch (and, if asymmetric crossings of repairs are to be considered, roll) and in structural modes — for combat aircraft the latter can sometimes be ignored. Particularly at high speeds, the tires may leave the ground on the trailing ramp; therefore, the tire representation has to yield zero forces in that condition and the shock-strut model must be appropriate to a condition of free (or rapid) recoil.

The modelling of the tires and the shock struts has to take into account the enveloping properties of the former and the non-linear spring-force characteristic and the orifice damping (force proportional to the square of stroking velocity) of the latter. A general analytical model is therefore not productive of closed-form solutions for the response to arbitrary inputs and yields results only by a marching solution of differential equations, allied to routines for the estimation of the forces produced in the system. For certain fundamental investigations it may be possible to obtain guidance on the effect of parametric variations by linearising the system and synthesising responses from those produced by primitive inputs, e g ramps or steps (as, for example, in Ref 3.1); however, that approach is likely to have limited applicability to specific programmes of assessment.

For 'design' purposes it is necessary only to consider the potentially most critical cases. Often judgements can be made from the outset on the conditions likely to produce them: the required calculations can thereby be restricted in number. For 'interoperability' purposes the situation is very different. The range of operational conditions which could initially be specified would probably require an unacceptably extensive programme of calculations to determine an aircraft's capabilities were each case to be considered separately. Also it would have to be recognized that other conditions might eventually have to be covered, raising the question of how to do so. What is required to solve those problems is a method of synthesising the loadings and responses for any given case from those for a limited number of basic cases. The programme of calculations would still be greater than for 'design' cases alone since critical conditions in the synthesized cases would generally be produced from non-critical conditions in the basic cases; however, it would be initially definable and not require later extension. At present no such method has been substantiated: a possible approach is described in Section 7.

The development of a method of synthesis could provide a link between the design of aircraft to operate from damaged and repaired runways and the determination of their operational capabilities by analytical methods. The calculations required for the former can readily be extended to provide the data for the latter. For a non-linear system any such method could produce only approximate results — also, for landing gears the 'hard' non-linearities of zero and maximum deflections of tires and shock struts will limit their validity. Therefore indicators of the range of applicability of the method must also be defined, which is probably best done as an offshoot of the design process. Any cases which were found to fall outside that range would necessitate either a full analysis or their exclusion from the aircraft's established operating regime, the choice depending on the implied operational restriction.

As is discussed in Appendix 2, the basic formulation of analytical models for the calculation of loadings and responses during operation on rough ground is well established and a multiplicity of computer programs for their implementation exist. Many of those programs incorporate features which are specific to the representation of the characteristics of particular landing gears, indicating that while general techniques for modelling the behaviour of system components are available practical complexities often demand their adaptation to suit individual designs. In some cases the ability adequately to predict component behaviour solely from design data is in doubt: experimental data must then be sought.

3.4 Use of experimental data

Landing gears are routinely tested in drop test rigs, of which many exist within the AGARD countries. Measurements are taken of the overall forces produced by the landing gears versus the deflections of tires and of shock struts and sometimes also of the internal pressures of the latter, which permits a more detailed assessment of their behaviour. The shock-strut operating conditions during such simulated landings are, however, markedly different to those during taxiing over obstructions: it has also been found that repeated cycling can alter both spring and damping characteristics. To produce more realistic conditions some drop test rigs have been equipped with hydraulically driven platforms which can be placed beneath the landing gear and driven in accordance with any desired programme of vertical displacement. An extension of that concept is seen in the AGILE facility at the Wright Aeronautical Laboratories of the USAF wherein such excitations can take place independently on all three landing gears of aircraft with masses up to about 25 t. A deficiency of all the above facilities for the direct simulation of taxiing cases is that the wheels are not rolling (save for spin-up prior to 'landing') and so the true action of the tires over obstructions is not represented. Rotary dynamometers have generally been employed to determine the characteristics of tires under various combinations of deflection, yaw, slip and camber. It is usually impracticable, however, to equip them for making measurements under conditions of varying ground elevation. A type of facility which provides the opportunity for measuring tire forces over any desired ground profile and for conducting representative simulations for complete landing gears is the linear dynamometer where a test carriage is guided by rails along a track and may be equipped with a variety of loaded tires or gears. The most capable of such facilities is the Landing Loads Test Track at NASA, Langley which permits the testing of landing gears of almost any size over their full speed ranges.

Further details of test facilities of the types reviewed above are given in Appendix 3.

The use of test facilities to supplement design data is of most value if embarked upon at an early stage in the assessment of a design since there is then the greatest opportunity to modify it to improve upon the consequent aircraft capabilities. Therefore the possible needs in that regard should be considered from the outset when operation from rough runways is required; it is generally the case that the more representative the necessary test the more complex will be the appropriate facility and associated equipment.

Some aspects of operations can be explored only by aircraft tests. The motion of the aircraft may be intolerable to the pilot or may have an adverse effect on his degree of control. Problems which analysis can cover only for zero or predefined control inputs may be ameliorated or exacerbated by piloting techniques. Directional control during asymmetric repair crossings cannot be assessed without the participation of a pilot.

To produce results which are valid for actual operations aircraft tests must reproduce the conditions therein as faithfully as possible. Because of the nature of those operations, however, hazard attends such tests; therefore their planning and conduct require great care. Appendix 4 discusses in detail those aspects, based upon experience to date.

Aircraft tests have frequently been employed to check the validity of analytical models under realistic conditions and to provide a basis for their modification. The usual lack of prior validation by means of data from test facilities has, however, considerably extended both pre-test planning and the test programme itself. With the benefit of such data aircraft tests can be more sharply focused on the aspects of assessment for which they are vitally required, though they will probably still be employed for the ultimate validation of analytical techniques.

REFERENCES

3.1 Olsen JJ
The response of a one-degree-of-freedom oscillator to two successive disturbances, AFWAL-TM-86-1-FIB, April 1986.

4 CURRENT DESIGN REQUIREMENTS

Design requirements provide the basic criteria which are necessary to define a new aircraft design. The structural design criteria are specified in order to ensure sufficient strength to cover the envisaged operational usage of the aircraft during its whole life cycle. For landing gears the design criteria are related to design mass, to notional landing procedures, to design sink rates, to defined runway obstacles, and so on. Design criteria, which remain constant once the basic design has been completed, must not be confused with clearance parameters, which are continually changing with changes of operational procedures, aircraft masses and configurations as well as with better knowledge of the real operating environment and of the actual structural strength, from test results. In most cases a specific clearance is given after an aircraft's capabilities have been assessed for a particular combination of configuration and environment to optimize its operational utilization. Occasionally structural reinforcement may even be required to permit a clearance for operationally acceptable masses and speeds for a new environment. Hence, design criteria are necessarily of a broad and general nature whereas clearance parameters are very specific in their application.

The problem of appropriately specifying design criteria for new aircraft projects is aggravated by the length of aircraft development. On average it now takes more than 10 years fully to develop a new type and by the time an aircraft fleet becomes operational the spectrum of usage can be quite different from that originally envisaged when formulating the design criteria.

An attempt may be made to make allowances for such 'imponderables'; however, specifying an all-embracing design envelope could lead to huge mass penalties. The great influence of landing-gear design criteria on total aircraft mass (and cost) is well shown by the difference between aircraft of the US Air Force and those of the Navy, which have to withstand operations from carriers. It is therefore necessary to strike a fine balance between a specification which does not unduly penalize the basic design and one which is likely to provide the desired operational capability without the need for structural modifications for many years to come.

Since the techniques of runway destruction and restitution are currently subject to change (as Appendix 1 shows) and will remain so in future it is impossible precisely to predict the profiles of repaired runways. Therefore it is to be expected that relevant design requirements will exhibit some lack of definition (in contrast, for example, to those for in-flight loading actions for conventional aircraft). However, it will be seen in the following reviews of existing requirements that they are often so broad that they cannot be applied to any particular case without additional specific quantification. It is an objective to provide quantitative guidance for design criteria, based upon the best evidence now available, so that in new designs the operational capabilities are balanced. Also, the definition of those criteria should assist the interoperability of aircraft among the NATO nations.

4.1 US Design Requirements

A former US specification for ground loads – MIL-A-8862(ASG) (Ref 4.1) –, which was common to Air Force and Navy aircraft, omitted consideration of ground roughness. It has been replaced by MIL-A-8862A(USAF) (Ref 4.2) for the Air Force and by MIL-A-8863A (Ref 4.3) for the Navy, both of which specify ground profiles.

In line with earlier practice, MIL-A-8862A(USAF) adopts the deterministic approach of defining the landing cases in terms of extreme conditions. MIL-A-8863A abandons that approach in favour of a more 'rational' probabilistic approach based on envelopes of combinations of variables. Both the probability distributions of those variables and the required combined probabilities are specified. That is similar to the philosophy adopted in MIL-8861 for some flight-loads cases where the limit-load conditions are not specified in absolute terms but are indirectly determined by specifying their maximum probability of occurrence. The probabilistic approach has not yet been carried over to the definition of ground profiles, though it would be consistent also to specify probabilities of encountering various magnitudes of roughness.

The ground profiles specified by MIL-A-8863A are summarized in Fig 4.1, together with those specified by the other current design requirements discussed here. Both take-off and landing roll-out are required to be conducted over ground with continuous roughness represented by an infinite sequence of identical (1-cosine) waves of which the heights and lengths are varied over the scope of the appropriate envelope shown in Fig 4.2 – the choice of envelope is linked to the aircraft type. In that process the most critical wavelength will be covered, giving a more severe condition for exciting aircraft resonances than applies on a real runway, for which the roughness is never completely tuned to the aircraft response. (The conditions pertaining to repaired runways may be expected to lie in the area between 'H3' and 'H4'.) In addition to symmetric traversing of the profiles MIL-A-8863A requires that they be traversed at angles of up to 45 degrees to their lateral axes; that could cause problems especially for larger, more flexible aircraft types. Aircraft for which STOL operations are specified are also required to land over obstacles, represented by (1-cosine)-shaped bumps, by steps and by holes. The first are single instances of the waves specified for continuous roughness, with lengths varying from 2 feet (0.61 m) to the distance travelled by the aircraft during the compression stroke of the landing gear (shock strut plus tire). The heights of steps and the depths of holes are specified at discrete values of 2 inches (51 mm) for semi-prepared runways and 4 inches (102 mm) for unprepared; those same dimensions are employed for the minimum lengths, the maximum being infinite. There are no explicit requirements in MIL-A-8863A for operations on repaired runways.

MIL-A-8862A(USAF), introduced by the US Air Force in 1971, is still the established guide for USAF design criteria and will remain so until the new MIL-Prime (MIL-A-87221) (Ref 4.4) replaces the whole 8860 series. It is expected that the specification of ground roughness in the MIL-Prime will essentially be based upon that of MIL-A-8862A(USAF). Dynamic taxi analyses are required to be performed for steps, for bumps and dips of (1-cosine) shape and for a continuous runway profile. Steps are to be of heights 1 inch (25 mm), 2 inches (51 mm) and 4 inches (102 mm) for paved, semi-prepared and unprepared surfaces, respectively. The bumps and dips comprise single and double obstacles of the sizes given in Fig 4.3; encounters are to be at all angles to their crest lines, so giving a multitude of unsymmetrical cases.The runway profile is not given but its level of roughness is defined by the requirement that its spectral density be at least that given by the appropriate graph of Fig 4.4. It is not required that landings be performed in the presence of ground roughness. The graphs of Figs 4.3 and 4.4 were initially derived from data on the Hughes Aircraft Company's soil runway and on the US Marine Corps' multi-matted-surface runway in California – data on two additional matted and eight unprepared runways were used to establish the final definitions. The spectra of Fig 4.4 could be used directly to predict loads; however, because of the strong non-linearities displayed by landing gears it would be difficult to derive reliable static design loads thereby – such an approach might be employed to derive repeated loads for fatigue analyses.

In addition to the foregoing, the MIL-Prime contains in its Appendix two further specifications of harmonic runway roughness, bumps and dips of (1-cosine) profile, as given in Figs 4.5 and 4.6. These introduce the new concept of two different speed regimes with associated roughnesses; thus two separate analyses are to be conducted for ground manoeuvring and for take-off and landing. For both regimes single and double obstacles are specified. A less severe surface is specified (Fig 4.6) for speeds in excess of 50 knots than for lower speeds (Fig 4.5) but for the former the height of a single obstacle is almost doubled. That somewhat complicated differentiation is aimed at reducing to a practical number the vast range of cases in MIL A 8863A, which has been found unworkable. However, the question remains whether the resulting requirements are adequate to cover the real environment – as with MIL-A-8862A(USAF), no runway repairs are specified in the MIL-Prime.

4.2 UK Design Requirements

The current UK specification for military aircraft landing gears is DEF STAN 00-970 Volume 1, Part 3 (Ref 4.5). In common with the MIL Specifications, (1-cosine)-shaped bumps and dips are specified; however their lengths and heights differ as well as their application. The DEF STAN 00-970 combination of a length of 250 mm and a height of 120 mm (for virgin ground) represents a discrete short obstacle which is to be encountered by one landing gear only whereas in the US specifications the emphasis is on longer obstacles which excite the rigid-body and flexible modes of motion of the aircraft.

A continuous runway profile of 1500 m basic length, derived from that of an actual unpaved runway, is included in DEF STAN 00-970. The profile to be used in a given application is obtained by factoring the basic profile, shown in Fig 4.7, as is appropriate for the class of runway under consideration. Factors generally range from 1 to 4. Though landing on such a runway is not specified, it may be noted that with a factor of 2, typical for a matted runway, the area at 'A' exhibits a slope of about 2%; then at a touch-down speed of 100 knots the equivalent increase in sink rate would be 1 m/s, about 1/3 of the usual design value for combat aircraft. The design cases associated with that profile are not fully defined, following the usual UK practice of providing detailed technical specifications as advisory information, to be utilized and amplified as appropriate for a particular project; MIL Specifications are generally complete and mandatory from the outset. For the production of fatigue loadings the utilization of simulated taxiing runs over a set of runways with appropriately distributed amplitude factors is admitted as a substitute for the application of a preset loading spectrum.

DEF STAN 00-970 contains explicit reference to runway repairs. Their dimensions (as shown in Fig 4.8) pertain to repairs of large craters using mats of UK Class 60 trackway and are not directly applicable for alternative repair methods. No sequence of repairs is specified.

Only symmetrical traversing of continuous runway roughness or a runway repair is required to be considered.

4.3 French Design Requirements

The recent French military requirements, AIR 2004E, (Ref 4.6) treat landing gear design criteria differently from the foregoing. Instead of specifying the profiles of obstacles from which loads are derived through dynamical analyses AIR 2004E specifies a simplified procedure whereby single-wheel loadings are obtained directly. Such methods had wide usage in the earlier US requirements because they were easy to apply, but have gradually been replaced by more realistic procedures wherein only the environment is specified and loads are derived analytically or by test.

No sequence of obstacles is specified in AIR 2004E. Unsymmetrical loading cases are dealt with in some detail.

4.4 Compa' son of Requirements

In comparing the above four major sets of requirements for defining aircraft structural integrity in ground operations it becomes obvious that since they are founded on widely differing concepts a common basis cannot be found. They cover a wide range of possible operating conditions but further specific requirements for rough-runway operation are needed. The approach of covering all existing requirements would probably lead to unacceptable design penalties without guaranteeing integrity.

A new common specification of repaired-runway profiles and associated operating conditions is therefore sought. To that end the characteristics of current aircraft are reviewed (Section 5), their capabilities assessed (Section 6) and design improvements considered (Section 8) . Methods for the definition and utilization of aircraft capabilities for the purpose of Interoperability are developed (Section 7). A set of design requirements consistent with those methods and with practical design aims is then formulated, and presented in Section 9.

REFERENCES

4.1 Airplane strength and rigidity, landing and ground handling loads, MIL-A-8862(ASG), May 1960

4.2 Airplane strength and rigidity, landing and ground handling loads, MIL-A-008862A(USAF), March 1971

4.3 Airplane strength and rigidity, ground loads for Navy procured airplanes, MIL-A-8863A, July 1974

4.4 Aircraft structures, general specification for, MIL-A-87221, February 1985

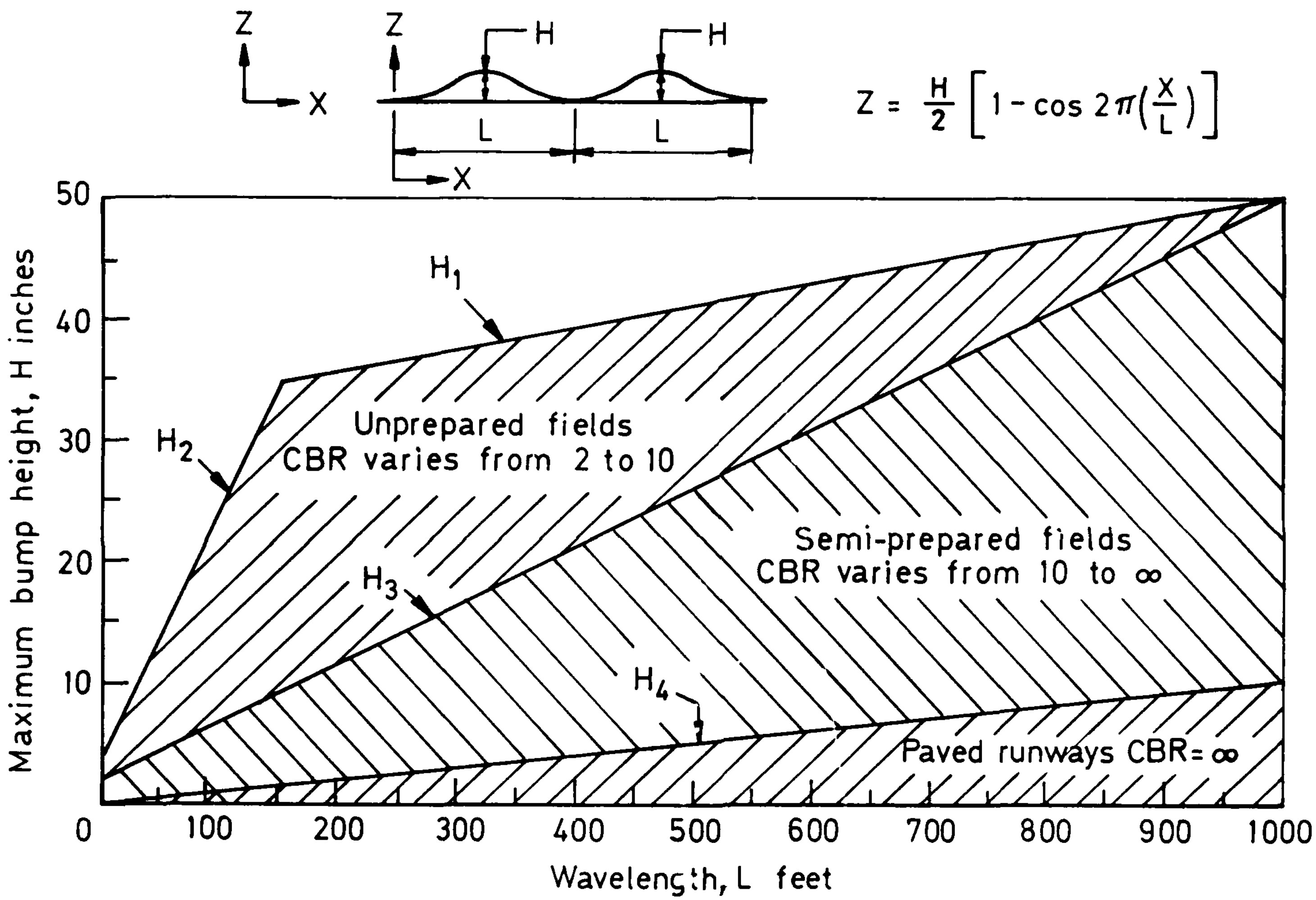
4.5 Structural strength and design for operation on specified surfaces, DEF STAN 00-970 Volume 1, Part 3, 1979

4.6 Resistance des avions, AIR 2004E

L = length of obstacle   H = height/depth of obstacle

	Single obstacle	Repeated obstacles
MIL-A-8863A	(STOL aircraft) (1-cosine) bump: L_{min} = 0.61 m L_{max} = distance travelled during landing-gear compression stroke H increasing with L (see Fig 4.2) Steps and hollows: L_{min} = 0.1 m H = 51 mm (semi-prepared surfaces) = 102 mm (unprepared surfaces)	Infinite series of identical (1-cosine) bumps: L chosen for maximum loads H increasing with L (see Fig 4.2) Traversed symmetrically and at 45 degrees
MIL-A-8862A (USAF)	(1-cosine) bump/hollow: H increasing with L (see Fig 4.3) Step: H = 25 mm (paved surfaces) = 51 mm (semi-prepared surfaces) = 102 mm (unprepared surfaces) Step and bumps/hollows traversed at all angles	Continuous runway profile with specified minimum spectral density (see Fig 4.4) Double (1-cosine) bumps/hollows: L and H as for single
DEF STAN 00-970	Step: H = 25 mm to 100 mm (1-cosine) bump: L = 0.25 m H = 30 to 120 mm Repaired crater (see Fig 4.8)	Continuous runway profile factored according to type of surface (see Fig 4.7)
AIR 2004E	No obstacle specified Loads derived from additional tyre compression of 30 mm for normal paved runways 60 mm for prepared grass or matted runways 100 mm for roughly prepared ground Symmetrical and unsymmetrical cases	Not specified

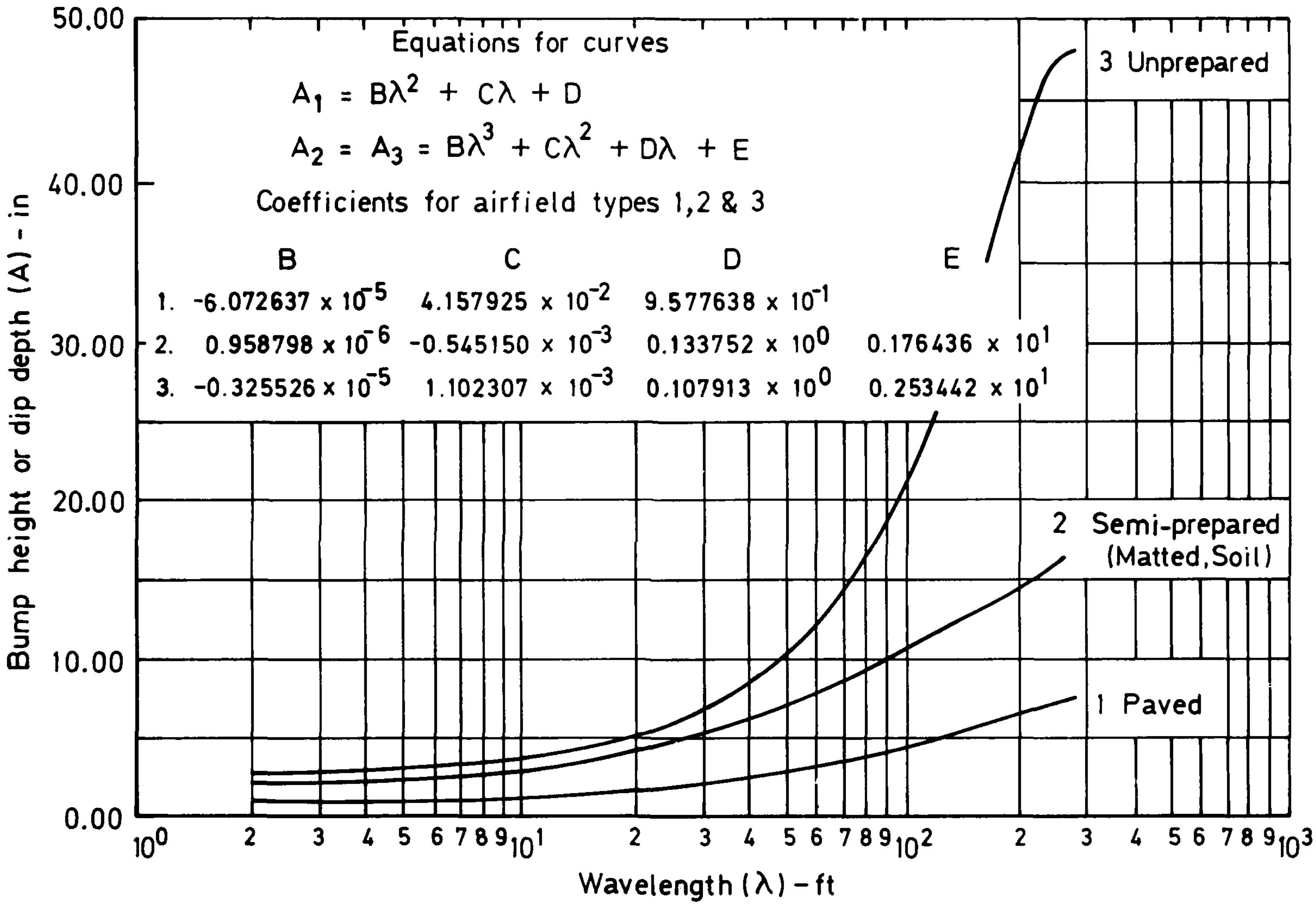
Fig.4.1 Ground roughness specified by design requirements



$$Z = \frac{H}{2}\left[1 - \cos 2\pi\left(\frac{X}{L}\right)\right]$$

$H_1 = .01765L + 32.35$	$H_2 = .2067L + 4$	$H_3 = .0480L + 2$	$H_4 = .01L$
$(150 \leq L \leq 1000)$	$(0 \leq L \leq 150)$	$(0 \leq L \leq 1000)$	$(0 \leq L \leq 1000)$

Fig.4.2 Dimensions of obstacles (MIL-A-8863A)



Discrete 1-cosine bump heights or cosine – 1 dip depths
for paved, semi-prepared and unprepared airfields

Fig.4.3 Dimensions of obstacles (MIL-A-8862A (USAF))

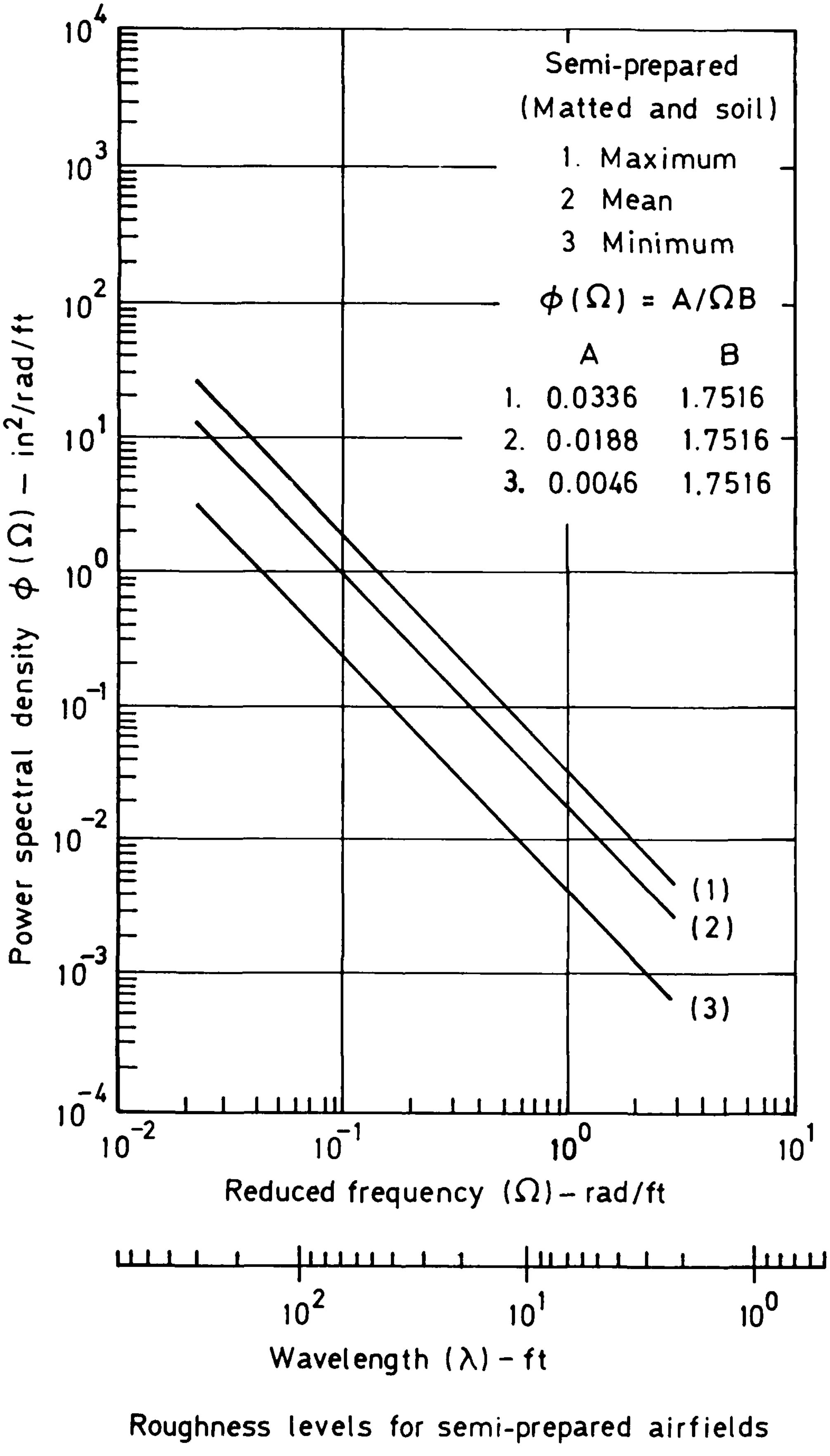
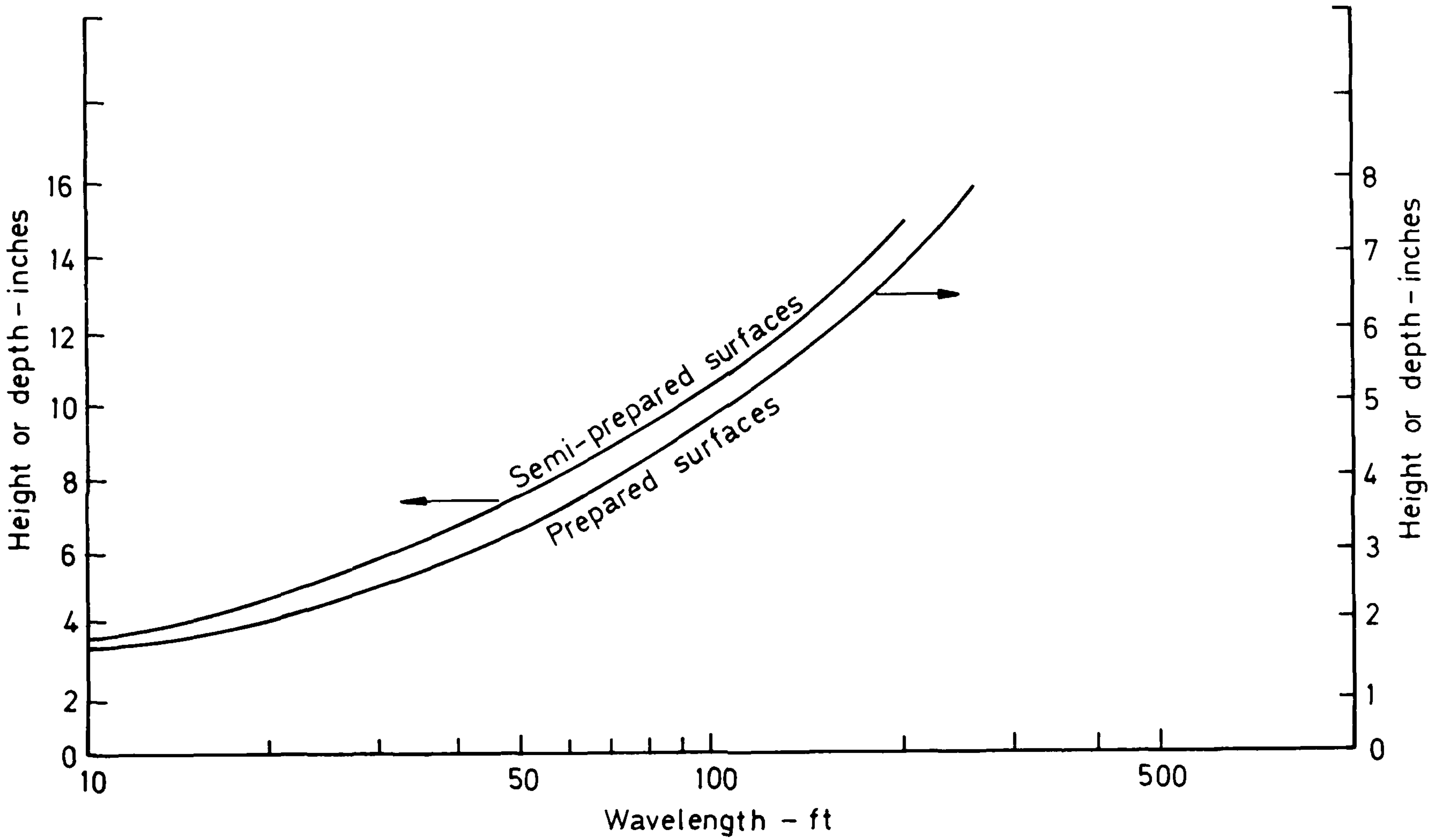
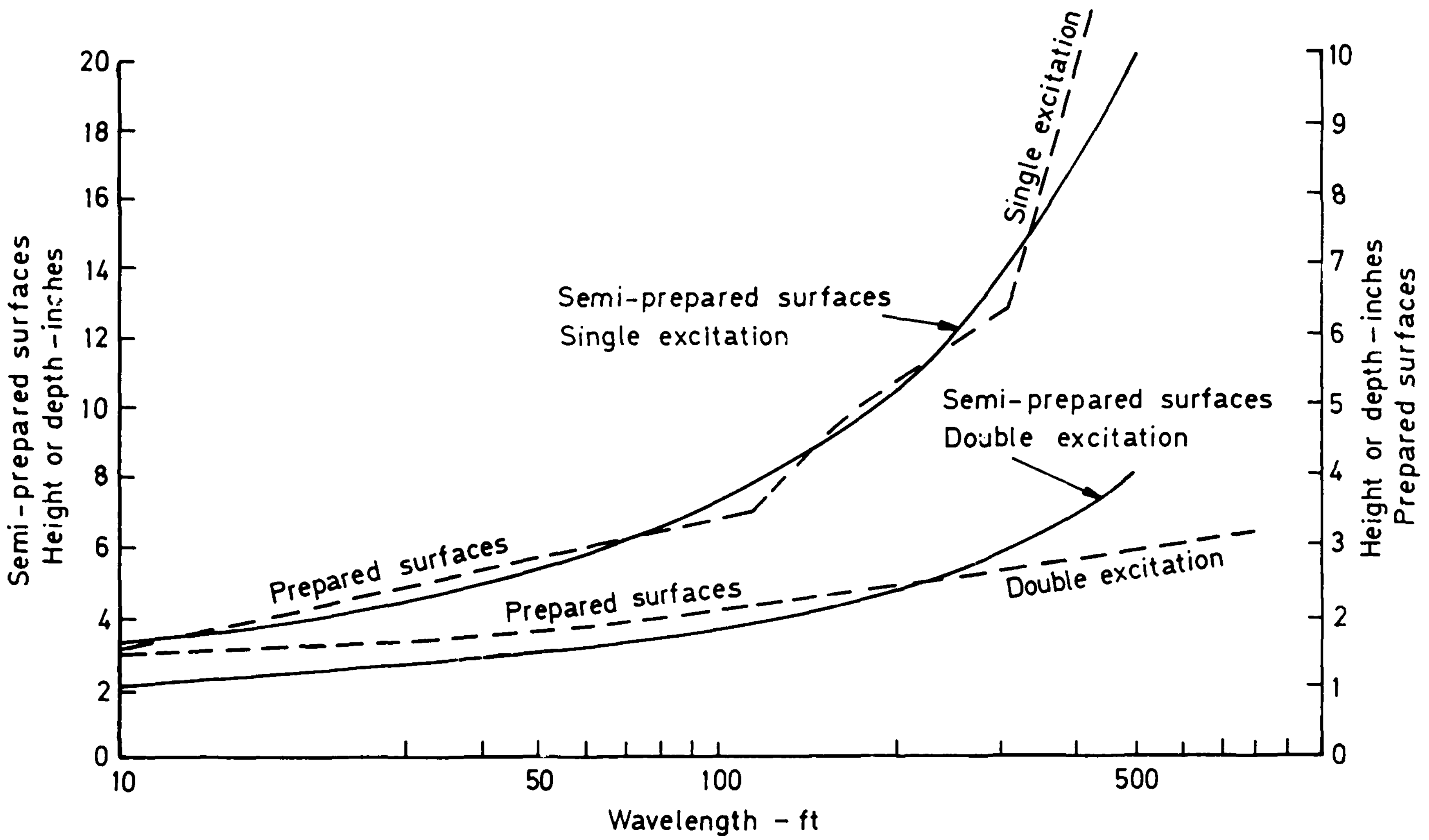


Fig.4.4 Spectral densities of ground profiles (MIL-A-8862A (USAF))



Discrete (1-cos) bumps and (cos -1) dips for slow speeds
up to 50knots - single and double excitations

Fig.4.5 Dimensions of obstacles — low speed (MIL-A-87221)



Discrete (1-cos) bumps and (cos-1) dips for high speeds
above 50knots - single and double excitations

Fig.4.6 Dimensions of obstacles — high speed (MIL-A-87221)

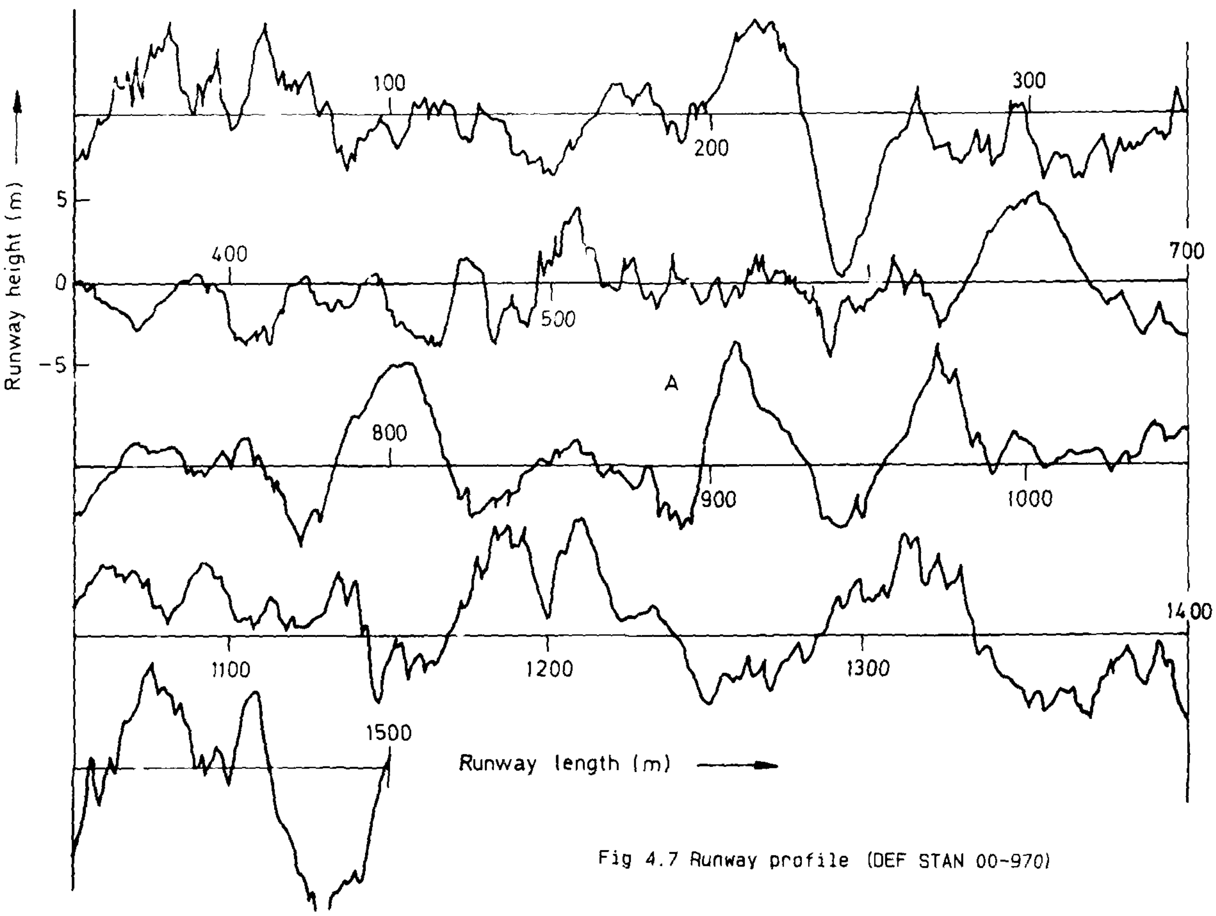


Fig.4.7 Runway profile (DEF STAN 00-970)

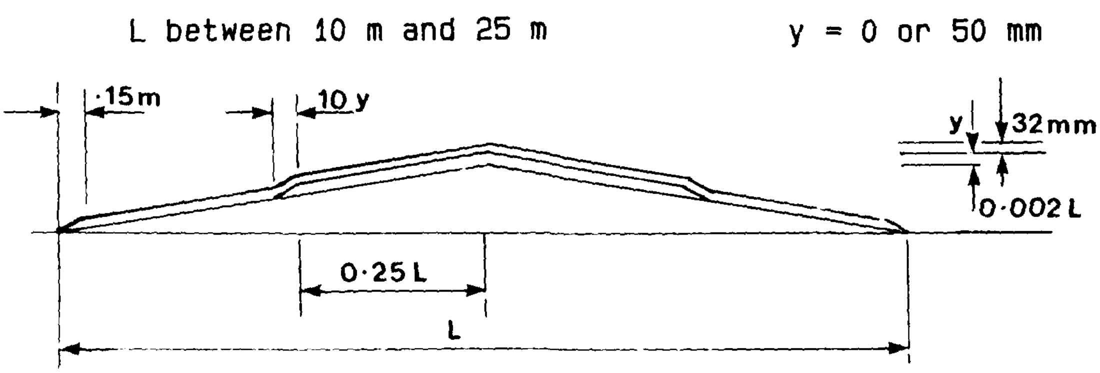


Fig.4.8 Repair dimensions (DEF STAN 00-970)

5 CURRENT MILITARY AIRCRAFT LANDING GEAR DESIGNS

The preceding Section reviewed the design requirements which have generally been applied to current NATO military aircraft, in accordance with their anticipated operational environments. The influence of those requirements on landing gear configurations and characteristics is now discussed. Data are presented for a variety of aircraft to demonstrate the trends and ranges in the characteristics of current landing gear designs. Detailed data for two aircraft, one a fighter and the other a transport, are presented in Appendix 5.

5.1 Design considerations

The design loads for landing gears are strongly dependent upon the operational requirements for the particular aircraft. The majority of current NATO aircraft have been designed to operate from good quality paved runways of unrestrictive lengths. The need to operate on a minimum operating strip on a repaired runway has not featured in the specified design conditions. Typically landing impact cases and ground manoeuvring and handling cases have been primarily considered, with the operational capability on rough ground examined later.

Landing impact design loads are determined for an aircraft weight and sink rate appropriate for the type. Two-and three-point landings and cross-wind conditions are considered. Ground manoeuvring and handling cases cover braking, turning, jacking and towing operations which determine horizontal and vertical loads for both symmetric and unsymmetric conditions.

The landing impact cases dictate that the landing gears absorb the high kinetic energy of descent, utilising most of the shock-strut stroke, with damping characteristics suitably chosen to keep the loads applied to the airframe within acceptable limits. The resulting characteristics may, however, give unsatisfactory behaviour for the case of traversing rough ground since inputs from repeated encounters with bumps or from overall unevenness may well result in the loads being amplified to levels above those which result from the application of current design requirements. There is thus no guarantee of the suitability of current landing gears for operations on damaged and repaired runways. Section 6 discusses the capabilities of current aircraft and Section 8 outlines the improvements which might be made in landing gears to extend those capabilities for future aircraft.

5.2 Landing gear configurations

The disposition of landing gears is dictated by the overall aircraft layout and the need to provide stability and manouevrability on the ground. Their general arrangements are mainly determined by operational requirements such as the necessary height for carriage of stores, loading and unloading and maintenance, together with limitations on stowage volume and airframe loadings. The landing-gear configuration is also influenced by the aim to minimize weight, cost and maintenance demands, as well as by the preferences of the designer. The three basic configurations shown in Fig 5.1 are currently in widespread use.

The 'cantilever', or 'telescopic', is the commonest configuration as it is usually the lightest and simplest type and requires the least stowage volume. It may suffer in its performance on rough ground because of the increased friction due to high bearing loads resulting from horizontal forces.

The 'levered', or 'articulated', landing gear has a fitting attached to the airframe, a lever pivoted at the lower end of the fitting which carries the wheel and a shock strut diagonally connecting the fitting and the lever. This type of landing gear is generally the heaviest and may require the greatest stowage volume. However, its rough-ground performance may be enhanced by the availability of a larger vertical axle displacement, by a reduced level of friction due to the absence of bending moments on the shock strut and by the tendency of drag loads to assist strut closure when the lever is at an angle below the horizontal.

In the 'semi-levered', or 'semi-articulated', configuration the lever carrying the wheel is pivoted at the bottom of the shock strut. The forward end of the lever is attached to a linkage which in turn connects to the fixed portion of the strut. The wheel motion is defined by motion of the linkage and shock-strut closure. This configuration can give improved stowage of the landing gear. In comparison with the fully levered type, provision of rough-ground performance may similarly be aided by an increased vertical axle displacement for a given shock-strut stroke and by the action of drag loads in closing the strut; however, the friction level is generally higher.

5.3 Landing gear characteristics

The spring and damping characteristics of current landing gears have been chosen to meet established design requirements and also to satisfy specific additional operational requirements for particular aircraft, and differ widely as a result.

The gas-spring characteristics which satisfy the basic load carrying requirements can usually be obtained by means of simple single-stage arrangements with compression ratios ranging from 4:1 to 12:1. Additional requirements imposed by specific operating needs, such as to control the aircraft attitude in particular situations, can force the use of a two-stage arrangement. The rough-ground performance of certain landing gears has been improved by the adoption of a two-stage gas spring which can provide a low stiffness at the static-load position while retaining the necessary maximum load carrying capacity. It has been shown that a linear spring characteristic with a mid-stroke static deflection would give a particularly good rough-ground performance. Liquid springs, which use hydraulic fluid instead of gas as the compressive medium, provide a near-linear load versus deflection characteristic but do not have the the same versatility in satisfying a variety of operating requirements.

Damping is obtained hydraulically within aircraft shock struts by restricting the fluid flow generated by stroking. Fixed orifices provide damping forces dependent on flow rate (or stroking velocity) and it is usual to provide for different orifices to be effective in compression and in recoil so that differing levels of damping are obtained. Control of the orifice size permits the variation of damping characteristics and is accomplished in several ways in current designs. Use of a metering pin within an orifice permits the damping level to depend on strut deflection. Various other types of valves have been employed in order to obtain damping characteristics which provide particular benefits including increased efficiency of energy absorption during landing impact, alleviation of design loads, reduction of aircraft response to inputs such as braking, and improvement of aircraft stability during touch-down and take-off. Control of damping can also assist in reconciling the often conflicting requirements of rough-ground operation and of landing.

The relevant characteristics of wheels and tires are size, pressure, contact area, load capacity, rated speed, life and the volume available for brakes. A restricted stowage volume will direct the choice of tires towards small, high pressure types and perhaps the use of multiple smaller tires rather than fewer larger ones; for encounters with discrete obstacles a certain minimum tire section height is needed if the tire is not to be burst or severely damaged by being compressed against the wheel rim. Also, high ground contact pressures demand a higher strength in the runway surface layer, and usually in the sub-layers too, if significant deformation of the runway is not to develop. Therefore the trend towards high-pressure tires is adverse to the ability to operate on rough ground.

Shock-strut and tire characteristics are usually defined for normal conditions of operation; however, they are affected by variability in servicing, by changes of environmental conditions and by shock-strut action. Some design requirements recognize the first and allow for tolerances in shock-strut pressurising and in oil filling. An example of the changes in shock-strut spring characteristics due to variations in gas pressure and in oil quantity can be seen in Fig 5.2. Such variations in servicing may influence the performance of landing gears in both landing and taxiing, particularly by causing premature bottoming with attendant excessive loads. Environmental changes, such as variations in temperature, can affect shock-strut and tire pressures and hydraulic oil properties. Shock-strut stroking can result in foaming of hydraulic oil and entrapment of gas, possibly to the extent of seriously affecting damping characteristics: this problem may be avoided by employing a separator piston between gas and oil.

5.4 Data for current aircraft

The tables of this Section summarize the landing gear characteristics of several current NATO aircraft.

Table 5.1 gives general data on aircraft type, mass, the design requirements applied and the design sink rate for landing.

In Table 5.2 the characteristics of the landing gears are given in terms of configuration, the static load, 'residual' load and axle movement between the static-load condition and that of full shock-strut closure, and normalized spring stiffness and damping coefficient at the static-load condition.

Table 5.3 gives the characteristics of the tires in terms of arrangement, pressure range ('low' or 'high' — the chosen dividing line at 8 bar corresponding roughly to that between tires for which a useful off-runway capability may be expected and those for which it is likely to be very limited), 'residual' load, percentage deflection at the static-load condition, and normalized spring stiffness.

Table 5.1
Aircraft data

Aircraft	Type	Mass Range (Kg)	Landing Gear Design Specs	Design Landing Sink Rate (m/s)
A	Fighter	10040-22860	-	3.05
B	Fighter	14230-26310	-	3.05
C	Fighter	4620-10100	MIL-A-8860 Series, MIL-T-5041	1.525 (1)
D	Fighter	13610-30840	MIL-A-8862 as modified by aircraft Prime Item Spec	3.05
E	Fighter	7380-17010	MIL-L-8552, MIL-A-8862, MIL-T-6053, MIL-L87139	3.05
F	Fighter	14000-29000	MIL-A-8860 Series with deviations	3.7
G	Fighter	7700-14060	-	3.6
H	Fighter	4850-8700	AvP 970. Grassy Airfield	3.35
I	Fighter	7340-12000	MIL-A-8860/-A-8862/-A-8866, MIL-T-5041, 35 Kt crosswind, 50 passes on CBR 10 ground	3.66
J	Transport	36000-79000	2g Taxi, 1.5g Dyn Taxi with max fuel, speed for 1st mode excitation	2.74
K	Transport	67000-156000		3.05
L	Transport	45770-82970	B.C.A.R.	3.05

(1) Design Sink Rate 3.66 m/s @ 5539 Kg Landing Mass, 1.525 m/s for heavier landing masses.

Table 5.2
Shock strut characteristics

A/C	Gear	Configuration	Static Load (% Max Airplane Weight)	Residual Load Ratio = Static Load / Compressed LD	Equivalent Spring Stiffness = Static Spring Rate / Static Load	Residual Axle Travel (Static to Compressed)	Equivalent Damping Factor at Axle, Static (1) (Compression)
			Percent		$\frac{kN/cm}{kN}$	cm	$\left[\frac{kN/(cm/sec)^2}{kN}\right] \times 10^5$
A	Nose	Cantilever	10.6	.31	.098	7.1	4.74
	Main	Cantilever	44.7	.54	.096	7.4	1.53
B	Nose	Cantilever	15.7	.38	.058	10.2	-
	Main	Cantilever	42.1	.36	.514	2.9	-
C	Nose	Cantilever	18.0	.26	.194	4.3	.792
	Main	Cantilever	41.0	.47	.107	5.1	1.67
D	Nose	Cantilever	14.8	.29	.950	17.0	22.3
	Main	Cantilever	42.6	.36	2.80	4.1	16.3
E	Nose	Cantilever	13.7	.27	.136	5.1	8.53
	Main	Levered	43.2	.50	.051	11.9	1.72
F	Nose	Cantilever	11.0	.28	.20	14.0	1.65
	Main	Cantilever	44.5	.42	.12	5.0	1.03
G	Nose	Semi-levered	10.8	.29	.158	9.8	3.57
	Main	Levered	44.6	.53	.083	6.1	1.47
H	Nose	Levered	10.4	.31	.357	7.0	21.4
	Main	Levered	44.8	.63	.210	2.9	31.9
I	Nose	Levered	8.0	.40	.070	9.5	19.2
	Main	Levered	46.0	.55	.260	4.0	8.87
J	Nose	Cantilever	8.2 max	.28	.106	6.7	20.2
	Main	Cantilever	max 47.9	.30	.161	4.3	2.71
K	Nose	Cantilever	9.0 max	.22	.132	5.9	9.25
	Main	Cantilever	max 47.3	.37	.096	6.9	1.00
L	Nose	Cantilever	7.1	.43	.097	6.6	1.71
	Main	Levered	46.5	.46	.095	5.5	1.22

(1) Strut Oil Damping Force = Damping Factor X (Axle Vert Vel)^2
Equivalent Damping Factor = Damping Factor/Static Load

Table 5.3
Tire characteristics

Aircraft	Gear	Tire Arrangement	Residual Load Ratio $= \frac{\text{Static Load}}{\text{Compressed Load}}$	Equivalent Spring Stiffness $= \frac{\text{Static Spring Rate}}{\text{Static Load}}$	Percent Deflection (Static)	Pressure Range (<8 bar = Low) (>8 bar = High)
				$\frac{kN/cm}{kN}$	Percent	
A	Nose	Single	-	-	-	Low
	Main	Single	-	-	-	High
B	Nose	Twin	-	-	-	High
	Main	Single	-	-	-	High
C	Nose	Single	0.24	0.55	31	High
	Main	Single	0.33	0.41	42	High
D	Nose	Single	0.31	2.20	37	High
	Main	Single	0.35	1.60	41	High
E	Nose	Single	0.21	0.72	21.5	High
	Main	Single	0.40	0.26	34	High
F	Nose	Twin	0.26	0.19	28	High
	Main	Single	0.38	0.26	34	High
G	Nose	Single	-	0.29	-	Low
	Main	Twin	-	0.13	-	Low
H	Nose	Single	0.20	0.36	30	Low
	Main	Single	0.34	0.19	35	Low
I	Nose	Single	0.36	0.07	38	Low
	Main	Single	0.57	0.24	32	High
J	Nose	Twin	0.16	0.24	21.3	Low
	Main	Tandem	0.26	0.11	31.3	Low
K	Nose	Twin	0.22	0.28	22.7	High
	Main	Twin-Tandem	0.34	0.14	33.4	High
L	Nose	Twin	0.26	0.26	26	Low
	Main	Twin-Tandem	0.33	0.20	30	High

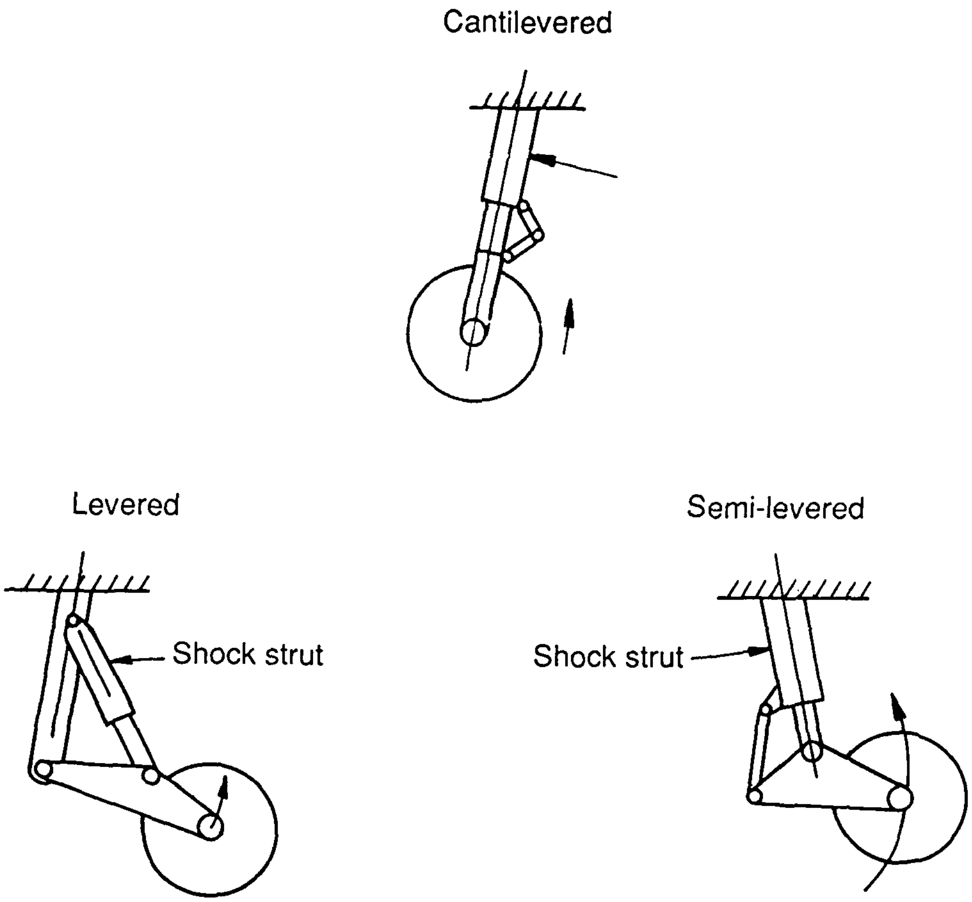


Fig.5.1 Basic landing configurations

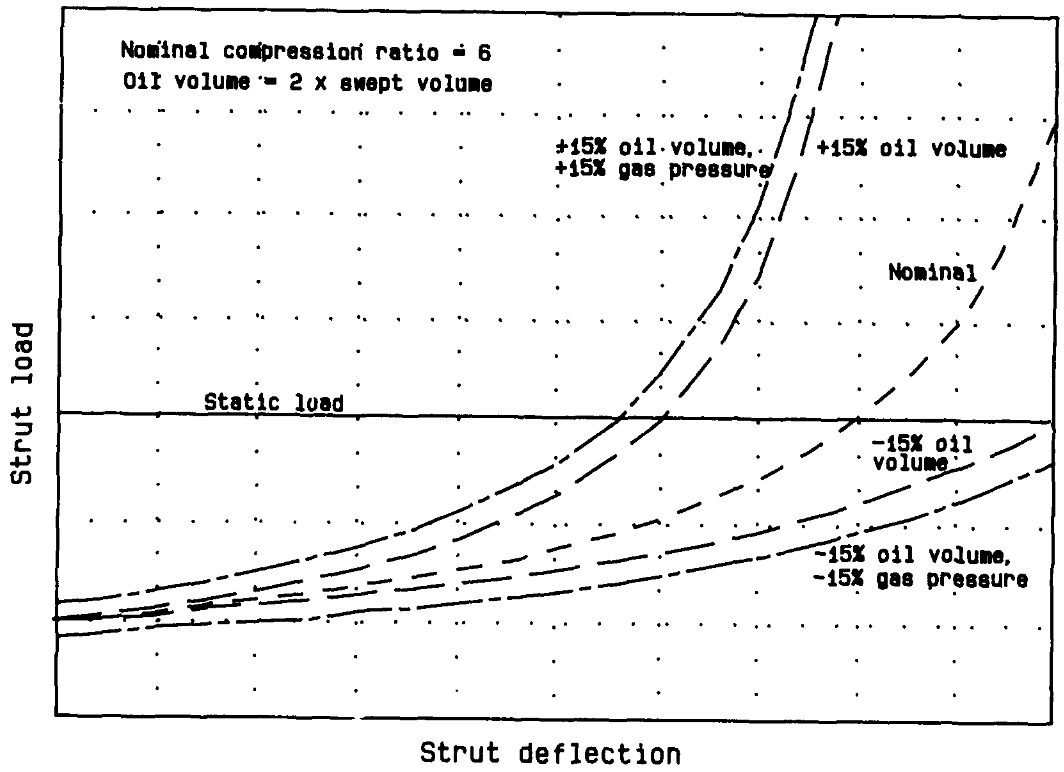


Fig.5.2 Shock strut service variations

6 CAPABILITY OF CURRENT DESIGNS

The need to take-off and to land using repaired runways was not considered in the establishment of the design criteria for most current aircraft; therefore their inherent capabilities in that respect are a consequence of the landinggear performance and structural properties provided for other loading situations. Generally those capabilities are found to be low, especially for randomly spaced multiple repairs of any less than excellent quality.

This section outlines the approaches to allowing for dynamic taxiing loads which have been typical for aircraft currently in service and which have given a foundation for their capabilities in coping with runway repairs. The evaluation of those capabilities and their exploitation in establishing operational clearances are then discussed. Examples are given of predicted operational limitations and discussed with reference to features of the histories of responses and loads during repair encounters.

6.1 Source of capability

Today's aircraft have mostly performed satisfactorily over smooth, well maintained paved runways. Several transport aircraft may also be operated from prepared unpaved airstrips. However, as indicated from the first-flight dates for current combat and transport aircraft given in Table 6.1, the design of their landing gears pre-dates both the introduction of the design requirements discussed above and the perception over about the last ten years of a need to operate from repaired and other sub-standard runways. It is therefore necessary to consider how the taxiing loads derived in their design might circumscribe their capabilities for repaired-runway operations.

Prior to the introduction of requirements to determine loads due to taxiing over prescribed runway profiles, vertical loads were established by application of the so-called '2 g' criterion, which assumes that a vertical load factor of 2 exists at all points on the airframe: thus the landing-gear design vertical loads and the wing root bending moment, for example, were twice their maximum static values. Other vertical ground loads on main landing gears have rarely exceeded those '2 g' loads. Dynamic taxi loads, calculated by such means, have usually not produced critical conditions for the design of much of the structure on current aircraft.

The most severe single obstacle which could safely be encountered was sometimes established by permitting an increment in load factor of about 0.5 g. For transport aircraft the worst case is generally with maximum fuel and when the speed and length of obstacle combine to excite the fundamental wing bending mode: in the absence of external stores wing loads are less critical for combat aircraft, which have a lower proportion of fuel in the wings and sometimes wing-mounted landing gears. The operational implications of such a restriction were, however, thought of little significance. It was reasoned that runway obstacles could be coped with by limiting taxiing speeds and that braking in their vicinity, which it was recognized would give rise to high nose-gear loads, could be avoided.

From the above discussion it can be appreciated that taxiing cases have not generally made a prime contribution to design loads and landing-gear function.

The lengths of runway repairs are typically much greater than those of the obstacles assumed previously; hence the correspondingly critical taxiing speeds are much higher. Their disposition in the runway may be such that braking over them is necessary. Also, the capability to cross successive repairs will be influenced by the dynamical characteristics of the aircraft. In recognition of the need to evaluate aircraft capabilities for a situation not considered in the establishment of the design criteria, programmes of analytical studies and testing have been conducted for a number of types.

6.2 Determination of capability

The calculation of dynamic loads due to repair encounter requires the accommodation of many influences not relevant for the previous single-bump wing-resonance analyses. The speed range is fully expanded and therefore variations in aerodynamic forces and thrust, as also influenced by the pilot's actions, must be considered. The level of braking required is of great importance since it not only directly increases nose-gear loading, because of the induced nose-down pitching moment, but the associated shock-strut compression reduces the amount of deflection available to give resilience to ground roughness, particularly succeeding repairs. The analytical methods employed are reviewed in Appendix 2.

In most cases an associated programme of trials has been conducted to gather data with which the results of simulations can be compared and to explore operational aspects which are not amenable to analysis. (Aircraft testing is considered in Appendix 4.) In comparing analysis and experiment inaccuracies and deficiencies in the former are identified, corrected where possible or allowed for subsequently.

Dynamical models which have been verified by comparison with experiment can be accepted as providing quite accurate predictions of aircraft loads and responses. Aircraft capabilities are then determined by applying criteria on operational safety. For all programmes so far conducted, and for the evaluations presented below, reaching the design limit load or known limit strength has marked a boundary of capability. In some instances additional restrictions have been imposed for reasons of functionality or recognized low capacity for further energy absorption, for example when tires or shock struts were at or near bottoming. Structural fatigue has not been a consideration because of the anticipated rare use of repaired runways. On such bases a variety of functional and structural limitations have been found, as outlined in Table 6.2, which taken together determine the tolerance to repair encounters.

In tests over simulated repairs a number of landing-gear operating peculiarities have been revealed, such as internal leakage, oil atomization, cavitation and consequences of incorrect servicing: such effects mostly tend to reduce the available shock-strut deflection for load absorption, particularly for multiple repair encounters, and thus reduce the potential capability.

In the evaluations referred to above the inadequacies of current designs have generally been very apparent. However, each programme has concentrated on deriving operational clearances for specific repair configurations which were typical of those produced by the evaluating nation at the time. A uniform evaluation of NATO aircraft requires a set of profiles which will reveal the critical features of any aircraft and which can represent practical profiles, produced by either present or future repair methods, in general. The lengths and spacings of those 'standard bumps' must be such that both rigid-body and primary flexible modes of motion can be excited within practical speed ranges and their heights must allow for the evaluation of the least and the most capable aircraft. As was seen previously, of the current sets of design requirements only DEF STAN 00-970 includes a repair profile, which is, however, of fixed dimensions and thus unsuitable for the intended exercise – also, successive repairs are not specified. Therefore, the development of a new set of profiles was necessary. Its derivation and definition are described in Appendix 6. The profile parameters which may be varied are given in Table A6.6. From consideration of several repair techniques the numbers of representative bump heights and lengths to be used in analyses have been reduced to 4 and 3, repectively: the number of repairs, and their locations on the selected operating strip cannot be predetermined.

The effects for several current combat and transport aircraft of operating over the standard bumps have been evaluated and the areas wherein tolerable combinations of heights, lengths and locations occur have been defined. The derivation of operational clearances from that basic information on capability requires further steps.

6.3 Exploitation of capability

The establishment of operational clearances which permit the exploitation of a particular aircraft's capabilities on the specific runways from which it might operate requires the following procedures:

Determination of the aircraft's tolerance to standard bumps

Possible modification of the landing gears to alleviate specific difficulties

Recommendation of pilot's actions which could reduce loads

Provision of methods for relating experience of the actual runway environment to encounters with standard bumps

Presentation of related data on aircraft position and velocity so as to minimize the likelihood of adverse combined loading conditions (such as transient response due to braking reinforcing that due to repair encounter)

Development of data summaries for use by airfield engineers and aircraft operators.

Working down the above list the emphasis progressively changes from the interests of the dynamical analyst to the needs of the Service user. It is the problem of the former to present the data so that it may be readily and reliably utilized by the latter to assess the feasibility of a desired operation. Thus the degree of detail which is conveyed must reflect a compromise between the most straightforward presentation which might however unduly restrict operational flexibility and one which would permit the fullest possible usage of capability but for which the on-site analysis would be unpractical.

The simplest and most conservative clearance is based on the determination of the height of repair which can be tolerated without regard for the number of repairs, their locations, or the speeds at which they are encountered. That height is given for a number of aircraft in Table 6.3 (for encounters with standard bumps – for simplicity of discussion, no distinction will be drawn here between them and actual repairs). It is seen that the operational latitude so afforded is very limited; indeed, in some cases the tolerable height is difficult to achieve by current repair techniques even given unlimited time. Such a restricted clearance is largely dictated by the need to cope with any number of arbitrarily located repairs at any speed since aircraft modes may be strongly excited by tuning to either repair length or spacing. Extensions of that clearance therefore require that such circumstances be isolated and avoided.

The first extension results from the explicit consideration of aircraft speed. Typical variations of tolerable repair height, for two combat aircraft, are shown in Fig 6.1. That extension of clearance may, however, still give too limited an operational utility.

The influence of speed on the nose-gear loads due to crossing two 22.5 m repairs with a 16 m separation is illustrated in Figs 6.2 to 6.6, which are for speeds of 40, 50, 60, 70 and 80 knots at the first repair encounter. For those simulations the aircraft was in the landing configuration, employing reverse thrust and a constant wheel-braking coefficient of 0.31. Several factors which contribute to the magnification or reduction of loads are revealed.

As was discussed in Section 3, two phases may be identified as the usual sources of high nose-gear loads. The first is that of tire and shock-strut compression as the runway surface rises at the leading edge of the repair. Under similar conditions the peak load increases with increasing speed; for subsequent repairs that primary effect may be masked by those of aircraft motion so that the corresponding load may be lower or higher than that due to the first repair. If aircraft motion strongly amplifies the load it may well reach or exceed its allowable limit. The second phase is that of aircraft response when the nose gear leaves the repair, when the pitching motion is reinforced by the influence of the main gears: at the lower speeds loads during this phase exceeded repair-impact loads for the example aircraft.

At a speed of 40 knots (Fig 6.2) the highest nose-gear load occurs on pitch-down after the first repair. The aircraft stops before the nose gear has fully traversed the second repair (as indicated by the time-history of repair height). The initial load is slightly increased at 50 knots, as shown in Fig 6.3, but phasing of motions reduces the response on leaving the first repair. On leaving the second repair the motions are phased for reinforcement so that the highest load is then produced. At 60 knots (Fig 6.4) the response phasing attenuates all loads after the initial encounter with the first repair while at 70 knots (Fig 6.5) approximately equal loads are caused by the two repair encounters. The most adverse phasing of the aircraft's motion is shown in Fig 6.6, for 80 knots, where the severity of the second repair encounter is greatly increased because the nose shock strut is then compressed due to aircraft pitching – limit load is exceeded by a substantial margin.

If the number of repairs considered is restricted to two, while leaving their spacing variable, a less restrictive clearance may be given: the likelihood of succeeding repairs being so spaced that tuned excitation is reinforced may be surmised to be low, especially if acceleration or deceleration prevents further tuning with repair length. Keeping their number to two, still further latitude is provided by consideration of the spacing of repairs. That allows the operating strip, and take-off and landing points to be positioned so that the most critical encounters with repairs are eliminated and piloting procedures to be modified so that, for example, brake application is avoided in certain parts of the strip. An example presentation of such a clearance which, for a particular repair height, divides the (aircraft speed)-(repair spacing) plane into permitted and prohibited regions is shown in Fig 6.7. (That type of presentation may be extended to show boundaries corresponding to the attainment of various load levels but it is considered that for Service use in the field the simple demarcation by those corresponding to limit load is most readily understood.)

Regions of permissible operations defined in terms of repair spacing, repair height and aircraft speed may be derived as illustrated in Fig 6.8. Again, the example aircraft is in landing configuration with reverse thrust and wheel braking being used. Nose-gear vertical load is the critical quantity which determines the limitations shown. The aircraft speed is defined as its value when the nose gear reaches the first repair; the speed subsequently decreases and may reach zero for the lower datum values. Prohibited regions, based on exceedence of limit load, are shown for four repair heights: 62 mm, 72 mm, 82 mm and 92 mm. The extent and, sometimes, number of those regions increase with repair height. The effect of the level of braking on operating limits is illustrated in Fig 6.9, which compares the prohibited regions for a repair height of 92 mm with a braking coefficient of 0.31 (as in Fig 6.8) and with zero braking. A smaller overall area of prohibited operation results with the latter but, somewhat surprisingly, there are some combinations of repair spacing and aircraft speed which are non-critical with braking but critical without. The underlying changes in the conditions for the tuning of response to repair spacing are indicated by a general upward shift in the boundary of permissible repair spacings with the reduction in deceleration. The variation of speed with distance from an initial value of 70 knots is given in Fig 6.10 for several levels of braking.

The variations of nose-gear load versus distance of Fig 6.11 show in detail the differences which can arise with and without braking. The initial aircraft speed is 70 knots and the repairs are 92 mm high and 22.5 m long with a 16 m separation. As would be expected, the load on the first repair encounter is higher with braking because the tire and the shock strut then have higher deflections. At encountering the second repair the load is increasing in the case without braking, indicating nose-down pitching, whereas with braking it is decreasing, indicating nose-up pitching — the influence of the latter in alleviating the load results in the peak load with braking being significantly less than that without.

Permissible speed-spacing regions for another aircraft are shown in Figs 6.12 and 6.13 for 22.5 m and 6.5 m repair lengths, respectively. The results follow generally the same patterns as those of Fig 6.8, indicating that the two aircraft have similar response characteristics. Overall, the regions of prohibited operations are smaller in extent for this aircraft because of differences in the design of airframe and landing gears and also, in part, because of a lower assumed coefficient of braking (0.2 v 0.31). The major effect of shortening the repair length is to shift the prohibited regions downwards in speed; in this example by about 30 knots.

To determine the feasibility of operations necessitating the crossing of more than two repairs it might be possible to utilize data derived for single repairs and for pairs; however, techniques which have been propounded require further evaluation before their validity can be established. Whether clearances for several repairs are so synthesized or derived directly the amount of information which they will entail is large, requiring the provision of means readily to apply it to making post-attack decisions.

The above discussion has outlined approaches to presenting data on the capabilities of a particular aircraft type which will permit assessments of the acceptability of a given runway. Clearly, when several types have to use the same runway the complications of its selection and preparation and of ensuring that operations are safe and successful are greatly increased. That topic is addressed in the following section.

The heights of repairs which can be tolerated by current aircraft with the most adverse location of repairs in the operating strip, shown in Table 6.3, are indicative of shortcomings in landing-gear performance, which stem directly from the lack of regard for repaired-runway operations at the design stage. Of the 19 aircraft cited only 2 are judged to have a capability to operate over 70 mm standard bumps without regard to spacing; possibly a total of 7 could do so over 52 mm standard bumps. For at least 5 types there are still spacing restrictions for a height of 38 mm. Clearly there is considerable scope for an improvement in aircraft capabilities. Section 8 considers changes to landing-gear characteristics which would bestow an improved performance and Section 9 sets down example design requirements which would ensure suitable consideration of repaired-runway cases.

Table 6.1
First-flight dates for several current NATO aircraft

First-flight dates for several current NATO aircraft

Aircraft	Date of first flight
A-7	September 1965
A-10	January 1973
C-5A	June 1968
C-130	August 1954
C-141	December 1963
F-4	May 1958
F-5A	July 1959
F-14	December 1970
F-15	July 1972
F-16	January 1974
F-18	November 1978
F-111	December 1964
Jaguar	September 1968
Nimrod	May 1967
Tornado	August 1974

Table 6.2
Limiting factors for various aircraft types

Limiting factors for various aircraft types

	Aircraft type							
Limiting factor	A	B	C	D	E	F	G	H
Nose gear load	*		*			*	*	*
Main gear load		*	*	*	*	*		*
Wing down bending				*				
Fuselage down bending						*		
Fuselage up bending					*	*		
Underwing store loads			*			*		
Cockpit acceleration	*							*

Table 6.3
Estimated capabilities to cross standard repairs of arbitrary spacing

Estimated capabilities to cross standard repairs of arbitrary spacing

Aircraft	Capability for repair height of 38 mm	52 mm	70 mm
1	?	N	N
2	Y	N	N
3	N	N	N
4	N	N	N
5	Y	?	N
6	N	N	N
7	Y	?	N
8	Y	Y	Y
9	Y	Y	N
10	Y	Y	Y
11	Y	?	N
12	?	N	N
13	N	N	N
14	N	N	N
15	Y	N	N
16	Y	Y	N
17	Y	N	N
18	Y	N	N
19	Y	N	N

(Aircraft numbers above do not correspond to others in this Section.)

Y - Aircraft is estimated to have the capability to take-off at high masses and to land at operational masses across pairs of repairs.

N - Aircraft is estimated to lack the capability either to take-off or to land (or both) across pairs of repairs.

? - The estimated aircraft capability is for a height close to that quoted, but it is uncertain which side of that value it lies.

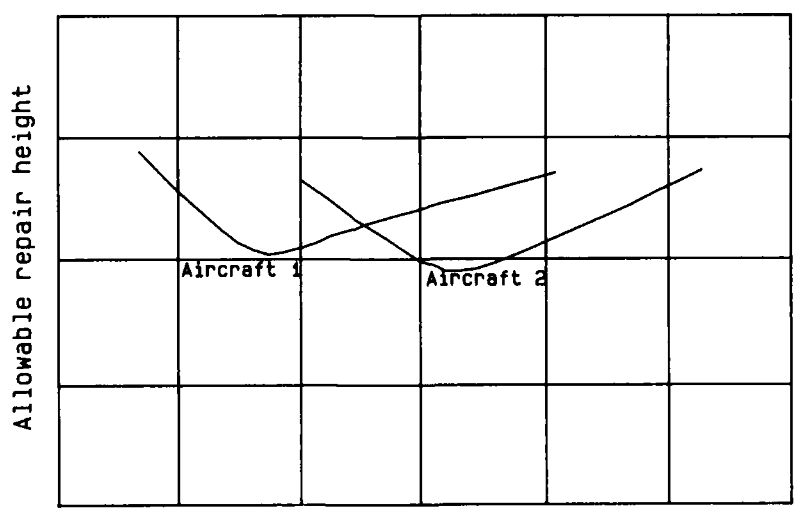


Fig.6.1 Variation of repair-crossing capability without consideration of repair spacing

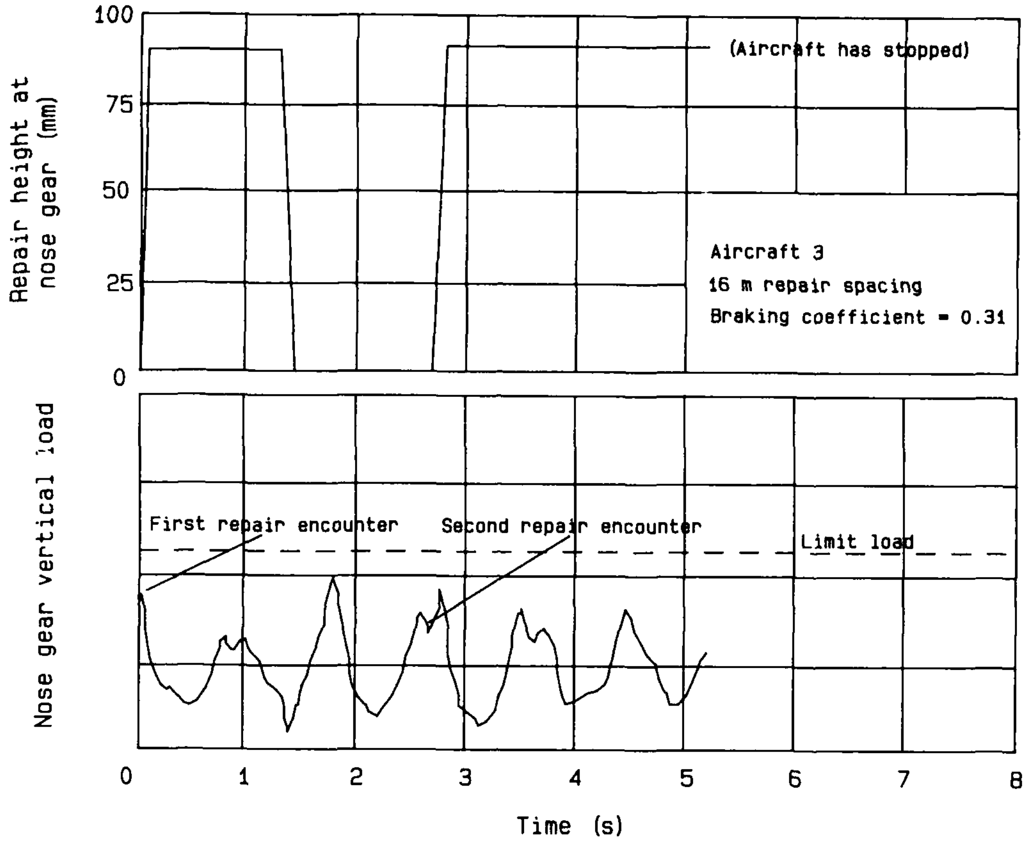


Fig.6.2 Nose gear vertical load for repair encounter at 40 kn

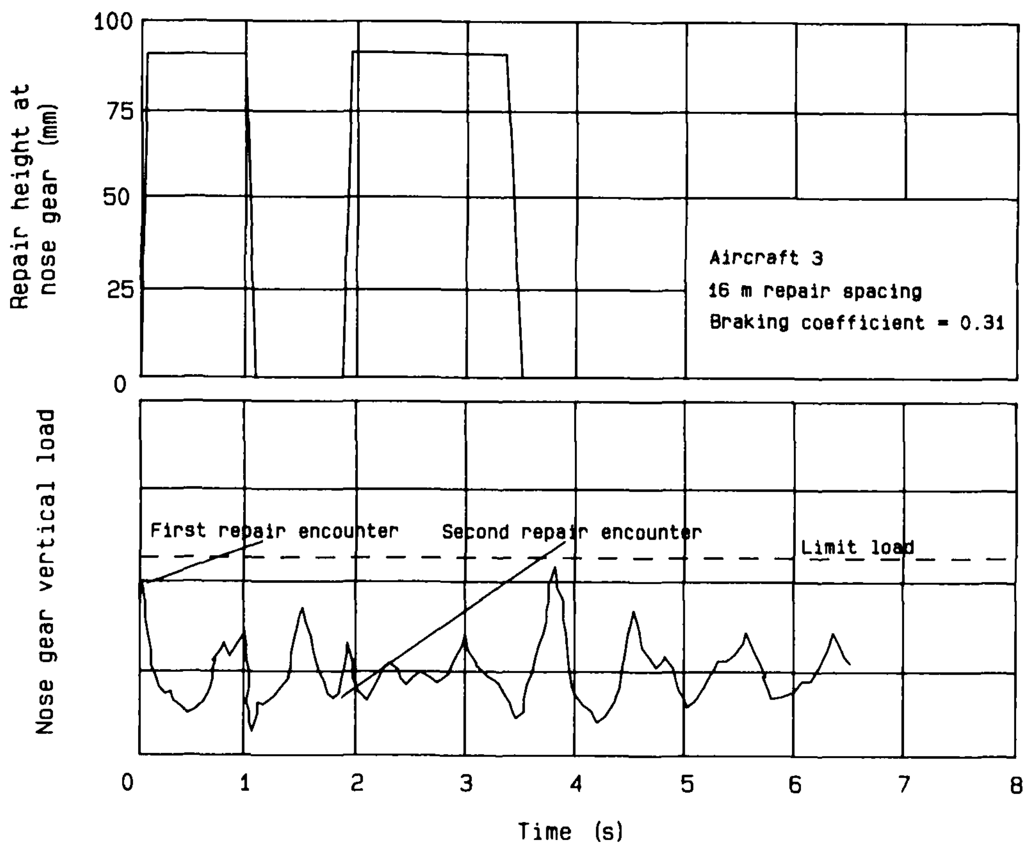


Fig.6.3 Nose gear vertical load for repair encounter at 50 kn

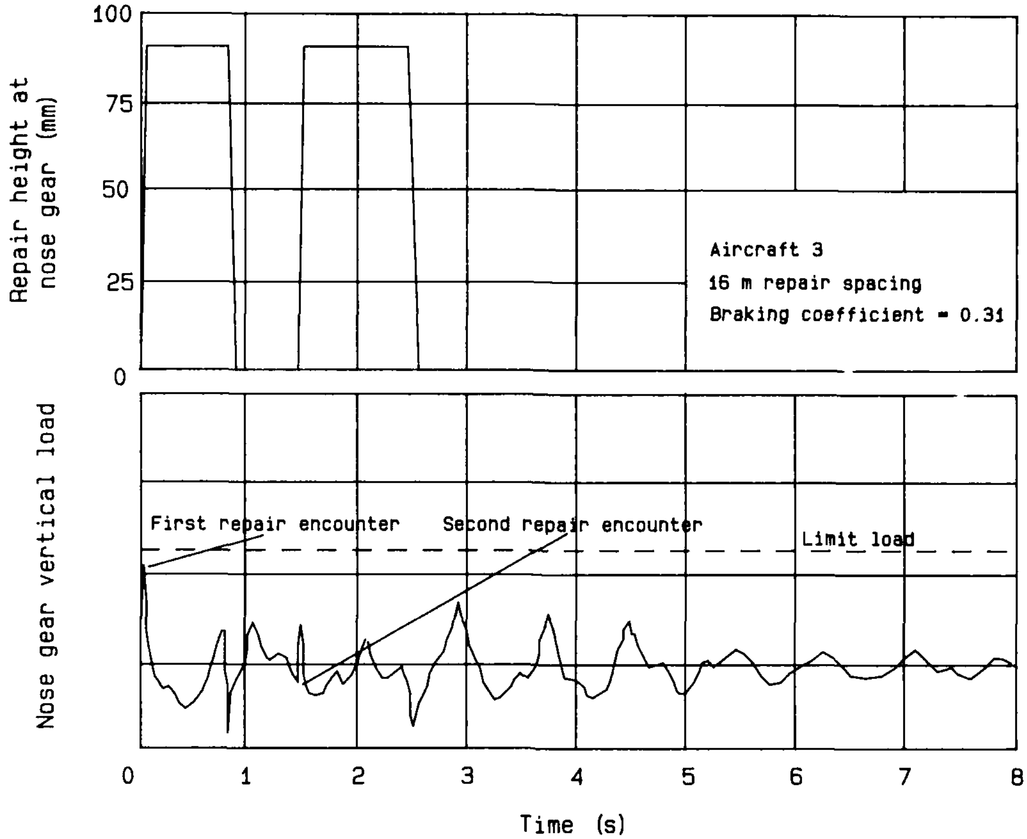


Fig.6.4 Nose gear vertical load for repair encounter at 60 kn

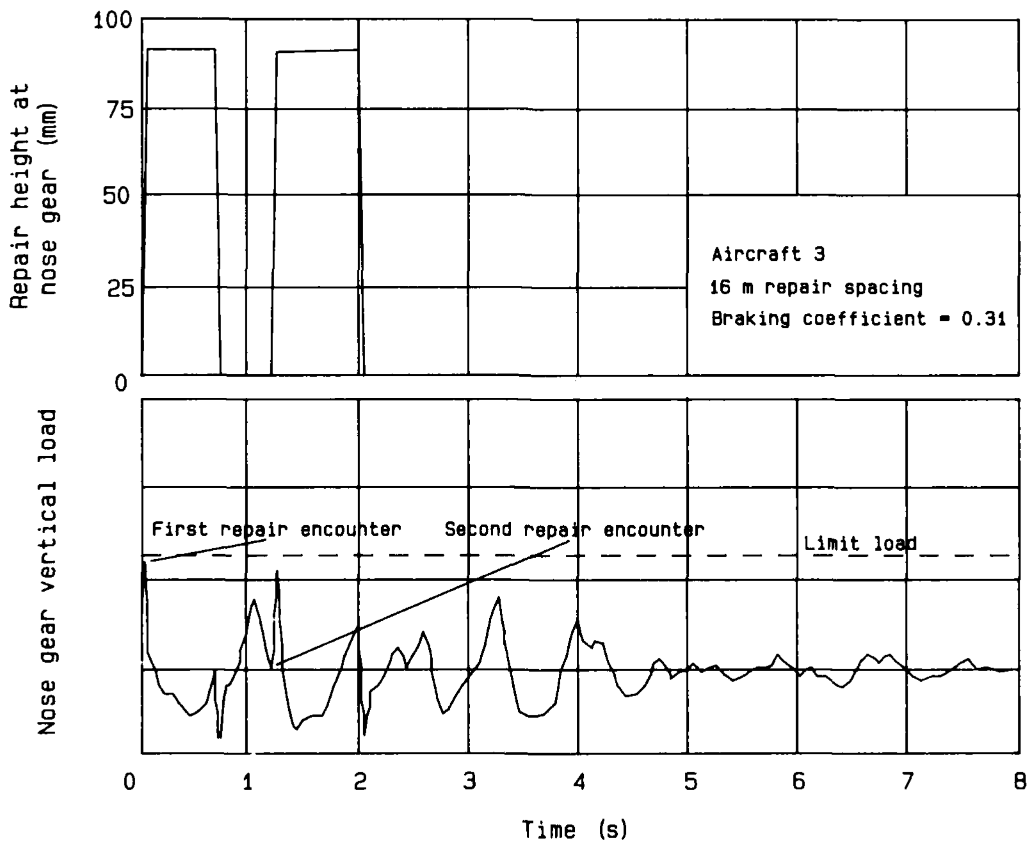


Fig.6.5 Nose gear vertical load for repair encounter at 70 kn

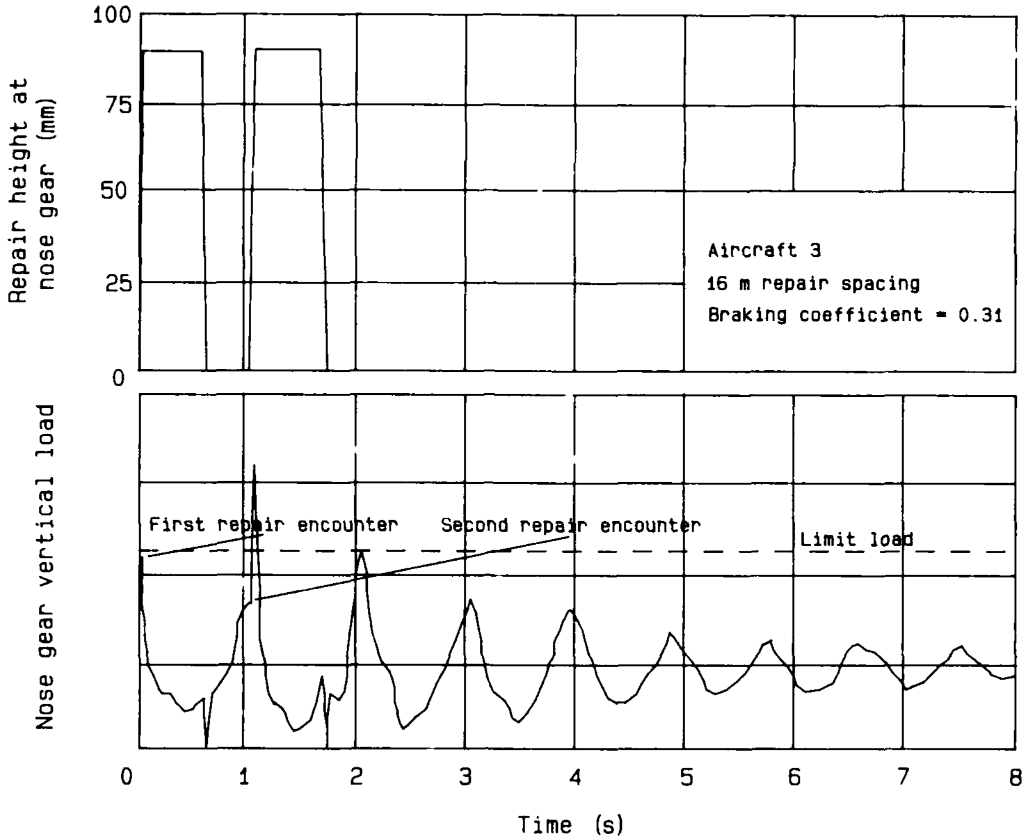


Fig.6.6 Nose gear vertical load for repair encounter at 80 kn

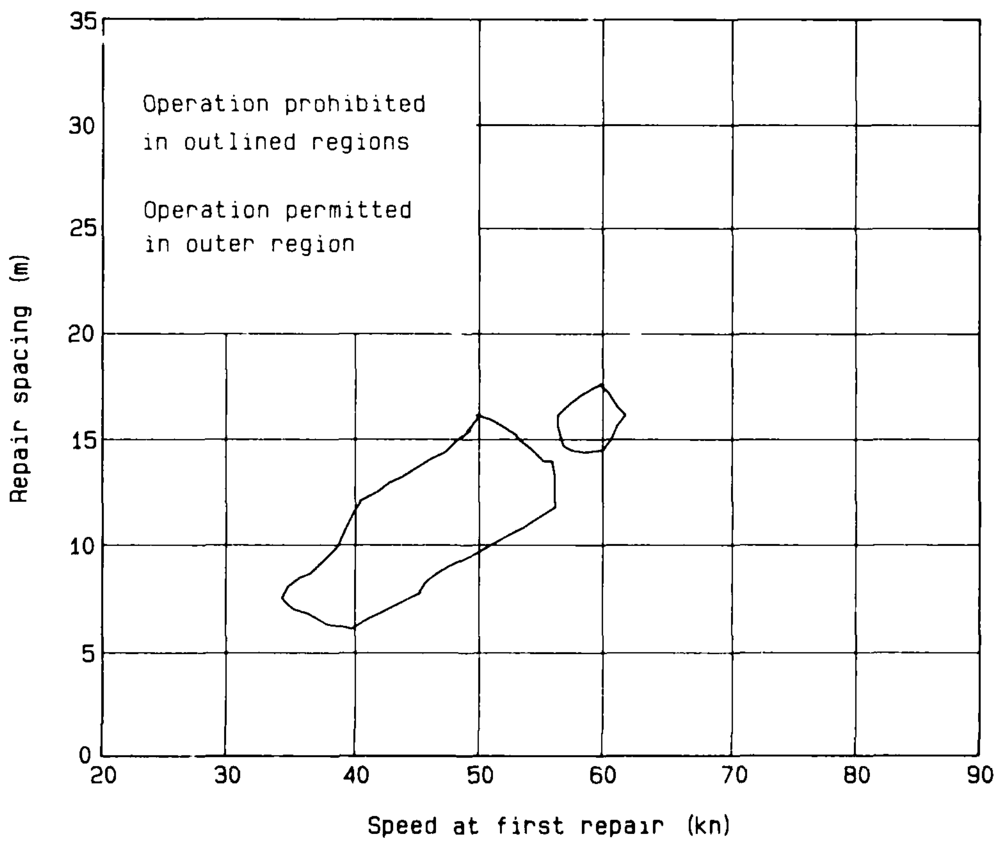


Fig.6.7 Illustration of operating restrictions with consideration of repair spacing

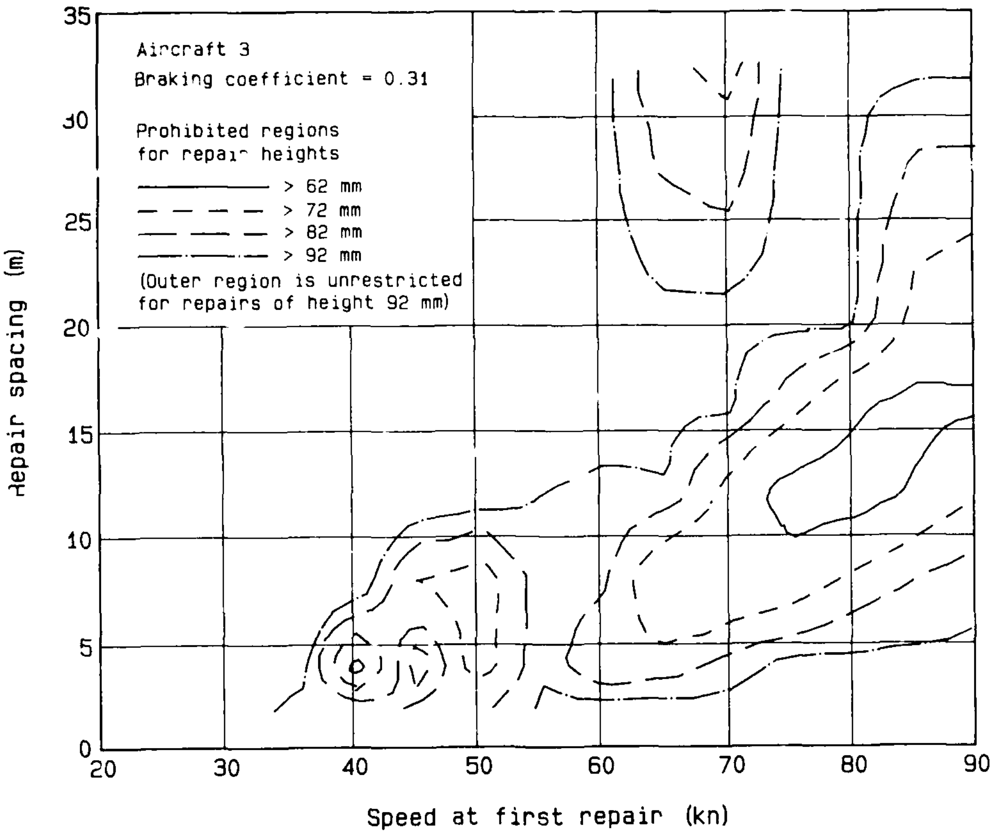


Fig.6.8 Spacing v speed restrictions for landing across 22.5 m repairs

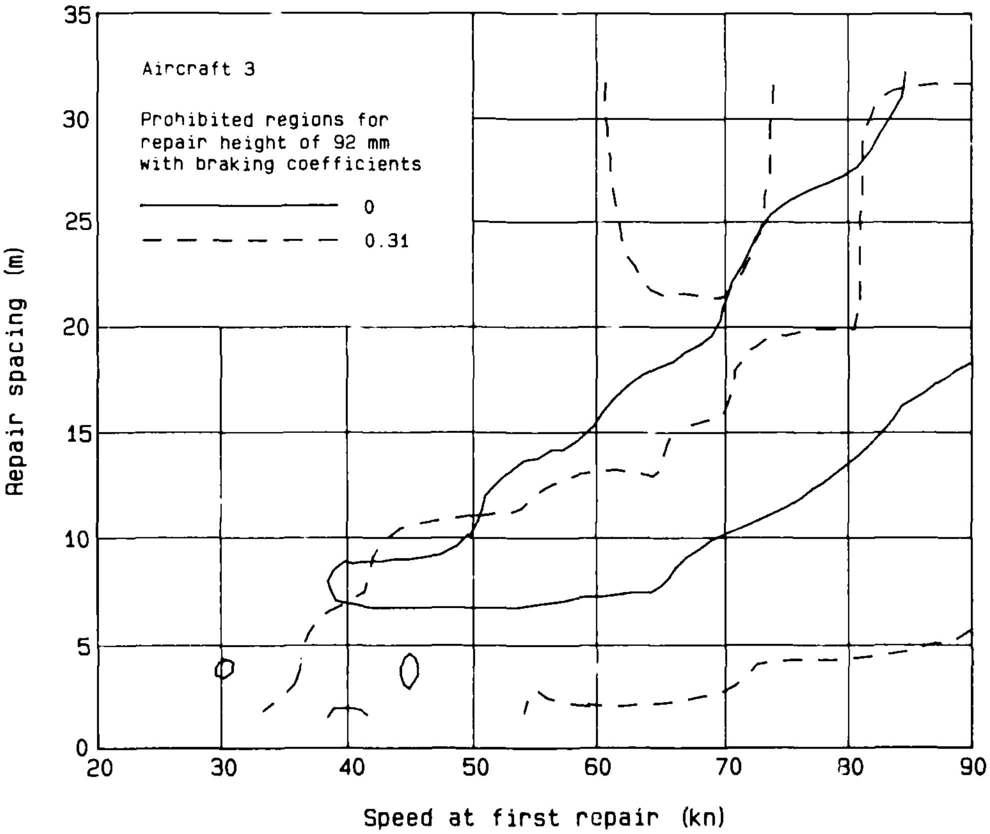


Fig.6.9 Effect of braking on speed v spacing restrictions for landing across 22.5 m repairs

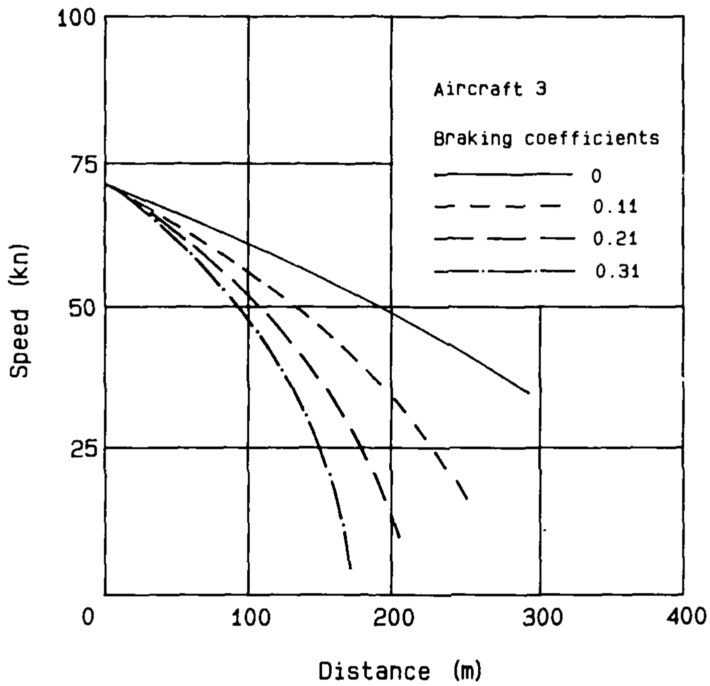


Fig.6.10 Speed v distance for various braking levels

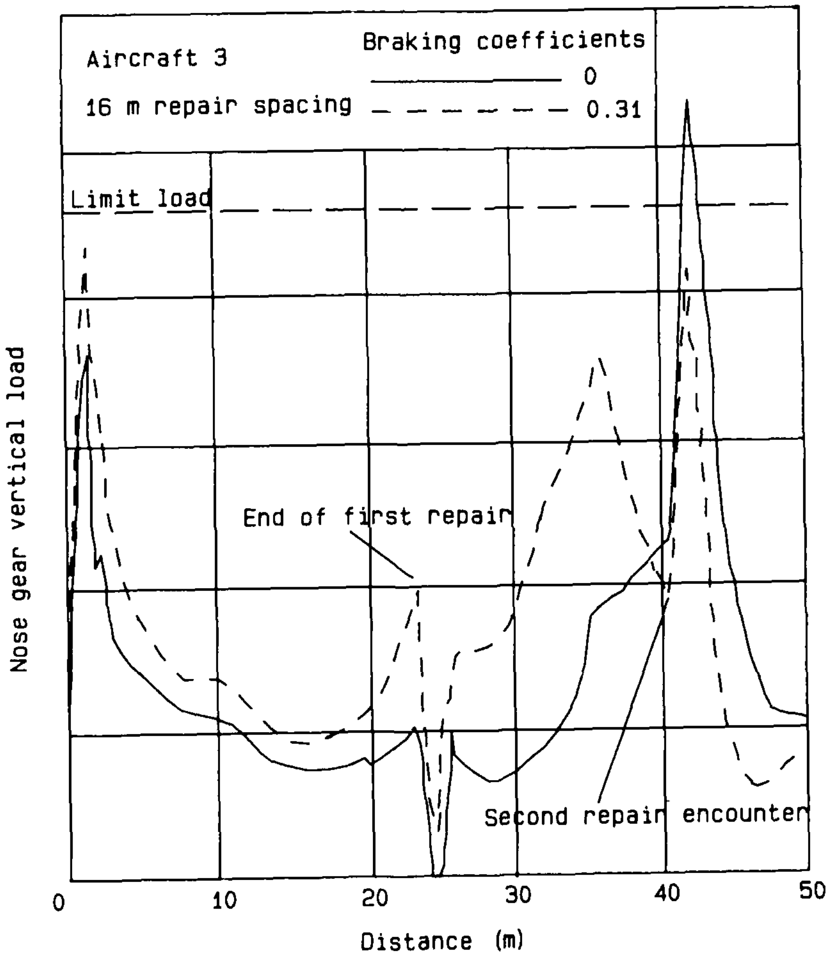


Fig.6.11 Nose gear vertical load without and with braking

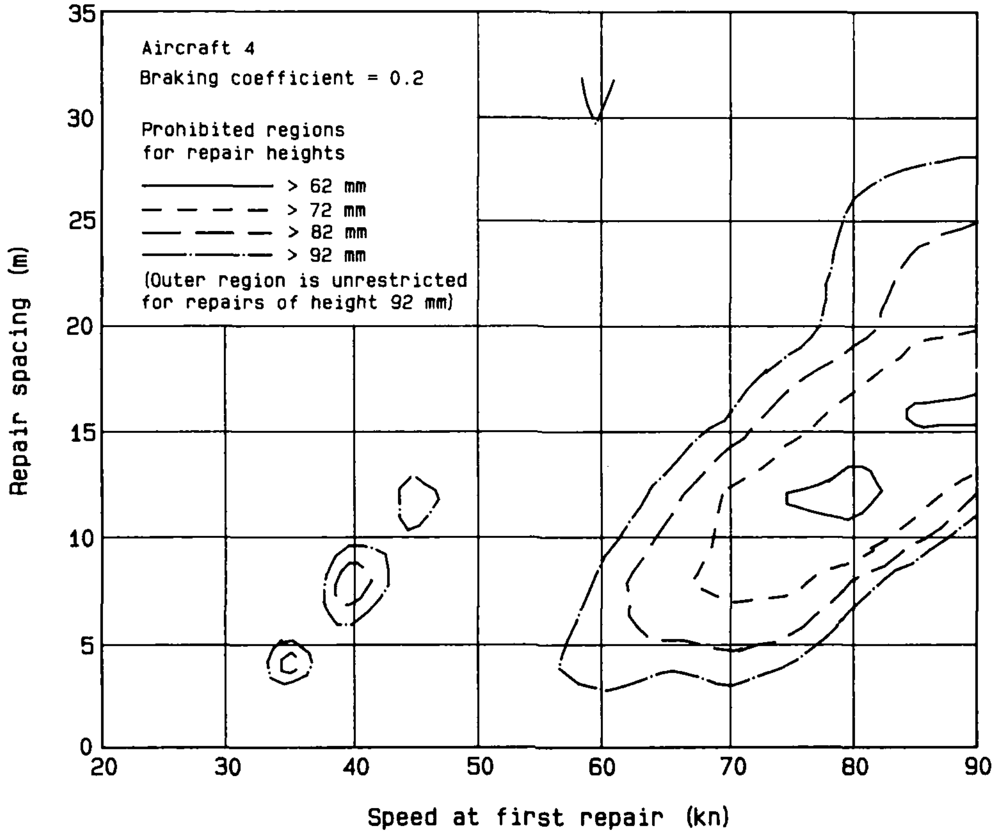


Fig.6 12 Spacing v speed restrictions for landing across 22.5 m repairs

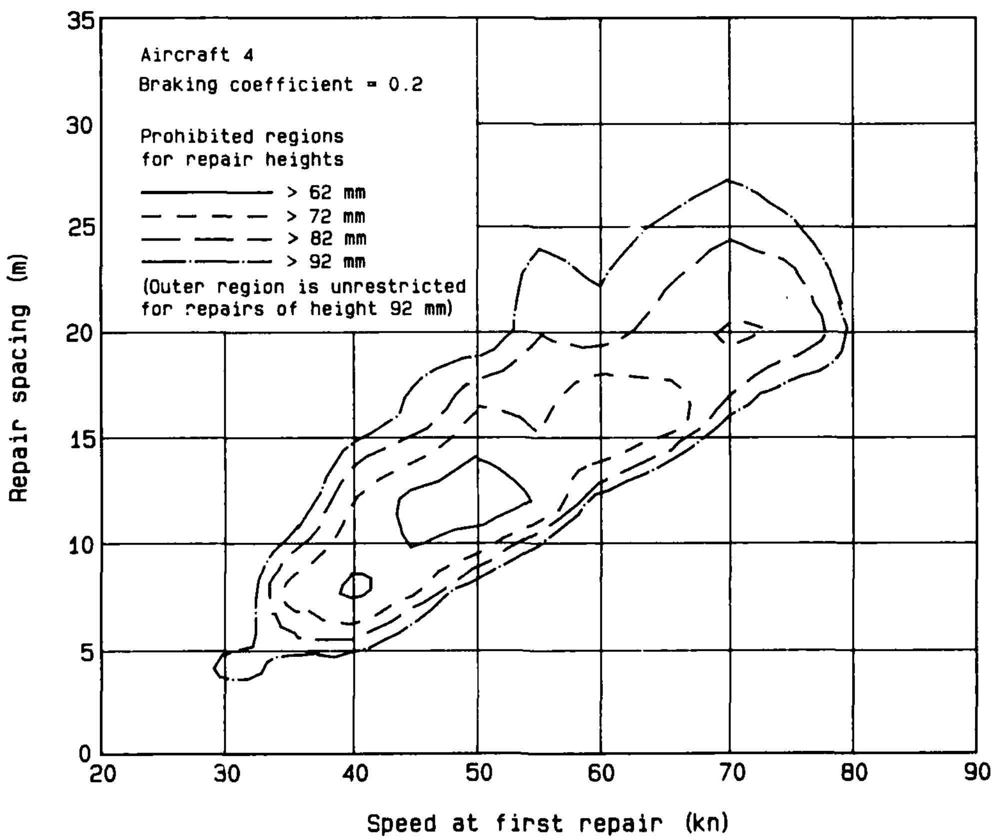


Fig.6.13 Spacing v speed restrictions for landing across 6.5 m repairs

7 INTEROPERABILITY

7.1 The concept of Interoperability

Faced by the results of an attack, the airbase commander must make many decisions to institute the measures which will minimize the disruption to operations. For the repair of aircraft operating surfaces the basis of those decisions is the information which is available to him on the location, type and extent of damage to the aircraft operating surfaces together with information on the remaining runway repair resources. The simplest policy is to deploy those resources to effect the best uniform repair standard under the specified time constraints. However, their optimum allocation also requires him to know the capabilities of aircraft to operate on repaired surfaces so that he can select a compatible repair scheme to permit their operation in their various roles or, conversely, specify those operations which could be undertaken in the conditions resulting from previous and new repairs.

Whatever the methods employed to process the information it is imperative that it be accepted in the terms in which it is most naturally obtained: for example, for potential repairs the primary data will be of the topography; viz the location of newly damaged areas, the nature and dimensions of the damage and the prior characteristics of the operating surfaces defined by both their original features and existing repairs. It is a prime aim to devise means by which such information, much of which can be obtained only from a post-attack survey, can be combined with information on aircraft capabilities, which must mainly be derived in advance, in order best to assist an airbase commander in the timely production of a plan of recovery.

The unity of action within NATO precludes the above tasks being performed within one nation without cognizance of the needs of another. Rather, it must be assumed that interoperation will exist in which an airfield operated by one nation will be utilized by the forces of another with aircraft produced by still another. Consequently the matching of aircraft capabilities with repaired-runway characteristics can vary in scope from a single 'native' aircraft type in well-defined roles to many 'foreign' types employing configurations and operating techniques which are known only vaguely. Despite that variability the matching process must be such that with the procedures available to him the airbase commander can cope with any required situation, though perhaps with varying degrees of precision depending on the extent of the available information.

7.2 Establishment of interoperability

To design, develop, implement and maintain the tools necessary to establish such interoperability is a major exercise. However, one may aim to divide it into initially self-contained tasks which may later be integrated towards the total objective.

In considering those tasks for aircraft in whose design repaired-runway operations have not been expressly considered and for which their relevant capabilities have at best been established for only a restricted set of configurations and environments it is to be expected that deficiencies will be revealed. Therefore an additional aim is to define enhancements to design requirements, evaluation and clearance procedures which will have the benefits of ensuring improved aircraft capabilities and more straightforward establishment of interoperability.

7.2.1 *Resolution of the objective*

The response of an aircraft to surface unevenness is influenced by a number of factors. Most fundamental are the parameters dictated by the required operation – configuration, mass etc. The associated operating technique will produce control actions, such as brake application and release, reverse-thrust initiation and cancellation and deflection of flying controls, which result in significant steady and transient effects. The runway roughness itself, which in the present context is realized by the number, locations and dimensions of repairs superimposed on the inherent roughness, is of primary influence. Also the variation of the aircraft's ground speed along the runway is of both direct influence in affecting the forces developed at a given location and of indirect influence in relating the spatial features of the runway to the temporal inputs to the landing gears.

Thus among the tasks to be tackled the following may be identified:

Define the required operations and associated aircraft characteristics and operating procedures

Specify the runway environment

Produce data on aircraft ground performance

Develop and validate methods to determine the effects on aircraft of operating on repaired surfaces

Establish the features which will define the limits of capability, e g structural strength and tolerance to vibration and shock

Derive aircraft capability data

Devise formats for presentation of aircraft capability data

Develop and evaluate methods for on-site processing of capability data.

7.2.2 *Representation of the environment*

Each of the many repair techniques currently fielded or under development (as described in Appendix 1) yields its characteristic profile, within which there is virtually infinite variation. Future techniques will produce still further variety. Hence in order that data may be produced from which aircraft capabilities can be derived whatever the repair technique employed it is necessary to generalize the description of repair profiles. An additional aim is that that generalization should give economy in the extent of the calculations required.

A family of 'standard bumps' has been developed to meet the above goals. Details of the choice of their characteristics and the supporting analyses are given in Appendix 6. The required properties were that the bumps should

(a) be capable of simple description but reasonably representative of the profiles resulting from current and projected NATO repair methods

(b) permit all potentially critical aspects of an aircraft's symmetrical response to runway repairs to be identified and evaluated

(c) be economical in application and allow simple presentation of results

(d) permit the variation of all parameters of the repair profile which might be subject to choice, e g height, length and spacing.

The chosen form is that of a flat plateau between identical straight leading and trailing ramps. The height and the length of the plateau are variable. To represent the complete profile over a repaired area several bumps may be placed in series, with variable spacings between them. The numbers of values chosen for those parameters as well as for those appropriate to aircraft configuration and state determine the resolution with which an aircraft's capabilities are established and thus can affect the extent to which they may be exploited. However, any increase in those numbers increases the cost of generating the information on capability and the complexity of its presentation and interpretation. Therefore a compromise may have to be struck, depending on the need for full exploitation of capability as against the problem of its assessment.

7.2.3 Synthesis of information

In order to establish operational limitations the information emanating from the above tasks must be synthesized. Those tasks, which are of a mainly technical nature, must be supplemented by regulatory and organizational procedures, such as

Establishment of criteria on operational safety

Specification of the limiting magnitudes of quantities such as structural loads, tire and shock strut deflections and accelerations applied to crew and equipment

Definition of the data to be supplied to the airbase commander, having regard for the format of data on runway repairs distribution of capability data to all potential users

Establishment of a scheme for the maintenance and extension of capability data in view of aircraft modifications, changes in operating procedures and developments in repair methods.

Clearly, many agencies may be involved in the task of synthesis, including

Aircraft manufacturers

'Home' Services, operating the aircraft

'Host' Services, managing the airbases

Airworthiness authorities of the manufacturers' nation

Airworthiness authorities of the 'home' nation

Airworthiness authorities of the 'host' nation.

The establishment of interoperability will depend upon a high level of integration between the activities of all those agencies, with their respective responsibilities and interconnections clearly defined. Several of the NATO nations have each achieved integration among their 'home' agencies and have provided their airbase commanders with data with which to assess the acceptability of operations for their own aircraft but many diversities exist between those nations in the specification of requirements and in the roles of various organizations. However, though attainment of the greatest level of interoperability would require the establishment of uniform procedures across NATO, agreement on definitions of the formats for partially synthesized data and of methods for their utilization would result in that goal being closely approached.

In pursuit of maximum progress within a set period and with a given constitution, two aims were defined:

(i) to conceive a method for determining the capability of aircraft to operate on repaired surfaces

(ii) to develop this method into applicable forms, while retaining as much flexibility as possible in order that they be suitable for all potential users and be insensitive to decisions as to the roles of existing or future agencies.

7.3 Application of the 'standard-bump' concept

With an established mathematical model of the aircraft, calculations may be performed to determine the effects of encountering one or more standard bumps. The multiplicity of influential parameters apart from the bump dimensions naturally allows a number of approaches to be adopted. Usually the aircraft configuration, mass and type of operation will be defined and kept constant for a set of calculations. The operating nation's standard procedure will be assumed, thus defining nominal performance and piloting technique. Calculations will then be performed as required for variations in bump dimensions and disposition, and aircraft speed.

The precise calculation requirements will depend to an extent on the eventual method of presentation of data on aircraft capability. That capability will be derived from an evaluation of the calculated values of response quantities in comparison with their limiting levels. For simplicity of argument it will be assumed that some load is the critical quantity. Then one may either present the attained load level when crossing bumps of a given height (with other bump dimensions varying) or the bump height which gives rise to the limiting load level: it may be expected that the calculation schemes will differ for the two methods. In Section 7.4 two approaches to the derivation and presentation of data on aircraft capability are described in detail; for now it is sufficient to consider the calculation and presentation of loads due to crossing standard bumps.

7.3.1 General basis of calculations

It has already been stated that the standard operating procedure for any particular case should usually be assumed. The nominal performance for the standard conditions of sea level, 15°C temperature, zero wind and zero runway gradient will then be defined. Most calculations should assume the corresponding acceleration or deceleration — constant-speed conditions should be assumed only for low speeds where otherwise it would be implied either that a take-off would start with the nose landing gear already on a bump or that a landing would end with the main gear still on a bump. Calculations may mainly be confined to cases where the aircraft is initially in a non-rotated condition and transient effects may be assumed to have declined to zero. (The disregard of transient conditions is, it is accepted, strictly unjustifiable since their importance may differ widely from one aircraft type to another, so leading to varying levels of risk for nominally comparable capabilities. However, detailed investigation must be left for future studies.)

The above recommendations simplify the basis of calculations; however, in the utilization of results they must be related to actual operating conditions rather than nominal. Also various other influences are for the moment being ignored; for example, an allowance should be made for inherent runway roughness. It has been noted (Section 2) that, particularly in landing, the relationship between an aircraft's speed and its position on the runway can vary considerably; therefore predictions of capability which depend on that relationship (as defining either speed across a repair or time between repair encounters) must take that variability into account. In both the approaches described below there are a number of levels of complexity in data presentation and utilization of data, in which the higher levels aim at a fuller exploitation of aircraft capability – to do so they take more detailed account of operating conditions and may thus be expected to be more greatly affected by differences between nominal and actual conditions; hence when those differences are considered and benefits of adopting them may be much reduced.

The availability of a validated mathematical model is vital. Section 3 discussed in general the requirements for such a model and Appendix 2 gives details of current modelling approaches. The topic of validation is outside the scope of this report; however, it may be commented that there is no universal consensus on an acceptable definition. While calculations are carried out and utilized only within one nation that little impact but standards are necessary for interoperability. For example, the host nation operating an airbase needs assurance that the generalized data for a potential visiting aircraft have been correctly derived so that when repairs have been effected the opportunity to operate from that airbase may confidently be offered; equally, the nation operating the aircraft must be confident that its capability to negotiate the repairs has been properly assessed.

7.3.2 Calculations for a single bump

For particular choices of bump height and length the maximum load due to crossing a single bump may be obtained as a function of aircraft speed. Additionally, information on characteristics of the dynamic response, such as damping, may be required for later analyses.

7.3.3 Calculations for two bumps

For simplicity, it is assumed that the two bumps are identical. Then the additional variable of spacing between the bumps is introduced.

The four ways in which the calculated maximum load may be presented are illustrated in Fig 7.1. The most complex, and the most informative, presentation is as a set of contours of load level above a speed-spacing plane, as shown in Fig 7.1 (a). Envelopes of the sections of those contours by constant-speed or constant-spacing planes give, respectively, the variations of maximum load level versus spacing and versus speed (the other variable always taking its most adverse value), as shown in Figs 7.1 (b) and (c). Finally a single value may be obtained which is the greatest load level attained when crossing two bumps of the chosen dimensions, whatever the speed and spacing.

The data required for each of the stages of condensation described above can be derived from those at the preceding stage; however, much of the latter are thereby discarded. For a particular required method of presentation it may be possible to perform only sufficient calculations to derive the data for that method, with the drawback that the influence of the condensation variables will be unknown.

7.3.4 Calculations for several bumps

The question arises – how many bumps should be considered? Current aircraft have low levels of damping in their rigid-body modes of response so it seems intrinsic that to cover all eventualities quite a high maximum number would be required, perhaps 6 or 7. Clearly, however, for a larger number of repairs it becomes increasingly unlikely that they will all be of similar dimensions or all be critically spaced. Current evidence is that consideration of crossing three bumps of critical length and spacing at all speeds gives a 'lower limit' for aircraft capability which is likely to cover all practical cases.

For three bumps the approach described above may be extended. In particular, a presentation similar to Fig 7.1 (c) (or, of course, of the single overall maximum) in which spacings took their most critical values could be produced for the case of three bumps; the other methods would require separate presentations for each value of the additional spacing variable, either first bump to second or second to third.

Direct extension of the above methods to cases involving four or more bumps is considered unpractical in view of the required scope of the calculations and, especially, the complexity and consequent difficulty of utilization of the results. Alternative approaches are therefore required to treat such cases, perhaps with some degree of approximation. One approach directs attention to pairs of bumps, as above, with the extension that the first bump may be encountered while the aircraft is in a non-equilibrium condition as a result of previous bump encounters: its practical application may necessitate some assumptions about the dimensions of the various bumps. Responses due to several bumps of arbitrary individual dimensions might be derivable by synthesis of those due to one and two bumps – an example of such a technique is described in Section 7.4.3.

7.4 Utilization of data for standard bumps

As discussed above, there is currently a lack of definition of the roles of the various organizations which might be involved in the process of establishing interoperability, and consequently of the appropriate means of presentation and utilization of data on the effects on aircraft of crossing runway repairs. Therefore the work reported here was neither guided nor constrained by pre-existing requirements. A variety of approaches could hence be pursued. Two which were given detailed attention were dubbed the 'contour-plot approach' and the 'top-down approach'. They are described below (Sections 7.4.1 and 7.4.2), first for the idealized standard-bump environment: their application to the actual runway environment is then discussed (Section 7.4.3). The two approaches are assessed in Section 7.4.4.

7.4.1 The contour-plot approach

The basis of this approach is the availability of the full set of data which the application of the standard-bump concept yields, as specified above. Aircraft capability is then to be derived by processing those data either for specification to an airbase commander prior to hostilities, or on the basis of the information available following an attack, or (most likely) a combination of the two.

From the family of standard bump profiles suitable members must be chosen. It is currently suggested that for a particular aircraft it will be satisfactory to choose two heights (from three set values) and three lengths – Appendix 6 gives specific guidance on appropriate values. Then, for each combination of bump height and length, the following are suggested as the data to be made available.

(a) The impact and overswing peaks due to encountering a single bump, for each potentially critical response quantity

(b) The overall peak response due to two, and possibly three, sequential bumps, without differentiating between response quantities or having regard for the times of occurrence of the peaks

(c) The variation of the single-bump response with distance travelled after the bump for a number of speeds, but only for the greater of the two chosen bump heights

All of the above may be presented either as a percentage of the maximum permissible value or as a percentage of the 'allowable' increment between the quasi-static value for the particular condition and that maximum. In either case the percentage which the quasi-static value is of the maximum permissible should be given.

The presentation of (a) will be similar to Fig 7.1 (c), though of course there is no implied choice of adverse spacing.

In the production of (b) the range of spacings should be such as to encompass the third major response peak after the first bump has been passed: beyond that the variability in the computed number of response cycles corresponding to a given bump spacing, due to uncertainties in speeds and frequencies, makes the phasing of the second bump encounter relative to the response from the first unpredictable. The peak response data to be presented exclude those prior to encountering the second bump, since they are already covered by (a). Load-level contours, as in Fig 7.1 (a) will generally be employed for presenting two-bump data; however, if the variation of the peak response depends only weakly on either speed or spacing then the data may be condensed as in Figs 7.1 (b) and (c). It is recommended that condensation be carried out at least for a fixed spacing of 16 m between two 6.5 m bumps in order to indicate the effects of sag in long repairs, by comparison with the data from (a) for 22.5 m bumps. The possible extension of these data to cover the three-bump case has been discussed above.

Presentation of single-bump response histories, (c), is suggested as a means of indicating the response decay over the region where the response due to the first bump is in excess of that typical for the unrepaired runway but beyond that for the three cycles covered by the two-bump presentation.

7.4.2 The top-down approach

This approach is based upon the precept that the data to be presented to the airbase commander should be as few and in as simple a form as are compatible with the objective of mounting effective operations. The programme of calculations is then not fully defined initially but proceeds through a number of levels, following the dictates of that requirement. Each successive level provides data which are more comprehensive than for the previous one, utilizing which may offer increased efficiency of runway repair and/or expansion of the permitted scope of operations, at the cost of employing more complicated methods of presenting and using the data. At each level the aim is to define the 'allowable standard bump height' (ASBH) in terms of chosen parameters so that the aircraft may be operated over corresponding repairs whatever the values of other parameters.

The successive data levels may each be established for configurations having one, two, three etc bumps, the distinction being based upon whether the distance between one bump and another (not necessarily the next) is sufficient for the aircraft response to have decayed to an insignificant level so that the bumps can be regarded as not being associated with one another.

The first data level gives the airbase commander a single ASBH without regard for aircraft speed, repair length and repair spacing; therefore in deriving that ASBH the most adverse combination of all those parameters must be found. (Also the value for the triple-bump configuration probably represents an overall lower limit for any number of bumps.) This data level gives a simple view of repaired-runway capability and may be readily utilized in development of repair techniques, with data for existing aircraft, and in aircraft design, with data on the probable bump heights with existing repair techniques. However, as has been seen in Section 6, the capabilities of existing aircraft in operationally useful configurations are often so limited that the ASBH's at this level are lower than could be achieved within acceptable costs in repair time and resources — in such a situation a higher data level must be exploited.

At the first data level speed was included in the set of variables to be searched for the worst combination; hence the location of the level-one ASBH 'point' can be determined. Away from that point the ASBH would be greater, even for the locally worst combination of bump length and spacing. At the second data level aircraft speed is an explicit variable against which the ASBH is presented, as in Fig 7.2, and thus becomes a parameter of the search procedure. For a given configuration and operation aircraft speed is nominally closely related to position on the MOS. (It was seen in Section 2 that there may be considerable variability in that relationship; however, since second-level ASBH data still encompass the worst combinations of bump length and spacing ignoring that variability may only slightly increase the risk of encountering unsafe conditions.) The utilization of data at this level is then straightforward since superposition of the ASBH versus distance graphs for the required operations (involving a variety of aircraft types and configurations) yields an envelope which defines the heights of repair which must be achieved along the MOS. If an MOS repaired to that standard is not practically achievable then recourse must be made to still more detailed data.

Bump length and spacing remain as candidates for explicit variables at the third data level: the former has been chosen for the following reasons. First, a choice of repair length may be possible, especially for smaller craters, whereas spacing is largely determined by the pattern of damage. Avoiding a particular bump length will avoid 'tuning' of aircraft response due to the effects of fore-and-aft landing gear spacing, which should be advantageous for all numbers of bumps. It has been found that for a single bump length the graph of ASBH versus distance has a much narrower trough than the corresponding graph from the second data level; hence a considerably less stringent repair requirement may result from releasing bump length from the search process. Finally, since the detuning of response by appropriate choice of bump length is less affected by errors in phasing than is detuning with respect to bump spacing, more confidence is obtained in the expansion of predicted operational capability by choosing the former rather than the latter as the additional variable for the third data level.

The presentation of data at the third level is similar to that of data at the second, except that there is now a graph for each of the bump lengths chosen. (Fig 7.2) The data may also be utilized similarly, with the additional aim of locating the MOS within the potentially repairable length so that bumps of a particular length do not come at critical points.

For the fourth data level bump spacing appears as an explicit variable. As discussed earlier, however, when the variability of actual operating conditions is taken into account exploiting this level may be of doubtful benefit as well as being complex of execution. For more than two bumps, as was seen for the contour-plot approach, direct calculation of the necessary data is an onerous task.

Data from the fourth data level cannot be presented on a two-dimensional graph to give ASBH as a continuous dependent variable: a choice is required of standard bump heights for which acceptable operational regions can be derived. Those heights would usually be specified by a regulatory agency and be related to the anticipated heights of actual repairs. At this level the data presentation is essentially of the same form as item (b) of the data for the contour-plot approach (see Fig 7.1 (a)) since the permissible regions correspond to the 100% contours. Because for each chosen bump height only that one contour is needed, contours for various bump lengths may be shown together, as in Fig 7.3.

7.4.3 Relating the data to an actual repaired runway

For the employment of the present concept to be valid the effects of actual repairs must be predictable from those for standard bumps. The diagram below indicates the derivation of corresponding standard bumps and the processes which may be applied to the data obtained for them in order to obtain data appropriate to the actual situation.

The contour of an actual repair must be analysed in order to derive the 'effective' corresponding height and length of a standard bump. For the contour-plot approach and the top-down approach at the fourth data level, where data are presented only for specific choices of standard bump height, that derivation must precede entering the interpolation process. For the lower levels of the top-down approach the allowable height for a standard bump is the objective of the search procedure and so is determined 'exactly' for each chosen combination of the explicit variables. For the contour-plot approach and the top-down approach at levels three and four the response data can be interpolated with respect to bump length: for the lower levels of the latter it is not an explicit variable.

The idealization of the actual repairs is valid for a particular aircraft type only if 'effective' standard-bump dimensions can be derived for any repair profile likely to arise from present and future repair methods. Additionally, for straightforward use of data for a mixture of aircraft, both 'native' and 'foreign', that derivation should be independent of aircraft type.

If either bump height or bump length is an explicit variable for data presentation in the contour-plot approach then, following the recommendations of Appendix 6, there are three values at which response data are available (including for the former zero increment at zero height). Thus quadratic interpolation could be employed. By presenting data contours against S/V (approximately the time between bumps) and using a single value of L/V (approximately the time to cross the first bump) some collapsing of the data is achieved, thereby reducing the errors in interpolation.

Examples of the variation with bump length of calculated response peaks for a single bump are given in Figs 7.4 and 7.5, for two types of large aircraft. It can be seen that while quadratic interpolation might give adequate accuracy extrapolation is unlikely to be acceptable.

An investigation into the derivation of effective standard-bump height is reported in Appendix 6. That used quadratic interpolation of loads data: by using the same form of interpolation in determining effective height and in interpolating the standard-bump response data to give the response quantities for actual repairs errors should be minimized.

A possible technique for synthesizing the responses due to several bumps from the data provided in the contour-plot approach consists of adding to the responses from the last pair of repairs the extreme values of the decaying responses due to preceding repairs. Fig 7.6 compares, for two aircraft types, the responses to three and to four repairs so derived with the results of direct calculation. Generally acceptable agreement is seen, but further investigation is needed before the method can be considered proven. As was discussed above, the alternative of direct calculations for more than two repairs entails considerable cost and possibly poor usability of results. No comparable technique has yet been developed for the top-down approach — the allowable standard bump height could be decreased by the amount already 'consumed' by the preceding bump(s) but the conservatism involved would often lead to a serious underestimate of capability (which can, though, be no lower than that given by the first-level ASBH for multiple bumps).

7.4.4 Assessment of the approaches to data presentation

Since both the contour-plot approach and the top-down approach are based upon description of the actual runway repairs in terms of standard bumps they both rely on the validity of the techniques just discussed. Where they mainly differ is in the view taken of the required outcome of the underlying programme of calculations.

The contour-plot approach seeks fully to exploit the potential of the standard-bump concept by the production

ACTUAL REPAIRS	**STANDARD BUMPS**	**DATA PROCESSING**
REPAIR HEIGHTS	EFFECTIVE REPAIR HEIGHTS	INTERPOLATION FOR REPAIR HEIGHT
REPAIR LENGTHS	EFFECTIVE REPAIR LENGTHS	INTERPOLATION FOR REPAIR LENGTH
REPAIR DISTRIBUTION	EFFECTIVE REPAIR SPACINGS	DIRECT USE OF DATA FOR 1, 2 (3?) BUMPS; SYNTHESIS OF DATA FOR SEVERAL BUMPS

of a comprehensive set of data on the response quantities. Those data are not, however, immediately in a form which can be utilized by the airbase commander and must be further processed, probably with the involvement of airworthiness authorities, in order to determine their ideal practical form. Decisions can then be taken on the appropriate compromise between their complexity of presentation and use and the full exploitation of aircraft capability. It may be that the data can be considerably simplified to permit a direct comparison with data on the repair profiles to be expected from a particular technique. On the other hand, final processing may have to wait until data from surveys of the damaged airfield are available and perhaps be carried out with the aid of a computer.

The top-down approach aims directly at the production of data which are readily usable, but are more restricted in content than those from the contour-plot approach. Utilizing this approach the main task for the airbase commander is to relate the pre-existing and projected repair profiles to standard bumps. For the first three data levels the derived standard-bump dimensions can then simply be compared with the allowable standard bump heights; for the fourth some interpolation of the data on acceptable operating regions is required. Hence for the top-down approach on-site processing is straightforward and generally performable 'by hand'.

The data provided at the various levels of the top-down approach can be obtained by progressively condensing the data from the contour-plot approach (level one corresponding to the final stage of condensation). Therefore which approach to follow will be decided by the efficiency of the whole procedure by which the airbase commander can eventually make decisions on the viability of operations.

One aspect of that efficiency is the economy of the basic programme of calculations. In Section 3 it was argued that the production of data for establishing interoperability should be undertaken as an extension of the aircraft design process; in Section 4, however, it was seen that present design requirements do not explicitly consider rough-runway operation. Rectification of that situation is necessary to permit the methods presented here to be developed and established. The proposed design requirements — Section 9 — utilize the standard bumps; therefore the capabilities which they require define global lower limits for interoperability. For the most critical configuration the required capabilities as regards bump height will generally be the same as the allowable heights for level one of the top-down approach. For other configurations additional data will be necessary even for that level. It was suggested in Section 3 that in the design process the potentially critical cases might be identifiable early on — the more successful that aim the fewer calculations will be performed for the non-critical cases. That same conflict will affect extension of calculations for the top-down approach to higher levels. For establishing the level-one capabilities a fairly comprehensive coverage of the speed range is necessary; hence, so long as all the results obtained along the way have been saved, extension to the second data level is attainable without further response calculations. However, because of the strong tuning effects associated with variations in bump length and spacing the search for critical conditions, whether guided by judgement or following a mathematical optimization procedure, will soon be concentrated on particular values of those variables; therefore, in extension to data levels three and four many more calculations will be necessary to provide full coverage.

The set of calculations required by the contour-plot approach is undeniably extensive. However, in the modern environment where computational costs continue to decrease its production may not be unduly expensive, especially since it can be predefined. Probably more important are the costs associated with post-processing and preparation of data for on-site use. It is highly desirable that data be passed from one stage to another in computer compatible form since manual re-entry of data is uneconomical and prone to error: while the tasks to be undertaken by various organizations are ill-defined standards for data transfer cannot be established.

For the top-down approach the full processing procedure must be established from the outset since the outcome is the set of data to be supplied directly to the airbase commander. Therefore it is imperative that all the agencies involved are agreed: there will be no chance for second thoughts.

The final aspect of efficiency is the effectiveness of the airbase commander's decisions in permitting operations of military value. Too conservative an approach and valuable sorties will be stopped (or its predictions will not be believed); too liberal and aircraft and MOS may suffer damage. The contour-plot approach scores here because of its potentially greater flexibility in dealing with a given practical situation. Full exploitation of that potential requires the development of methods for its general application, which may demand the availability of post-attack computational resources. Thus at present the use either of contour-plot data for specific repair configurations (which require no further processing) or of data for the top-down approach may be favoured: the latter may be the more straightforward and economical to derive providing the appropriate data level can be initially defined.

7.5 The present status of Interoperability

At the start of the work reported here no clear route towards achieving the goal of interoperability existed. A major contribution is the conception, definition and proving of the standard-bump concept. Methods of data preparation and presentation have been investigated and in the contour-plot and top-down approaches described above two apparently antithetic but in fact linked concepts have been pursued; their further development is necessary to resolve a number of outstanding technical issues. Also the roles, capabilities and requirements of the many agencies which might be involved must be clarified before interoperability can be broadly established. The way in which the airbase commander comes to his decisions on deploying airfield repair resources and on permitting operations will depend vitally on the quality of the information provided to him and the means he has to handle it.

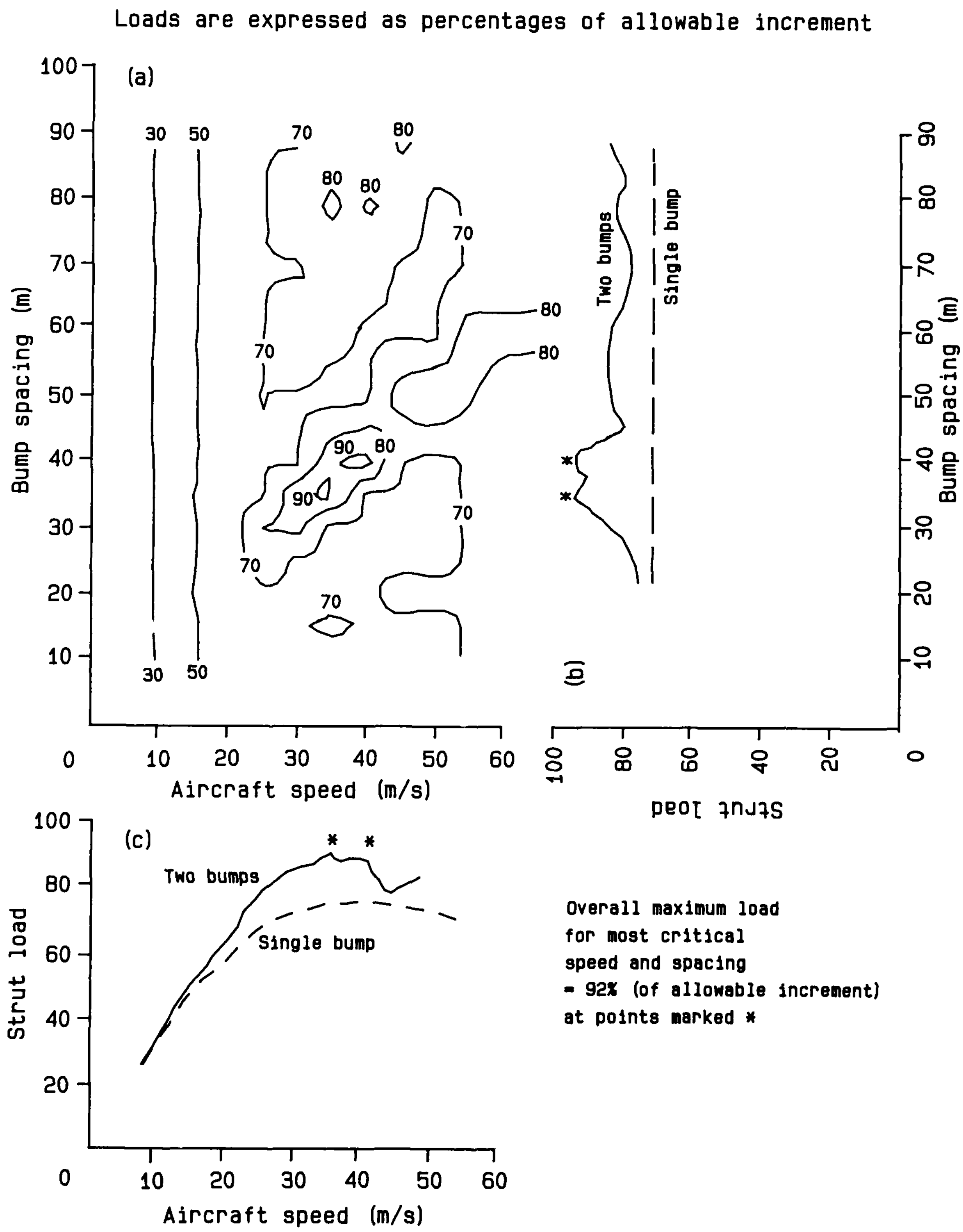


Fig.7.1 Presentation of data on maximum load for two bumps

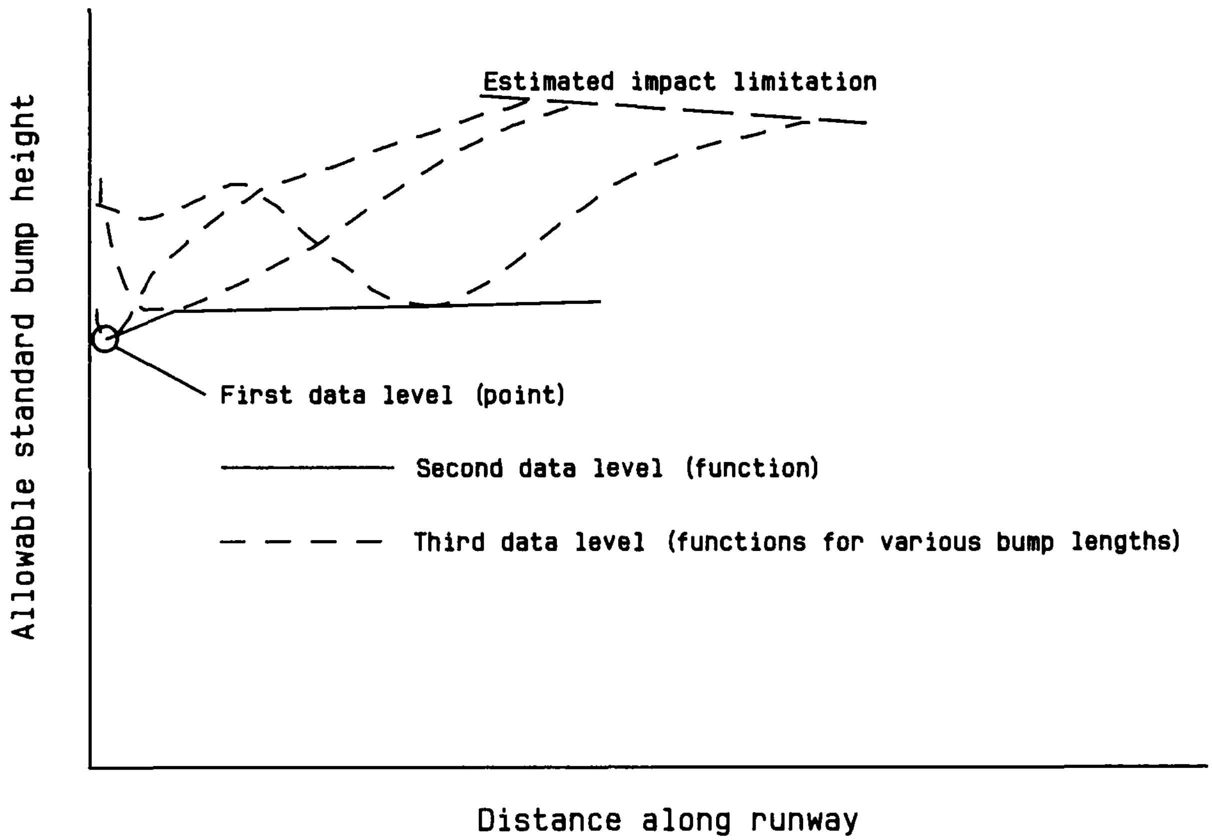


Fig.7.2 Presentation of data for the top-down approach (data levels 1 to 3)

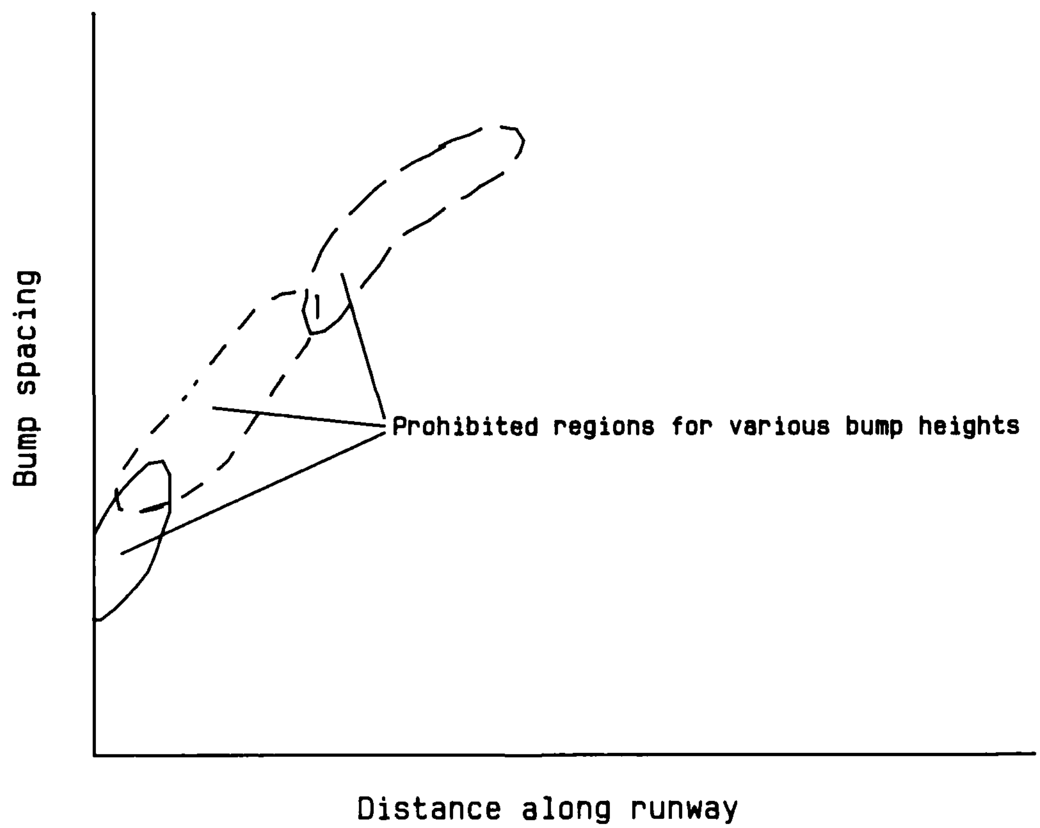


Fig.7.3 Presentation of data for the top-down approach (data level 4)

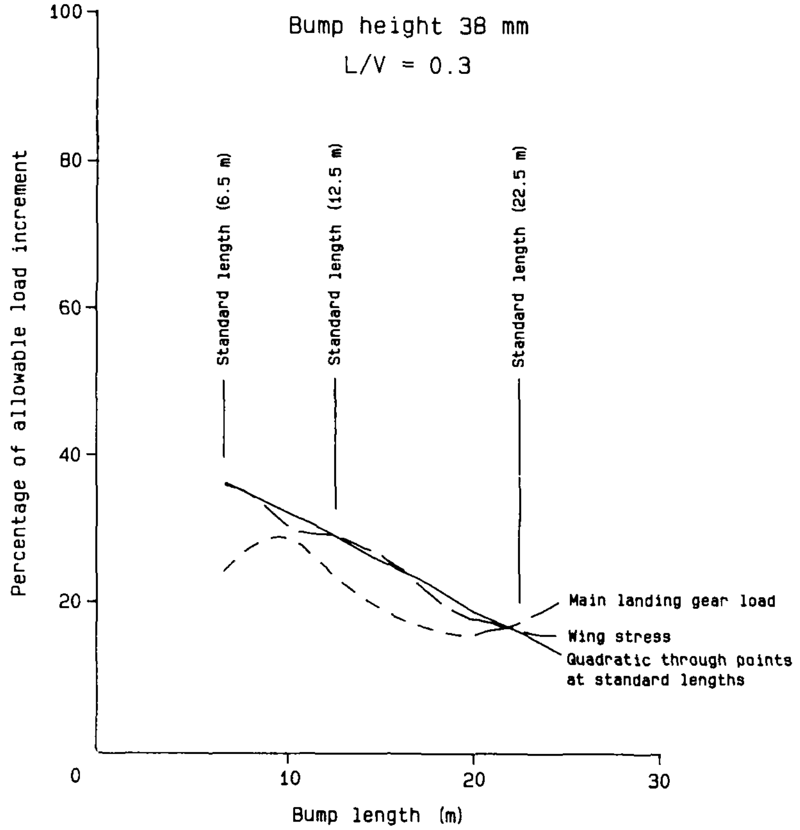


Fig.7.4 Variation of maximum loads with bump length

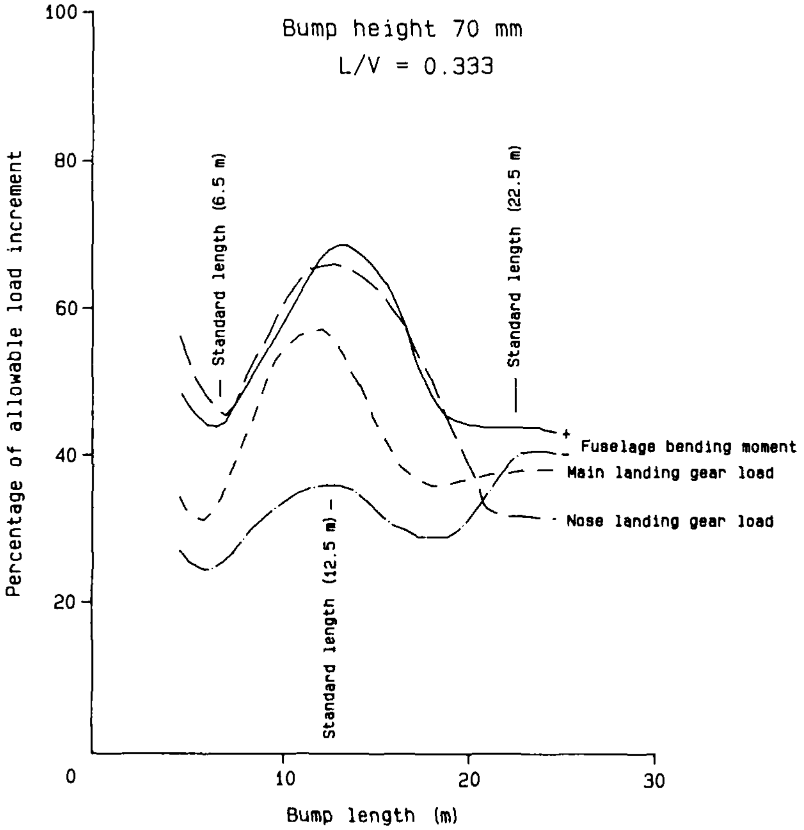


Fig.7.5 Variation of maximum loads with bump length

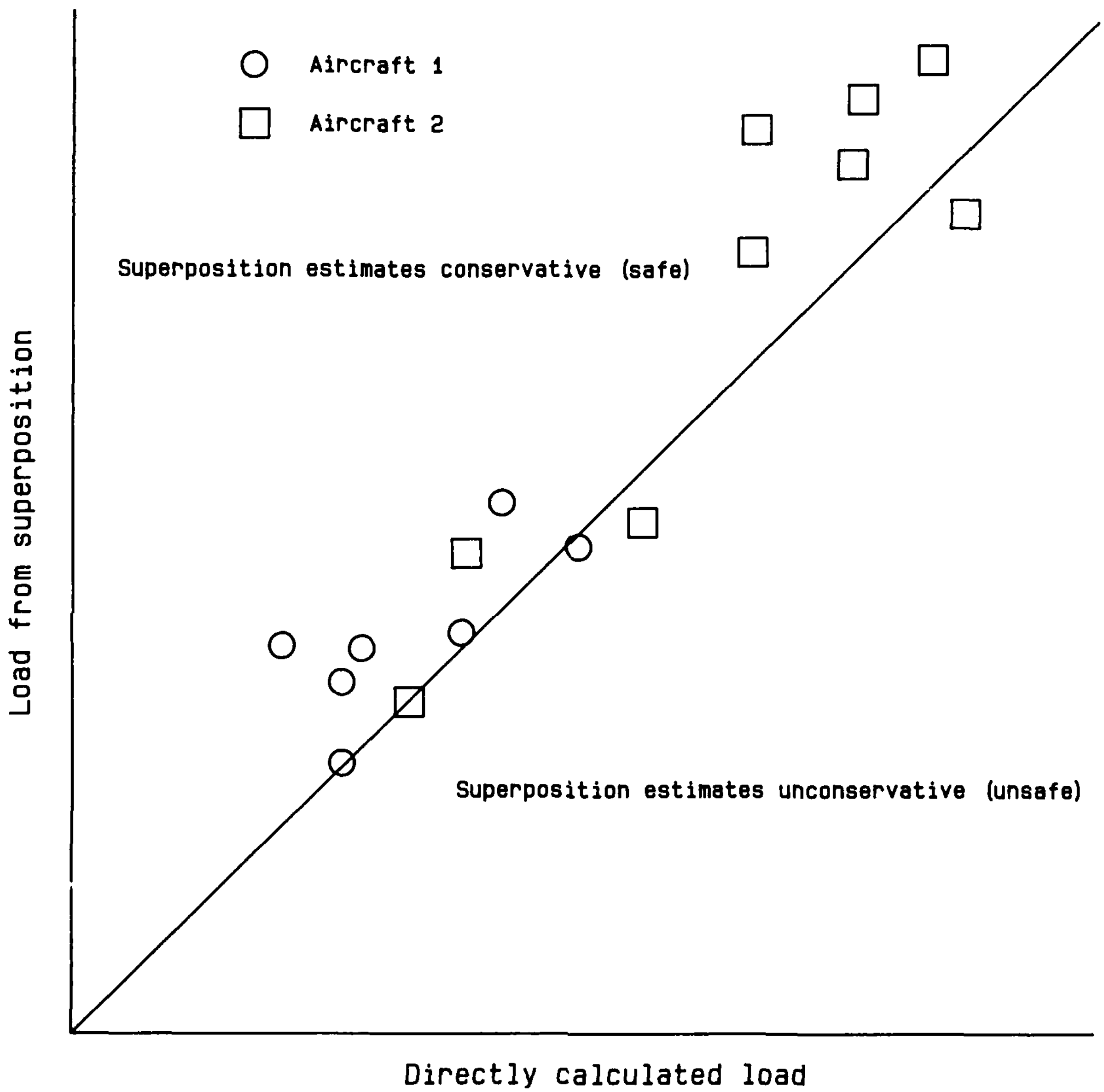


Fig.7.6 Comparison of loads from superposition and direct calculation

8 POTENTIAL DESIGN IMPROVEMENTS

Means whereby an increased tolerance to operations from repaired runways may be obtained can range from simple changes in operational procedures to the adoption of radically changed landing gears with greater capabilities for energy absorption and control. Automatic control systems also promise improvements. Practical constraints on weight, cost and stowage space will, however, have a significant impact on the choice of solutions.

The most readily obtained improvements are via better use of or minor modifications to existing equipment. For a number of aircraft the capability for repaired-runway operation can be increased by raising the shock-strut inflation pressures, thereby increasing the deflection (from the static position) which is available for energy absorption and lowering the stiffness of the suspension. Increased inflation pressures may, however, cause other problems such as a reduction in maximum allowable sink rate, reduced stability in ground manoeuvres, difficulty in retracting the landing gear if the shock strut must be shortened, malfunction of anti-skid systems, or a necessity to produce higher loads in steering mechanisms. More careful servicing can also make a contribution by negating the need to allow for discrepancies when predicting aircraft capability.

The detailed design of shock struts can greatly influence their performance in coping with ground roughness. As an example, it has been calculated that the tolerable repair height for a particular aircraft could be increased from 52 mm to 70 mm by elimination of gas-oil mixing in the nose-gear strut. The existing configuration of that shock strut and the required modifications are shown in Fig 8.1. The percentages of nose-gear limit load reached for 70 mm standard bumps with the unmodified and modified struts are given in Figs 8.2 and 8.3: it is seen that with the latter the boundary corresponding to 80% is little greater in extent than is the 100% boundary with the former. Internal friction in shock struts should be minimized by careful choice of bearing layout and materials. (In existing struts which exhibit high levels of friction some improvement may be obtained by the use of new liner materials, by increases in bearing stiffness and by chamfering of the bearing ends.)

Beyond the above, which may be regarded as 'good design practice', more positive steps may be taken to obtain shock-strut characteristics which are suitable for rough-ground operations. Ideally, there should be no consequent penalty for the landing case. A number of possible improved landing gears have been studied, with the common feature that they seek to reduce the dynamic loads transmitted to the airframe by reductions in the pneumatic (spring) force or the hydraulic (damping) force, or both, and to give better control of the aircraft's dynamical response. The promising directions are to decrease the spring stiffness at the static balance point, to increase the available deflection from that point to full closure — for the aircraft cited above an increase in nose-strut stroke could permit encounters with 95 mm bumps — and to improve the damping characteristics.

The first two of the above aims could be achieved if the effective length of the column of gas under compression were increased during taxiing. That is accomplished in the dual-mode adaptive system, which provides a low-slope spring curve during taxiing and a conventional characteristic during landing, by using a higher pressure auxiliary gas chamber separated by a valve from the primary shock-strut gas chamber. External gas chambers, which would similarly be activated only during taxiing, have also been proposed. The additional weight and volume inherent in such systems make their use unattractive, however.

A variety of valves have been employed to switch and/or modulate damping levels, usually to satisfy landing or braking requirements. Attempts to use them for damping-force control during taxiing have often met with limited success because of unpredictable behaviour.

As a result of recent studies and engineering developments it has been demonstrated that satisfactory multi-stage shock-strut designs which give advantageous spring-force characteristics can be produced within normal weights and dimensions. Also, valves have been developed which function reliably. With such designs the dynamical response to ground roughness can be much improved while incurring no penalty for landing. As yet no aircraft type has been routinely fitted with such improved shock struts but the associated design methods and technology are available for future aircraft.

Historically, the design of landing gears has not been a target area for fundamentally new technology: gradual evolution, for example in the application of new materials for weight reduction, has been typical. Recently the study of loads developed on rough ground has prompted a more fundamental reappraisal of their function. As well as the improvements to conventional passive shock struts, cited above, there is the opportunity to apply active-control techniques to landing gears. Active landing gears differ from passive in that the forces they produce are based upon continuous feedback from transducers which are monitoring the response of the aircraft. Three basic types have been considered: 'series hydraulic', 'parallel servo' and 'active orifice control'.

Theoretically the most capable is the series hydraulic type in which servo valves control the flow of pressurized hydraulic fluid to and from the shock strut. With an ideal system having unlimited gain and bandwidth, unrestricted power and perfect sensing of the aircraft's state any desired variation of shock-strut force may be obtained. Practical experimental implementations of series hydraulic systems have been constructed and Fig 8.4 gives an example of the performance realized: in a laboratory test the landing gear was mounted in a drop tower and forced by a 63 mm (2.5 inch) step input by means of a hydraulic shaker. Though their potential has thus been demonstrated the demands on hydraulic power of such systems necessitate massive pumps, reservoirs and piping, resulting in weight and volume penalties which will, it currently seems, make them unpractical especially for smaller aircraft.

To lessen the power requirements it may be sought to divorce low-frequency load-levelling from the function of control in dynamical response modes. To that end the parallel servo design places a load-supporting spring in parallel with a hydraulic actuator which provides forces to counteract the dynamic response produced by ground roughness. That concept has been shown to be readily applicable to vehicles on trackways, for example, but for aircraft the lack of an absolute height reference will make the overall integration of the system more difficult and limit the advantages gained.

Finally, active orifice control utilizes a control valve to vary the hydraulic orifice area and so the damping force which results from a given stroking velocity. This type of system differs fundamentally from passive systems because the damping force can be made to depend on the motion of the aircraft and not just that within the landing gear. Clearly the scope for modulating the total shock-strut force is restricted in comparison with either of the other two types of active system but the very low power requirement and absence of massive components may make the active orifice control system the practical choice when it is shown that the performance of even the best passive system is inadequate.

The benefits of using automatic control systems during take-off and landing with the aim of reducing response and loads due to ground roughness have received little attention. Potential areas for investigation include automatic braking and control of pitching by aerodynamic means. For current aircraft the applicability of these techniques may be limited by the undesirability or unpracticality of adding more modes to existing control systems but the emergence of integrated, high-authority digital systems make their consideration worthwhile.

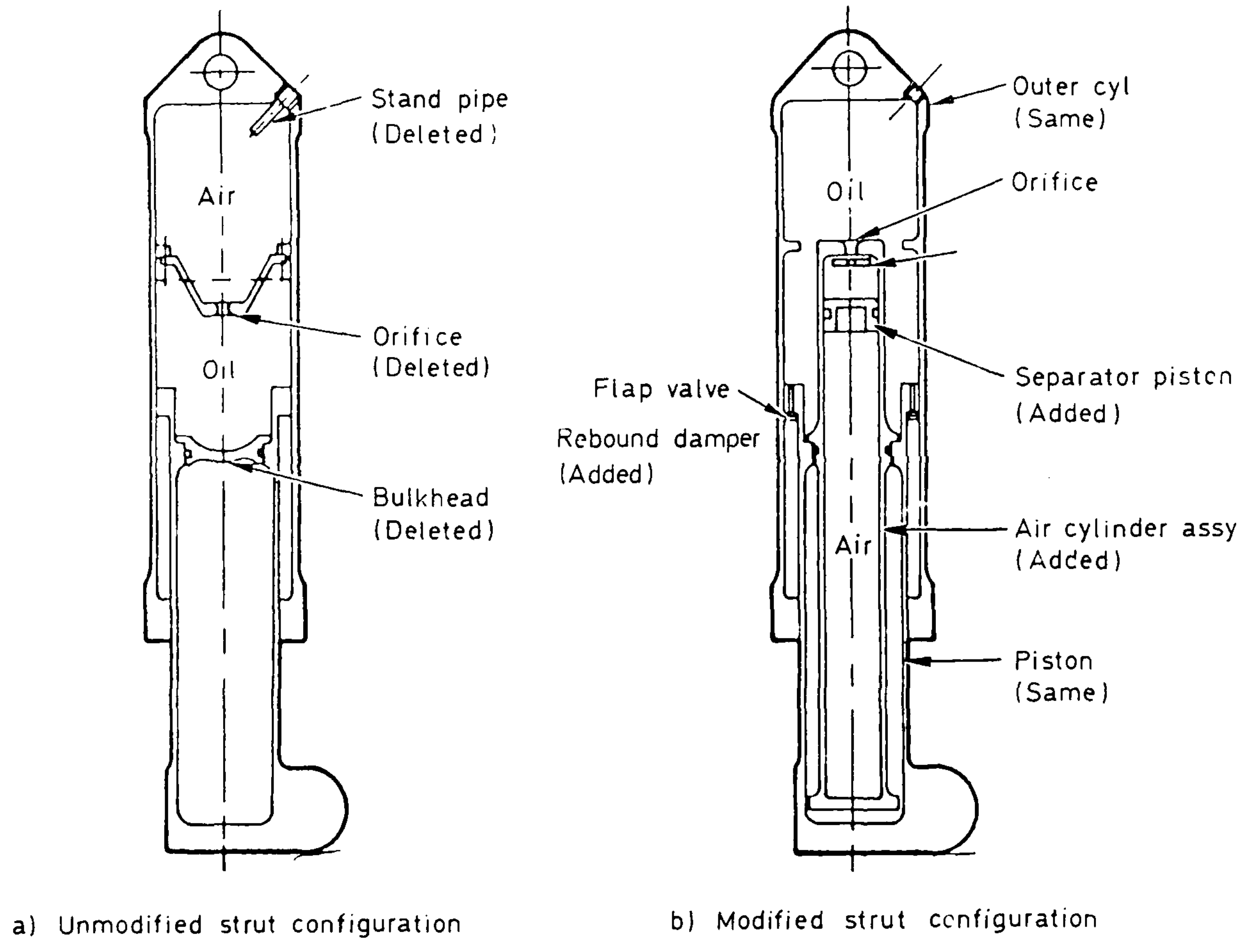


Fig.8.1 Modifications to improve performance of a landing gear strut

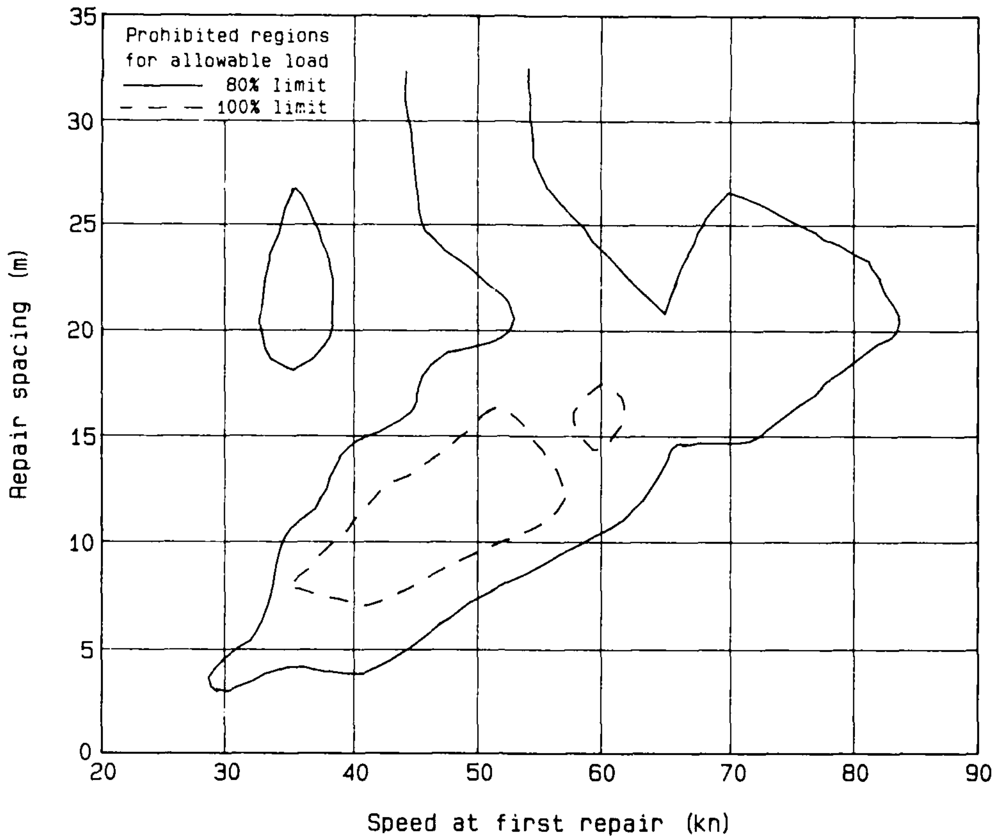


Fig.8.2 Speed v spacing restrictions for 70 mm repairs with unmodified nose landing gear

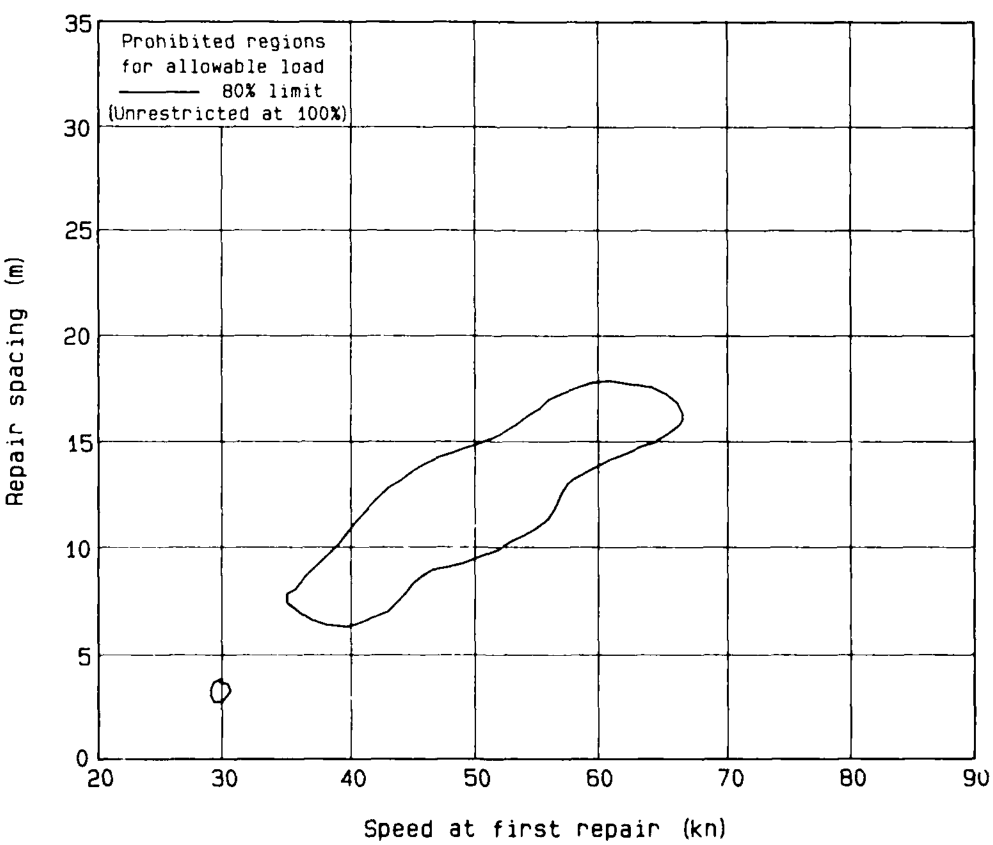


Fig.8.3 Speed v spacing restrictions for 70 mm repairs with modified nose landing gear

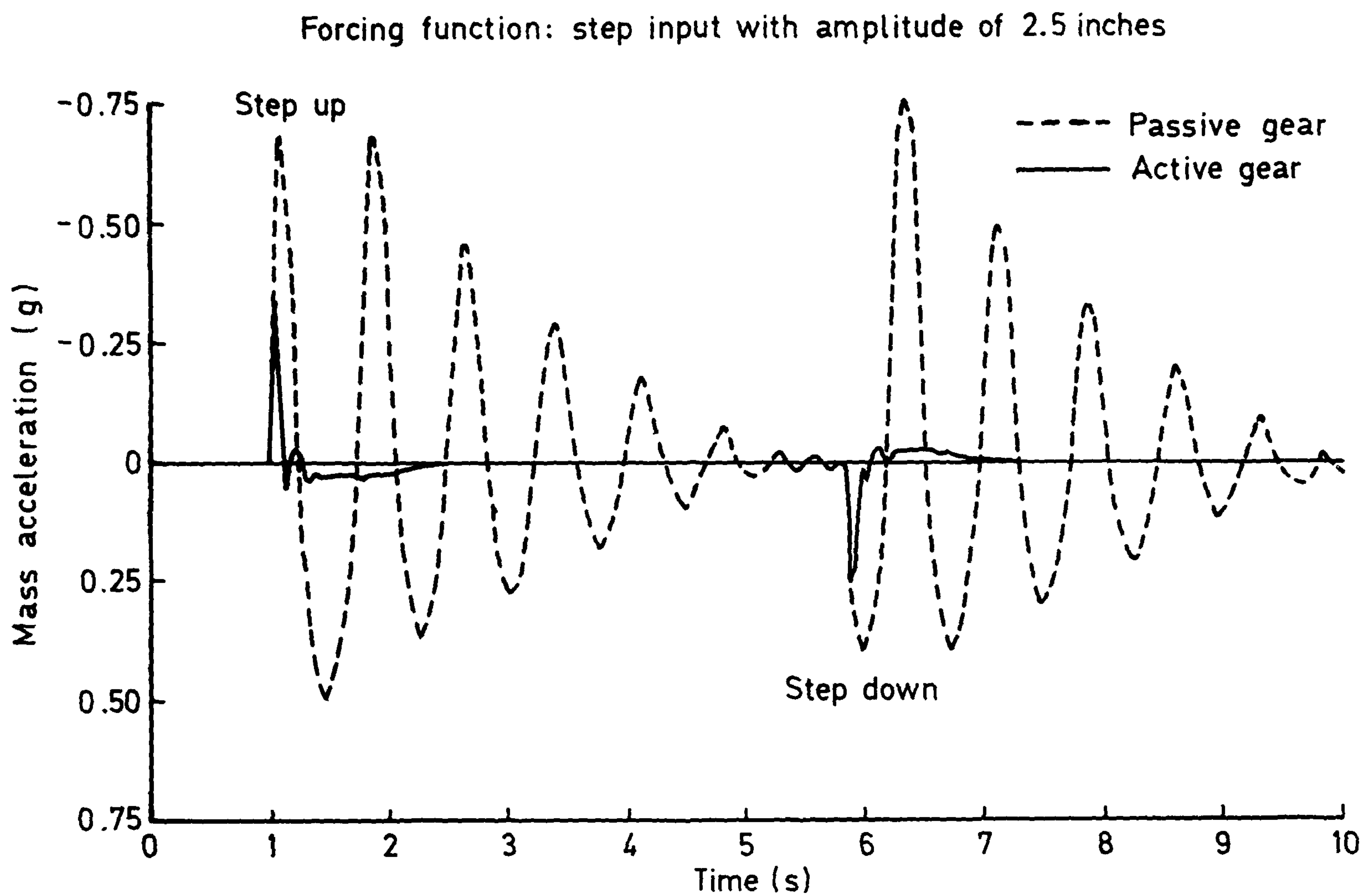


Fig.8.4 Reduction of acceleration response by use of a series damper active control system

9 FUTURE DESIGN REQUIREMENTS

The preceding sections have shown that existing aircraft vary considerably in the capability to operate from uneven runways and that many of them have difficulties in coping with the envisaged operational environment. That is partly because rough-runway operation has not been covered adequately in design specifications and partly because (as was concluded in Section 4) current design requirements are too broad in scope to give specific guidance thereon.

The main objective of design requirements is to ensure the production of aircraft which satisfy operational needs, which are generally specified in Service terminology and not in the engineering terms which could readily and unambiguously be translated into an aircraft design.

This section presents proposals which extend existing requirements for rough-runway operation to include the consideration of runway repairs of forms compatible with the approach to establishing interoperability set out in Section 7. As well as defining the repair profiles and the conditions of repair encounter the section specifies landing impact conditions which are appropriate to short-field operation (such as on a minimum operating strip). For each defined case a summary of the underlying reasoning is included.

The values of sink rate and pitch rate given are believed to be representative for current combat aircraft: the proposed cases are, however, applicable to other types if suitable changes are made to those quantities.

9.1 Landing

The basic definitions and design cases shall be those of DEF STAN 00-970 (Volume 1, Chapter 304 – the primary stressing cases, which relate to landing conditions, are shown in Table 9.1). The design parameters shall be defined in accordance with the following paragraphs.

Although the landing cases, which have in the past been the primary influence in landing-gear design, are not directly related to the operations considered herein, experience has shown that the choice of the basic design parameters has a significant indirect effect on an aircraft's capability to cope with rough runways. Even so, the specification of high sink rates, such as for carrier operation, does not in itself ensure a good rough-runway capability (witness the F-4 which is very restricted in that respect). Rather, a balanced combination of criteria for landing and for rough-ground operation is needed for a satisfactory design.

9.1.1 Sink rates

Design (limit) sink rate (w2d):	4.5 m/s
Ultimate sink rate (w_u):	$1.2 \times 4.5 = 5.4$ m/s
Reduced sink rate (w2r):	$0.8 \times 4.5 = 3.6$ m/s

Because of the basis of selection of a minimum operating strip, repaired runways will be short, with a very restricted undamaged or perfectly repaired length available for touchdown. Consequently short-field landing techniques will be employed to achieve acceptable dispersion of the touchdown point. That inevitably leads to higher sink rates than normal. Two independent studies have been conducted by Northrop and by MBB.

In their study Northrop attempted, based on their experience of the F-18L and the STOL Technology Design Study, to derive a procedure for balanced landing-gear design. Design sink rates of 10 ft/s (3 m/s), 15 ft/s (4.6 m/s) and 24 ft/s (7.3 m/s) were investigated for their implications for loads during landing, taxiing over bumps and ground handling. Capability on soft ground is critically dependent on tire pressure. It was shown that a sink rate greater than 15 ft/s did not permit a sufficiently low tire pressure while avoiding bottoming. On the other hand the dispersion of the landing point increased dramatically for lower values: for a glide slope of 3° dispersion was 328 ft (100 m) for 10 ft/s as against 56 ft (17 m) for 24 ft/s. The study concluded that the best compromise for rough-field capability was to design for a 15 ft/s sink rate.

MBB showed that for landing on restricted repaired runways an unflared technique was necessary, with a nominal glide slope of 3°. Allowing for a ground slope of 1% in the touch down area (in accordance with NATO standards) and a variability in the actual glide slope of 0.75° a sink rate of 4.5 m/s was derived for a typical landing speed of 60 m/s.

Hence although the approaches used in the two studies were different they lead to a common conclusion that design sink rates of about 4.5 m/s give a suitable compromise.

9.1.2 Masses

Design take-off mass M_T for take-off and taxiing
Design landing mass M_L for landing

(M_T and M_L as defined in the aircraft specification)

These masses are generally not the highest in later operational use. Careful consideration of probable mass growth, external stores configurations, possibility of emergency stores jettison etc is required before M_T and M2L can be finally specified.

9.1.3 Landing impact conditions

(a) Symmetrical impact at mass M_L with sink rate w_d in the range of touchdown attitudes consistent with the defined operational procedures

(b) Symmetrical impact at mass M_L with sink rate w_u in the average non-flared touchdown attitude (ultimate loading case)

(c) Asymmetrical impact at mass M_L with sink rate w_r with yaw and roll attitudes consistent with the maximum specified cross-wind component

(d) Symmetrical impact at mass M_L with sink rate w_r in the average non-flared touchdown attitude.

NOTE: It is normally assumed that the aerodynamic lift is equal to the aircraft's weight at the touchdown point but if lift dumping is part of the defined landing procedure allowance shall be made for its effects.

These landing impact conditions are more specifically applicable to the design of landing gears for repaired-runway operation than are the corresponding DEF STAN 00-970 cases.

9.2 General rough-ground operations

The landing impact shall be on a smooth, level portion of the runway (undamaged or perfectly repaired).

Although most aspects of operating in the repaired-runway environment remain in a state of flux, it appears to be generally agreed that an attempt will be made to place the impact point in a region without additional roughness due to repairs. Though that may not be achievable it is considered acceptable not to associate landings at design sink rates with repair encounters.

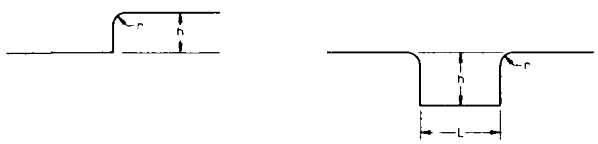
9.2.1 Sine-wave obstacles

(a) (Ref Fig 4.6) Single and double (1-cosine) bumps and (cosine-1) dips for semi-prepared surfaces (left-hand scale) for take-off at mass M_T and landing roll-out at mass M_L, at all speeds

(b) (Ref Fig 4.5) Double (1-cosine) bumps and (cosine-1) dips at mass M_T, at taxiing speeds less than 50 knots

Harmonic runway undulations are valuable in analyses for identifying critical dynamical conditions in ground operations. A variety have been employed in past design requirements (see Section 4), ranging from a single (1-cosine) bump to an infinite sequence. The definition here follows that introduced by the US Air Force in the MIL-Prime. It is not intended that these cases and those of Paragraph 9.3 should both be comprehensively analysed — if the most severe cases for the latter are covered then it could be assumed that the critical tuning for obstacles has been found and parts of the former could be waived.

9.2.2 Discrete obstacles



Sketch 9.1

(a) Steps: $h = 40$ mm; $r = 10$ mm; mass M_T;
$V < 50$ knots

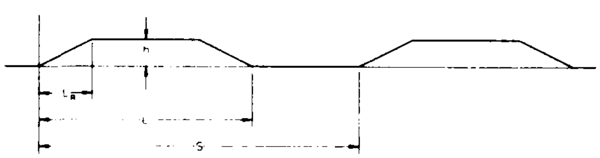
(b) Holes: $h = 50$ mm; $r = 10$ mm;
$50 \text{ mm} < L < \infty$; mass M_T;
$V < 50$ knots

These cases are often critical for tire selection (size and pressure) and should always be covered independently.

9.3 Repaired-runway operations

The repair profiles proposed are those of the standard bumps derived for the evaluations of aircraft capability and studies of interoperability presented earlier.

9.3.1 General definitions



Sketch 9.2

2 identical obstacles
3 obstacle lengths – $L = 6.5$, 12.5, and 22.5 m
$L_R = 1.25$ m

S to take all values so that the most critical conditions for loading and aircraft response are identified

Vertical velocity zero at first obstacle encounter

For landing roll-out cases, maximum deceleration corresponding to the specified operational short-field landing procedure.

At the start of the investigations reported here it was proposed to require consideration of the most critical conditions produced by three arbitrarily spaced obstacles. That has been abandoned because of the prohibitive extent of the required calculations and the inclusion of a third obstacle (not at an independently determined location) is now only to provide a check case to prevent inadequately damped modes of ground response. Also, where it was originally proposed to investigate the whole range of obstacle lengths, only three selected values are now suggested (in accordance with earlier sections).

The level of deceleration after touchdown is critical for the nose landing gear. It is important to adopt the same assumptions for performance analysis and for landing-gear design. For the former a complicated sequence involving pre-armed thrust reversers, lift dumping, wheel braking etc is often assumed, to predict the best possible short-field performance. That may not account for loading limitations and may not be operationally realistic; therefore it is required that the cases of this paragraph be analysed with the operational short-field landing procedure specified at the design stage.

9.3.2 Design cases

Symmetrical obstacle encounter

(a) Limit case: $h = 70$ mm, for take-off at mass M_T and for landing roll-out at mass M_L.

(b) Ultimate case: $h = 90$ mm, for take-off at mass M_T and for landing roll-out at mass M_L.

NOTE: 'Limit' and 'ultimate' cases defined as in DEF STAN 00-970, Volume 1, Chapter 304, Para 4.3 and 6.1

This is one of the rare instances when an ultimate loading case is specified in airworthiness requirements. The non-linear behaviour of landing gears means that to specify only limit cases, with the usual safety factor, could provide much less protection against structural failure in a slightly more severe environment than is desired. The case specified here and the definition of 'ultimate' conditions ensure the required margin for energy absorption capacity.

Cases (a) and (b) are for zero pitch rate at first obstacle encounter.

(c) As Case (a) but for one obstacle only, for touch-down speed at mass M_L; derotation at obstacle encounter with pitch rate 10°/s

Because of the assumption that the landing impact is on a perfect section of the runway the combination of three-point touchdown and obstacle encounter is excluded. However, derotation of the nose landing gear onto all sections of repaired runways following main-gear impact must be covered. A theoretical assessment together with a survey of measurements for 45 landings of a combat aircraft led to the conclusion that pitch rate at touchdown should be derived by multiplying by 1.3 the average rate assumed for short-field landing performance calculations. On that basis the chosen value of 10°/s represents a lower bound for the pitch rates which may be expected for a combat aircraft landing on a repaired runway.

(d) Ultimate case (dynamic braking): one obstacle only; $h = 70$ mm, for touch-down speed at mass M_L and for speeds below 50 knots at mass M_T; maximum achievable braking at obstacle encounter.

The above case may not be required if the brake control system is suitably designed to relieve severe loading conditions. Since performance is often the aim without regard for the resulting loads, it seems prudent to investigate the consequences of adverse brake application. 'Maximum achievable braking' is that resulting from maximum pedal force and realistic assumptions regarding tire friction on a dry runway.

(e) A third identical obstacle at the same spacing from the second as the most adverse spacing for the conditions of Case (a) must not raise any critical load by more than 10%.

This case is to ensure the provision of adequate damping.

Table 9.1
Primary stressing cases for all landing gear units (DEF STAN 00-970)

Primary stressing cases for all landing gear units (DEF STAN 00-970)

No.	Case	Vertical Force	Drag Force	Side Force	Shock absorber closure %
1	Combined drag and side load	R	0.4R	±0.25R	30
2	Side load inboard	0.5R	0	0.4 R	50
3	Side load outboard	0.5R	0	0.3 R	50
4	High drag and spring back	0.8R	±0.64R	0	15
5	One wheel landing	R	0.4 R	±0.25R	30
6	Rebound of unsprung parts	20W	0	0	0

Notes:

1. For main units $R = R_M$. For nose units $R = R_N$. For auxiliary units $R = R_A$. See para 3.1.6.
2. All side forces between zero and the values given shall be considered.
3. Tyre closure appropriate to the vertical reaction may be assumed.
4. For a unit on the centreline of the aeroplane case 2 will apply to both port and starboard and will override case 3.
5. Cases 2, 3 and 5 do not apply to nose-wheels.

10 CONCLUDING DISCUSSION

This report presents an integrated view of the topic of operation from repaired runways, from the central standpoint of Structural Dynamics. From a definition of the operating environment the major influences on aircraft response and loading have been identified. The relevance of current design requirements and practices to the provision of those capabilities has been reviewed and the adequacy of the available methods of evaluation of aircraft capabilities assessed. The scope of those capabilities for current aircraft types has been evaluated and the means of presenting data to define permissible operations within the established limitations considered. Modifications to landing-gear design which could expand aircraft capabilities have been identified and supplementary design requirements set down.

Few current design requirements for ground operations address the problem of operating on repaired runways; thus aircraft capabilities thereon are as a by-product of other requirements. Also they exhibit wide disparities in the ground profiles they specify. Therefore additional requirements are needed so that repaired-runway operation is assuredly covered. Moreover, the target of interoperability recommends that they be standardized within NATO.

The variations in the repair profiles achieved by a variety of repair techniques necessitate the generalization of their description for the purposes of aircraft design. A family of 'standard bumps' has been developed from which repair profiles can be specified for application to the design and assessment of existing and future aircraft. Such a description may also serve as the vehicle for the exchange and utilization of data on aircraft capabilities which is required for the attainment of the objective of interoperability. Thus the establishment of a standardized description of the environment to which aircraft capability can be related at all stages is seen as a major contribution to the unification of the field of repaired-runway operation.

Evaluations of the capabilities of existing aircraft have shown the serious deficiencies which have resulted from the lack of express consideration of the repaired-runway environment at the design stage.

The production and presentation to airbase operators of data which gives an appropriate level of definition of aircraft capabilities is vital to the success of employing the 'standard bump' approach to achieve interoperability. Compromise may be necessary since while simplification is desirable to permit ready utilization of such data the attendant conservatism may result in the prohibition of safe, valuable sorties. This problem has been considered in general terms and two complementary approaches have been pursued in depth; either may be appropriate, depending on the individual circumstances of their application.

The theoretical and experimental tools for proving the capability of an aircraft to cope with a specific runway profile are constantly being improved and, though refinements and extensions are desirable in some respects, do not generally fall short of requirements; it has been established that theoretical predictions can be brought into good agreement with measurements. Therefore the assessment of aircraft capabilities is not hindered by inadequate methods; however, the lack of early consideration of repaired-runway operations has reduced the efficiency of their application.

Potential improvements for landing gears have been investigated and a number of measures identified which could improve an aircraft's capabilities on repaired runways and for rough-ground operations in general.

The introduction of design requirements which take account of the repaired-runway environment is necessary to ensure that future aircraft have the required capabilities. The content of such requirements has been considered and an example set presented.

In general the objectives for the investigations reported herein have been met. However, the approaches proposed need to be further defined and other aspects remain to be fully explored. It must be ensured that certain restrictions, imposed to permit adequate progress, have not led to the neglect of important factors. The adoption of standard bumps must be substantiated by an appraisal of its implications for design and the validation of predictions of aircraft capability for actual ground profiles. Its potential for producing data in forms which are suitable for operational use requires, as well as further technical development, a broadening of discussions to include other agencies, who could specify their needs and contribute additional information to facilitate the establishment of practical procedures which are understood across the NATO nations.

APPENDIX 1

AIRFIELD DAMAGE, REPAIR PROCEDURES AND REPAIR PROFILES

This Appendix provides details of the repaired-runway environment, to supplement the discussion of Section 2. It describes methods used to repair airfield damage, the resulting initial repair profiles and their subsequent deterioration due to aircraft traffic.

Airfield damage is classified according to severity, ranging from small scabs produced by cannon fire to large craters produced by bombs.

A1.1 STEPS IN PREPARING A MINIMUM OPERATING STRIP

After an airfield attack a minimum operating strip (MOS) must be located and prepared for use as rapidly as possible, so that aircraft operations can commence. Civil engineers and repair crews have the task of preparing that MOS and must produce a co-ordinated effort in an environment of high risk. A complex series of events chosen from the following list is necessary:

Establish a new temporary runway centre-line

Identify craters and scabs to be repaired

Clear unexploded ordnance

Commence clearing, sweeping and marking the temporary runway

Remove broken pavement from around each crater in the MOS

Push ejecta (broken pavement and soil) back into the crater

Transport crushed stone to the MOS and fill the crater

Compact the debris and stone in the crater

Level the surface

Perform an initial survey and rectify the levelling if necessary

Assemble, position and anchor a cover over the crater to provide surface strength and prevent foreign-object damage to aircraft

Survey the repair to determine its profile

Repair scabs, using a filling compound or steel plates

Complete sweeping and marking the runway

Repair and mark access routes to the MOS

Install aircraft arresting systems

Establish radio communications

Perform periodic inspection and maintenance on the repaired surface between aircraft operations.

The repair crews may be required to perform those activities in an environment containing chemical agents, anti-personnel and anti-equipment bomblets and other unexploded ordnance. Sight, ease of movement and endurance will be restricted by respirators, chemical-warfare protective clothing and armouring of construction equipment. Despite possible jamming of communications, activities must be well co-ordinated since they are performed in parallel by separate groups that could interfere with each other. Though good organisation and training will permit the production of the best possible repairs it must be appreciated that constraints on time may enforce the sacrifice of repair quality.

A1.2 DAMAGE DESCRIPTION

The nature and extent of damage to airfield pavements inflicted by conventional munitions vary greatly depending on the size of the explosive charge, the type and condition of the pavement and the sub-surface soil strength and moisture content. Damage can, however, be categorized into three general classes: scabs (also called 'spalls'), small craters and large craters. The characteristic features of those classes are shown in Fig A1.1: different repair techniques are required for each.

A1.2.1 Scabs (spalls)

Scabs do not completely penetrate the pavement and thus do not disturb the sub-surface soil. Damage of this category is limited to an area less than 1.5 m (5 ft) in diameter (see Diagram A in Fig A1.1). It is mainly caused by aircraft cannon and small rockets, with or without explosive warheads.

Since the sub-surface soil is not disturbed and the surrounding area is fairly clean, the damage can be repaired by using fast-setting filling compounds or steel plates: in the former case the resulting surface is flush with the surrounding pavement and in the latter there is only a minor protrusion over a small area. Repaired scabs therefore are of little consequence in the production of aicraft loading.

A1.2.2 Small craters

A small crater is defined as pavement damage which involves penetration or disturbance of the sub-surface soil, with an apparent crater diameter of less than 4.5 m (15 ft) and a total extent of damage of diameter less than 6 m (20 ft) (see Diagram B in Fig A1.1). Likely sources are concrete penetrators, clustered munitions or surface-fused bombs.

The depth of burst has a major influence on the extent of damage and the crater shape. The principal types of crater which would be produced by a charge of a given size with differing depths of detonation are shown in Fig A1.2. Generally, the crater size and the amount of pavement upheaval increase with that depth until an optimum is reached, after which the surface damage becomes less severe and a camouflet develops.

A1.2.3 Large craters

Large craters have dimensions exceeding those given above. They are most likely to be caused by large general-purpose bombs, delay-fused munitions or large concrete penetrators. In the repair of large craters debris may be pushed back into the crater before filling with crushed stone, compacting the fill material and capping.

A1.3 SCAB REPAIR PROCEDURES

Constraints on time are likely to prevent the repair of all of the scabs in a runway – whether a particular scab or combination of scabs must be repaired depends on the type of aircraft to be operated. Airfield personnel are equipped with the necessary data, which generally include criteria on

Maximum scab depth

Maximum scab length and width

Maximum change in slope from the undamaged surface

Minimum spacing between scabs.

All loose debris and damaged pavement are cleared before applying either of two repair methods. One involves placing steel plates over the scabs and fastening them to the pavement, the other filling the scabs with a fast-curing compound. Any scabs to be left unrepaired will be initially swept and repaired later when time and runway utilization permit.

The steel plates employed are pre-manufactured in various sizes with counter-bored holes for bolts.

The polymers currently used for filling consist of three parts: powder adhesive, liquid hardener and catalyst. After mixing, the compound is placed into the scab and smoothed with a trowel. Curing can be accelerated by heating – in bad weather polyethylene sheeting is used for protection during curing. Such polymers adhere best to dry surfaces and may give off toxic fumes as they cure. Safer, faster-curing polymers are being tested as supplements to the polymer concretes currently fielded. These plastic-based liquid compounds may eventually replace present materials since they cure faster, displace water, adhere better to wet surfaces and may also be used in making structural caps for craters.

A1.4 CRATER REPAIR PROCEDURES

The stages involved and the methods employed, described below, are essentially applicable to the repair of all sizes of crater. However, there are certain respects in which repairs of small craters and of large differ, as follows.

Large craters normally have sufficient volume for debris to be pushed back into the crater prior to filling. Small craters generally cannot contain both debris and sufficient filling material to create a strong repair. Excess debris must be removed from the MOS.

Small craters may be too shallow to accommodate the depth of fill needed for strong repairs. Material which has fallen back into the crater must first be removed.

Small craters and scabs may be too numerous and too closely spaced for the employment of procedures used for large craters. As the repair area becomes smaller the use of matting becomes less efficient since more anchor points are needed and the ratio of mat area to damage area increases rapidly if the entire width of an MOS must be covered. Several small craters may therefore be dealt with in combination by one very large repair.

d Small craters and camouflets do not permit excavation equipment to operate efficiently from within the crater. That increases the difficulty of removing upheaved pavement and hinders compaction of the debris.

Surveys of the runway are used to identify a new temporary runway and associated access routes. Measurements of damage are made by stretching a string and a tape measure across each crater, as shown in Fig A1.3, and used to decide the plan of reconstruction, the time needed, and the required repair qualities.

The sequence of events in repairing a crater is shown in Fig A1.4. There are four major elements: (1) clearing and cleaning the crater, (2) filling the crater with debris, ballast rock and/or crushed stone, (3) compacting and levelling the filling material, and (4) covering the repair for strength and FOD prevention.

A1.4.1 Preparing the crater

As soon as the surrounding area is sufficiently clear, excavators are taken to the crater edge to pull away upheaved pavement and clean the crater of large fragments and broken utilities conduits and to remove ruptured soil under the upheaved periphery. Hydraulic hammers and concrete saws are used to break up large slabs and to trim the crater edges. Debris is then pushed back into the crater or removed. The endurance of a repair under trafficking is much improved if the filling material is of uniform size; therefore all large chunks of debris should preferably be removed. However, shortages of time and materials will probably force a compromise.

If time permits, all upheaved pavement is removed so that 'flush' repairs may be created. However in some circumstances some of it must be left, sacrificing repair quality to save time. Charts of 'allowable upheaval', based on the combined capabilities of the aircraft which will use the runway, will then be employed.

So-called 'dynamic compaction' is employed by some teams to flatten upheaved areas or to pulverize large chunks of debris in situ by dropping a weight from a specially modified crane. Alternatively, upheaved pavement can be broken back but if the slabs do not fragment easily it may be decided to pull them away to save the time which would otherwise be consumed in smashing them.

A1.4.2 Filling, compacting and levelling

If the debris does not provide sufficient material, coarse uniformly-sized stone is used to fill the crater to within about 450 mm (18 in) of the rim. The surface of the fill is then roughly levelled. Layers of finely graded stone are laid on top, levelled and compacted. The surface is finally screeded to within prescribed tolerances.

Crushed stone is made to close grading specifications to give the best quality of compaction and durability of repair. Variations exist in repair techniques, to allow for soil strength, ground water conditions and the availability of particular grades of stone.

A1.4.3 Capping

After compacting and levelling have been completed a structural cap is placed over the crushed stone which as well as guarding against FOD prevents rain seeping into the crater and softening the underlying soil, and reduces the depth of ruts caused by aircraft. Four types are currently available in the field – pre-cast concrete slabs, interlocking aluminium mats, rolled aluminium mats and fibreglass mats. Fast-curing polyurethane may be fielded in the future. These will now be described.

(a) Pre-cast concrete slabs

When pre-cast concrete slabs are to be used a rectangle is cut in the pavement to contain the crater and surrounding upheaval and accommodate a whole number of standard-sized slabs. The pavement within that rectangle is then broken and removed. The compacted stone in the crater is levelled to give a surface slightly below that of the original pavement, a layer of sand is put over it to provide a bed for the slabs and to prevent them rocking as the repair deteriorates. The slabs are then set into place and bedded in by a vibratory roller or plate. A cross-section of a completed repair is shown in Fig A1.6.

(b) Interlocking aluminium mats

The AM-2 matting developed in the US comprises plates 38 mm (1.5 in) thick which interlock to form a complete mat. The mat is assembled next to a crater and dragged into position following levelling, as shown in Fig A1.7. The mat is anchored to the pavement using expanding bolts.

AM-2 mats can be traversed by combat aircraft and some transports but are inadequate on runways to support the largest cargo aircraft because their anchoring system leaves them liable to be dislodged by high tire drag loads and by high-velocity air from thrust reversers. They may be used on taxiways and aprons for all aircraft, providing tight turns are not made over them.

(c) Rolled aluminium mats

The UK Class 60 trackway mats are thinner – 32 mm (1.25 in) – and more flexible than AM-2 mats and are pre-assembled and rolled for storage. When needed, a mat is taken to the crater edge, aligned and unrolled. The mat is then tensioned to remove slack in its joints and anchored using expanding bolts. Side fairings are installed if the mat is to be crossed asymmetrically.

(d) Fibreglass mats

Fibreglass mats are made in two standard sizes for repairing small and large craters. They are dragged from storage to their required positions and then secured similarly to aluminium mats. If the area of damage cannot be covered by one mat then two or more can be joined with resin, using a single lap joint.

Folded fibreglass mats are produced for use by Rapid Deployment Joint Task Forces. They are made in panels jointed by hinges of glass fibre impregnated by polyurethane. The panel size is dictated by the floor area of the delivery aircraft. A mat is unfolded at the repair site, tensioned and anchored. An unfolded mat is shown in Fig A1.8 and its application to crater repair in Fig A1.9.

(e) Magnesium phosphate cement

A magnesium phosphate compound is formed by mixing finely ground magnesium limestone with a complex ammonium phosphate solution. After mixing, the reactants are spread over a screeded crushed-stone surface and smoothed. The mixture cures rapidly, forming a high-strength cement. In cold weather curing can be accelerated by adding a catalyst.

(f) Polyurethane cement

A polyurethane cement has been developed to supplement the above materials. It consists of three components, two resins and a catalyst, and is mixed just prior to percolation into a permeable material placed in a crater. Use of that technique to replace capping of compacted stone by mats should reduce the time needed to effect repairs, improve repair surface quality and reduce subsequent maintenance.

Fig A1.10 shows a cross-section of a polyurethane cement repair. The crater is partially filled with debris and/or ballast rock. Those bulk fill materials are compacted and levelled to about 250 mm (10 in) below the surface and a sheet of plastic laid on them which limits the depth to which the liquid polymer percolates. Filling is then completed and the polymer poured into the permeable material. Because of the large volume of cement required and overall constraints on the time for reactivation of the airbase, rapid dispensing and curing are necessary. Special equipment to meet those requirements is now being developed.

A1.5 EFFECT OF AIRCRAFT TRAFFIC ON REPAIRS

Most investigations of the effects of repair encounter on aircraft assume a profile which represents a nominal newly produced repair with a certain level of pavement upheaval and a flat central region. In reality every pass by an aircraft results in some deterioration of the repair cap and the underlying material. As each tire passes over a repair the soil directly beneath is compacted and displaced slightly to the side. The cumulative result appears as ruts in the surface and voids under the cap. Such effects are difficult to predict as they depend in a complex way on many variables, e g tire load and pressure, soil moisture content and the degree of compaction of the crater fill material; however, some general observations can be made.

Sag in the repaired surface can begin at any location but usually appears first at the edges and progresses towards the centre (see Fig A1.11) because the proximity of the undamaged pavement decreases the effectiveness of compaction. That is so particularly when a vibratory roller is employed – its operators must be sure not to drive onto the undamaged pavement – but less when using a vibratory plate on an excavator boom.

Overfilling the crater to produce a crown increases the life of a repair but is only acceptable if the additional initial height can be tolerated by aircraft.

The dynamic interaction between the aircraft tires and the repair surface strongly influences the resulting profile. Sagging will tend to be greatest at the points where peak loads occur. As sagging develops in the centre of the repair it will progressively resemble to the aircraft a closely spaced pair of shorter repairs, so affecting the dynamical response and the most critical crossing speeds.

For the most effective compaction and greatest durability of repair the soil moisture content must be at a particular level – repairs made on soil that is too wet or too dry will degrade much faster. Given sufficient time, repair crews will adjust moisture content but often correction may have to be confined to pumping out standing water before starting repairs.

For pre-cast concrete slabs criteria on repair deterioration must limit the sag and also the rocking of an individual slab. Fig A1.12 shows the profiles of a slab repair before trafficking and after 500 passes by the tire of an F-4 main landing gear. The profile of the underlying sand, measured after removal of the slabs, does not match the latter, which gives evidence of the rocking motions which develop for each slab. Such motions increase the risk of cutting a tire on a slab edge so when they exceed a predefined limit the slab must be removed and the sand below repacked. A heavy vehicle must be used to permit the amount of rocking to be measured.

Voids also occur under mats – again, loading by a heavy vehicle prior to measuring the repair profile is necessary to detect them. They are prevalent where rutting occurs as a result of sub-surface soil failure or heavy local loading. Voids increase the likelihood of the mat cracking, which permits the influx of water and jet exhaust gases.

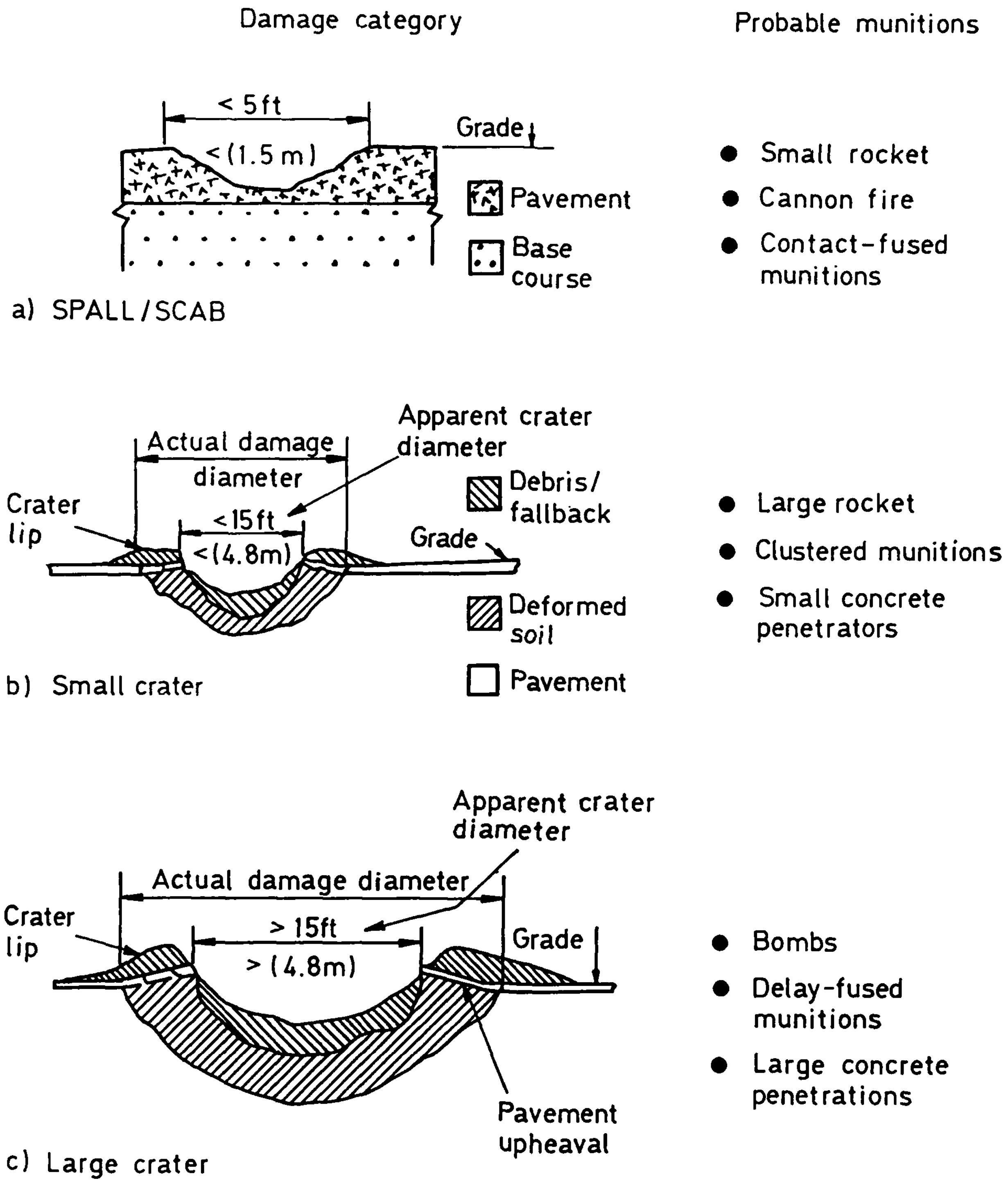


Fig.A1.1 Pavement damage categories

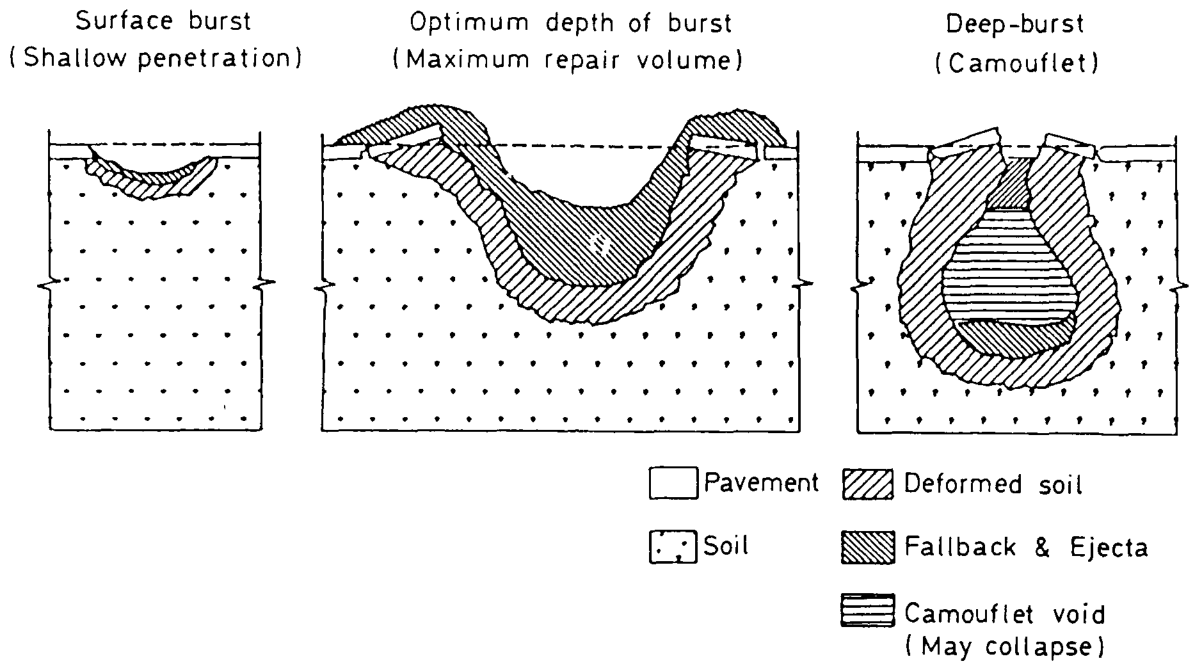


Fig.A1.2 Variation of crater damage with depth of bomb burst

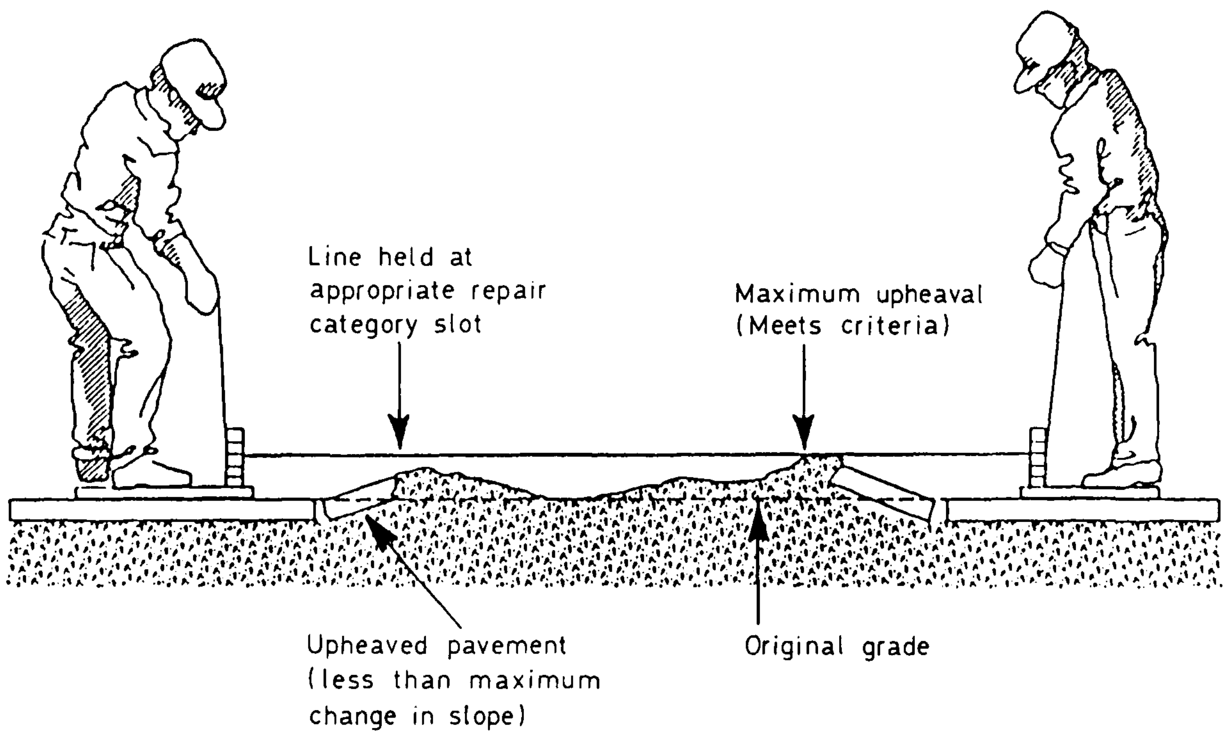


Fig.A1.3 Inspecting for maximum allowable upheaval

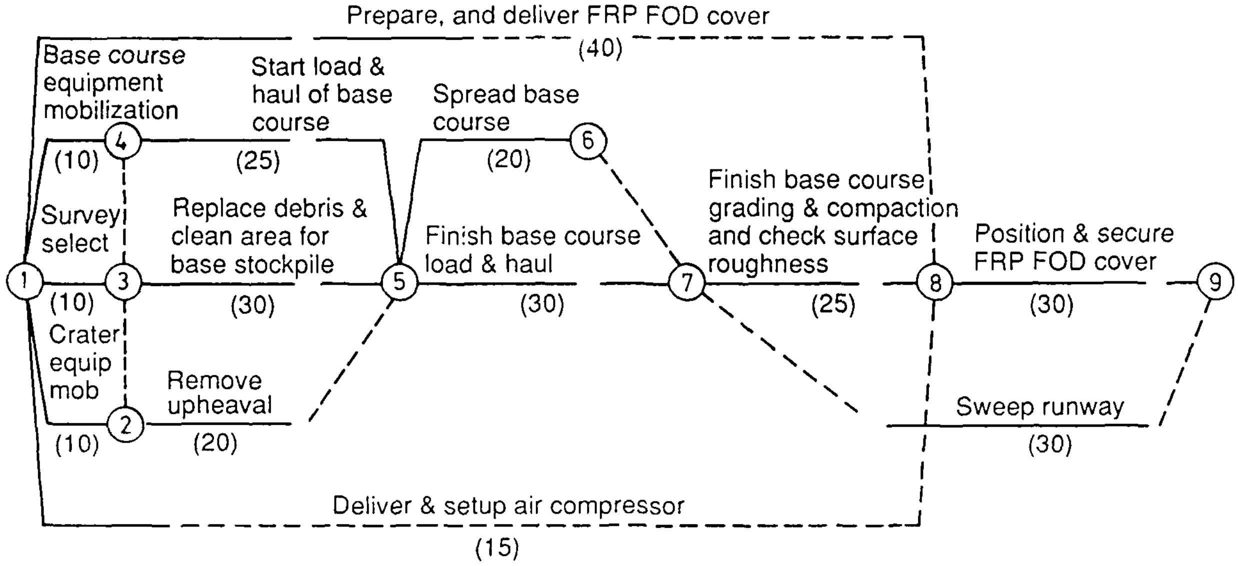


Fig.A1.4 Sequence of crater repair activities

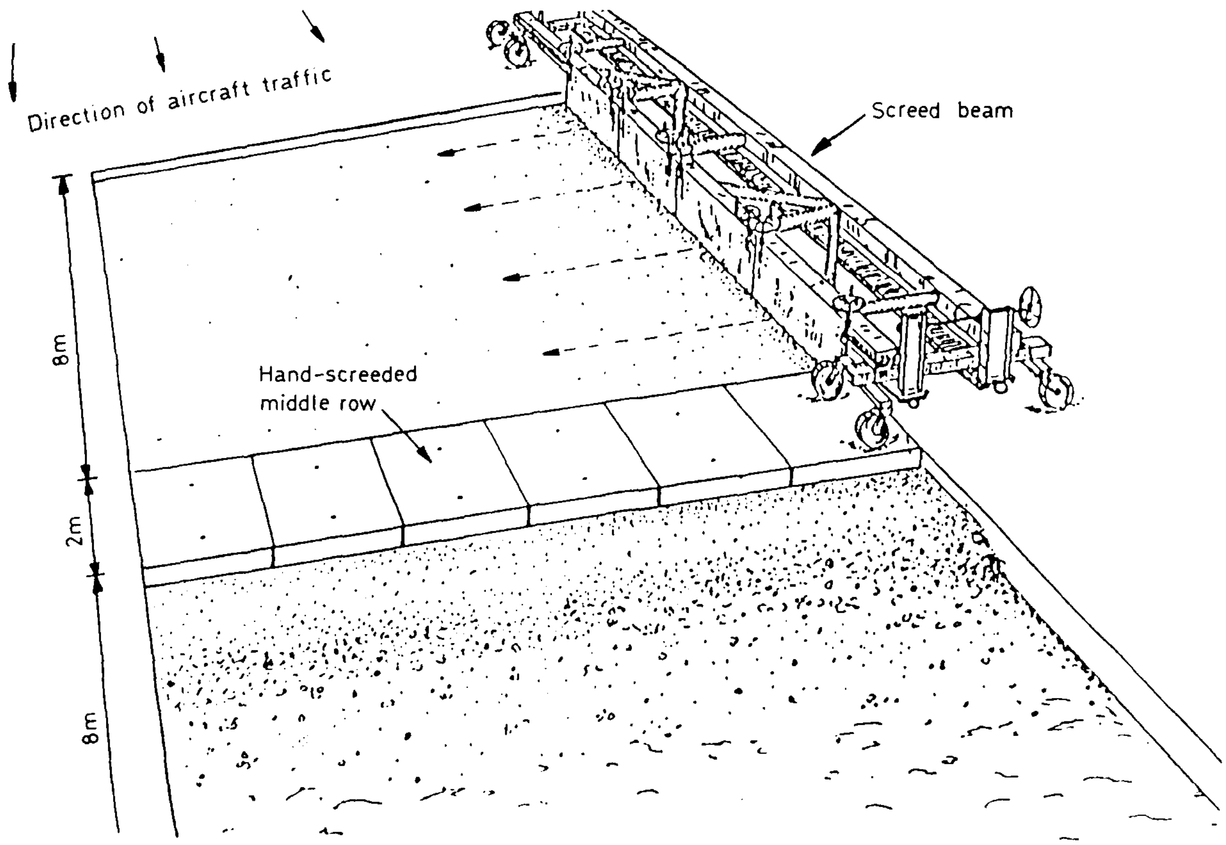


Fig.A1.5 Screed beam for precast concrete slab repairs

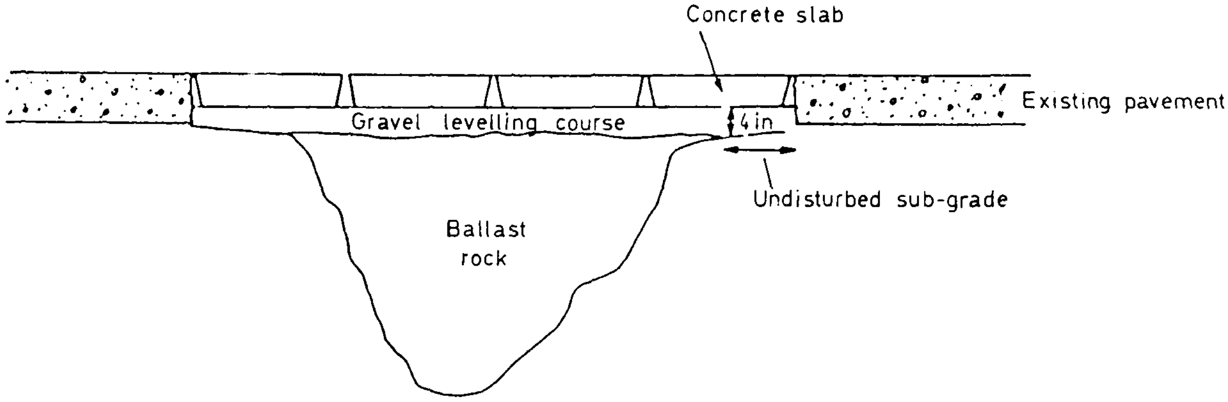


Fig.A1.6 Precast concrete slab repair

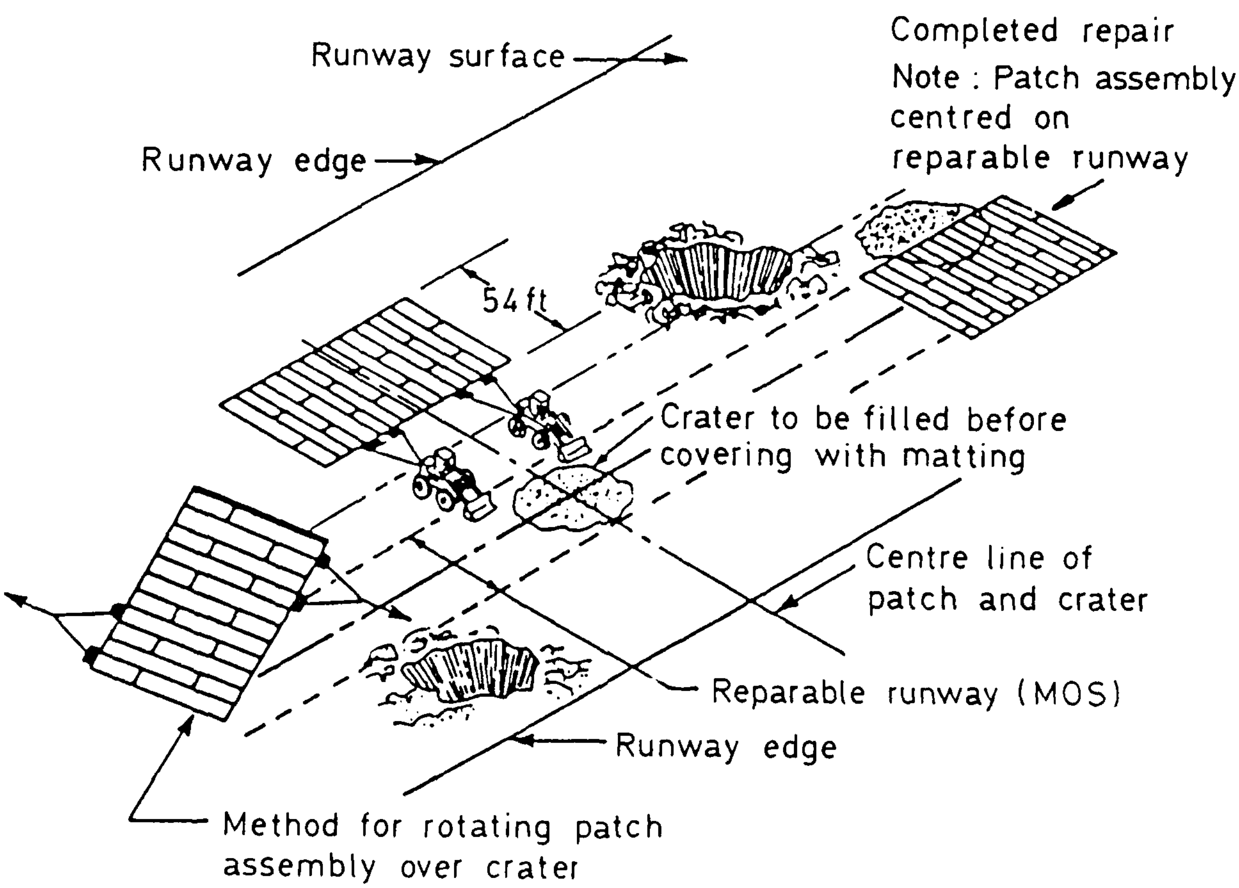


Fig.A1.7 Positioning an aluminium mat

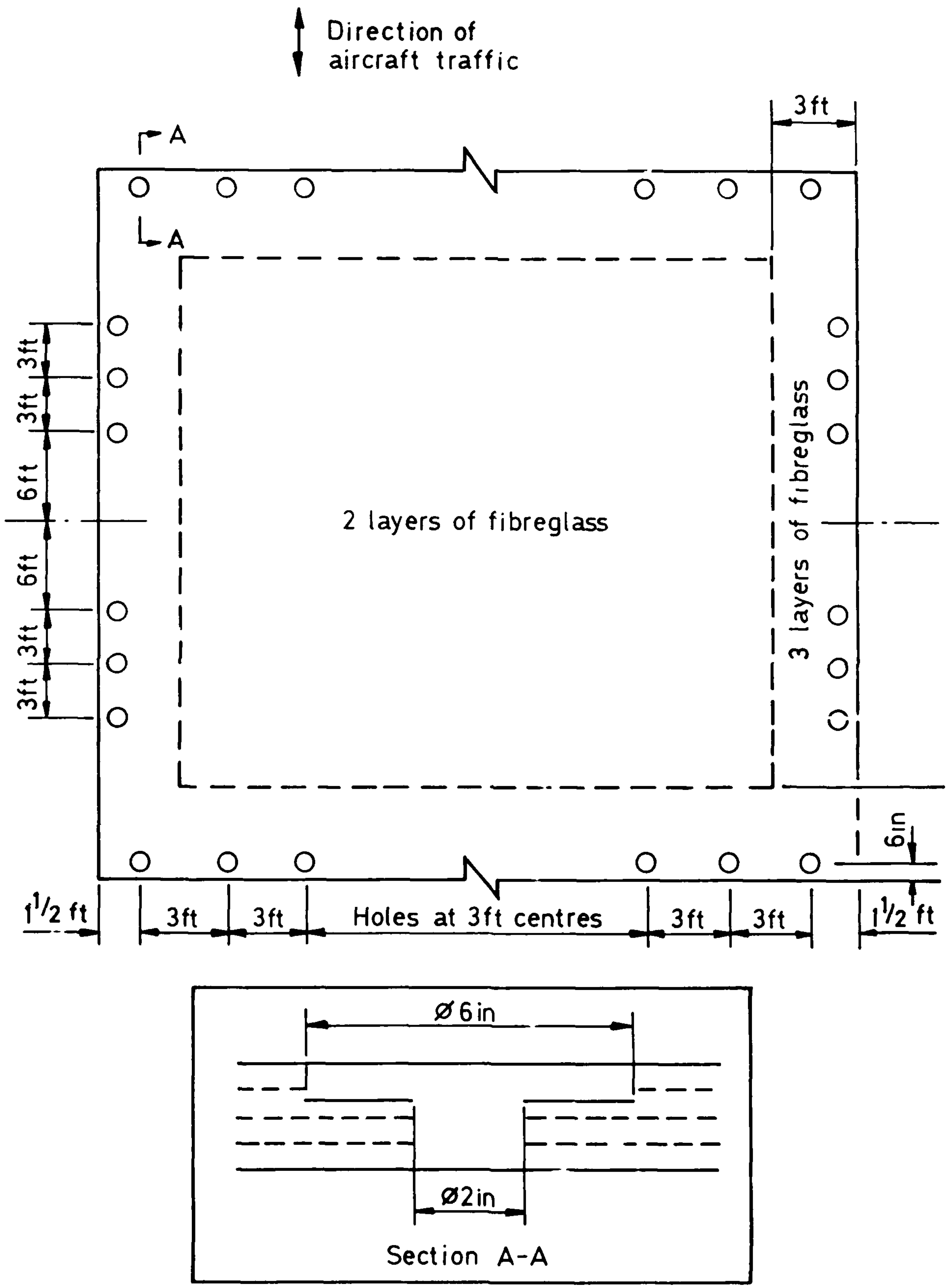


Fig.A1.8 Unfolded fibreglass mat with pre-drilled holes

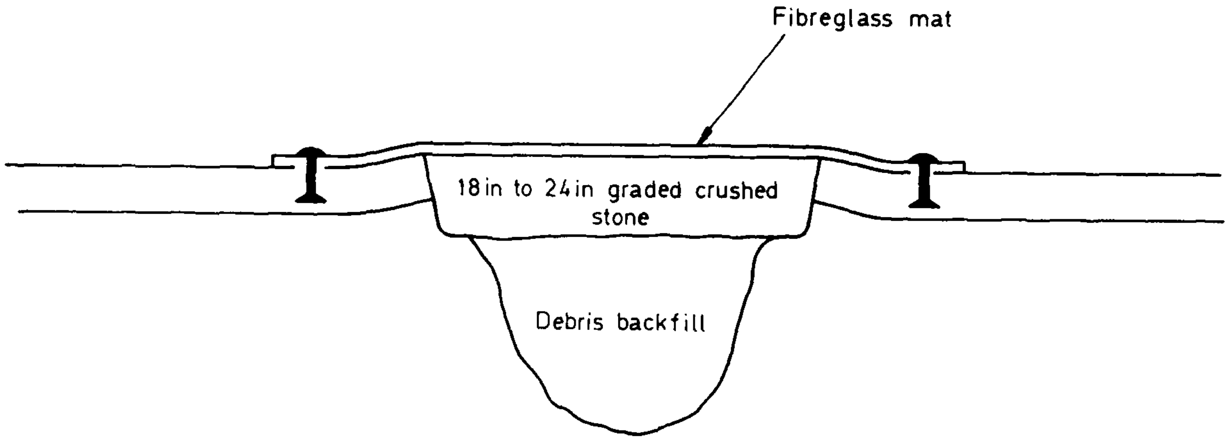


Fig.A1.9 Fibreglass mat repair with debris backfill

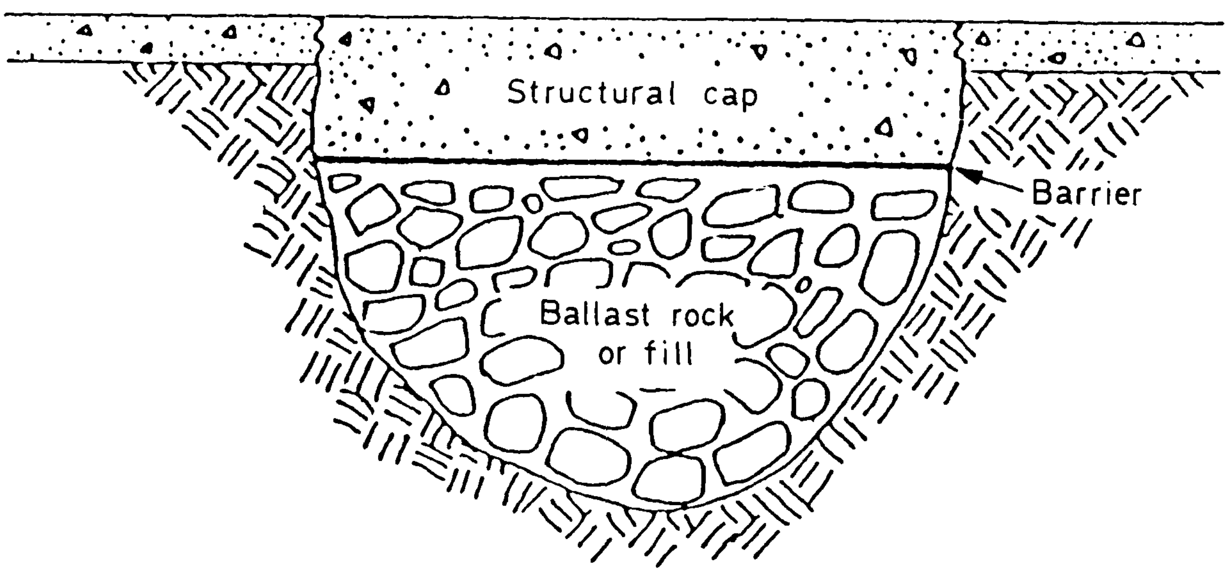


Fig.A1.10 Structural cap repair

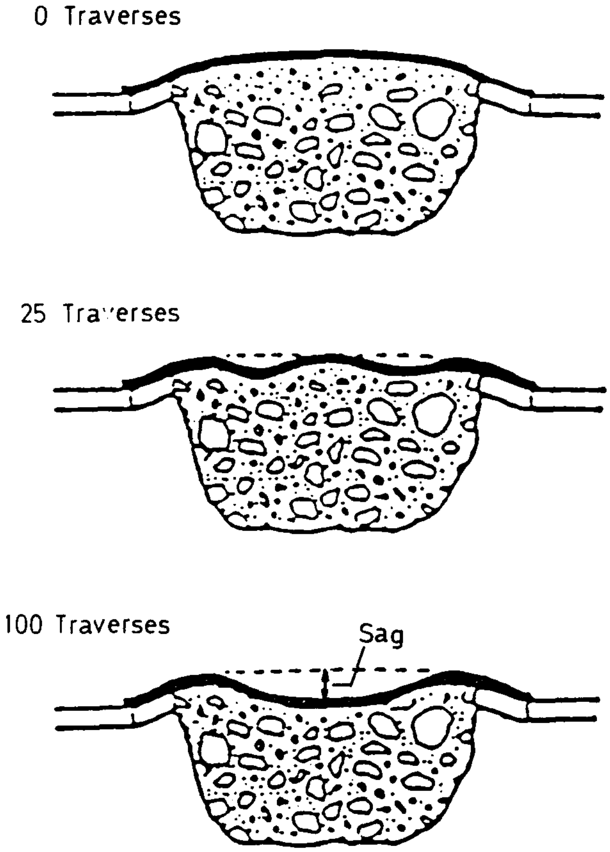


Fig.A1.11 Repair deterioration with trafficking

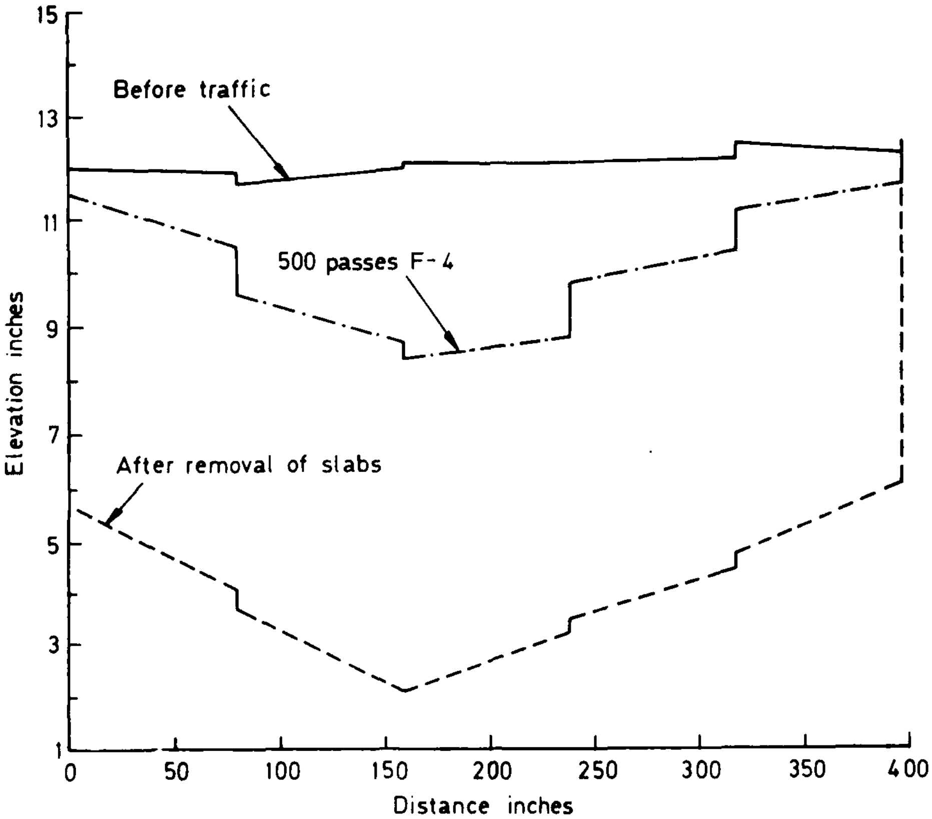


Fig.A1.12 Development of voids in precast slab repair

APPENDIX 2

ANALYTICAL PROCEDURES

A2.1 THE AIRCRAFT MATHEMATICAL MODEL

Mathematical models used for calculating the loads induced by runway roughness represent the aircraft by combinations of masses, springs and dampers. While the resilience of the landing gears is always represented (usually in association with a single lumped mass for each) the characteristics of the remainder of the structure may be represented assuming a number of either rigidly or flexibly connected masses. A typical model for a rigid airframe is shown in Fig A2.1. The production of tire-ground forces is accounted for by a spring. A lumped mass represents the combined masses of the tires, the wheels, the brakes and the shock-strut piston: that is referred to as the 'unsprung' mass since it is not supported by the strut. The combined pneumatic-hydraulic system of the shock strut is generally represented by a non-linear spring (reflecting gas pressure as a function of compression) in parallel with a damper. That is the simplest possible representation and may be supplemented to account for features peculiar to each landing gear such as auxiliary gas chambers, metering pins and damping control valves: since a general representation which could encompass them all would be complex such enhancements are incorporated as required.

In the representation of Fig A2.1 all six rigid-body degrees of freedom are included – if the loadings are symmetric there will be no lateral translation, rolling or yawing and the system can be simplified by combining both main gears into one.

The main airframe structure is represented to the level of detail required in a particular analysis. For the simplest case of a symmetric, rigid aircraft the structural properties reduce to the overall mass and pitching inertia. If asymmetric motion is considered the inertias in roll and yaw are also relevant. For a flexible aircraft – a large transport especially – the structural information must represent distributions of mass, stiffness and damping.

The above components of the aircraft mathematical model will now be considered individually.

A2.1.1 Modelling of tires

A number of different approaches have been made to the calculation of the forces developed by tires on uneven surfaces; all, however, utilize and seek to match the data produced by the tire manufacturer on the forces due to static deflection on a flat surface.

A simple assumption is that the tire force is linearly proportional to the local deflection at a point directly below the axle. That approach may be extended by adopting alternative methods of data fitting so that typical nonlinearities can be matched and the calculated forces agree with the manufacturer's force data over the deflection range from zero up to the point of tire bottoming, when the method becomes unreliable, and are zero when the tire is off the ground.

The above 'point-contact' approach depends upon the mode of deflection of the tire resembling that for which the flat-surface data were obtained. Clearly that may be so for operations on an undamaged paved runway but will be less valid when, as on a repaired runway, the ground elevation changes abruptly. A 'distributed-contact' tire model which accomodates the latter situation may then be thought desirable. It may also be sought to allow for the effects of dynamical response of the tire carcase.

Tire models have been developed which are based upon a multiplicity of radial and torsional springs with or without associated masses, depending on whether or not carcase dynamics are to be considered. Particularly in the former case, when additional modes of response are introduced, the use of such models can be costly in computer time because of the complexity of calculating the tire forces at each time step. Little assessment of these models has so far been undertaken, a major problem being the derivation of the data which they require.

Alternative models which recognize differential deflections within the tire footprint but which, like the simple point-contact model, utilize data which can be readily derived by the tire manufacturer have also been formulated. If carcase dynamics can be ignored then this class of models, which are computationally fairly economical, may present the best choice.

Finite-element analyses are being increasingly applied to tires. The complexity of such analyses and their computational demands precludes their being directly used in dynamical analyses of the whole aircraft but they can be seen as a potential alternative to manufacturers' tests as a source of data for simpler approaches.

From the foregoing it can be seen that as yet no definite recommendation can be made on the most appropriate tire model – while it is considered desirable to employ a distributed-contact model so that allowance can be made for the effects of local variations in ground height the need to allow for carcase dynamics has not been assessed. It is not thought that the lack of a definitive model seriously impairs the dynamical analyses currently made.

A2.1.2 Modelling of shock struts

In an oleo-pneumatic shock strut the total force developed is produced by a combination of fluid compression (both gas and oil), pressure differences caused by oil flow through constrictors and internal friction. A strict modelling of that system would require a hydrodynamic and thermodynamic analysis of both fluid media at each instant of the motion, which would be very expensive in computational effort. A great simplification is achieved if the spring-force and damping characteristics can be separated with little associated error: fortunately most shock-strut designs permit that. Therefore the predictions of spring and of damping forces will be discussed separately.

(a) Prediction of spring forces

The spring force is calculated using some variant of the polytropic gas state equation, usually for an ideal gas but for high-pressure struts including terms to allow for real-gas effects. The polytropic index used depends on the particular design. For shock struts without a separator between gas and oil it is often assumed that because spray from the oil passing through the damping orifice cools or heats the gas so that its temperature remains close to the ambient temperature of the oil the process is near to isothermal, for which the index would be unity. Conversely, if there is a separator piston the process is near to adiabatic, for which the index would be 1.4: to allow for some departure from that ideal due to heat loss a value of about 1.3 is often taken. Some shock-strut models seek to allow for heat transfer by varying the index with time – they are referred to as 'leaking adiabatic' or 'chronotropic' models.

Test data indicate that some shock struts without a separator develop pressures which are substantially below those predicted for an isothermal process. In the absence of an appropriate model a characteristic derived from averaging those data has then been used.

(b) Prediction of damping forces

The equations for steady fluid flow through an orifice show that the pressure difference (which when multiplied by the associated area gives the damping force) is proportional to the square of the flow rate: hence for a shock strut the damping force is at any instant given by the square of the stroking velocity multiplied by some coefficient. That coefficient may be constant, may vary progressively if metering pins or orifices are incorporated or may change suddenly with the action of valves. Thus in general the damping coefficient may be a function of stroking position, velocity and direction.

The calculation of damping forces on the above basis has generally been found to be adequate, though the effective values of damping coefficients have not always agreed with those predicted from the orifice geometry; therefore it is advisable to confirm them experimentally. Exceptional conditions are when oil flow through an orifice results in foaming, with an almost total loss of damping, when severe pressure drops result in cavitation, and when flap or plate valves cause non-ideal flow characteristics. For struts which exhibit those phenomena modifications to the modelling approach are needed and are being pursued; however, probably the better solution for the future is to avoid designs which exhibit such deficiencies.

(c) Prediction of friction forces

The effects of friction resulting from shock-strut bending moments should be considered for cantilevered designs, especially if the axle is offset from the strut centreline. An example of the stick-slip motion caused by high friction levels is shown in Fig A2.2. While current models are capable of predicting the overall features of that phenomenon they are incapable of precisely representing the stick-slip motion evident in tests. Assessment of the adequacy of predictions of friction forces is hampered by the inability to measure them directly, and by their apparently considerable variability under nominally similar conditions.

A2.1.3 Modelling of the airframe structure

For combat aircraft with low-aspect-ratio wings, fuselage-mounted landing gears and no wing-mounted stores the critical loading conditions may usually be determined on the assumption that the airframe is rigid. For wing-mounted gears only a quasi-static allowance for structural flexibility may suffice. (The prediction of higher-frequency responses which might cause piloting difficulties would require its fuller consideration, however.) For other aircraft – combat aircraft with heavy wing-mounted stores and transports –the dynamic response of the flexible airframe structure should be modelled. The structural characteristics are generally described in terms of free-free normal modes, which are determined by prior calculation. In some studies adequate allowance has been made by including only the first symmetric mode, though most have considered several higher-order modes as well. The use of modal data is well established and straightforward, but the calculation of structural responses naturally increases the required computational effort.

A2.1.4 Representation of aerodynamic forces

A variety of sources of aerodynamic forces may be active for ground operations: the airflow over the airframe (as influenced by structural response as well as for the rigid-body configuration), engines and propellers, and brake parachutes. It is usual to include such forces in mathematical models for ground operations. Their importance can be illustrated by a comparison of the calculated and measured wing bending moments in Figs A2.3 and A2.4. The former is for a constant taxiing speed of 20 m/s, where the dampings of the responses to a repair are in good agreement. In the latter, where the repair is met at a speed of about 48 m/s during take-off, the damping exhibited by the measured data is considerably increased, which is attributed to the aerodynamic damping in heave. Attempts to allow for aerodynamic damping have sometimes been made by increasing the structural modal dampings above their typical values of from 2% to 4%: the required increase depends on speed and it has been found necessary to increase dampings to up to 20% for speeds near to take-off. A more satisfactory approach within the modal framework is to determine the generalized aerodynamic force coefficients for the structural modes, which then yield forces proportional to kinetic pressure. An alternative would be to include the calculation of transient aerodynamic forces by methods similar to those developed for simulating gust encounters but there appears to have been no application of that approach in ground response analysis.

The analytical and experimental determination of aerodynamic data for the estimation of aircraft performance can fail to cover effects which are of importance in ground operations. For example, nose-gear loads on propeller-driven aircraft have been found to alter significantly as the direction of thrust is reversed, as shown in Fig A2.5, due to changes in the aerodynamic pitching moment which correspond to variations in the air velocity over the horizontal tail as the propeller pitch is varied. Current representations of this phenomenon are inedequate and require supplementary test data to define the true aerodynamic conditions. The aerodynamic effects of reverse jet thrust too are often in doubt until aircraft test results become available.

A2.2 COMPARISONS OF SIMULATIONS WITH TEST DATA

The validity of a mathematical model will generally be checked by comparison of its predictions with data from test rigs or aircraft trials. It is clearly desirable that comparisons be made for exactly matching conditions; therefore it is necessary to consider the factors which may cause discrepancies.

Simulations will generally assume that the shock struts will have been serviced to give their nominal characteristics; however, experience has shown that significant deviations can occur in practice. To cover their effects the simulation programme should be extended to allow for them and in test programmes sufficient measurements should be made to establish the exact state of the strut at the time of a test.

The correlation between simulations and tests may be influenced by motions present in the latter which could not be included in the former. In aircraft tests pilots are generally instructed to establish as nearly steady conditions as possible and to avoid abrupt control actions; however, oscillations may still remain from earlier control actions and in general there will be some motion specific to a particular test. Simulations for comparison may then have to be commenced with initial conditions derived from a sufficiently early stage in that measured motion to ensure matched conditions at the time of repair encounter. Some attempts to start simulations at the instant of nose-gear encounter wih a repair have given unsatisfactory comparisons because of the influence of the initial motion.

The quantities predicted and measured should include those which reveal the behaviour of the system as well as those considered the potentially most vital responses. For example, cross plots of shock-strut pressure versus stroke have been found valuable in determining if the behaviour of the strut on test is in accordance with theoretical predictions: the gas-law exponent or damping coefficients assumed in the latter can be adjusted to obtain agreement. Also, it is useful to obtain pressure and stroke data for all chambers of the strut if both compression and recoil characteristics are to be accurately simulated, though restrictions on access may preclude that in some designs.

A comparison between predicted and measured responses requires that the same quantities be available and in compatible forms. Analogue trace recording systems present considerable problems in handling data, often leading to considerable restriction of analysis because of the effort required. Most data acquisition systems now used for aircraft tests are based on conversion to digital form either directly or prior to utilization. The flexibility of the digital approach greatly facilitates the comparison with simulated results. It is, however, still not practical to make comparisons for all of the data which may be gathered in a test programme; therefore a few tests are selected as representative and their results used to adjust the mathematical model. There is a need for development of computer programs which will reduce the manual effort associated with the production of test simulations and evaluating the modelling accuracy – currently there are no accepted methods for defining the overall quality of agreement between time histories of test data and corresponding simulated results.

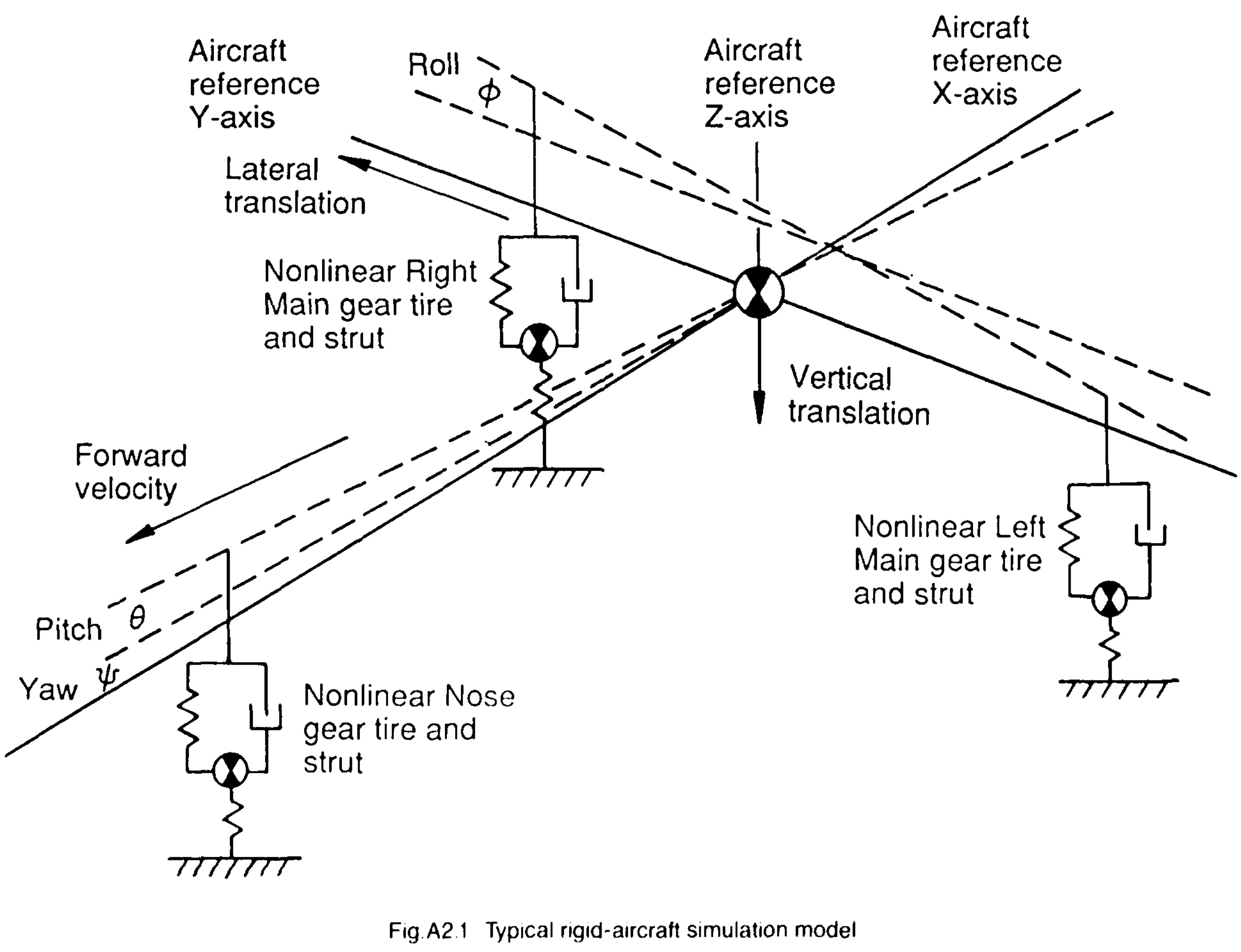


Fig.A2.1 Typical rigid-aircraft simulation model

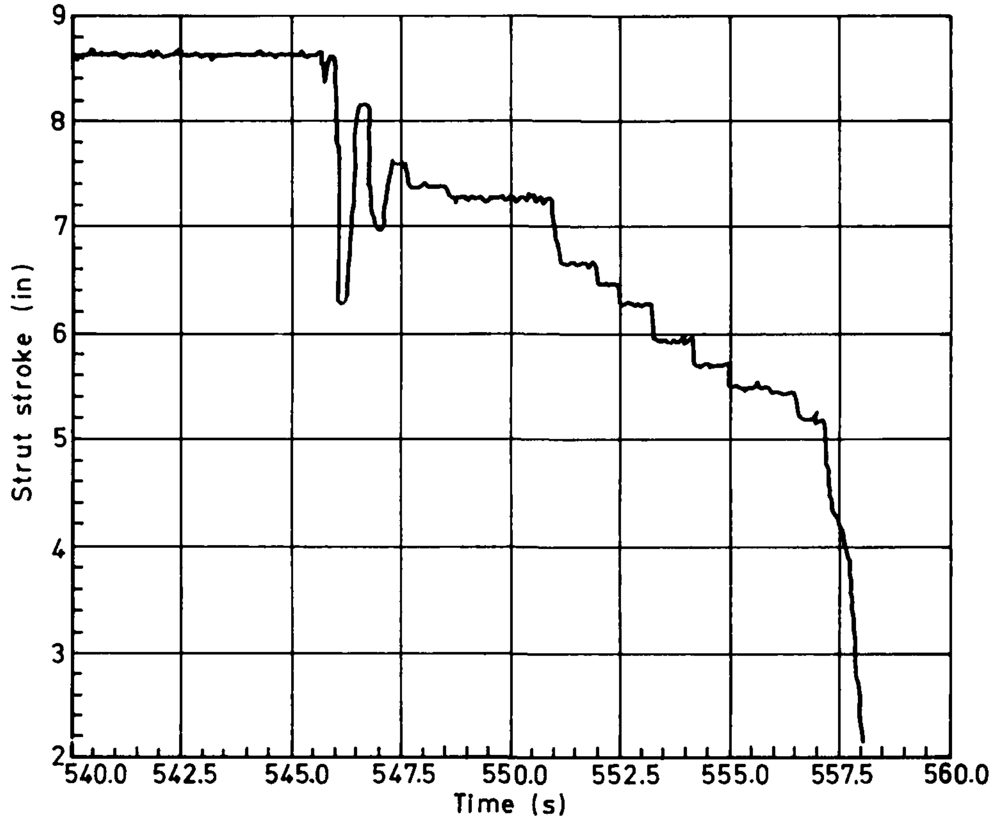


Fig.A2.2 Stick/slip strut behaviour for an offset main landing gear

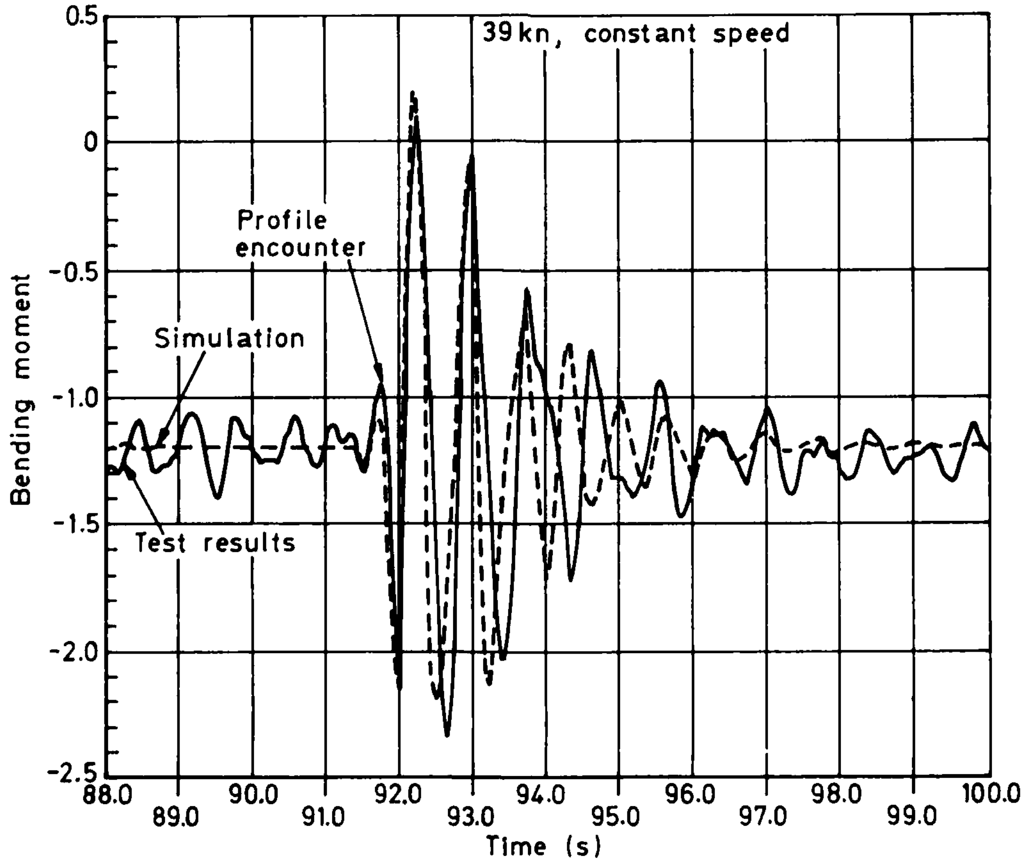


Fig.A2.3 Accuracy of bending moment calculation for low-speed taxi

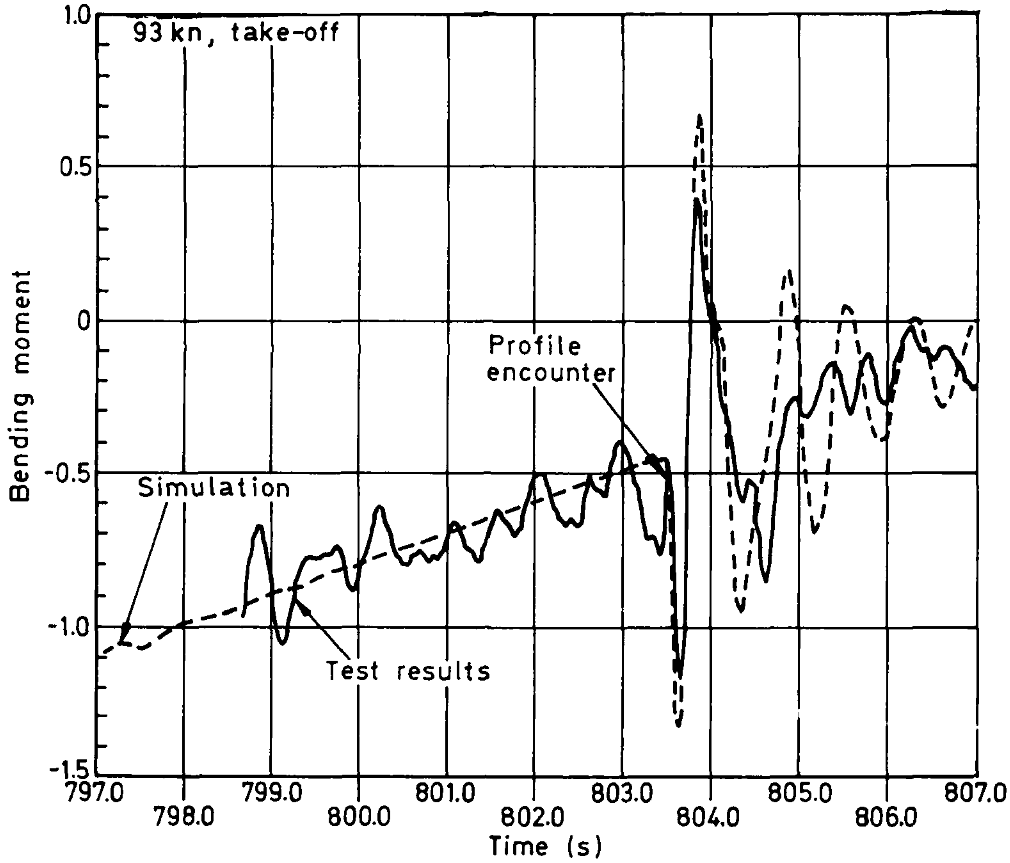


Fig.A2.4 Accuracy of bending moment calculation for high speeds

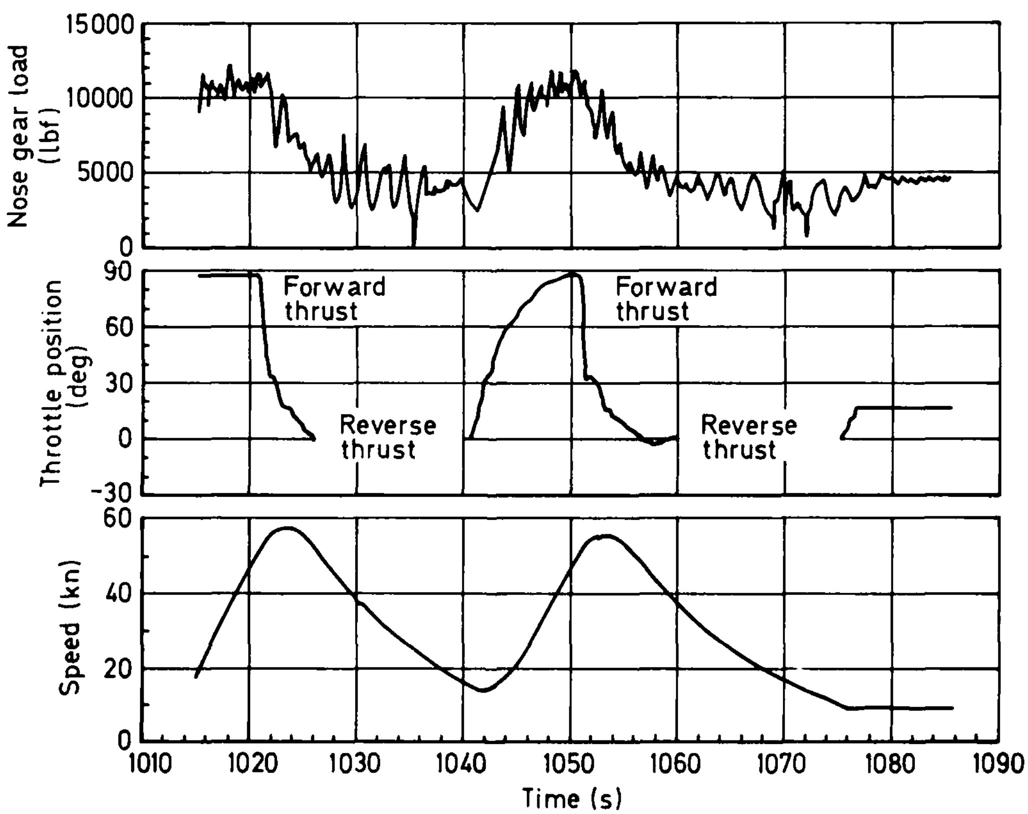


Fig.A2.5 Effect of propeller thrust on nose landing gear load

APPENDIX 3

TEST METHODS AND EQUIPMENT

As landing gears have become more complex and the requirements for the verification of their performance more demanding so the equipment used to test them has become more capable and versatile. In the past the approach was to evaluate each aspect of their function in isolation; hence loading rigs were used to determine their static behaviour (deflection versus load), drop towers were used to explore energy absorption and load development in landing impacts and to allow adjustments to damping orifices, special rigs were built to test such functions as retraction, and wheels, tires and brakes were tested under a rather limited range of conditions on rotary dynamometers. The first step towards integrated and more realistic testing came with the positioning of drop towers over dynamometer flywheels, which permitted better measurements to be made of spin-up loads and interactions between the wheel assembly and the shock strut to be investigated. Rotary dynamometers were improved by being given the capabilities of simulating velocity of descent, rapid cycling of the applied loads and dynamically varying yaw and camber — the whole wheel package could then be tested together with the brake control system. Landing-gear test tracks were conceived; early on they had limited capabilities in speed and loading but upgraded facilities can now provide extended coverage. The concept of simulating the driving of a landing gear by variations in ground elevation was initially realized by installing an exciter under a landing gear mounted in a drop tower. The US Air Force's AGILE research facility has expanded that approach by placing an exciter under each landing gear of an aircraft so that the airframe structural response to simulated ground roughness can be evaluated.

The characteristics of existing test equipment are given in Tables A3.1 to A3.5. The equipment has been classified into Drop Test Equipment (Table A3.1), Dynamometers (restricted to those with a speed capability of at least 180 knots, for aircraft applicability) (Table A3.2), Tire Force Machines (Table A3.3), Ground Input Simulators (Table A3.4), and Test Tracks (Table A3.5).

A3.1 UTILIZATION OF TEST EQUIPMENT

The scope of the tests which can be performed with existing eqipment is here discussed, by primary reference to the components tested rather than to the test facilities.

A3.1.1 Tire testing

The majority of aircraft tire testing is accomplished using drum dynamometers while the remaining tests are performed on test tracks and using flat-surface testing machines. Dynamometer testing encompasses static, dynamic, qualification/certification, and extended-life tests.

For the most part, static testing (non-rotating tire) consists of acquiring tire mechanical properties by loading the tire against the dynamometer drum and recording the corresponding tire deflection and footprint area. Structural integrity (of tread and carcase), qualification/certification, extended-life and retreadability tests are performed under dynamic conditions (rotating tire) in which the speed, load and yaw and/or camber angles can be varied. Data acquired during dynamometer tire testing typically includes the number of test cycles, the temperatures of the contained air and the carcase, internal pressure, and variations of temperature and pressure. Loads, moments, distance rolled, speed, deflection and other parameters may additionally be measured.

On occasion it is necessary to determine tire frequency response, primarily to provide data for the mathematical modelling of landing-gear systems. As very few of the existing dynamometers permit sufficiently rapid cycling of loads for a rolling tire other equipment is used, with a non-rolling tire; correct data will not thereby be obtained, which could lead to an erroneous input to the mathematical model. To alleviate this problem the tire may be lubricated to reduce frictional forces in the footprint — experimental data show quite close agreement for the frequency responses of a rolling tire and a lubricated non-rolling tire.

Flat-surface testing machines (or tire force machines) basically simulate a quasi-static state. They are used to obtain tire mechanical properties for different surface types, profiles and conditions.

Tire testing for research includes all the above types of test as well as special tests for specific investigations.

A3.1.2 Brake testing

Virtually all aircraft brake testing uses a dynamometer, coupled to the brake either directly or in conjunction with a tire-wheel assembly. Some testing is conducted at test tracks, mainly for research, but the proportion is low. Both static and dynamic conditions can be investigated on the dynamometer. Static tests include those of structural integrity under torque, hot and cold static performance, and response to cycling. Dynamic tests investigate dynamic structural integrity, performance, wear, and life. They are also conducted for qualification/certification, the procedure for which differs between steel and carbon brakes. Both types are subjected to normal-energy stops, overload stops and refused-take-off stops; in addition the latter may be required to withstand numerous service-energy stops.

Brake test data consist of temperatures of components (heat sink, housing etc), hydraulic pressure and temperature, wear, dynamometer drum velocity, test wheel velocity, torque, simulated deceleration and stopping distance, coefficient of friction developed, and kinetic energy.

A3.1.3 Wheel testing

Aircraft wheel testing is also divided into static and dynamic phases. Wheel tests are generally either for qualification/certification or for research.

During static tests wheels are subjected to service loads, proof loads or ultimate loads. Loads are applied radially, laterally, or in some combination of both.

Most dynamic wheel tests are conducted on dynamometers, although some research uses test tracks. Qualification/certification and endurance tests are run on dynamometers; yawed conditions are included as well as straight rolling.

A3.1.4 Testing of brake control (anti-skid) systems

The most effective tests of brake control systems are on aircraft; however, dynamometers and test tracks permit the evaluation of some aspects of performance. Dry-surface dynamometer tests can provide performance comparisons for different tires and conditions — the system can be adjusted to some extent and the compatibility of components examined. Wet-surface dynamometer tests have limited validity but can give a measure of performance comparison.

A3.1.5 Landing-gear testing

Landing-gear tests are generally in one of three categories: drop tests for qualification/certification, dynamometer tests and tests for research.

Qualification/certification tests for landing gears involve dropping the suitably loaded gear onto a reaction platform from various heights. Realistic simulation of the forces from the airframe and those developed at the ground is attempted by applying appropriate constant vertical forces at the attachment points and by spinning up the wheels prior to the drop (or by dropping onto a rotating drum). The data acquired generally comprise shock-strut load and deflection, tire deflection, drop-carriage acceleration and displacement, pressures (and possibly temperatures) within the strut, and reaction-platform loads.

Tests of landing gears using dynamometers are generally related to investigations of shimmy. The gear is mounted over the dynamometer so that the wheel can be spun up under load; if the gear is then excited the level of damping can be determined. Accelerations and displacements are generally recorded but the prime data are visual observations.

Tests for research generally extend beyond the usual drop tests by employing exciters to simulate ground inputs. Those inputs are then measured in addition to the quantities listed above. Test tracks may also be used and provide the most realistic operating conditions of all facilities, but at the expense of rather less control of the test and more difficulties in data acquisition.

A3.2 ASSESSMENT OF CURRENT METHODS

In utilising the results from test facilities their shortcomings have to be appreciated. The most general is an inadequate reproduction of the interaction between the component under evaluation and the remainder of the aircraft-landing-gear system. That and other limitations of current testing methods are discussed below.

A3.2.1 Tire tests

Dynamometer testing does not provide the coupling with the landing gear that occurs in practice. Also, because of the unrepresentative surface texture and the curvature of the drum correct determination of tire traction and wear is not possible. Track tests can provide usable traction data but wear characteristics can be obtained only from aircraft tests. Tire force machines with rigid test surfaces are limited to very low speeds and do not permit the changing of yaw or camber during a test; the flat-belt types do offer variations in speed and some dynamic parameter changes but have a limited load capacity due to their construction.

A3.2.2 Brake tests

Brake tests on dynamometers do not normally simulate the couplings between the brakes, the landing gear and the airframe. Brake chatter and squeal may be masked by the rigid mountings and therefore not become apparent until installation on the aircraft. Work to overcome these problems is in hand.

A3.2.3 Wheel tests

The major deficiency in the testing of wheels is the absence of specifications which require the wheel to be tested together with a tire and brake; thus the wheel is not subjected to brake torque or heating cycles. Test results therefore do not agree with operational experience. While wheels, like tires, are relatively sophisticated components the existing methods for analysing them are not. Substantial expenditure will be required to develop adequate analytical tools and associated test specifications but is needed if comprehensive test requirements are desired.

A3.2.4 Anti-skid-system tests

On dynamometers the conditions in the tire-ground interface differ markedly from those on an actual runway, particularly for wet surfaces. Performance evaluations are therefore restricted to comparisons for some system changes. Interactions with the landing gear and airframe can also play an important part.

A3.2.5 Landing-gear tests

A limitation of current landing gear tests is in the realism of the representation of the interaction with the aircraft structure and the environment (for example as evidenced by aerodynamic and tire-ground forces).

A3.3 FUTURE DEVELOPMENTS

Testing in the laboratory, and on test tracks, confers many advantages in the repeatability of test conditions, in the relative ease of instrumentation and data acquisition, in safety, and in cost. Components and subsystems can be studied in great detail and their behaviour determined either for direct application or for the derivation of data for mathematical modelling. In the areas described above reliable results can be obtained. However, uncertainty arises when those results are interpreted as predicting the behaviour of complete systems on an aircraft. Unrepresented interactions with airframe modes and with pilots' inputs can be highly significant even to the extent of giving a landing gear designer some nasty surprises over a gear which has passed the test in the laboratory.

Laboratory tests have made great strides in the direction of increased realism and, with facilities like AGILE, will doubtless continue to do so. That trend reduces the risk in extrapolating from component and subsystems test data and the path should be followed further. Also, the integrated pursuit of more representative testing methods and of associated improved analytical methods which could guide, evaluate and extend their application is desirable so that best use may be made of test facilities.

Table A3.1
Landing gear drop test equipment

Organisation	Max Load (lbf)	Max Ht (Ft)	Wheel Spin-Up	Aero Lift Sim	Other Features
BAE	20 000		Yes	No	
BAE	80 000		Yes	Yes	Moving table for side force
BAE	200 000		Yes	Yes	Two moving tables
BENDIX	20 000	24	Yes	Yes	
BENDIX	40 000	19	Yes	Yes	
BENDIX	168 000	17	Yes	Yes	
BENDIX	750 000	30	Yes	Yes	
BENDIX	60 000	15		Yes	Over 120" dyn 250 mph
BOEING	150 000	16	Yes	Yes	
CPC	4 000	13	Yes	Yes	
CPC	11 000	14	Yes	Yes	
CPC	95 000	15	Yes	Yes	
CPC	375 000	39	Yes	Yes	Fatigue test capability
CRANFIELD TI	50 000			No	Rotating platform 115 mph
DOUGLAS					
DOWTY	28 000		Yes	No	
DOWTY	55 000		Yes	No	
DOWTY	140 000		Yes	Yes	
DOWTY	230 000		Yes	Yes	
IABG	32 000	11	Yes	Yes	Over 157" dyn 250 mph
LOCKHEED	300 000	16	Yes	Yes	Max vert react 600 000 lbf
LOCKHEED	150 000				Over 132" dyn 184 mph
MENASCO	120 000	45	Yes	Yes	
MENASCO	100 000	18	Yes	Yes	
MENASCO	200 000	45	Yes	Yes	
MENASCO	200 000	45	Yes	Yes	Over 144" dyn
USAF	3 600	18	Yes	Yes	
USAF	10 000	21	Yes	Yes	
USAF	35 000	27	Yes	Yes	
USAF	150 000	27	Yes	Yes	
USAF	20 000	7		No	Hyd load Over 192" dyn 200 mph

Table A3.2
Dynamometers (speeds of 200 mph and higher)

Organisation	Flywheel Size (in)	Max Load (lbf)	Max Speed (mph)	Brake Test	Yaw	Camber
BFG	120	100 000	400	No	Yes	Yes
BFG	96	60 000	300	No	No	Yes
BFG	120	60 000	215	Yes	No	Yes
BENDIX	120	70 000	250	Yes	No	Yes
BENDIX	84	30 000	200	Yes	No	Yes
CEAT	120	80 000	400		Yes	Yes
CEAT	120	160 000	310		Yes	Yes
CEAT	120	79 000	250		No	No
DUNLOP	112	100 000	335	Yes	Yes	Yes
DUNLOP	67	40 000	350	No	No	No
GOODYEAR	120	100 000	320	No	Yes	Yes
GOODYEAR	120	60 000	250	Yes	No	Yes
GOODYEAR	120	70 000	200	Yes	No	Yes
GOODYEAR	120	45 000	200	Yes	No	Yes
GOODYEAR	84	28 000	200	Yes	No	Yes
GOODYEAR	84	25 000	200	Yes	No	Yes
USAF	120	150 000	350	Yes	Yes	Yes
USAF	84	40 000	250	Yes	No	Yes
USAF	192	301 000	200	Yes	No	Yes

Table A3.3
Special rolling stock test equipment

Organisation	Type Equip	Load (lbf)	Speed	Yaw	Camber	Tire Size (in)
CALSPAN	Endless Belt	13 500	200 mph	Yes	Yes	46
	FEATURES: DYNAMIC YAW AND CAMBER, WATER SPRAY, FORCE AND MOMENT READOUT, SIMULATED ROAD SURFACES.					
USAF	Dynamometer	150 000	350 mph	Yes	Yes	57
	FEATURES: DYNAMIC LOAD, YAW AND CAMBER, HOT AND COLD CHAMBERS, FORCE AND MOMENT READOUT, BRAKE TEST CAPABILITY. EIGHT TIRES IN SYSTEM.					
USAF	Tire Force Machine	80 000	.25 ft/sec	Yes	Yes	56
	FEATURES: DYNAMIC LOAD, VARIABLE SURFACES AND SURFACE TEMPERATURES, BRAKE TORQUE (SLIP RATIO), FORCE AND MOMENT READOUT, TIRE FOOTPRINT CONTACT FORCES.					

Table A3.4
Landing gear ground load simulators
Maximum conditions for each column shown — in combination capabilities are reduced

Organisation	Max Static Load (lbf)	Max Dynamic Load (lbf)	Max Stroke (in)	Max Frequency (Hz) at 0.1" double amplitude	Other Features
BOEING	60 000	60 000	17	15	System checkout in progress
DOWTY		14 000	18		
McDONNELL	16 000	25 000	6	20	6" double amplitude at 1.5 Hz 0.15" double amplitude at 10 Hz (at 24 300 lbf load)
USAF (AGILE)	50 000	60 000	10	90	One shaker under each gear 10" double amplitude at 2 Hz 0.35" double amplitude at 10 Hz (at 32 700 lbf load)
USAF (LGDF)	100 000	120 000	25	70	25" double amplitude at 0.4 Hz 0.4" double amplitude at 10 Hz (at 35 000 lbf load)

Table A3.5
Landing gear test tracks

Organisation	Max Load (lbf)	Speed (mph)	Test Distance (ft)	Remarks
CEAT		110	1300	
NASA	50 000	253	1800	
NAVY	61 000	345	1400	Five Tracks
RAE	33 000	138	300	Will be extended to 500 ft

APPENDIX 4

AIRCRAFT TRIALS

Of all the activities needed to define an aircraft's capability to operate from repaired runways aircraft trials are the most expensive and potentially dangerous; therefore in any programme the aim will be to minimize the demand for them. That has implied the undertaking of laboratory tests such as those discussed in Appendix 3 and then utilising data from them and other sources in computer simulations using the mathematical modelling techniques outlined in Appendix 2. Ideally such models should be capable of accurately predicting the aircraft's response to ground roughness, but so far that has rarely proved to be the case. That was partly due to the inadequacies of methods of testing and modelling, exacerbated by the fact that none of the aircraft tested had been designed for such operations. Those methods are constantly being improved but it is unlikely that in the foreseeable future mathematical models could be confidently used unless they had been validated by comparison with dedicated aircraft trials. The aircraft's effect on runway repairs may also be predicted by analysis and experiment, but requires confirmation by trials. Piloting techniques can have a major influence on an aircraft's capability to operate from repaired runways – only through aircraft trials can appropriate techniques be devised and evaluated.

A4.1 TRIALS PLANNING

In view of the costs and risks involved, the role of trials planning is paramount. Initial planning centres on the collection of data on the characteristics of the system, formulation of a model for computer simulation and consideration of limitations on system performance and integrity. As initial simulation results become available it is possible to identify potentially critical areas of operation and to establish the sensitivity of the predicted responses to variations in the system data and formulation. At that stage careful appraisal is needed of the validity of the data on system characteristics and limitations, of the justification for the idealizations inherent in the system model, the scope for model enhancement or simplification, and the benefits from possible further laboratory tests. When the standard of the model is judged to be appropriate the predictions of system response can be used for a number of purposes. First, instrumentation needed to monitor critical responses and the quantities most vitally affecting them can be defined. Second, a number of aircraft and repair configurations can be investigated to determine the best choices for trials, and to predict limiting operating conditions to guide their progressive exploration. Third, modelling can indicate desirable system adjustments, such as tire and shock-strut inflation pressures and aerodynamic control settings, and the advantages of various operating techniques, such as usage of braking and reverse thrust. That early use of modelling helps to ensure that the aircraft configurations tested are those with the best capabilities on repaired runways, consistent with other operational requirements, and to reduce the degree of extrapolation of data required after the trials. When those aspects have been resolved planning of all the usual features of aircraft trials can proceed.

A4.2 INSTRUMENTATION

Instrumentation is required so that limitations on system responses (loads, deflections, accelerations, tire temperatures, brake temperatures, etc) can be observed, to record the test conditions and system inputs (aircraft speed, engine settings, control inputs, wind speed, ground profile and aircraft location, etc) and responses, and to provide for the pilot any data which he requires for the execution of the trial (ground speed, longitudinal acceleration, etc). With present techniques the core of the instrumentation system is usually an on-board digital magnetic tape recorder, which may be supplemented by telemetry and analogue recorders. Since the required accuracy will usually be quite high, better than 5% typically, the calibration of sensors may present a difficulty, which should be considered in parameter selection. Film or video recordings from on-board and ground cameras can prove very useful in the analysis of results and may be the only practical medium for some parameters. They may also provide the only record in the event of an accident. The value of visual records is considerably enhanced if they can be correlated in time with one another and with the aircraft instrumentation records.

Suitable sensors (e g pressure transducers, strain gauges, load cells, accelerometers, potentiometers, gyroscopes, LVDT's) are available for most purposes. The exceptions are for the measurement of tire deflection and height above the ground: some development work has been done on possible solutions. Recording systems are generally well developed and signal processing techniques, though already adequate, can be expected to improve.

A4.3 CHOICE OF AIRCRAFT

Often there is little choice in the aircraft used for trials but it is important that it is verified as representative of the fleet for which information is required, which often includes several variants. Simulation can assist in identifying the relevant differences. The test aircraft should have no unrepresentative structural limitations, must be configurable as required and must behave typically. In particular, the landing gears must function correctly and be serviced to the set procedures: since they may receive harsh treatment during the trials those aspects must be continually checked. In preparation for trials the aircraft should be weighed and its centre of gravity determined, preferably in the most appropriate configuration and fuel state. Tire and brake heating frequently limit the number of tests in a given sortie. The former is usually manifested by heating of the tire beads due to rolling; excessive taxiing distances can lead to catastrophy since fusible plugs afford no protection. The latter becomes critical in the need to ensure that the brakes retain sufficient heat capacity to stop the aircraft under the most severe trials conditions.

A4.4 PROVISION OF TEST SURFACE

The test surface will be selected on the basis of results from simulations. The simulated repairs should be representative, easy to construct and be capable of generating near-limiting responses of the test aircraft. Repair configurations which depend for their effectiveness on sharp tuning of responses should be avoided since the difficulties of achieving accurate ground speeds make a progressive trial hard to conduct. The positioning of the test repairs will be largely dictated by the crossing speeds required and the associated acceleration and stopping distances. There may be a need for alternative locations if, for example, rotation on take-off and following landing impact are both required to be on a repair.

A4.5 PILOTING ASPECTS

In general there is a conflict between making the trials as representative as possible and obtaining good data for the validation of mathematical models. For instance, in evaluating the effects on the pilot it is important to check his ability to keep to the runway centre-line in a high crosswind but for matching to simulations steering inputs should be minimized and crosswinds avoided. The resolution of that conflict is dependent on the aims of the specific trial; in some cases there may be a need to repeat runs using different piloting techniques.

The test site itself may also influence the realism of trials. For tests to simulate repair encounters during take-off it is more realistic to conduct accelerating runs than ones at constant speed. However, to facilitate matching to simulations it is desirable to avoid braking for 2 to 3 seconds after crossing a repair. For a high-performance aircraft the gain in speed during that time in an accelerating run may be considerable, so increasing the demand for distance in which to stop.

A4.6 TEST LIMITS

The limits to be observed in testing will initially be determined during trials planning but will not necessarily remain the same throughout the trials. Generally test limits will be within the structural limit loads/strength, with margins reflecting the precision of measurement of critical quantities and the risk of exceeding their limits in a given test. The latter depends on the extent of agreement between simulation and measurement and on the influence that minor variations in test conditions may have. The setting of test limits can also depend on the desirability of approaching critical conditions. For systems which behave linearly there is probably little to be gained for model matching in pushing the responses to high levels whereas for non-linear systems it may be important to approach the acceptable limits as closely as possible. When it is necessary to operate close to structural limits the early availability of measured data and their use to check simulations run by run become highly desirable; in those circumstances the trials can become greatly protracted.

A4.7 INTERPRETATION OF DATA

The analysis of trials data seeks to answer a whole range of questions: 'Is the instrumentation system working correctly?', 'Is the landing gear functioning as expected?', 'Are test limits being approached?', 'Are the trials results following the predictions?', 'Is the pilot achieving the required test conditions?', 'Are the input data for the mathematical model being confirmed?', 'Is a critical feature being revealed which was not adequately modelled?', and so on. These questions are of importance at various stages in the trials programme and require differing methods of analysis. Checks on instrumentation can be made by checking the consistency of the behaviour they portray – do forces and acceleration-mass products agree, for example? Simulation can play a part in answering some of the above questions. If a mathematical model of the landing gear is driven by the measured shock-strut deflections the predicted forces and pressures should agree with those measured. If they do then the instrumentation system, the functioning of the landing-gear and the mathematical modelling are likely all to be in accordance with expectations; if they do not an error is indicated, the source of which may be located by the nature of the discrepancies.

Another important area for post-trial analysis is that of performance in take-off and landing, particularly if revised flap settings for take-off or restricted use of braking systems (wheel brakes, reverse thrust or brake parachute) are advocated for the enhancement of repaired-runway capability.

A4.8 REVIEW

The above paragraphs briefly discussed some of the considerations involved in testing aircraft over runway repairs. As aircraft design practice is extended to include adequate consideration of rough-ground operations and the roles of analysis, laboratory tests and aircraft trials in evaluating their capabilities become more resolved, trials planning and conduct should become progressively easier.

APPENDIX 5

LANDING-GEAR DATA FOR CURRENT AIRCRAFT

This Appendix presents detailed descriptions of landing gears for a fighter and a transport aircraft as representative examples of current landing gear designs.

The NF-5 is a land-based, twin-engine light fighter. Relevant aircraft data and the layout of the landing gears are given in Fig A5.1. Both the main and the nose landing gears are single-wheel cantilever designs, the former retracting inboard and the latter forward. The configurations of the landing gears are shown in Fig A5.2. Each shock strut has a single pressure chamber with a metering pin to modulate the damping. The characteristics of the main gear, including load-stroke and damping functions, are given in Fig A5.3; corresponding data for the nose gear are given in Fig A5.4.

The Nimrod is a transport aircraft for which general and layout data are presented in Fig A5.5. The main landing gear, of which the configuration is shown in Fig A5.6, has a split bogie comprising forward and rear pivoted arms each of which carries two wheels. The main shock strut connects the two arms through a rocker arm near the top of the leg assembly and a balance strut so that rotation of either arm separately exercises the main shock strut. An auxiliary shock strut restrains the rear arm. The nose landing gear is a twin-wheel cantilever design, also shown in Fig A5.6. Each of the shock struts has a single gas chamber and larger damping orifices (lower damping coefficient) for compression than for extension. The characteristics of the main and the nose landing gears are given in Figs A5.7 and A5.8, respectively.

AIRCRAFT DATA

Maximum take-off mass (MTOM)	10.103 t
Design landing mass (DLM)	9.307 t
Design sink rate at DLM	1.525 m s^{-1}
Pitch moment of inertia about c g at MTOM	58.525 t m^2

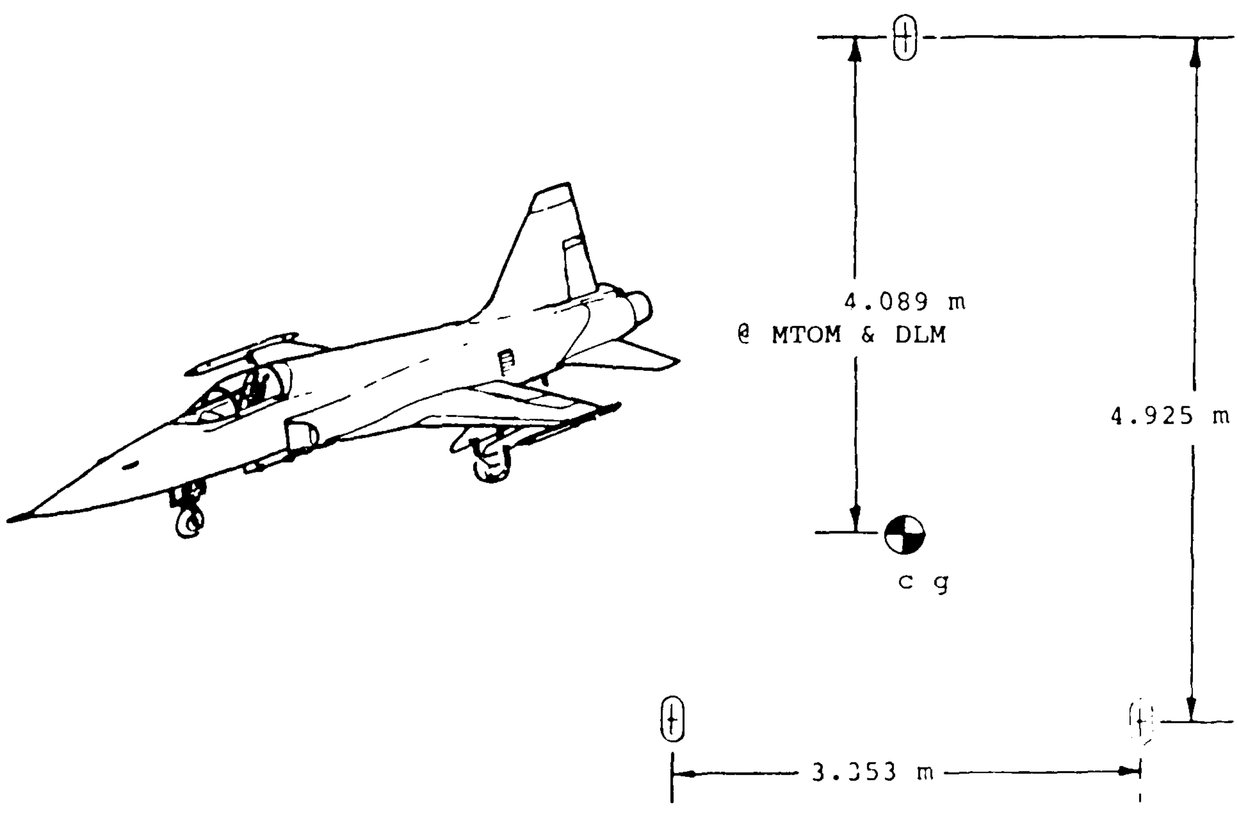
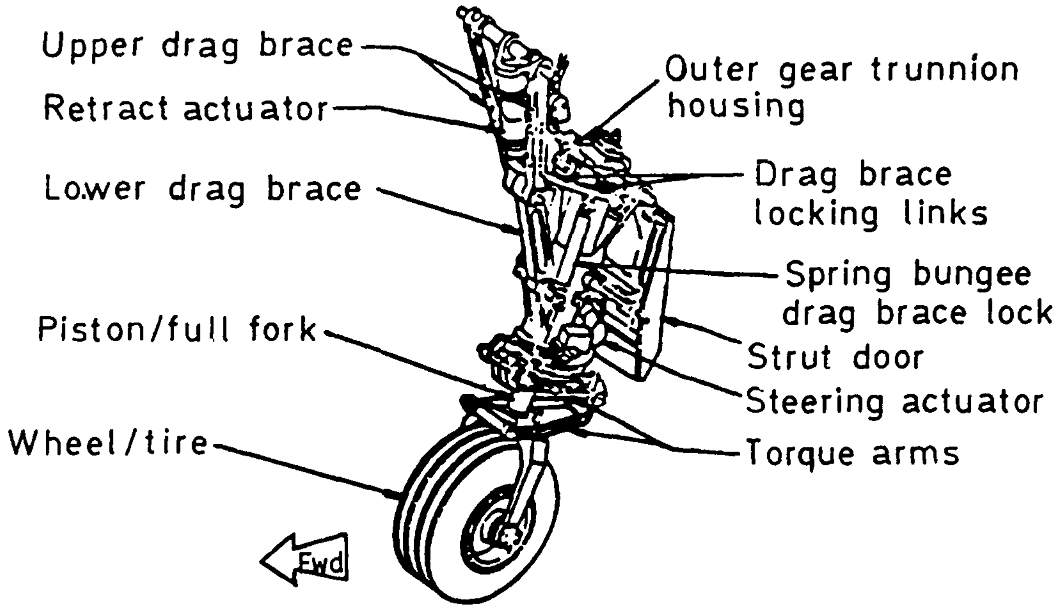
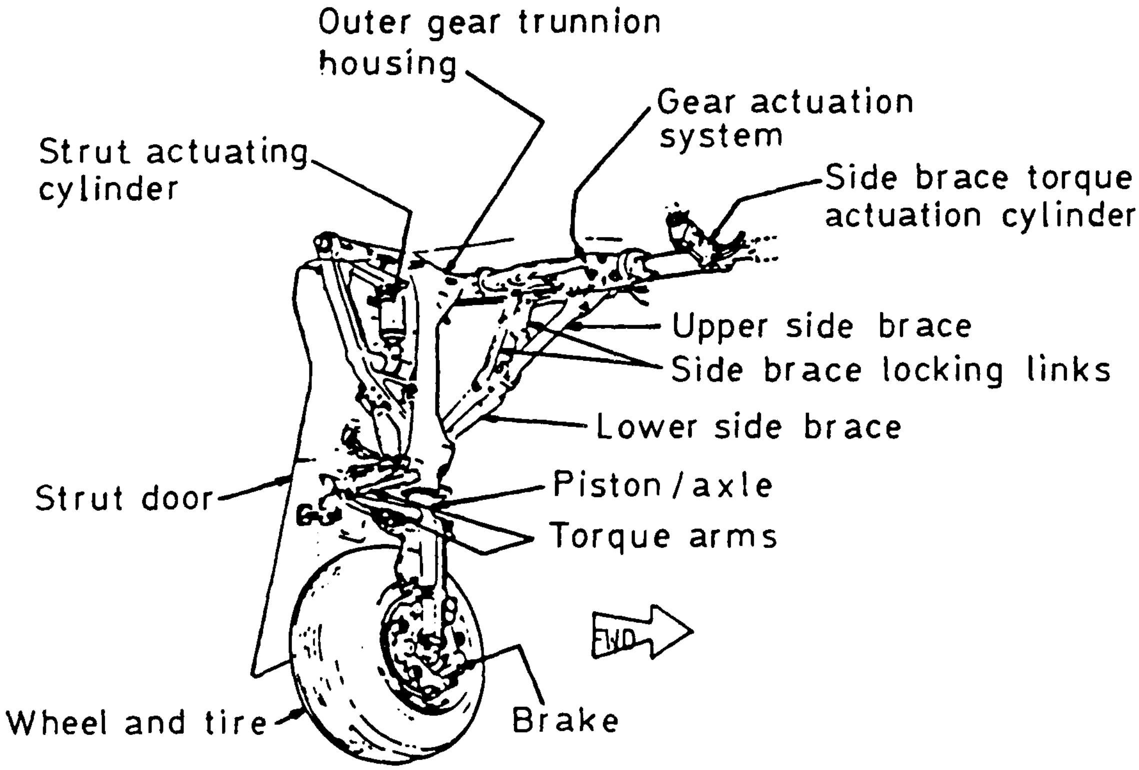


Fig A5.1 NF-5 aircraft data and landing gear layout



Nose gear



Main landing gear

Fig A5.2 NF-5 landing gear configurations

Shock strut

Stroke	260.4 mm
Piston diameter	69.8 mm
Pressure (unloaded, extended)	33.3 bar
Gas volume (unloaded, extended)	1.165 l

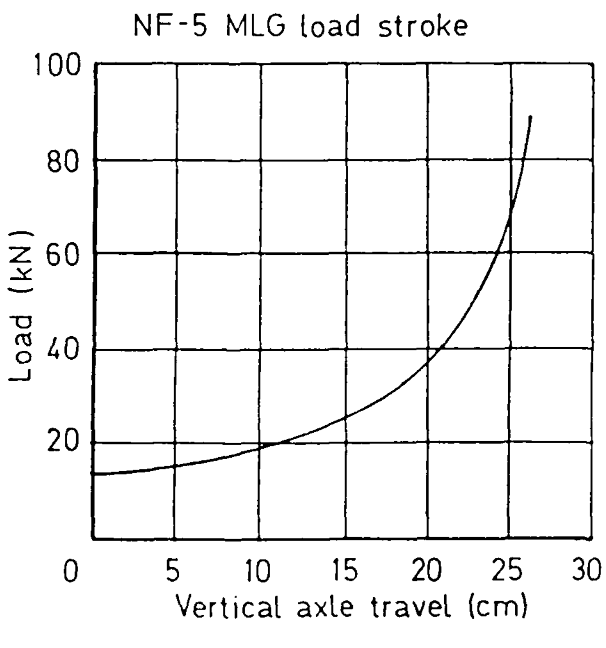
Tire

Size	22x8.50-11
Unloaded inflation pressure	14.3 bar

Static load at MTOM	41.095 kN

Design load (limit)

Vertical	81.503 kN
Drag	46.408 kN



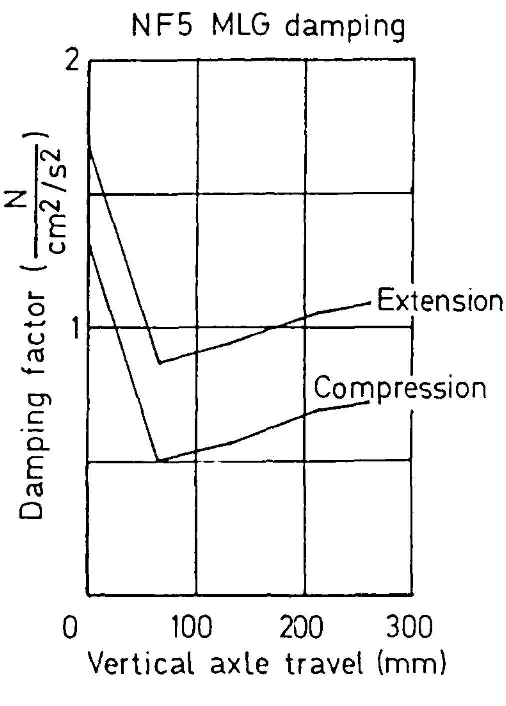


Fig.A5.3 NF-5 main landing gear characteristics

Shock strut

Stroke	209 mm
Piston diameter	56.9 mm
Pressure (unloaded, extended)	17.7 bar
Gas volume (unloaded,extended)	0.5768 l

Tire

Size	18x6.50-8
Unloaded inflation pressure	11.6 bar

Static load at MTOM	16.791 kN

Design load (limit)

Vertical	53.445 kN
Drag	26.722 kN

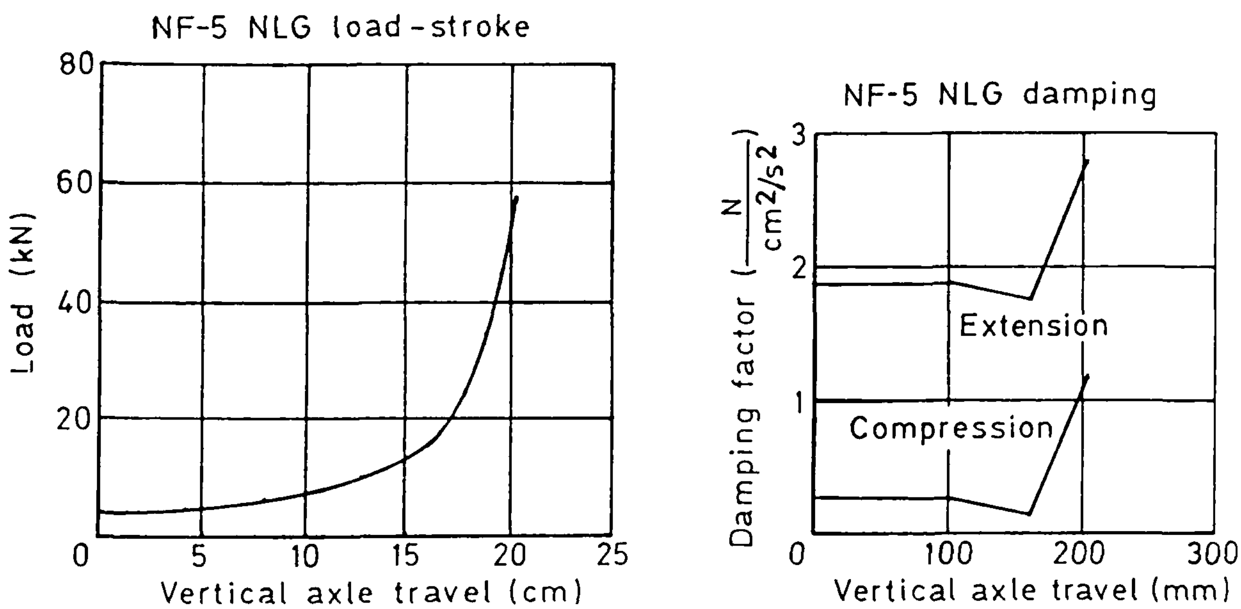
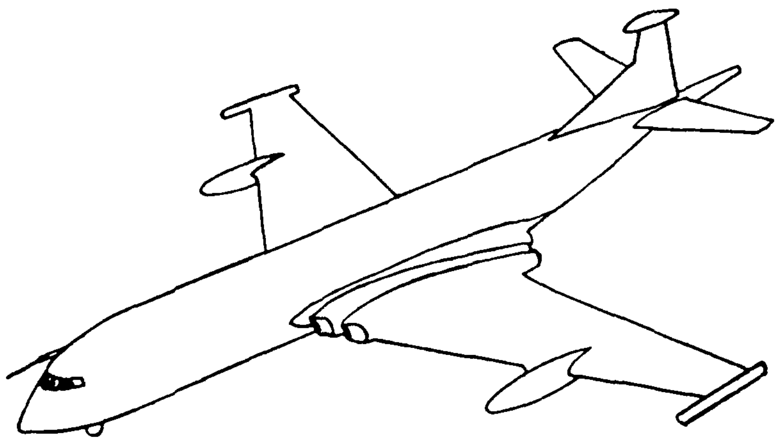


Fig.A5.4 NF-5 nose landing gear characteristics

AIRCRAFT DATA

Maximum take-off mass (MTOM)	82.970 t
Design landing mass (DLM)	54.431 t
Design sink rate at DLM	3.05 m s^{-1}
Pitch moment of inertia about c g at MTOM	2740.1 t m^2



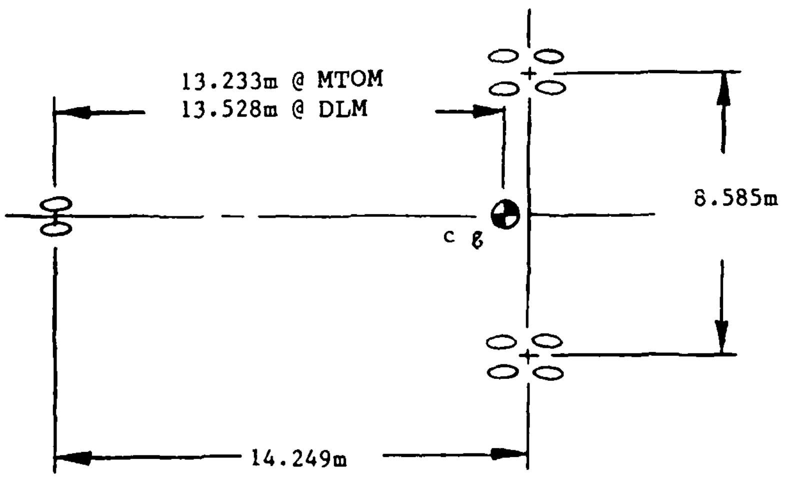


Fig.A5.5 Nimrod aircraft data and landing gear layout

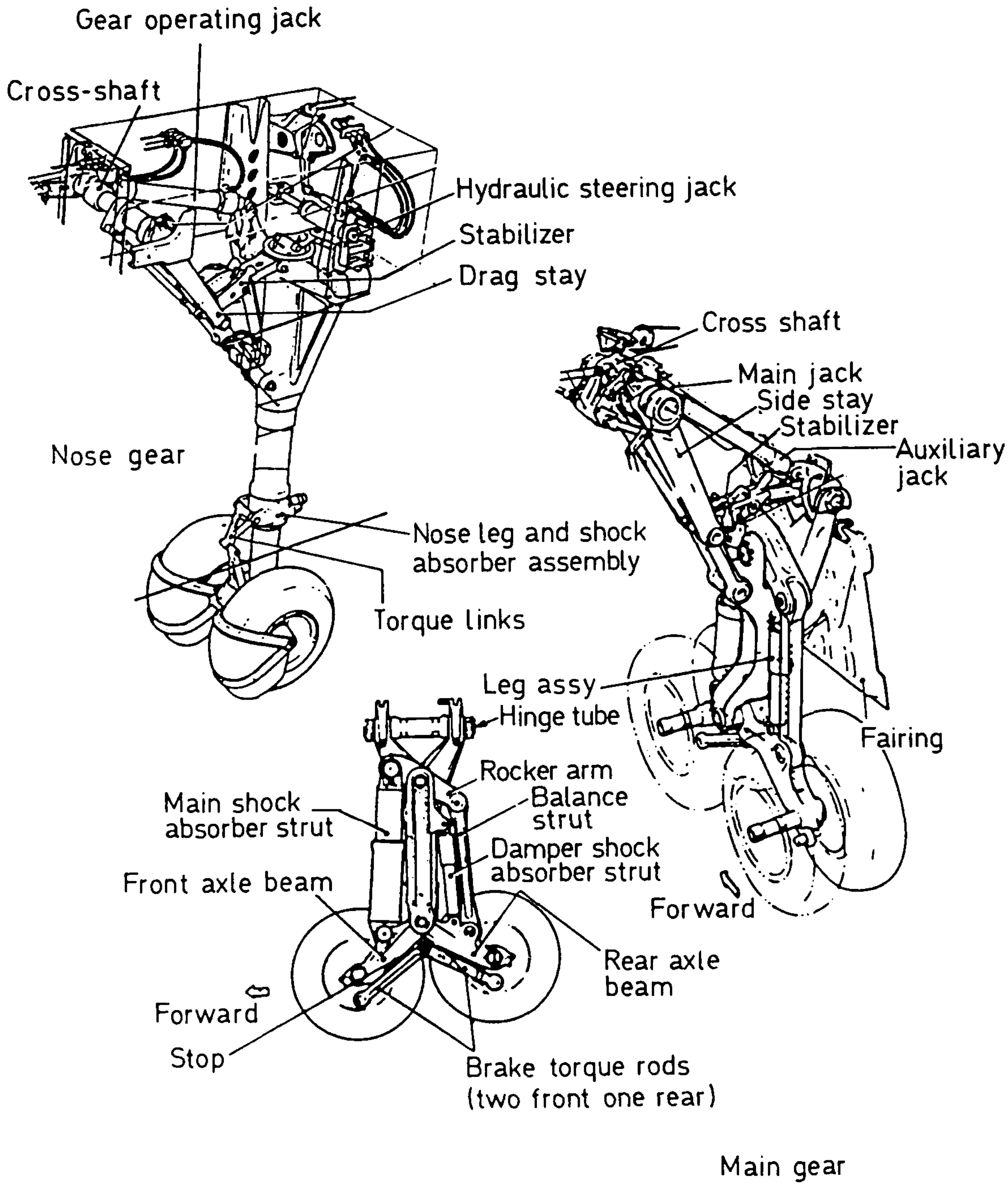


Fig.A5.6 Nimrod landing gear configurations

Shock struts

Vertical travel	357 mm
Stroke - main strut	349 mm
- auxiliary strut	170 mm
Piston diameter - main strut	175 mm
- auxiliary strut	63.4 mm
Pressure (unloaded, extended) - main strut	34.5 bar
- auxiliary strut	69.0 bar
Gas volume (unloaded, extended) - main strut	9.186 l
- auxiliary strut	0.669 l

Tires

Number	4 per leg
Size	36x10.00-18
Unloaded inflation pressure	12.75 bar

Static load at MTOM	377.8 kN

Design load (limit)

Vertical	607.9 kN
Drag	-

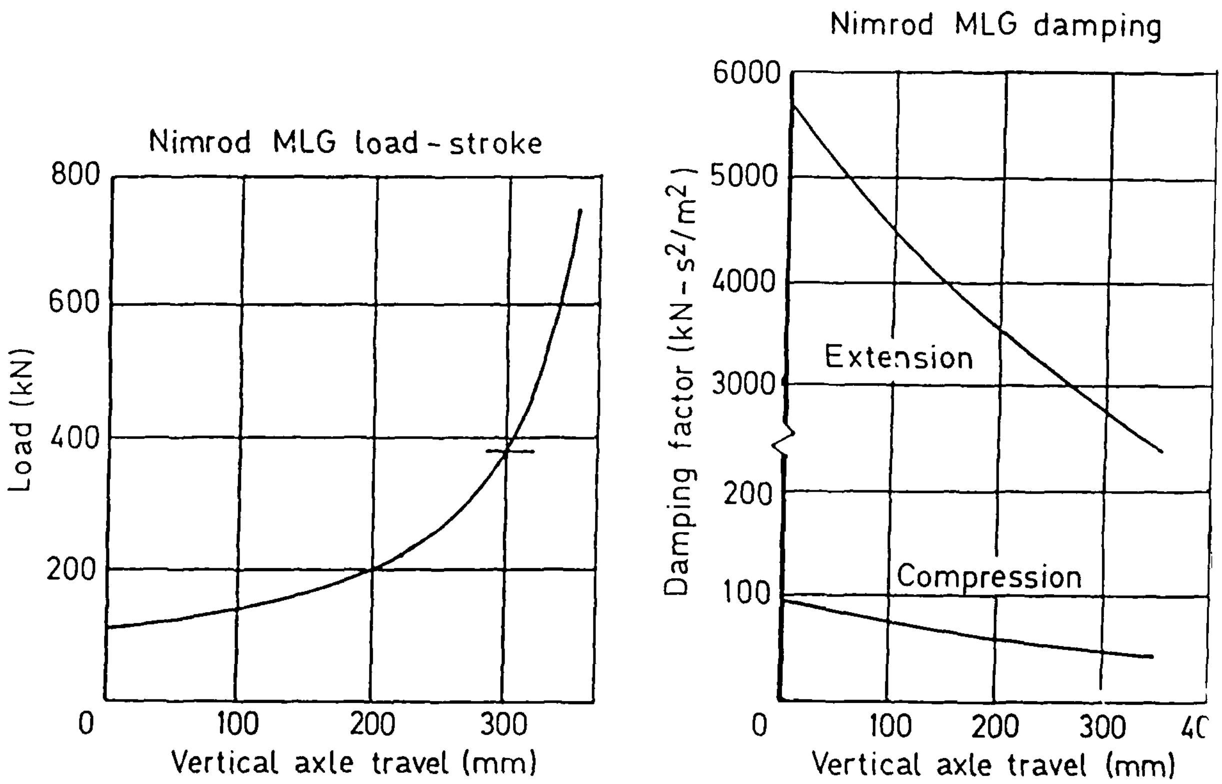


Fig.A5.7 Nimrod main landing gear characteristics

<u>Shock strut</u>

Stroke	330 mm
Piston diameter	127 mm
Pressure (unloaded, extended)	13.1 bar
Gas volume (unloaded, extended)	4.76 l
Damping factor - compression	9.86 kN s^2 m^{-2}
- extension	312.3 kN s^2 m^{-2}

<u>Tires</u>

Number	2
Size	30x9.00-15
Unloaded inflation pressure	6.2 bar

<u>Static load at MTOM</u> 58.02 kN

<u>Design load (limit)</u>

Vertical	189.8 kN
Drag	-

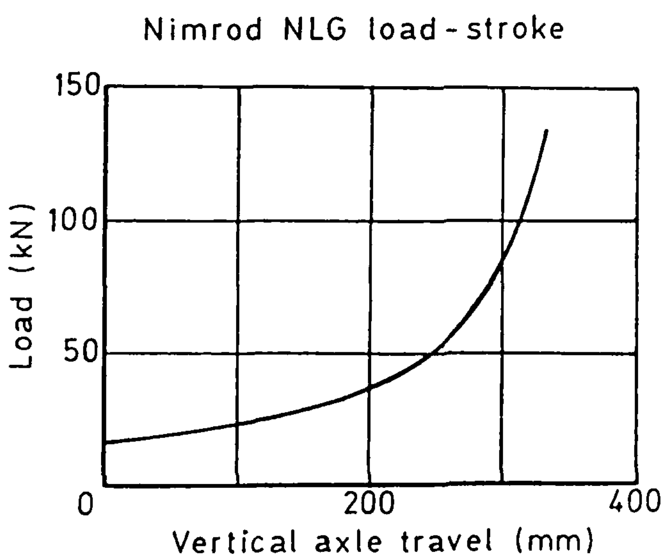


Fig.A5.8 Nimrod nose landing gear characteristics

APPENDIX 6

THE DEVELOPMENT OF STANDARD BUMPS

As was illustrated in Appendix 1, the nature and dimensions of damage to a runway are widely variable. The repair techniques developed to deal with them have their individual features, within which there are also considerable variations. In a situation where changes may occur at any time in the likely form of damage and in the methods for its rectification it is clearly unpractical to expect aircraft design requirements to keep pace. For existing aircraft it would be a major task to re-evaluate their capabilities from scratch each time the expected repair profiles changed. Also, since each nation may have its own repair methods, interoperability would demand continuing evaluation of all aircraft for all methods, 'native' and 'foreign', were there no common standard for expressing capability. Therefore it was sought to define standardized repair profiles which could be applied to aircraft design and which would be a vehicle for the exchange and utilization of information on aircraft capability.

Damage to a runway presents itself as a variety of disruptions of the surface at random locations. The latter clearly cannot be pre-determined or generally characterized but an attempt may be made to condense all the features of repairs into a few parameters for 'standard bumps'. For the purposes of design it is necessary that those bumps produce in an aircraft all of the critical conditions that actual repairs do; further, for interoperability, it must be shown that they can be related to actual repairs in a way which is invariable for a particular aircraft.

A6.1 BUMP SHAPE

From a consideration of the profiles of actual repairs, the simplest shape which a standard bump might take is a level plateau between two identical ramps, as shown in Fig A6.1. For some repair techniques the ramps typically have a step at the leading (/trailing) edge and may exhibit a double slope: the need to incorporate such features was initially admitted, to be investigated by simulation of their effects on aircraft. The minimum set of parameters is thus bump height (h), bump length (L) and ramp slope (or length). Fig A6.1 also gives the definition of bump spacing (S): it is assumed that the spacing between the centres of bumps will be the same as between the centres of the areas of damage.

A6.2 BUMP DIMENSIONS

It is necessary to specify in design requirements the bump dimensions to be assumed and advantageous if information on aircraft capability subsequently refers to those same dimensions. To restrict the extent of analyses and the volume of information to be presented it is desirable that each parameter take only a small number of values, sufficient to cover the practical range of repair dimensions and to reveal the major features of aircraft response. Definitions for actual repairs (from Ref A6.1 – Paper 1, Ref A6.2 – Paper 1, and unpublished data) were considered in order to define suitable values. Known and likely aircraft characteristics were also considered in their definitions.

A6.2.1 Bump height

(All dimensions given below are in mm)

Published US definitions give

Class of repair	Maximum height	Maximum sag	Maximum nominal sag
A	38	25	13
B	64	25	13
C	64	64	50
D	76	64	50
E	114	64	50

UK definitions give

Maximum height including repair mat	69
Maximum average height including repair mat	57
Maximum sag	37

At least 20 NATO aircraft have been investigated for their capabilities in crossing repairs. They have been found to range from the capability to cross multiple Class A repairs, subject to stringent limitations on spacing and speed, to that to cross multiple UK repairs with virtually no restrictions. The most severe class of US repair cleared in any case for multiple encounters on a two-way MOS is C.

When the method used to establish interoperability relies on the interpolation for actual repairs of data on aircraft capability for particular repair heights, as does the contour-plot approach, the latter must be determined for at least two heights. The choice of those heights is to an extent arbitrary but the difference between them must not be so great that the corresponding aircraft capabilities go from one extreme to another. For example, if an aircraft had unlimited capability to cross pairs of bumps at the lower height but could not cross a single bump at the higher then those data could not be utilized. It is thought that the appropriate ratio between the heights is about 1.33.

The range of repair heights tabulated above is considered to be too great to be properly covered by two heights. Therefore an approach is suggested based on two standards, viz

Standard	Repair heights
Minimum	38 & 52 (ratio 1 : 1.37)
Normal	52 & 70 (ratio 1 : 1.35)

Thus all aircraft would be evaluated for a 52 mm repair height and, depending on the results obtained or the established capability of the aircraft, one of the other two heights would be chosen. Thereby the number of calculations required would be minimized while making them the most appropriate for the particular aircraft.

For a method, such as the top-down approach, which directly yields the allowable standard bump height no interpolation of data is necessary; however, it is considered that initial consideration of two fixed heights, as above, is valuable to give a general indication of aircraft capability.

A6.2.2 Bump length

US AM-2 repair-mat kits produce mats 23.7 m long, though there is no reason why some of the panels could not be omitted to produce shorter mats. According to US repair definitions, longer mats may be made up to be used with repairs of classes A to C.

UK Class 60 trackway is stored made up into 11 m and 22 m lengths.

Pre-cast concrete slabs are generally 2 m square.

The length of repair affects an aircraft's ability to cross it in a number of ways:

The length dictates the frequencies of inputs which can be generated for a given speed range.

The longer the repair the higher the speed which will be required to produce a given modal frequency, with a consequent increase in aerodynamic damping and aerodynamic load relief.

The aircraft's response will be dependent on the ratio of repair length to its wheelbase.

The effects of repair spacing as well as their lengths in relation to the wheelbase have to be taken into account; the former is approximately at its worst when the gap between repairs is equal to the plateau length. Examination of 29 NATO aircraft has shown that they may be placed into three distinct groups as regards wheelbase, as shown in Table A6.1, with a mean value (defining one of the desirable bump lengths) for each. Consideration of the probable highest frequencies of significant structural modes led to the conclusion that the maximum 'tuned' repair length is about 11 m.

The bump lengths eventually chosen on the basis of the arguments outlined above are 6.5 m, 11.5 m, and 22.5 m, which are compatible with the expected repair lengths for various types of damage and repair technique. (Those lengths encompass a pair of ramps, the length of which is discussed below.)

A6.2.3 Ramp slope

The US repair definitions given in Ref A6.1, Paper 1 specify a maximum change of slope of 3%; more recent unpublished definitions give 5%. The slope of an AM-2 end ramp, which is assumed to be laid over undamaged pavement, is 3.3%. The UK definitions allow the end ramp to be laid over fill material — then ith the defined maximum slope of fill of 3% the average slope to a peak of maximum slope is 5.6%.

There are two aspects to be considered for the influence of bump slope on aircraft response, the overall gradient and the detailed shape. For now it is assumed that a simple ramp is adequate: the latter aspect is discussed in Paragraph A6.3.1. From exploratory simulations it was concluded that since the loads generated at the near side of a repair are significantly influenced by the slope representative values should be chosen. However, the effect of a change in slope is predictable so that (a) it is unnecessary to specify more than one value and (b) within reasonable limits, the same length of ramp can be specified independent of bump height.

A ramp length of 1.25 m was chosen. The slopes for the three bump heights previously suggested are then 3.0%, 4.2% and 5.6%, which are in close agreement with the defined values above. (It seems reasonable that for the 'minimum' standard the slopes too should be lower than for the 'normal'.)

A6.3 VERIFICATION OF SHAPE

The validity of the choices made on the shape of standard bumps was subjected to two tests. First, the acceptability of the simple ramp shape had to be established; second, the substitution of standard bumps for actual repairs in specifying aircraft capabilities had to be assessed. Both were accomplished by means of simulations.

A6.3.1 Ramp shape

The effect of ramp shape was investigated by simulating the response of an aircraft for which the nose-gear loads generated on ramp encounter were known to be potentially critical. The ramp profiles assumed were as shown in Fig A6.2. The loads produced for encounters with each are shown in Figs A6.3 to A6.5. The general conclusion was that while the loads were significantly affected there was no consistent pattern that would justify departing from the simple shape — for example, the introduction of a step can reduce the loads at some speeds because of the effect of the initial impulse in causing earlier deflection of the shock strut. Similarly, there would be no advantage from assuming the double slope which often arises in practice.

A6.3.2 Relationship to actual repairs

A number of simulations were carried out to determine the height of a standard bump which gave the same maximum value of a critical load as a measured repair profile. Two large aircraft which had a number of significant flexible modes were considered. If the shape chosen for the standard bumps is to provide an acceptable representation of actual repairs then the statistical properties of the distribution of effective bump heights should be insensitive to aircraft speed. That was established for both aircraft, with almost identical mean effective heights. Thus confidence was established that data on aircraft capabilities for standard bumps could be used to predict their abilities to cross actual repairs.

REFERENCES

A6.1 Aircraft response to damaged and repaired runways, AGARD CP-326, August 1982

A6.2 Aircraft dynamic response to damaged runways, AGARD R-685, March 1980

Table A6.1
Wheelbases of some NATO aircraft

Group 1

Alpha Jet, Buccaneer, Hawk, Jaguar, Lightning, Tornado, A-10, F-4, F-5, F-15, F-16, F-18, F-104, F-111

Mean wheelbase:	5.39 m
Wheelbase range:	4.00 m (F-16) to 7.01 m (F-4)
Mass (approx):	up to 50 t (F-111)

Group 2

Atlantic, Nimrod, Transall, Victor, C-130, KC-135

Mean wheelbase:	11.1 m
Wheelbase range:	7.47 m (Victor) to 14.2 m (Nimrod)
Mass (approx):	50 t (Atlantic) to 150 t (KC-135)

Group 3

Model 747, TriStar, VC10, C-5A, C-141, DC-10, E-3A

Mean wheelbase:	21.12 m
Wheelbase range:	17.98 m (E-3A) to 25.6 m (Model 747)
Mass (approx):	over 150 t

Heights: 38 mm, 52 mm and 70 mm (Both bumps identical)

Lengths: 6.5 m, 12.5 m and 22.5 m

Ramp Length: 1.25 m (All ramps identical)

Spacing: Variable

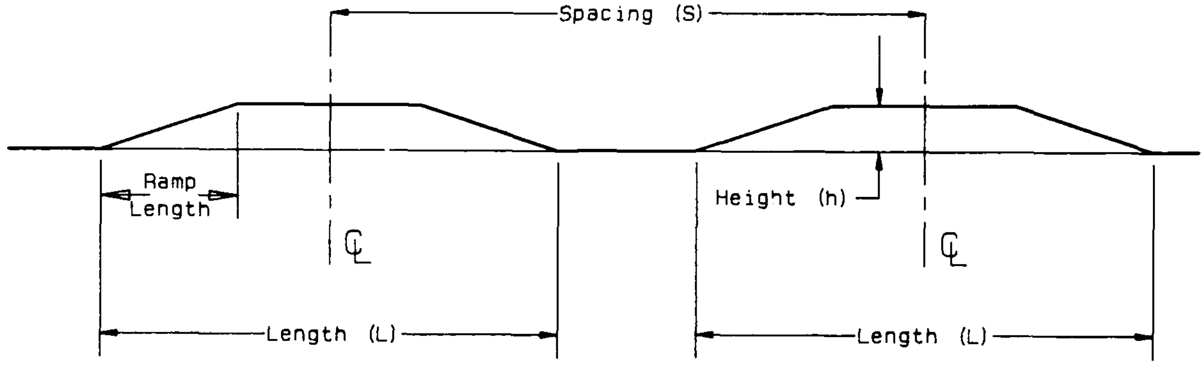


Fig.A6.1 Definition of standard bumps

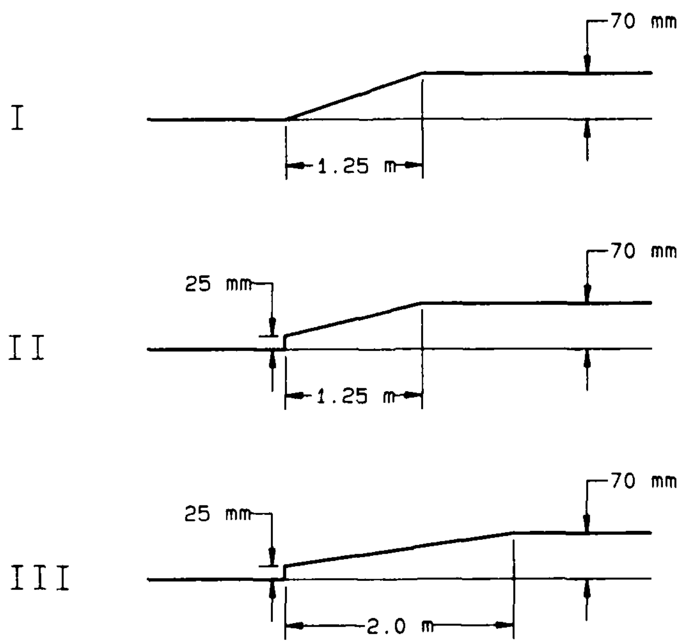


Fig.A6.2 Ramp profiles

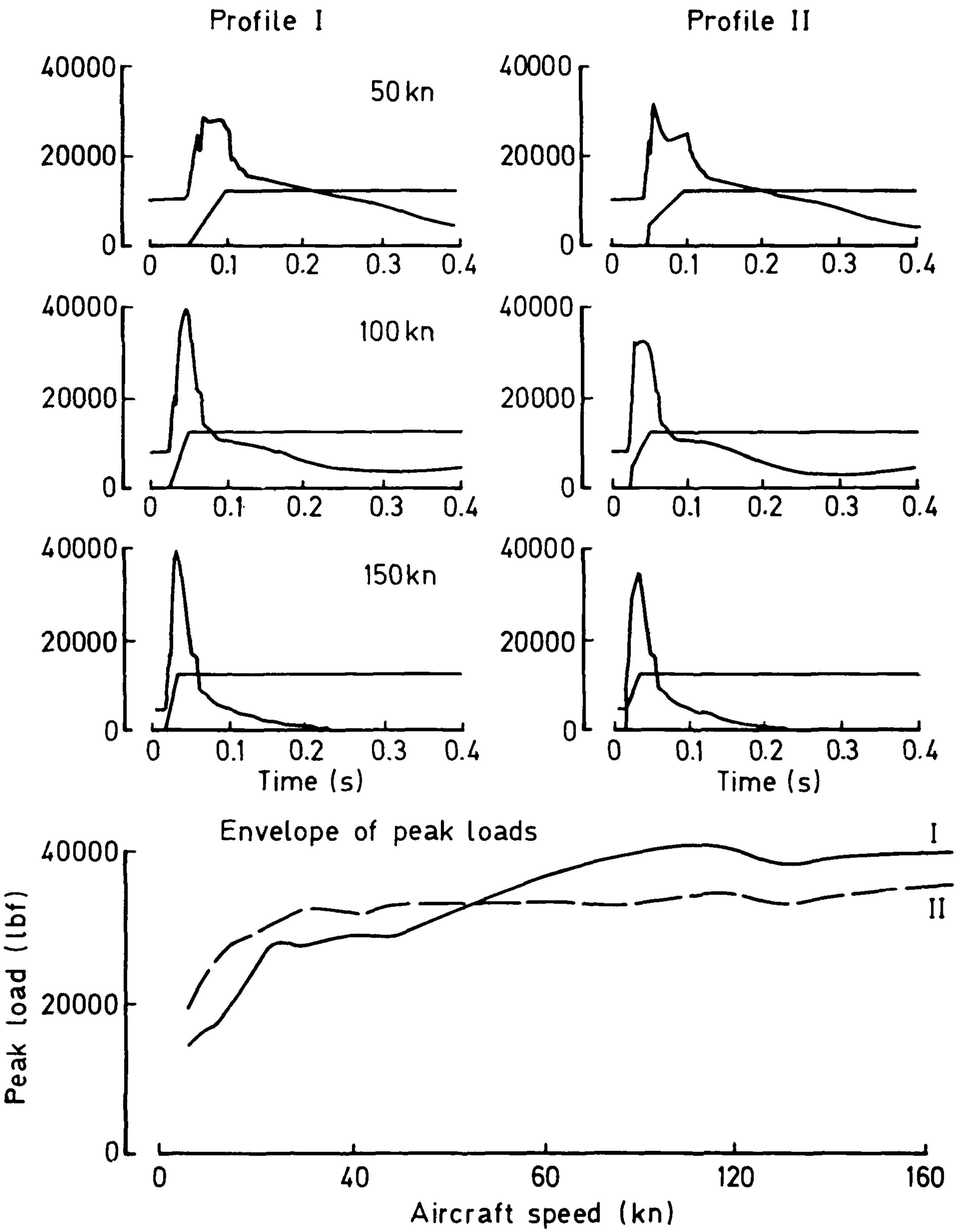


Fig.A6.3 Effect of a step on nose landing gear load

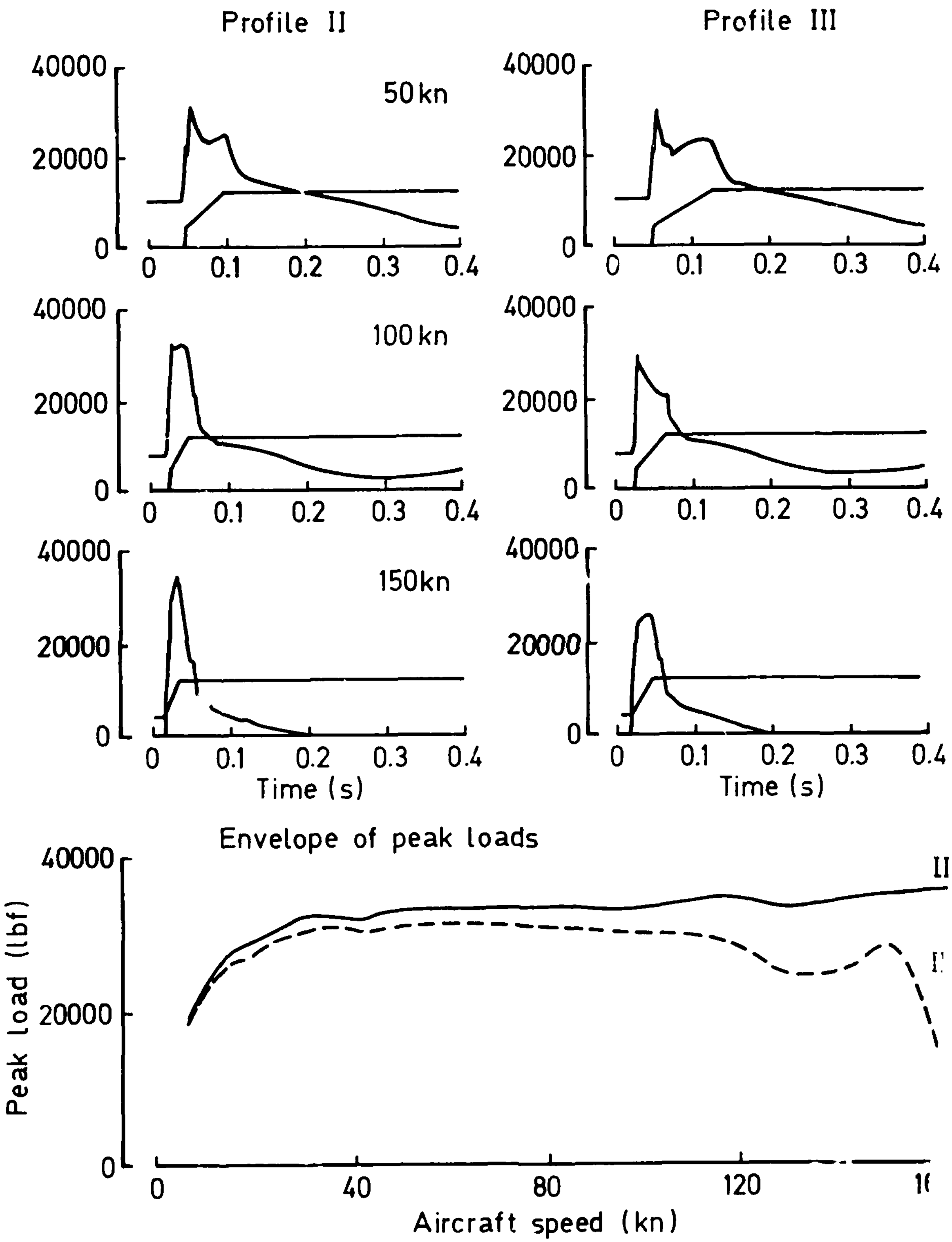


Fig.A6 + Effect of gradient on nose landing gear load

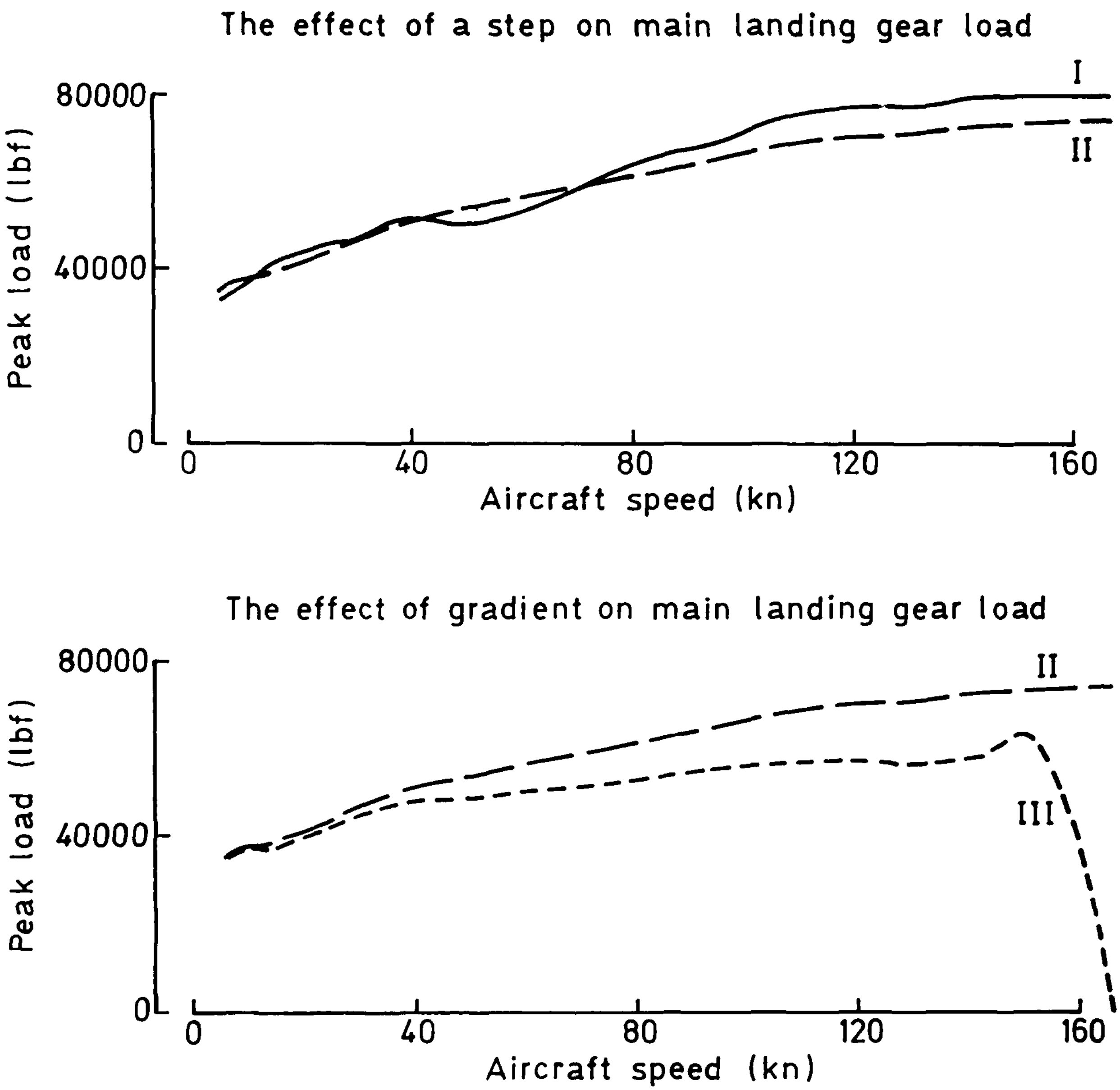


Fig.A6.5 Effects of step and of gradient on main landing gear load

APPENDIX 7

DATA ON THE CAPABILITIES OF CURRENT AIRCRAFT

The capabilities of current aircraft to cross runway repairs are indicated by the data presented in this Appendix on the resulting loads for the two aircraft – the NF5 and the Nimrod – for which general and landing-gear data were given in Appendix 5. The repairs are of the form of standard bumps (Appendix 6) on an otherwise flat runway. The results are presented in the formats discussed in Section 7.

For the NF5, results are presented for two masses; a 'high' mass (about 9.3 t) corresponding to a heavily laden and fully fuelled aircraft and a 'low' mass (about 4.6 t) corresponding to an almost clean and empty aircraft. Results are given for crossing two repairs of length 6.5 m or 12.5 m and height 38 mm or 52 mm at a constant speed.

Figures A7.1 to A7.4 define for the high aircraft mass the contours for 100% of limit load for the main landing gear. If non-exceedence of that load is the chosen criterion then for a repair height of 38 mm the prohibited regions are fairly small and localized whereas for a repair height of 52 mm they are more extensive and define some prohibited combination of speed and repair spacing for all values of those parameters individually. Corresponding results for nose landing gear load are given in Figs A7.5 to A7.8; it can be seen that equivalent criteria for that quantity will give considerably more restriction than for the main landing gear load. Also shown for the nose landing gear load are the contours for 150% of limit load, the 'ultimate' load at which total structural failure may occur, which define regions of significant extent for a repair height of 52 mm.

In the results for the low mass given in Figs A7.9 to A7.16 contours are shown for 60%, 80% and 100% of limit load, where those load levels are reached. On a criterion of 100% of limit load the main landing gear load never gives rise to a limitation; for the nose landing gear load the prohibited regions are fairly small and within a narrow band of repair spacings.

For the Nimrod, results are given for crossing one or two repairs of length 6.5 m, 12.5 m or 22.5 m and height 38 mm or 52 mm. Loading levels are expressed as percentages of the 'allowable increment', i e the limit value minus the quasi-static value – the latter is given as a function of speed in Fig A7.17.

The maximum main landing gear load and maximum wing stress in crossing a single repair are given in Fig A7.18 and Fig A7.19, respectively – the latter is the more critical but never exceeds 60% of its allowable increment for any of the repairs considered.

Results for two repairs are derived assuming the aircraft's speed follows the (zero wind) take-off performance shown in Fig A7.20. Contours are given at intervals of 10% of the allowable increment in Figs A7.21 to A7.26 for main undercarriage load and in Figs A7.27 to A7.32 for wing stress. It is seen that the latter quantity is rather more restricting than the former and that of the three repair lengths considered the intermediate one gives generally the most extensive regions for a particular load level. However, the 90% contour is absent from all Figures, showing that for the cases considered that percentage of the allowable increment is never reached.

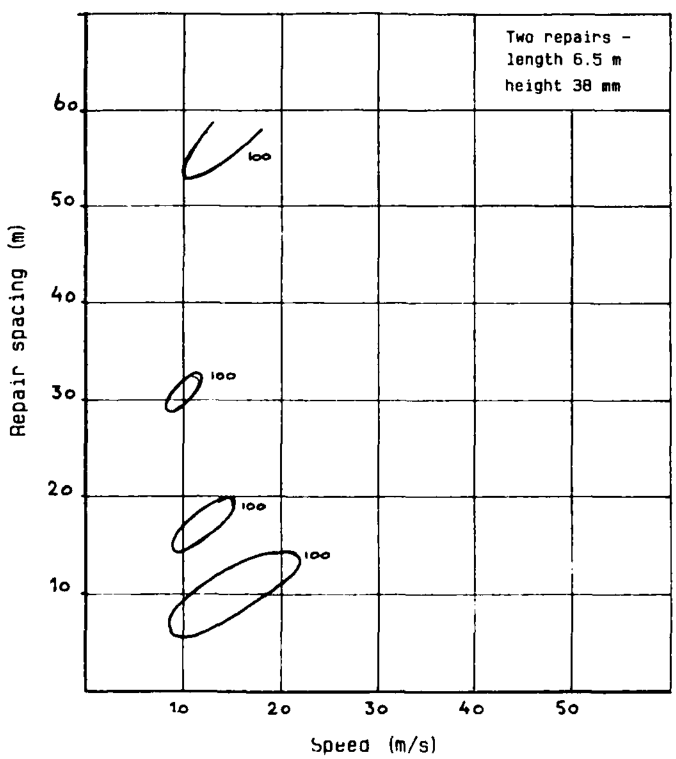


Fig. A7.1 NF5 maximum main landing gear load (percentage of limit): high mass; two repairs, length 6.5 m, height 38 mm

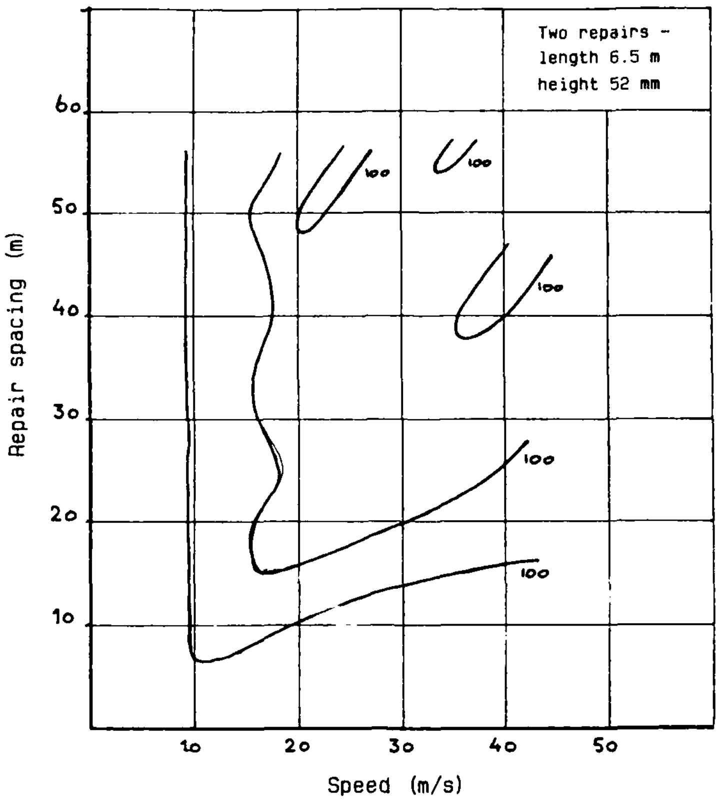


Fig.A7.2 NF5 maximum main landing gear load (percentage of limit): high mass; two repairs, length 6.5 mm, height 52 mm

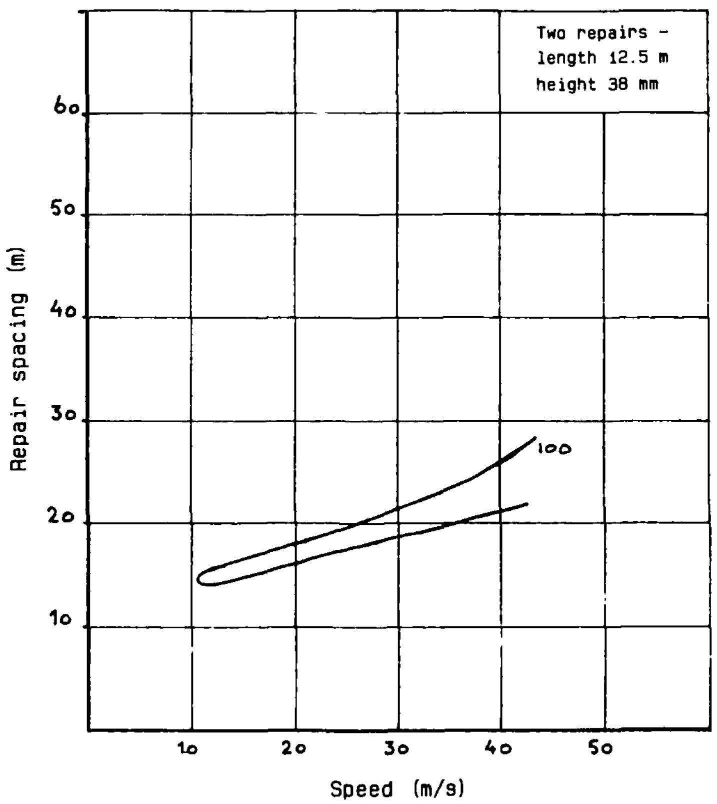


Fig.A7.3 NF5 maximum main landing gear load (percentage of limit): high mass; two repairs, length 12.5 m, height 38 mm

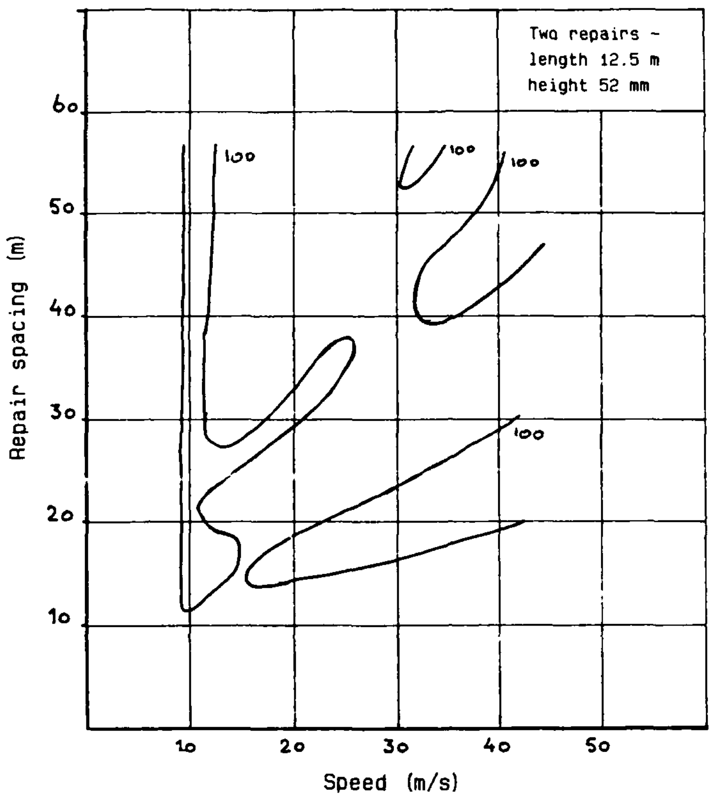


Fig.A7.4 NF5 maximum main landing gear load (percentage of limit): high mass; two repairs, length 12.5 m, height 52 mm

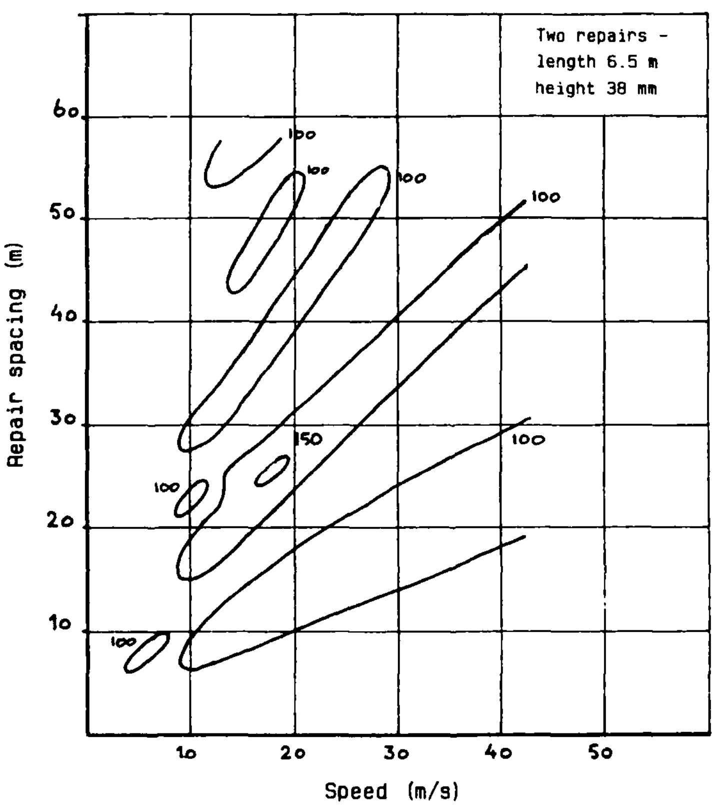


Fig.A7.5 NF5 maximum nose landing gear load (percentage of limit): high mass; two repairs, length 6.5 m, height 38 mm

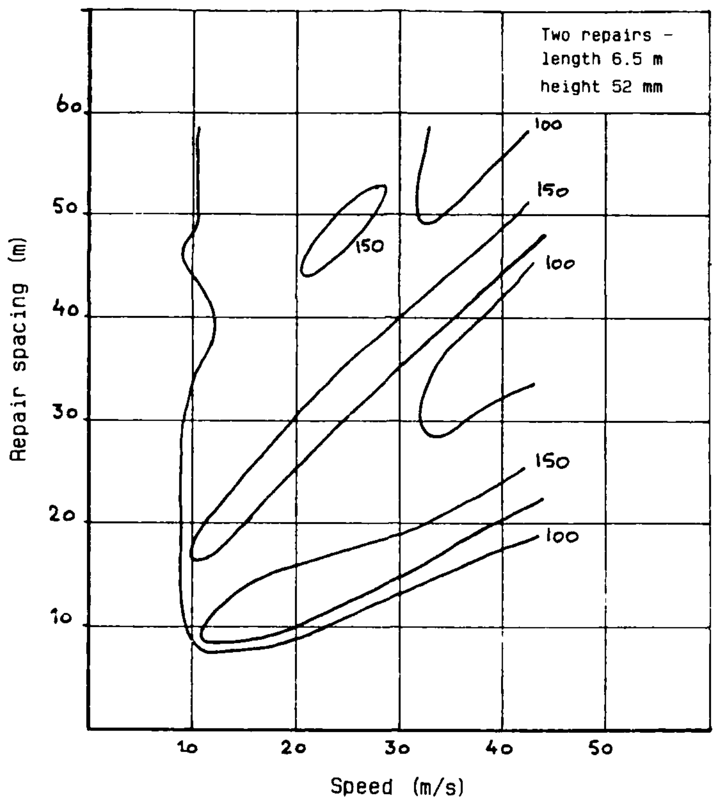


Fig.A7.6 NF5 maximum nose landing gear load (percentage of limit): high mass; two repairs, length 6.5 m, height 52 mm

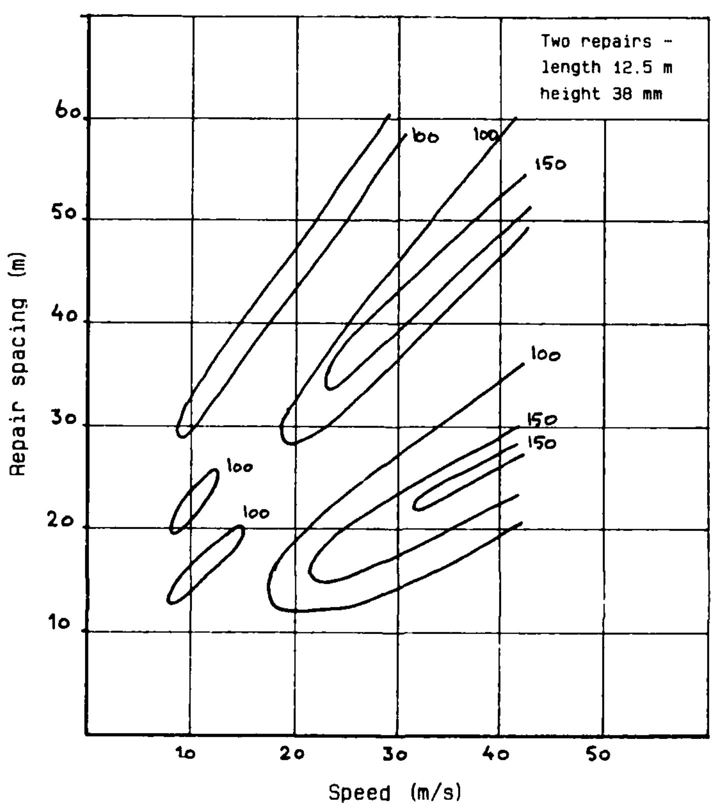


Fig.A7.7 NF5 maximum nose landing gear load (percentage of limit): high mass; two repairs, length 12.5 m, height 38 mm

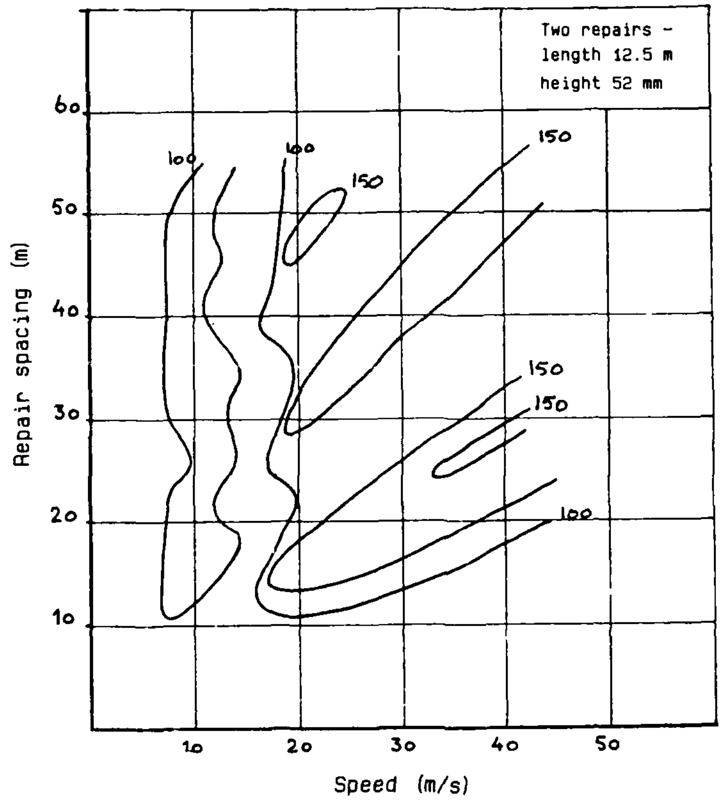


Fig.A7.8 NF5 maximum nose landing gear load (percentage of limit): high mass; two repairs, length 12.5 m, height 52 mm

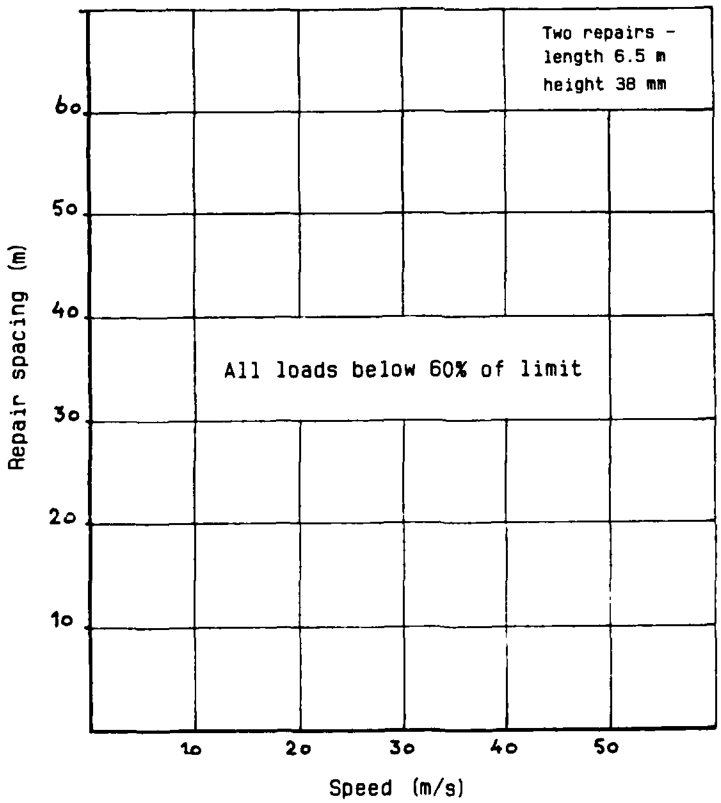


Fig.A7.9 NF5 maximum main landing gear load (percentage of limit): low mass; two repairs, length 6.5 m, height 38 mm

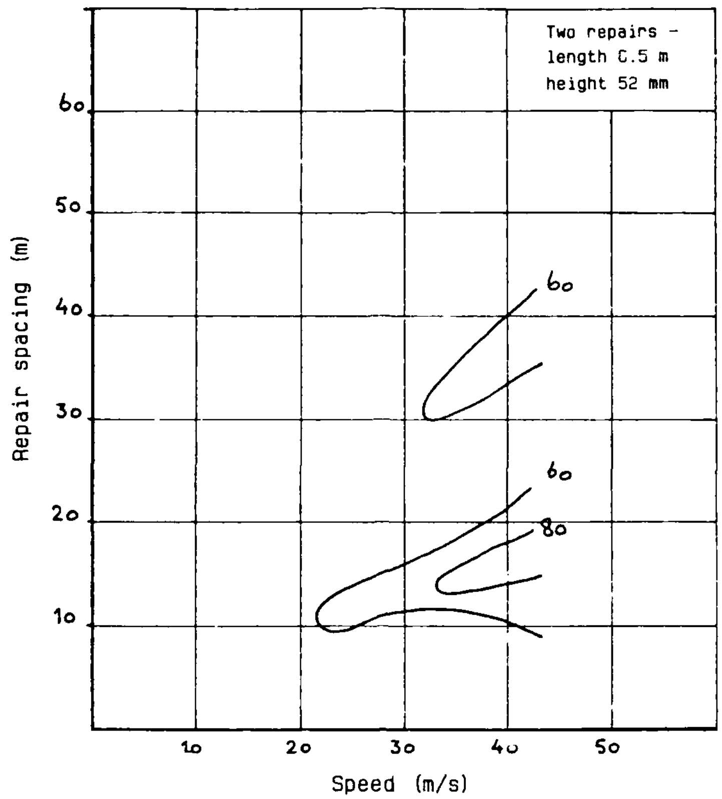


Fig.A7.10 NF5 maximum main landing gear load (percentage of limit): low mass; two repairs, length 6.5 m, height 52 mm

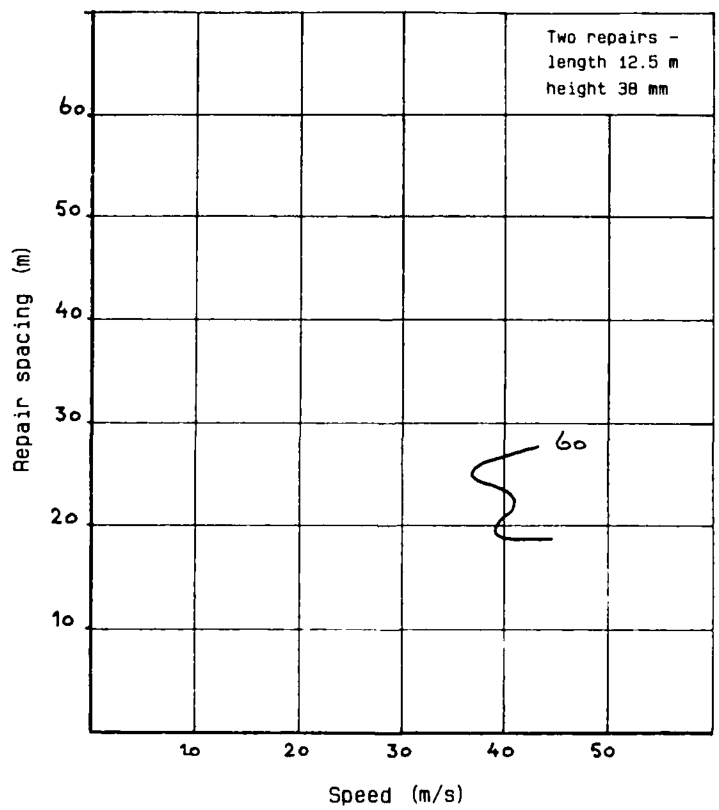


Fig.A7.11 NF5 maximum main landing gear load (percentage of limit): low mass; two repairs, length 12.5 m, height 38 mm

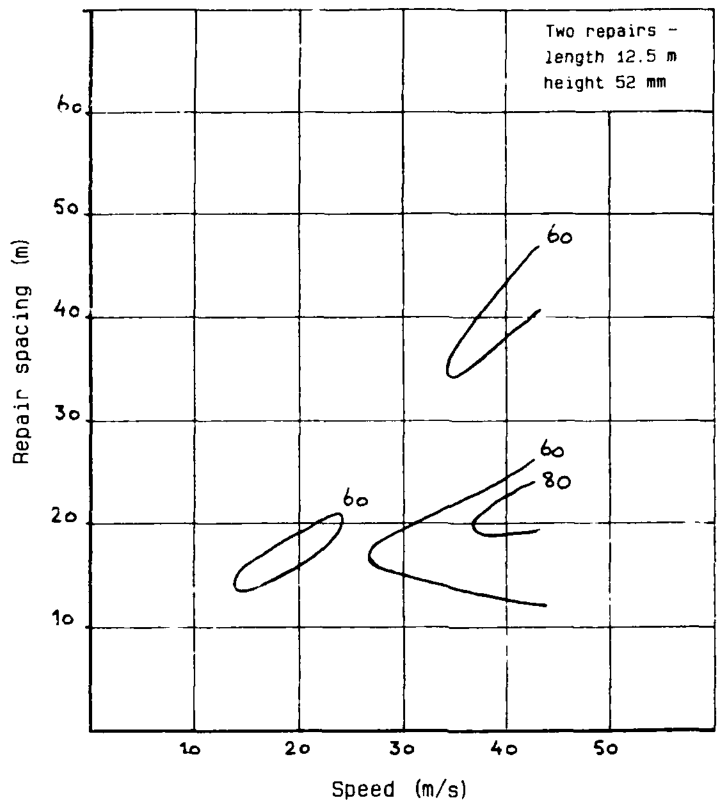


Fig.A7.12 NF5 maximum main landing gear load (percentage of limit): low mass; two repairs, length 12.5 m, height 52 mm

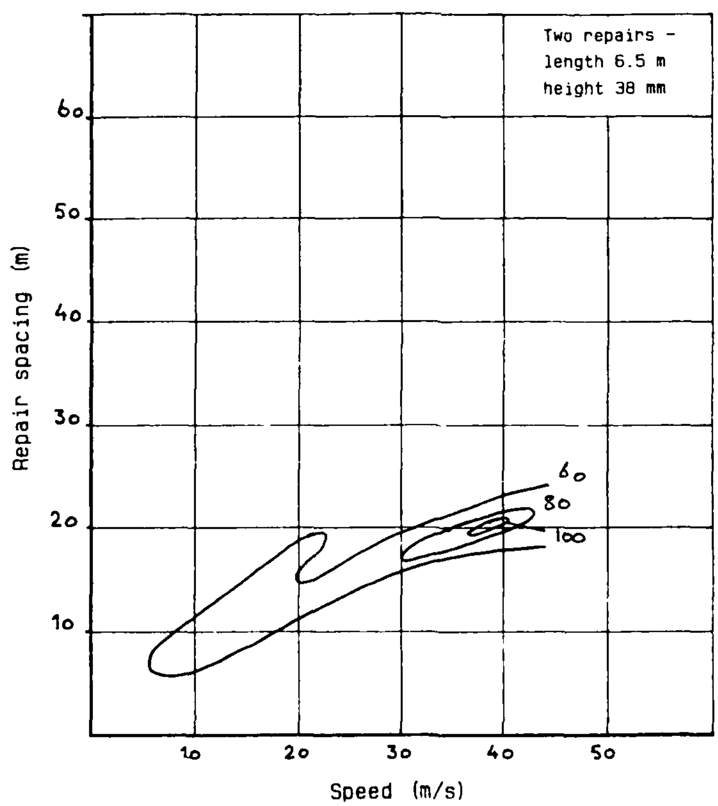


Fig.A7.13 NF5 maximum nose landing gear load (percentage of limit): low mass; two repairs, length 6.5 m, height 38 mm

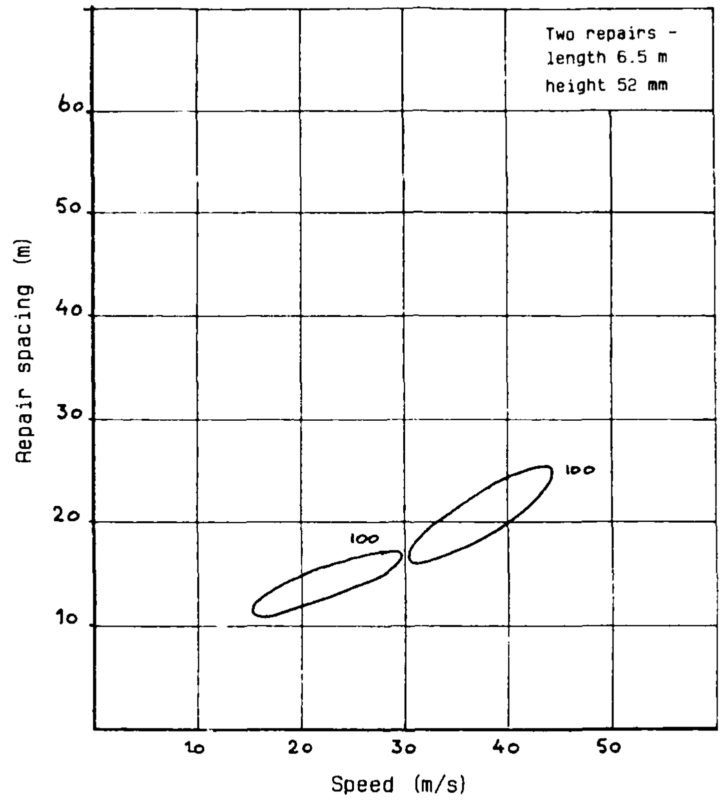


Fig.A7.14 NF5 maximum nose landing gear load (percentage of limit): low mass; two repairs, length 6.5 m, height 52 mm

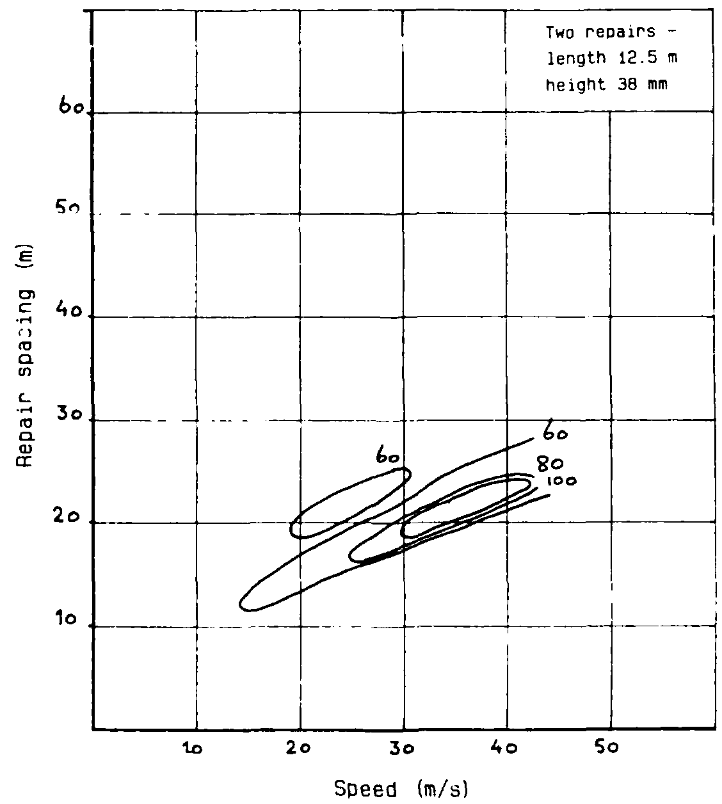


Fig.A7.15 NF5 maximum nose landing gear load (percentage of limit): low mass; two repairs, length 12.5 m, height 38 mm

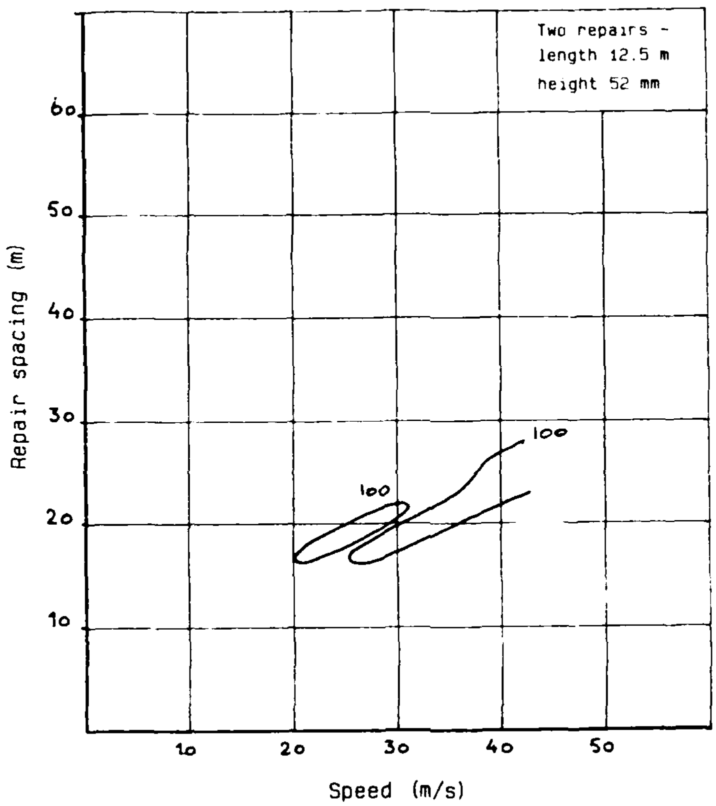


Fig.A7.16 NF5 maximum nose landing gear load (percentage of limit): low mass; two repairs, length 12.5 m, height 52 mm

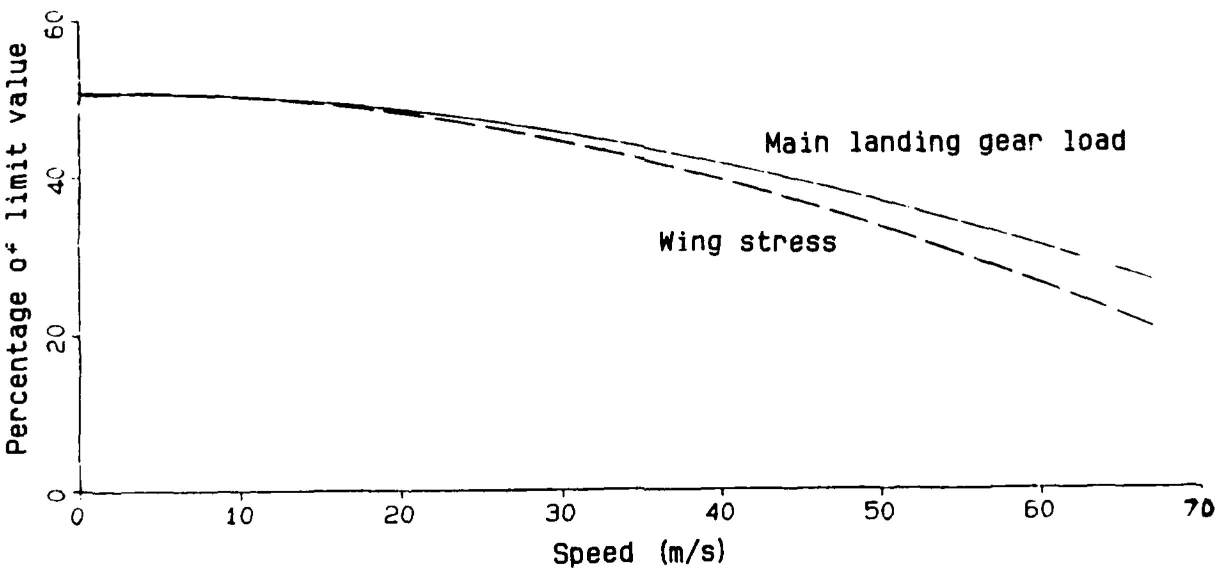


Fig.A7.17 Nimrod quasi-static loadings

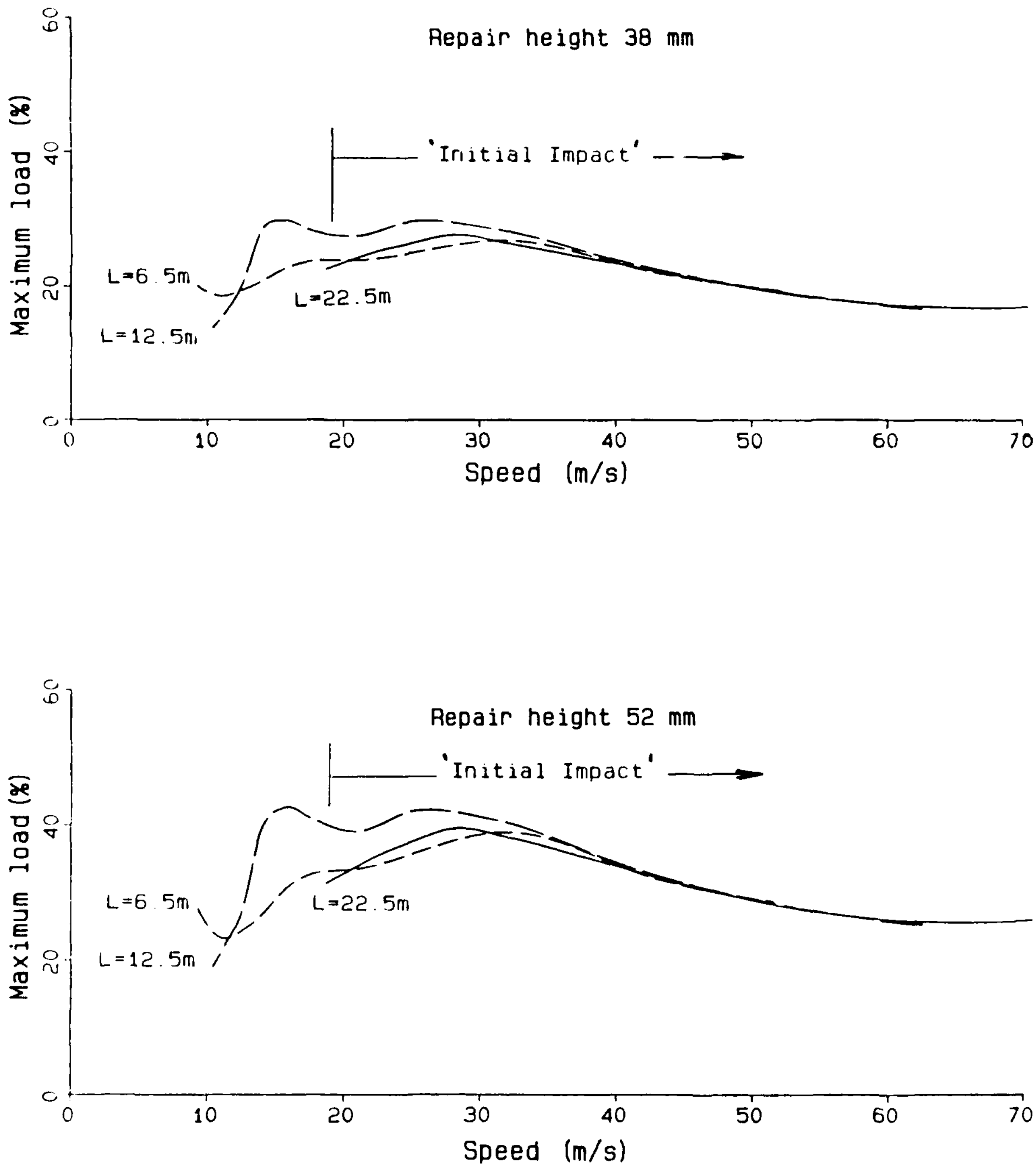
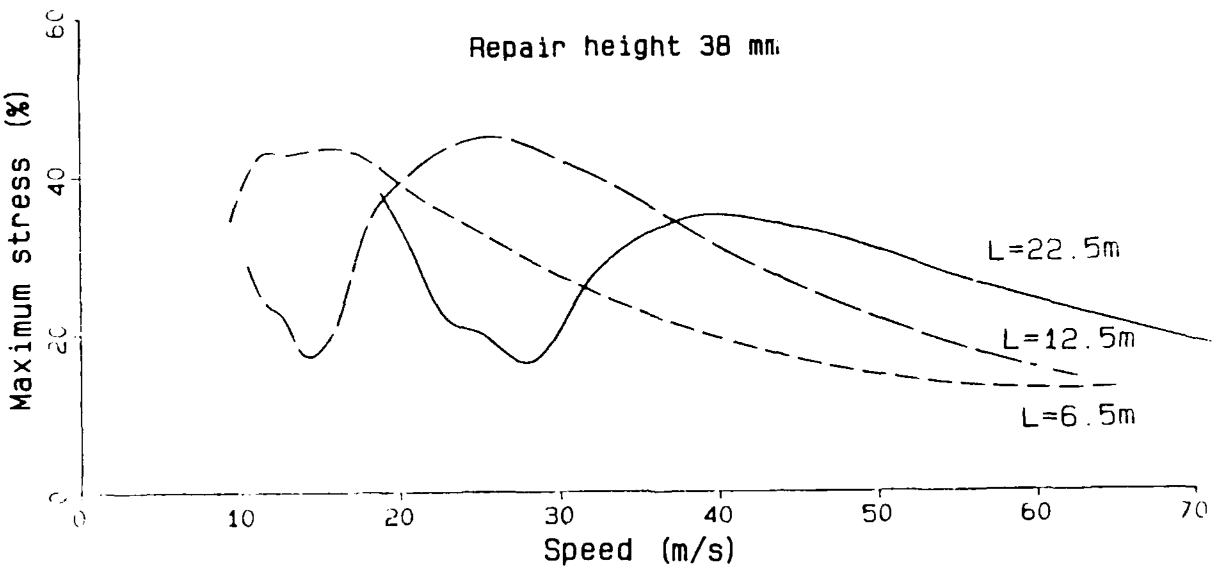


Fig.A718 Nimrod maximum main landing gear load (percentage of allowable increment): single repair



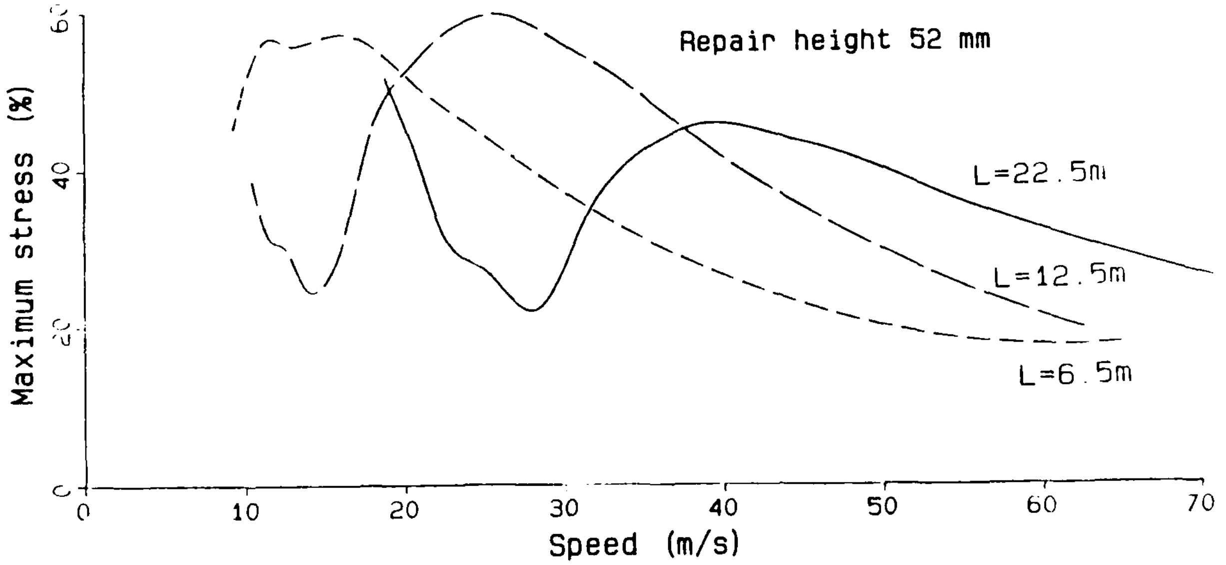


Fig.A7.19 Nimrod maximum wing stress (percentage of allowable increment): single repair

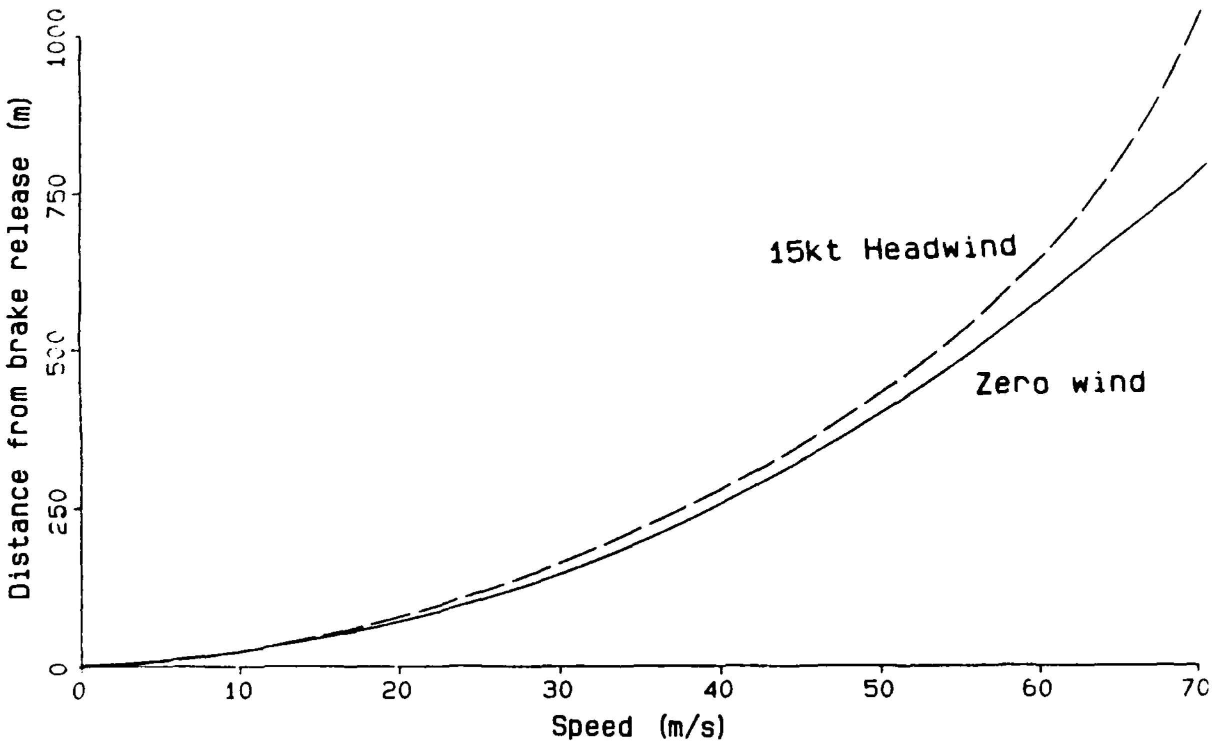


Fig.A7.20 Nimrod take-off performance

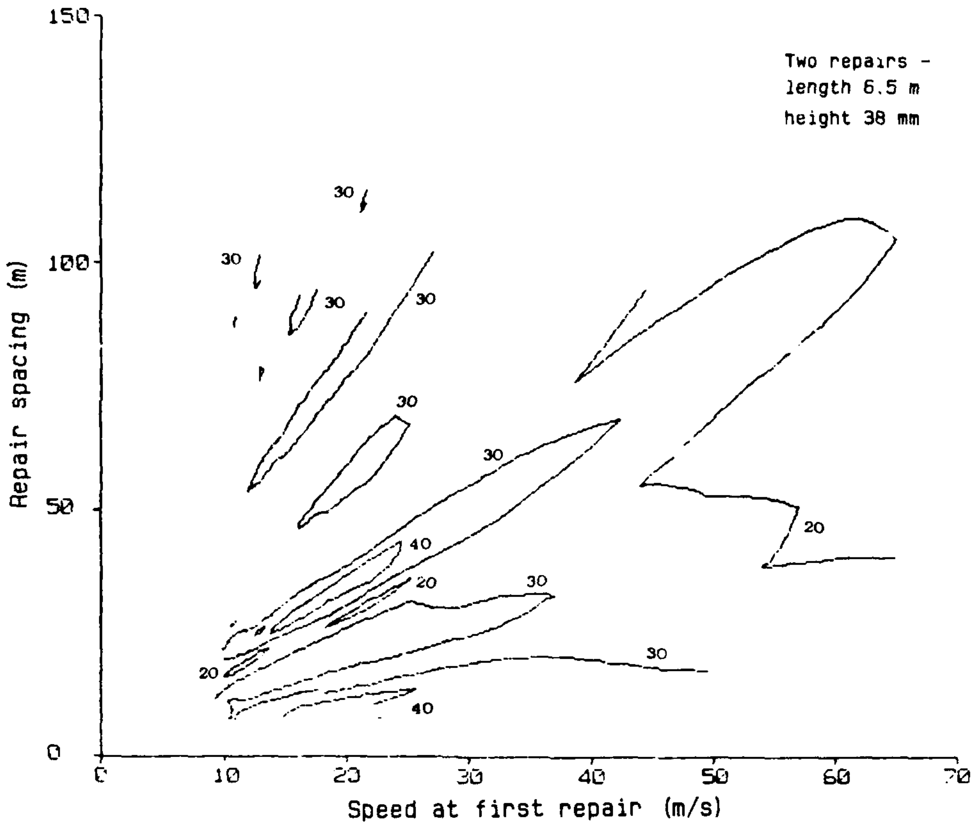


Fig.A7.21 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 6.5 m, height 38 mm

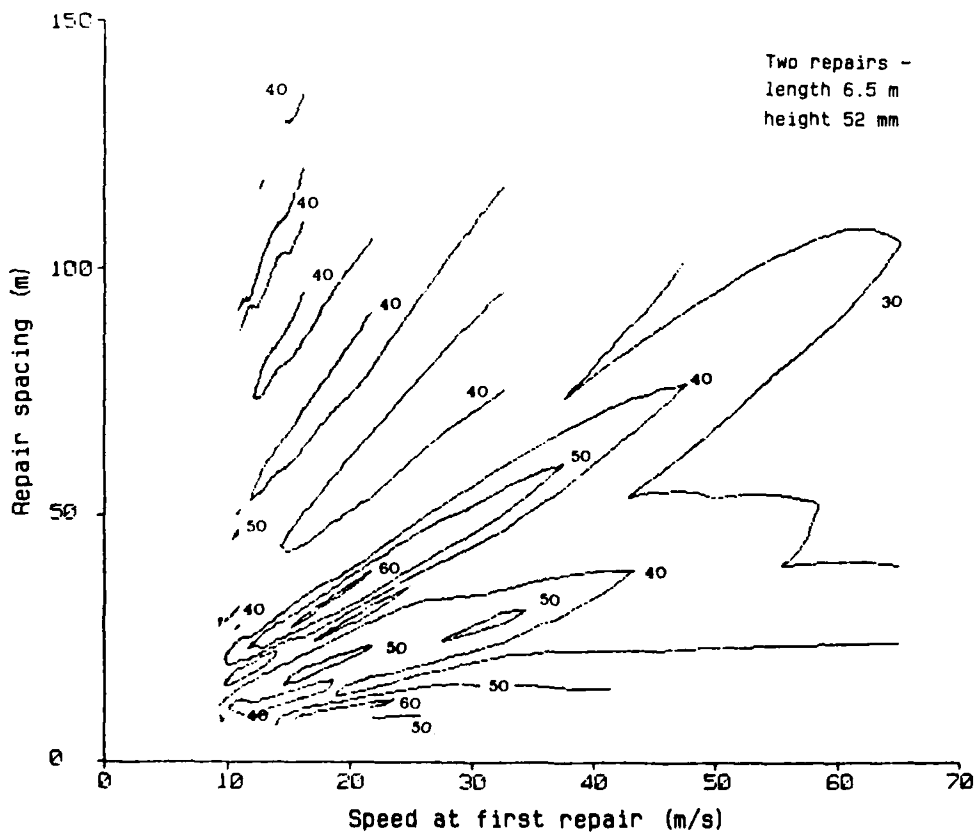


Fig.A7.22 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 6.5 m, height 52 mm

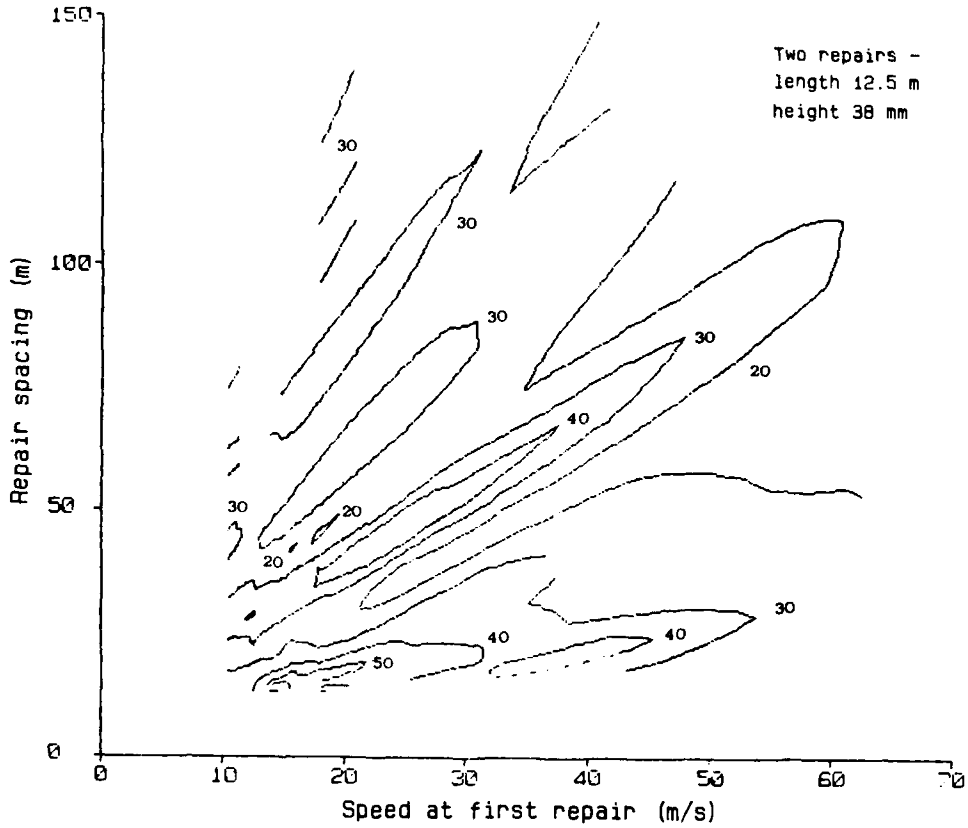


Fig.A7.23 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 12.5 m, height 38 mm

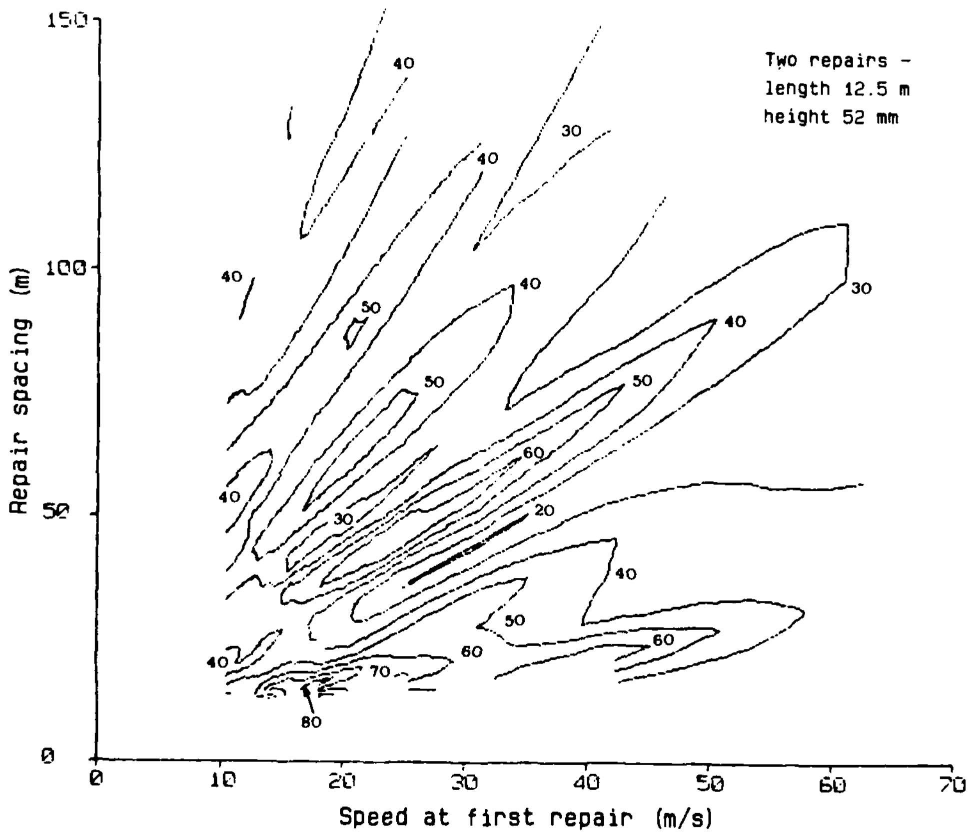


Fig.A7.24 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 12.5 m, height 52 mm

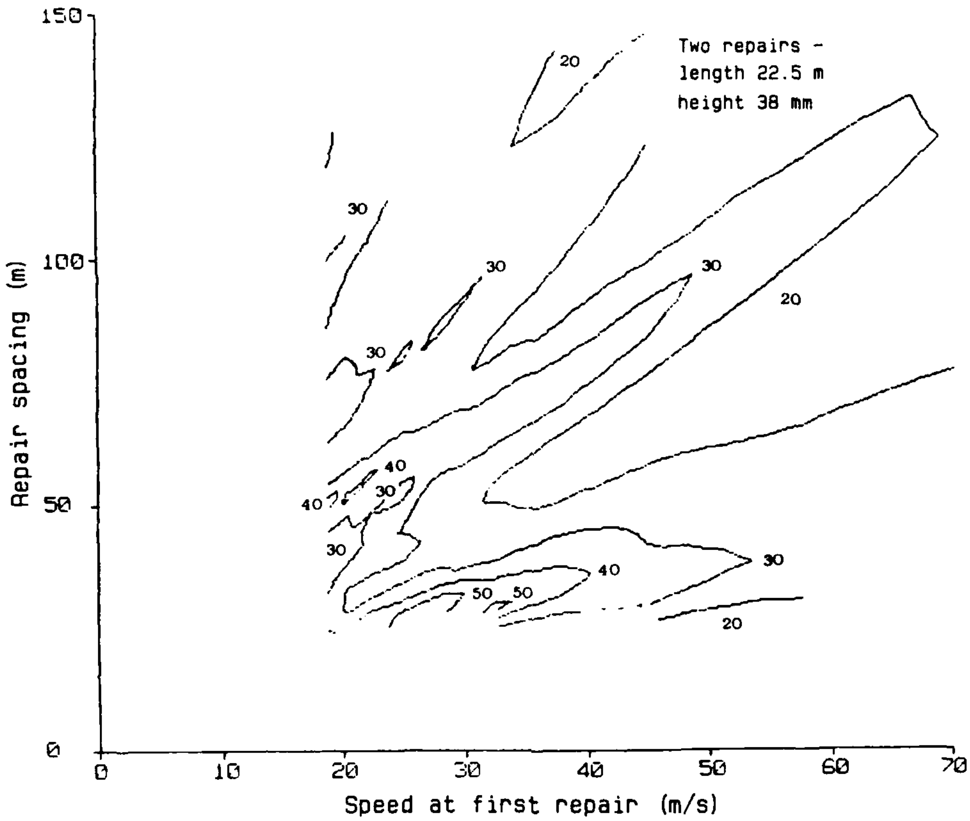


Fig.A7.25 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 22.5 m, height 38 mm

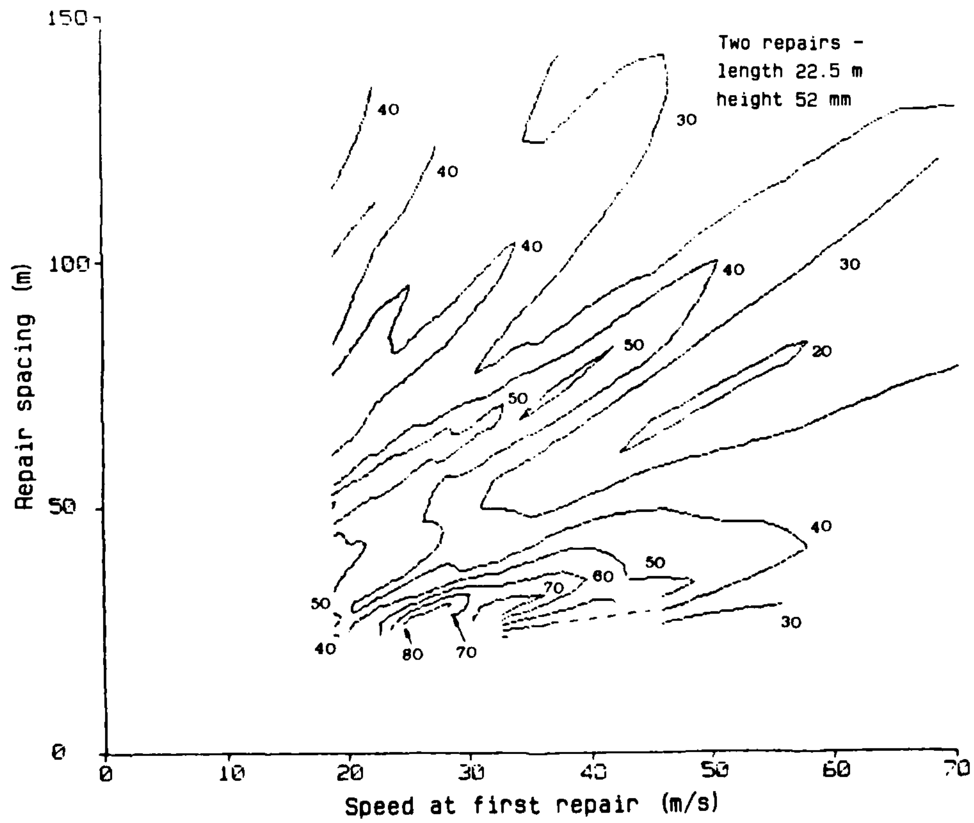


Fig.A7.26 Nimrod maximum landing gear load (percentage of allowable increment): two repairs, length 22.5 m, height 52 mm

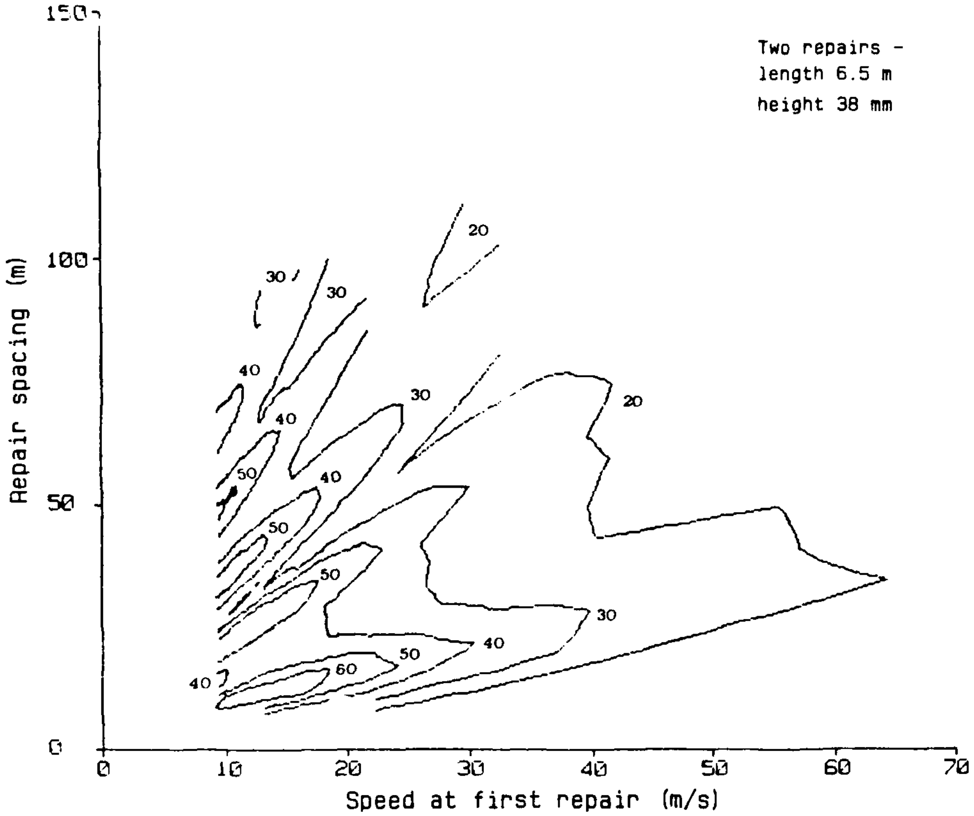


Fig.A7.27 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 6.5 m, height 38 mm

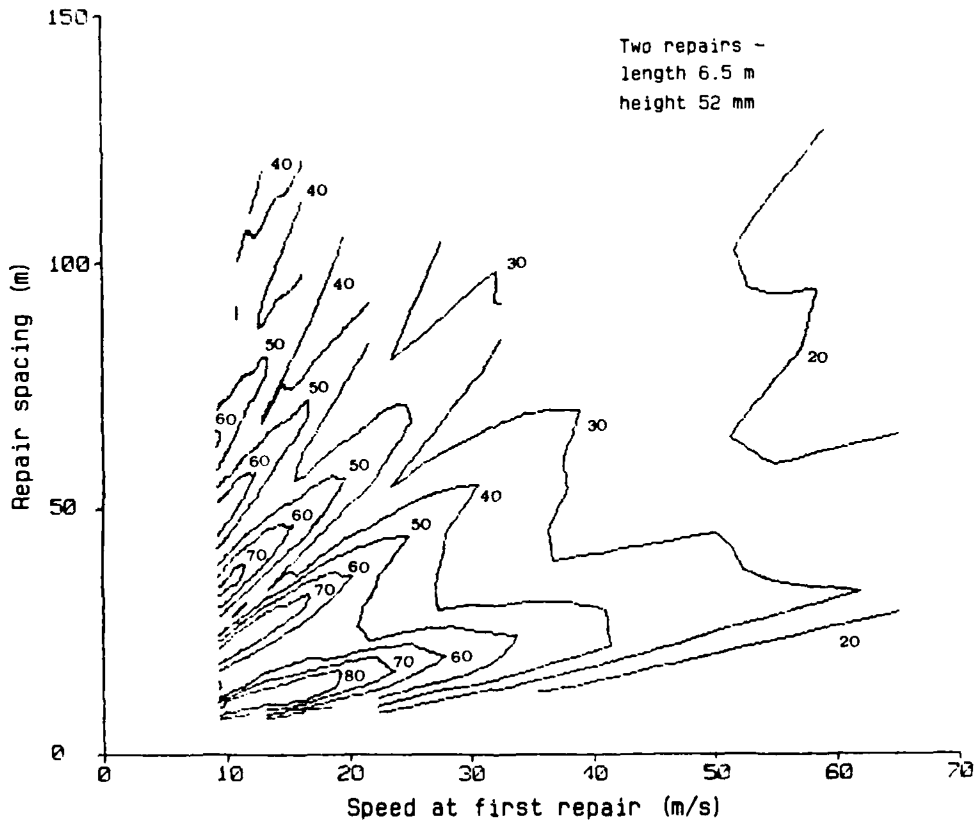


Fig.A7.28 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 6.5 m, height 52 mm

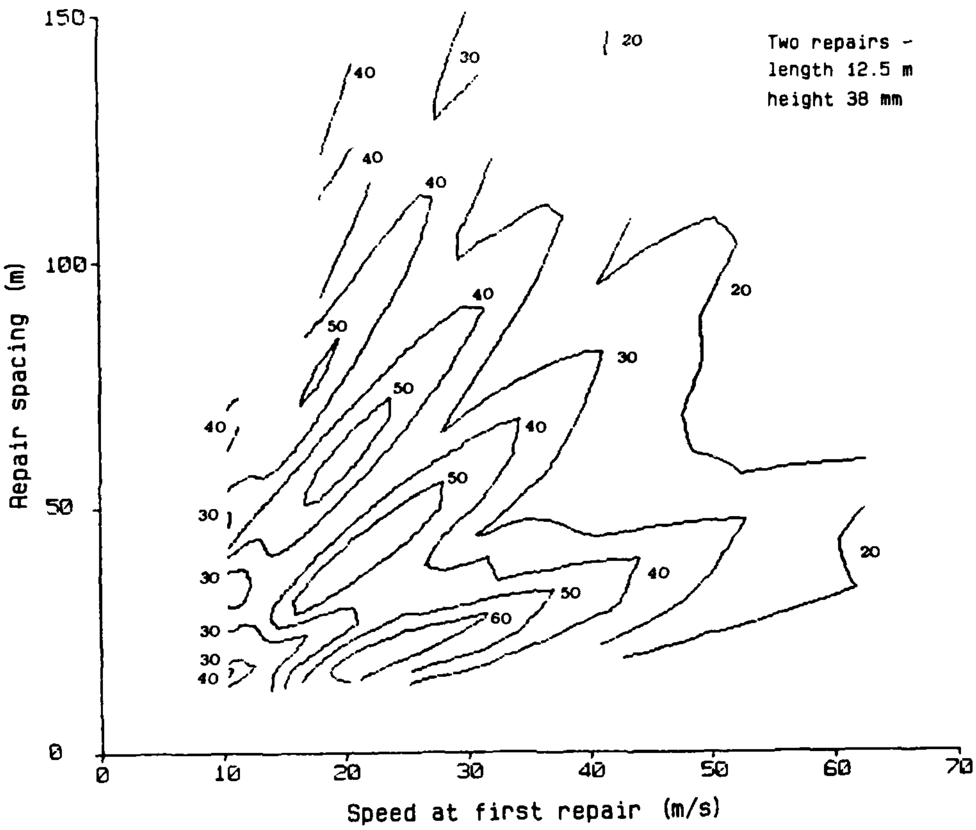


Fig.A7.29 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 12.5 m, height 38 mm

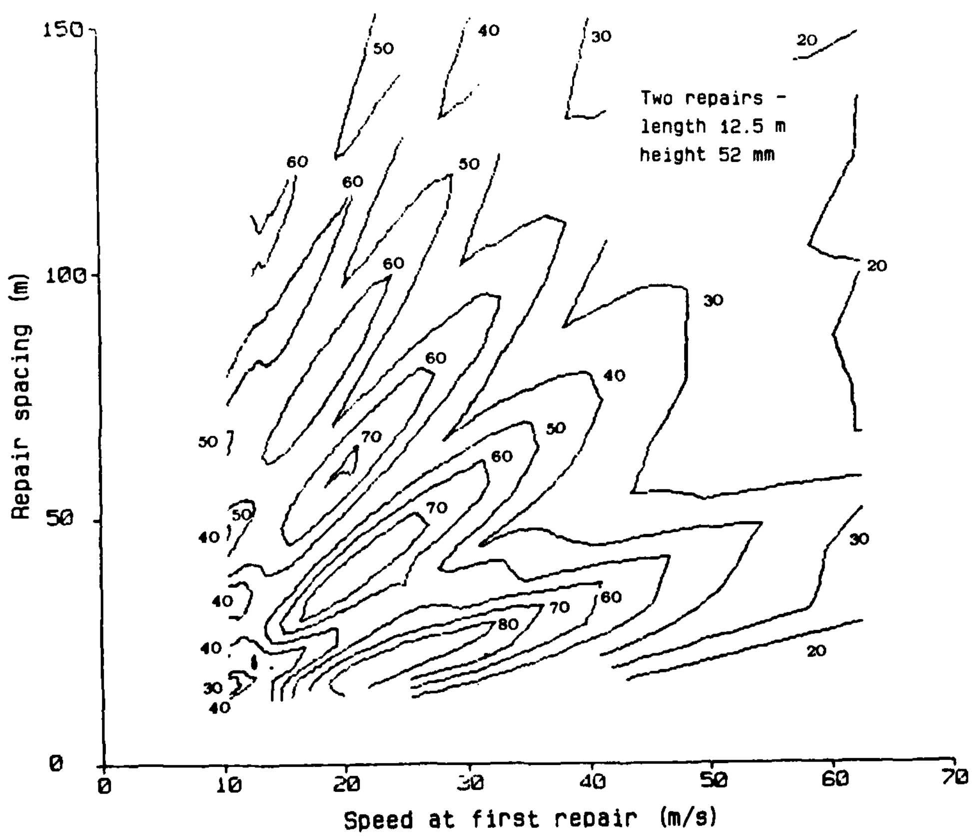


Fig.A7.30 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 12.5 m, height 52 mm

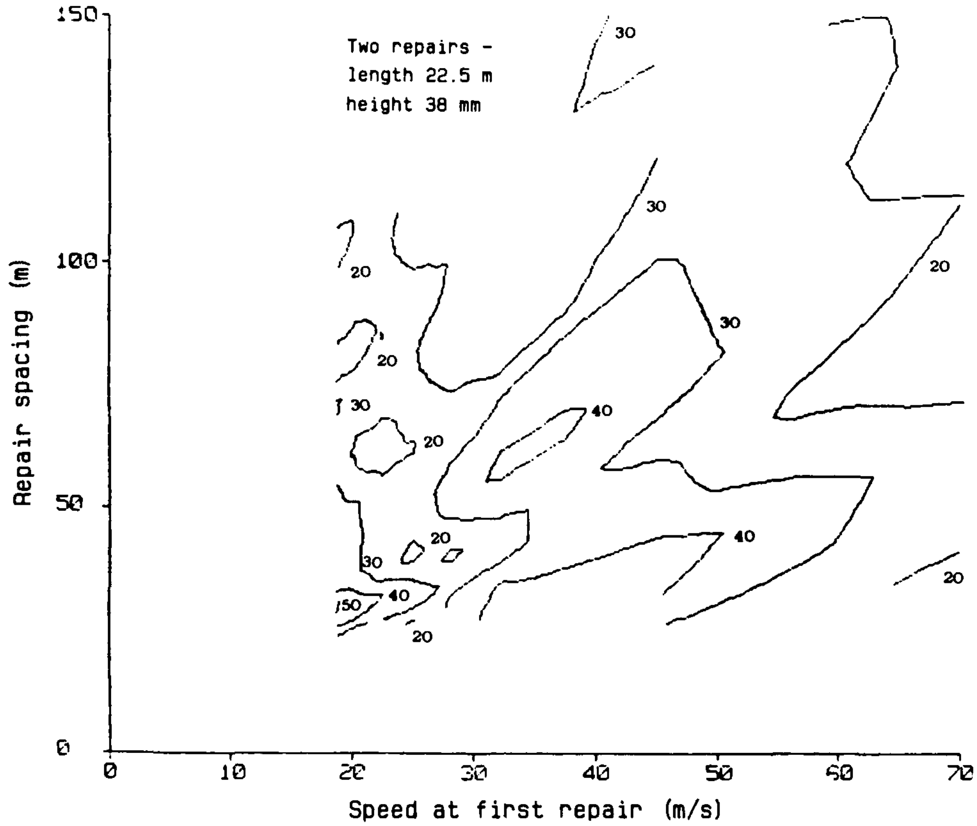


Fig.A7.31 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 22.5 m, height 38 mm

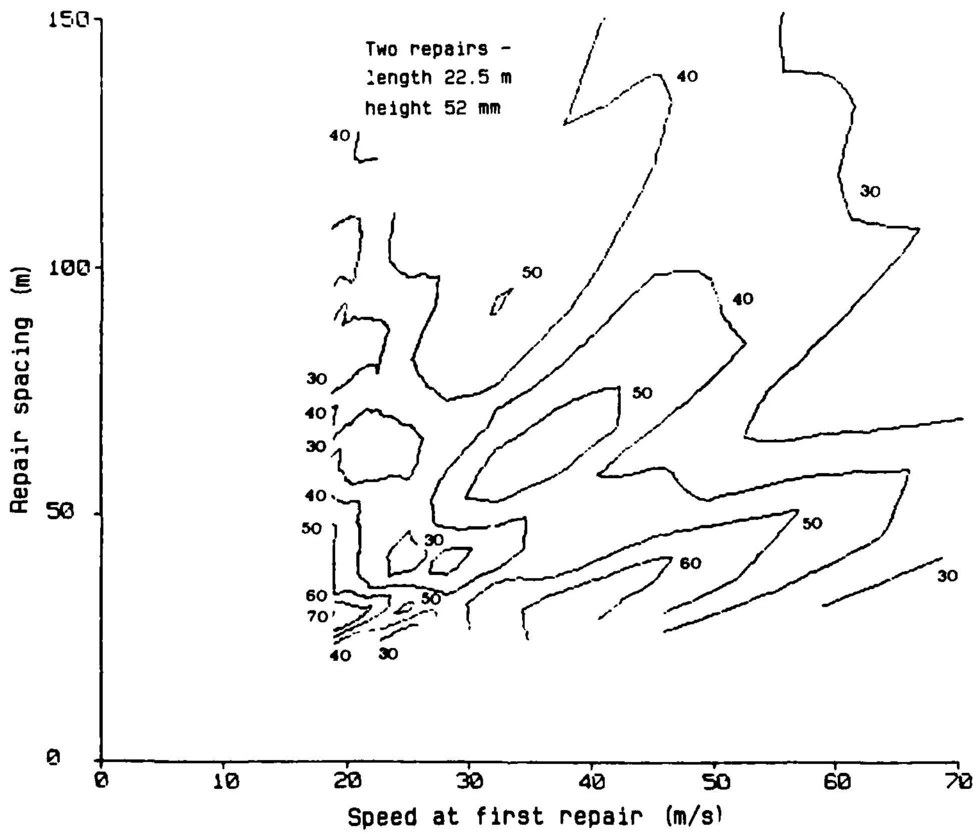


Fig.A7.32 Nimrod maximum wing stress (percentage of allowable increment): two repairs, length 22.5 m, height 52 mm

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14. Abstract

This report presents the results of an AGARD Working Group, (WG.22) directed by the Structures and Materials Panel. The Working Group was tasked to develop design requirements and qualification methods the application of which, across NATO, would improve aircraft utilization and interoperability.

This report, develops and illustrates the subject of repaired-runway operation; its sections reflect the various aims of the Working Group while the appendices amplify particular aspects. Throughout, topics are discussed from fundamentals so that it may provide an introduction to the structural and dynamical implications of repaired-runway operation as well as a statement of the current level of development of techniques in design, assessment and operational clearance.

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P.T.O.

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AGARD-R-731

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AGARD Report No.731
Advisory Group for Aerospace Research and Development, NATO
AIRCRAFT OPERATIONS ON REPAIRED RUNWAYS
Edited by Duncan J.Eckford
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