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The Dynamic Behaviour of Crash Helmets

by

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THE DYNAMIC BEHAVIOUR OF CRASH HELMETS

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SUMMARY

This paper summarises work carried out at R.A.E. on the protection of the head in crashes. In general, two problems are seen to exist; the prevention of skull fracture and the prevention of concussion.

The skull can be protected within quite wide limits by spreading the load, but little can be done directly by helmets of practicable size to prevent concussion. The likelihood of brain injury can be reduced slightly by designing helmets with low elasticity and a tendency to deflect blows.

Kinetic energy and the peak force transmitted to the head are often regarded as the sole criteria needed to define a blow, but it is shown that the coefficient of restitution and stopping distance are also important parameters. Account should be taken of the effect of the ratio of the colliding masses and the effect of varying momentum when comparing test results from various rigs. A simple calibration device using a shaped plasticine test-piece is put forward to compare the behaviour of different test machines under given conditions.

The effect of varying different parameters is illustrated by experiments on two test rigs and tests on existing Service helmets are reported.

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1 INTRODUCTION

In recent years, the weight and bulk of crash helmets have been much criticised and proposals have been made to develop new lightweight models. Because the lightening of the structure of existing types might lead to a lowering of the accepted standards, a new investigation of the dynamic mechanism of head protection was undertaken.

This paper presents recent work by the author on crash helmets. It reviews the basic factors of their design and underlines problems that arise because human tolerance to blows cannot be precisely defined. The difficulty of providing adequate protection against concussion with helmets of practicable size is discussed and the broad outline of requirements for a protective helmet is stated.

The paper next describes specifications for the design of crash helmets, methods of testing them, and the limitations of the test methods. Because of difficulty in correlating test results from various sources a special test-piece made from plasticine is put forward as a means of comparing the behaviour of different test machines under given conditions.

Finally, experiments made on the R.A.E. test rigs are reviewed and the paper concludes with a summary of tests made on existing Service helmets.

2 BASIC FACTORS IN THE DESIGN OF CRASH HELMETS

2.1 Tolerance of the head to impact

Precise definition of tolerable blows to the head or those which would cause only minor or reversible injury, is impossible owing to the natural variation between individuals and because different types of injury can be caused by similar blows. Further, if as many authorities suggest, the rotation of the brain within the skull is the major cause of damage, the likelihood of injury will depend on the exact direction of the blow.

Tolerance curves have, however, been constructed by several authors from data obtained from experiments made on animals and cadavers and also from accidents. The direct comparison of these two types of data presents some difficulty, since experimental results are generally obtained in the form of acceleration-time curves, while in accident cases the only parameters available are the impact velocity and the dimensions of the impression left in the impacted surface. Accident data are usually analysed rather roughly as follows:

If the impact velocity is v ft/s, the depth of the impression is d ft, zero rebound is assumed and a constant force F is supposed to resist motion during impact, then if the weight of the impacting body is W lb,

$$F d = \frac{Wv^2}{2g} \quad . \tag{1}$$

The constant deceleration throughout the impact

$$\frac{Fg}{W} = \frac{v^2}{2d} \quad ft/s^2 \tag{2}$$

and the duration is

$$\frac{2d}{v} \quad sec \quad . \tag{3}$$

This is obviously an over simplification, for the resisting force is unlikely to be constant and there will usually be some rebound. On the other hand, it can be shown that if the acceleration pulse is symmetrical with respect to time, equation (3) is exact and the average deceleration is therefore given by equation (2). In fact, most recorded impacts give approximately symmetrical pulses as shown for example, by many of the experimental records reproduced in this paper, and most observed rebounds are small. Considering the wide scatter of tolerance to impact between individuals and the kinds of blows that occur in accidents, it is not unreasonable to use these calculated durations and accelerations. Average deceleration/duration, average deceleration/velocity or velocity/duration plots can thus be used interchangeably, relating the parameters by the equation

duration × average deceleration = change of velocity.

2.1.1 Skull fracture

The force likely to fracture cadaver skulls has been found by Gurdjian et al.[1] and other workers in France and Germany from experiments in which the heads were dropped on to hard flat surfaces. The force on impact was very concentrated; being spread only by the scalp over an effective area of the order of 2 in^2 (12.9 cm^2). These data are summarised in curve 1 of Fig.1. It is believed however, that the skull is more resistant to fracture in life, than the cadaver skull. The addition of a helmet will spread the load more than the scalp, so that impacts indicated by this curve would be less likely to cause fracture in a living helmeted head. The curve may however, be taken as a limit for helmet performance; a safety factor being included.

2.1.2 Accident survival

Cases of survival after falls from heights up to 175 ft (53 m) have been analysed by de Haven[2] and Snyder[3] using formulae 2 and 3 to calculate the average deceleration of the body and the duration of the impulse. Impact was made on various parts of the body, but 21 out of Snyder's 137 subjects landed head first. From these and other data Thompson[4], and Kornhauser and Gold[5] have constructed survivable and fatal curves relating to whole body impact. Curves 2 and 3 of Fig.1 have been adapted from their results. The head shows significantly less tolerance to the effects of impact than other parts of the body, so it is to be expected that the fatality line for head impacts should be somewhat lower than curve 2.

2.1.3 Angular acceleration

The great majority of blows to the head must cause angular rather than translational movement, unless the neck muscles are deliberately used to hold it rigid, as footballers do when heading the ball. Holbourn[6] and others have suggested that the principal cause of concussion is, in fact, the angular displacement of the brain within the skull. However, the precise relationship between angular velocity change and linear velocity change will depend on the position and direction of the impact, the resilience and the friction between the impacting surfaces. Some idea of this relationship can be gained from simple considerations. Suppose a spherical body travelling at a velocity of v ft/s with no spin, strikes a fixed surface at an angle of incidence ϕ. Then, if friction prevents sliding at the point of impact, an angular velocity $v \sin \phi / r$ will be produced about that point, where r is the radius of the sphere. If any value of the angle ϕ is equally probable, the mean value of the expression is $2v/\pi r$. Yielding of the surfaces at the point of impact and sliding will modify the value of the resulting angular velocity, but its order will usually remain the same. The radius of the head lies between 3 and 4 in (7.5 and 10 cm), so that a linear impact at v ft/s would be likely to cause an angular change of velocity of the order of 2v rad/sec. This probable value is reduced to some extent by the addition of a helmet, which increases the effective radius of the head and presents a smoother surface so that slipping can take place at the point of contact.

There appears to be no published data on the level of angular acceleration likely to cause brain damage, but some data on tolerance to angular acceleration in normal activities have been determined by Parker[6] from news reel films of dancers, boxers and skaters, and his results are shown in Fig.2. High speed films (4000 frames/sec) of a dancer pirouetting and of a youth turning his head as sharply as possible, have also been taken at R.A.E. The films were taken directly above the subjects, who wore white skull caps marked with a black arrow to facilitate analysis. Plots derived from these films, of angular displacement, velocity, and acceleration with respect to time are shown in Figs.3, 4 and 5, and points taken from them are included in Fig.2. The acceleration data in Fig.2 can be transformed to angular velocity plots (angular acceleration × duration = angular velocity), from which it can be shown that a change of 15 rad sec^{-1} in about 5 msec is easily tolerated rising to 40 rad sec^{-1} for a duration of 200 msec. Thus from this point of view, the order of linear change of velocity that is easily tolerable is about 7.5 ft/s (2.3 $msec^{-1}$) in 5 msec rising to 20 ft/s^{-1} (6 $msec^{-1}$) in 200 msec.

2.2 Head protection - a problem in packaging

Like many problems in packaging, the protection of the head involves the prevention of shock damage to delicate apparatus when blows are stopped by the skull or outer packing case. Thus, the occurrence of most kinds of head damage depends on the displacement response of the skull and its contents to sudden changes of velocity. This response depends on the mechanical properties of the part struck, but the characteristics will differ for blows struck from different directions, and as between the skull itself (danger of fracture) and the brain (danger of concussion).

No single system can cover all the possibilities, but some idea of the response to be expected can be gained from consideration of the effect of various input pulses on a simple mass-spring system with viscous damping.

Consider such a system mounted on a platform which is subjected to a known acceleration pulse. If the displacement of the mass with reference to the platform is x, the circular natural frequency of the system is Ω, and the damping coefficient is H, the equation of motion is:

$$\frac{d^2x}{dt^2} + 2H\,\Omega\,\frac{dx}{dt} + \Omega^2\,x = F(t) \tag{4}$$

where $F(t)$ represents the acceleration of the platform. A precisely similar form would hold for a pivoted arm mounted in a case subjected to angular acceleration, with the substitution of the angle θ for the linear displacement x.

The solution of this equation for various input acceleration pulse shapes (half sine, rectangular, triangular) and for various values of H has been investigated by a number of authors[8,9], and gives results which are complicated in detail, but are all approximately of the form shown in Fig.6. The general conclusion can be stated as follows:-

For any system with known characteristics, given the pulse shape and the total velocity change,

(1) If the duration of the pulse is comparable with or longer than the cycle time $(2\pi/\Omega)$ of the system, then the displacement is proportional to the peak acceleration. This holds for durations greater than about half the cyclic time, $(\pi\Omega)$.

(2) If the duration is short compared with the cyclic time, the displacement is proportional to the total change of velocity. This holds within 10% for durations less than about one quarter the cyclic time $(\pi/2\Omega)$.

For intermediate durations, displacement adjusts between the two factors. There is considerable variation between pulse shapes and between values of H, but the general conclusion holds, that unless a helmet or other protective device can extend the duration of an impact beyond one quarter of the cyclic time of the impacted system, it can do little to reduce the danger of injury.

The most likely parameter to influence skull fracture is the flexing of the bone in the area of the impact. The platform in this case is taken to be the body that impinges on the head and the linear spring characteristics are those of the skull with its scalp covering in this location. On the other hand, relative displacement between the brain and the skull is the important factor in brain injury; the spring characteristics in this case, being those of its suspension in the plane of rotation within the skull.

We have no direct information about the value of Ω and of H for the skull and the brain, and it is clear that there can be no single answer in either case. However, it seems likely that the order of natural frequency is the same for all responses of the skull, and similarly for all angular responses of the brain. From curve 1 of Fig.1, the changeover for cadaver skulls from sensitivity to change of velocity to sensitivity to acceleration, seems to occur in the neighbourhood of 5 to 10 msec (giving a cyclic time between 10 and 20 msec). Since this time is well within the duration of many pulses through helmets, the maximum acceleration is the relevant figure when discussing damage to the skull, with the proviso that it has little meaning unless the load bearing area is also taken into account.

As regards the brain, an estimate of the period can be obtained from Holbourn's conclusion that force is the important factor for durations greater than 200 msec. This would make the period about 400 msec; a natural frequency of 2.5 c/s (2.5 Hz). Professor Floyd of Loughborough University has however, quoted a figure of 250 msec. Taking the mean of these two estimates (325 msec) it seems that the likelihood of concussion will depend on the total change of velocity for durations of less than 80 msec and on peak acceleration for durations greater than 160 msec. Several authors have suggested that a change of linear velocity of about 20 ft/s (6 $m sec^{-1}$) is likely to cause concussion, so that curve 4 of Fig.1 is given as a possible threshold line. This curve can only be regarded as a tentative approximation to the impact that might cause concussion, but its similarity to the other curves of Fig.1, especially to curve 3 does suggest that the argument is along the right lines. Comparison with the changes of angular velocity found tolerable in normal activities (section 2.1.3) gives a safety factor of about 2 between the tolerable and danger levels.

In considering head protection, the enforced limitation of the size of crash helmets by the conditions of use, means that it is impossible to extend the duration of an impulse beyond about 50 msec, as is shown by the straight lines in Fig.1 (the derivation of these will be discussed later). It is therefore, impossible for a helmet of practicable dimensions to guard against concussion, other than by ensuring that it has no projections likely to cause increased angular movement, and that there is as low a coefficient of restitution as possible between the headpiece and the impacting surface, to prevent increase in the total change of velocity. Even buffet blows can have impact velocities as high as 12 ft/s (3.65 $msec^{-1}$), which is getting close to the possible threshold of concussion. Protection of the brain therefore lies more in the field of vehicle than of helmet design, where likely impact areas can be made yielding so as to spread the impulses over much longer periods.

Let us consider how force is transmitted through a crash helmet to accelerate the head beneath it. A protective helmet usually consists of a hard outer shell with a webbing head cradle and/or padding material used as a shock absorber liner. The response of such materials to impact loads is usually non-linear, and in some cases their behaviour is probably influenced by sliding displacement resisted by friction forces. Some insight into the problem can be gained as before, by considering the behaviour of a simple mass-spring system with viscous damping. It can be shown that if a body impacts a second body through a spring, the worst case as far as spring compression is concerned, occurs when the second body is rigidly fixed. We shall therefore, take this case.

The equation of motion is

$$\frac{d^2x}{dt^2} + 2h\,\omega\,\frac{dx}{dt} + \omega^2\,x = 0 \qquad (5)$$

where x is the displacement, W is the weight of the impacting body, K is the spring stiffness, c is the damping force and $\omega = Kg/W$, $h = c^2g/4\,KW$. The initial conditions are, $x = 0$, $dx/dt = U$ where U is initial velocity.

From the solution of this equation (see Appendix B), the maximum spring compression x_{max}, the duration of the pulse time T, the maximum acceleration a_{max}, and the coefficient of restitution E, can be deduced. Fig.7 shows non-dimensional plots of these variables against E.

The requirements for a crash helmet can be stated as follows:-

(i) the deflection x_{max} should be as large as possible short of actual contact between the head and the inside of the shell,

(ii) the pulse duration T should be as long as possible to keep peak acceleration down and reduce the danger of skull fracture,

(iii) The total change of velocity should be as small as possible, that is, the coefficient of restitution E should be small to reduce the danger of concussion.

From Fig.7 it can be seen that these requirements are difficult to reconcile, but as a compromise it is suggested that the value of E should be about 0.3 and ω should be as small as is consistent with the maximum allowable deflection.

Blows of considerable kinetic energy can in some circumstances be inflicted at relatively low impact velocity. Such a case could occur in rough conditions in an aircraft or land vehicle if, for example, a crew member was thrown vertically against the roof with much of the body weight behind the blow, but it can be seen that all the parameters would be altered in these circumstances, since the value of W could be several times the weight of the head alone. Fig.8 shows how, for a given kinetic energy, the deflection of a mass-spring system on impact, tends to increase with increases in the weight of the colliding body, although in other respects the effect of the blow on the head tends to become less severe. It will be seen that the increase in deflection is most marked for low values of E, which lends support for the view that 0.3 is a reasonable compromise value.

The theoretical helmet displacement lines shown in Fig.1 were deduced from Fig.7, assuming that E = 0.3. They represent the relation between displacement, impact velocity, acceleration and time in spring systems with a damping coefficient of 0.5. The pulse duration for a given weight colliding with a linear spring system is constant so that any particular theoretical head and helmet assembly is represented by an ordinate in Fig.1. For example, if the velocity change during impact for a given system were 25 ft/s (7.62 $msec^{-1}$) and the duration of the impulse 10 msec, then the displacement of the helmet would be 0.5 in (1.25 cm). Actual helmets have non-linear characteristics however, and their liners tend to become stiffer with increasing deflection. Thus the duration of pulses for impacts at higher velocity tends to be reduced as is shown in the experimental results in Fig.9.

3 THE SPECIFICATION, AND DESIGN OF CRASH HELMETS

3.1 Specifications

The design of crash helmets is limited by the bulk a man can carry on his head and yet perform his special task. If the load is well distributed and he suffers no acute discomfort, he can accept a weight of 4 or 5 lb (1.82 or 2.27 kg) on his head for several hours, but each small addition to the weight increases the difficulty of tolerating the helmet for long periods.

The increased moment of inertia of the head when wearing a helmet may also cause difficulty, especially when the wearer is subjected to vibration. Since the weight of the helmet is distributed round the circumference of the head, the moment of inertia increases more than the corresponding weight.

Allowable size and weight are not always precisely defined in existing helmet specifications, but it is generally agreed that the height above the wearer's crown should not exceed 2 in (5 cm) and the width across the ears should not be more than about 11 in (27.5 cm).

Current performance specifications generally define the maximum allowable transmitted force or acceleration in certain standard helmet tests and the maximum permitted penetration of the shell and liner by a sharp object in given circumstances. In Europe, for various types of crash helmet, a maximum transmitted force of 2000 kg (4400 lb) must not be exceeded in a standard drop test, in which a 5 kg weight (11 lb) with kinetic energy from 102 to 204 J (75 to 150 ft lb) depending on the role of the helmet, collides with the test specimen on a rigidly mounted head form.

A corresponding American specification states that when the test helmet is subjected to blows by an 11 lb (5 kg) weight, the acceleration transmitted to the head form shall not exceed

150 g for more than 4 msec
200 g for more than 1 msec
400 g at all.

Assuming that a flat striker is used, in ASA Z90 the kinetic energy of the test blow is to be 66 ft lb (89.5 J) when the head form is mounted on a rigidly fixed anvil or 160 ft lb (217 J) when the head form is mounted on a freely pivoting arm. Other values for the kinetic energy for the test blow apply when the striker is radiused. These criteria are meant to apply to helmets designed to meet crash conditions, but no specification for helmets designed to give protection against head buffeting or repeated low energy blows has been found.

There is little to show how these specifications are related to conditions actually obtaining in crashes. Evidence is naturally scanty but according to Moseley and Zeller[10], aircraft speed at the time of impact in a large number of take-off and landing accidents investigated by them, varied from 40 kt (67 ft/s) or (20.4 $msec^{-1}$) to about 140 kt (236 ft/s) or (72 $msec^{-1}$) while the stopping distance of the aircraft varied from just under 100 ft (30.5 m) to over 7000 ft (2140 m). Within this range a great variety of conditions could occur as the aircraft collides with ditches, embankments and other typical obstacles causing very abrupt decelerations. Injuries to the crew and passengers are brought about by heads and other parts of the body striking fixed parts of the aircraft and to a lesser extent collisions with flying objects.

If it is assumed that the head moves 1 ft (0.305 m) before impact at a constant acceleration ng relative to the structure, the closing velocity v ft/s on impact is given by $v^2 = 2\ ng$. The impact energy, 75 to 150 ft lb (102 to 204 J) of European standard tests corresponds to values of n between 7 and 13.5. Fig.10 shows the relationship between aircraft stopping distance and average aircraft deceleration as calculated by the simple assumptions in 2.1 and it will be seen that average decelerations of approximately 10 g are obtained in reducing an aircraft speed from 140 kt (72 $msec^{-1}$) to zero in 100 ft (30.5 m). These average decelerations may contain some high peaks, which being sustained long enough, tend to initiate the break up of the aircraft structure and seat fixings. Thus the likelihood of fatalities from multiple injuries is increased, and it is reasonable to conclude that a crash helmet designed to protect the head against blows of greater kinetic energy than 150 ft lb (204 J) could do little to improve the chance of survival.

Crash helmets can be considered worthwhile so long as there are survivers from crashes that would otherwise have been fatal, but they may not attenuate the effects of moderate blows enough to give adequate protection against the repeated impacts that could occur in some conditions of routine use. These conditions come under the blanket term, buffeting, and cover a wide range of blows that might be experienced in tanks, or in aircraft in low-level high-speed flight. The specification of the performance of anti-buffet helmets in response to such conditions has not yet been attempted, but it is clear that such situations demand that the wearers shall not be deprived of consciousness or of mental efficiency, even for a few seconds.

Analysis of rather extreme cases of impact that could occur in flight, for example, to the pilot rising in his seat under negative g, or a standing crew member being taken off balance in similar circumstances, suggest that the head might strike fixed objects with closing velocities up to 12 ft/s (3.66 $msec^{-1}$). It is thought that the mass of the head alone is usually involved in such accidents, but occasionally some or all of the body mass could be behind the impact. The range of kinetic energy to be expected could therefore extend from about 30 ft lb (40.7 J) for the head alone, to over 150 ft lb (204 J) for the case where a large part of the body weight is involved.

3.2 Current helmet designs

Two types of helmet liner are in common use. These are:-

(i) webbing head suspension harness,

(ii) crushable lining material.

The webbing harness spreads impact loads in conjunction with the shell of the helmet by means of strong fabric tapes, which cradle the skull. The shape and duration of the transmitted impact pulses are determined by the stretch of the tapes, the deformation or breaking of their fixing points, and flexing of the shell. A layer of compressed cork or similar material is fixed to the inner surface of the shell where it acts as a buffer to keep the rate of change of velocity of the head low should the webbing harness break down. Very sudden arrest of the head, as when the skull makes contact with the helmet shell is termed 'bottoming'.

Crushable liners are made from relatively stiff materials such as expanded polystyrene, with very limited powers of recovery after compression. Aluminium and paper honeycombs have also been used to dissipate the energy of impact; a soft foam material being worn next to the scalp to reduce load concentrations and improve comfort.

The role of both types of liner is to reduce the effect of blows received in crash conditions, but as their deformation before collapse begins is very small, the forces transmitted to the skull due to impacts of less than critical magnitude are attenuated very little. After collapse begins these materials are deformed with a nearly flat characteristic until fully stretched or compressed, when the force/deflection curve becomes steep once more. Helmets employing such liners are therefore uncomfortable when subjected to repeated blows of less than critical magnitude. To allow for the dissipation of relatively large amounts of kinetic energy in a helmet designed for buffeting conditions, the stiffness of the deflecting material must be low enough to accommodate the greatest possible displacement within practicable dimensional limits.

With a liner of the right stiffness and hysteresis, it should be possible to design a helmet capable of giving both crash and buffet protection. Several plastic foams already exist which show some promise in this direction. Their restoration time is of the order of one or two seconds, so that relative even to the longest pulse their behaviour is non-elastic. These foams may be found unsuitable for use in very lightweight helmets however, as they tend to be rather dense.

Pneumatic helmet liners have been used in experiments concerning the stopping distance of the shell in relation to the skull. They show promise over a limited range of input energy, in that a long stroke is possible without compression stiffening of the material, but careful design and development of a discharge valve is required to control the air pressure rise in the liner during impact. In addition, a good buffer material is required as an extra precaution against bottoming in extreme conditions.

4 CRITERIA IN THE TESTING OF CRASH HELMETS

4.1 Range of test equipment

To examine and compare the dynamic performance of crash helmets, requires a means of subjecting test specimens to blows simulating impacts that could be expected in use. Three main types of test machine and some variants are being used by different establishments.

These are:-

(a) vertical drop rig,
(b) pendulum rig,
(c) Snively swinging arm rig.

All three machines use gravity as a means of accelerating the striker up to a suitable impact velocity, but in a few special rigs a means has been provided for accelerating the striker beyond 1 g in order to achieve higher closing velocities without increasing the dropping height.

The parameters measured on impact are either the force or acceleration transmitted through the test helmet to the dummy head with respect to time. A summary of the possible variants is given in Table 1.

4.1.1 Vertical drop rig

The vertical drop rig, as originally developed by the Road Research Laboratory, consists of a monolithic block of concrete resting in a sand tray on a strong concrete floor. The block weighs at least a ton (1.016 tonne) and a quartz crystal load cell bearing a wooden dummy head form is rigidly mounted on its surface. A flat ended striker of 10 lb weight (4.54 kg) drops on to the mounted test helmet from a height chosen to give the desired kinetic energy at impact. During its descent, the striker is guided by two tightly strung piano wires.

The rig built at R.A.E. is essentially similar to the R.R.L. design, but the crystal load cell has been replaced by one based on semi-conductor strain gauges. Fig.11 is a photograph of the rig. An advantage gained by the use of these strain gauges is that the load cell can be calibrated statically whereas quartz crystal cells should be calibrated at least quasi-dynamically.

4.1.2 Pendulum rig

The R.A.E. pendulum rig shown in Fig.12 consists of a large mass of approximately 320 lb (145 kg) suspended by fine steel cables. A flat load cell is mounted at one end of the mass to form an anvil and accelerometers may be fitted in either the head-form or the mass. The head-form is mounted on a very light suspended carriage and together these weigh approximately 10 lb (4.54 kg). The design of the carriage is such that almost any point on the test helmet shell can be presented for collision with the anvil. In this case the test helmet is the moving member of the rig and it is made to strike the stationary load cell.

An alternative arrangement of the rig can be set up, in which a striker is made to collide with a stationary test helmet assembly of approximately equal weight. The performance of the helmet is measured in terms of time and either deceleration of the striker or acceleration of the head form.

4.1.3 The Snively rig

A particular form of test rig has been developed by Snively[11] at the Snell Memorial Foundation in the United States and a diagrammatic representation is shown in Fig.13. In this arrangement, a hollow magnesium alloy head form is mounted at the end of a relatively short arm which is pivoted at a given distance from the crown and an accelerometer is fixed to the inner surface of the head form directly below the point of impact of the striker. A delicate shear-pin (see Fig.13) which requires the dissipation of only two or three foot pounds of kinetic energy to break it, holds the assembly in the ready position. The striker - 16 lb weight (7.26 kg) falls vertically on to the helmet and head form, which together have approximately the same mass. The shear-pin breaks immediately on impact, allowing the assembly to fall freely at 1 g acceleration.

4.2 Impact parameters

4.2.1 Kinetic energy as a criterion

The requirements for a crash helmet stated in section 2.2, were deduced by considering the equation of motion for a simple mass-spring system. This shows the need to examine the effects of different parameters when making experiments on the dynamic behaviour of crash helmets. In particular, blows at various kinetic energy levels are required; but the mass of the striker is usually fixed, so that the only way to increase the magnitude of a blow is to raise its impact velocity, e.g. by increasing its dropping height.

The kinetic energy of a blow is given by:-

$$Ke = \frac{m\,v^2}{2} = W\,h \qquad (6)$$

where m is the mass of the colliding body, v is its impact velocity, W its weight and h the height of drop. An alternative which has been provided for in the two R.A.E. rigs, is the ability to vary the weight of the striker. Thus the impact velocity of a range of blows can be held constant while varying the collision energy by adjusting the mass of the colliding body.

4.2.2 Momentum and the coefficient of restitution

Fig.14 shows three force-time traces obtained when a helmet shell fitted with a recoverable foam liner was subjected to blows of 40 ft lb (54.2 J) kinetic energy. The closing velocity of the striker on impact was varied from 15 ft/s to 20 ft/s (4.6 to 6.1 $msec^{-1}$), while its weight was decreased from 11.75 to 6.25 lb (5.33 to 2.84 kg). The total change of momentum is equal to the area under the force-time traces and it can be seen that the greatest change is associated with the greatest mass (curve 1) and the lowest impact velocity.

To convert the traces shown in Fig.14 to acceleration-time curves, only a change of scale is required and the area under the replotted curves is then equal to the total change of velocity. By double integration, the maximum displacement of the helmet used in this experiment was found in each case and is shown in the following table:-

Striker weight lb	Impact velocity ft/s	Deflection inches
11.75 (5.35 kg)	14.7 (4.5 $msec^{-1}$)	1.1 (2.75 cm)
8.25 (3.75 kg)	17.6 (5.36 $msec^{-1}$)	0.85 (2.12 cm)
6.25 (2.83 kg)	20.4 (6.2 $msec^{-1}$)	0.83 (2.08 cm)

It can be seen that the greatest change of momentum was associated with the largest deflection, but Fig.8 shows that this effect is influenced by the coefficient of restitution E of the system. For instance, where $E = 1$, varying weight of the striker at constant kinetic energy has no effect on the maximum deflection, but when $E = 0$ variation in the value W should have a large effect.

The force-time traces obtained when a striker was made to collide with a helmet on a rigidly mounted head form and when a helmet on a free head form was dropped on to a rigidly mounted anvil are shown in Figs.15 and 17 respectively. The areas under the curves are proportional to the total change of momentum, which includes the negative velocity at rebound; the coefficient of restitution E between the colliding masses being equal to the ratio of the momentum at impact and rebound. That is:-

$$\frac{m\,v_r}{m\,v} = \frac{v_r}{v} = -E \tag{7}$$

where v and v_r are the impact and rebound velocities respectively and m is the mass of the moving body. In the example shown in Fig.15 the momentum of the striker before impact is

$$m\,v = \frac{W\,v}{g} = 11.25 \times \frac{14.7}{32.2} = 5.14 \text{ lb sec } (2.33 \text{ kg sec}) \quad .$$

From Fig.15b, the total change of momentum is about 7.9 lb sec (3.6 kg sec) and the momentum of the rebound is therefore approximately 2.8 lb sec (1.27 kg sec) whence

$$E = \frac{2.8}{5.1} = 0.55 \quad .$$

From Fig.17a, the momentum of the falling mass is:-

$$10 \times \frac{16}{32.2} = 4.97 \text{ lb sec } (2.25 \text{ kg sec}) \quad .$$

From Fig.17b, the total change of momentum is about 6.9 lb sec (3.13 kg sec) and the momentum of the rebound is therefore approximately 1.9 lb sec (0.86 kg sec) whence

$$E = 0.38 .$$

Fairly consistent values of E are obtained when hard bodies collide at low velocities, but some variation does occur with changes in the velocity of of the impact. In helmet testing, the indicated value of E is influenced by the design of the test assembly and by the way the test helmet is mounted. For conditions of impact imposed on different helmets tested at R.A.E., the value of E lies between 0.3 and 0.6, but when bottoming occurs the value of E becomes larger.

4.2.3 The effect of mass ratio

In contrast with the vertical drop test rig, the head masses in both the R.A.E. pendulum and the Snively swinging arm rigs are free to some extent following impact. In a variation of the pendulum rig, the colliding masses are made equal[12] with consequences that are discussed in more detail in Appendix A.

Briefly, if E is the coefficient of restitution of the system, U the initial velocity of the striker and m_1 and m_2 the masses of the striker and the complete test-piece respectively, then the kinetic energy lost by the striker when the colliding masses m_1 and m_2 are equal and $E = 0$ is given by:-

$$Ke = \frac{m U^2}{4} . \tag{8}$$

On the other hand when the ratio of the masses approaches infinity, the energy lost is given by:-

$$Ke = \frac{m U^2}{2} . \tag{9}$$

That is to say, a blow between masses of equal weight needs approximately twice the energy of a blow against an infinite mass to produce a comparable effect, when the value of E is close to zero.

4.3 Correlation between impact test methods

Many different methods of testing crash helmets are possible, but all of them come under one of the three following headings:-

(i) Rigidly mounted stationary head form and colliding mass.

(ii) Moving head form colliding with a fixed rigid mass.

(iii) Moving head form colliding with movable mass, or vice versa.

Based on the above categories, Table 1 summarises various kinds of tests that have been used by different workers and the measuring instruments employed. Any of these tests could be, and sometimes are, regarded as equivalent so long as the kinetic energies of the moving body on impact are equivalent. This is not necessarily true as has been shown in 4.1, so that care must be taken in comparing the results of tests made on different kinds of rig. It is also usually assumed, incorrectly, that the peak measured acceleration of the striker multiplied by its weight is equivalent to the peak force transmitted through the load cell.

In this section the relationship between various types of test is discussed and illustrated by experimental data, and a device for correlating the outputs of impact rigs is described.

4.3.1 The force transmitted to the skull in arresting the striker

Fig.15 shows the result of an experiment, in which a striker carrying an accelerometer was dropped on to a test helmet on a rigidly mounted head form. The effective mass ratio was infinite and the transmitted force was measured by means of a load cell beneath the neck of the dummy head. The two traces shown in Fig.15a were recorded simultaneously; curve 1 representing the input pulse and curve 2 the transmitted pulse in terms of force and time. As would be expected, the areas under the two curves representing the total change of momentum are approximately equal, but the helmet has a damping effect, as shown by the smoother shape of the transmitted pulse. This means in effect, that if the significant parameter is the peak, then the input pulse will show a higher value. Integration of the force-time curves gives the momentum change of the two bodies as shown in Fig.15b. The total changes of momentum must be equal and it will be seen that the results obtained by the two methods correlate very well. The peaky form of the input acceleration pulse must be due to the initial distortion of the shell of the helmet in response to the blow.

Fig.16 shows an attempt to illustrate such distortion photographically in two sequences of pictures when Mks.1 and 2 R.A.F. crash helmets were subjected to blows at 97 ft lb (132 J) kinetic energy at about 25 ft/s (7.62 $msec^{-1}$) impact velocity. It will be seen that the position of the edge of the helmets relative to the brow of the dummy head moved very little although a considerable deflection of the crowns occurred.

4.3.2 The effect of a collision between a moving helmeted head and a large fixed mass

The effect of dropping a test helmet on to a load cell anvil, was compared with the effect of dropping a striker on to the same specimen rigidly mounted on a load cell. The results are shown in Fig.17. Care was taken to make the combined weight of the dropped helmet and head form equal to the weight of the striker (10 lb (4.54 kg)); the kinetic energy input being 40 ft lb (54.2 J) at 16 ft/s (4.9 $msec^{-1}$) impact velocity. The result of dropping the test helmet was measured as an input pulse and is shown in Fig.17a trace 1. Trace 2 is the transmitted pulse due to the striker dropping on to the mounted helmet and this curve shows the damping effect of the helmet. That the total change of momentum was the same for both blows is shown approximately by the integration of the two traces in Fig.17b.

Comparing this result with that described in the previous section, it can be seen that the effect of dropping a helmet is not significantly different from subjecting it to a blow from a falling mass, provided that the input conditions are the same. However, if the parameter measured is peak force or acceleration, allowance should be made for some damping during transmission through the helmet.

4.3.3 Standard test-piece

It is difficult to correlate experimental results obtained from different sources. The main reason for this is probably the variability of the value of E. When equal masses are subjected to blows with the same kinetic energy, the same velocity at impact and the same striker, the areas under the force or acceleration-time curves will only be equal when the value of E is constant. The use of a standard test-piece makes it possible to compare the behaviour of different test machines under given conditions. This is of value in correlating the results of comparable tests from different sources. The requirements for the characteristics of such a test-piece are as follows:-

(i) the coefficient of restitution should be as close to zero as possible,

(ii) the performance of the test-piece should be repeatable for any given condition within specified limits,

(iii) if the test-piece is recoverable, it should return to its original dimensions and rate within a few minutes of impact,

(iv) the test-piece must not be unduly sensitive to temperature changes.

The possibilities for such a device are quite wide, ranging from damped springs and fluid metering orifices to special plastic materials.

Only two possibilities have been examined so far. In the first of these a stiff helmet shell combined with a one inch (2.5 cm) thick liner made from a slowly recoverable, but rather dense plastic foam was employed. When this assembly was submitted to blows of 97 ft lb (132 J) kinetic energy with an impact velocity of 25 ft/s (7.62 $msec^{-1}$), the force-time pulses transmitted to the dummy head were reproducable and the following results were obtained by Ellis Research Laboratories on their vertical drop rig:-

Test No.	Transmitted peak force lb	Time interval between blows sec
1	2780 (12.36 kN)	-
2	3260 (14.5 kN)	30 sec
3	3800 (16.9 kN)	30
4	2841 (12.64 kN)	3 hr
5	3310 (14.72 kN)	30 sec
6	3680 (16.38 kN)	30

It will be seen that the efficiency of the foam is steadily reduced in a rapid series of impacts, but 3 hours rest between blows gives almost complete recovery.

The results of impact tests made on this shell at R.A.E. and at Ellis Research Laboratories are shown in Fig.18. The input kinetic energy in each case was approximately 100 ft lb (135.5 J) and the closing velocity of the striker was about 25 ft/s (7.62 $msec^{-1}$). They are not satisfactory however, since the value of E in the two cases lies between 0.6 and 0.8, which is too high for a practical test-piece. Also, comparison of the trace shapes suggests that the test assemblies were not truly identical.

Classic examples of materials that are almost non-elastic are, putty, wet modelling clay and plasticine. Plasticine was chosen as a very suitable material for experiment, since it does not require the addition of oil or water it is moderately stiff at room temperature, its response to temperature changes is reasonably slow and its consistency does not vary much.

The first experimental test-pieces were made in the form of cylinders 2 in (5 cm) in diameter and 1 in (2.5 cm) deep. Fig.19a shows two acceleration-time traces recorded when a pair of such cylinders were subjected to blows of 100 ft lb (135.5 J) kinetic energy at 25.4 ft/s (7.75 $msec^{-1}$) impact velocity. In case 1 the plasticine was taken from a freshly opened packet, but in case 2 the specimen was very old and had been open and exposed to the air for many months. The difference between the traces is insignificant and the velocity change indicated in Fig.19b is only 28 to 29 ft/s (8.5 to 8.8 $msec^{-1}$), giving a value of about 0.1 for E. The average thickness of the plasticine after the impact was 0.25 in (0.625 cm); a displacement of 0.75 in (1.88 cm). Integration of the velocity change curves gives a displacement of 0.7 in (1.75 cm) approximately.

Fig.20a shows the effect of using a plasticine cone frustum 1 in high, with a base diameter of 2 in (5 cm) and a $\frac{3}{4}$ in (1.88 cm) diameter apex. The striker in this experiment lost relatively little velocity during the first millisecond of the impulse, although the cone was displaced by 0.3 in (0.75 cm). Afterwards it slowed down more rapidly and a high peak of deceleration resulted. Integration of the acceleration-time curve, Fig.20b shows that the total change of velocity was only just over 25 ft/s (7.6 $msec^{-1}$), so that the value of E was almost zero.

To allow for blows of greater kinetic energy than 100 ft lb (135.5 J) using the standard 10 lb (4.5 kg) striker, the height of the truncated cone was increased to $1\frac{1}{2}$ in (3.75 cm), while the diameters of the base and apex remained the same. Fig.21 shows the results of an experiment in which two of these test-pieces were subjected to blows of 100 ft lb (135.5 J) kinetic energy in the pendulum test rig; the weight of the striker being 10 lb (4.5 kg). The difference between the two force-time traces is insignificant. The experiment was then repeated using the vertical drop rig and the results of the two blows are shown in Fig.22, from which it can be seen that the traces are similar to those obtained in the former test. The ringing that appeared in this case is due to the relatively long load cell shaft, and it occurs mainly when the energy absorbent material has reached its compressive limit, that is, when there is a tendency to bottom.

5 RESULTS OF EXPERIMENTAL TEST PROGRAMME

5.1 Stopping distance

When a helmeted head collides with a fixed mass the shell is stopped almost instantaneously at the point of impact, but the head inside continues to move until it is brought to rest by the liner, or in extreme cases by collision with the inner surface of the shell[13,14]. For constant deceleration of the head the stopping distance s is given by:-

$$s = v\,t - \tfrac{1}{2} f t^2 \tag{10}$$

where v is the initial velocity and t is the time from the start of the impulse.

An experiment using the vertical drop rig was made to illustrate the effect of stopping distance on the forces acting on the skull during an impact pulse. A stiff polycarbonate industrial helmet shell was used as a test-piece in conjunction with three different liner[15] arrangements. These were:-

(i) a slowly recoverable plastic foam liner, 1 in (2.5 cm) thick,

(ii) a pneumatic liner, 1 in (2.5 cm) thick with a restricted outlet orifice,

(iii) a pneumatic liner as in (ii), but backed up with a soft plastic foam of very low density. The total thickness of the liner and its backing was 2 in (5 cm).

The liner material used in case (i) was rather dense, but it possessed some hysteresis; returning to its original thickness in one or two seconds following compression. In case (ii), an air impervious bag shaped to form a skull cap was filled with very low density polyether foam to give it form. During impact, the stiffness of this liner was controlled by an orifice which resisted the flow of displaced air to atmosphere. In case (iii), the pneumatic liner was backed up with another layer of low density foam 1 in (2.5 cm) thick, and the displacement of air from the cellular structure of this layer was restricted by its sandwich position between the top impervious skin of the skull cap and the inner surface of the helmet shell.

Industrial helmets are not usually fitted with chin straps and so they cannot be pulled hard down on the head. In this experiment, the fit of the helmet on the dummy head was such that the distance between the crown of the head and the shell was greater than the thickness of the liners. Fig.23 shows the results of blows at 40 ft lb (54.2 J) kinetic energy and 16 ft/s (4.9 $msec^{-1}$) impact velocity on the three assemblies. It will be seen that the peak forces decreased as the duration of the pulse increased with increasing shell displacement. The displacement of the shell, obtained by double integration of the acceleration-time curve, indicates that it was held away from the skull by a distance of about 1 in (2.5 cm) in excess of the actual thickness of the liner.

5.2 Contact pressure on the skull

The experiments so far described illustrate the relationship between change of velocity, stopping distance and force as a helmeted head collides with a second body, but they have nothing to say about the pressure of the impact load on the head and no means of measuring such pressure has yet been devised. However, the impact load must be spread over as large an area as possible and this will be helped by the use of a very stiff shell and a suitable liner. It has been shown that the shells of current head-pieces are much less stiff during impulsive loading than might be supposed and that they are probably quite vulnerable to blows from objects with sharp corners or small radii. When crushable or recoverable foam liners are employed, local bending of the helmet shell tends to produce differential compression of the energy absorbent material and a high contact pressure beneath the point of impact results. In helmets fitted with cradle suspension systems for the head, this difficulty is avoided unless the skull actually bottoms on the buffer material covering the inner surface of the shell. In the back and sides of such helmets however, these suspension systems are less effective.

Experiments with pneumatic[16] liners suggest that impact loads can be well spread by them and since the foam used to shape the skull cap is very tenuous, there is no danger from differential compression, but failure of the air discharge valve or actual penetration of the liner might have serious consequences. Fig.24 shows the results of an experiment, in which a Mk.1 helmet shell fitted with a pneumatic liner shaped like a soft flying helmet to give full cover for the head, was subjected to two blows of 30 ft lb (40.7 J) kinetic energy at a closing velocity of 14.3 ft/s (4.36 $msec^{-1}$); the weight of the striker being about 9.25 lb (4.2 kg). The pressure rise within the air bag was measured simultaneously with the transmitted force and this shows a peak of 70 lb/in^2 (483 $kN\,m^{-2}$) for both blows. The force measurements suggest that the load was spread over the crown of the head form covering an area between 11.4 to 14 sq in (73 to 90 cm^2). The volume of air displaced by the impact was apparently employed in inflating remote parts of the liner, while the leakage to atmosphere through the 1 mm orifice was apparently small. Experiments using pneumatic skull caps show that better results are obtained when the volume of the air bag is kept small - see Fig.23, trace 2. In fact, if the volume of a pneumatic liner is too large, it will lack adequate stiffness during impact and be potentially dangerous. From Fig.24 it can be seen that there is already a tendency to bottom, although the kinetic energy of the impact was only 30 ft lb (40.8 J).

5.3 Displacement and velocity change of helmet shells during impact

The way in which the closing velocity between the head and the helmet shell changes with respect to the distance between them during impact is important. For instance, soft padding materials reduce the relative velocity very little at first and the head may finally be arrested in a short distance from a relatively high approach speed. If the load cannot be effectively spread, and this is likely when the helmet deflects appreciably at the point of impact, the contact pressure on the skull will be high.

On the other hand, when the padding material or harness is stiff, the closing velocity between the head and helmet shell falls off very rapidly at first, leading to a high force acting on the skull. Once the resistance of the liner to deformation breaks down, the stopping distance then available may be relatively large.

The change of velocity with respect to displacement in the case of two plasticine test-pieces and three helmets subjected to blows of 100 ft lb (135.5 J) kinetic energy at about 25 ft/s (7.62 $m\,sec^{-1}$) is represented by the curves in Fig.25. These curves show that in current helmets, comparatively little velocity is lost initially, so that the rate of change of momentum during the latter part of the stroke tends to be high. In case 3, the helmet bottomed, producing a peak deceleration of more than 700 g and it can be seen that for a displacement of only 0.03 in (0.07 cm) the approach velocity was reduced from about 10 ft/s (3 $m\,sec^{-1}$) to zero.

The shapes of the acceleration pulses generated in this experiment were all approximately triangular with respect to time. If a rectangular pulse could be achieved in practice for a given impact energy, the peak deceleration would be half that for a triangular pulse, assuming the value of E to be zero. The very fast rise time of a square wave type of impulse implies that the helmet liner is very stiff up to the point where it suddenly breaks down. So far as the skull is concerned, there is practically no attenuation of the blow when the kinetic energy dissipated is less than that needed to cause the liner to collapse. The protective function of such a shell and liner combination would be limited to crash conditions. It is possible however, that the relatively long dwell at maximum acceleration (say 250 g) might be intolerable.

6 THE IMPACT TESTING OF SERVICE HELMETS, USING VERTICAL DROP AND PENDULUM RIGS

To conclude this preliminary work on the dynamics of head protection, it was decided to examine the response of complete Service helmets to given blows in both the vertical drop and the pendulum rigs; the colliding masses being made approximately equal in the latter case.

6.1 The vertical drop test

Samples of new Mks.1 and 2 type aircrew crash helmets were subjected to blows of 97 ft lb (132 J) at 25 ft/s (7.62 $msec^{-1}$) impact velocity and Fig.26 shows the results of tests on the two helmets. It can be seen that there was a difference of only about 30 g between the peak accelerations, but the value of E indicated by the total velocity change, see Fig.26b, was higher for the Mk.2 than the Mk.1 helmet. The fibreglass shell in the Mk.2 helmet cracks and delaminates easily, so that it would not be expected that very much energy would be restored in the rebound. It is concluded therefore, that the cork buffer, which is very elastic because of air trapped in its closed cell system, was involved in the impact.

From Fig.26c it will be seen that the displacement of the Mk.1 shell was slightly greater than the Mk.2 and the values obtained by integrating the velocity-time curves of Fig.26b were 1.4 and 1.3 in (3.6 and 3.3 cm) respectively. The displacements measured from a high speed cine film taken during the impact were in close agreement as shown in Fig.26c. It was found that the actual distances between the dummy head and the inside surface of the helmet shells in the crown area in the Mks.1 and 2 helmets respectively, are about 1.6 and 1.9 in (4 and 4.75 cm).

In contrast Fig.27 shows the results of an experiment in which a Mk.1 helmet bottomed when subjected to a crown blow by a striker of 10 lb (4.54 kg) weight at 25ft/s (7.62 $msec^{-1}$) impact velocity. This helmet had previously been subjected to several blows which damaged the head suspension harness, so that the clearance between the skull and the shell was reduced. The acceleration-time trace peaked beyond 700 g and double integration shows that the shell was stopped in about 1 in (2.5 cm). During the first 0.8 in (2 cm) of this displacement the velocity change was only about 8 ft/s (2.44 $msec^{-1}$), but in the final 0.16 in (0.4 cm) the change of velocity, 17 ft/s (5.2 $msec^{-1}$), was much more rapid due to the impact of the dummy head on the buffer material. It is noteworthy that the value of E shown by this test is 0.7; that is, about double the value for a new Mk.1 helmet.

6.2 The pendulum rig test

On the pendulum rig, new Mks.1 and 2 helmets were then subjected to blows of the same kinetic energy and the same impact velocity as before on the crown and over the ear. The conditions of the experiment were altered however, in that the weights of the striker (10 lb (4.5 kg)) and the test helmet with its headform and mounting platform (13 lb (5.9 kg)) were of the same order. The striker was instrumented with an accelerometer in its nose, so that the recorded traces are typical for input pulses. The test assembly which was suspended by fine wires was free to move following impact with consequences already discussed in section 4.1.2 and Appendix A.

Figs.28 and 29 show the results of the experiment and from the integration of the acceleration-time traces 28a and 29a, it can be seen that the total change of velocity of the striker in each case was about 15 ft/s (4.57 $msec^{-1}$) (Figs.28b and 29b) compared with 33 to 40 ft/s (10 to 12.2 $msec^{-1}$) for the vertical drop test: the value of E was between 0.3 and 0.4. This loss of velocity by the striker was more than half its initial velocity on impact because its mass was less than that of the test assembly.

The integration of the velocity-time curves, see Figs.28c and 29c shows that the displacement of the helmet shells was between 0.6 and 0.8 in (1.5 and 2 cm) or about half the displacement that took place in the vertical drop test.

It can be seen that although the same impact energy was supplied in both of these tests, the blows inflicted in the pendulum rig were much less severe. To make the two tests comparable it is therefore necessary to make the kinetic energy of the blow approximately twice that supplied in the vertical drop test. The precise figure will depend on the mass ratio employed.

7 CONCLUSIONS

Although, at the present time it is impossible to define precisely the threshold of injury in man caused by blows to the head, a maximum peak force of 4400 lb (19.6 kN) acting on the skull is used as a criterion in specifications for the design of crash helmets. This value was originally derived from the force required to fracture the average cadaver skull, when acting through the scalp on an area of about 2 in^2 (12.9 cm^2). As an arbitrary measure for comparing the performance of different helmets in response to given impact conditions, the figure is quite useful, but its connection with real conditions is not clear. In practice, however, it is possible to give a fair measure of protection against skull fracture by means of stiff helmet shells with suitable load spreading and energy absorbent liners, when the impact energy reaches between 120 and 150 ft lb (163 and 204 J).

Angular acceleration of the brain is believed to be one of the chief causes of injury and death during accidents involving impact. Unfortunately, little can be done to prevent this because of the real difficulty of arresting rotational movement with a helmet of practicable design and also because of the slow response of the brain to changes of velocity.

The same type of difficulty applies to translational movement, when the response of the brain to impact is slow compared with that of the skull. To make these impulses long enough to give the brain time to respond closely, would require a helmet of impracticable size.

Some improvement to existing helmet designs could be made however, by ensuring that the shells are stiffer and more resistant to penetration than at present, that they are smooth and spherical enough to deflect a high proportion of blows to the head and finally that the whole assembly has a low coefficient of restitution (preferably no higher than 0.3) to keep the total change of velocity of the head as low as possible.

Our work so far, has been mainly concerned with the development of techniques for examining the characteristic behaviour of crash helmets during impulsive loading. The impact test rigs used in our experiments have been made more flexible than is usual, in that mass and impact velocity can be varied at will to suit any reasonable test. Also, the impact records we have made are clear and of sufficiently large scale to allow the extraction of useful information about the velocity change and displacement of the test helmet shell, as well as the maximum force and acceleration transmitted to the dummy head.

Our experiments suggest that crash helmets function mainly as a means of reducing the danger of skull fracture. This is achieved by the liners which spread the impact load and keep the rate of interchange of momentum between the head and the colliding body or structure as low as possible. Stiff or highly rated liners make the rise time of the force acting on the skull short and it may be uncomfortably large even when the helmet is subjected to otherwise unimportant blows. Lowly rated liners on the other hand, allow a large displacement of the head while the closing velocity falls by a relatively small amount. In the limit, nearly all the kinetic energy of the impact is dissipated while stopping the head in a very small distance from a considerable velocity. This is the bottoming case, where very high forces act on the skull, although their time of action at extreme values is very short.

Compromise on the characteristics of helmet liners is necessary to prevent on the one hand, the dissipation of nearly all the energy of impact on the skull during moderate blows while little or no work is done on the helmet, and on the other, early bottoming due to over soft head harness or padding.

Difficulties in the correlation of the results of experiments from different sources have led to the suggestion that some form of standard test-piece is needed to check the output from different rigs. We have found that such a device can be made from plasticine moulded to the form of a truncated cone of given dimensions.

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Appendix A

THE EFFECT OF MASS RATIO

In contrast with the vertical drop test rig, the striker and head-mass are freely suspended in the R.A.E. pendulum test rig and the consequences of making their masses approximately equal can be shown.

Suppose that two masses m_1 and m_2, moving in the same straight line collide, that their initial velocities are U_1 and U_2 their coefficient of restitution is E and their relative velocities after impact are v_1 and v_2.

Then by Newtons law of impact

$$v_1 - v_2 = - E\,(U_1 - U_2) \quad . \qquad \text{(A-1)}$$

The momentum of the masses is conserved, so that

$$m_1\,v_1 + m_2\,v_2 = m_1\,U_1 + m_2\,U_2 \quad .$$

From these two equations the values of v_1 and v_2 can be found. They are

$$v_1 = U_1\,(1 - E)/2 \qquad \text{(A-2)}$$

and

$$v_2 = U_1\,(1 + E)/2 \qquad \text{(A-3)}$$

when $m_1 = m_2$ and $U_2 = 0$.

If $E = 1$ then $v_1 = 0$ and $v_2 = U_1$ and if $E = 0$ then $v_1 = U_1/2$ and $v_2 = U_1/2$.

The kinetic energy lost by the striker is:-

$$m_1\,m_2\,(1 - E^2)\,(U_1 - U_2)^2/2\,(m_1 + m_2)\ .$$

When the colliding masses are equal as in one arrangement of the R.A.E. pendulum impact test rig

$$Ke = m_1 U_1^2 (1 - E^2)/4 \tag{A-4}$$

and when $E = 0$

$$Ke = m_1 U_1^2/4 \tag{A-5}$$

but when $E = 1$ no energy is lost. That is, all the energy is converted back to potential energy.

On the other hand, in the R.A.E. pendulum rig fitted with its large suspended anvile mass,

$$m_2 = 30 m_1 \text{ approximately and } U_2 = 0$$

therefore

$$Ke = 15 m_1 U_1^2 (1 - E^2)/31 = 0.485 m_1 U_1^2$$

or nearly

$$m U^2/2 \tag{A-6}$$

but when $E = 1$ there is no difference between the two cases because the original potential energies were equal.

This means that when the value of E is close to zero, a blow between equal masses must contain twice the energy of a blow against an infinite or very large mass to produce a comparable effect.

Appendix B

THE HELMET AND HEAD ASSEMBLY REGARDED AS A SIMPLE MASS SPRING SYSTEM

Any mathematical model of a head and helmet assembly is likely to be over simplified. Nevertheless, analysis of such a system regarded as a simple mass-spring arrangement with damping, at least yields a picture in which the order of events can be visualised.

Consider a body of weight W lb colliding with a stationary body of weight λ W lb, through a linear spring of stiffness K lb/ft, with an associated damping force c lb sec/ft. Initially the velocity of the first weight is u ft/s and both are free to move in a straight line after impact. If the displacement of the first body in space from its position at the moment of impact is x ft and the second body is y ft the equations of motion are:-

$$W \ddot{x}/g = c(\dot{y} - \dot{x}) + K(y - x) \tag{B-1}$$

and

$$W \lambda \ddot{y}/g = -c(\dot{y} - \dot{x}) - K(y - x) \tag{B-2}$$

with the initial conditions x, y and $\dot{y} = 0$, $\dot{x} = U$.

Multiplying equation (B-1) by λ and subtracting equation (B-2) we have

$$W \lambda (\ddot{x} - \ddot{y})/g + c(1 + \lambda)(\dot{x} - \dot{y}) + K(1 + \lambda)(x - y) = 0 \,. \tag{B-3}$$

Whence, putting $x - y = \zeta$,

$$c(1 + \lambda)\, g/W\lambda = 2 h \omega \quad ,$$

$$K(1 + \lambda)\, g/W\lambda = \omega^2$$

we have

$$\ddot{\zeta} + 2 h \omega \dot{\zeta} + \omega^2 \zeta = 0 \tag{B-4}$$

with the initial conditions $\zeta = 0$, $\dot{\zeta} = U$.

The solution of equation (B-4) is given by

$$\left.\begin{aligned}
\zeta &= U \sin(\sqrt{1 - h^2}\,\omega t) e^{-h\omega t}/\omega\sqrt{1 - h^2} && \text{if } h < 1 \\
\zeta &= U\, t e^{-\omega t} && \text{if } h = 1 \\
\zeta &= U \sinh(\sqrt{h^2 - 1}\,\omega t) e^{-h\omega t}/\omega\sqrt{h^2 - 1} && \text{if } h > 1
\end{aligned}\right\} \tag{B-5}$$

Differentiating,

$$
\left.
\begin{aligned}
\dot{\zeta} &= U\,[\sqrt{1-h^2}\;c - hs]\,e^{-h\omega t}/\sqrt{1-h^2} \\
&\text{if } h < 1, \quad c = \cos(\sqrt{1-h^2}\,\omega t), \quad s = \sin(\sqrt{1-h^2}\,\omega t)\,. \\
\dot{\zeta} &= U\,(1 - t\,\omega)e^{-\omega t} \qquad \text{if } h = 1 \\
\dot{\zeta} &= U\,[\sqrt{h^2-1}\;ch - h\;sh]\,e^{-h\omega t}/\sqrt{h^2-1} \\
&\text{if } h > 1, \quad ch = \cosh(\sqrt{h^2-1}\,\omega t), \quad sh = \sinh(\sqrt{h^2-1}\,\omega t)\,.
\end{aligned}
\right\} \qquad \text{(B-6)}
$$

From these basic equations we may deduce the coefficient of restitution E, the duration of the impact T, the maximum acceleration a_{max} and the transmitted force P_{max}, and the maximum relative displacement of the weights.

B.1 <u>Duration of impact T and coefficient of restitution E</u>

The final velocities of the weights are reached when their accelerations become zero, that is when

$$2h\dot{\zeta} + \omega\zeta = 0 \qquad \text{(B-7)}$$

Using equations (B-5) and (B-6) we find that equation (B-7) is satisfied at time T given by

$$\sin[\sqrt{1-h^2}\,\omega T - 2\cos^{-1} h] = 0\,, \quad \text{i.e.} \sqrt{1-h^2}\,\omega T = 2\cos^{-1} \quad \text{if } h < 1 \qquad \text{(B-8)}$$

$$\omega T = 2 \quad \text{if } h = 1 \qquad \text{(B-9)}$$

$$\sinh[\sqrt{h^2-1}\,\omega T - 2\cosh^{-1} h] = 0\,, \quad \text{i.e.} \sqrt{h^2-1}\,\omega T = 2\cosh^{-1} h \quad \text{if } h > 1 \qquad \text{(B-10)}$$

The relative velocity at time T is

$$-Ue^{-h\omega T} \qquad \text{(B-11)}$$

in each case, so that

$$E = e^{-h\omega T} \qquad \text{(B-12)}$$

in each case.

B.2 Change of velocity of striker

Adding equations (B-1) and (B-2) we find

$$\ddot{x} + \lambda \ddot{y} = 0 , \tag{B-13}$$

whence integrating and putting in initial conditions

$$\dot{x} + \lambda \dot{y} = U$$

$$x + \lambda y = U t$$

so that

$$\left.\begin{aligned} \ddot{x} &= \lambda \ddot{\zeta}/(1 + \lambda) \\ \dot{x} &= (U + \lambda \dot{\zeta})/(1 + \lambda) \\ x &= (U t + \lambda \zeta)/(1 + \lambda) \end{aligned}\right\} \tag{B-14}$$

Hence the total change of velocity of the striker is

$$V = U - (U - \lambda E U)/(1 + \lambda) = \lambda U (1 + E)/(1 + \lambda) . \tag{B-15}$$

In this particular case where the second body is very large compared with the striker

$$V = U (1 + E) . \tag{B-16}$$

B.3 Maximum acceleration a_{max}

The maximum relative acceleration a_{max} occurs where

$$\ddot{\zeta} = - (2 h \omega \dot{\zeta} + \omega^2 \zeta)$$

has minimum, that is at time t_1, say, where

$$2 h \ddot{\zeta} + \omega \dot{\zeta} = 0 . \tag{B-17}$$

For $h < 1$ this occurs when

$$\sqrt{1 - h^2} (1 - 4 h^2) \cos \sqrt{1 - h^2}\, \omega t_1 - h (3 - 4 h^2) \sin \sqrt{1 - h^2}\, \omega t_1 = 0 \tag{B-18}$$

that is

$$\cos [\sqrt{1 - h^2}\, \omega t_1 + 3 \sin^{-1} h] = 0$$

or

$$\sqrt{1 - h^2}\,\omega t_1 = \pi/2 - 3\sin^{-1} h \ . \tag{B-19}$$

This equation is only soluble for real time if $\pi/2 - 3\sin^{-1} h > 0$ that is, if $h < 0.5$, and substitution in equation (B-4) gives:

$$\ddot{\zeta}_{max} = -\omega U e^{-h\omega t_1} \ . \tag{B-20}$$

The maximum acceleration of the striker using equation (B-14) is given by

$$a_{max} = \lambda\,\ddot{\zeta}_{max}/(1 + \lambda)$$

so that, when λ is very large

$$a_{max} = \ddot{\zeta}_{max} = -\omega U e^{-h\omega t_1} \tag{B-21}$$

For $h > 0.5$, the maximum acceleration occurs at the moment of impact and is given by

$$\begin{aligned} \ddot{\zeta}_{max} &= -2 h \omega U \\ &= a_{max} \text{ for large } \lambda \end{aligned} \tag{B-22}$$

B.4 Force acting on bodies

The force is given by

$$P = c\,\dot{\zeta} + k\,\zeta = W \lambda \ddot{\zeta}/g\,(1 + \lambda)$$

so that for $h < 0.5$

$$P_{max} = W \lambda \omega U e^{-h\omega t_1}/g\,(1 + \lambda)$$

and for $h > 0.5$ (B-23)

$$P_{max} = 2 W \lambda \omega U\, h/g\,(1 + \lambda)$$

or, for large λ, $h < 0.5$,

$$P_{max} = W \omega U e^{-h\omega t_1}/g$$

$h > 0.5$ (B-24)

$$P_{max} = 2 W \omega U h/g$$

B.5 Maximum spring deflection

The maximum deflection occurs when $\dot{\zeta} = 0$. That is, using equation (B-6) when

$$\sqrt{1 - h^2}\,\omega t = \cos^{-1} h \qquad \text{if } h < 1$$

$$\omega t = 1 \qquad \text{if } h = 1 \tag{B-25}$$

$$\sqrt{h^2 - 1}\,\omega t = \cosh^{-1} h \qquad \text{if } h > 1$$

That is, when $t = T/2$, (from equations (B-8), (B-9) and (B-10)). (B-26)

Hence

$$\omega\,\zeta_{max} = U\,e^{-h\omega T/2} \tag{B-27}$$

Using equation (B-14),

$$\omega\,x_{max} = (U\,T + \lambda\,U\,e^{-h\omega T/2})\,(1 + \lambda)$$

$$= U\,e^{-h\omega T/2} \tag{B-28}$$

when λ is large.

B.6 Relationship between change of striker velocity and duration of impact for a fixed deflection δ

The change of velocity is

$$V = U\,(1 + E) \qquad \text{(equation B-16))}$$

$$T = \log_e\,(1/E)/h\,\omega \qquad \text{(equation (B-12))}$$

$$\delta\,\omega = U\,\sqrt{E} \qquad \text{(equation (B-28))}$$

hence

$$V\,T = [\delta\,(1 + E)\,\log_e\,(1/E)]/h\sqrt{E} \tag{B-29}$$

B.7 <u>Variation of maximum spring deflection with velocity of striker using constant energy input, for λ infinite</u>

If we maintain a constant kinetic energy in the striker impacting a fixed body through a particular spring, using definitions of ω, h, and kinetic energy formula we can say

$$W = W_1 q^2 , \quad U = U_1/q , \quad W = W_1/q , \quad h = h_1/q \qquad \text{(B-30)}$$

so that the relation between x_{max} and $x_{1\,max}$ can be calculated using equations (B-8), (B-9), (B-10) and (B-28).

A simpler method however, is to write equation (B-28) in the form: $(x)_{max} = (U/\omega)\sqrt{E}$ from equation (B-12), whence using equation (B-30)

$$(x)_{max}/(x_1)_{max} = (U\,\omega_1/U_1\,\omega)\sqrt{E/E_1} = \sqrt{E/E_1} \qquad \text{(B-31)}$$

and deduce the ratio from the h versus E curve of Fig.7, and the equation $h = h_1/q$. The only difficulty arises for h very large, when E and $E_1 \to 0$ but this can be resolved in the limit.

For $h > 1$, since $E = e^{-h\omega T}$ and $\omega T = 2\cosh^{-1} h\Big/\sqrt{h^2 - 1}$ (equations (B-12), (B-10))

$$\log_e E = -2h(\cosh^{-1} h)\Big/\sqrt{h^2 - 1} \to -2\cosh^{-1} h \quad . \qquad \text{(B-32)}$$

If we write $\phi = \cosh^{-1} h$

$$h = \cosh\phi = (e^{\phi} + e^{-\phi})/2 \to (1/2)\,e^{\phi} \qquad \text{(B-33)}$$

therefore

$$\log_e E \to -2\log_e 2h , \quad E \to 1/(2h)^2 \qquad \text{(B-34)}$$

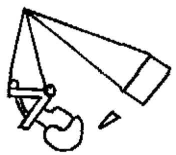
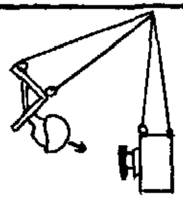
hence

$$(x)_{max}/(x_1)_{max} \to h_1/h = q \quad .$$

The relationships between E, h, T, a_{max}, x_{max} are shown in Fig.7 for the case where λ is large. The relationship between VT for different values of δ is shown in Fig.1 for the case $E = 0.3$, $h = 0.5$. The effect of variation of striker parameters with constant kinetic energy is shown in Fig.8.

Table 1

SUMMARY OF TEST METHODS

Mode	Helmet and head form first body		Striker or anvil second body		Methods of measurement	Remarks
	Effective weight	Initial velocity	Effective weight	Initial velocity		
A 	W ∞	U = 0	w	u	(1) Load cell under head form. (2) Accelerometer in striker or (3) both	B.S.I. standard test (1): w = 11 lb (5 kg), u varied for impact energy. Also R.A.E. vertical drop rig. R.A.E. vertical drop rig (2 or 3): w and u as above. If desired w can also be varied for impact energy.
B 	W	U	w ∞	u = 0	(1) Accelerometer in head form. (2) Load cell under anvil.	ASA vertical drop test (1): U is varied for impact energy. Can be set up on R.A.E. vertical drop rig (2) U is varied for impact energy. In both, W varies with helmet type under test.
C 	W	U = 0	w	u	(1) Accelerometer in head form or (2) Accelerometer in striker.	Snively test rig W = w = x lb: (1) u is varied for impact energy. Also ASA test. R.A.E. pendulum rig (2): W = w approx., u is varied for impact energy. Also w can be varied.
D 	W	U	w = x W	u = 0	(1) Accelerometer in head form or (2) Load cell under anvil.	Applicable to R.A.E. pendulum rig but not yet tried. (1) In both Modes C and D the impacted mass is free to move following the blow. R.A.E. pendulum rig: (2) w = x W, U is varied for impact energy.

<u>NOTE</u> Read table as follows:-

For example Mode C:- Striker (weight w) collides with stationary (u = 0) head form (weight W) at impact velocity u.

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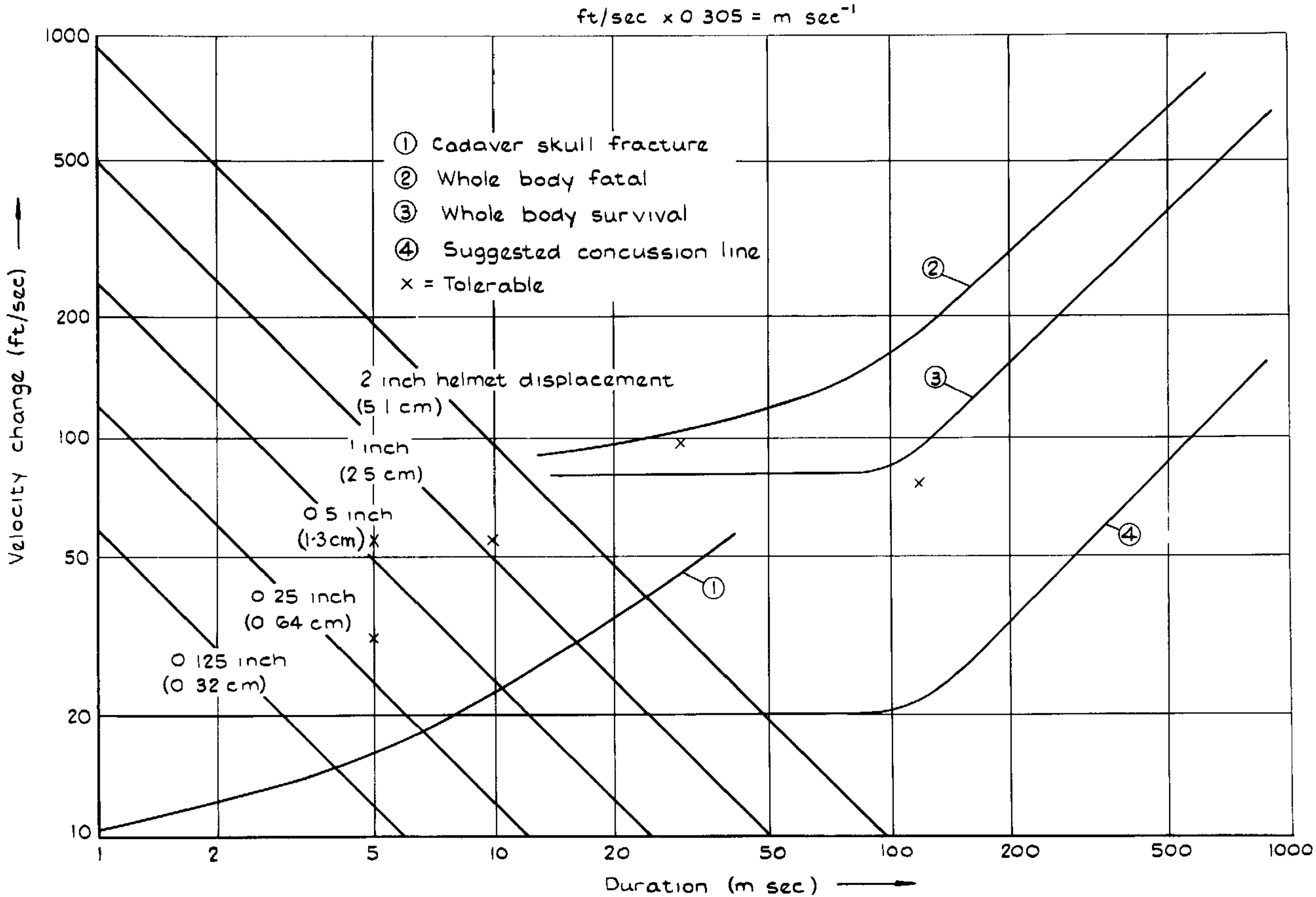


Fig 1 Human tolerance to impact acceleration

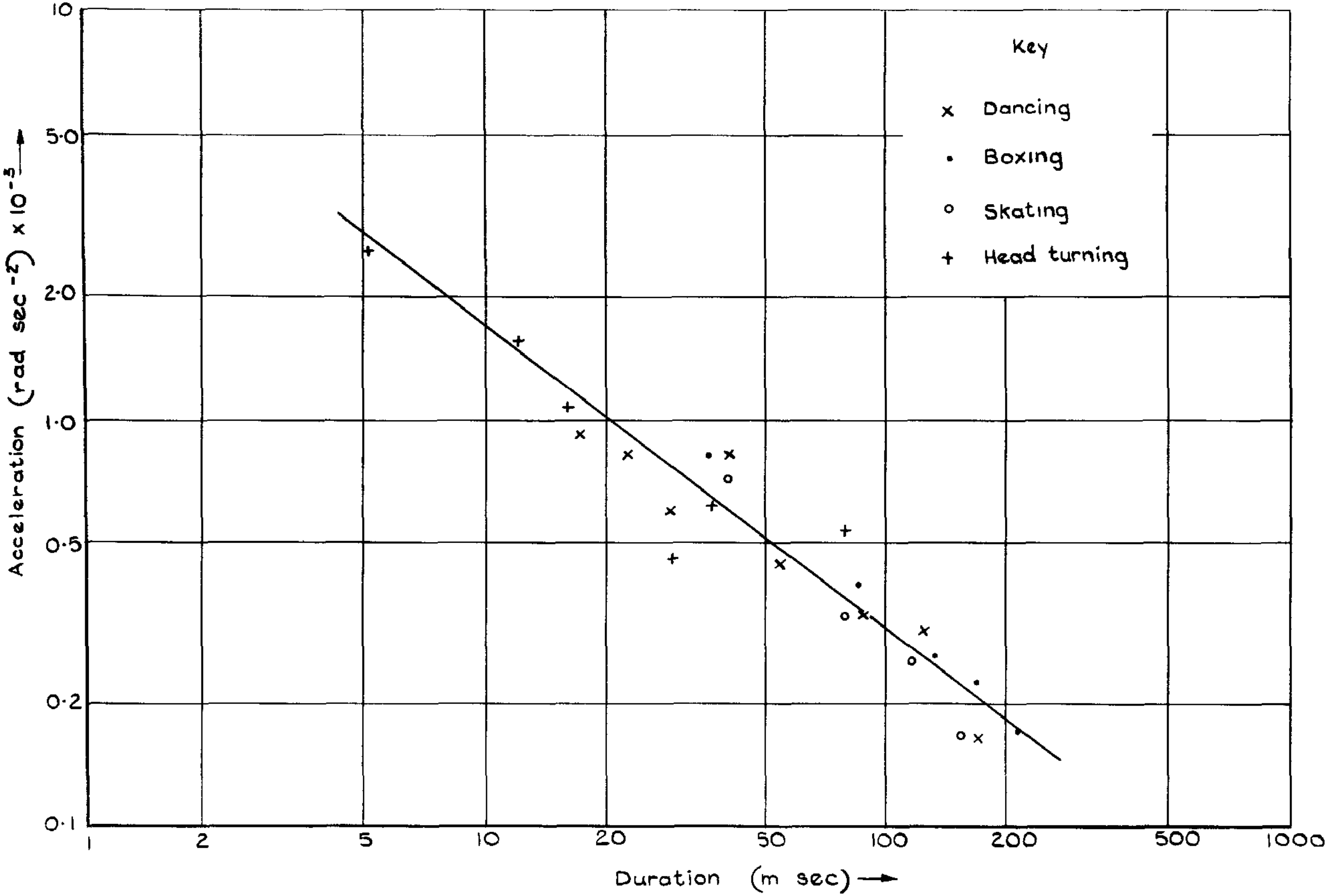


Fig. 2 Angular acceleration of the head developed in some normal activities

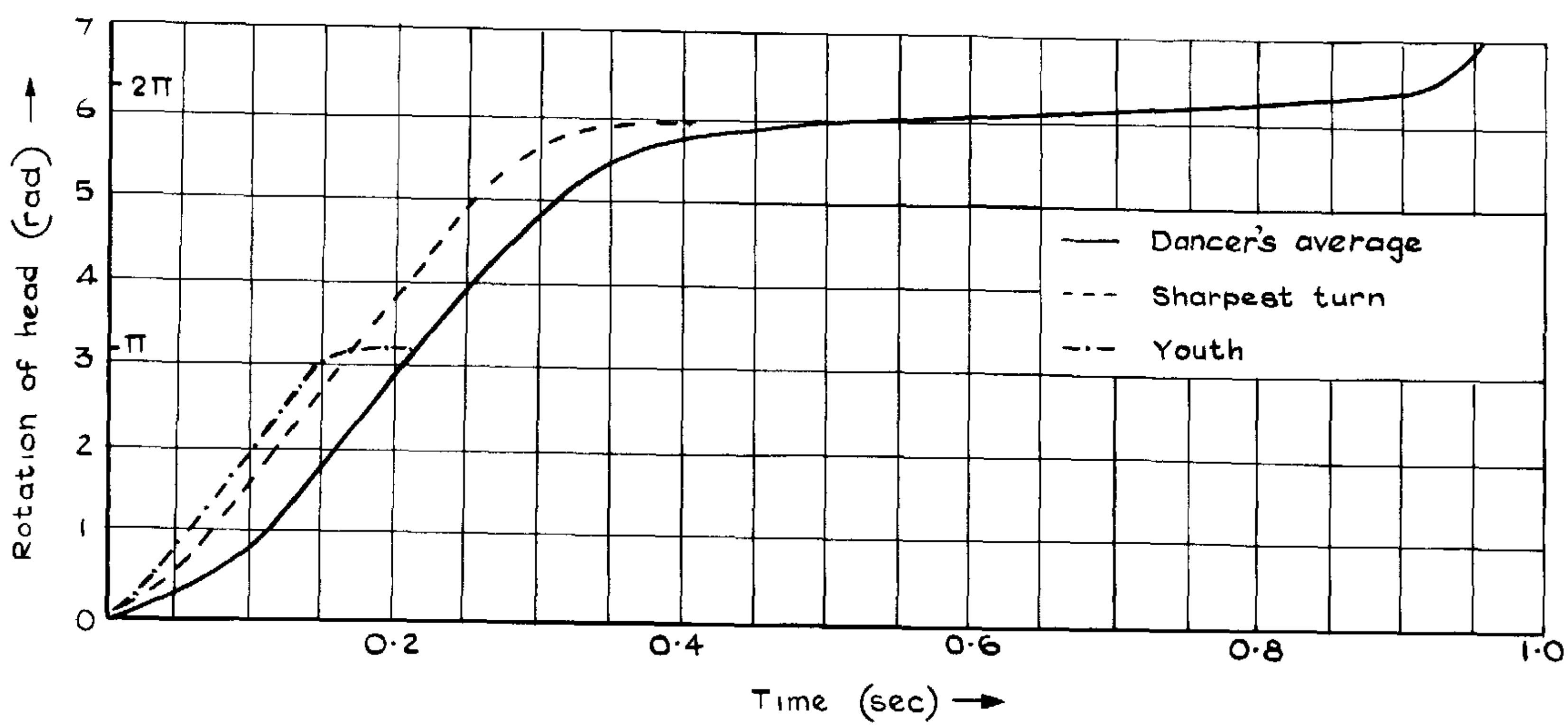


Fig. 3 Angular displacement of the head in some normal activities

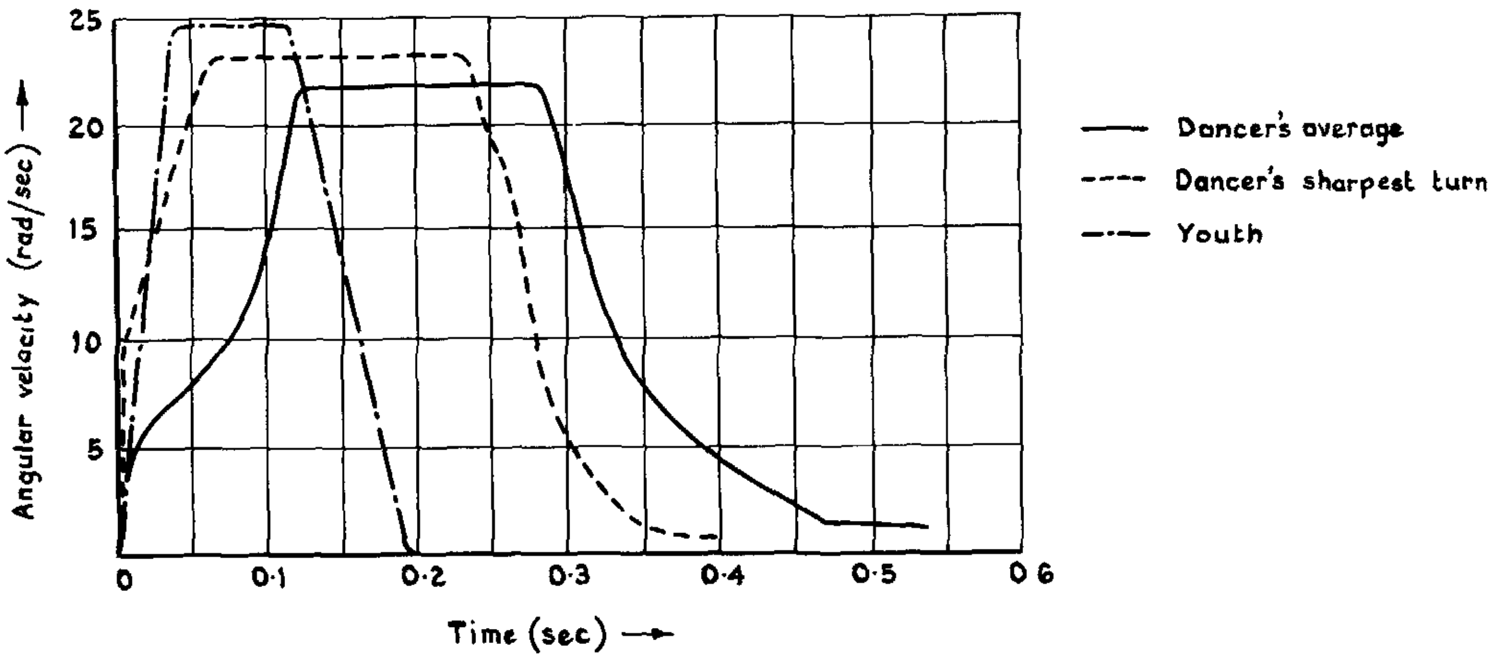


Fig. 4 Angular velocity of the head in some normal activities

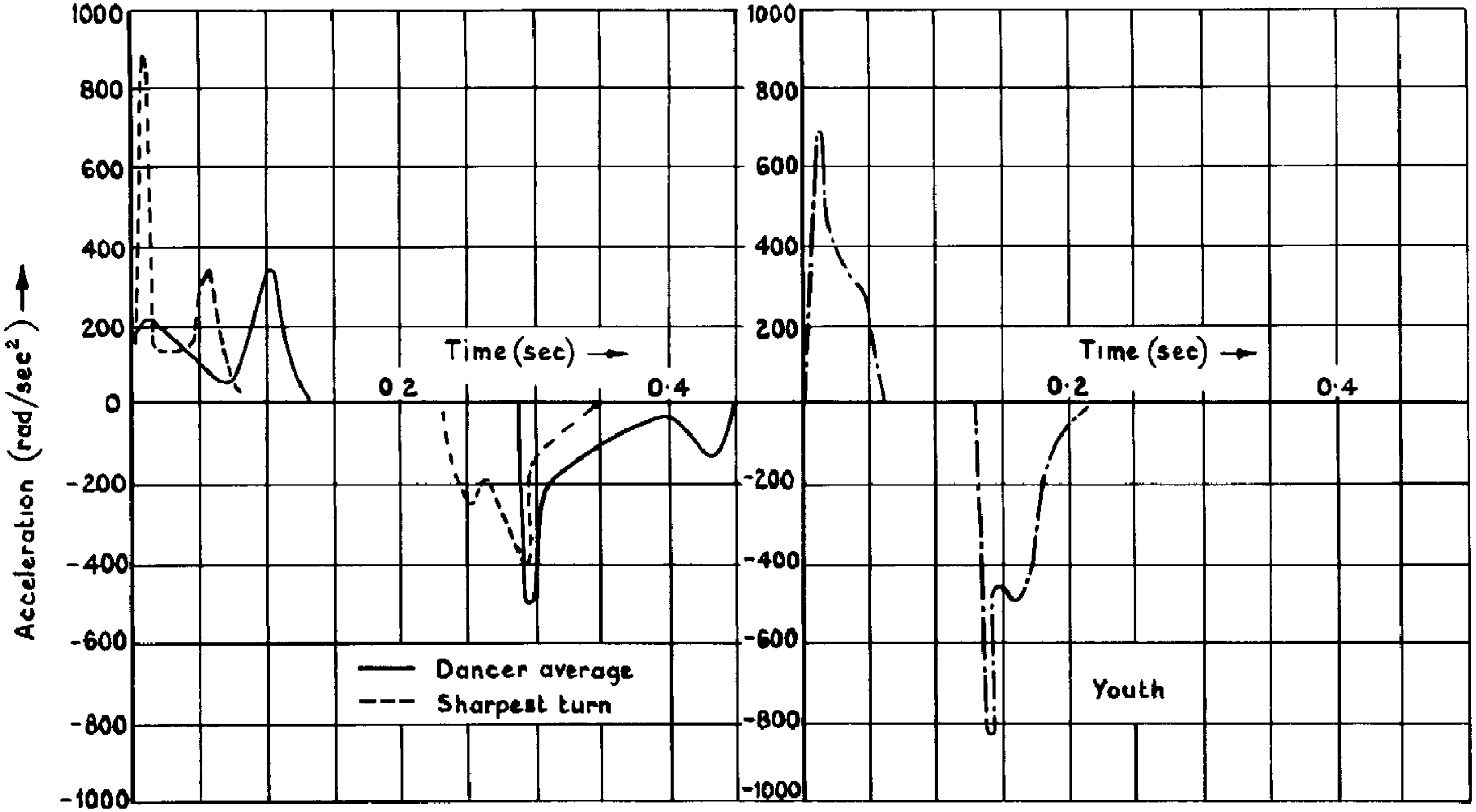


Fig. 5 Angular acceleration of the head in some normal activities

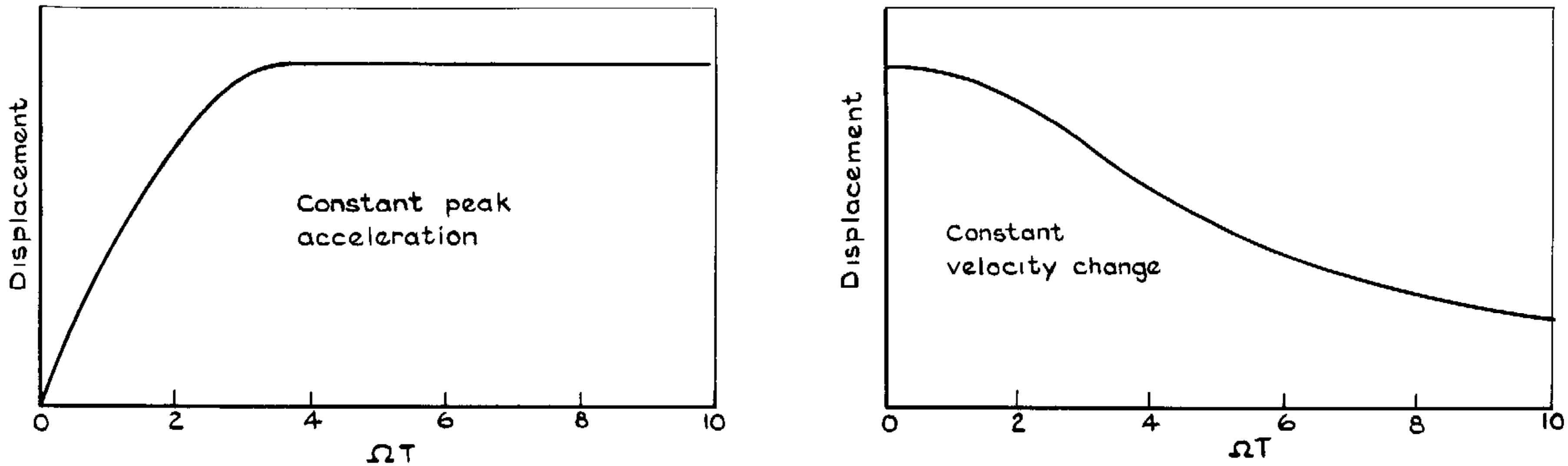


Fig. 6 Displacement response of spring mass system of period $(2\pi/\Omega)$ to acceleration pulse of duration T sec

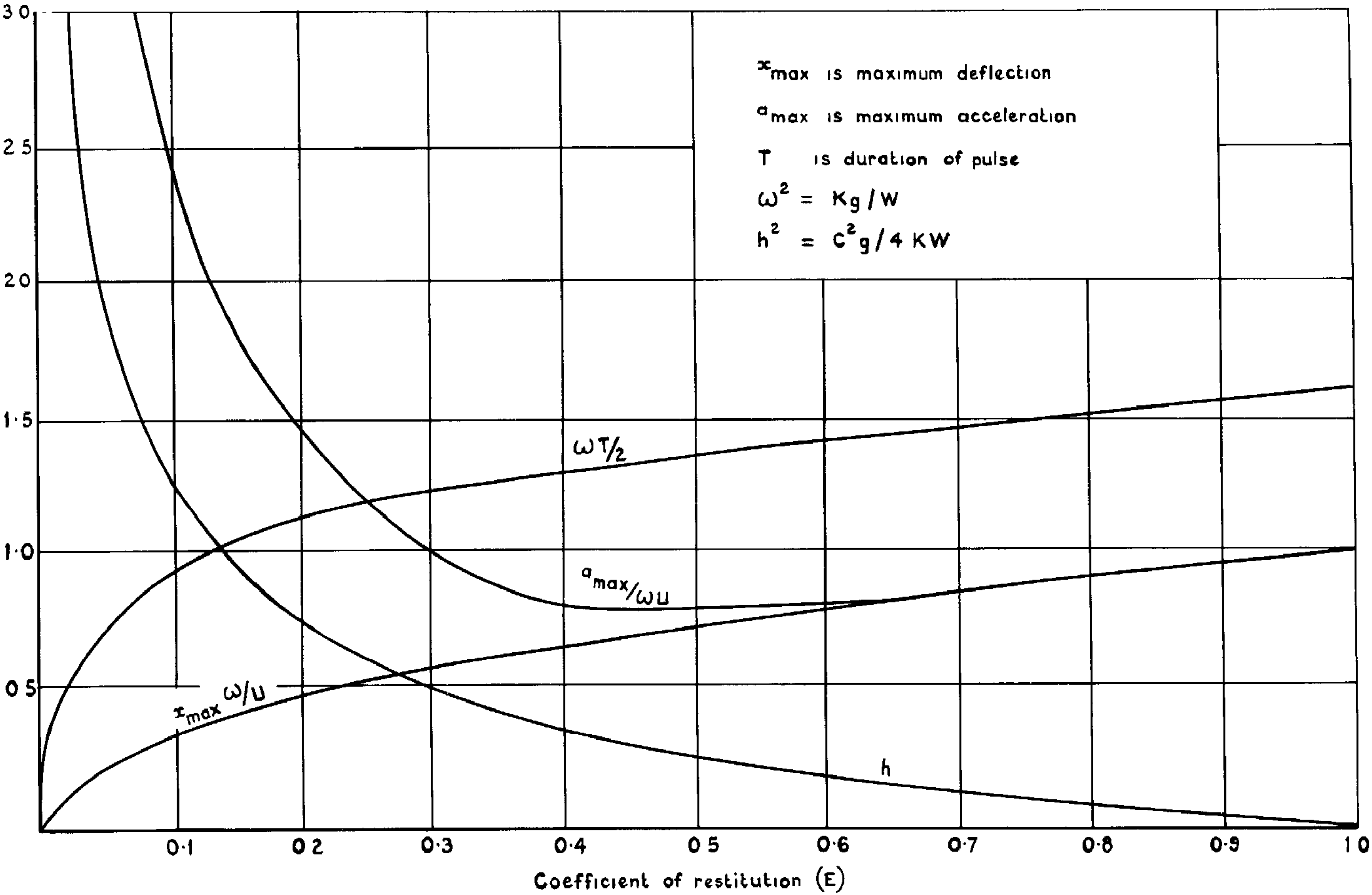


Fig 7 Variation of impact parameters for a weight striking a fixed body through a spring of stiffness K, damping force C, with initial velocity U

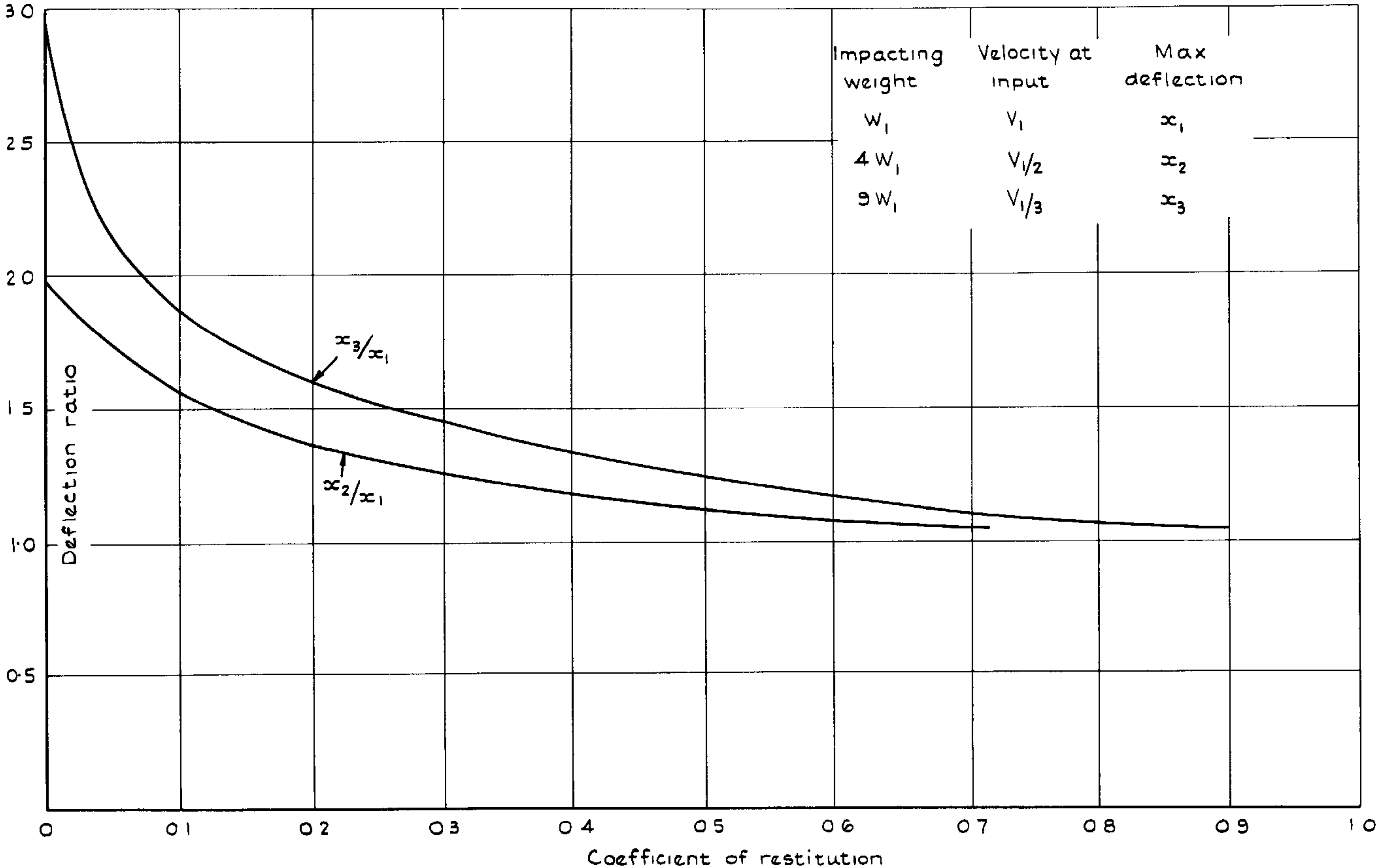


Fig 8 Variation of maximum deflection for constant impact energy with weight of impacting body

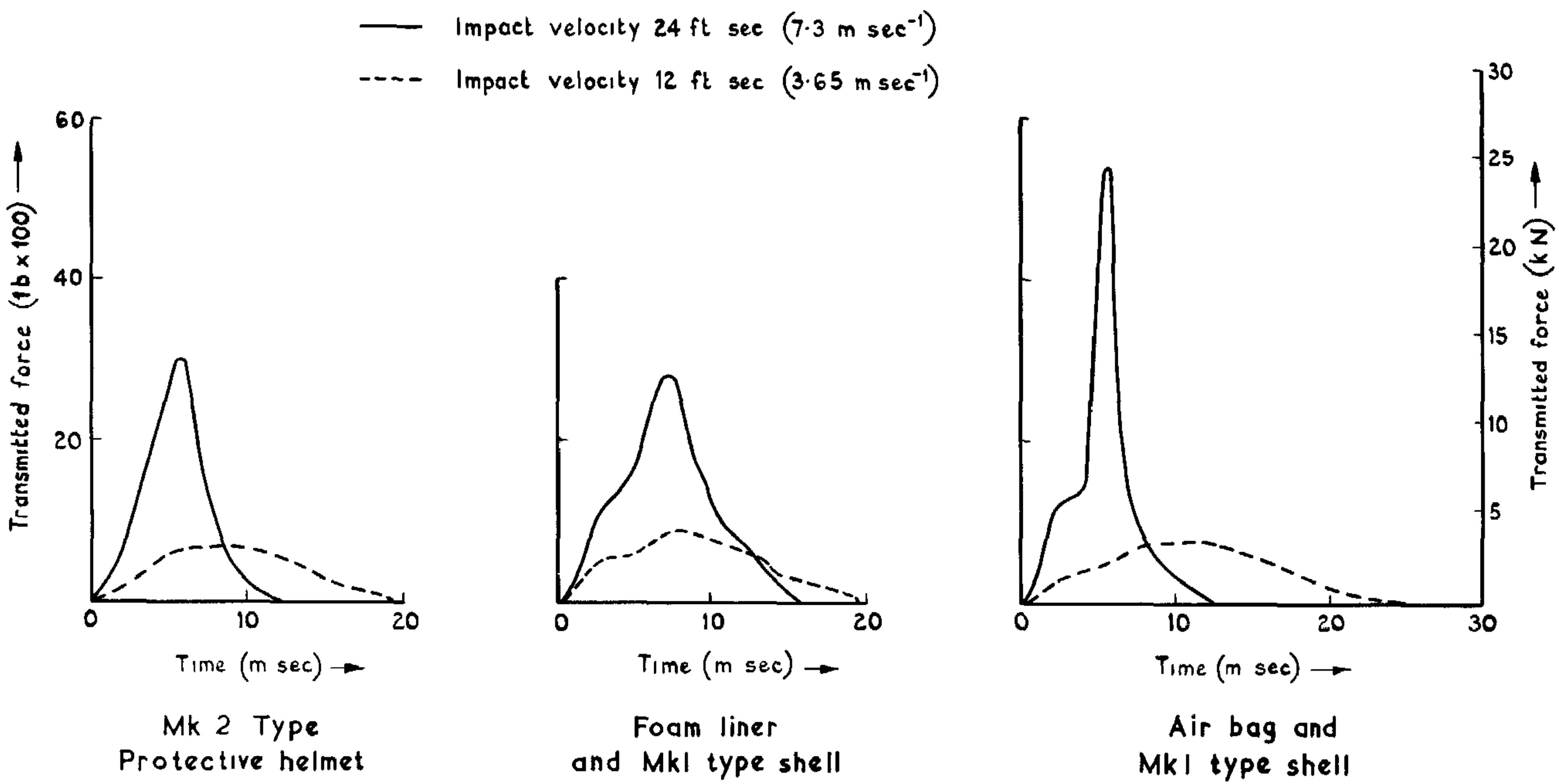


Fig 9 Load transmission for various types of helmet liner

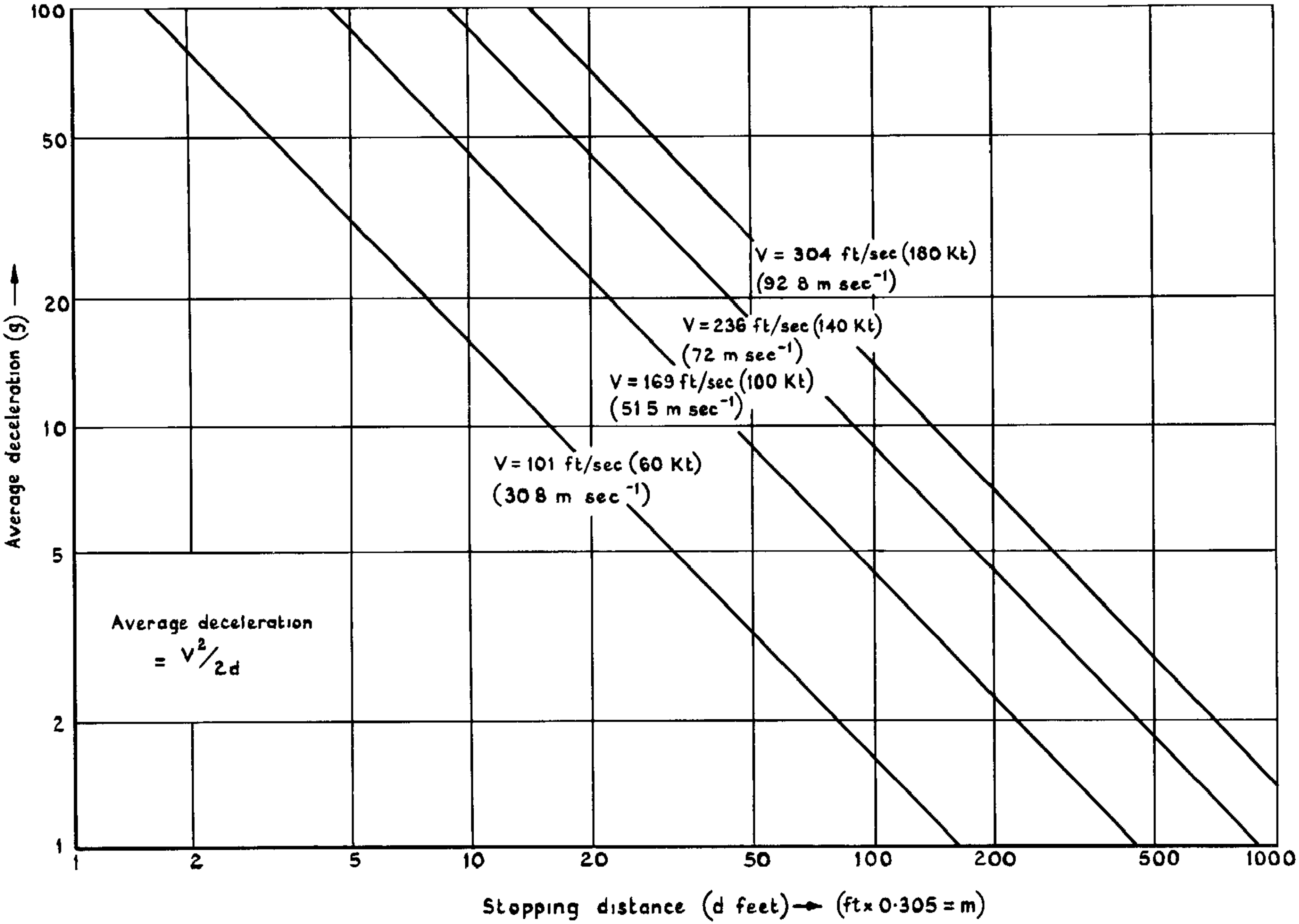


Fig. 10 Deceleration in landing and take-off crashes

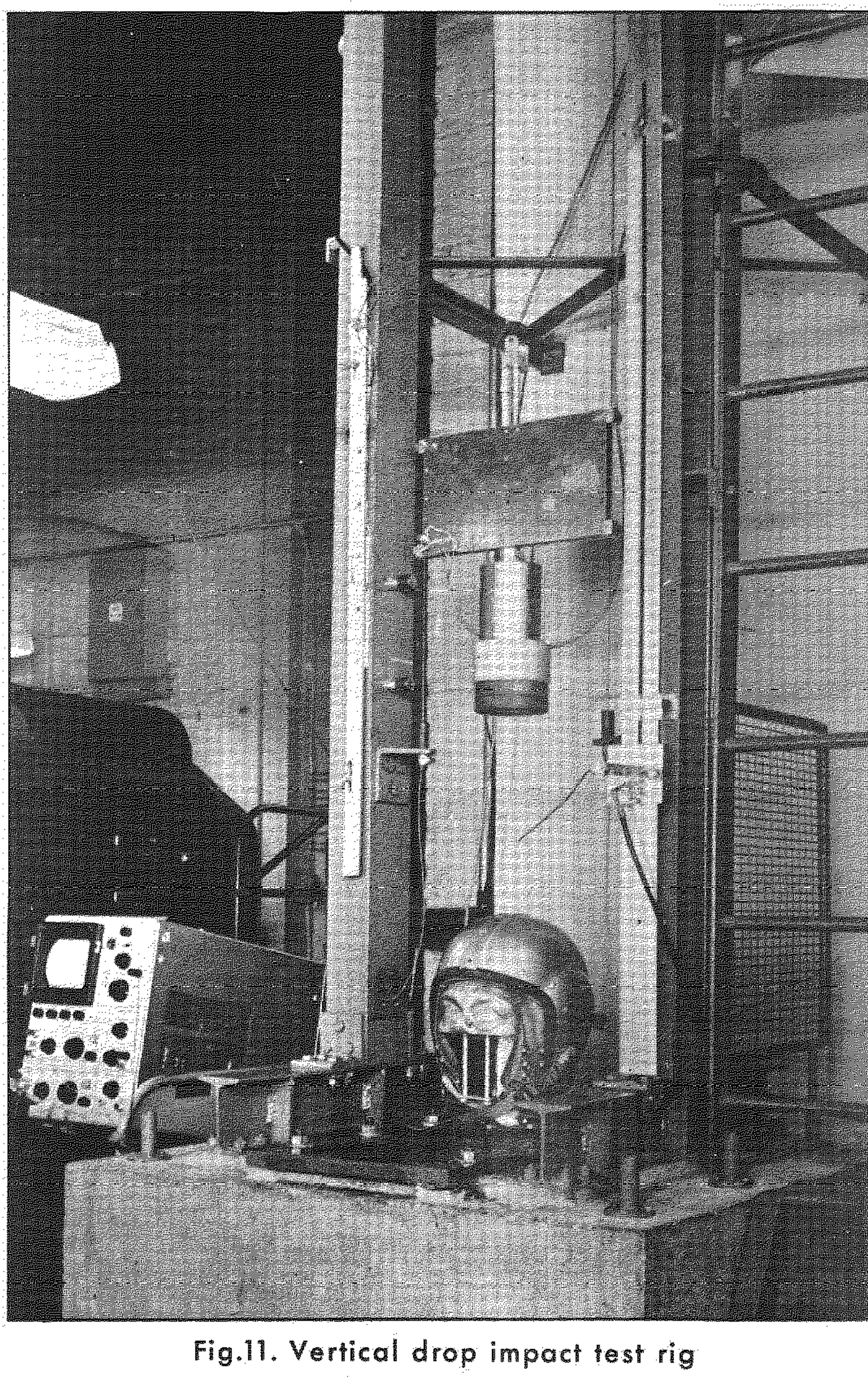


Fig.11. Vertical drop impact test rig

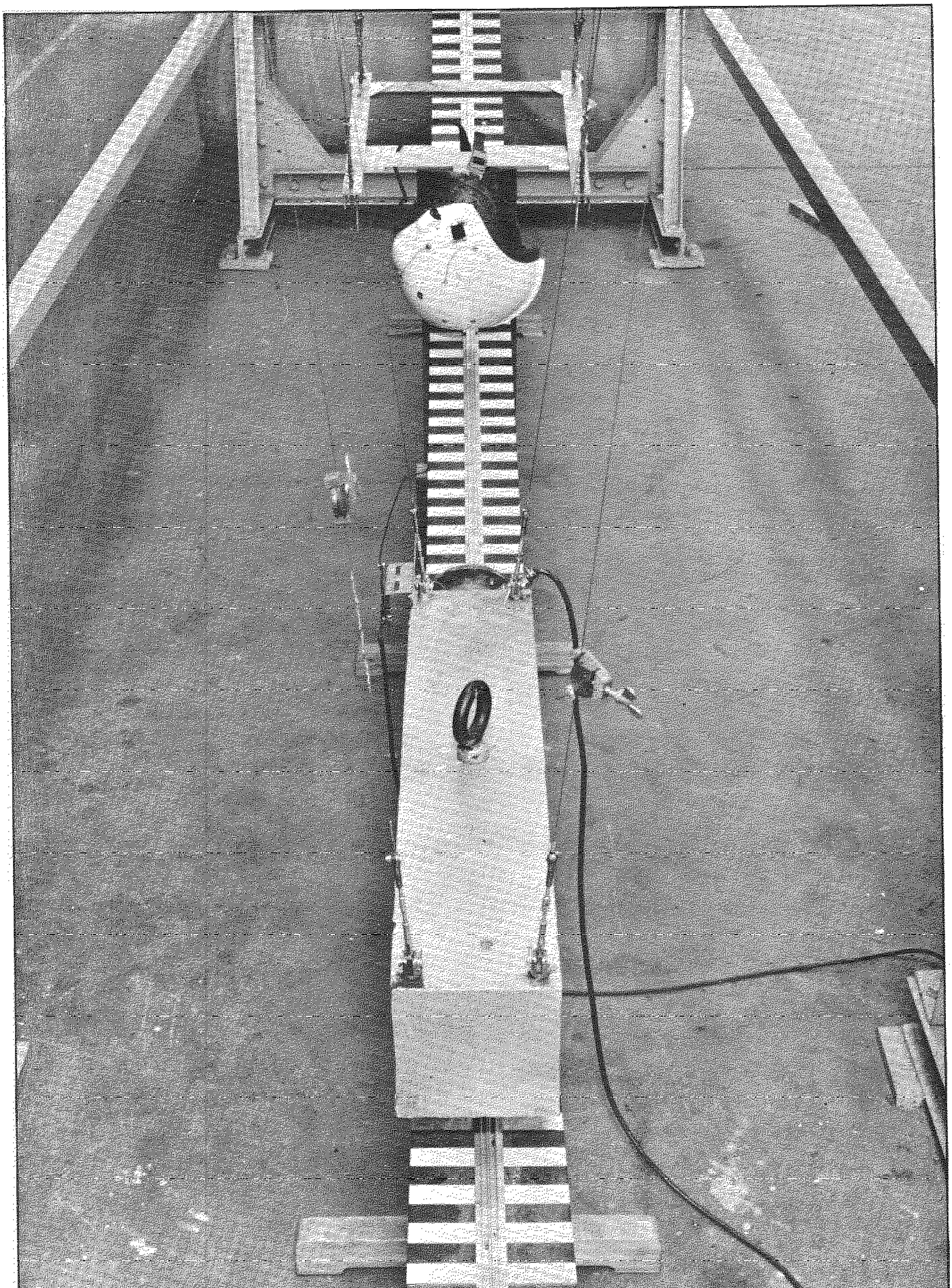


Fig.12. Pendulum impact test rig

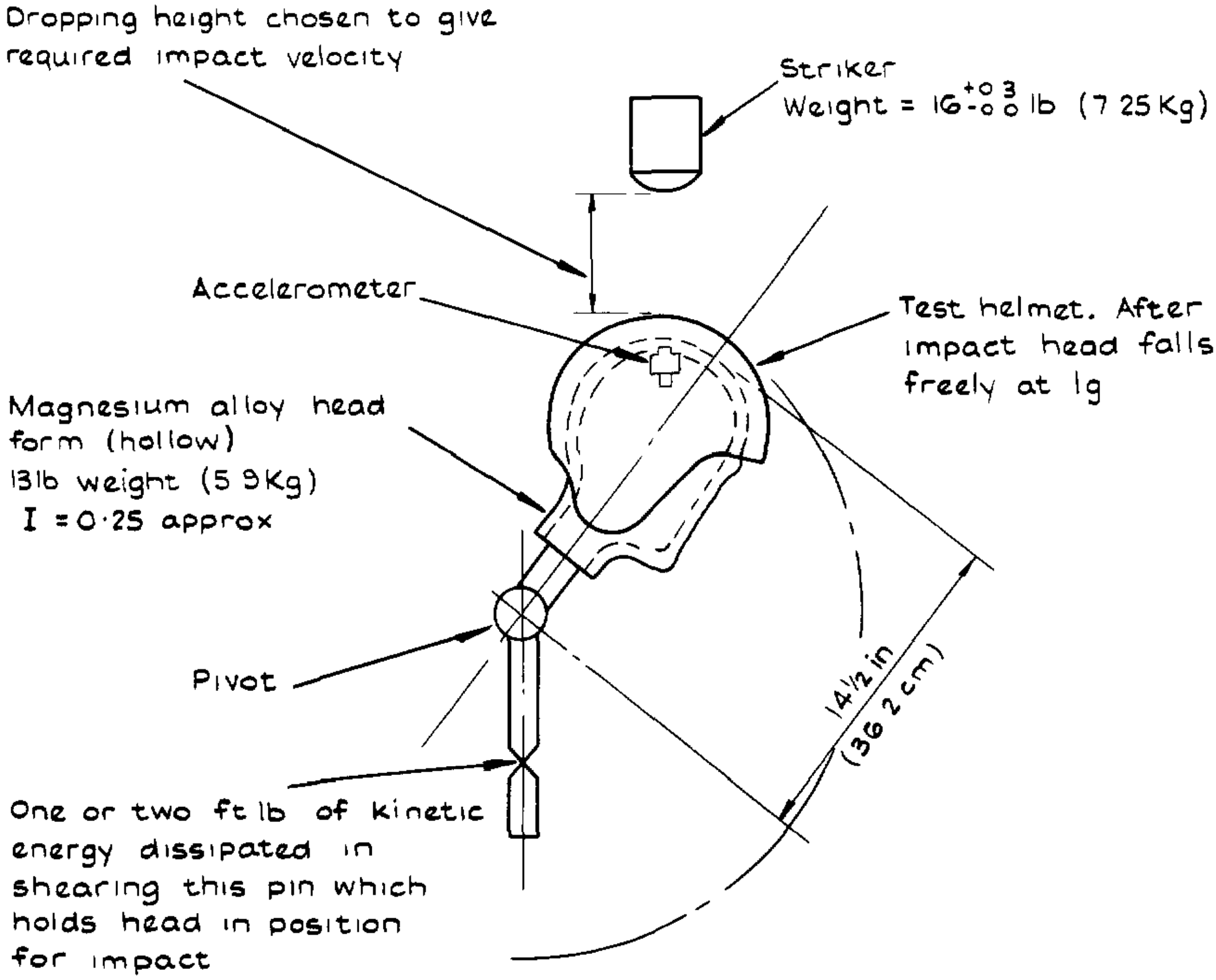


Fig 13 Diagrammatic representation of Snively helmet test apparatus

Rig used Vertical drop

Test-piece. Mk I helmet shell with recoverable foam liner 3lb weight (1 35Kg)

Kinetic energy. 40ft lb (54 3 J)

Mass ratio ∞

Striker weight		Impact velocity
1	11 75lb 5 3 Kg	14 7ft/sec (4 5 m sec^{-1})
2	8 25 lb 3 75 Kg	17 6ft/sec (5 4 m sec^{-1})
3	6 25 lb 2 8 Kg	20·4ft/sec (6·2 m sec^{-1})

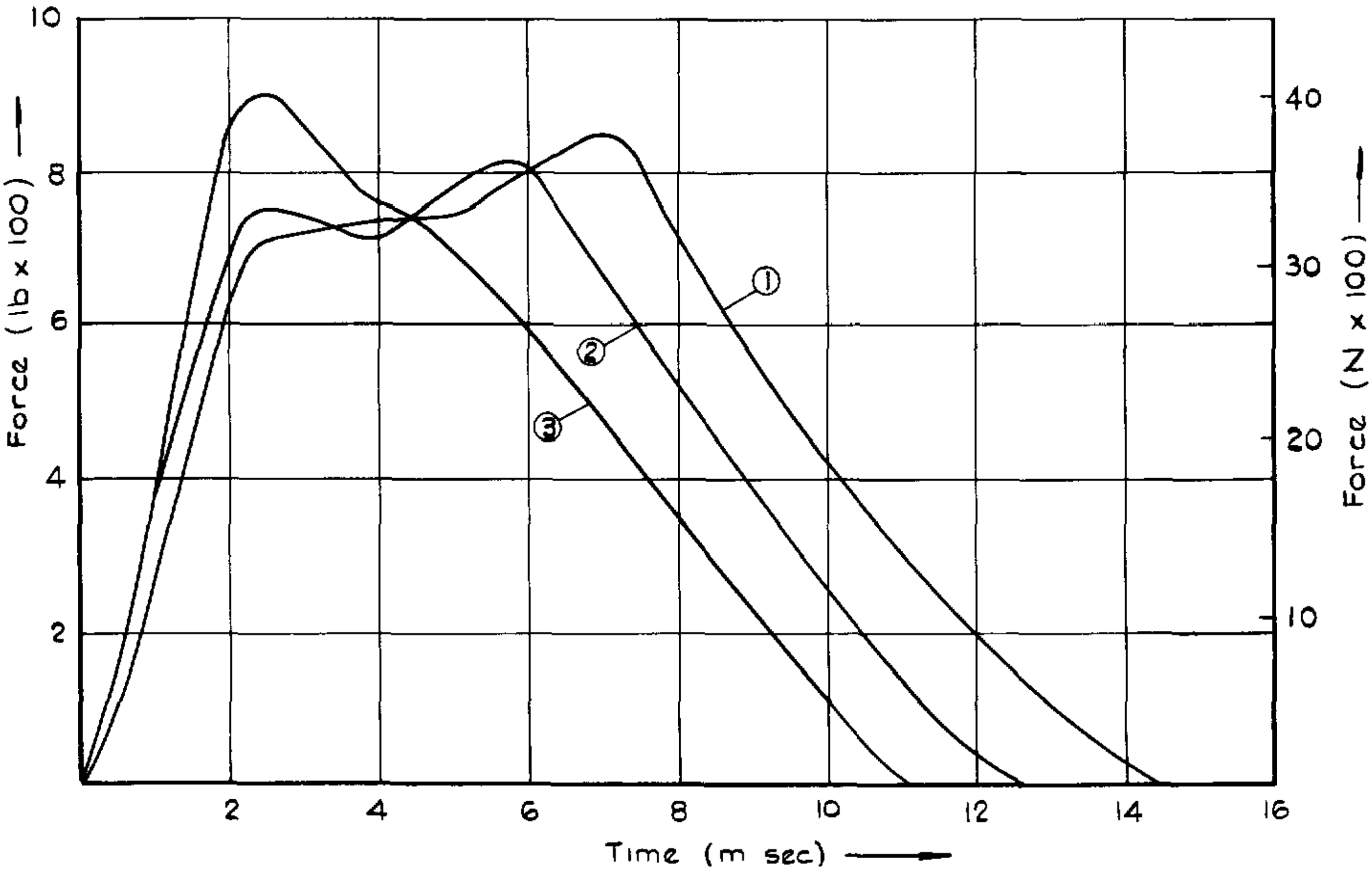
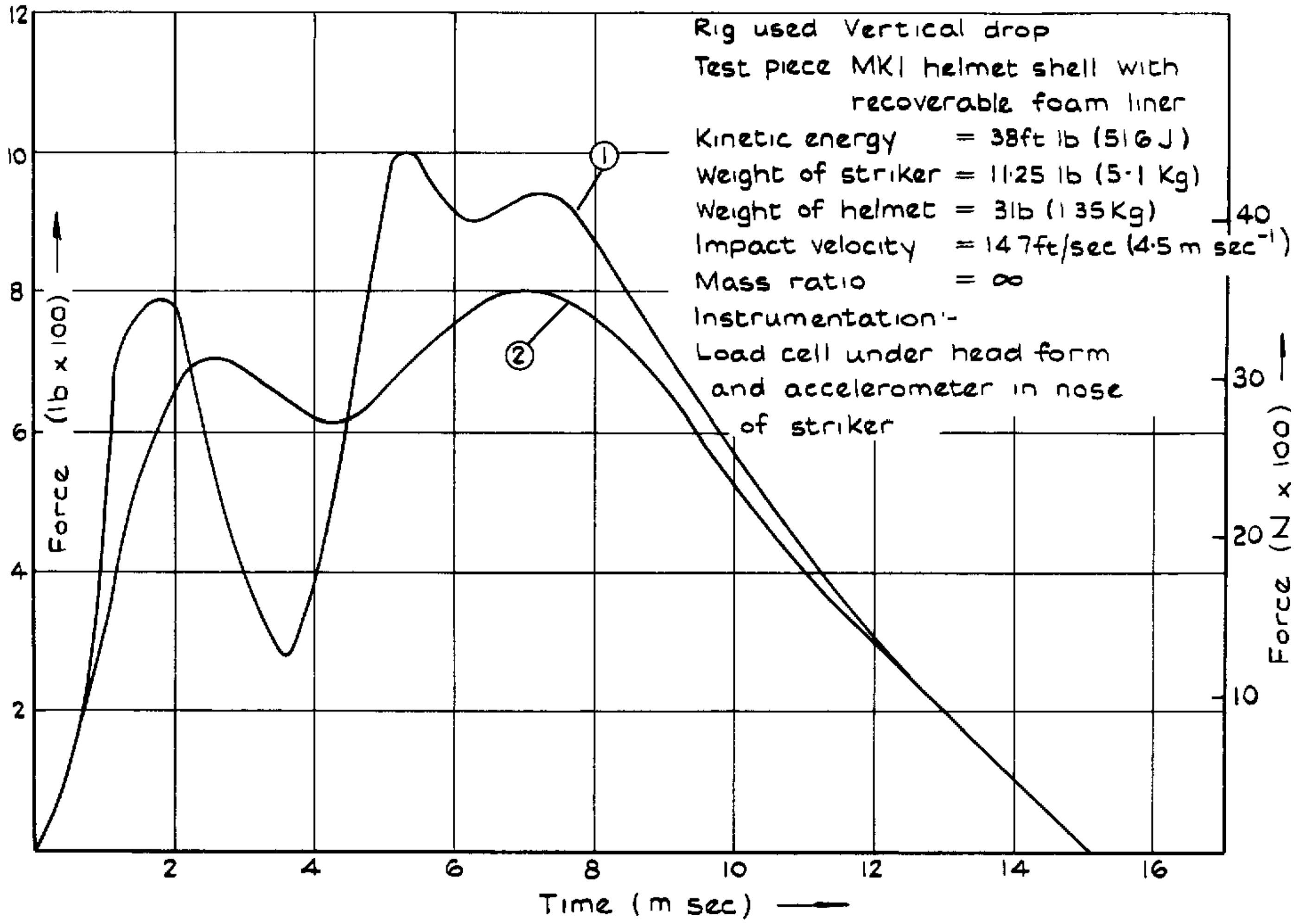
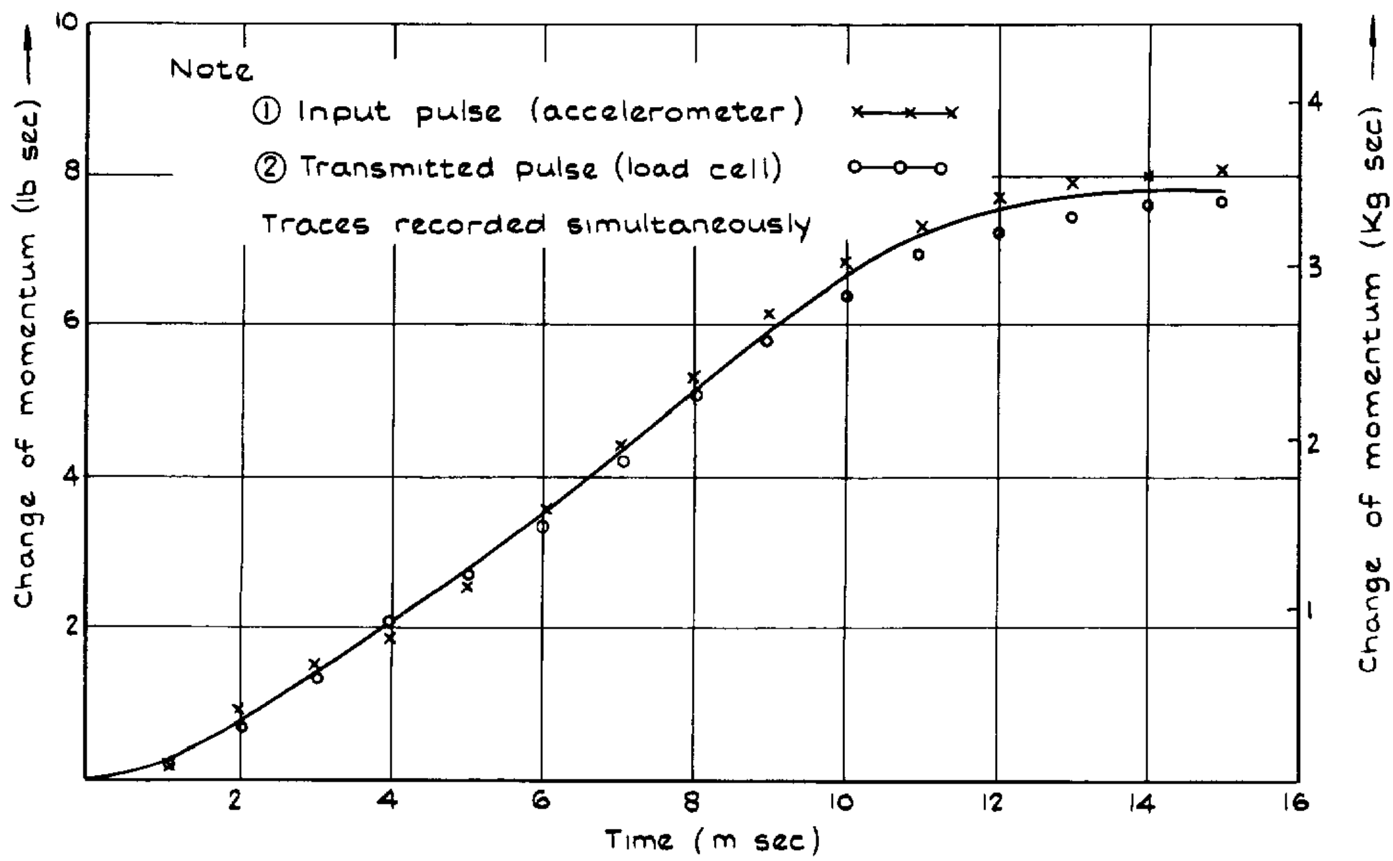


Fig 14 Constant kinetic energy: varying momentum

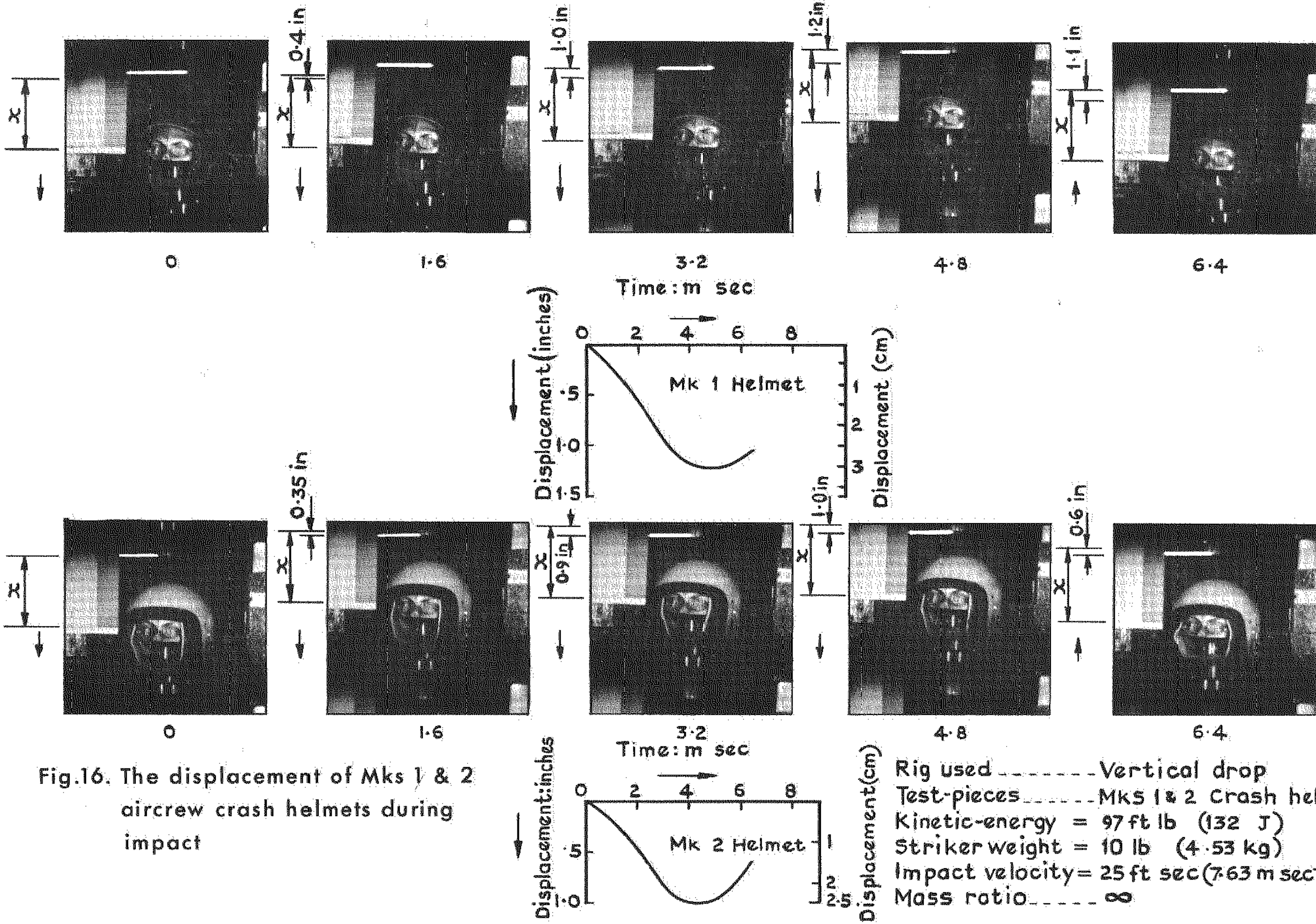


a Force-time



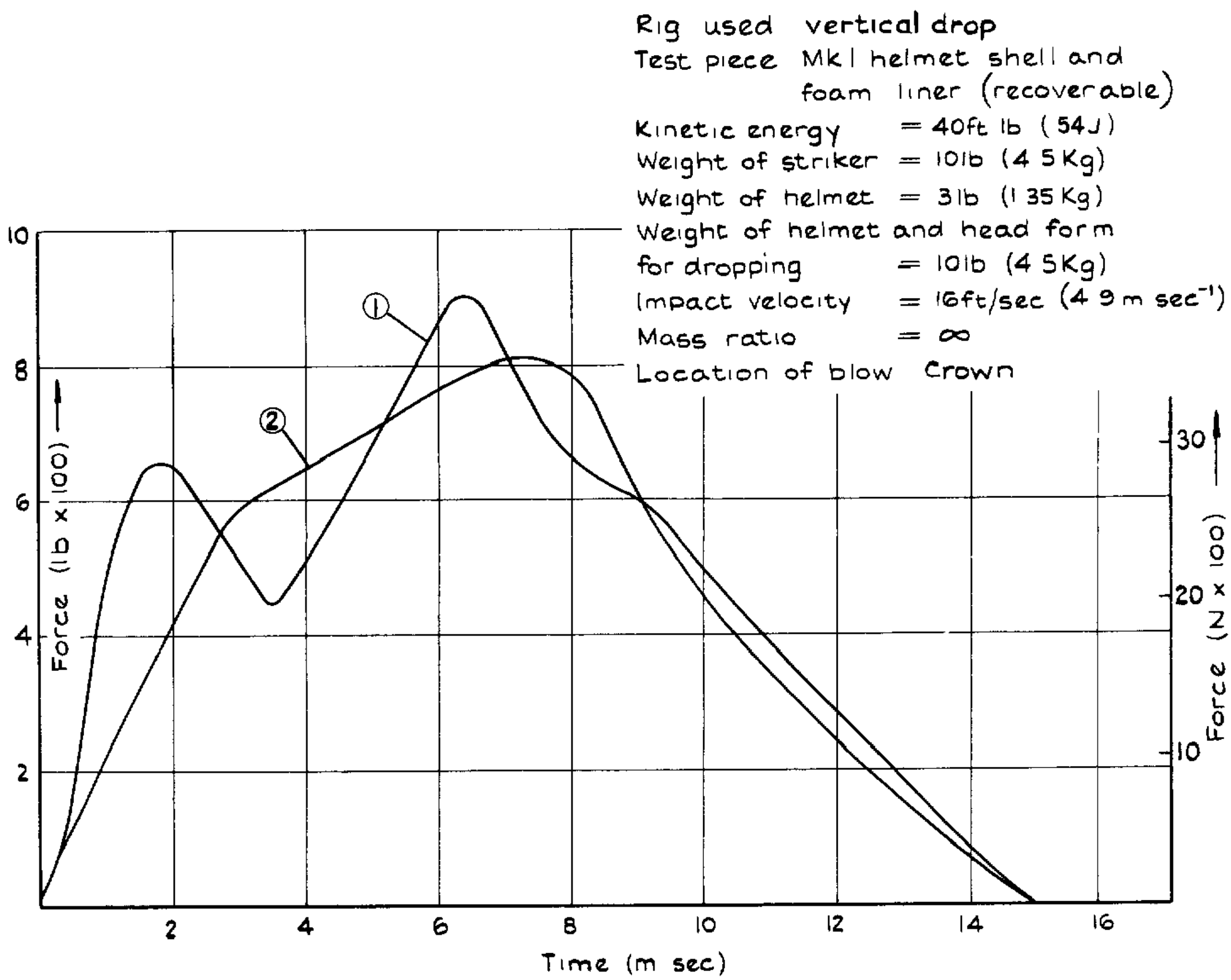
b Change of momentum-time

Fig 15a & b Input and transmitted pulses compared

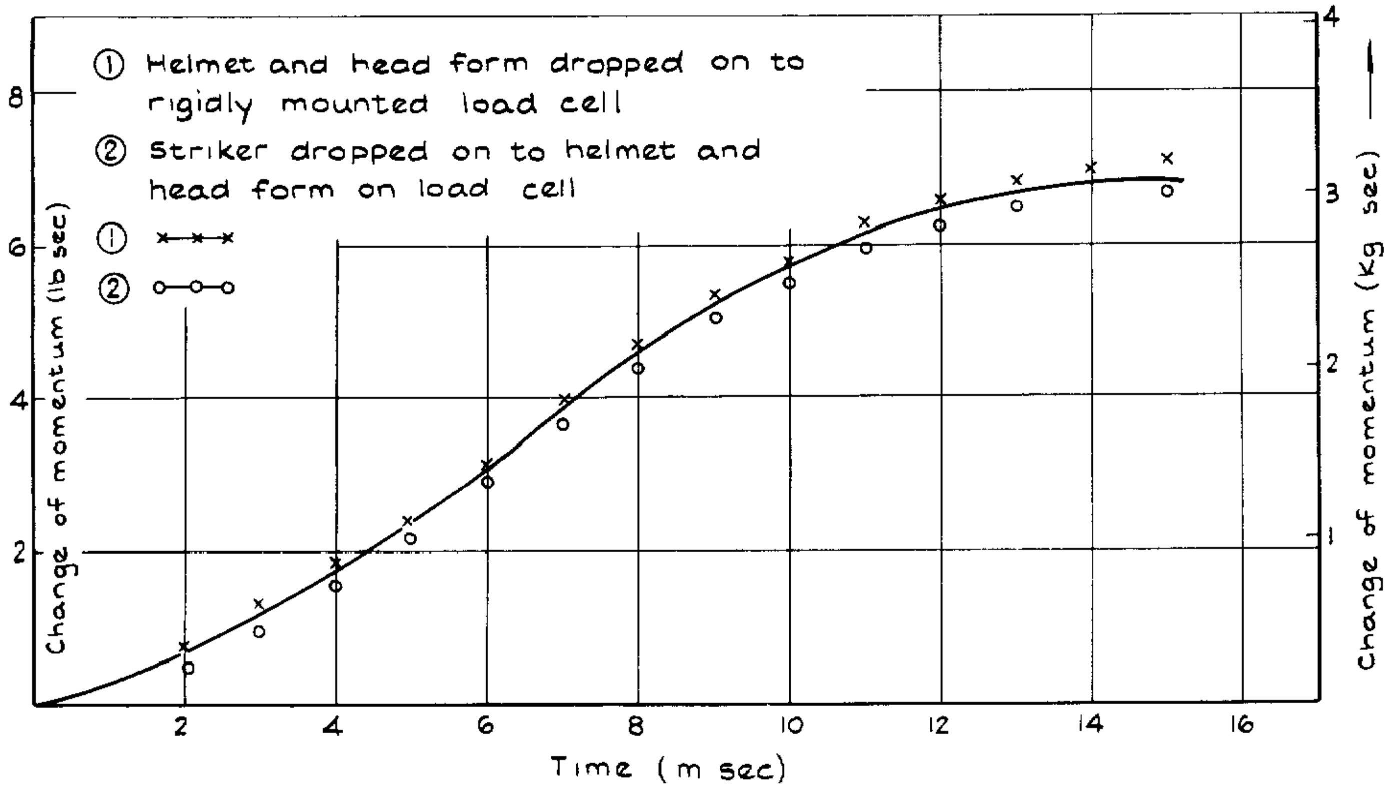


Rig used .... Vertical drop
Test-pieces ...... Mks 1 & 2 Crash helmets
Kinetic-energy = 97 ft lb (132 J)
Striker weight = 10 lb (4.53 kg)
Impact velocity = 25 ft sec (7.63 m sec^{-1})
Mass ratio ..... ∞

Fig.16. The displacement of Mks 1 & 2 aircrew crash helmets during impact



a Force -time



b Change of momentum -time

Fig 17a & b The effect of dropping a test helmet

Rig used		Vertical drop
Test piece		Mk I shell with foam liner
Kinetic energy	=	97 to 100 ft lb (132 to 136 J)
Weight of striker	=	10 lb (4.5 Kg)
Impact velocity	=	25 to 25.4 ft/sec (7.65 to 7.75 m sec^{-1})
Mass ratio	=	∞
Location of blow	=	Crown

Test done on:-

① RAE rig at 97 ft lb Ke (132 J)

② Ellis Research lab rig at 100 ft lb Ke (136 J)

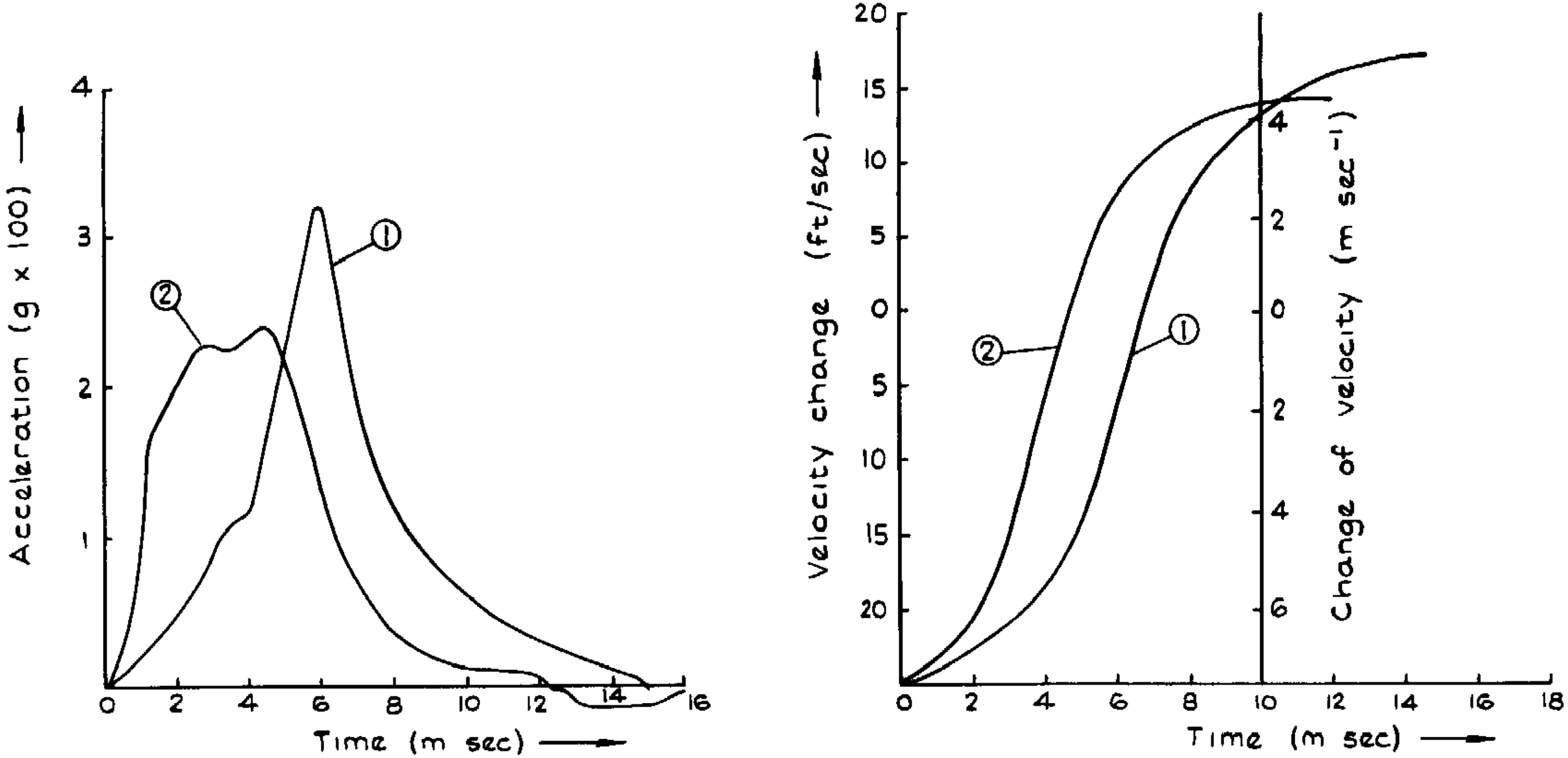


Fig. 18 Comparison of the effects of blows measured on different rigs

Rig used Vertical drop

Test piece' 2 in dia x 1 in plasticine cylinder

Kinetic energy = 97ft lb (132 J)

Weight of striker = 10lb (4 5 Kg)

Impact velocity = 25ft/sec (7 65 m sec^{-1})

Mean measured displacement = 0 75 in (1 88cm)

Mass ratio ∞

2 specimens

(1) Plasticine from new packet ×—×—×

(2) Old plasticine, exposed to air for many months o—o—o

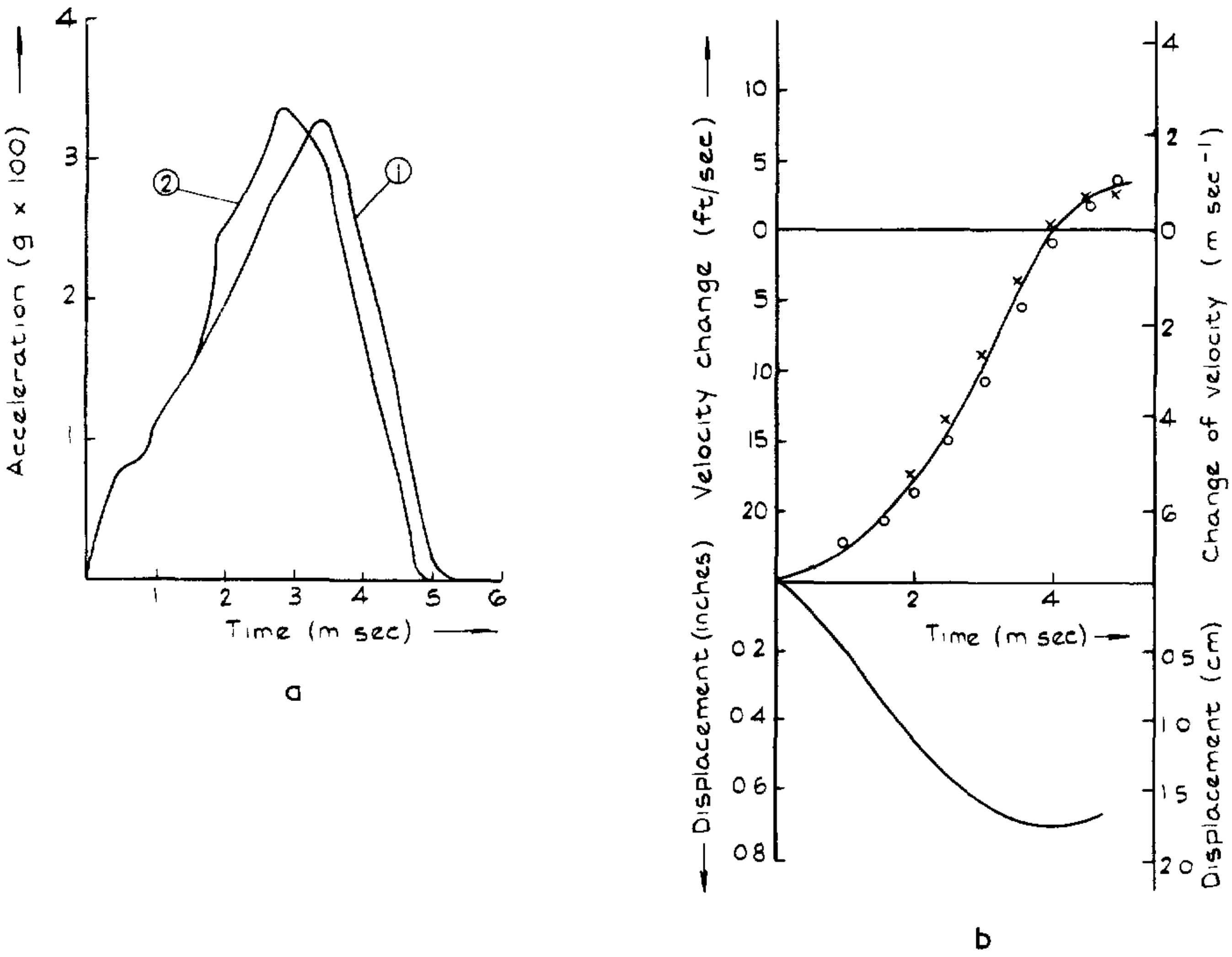


Fig 19a & b A cylindrical plasticine test-piece

Rig used: Pendulum

Test piece: Plasticine cone frustum

Kinetic energy = 100 ft lb (136 J)

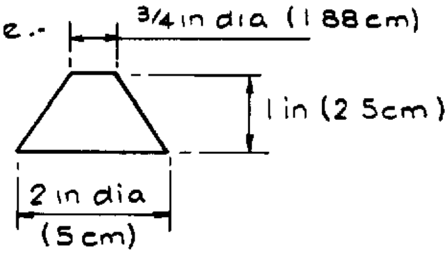
Weight of striker = 10 lb (4·5 Kg)

Impact velocity = 25·4 ft/sec (7·75 m sec^{-1})

Mean measured deflection = 0 825 inch (2 06 cm)

Mass ratio = 32 : 1

Dimension of test-piece:-



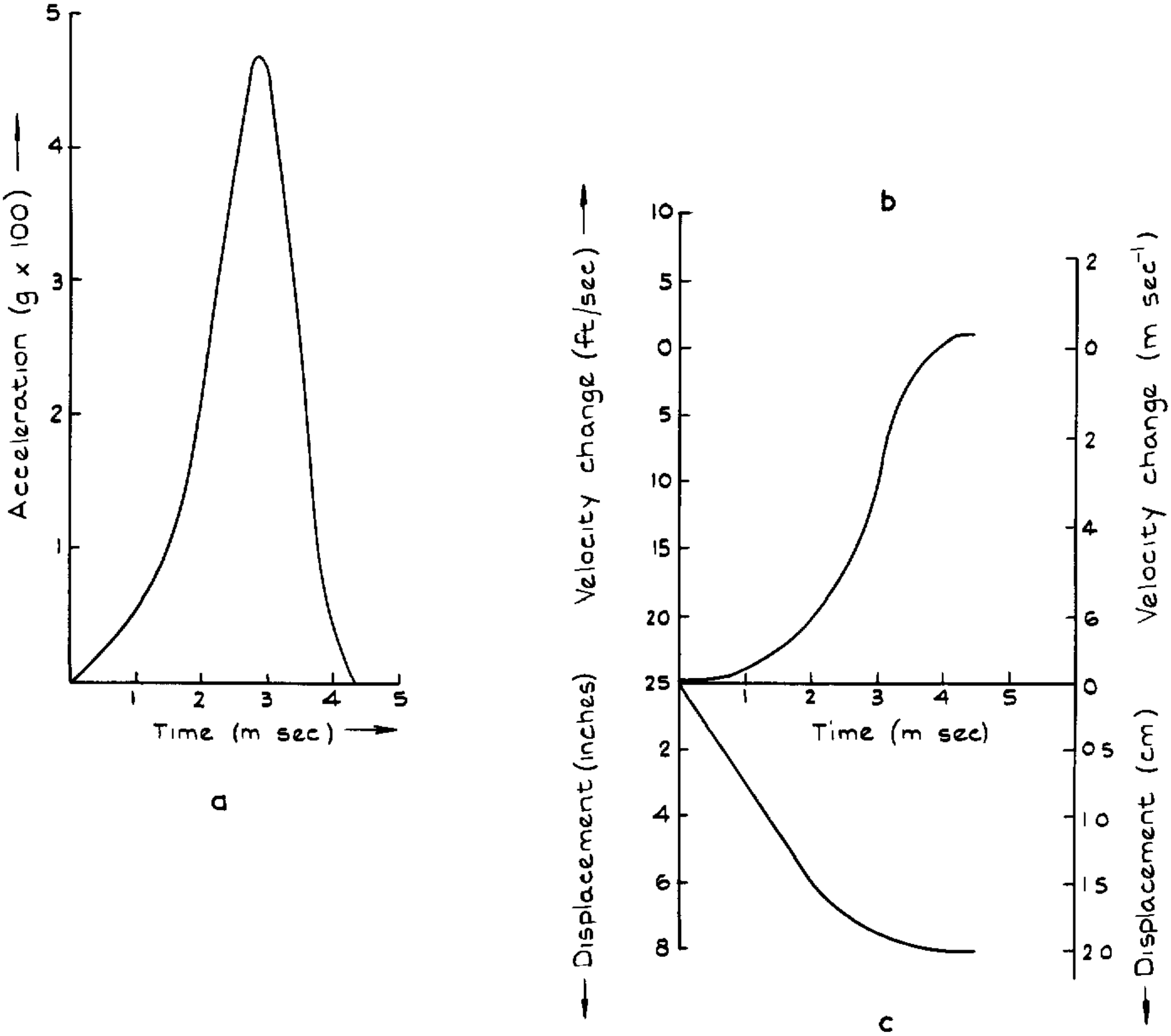


Fig 20 a-c A 1 inch conical plasticine test-piece

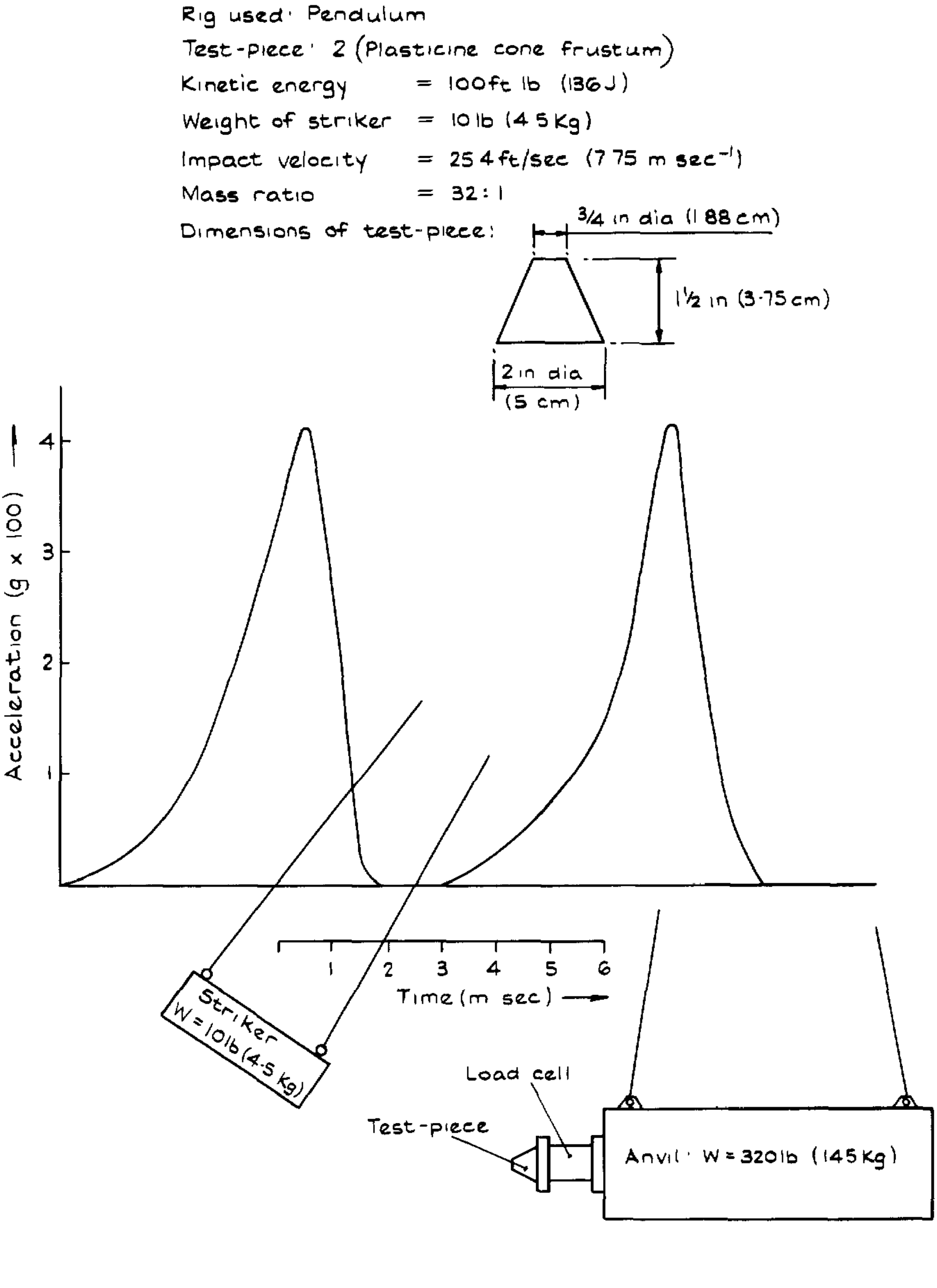


Fig. 21 1½ inch conical plasticine test-pieces compared on pendulum rig

Rig used Vertical drop

Test-piece 2 (Plasticine cone frustum)

Kinetic energy = 100ft lb (136J)

Weight of striker = 10lb (4 5Kg)

Impact velocity = 25 4ft/sec (7 75m sec^{-1})

Mass ratio = ∞

Dimensions of test-piece

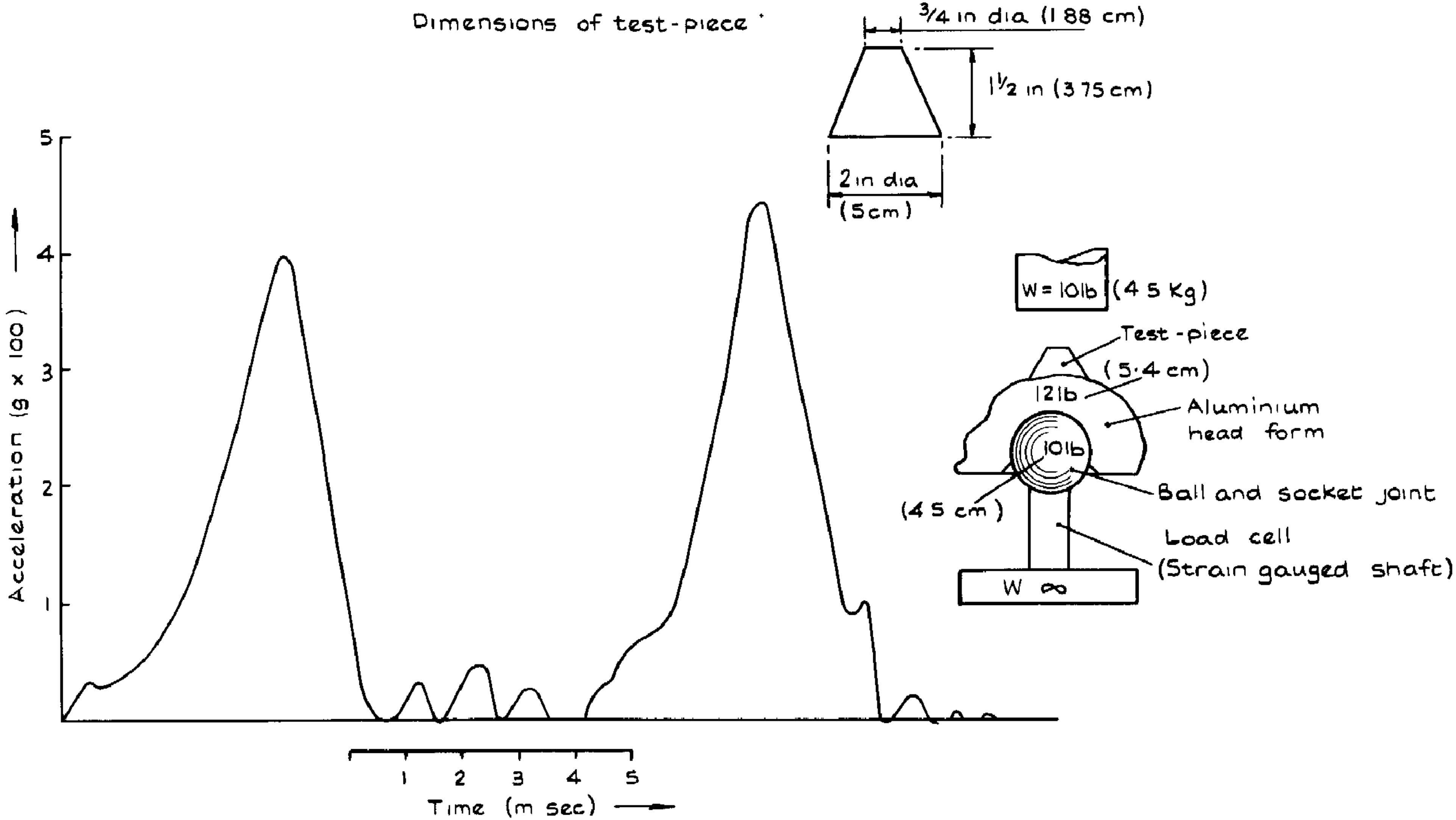


Fig 22 1½ inch conical plasticine test-pieces compared on vertical drop rig

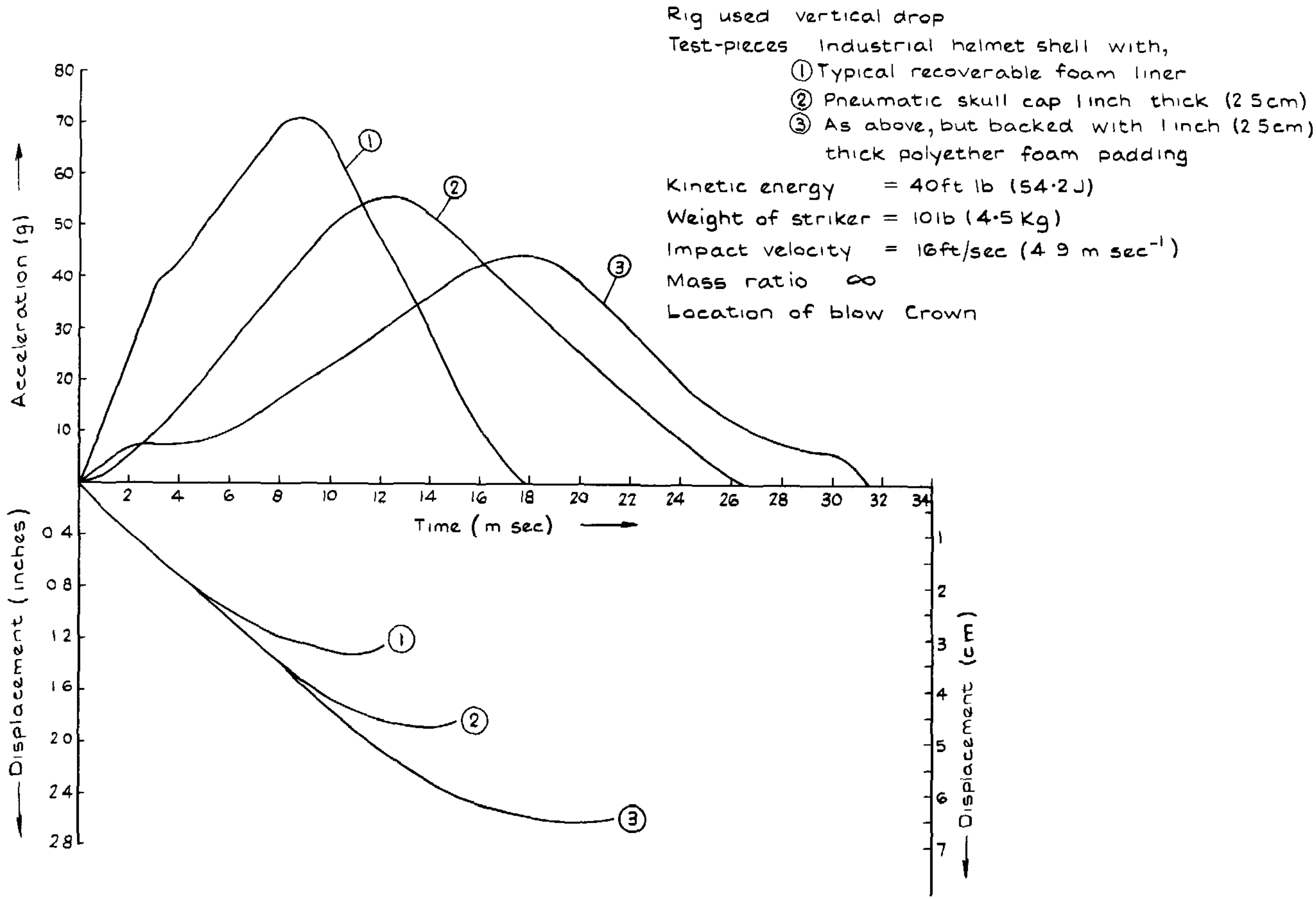


Fig 23 Stopping distance

Note
Volume of liner was too large and during impact displaced air inflated remote parts of air bag instead of escaping to atmosphere

Rig used: Vertical drop
Test-piece: MkI shell with full cover pneumatic liner
Kinetic energy = 30ft lb approx (40 6 J)
Impact velocity = 9 25ft/sec (2 8m sec^{-1})
Mass ratio ∞
Location of blows: Crown
Pressure transducer fitted in liner
Trace ① Liner sealed
② 1mm dia jet outward leak

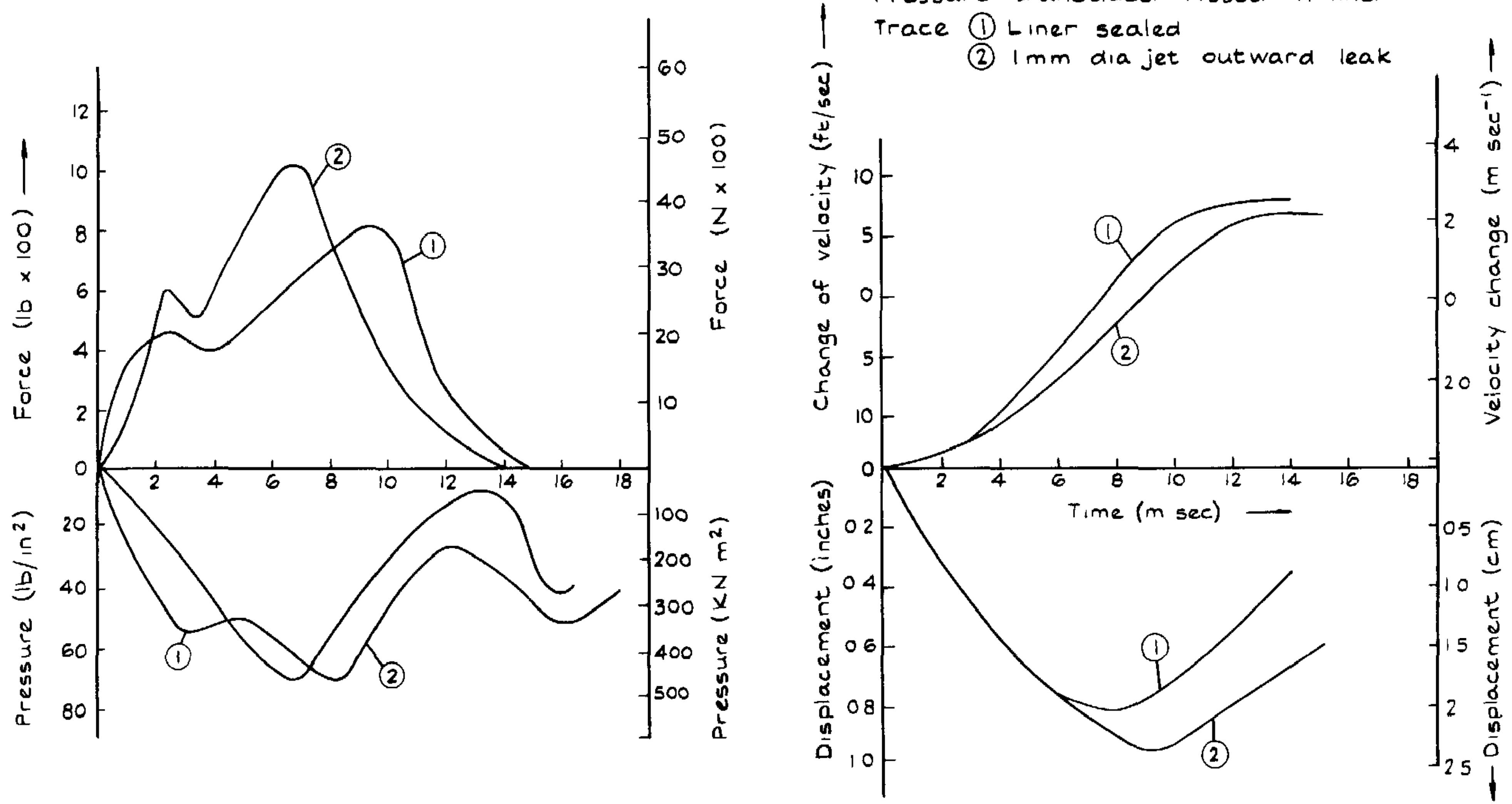


Fig 24 Pressure rise in pneumatic helmet liner during impact

(1) Plasticine cylinder 2 in dia x 1 in long
Peak acceleration = 325g
Measured displacement = 0 75 inch (1 9 cm)

(2) Plasticine cone frustum base 2 in dia, apex 3/4 in dia, height 1 1/2 inches (base 5cm, apex 1 9cm, height 2 5cm)
Peak acceleration = 475g
Measured displacement = 0 825 inch (2 06cm)

(3) Damaged Mk1 helmet
Peak acceleration = 725g (bottomed)

(4) Mk 2 helmet
Peak acceleration = 230g
Measured displacement (film) = 1 2 inch (3cm)

(5) Mk1 helmet (new)
Peak acceleration = 185g
Measured displacement (film) = 1 4 inch (3 5cm)

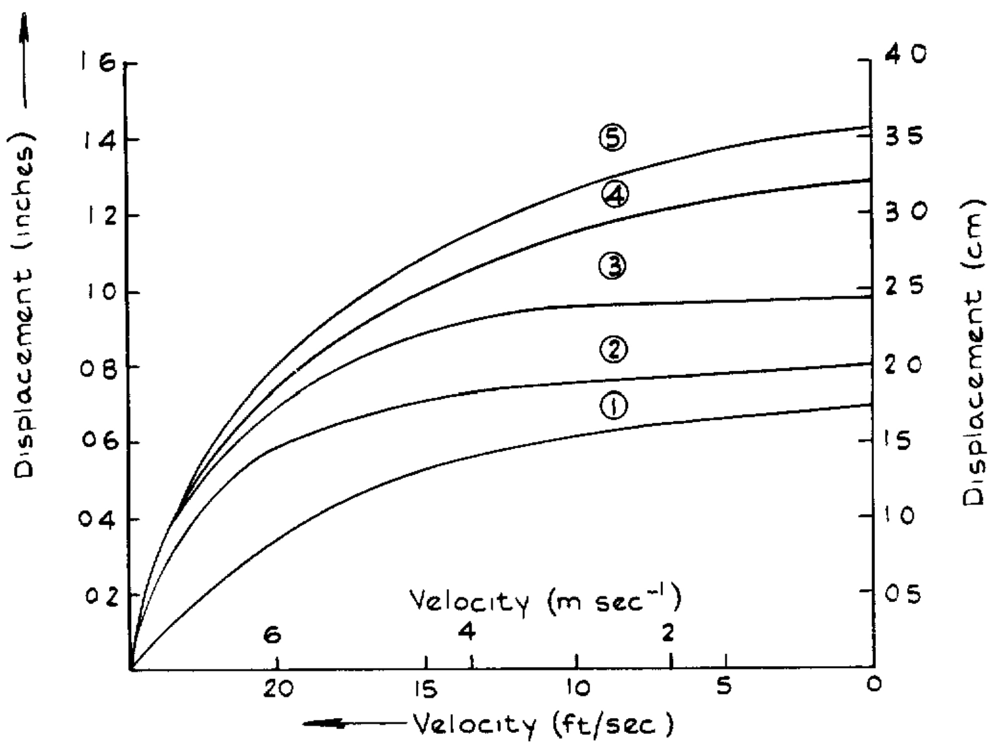


Fig 25 Displacement and velocity change for several test specimens during impact

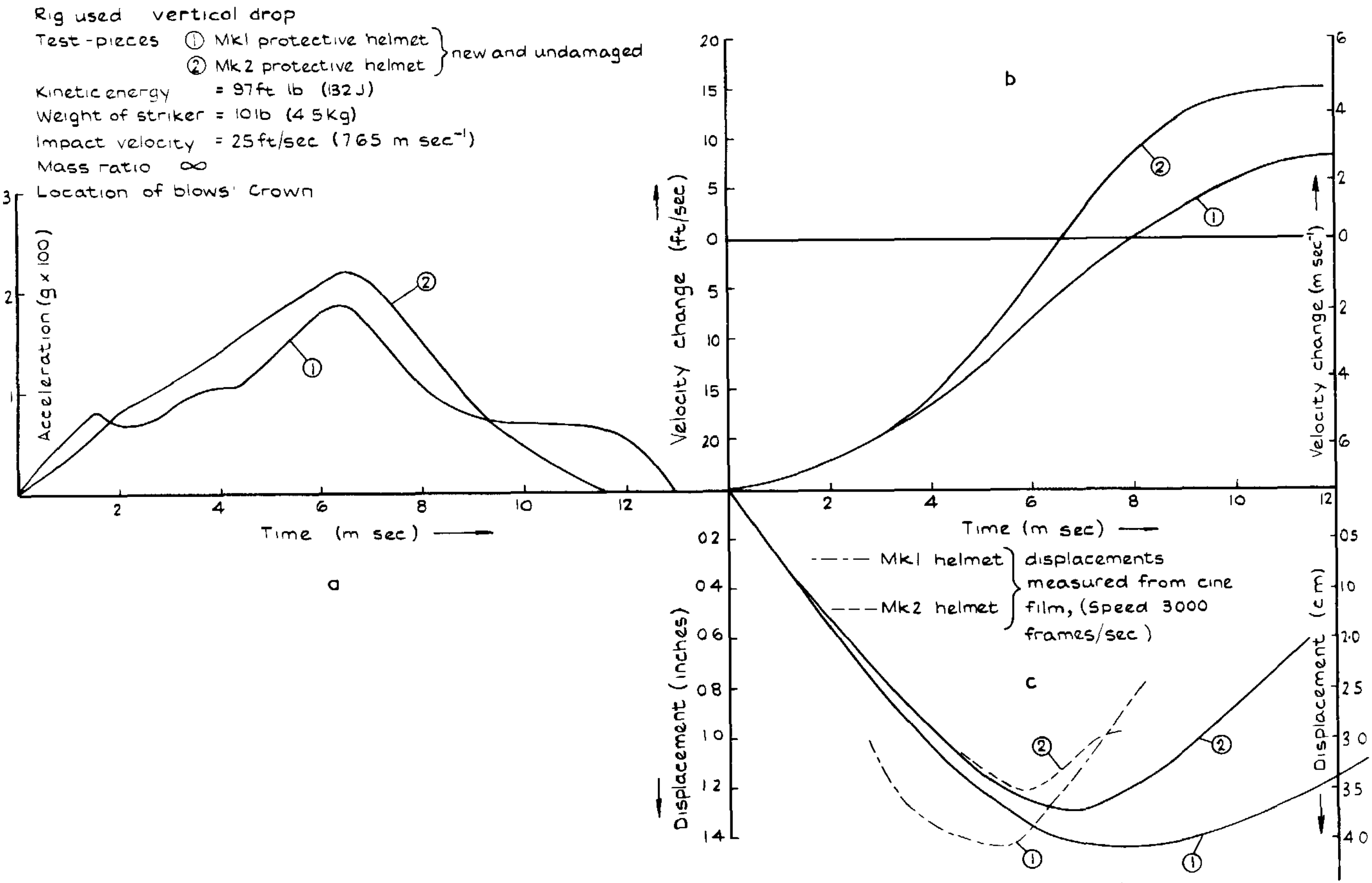


Fig 26 a-c Blows on Mks 1 and 2 protective helmets compared

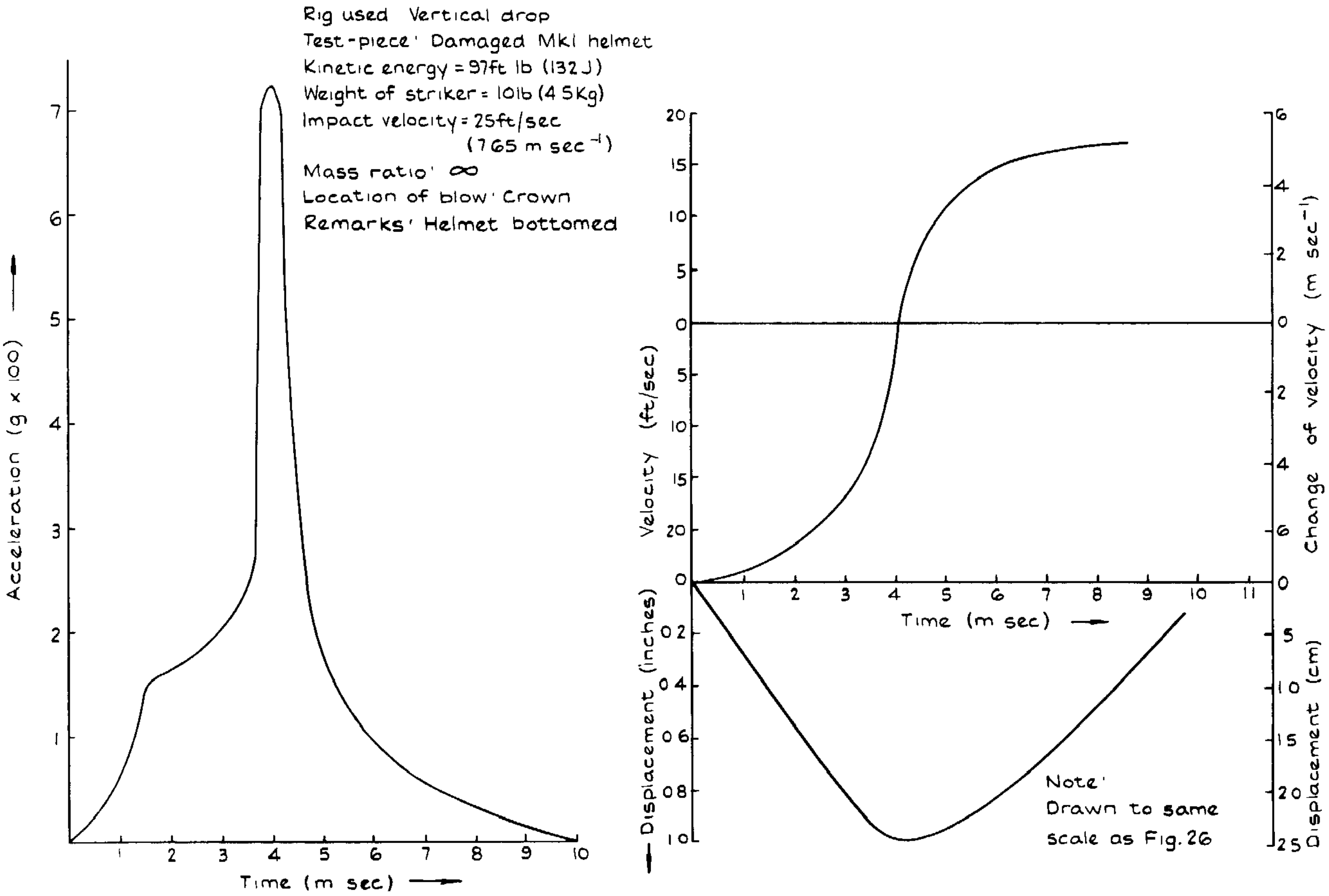


Fig 27 A case of bottoming - Mk I protective helmet

Rig used: Pendulum

Test-piece: Mk I helmet complete

Kinetic energy = 100ft/lb (136J)

Weight of striker = 10lb (4·5Kg)

Weight of helmet and mounting = 12 5lb (5 6Kg)

Impact velocity = 25 4ft/sec (7 75 m sec^{-1})

Mass ratio = 1 25 1

Location of blows:

Trace (1) :- Crown

Trace (2) :- Ear cover

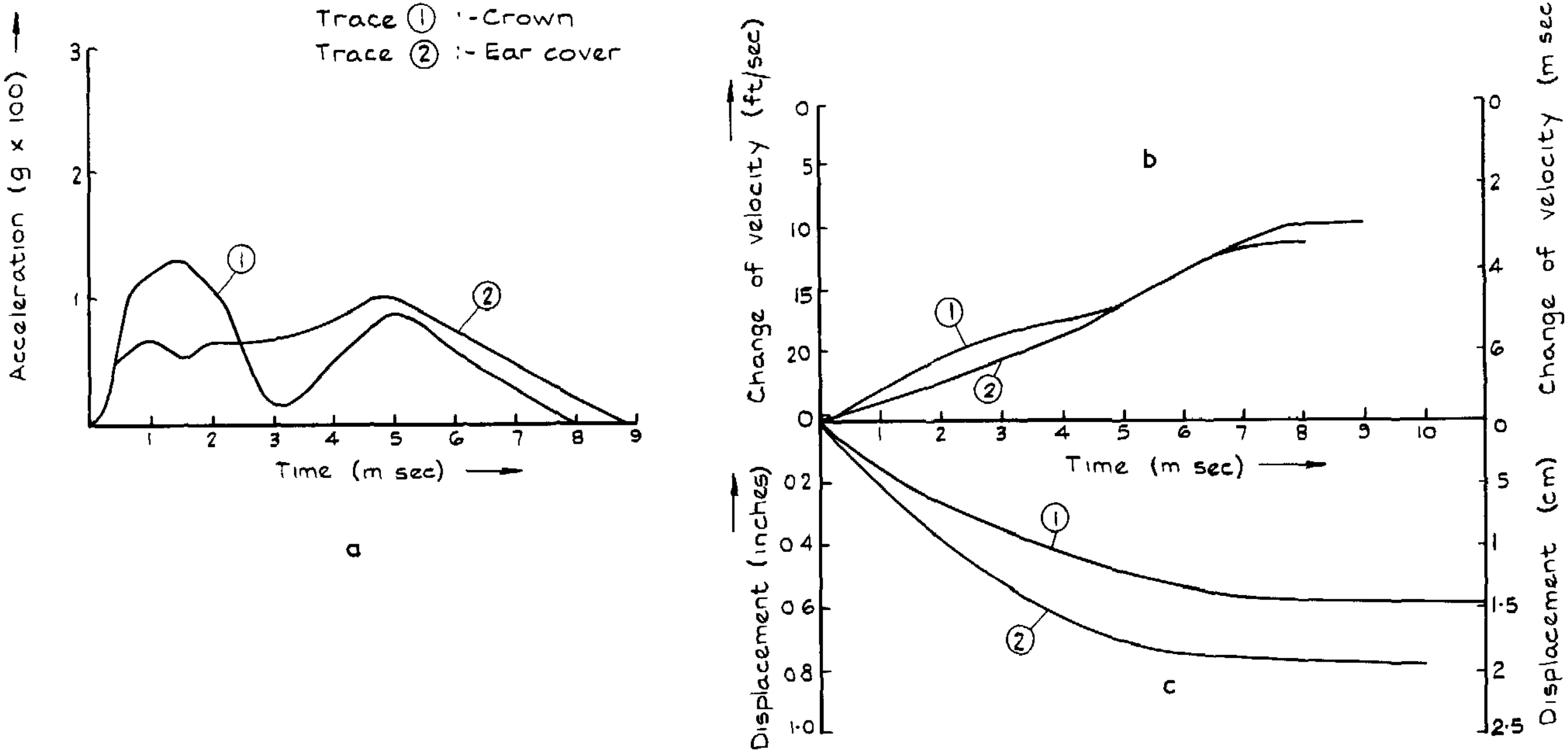


Fig 28 a-c Mk I protective helmet tested on pendulum rig

Rig used Pendulum

Test-piece: Mk 2 helmet complete

Kinetic energy = 100ft/lb (136 J)

Weight of striker = 10 lb (4·5 Kg)

Weight of helmet and mounting = 13 lb (5 8 Kg)

Impact velocity = 25 4 ft/sec (7 75 m sec^{-1})

Mass ratio = 1 3 : 1

Location of blows

Trace (1) :- Crown

Trace (2) :- Ear cover

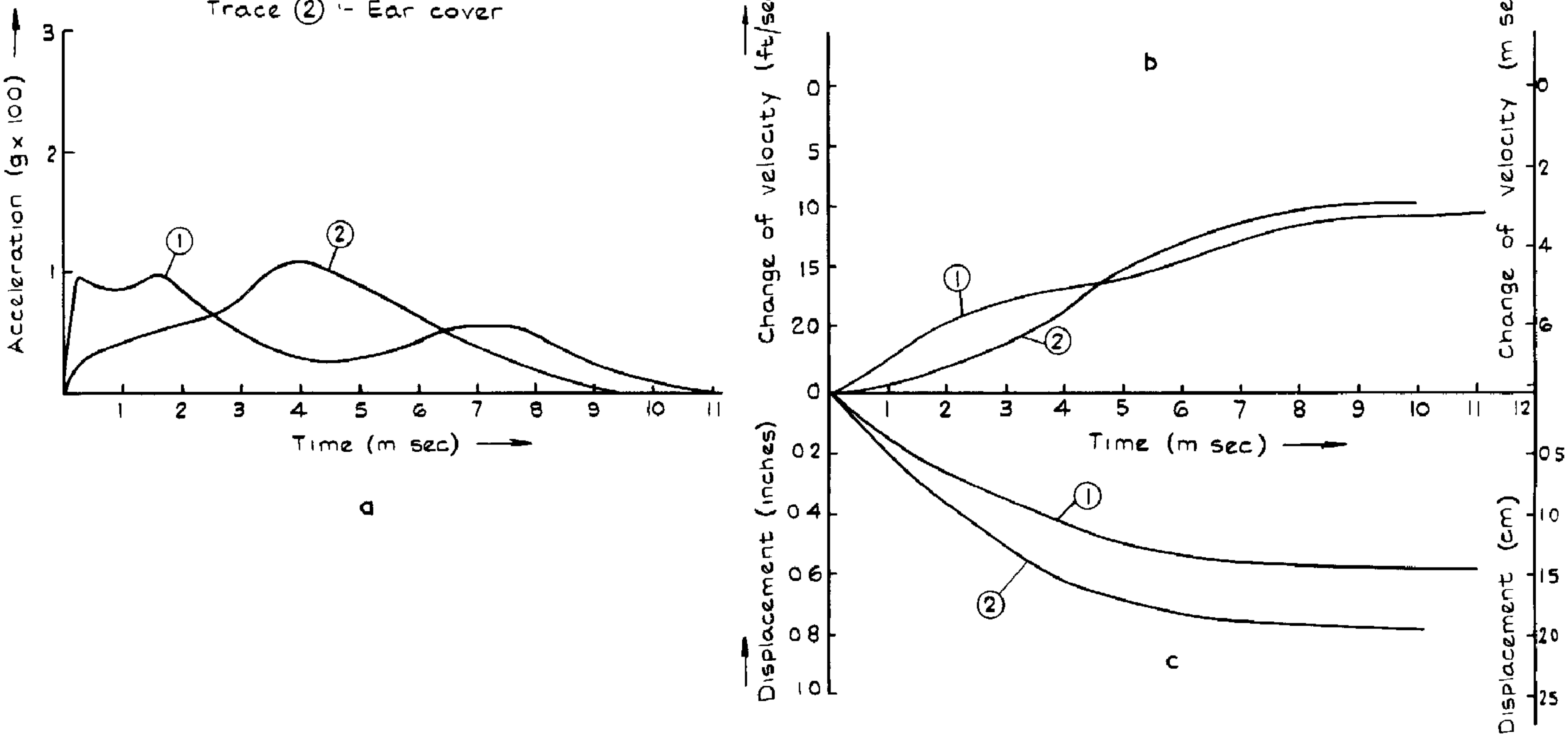


Fig. 29 a–c Mk 2 protective helmet tested in pendulum rig

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Rayne, J M

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